Test Report

bsi.

Report No	TR/12/562
Client	UK Water Treatment Association Unit 27 Loughborough Technology Centre Epinal Way Loughborough Leicestershire LE11 3GE
Authority & date	Project No. 2/36622 (SMO 7909483) 21 March 2012
Items tested	Corrosion Tests in Central Heating Systems filled with Hard and Base-Exchange Softened Hard Mains Water.
Specification	Bespoke Corrosion Test Schedule
Results	The above heating systems have been evaluated to the requirements of the above specification with the results detailed in this test report.
Prepared by	S Mingle
Authorised by	Robert J Floyd R J Floyd
Issue Date	28 November 2012
Conditions of issue	This Test Report is issued subject to the conditions stated in current issue of CP0322 'Conditions of Contract for Testing'. The results contained herein apply only to the particular sample/s tested and to the specific tests carried out, as detailed in this Test Report. The issuing of this Test Report does not indicate any measure of Approval, Certification, Supervision, Control or Surveillance by BSI of any product. No extract, abridgement or abstraction from a Test Report may be published or used to advertise a product without the written consent of the Managing Director, Testing Services, who reserves the absolute right to agree or reject all or any of the details of any items or publicity for which consent may be sought.

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Description of Heating Systems

This report covers the laboratory evaluation of the corrosivity of hard and base-exchange softened hard mains water in central heating systems (detailed below) as requested by the UK Water Treatment Association.

The heating systems evaluated consist of the following:

Description of Heating Systems	
Hard Water System	**Softened Water System**
Ideal Logic + Combi 24 (Serial no. ZJ 20487300024851) (BSI sample no. 7856)	Ideal Logic + Combi 24 (Serial no. ZJ 20487300024853) (BSI sample no. 7855
10 off Convector Radiators (8 single & 2 double)	10 off Convector Radiators (8 single & 2 double)
20m, 15mm dia copper piping	20m, 15mm dia copper piping
10m, 22mm dia copper piping	10m, 22mm dia copper piping
Sample Attleborough mains water	Sample Attleborough mains water (softened)

The laboratory evaluation consists of three phases as follows:

Phase 1 Setting up & commissioning of the central heating systems corrosion resistance test rigs

Phase 2 The corrosion rigs being operated in a 2 hours ON/ 2 hours OFF cycling mode in Maximum rate, Full Load central heating mode (nominal 80°C/60°C flow and return).

Phase 3 The data analysis of the corrosivity of natural hard and base-exchange softened hard mains water against a range of metals.

Phases 1 and 2 was carried out by BSI to enable the above mentioned data analysis to be undertaken.

Phase 3 was carried out by Midlands Corrosion Services Ltd. (on behalf of the UK Water Treatment Association). The analysis report (Midland Corrosion Services report number 0399) is included in Appendix A of this report.

Photograph of Test Rig

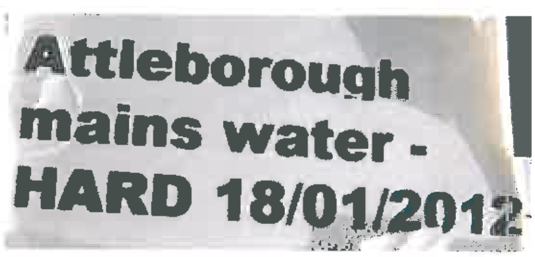
Heating Systems

Typical rack configuration of weight loss coupons

Coupon Vessels

<u>Specification details of Soft and Hard Waters</u>

The hard and softened waters supplied for testing were marked as follows:

<table>
<tr><th>Soft-water</th><th>Hard water</th></tr>
<tr><td>
</td><td>
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Test Programme

At the request of UK Water Treatment Association, the test rigs were operated as follows:

1) 3 off metal coupon bundles (one per heating system) being installed in the test rigs and with the boilers being operated on a 2 hours ON/ 2 hours OFF cycle in the maximum rate, Full Load central heating mode for a six month duration.

2) The coupon bundles being removed and examined after a 1 month, 3 months and 6 months periods. In addition, the following components being examined after the 6 months period:

   - Main boiler heat-exchanger of both the hard and base-exchange softened hard mains water circuits
   - 1 off Radiator (hard water circuit)
   - 1 off Radiator (base-exchange softened hard mains water circuit)

3) BSI engineers witnessing the methodology of determining the corrosion rates of final coupon bundles at Midland Corrosion Services Ltd.

Comments on Test Programme

Item	Comments
General	Midland Corrosion Services Ltd. operates a quality management system to ISO 17025 for Buildcert testing accreditation.
General	BSI engineers witnessing of the final results was restricted to the methodology of determining of the corrosion rates of final metal coupon bundles. The analysis was carried out by Midland Corrosion Services Ltd.

Interpretations and General Conclusions

Over the lifetime of a modern central heating system, filling with base-exchange softened hard mains water would appear to present no significantly greater risk of corrosion of system metals than filling with hard mains water.

The test rig corrosion study has shown that base-exchange softened hard mains water is more corrosive towards aluminium than hard mains water in the first few weeks after filling a central heating system, but the corrosion rate soon settles to a level that is insignificant in practical terms. Extrapolation of aluminium general corrosion rates determined in the test rig corrosion study show long term performance in base-exchange softened hard mains water that equates to a service life in excess of 100 years for a heat exchanger with 5 mm wall thickness.

In addition, although a few pits were found in the bottom waterways of the heat exchangers from both rigs after 6 months testing, these were very shallow and indicate that base-exchange softening would not lead to premature failure of cast aluminium heat exchangers due to localised attack. The test rig corrosion study has shown that in de-aerated central heating system conditions (the normal operating environment) a protective layer builds up on aluminium over time in base-exchange softened hard mains water that appears to protect the underlying aluminium from further corrosion.

The test rig corrosion study has shown that base-exchange softened hard mains water is actually less corrosive towards steel components than hard mains water under the same conditions. In both hard and base-exchange softened hard mains waters the corrosion rate of steel in de-aerated central heating system conditions is insignificant in practical terms.

Whilst the levels of corrosion in the test rig corrosion study of the common system metals in de-aerated central heating system conditions was insignificant in practical terms, the use and maintenance of appropriate scale and corrosion control measures, such as inhibitors, is recommended to ensure that system efficiency and performance is maintained in the longer term when aeration of system waters is always possible.

Appendix

Midland Corrosion Services Ltd.

Report No. 0399

Results from Testing Corrosivity of Hard and Softened Water in Model Central Heating Systems

Midland Corrosion Services Ltd.

Report Number: 0399

Results from Testing Corrosivity of Hard and Softened Water in Model Central Heating Systems at BSI, Loughborough

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1) Introduction

Two identical model central heating systems have been constructed at BSI, Holywell Park, Loughborough to determine the corrosivity of natural hard water and following base-exchange softening against a range of metals.

Metal coupon bundles were installed at the start of the test by Midland Corrosion Services Ltd and removed after 1 month, 3 months and 6 months for determination of corrosion rates. In addition, at the end of the 6 months period, the aluminium heat exchangers from Ideal Logic+ boilers and a radiator from each of the test rigs were sectioned by MCS and inspected for any internal damage. Water samples were also taken for chemical analysis at the start of the test and at 1, 3 and 6 month intervals. Midland Corrosion Services Ltd. are a BuildCert approved laboratory for carrying out the DWTA evaluation test for chemical inhibitors for use in domestic central heating systems. In order to maintain this accreditation, annual audits to ISO 17025 quality management system are carried out by BuildCert. The work reported in this report has also been carried out according to ISO 17025.

2) Method

The metal coupons used were supplied by European Corrosion Supplies Ltd and had dimensions 50 x 25mm central hole with a bead-blast finish. The specification of the alloys used is shown in table 1 below.

Metal	Specification
Steel	EN 10130:1999 Grade DC01
Copper	CW024A
Aluminium (extruded)	AW-6063
Brass	CW505L
Stainless steel	1.4307 (304S11)

Table 1 Grades of metal coupons used in tests

Before exposing to the test waters, the coupons were rinsed in demineralised water, rinsed in methanol and then dried in warm air. They were then weighed individually to 5 decimal places using a Mettler Toledo analytical balance. Coupon bundles were then made by assembling the coupons onto a brass threaded bolt with PTFE sleeves and PTFE spacers to stainless steel plates so that there was no electrical contact between any of the coupons and between the coupons and the stainless steel plates. The order of assembly of the coupons was aluminium, mild steel, stainless steel, brass and copper. Two coupon bundles were tightly fastened to the stainless steel plates so that there were duplicate measurements for each test water and time period. After assembly of the coupon bundles, they were stored in a desiccator until placed in the test rigs.

At the start of the 6 month tests, the coupon bundles and holders were placed separately in 1 litre stainless steel vessels (3 for each rig). The vessels were then quickly filled with the recirculating test waters and the tests started. Fig 1 shows two coupon bundles attached to the stainless steel plates after removal from a stainless steel vessel at the end of a test period.

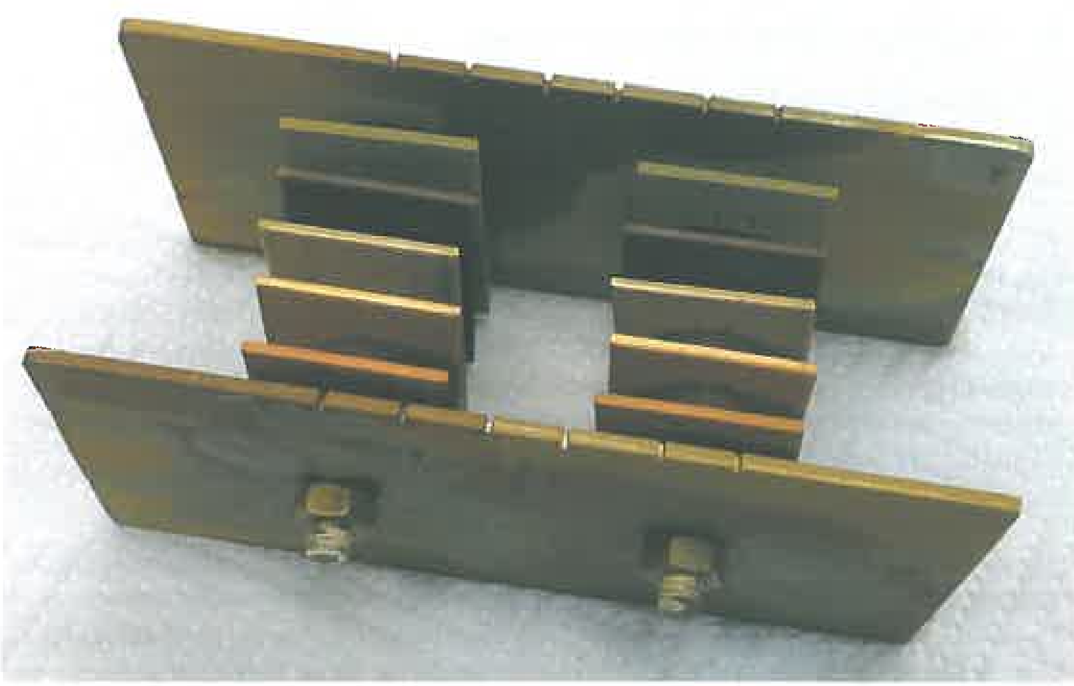


Figure 1 Coupon bundles after removal from rig.

Upon removal of coupon bundles from the rigs after the 1, 3 or 6 month time period, the bundles were rinsed in demineralised water, rinsed in methanol and dried in warm air before disassembly. They were then wrapped individually in paper towelling and transported back to MCS's laboratory in sealed plastic bags containing silica gel.

Coupons were photographed after testing and before weighing and cleaning. The coupons were weighed using the same Mettler Toledo analytical balance. Cleaning was carried out according to ASTM G-1 (the same procedure as specified in the BuildCert approved inhibitor evaluation test). By conducting several cleaning and weighing steps until the mass loss between each step was less than 1mg, a corrected mass loss was obtained. From this, a general corrosion rate for each coupon was obtained and a mean corrosion rate for the 2 coupons of the same metal and under similar exposure conditions was determined.

The two heat exchangers and two radiators removed at the end of the 6 month test period were sectioned using a band saw. The internal surfaces which had been exposed to the test waters were then photographed. Assessment of any pitting on the aluminium heat exchangers was carried out after removal of any alumina deposits using phosphoric acid/chromic acid solution. The depth of any pits was determined using a digital indicator with narrow tip, which gives a resolution of 0.05mm.

3) Results

a) Appearance of Metal Coupons after Testing

The appearance of the coupons after testing is shown in Appendix 1 in figures 2 to 7. Only one coupon bundle is shown for each test water and duration, since the appearance of coupons from the second bundle were similar.

For the coupons exposed to artificially softened water (Figs 2-4), it was apparent from the appearance that there had been some general rusting of the mild steel coupons after 30 days exposure. The aluminium coupons had also blackened within 30 days. There may have been general corrosion of the copper and brass coupons but the discolouration, as on the stainless steel coupons, may have been due to deposition of other corrosion products. The appearance of the coupons removed after 3 months and 6 months had not changed appreciably from that of the coupons after 1 month exposure.

For the coupons exposed to hard water (Figs 5-7), all of the coupons appeared black or at least darkened on removal after 30 days. It was apparent that this was due to magnetite deposition due to corrosion of steel in the system. The coupons removed after 3 and 6 months also exhibited magnetite deposition, with increasing amounts of deposition with time.

b) Corrosion Rates of Metal Coupons

In appendix 2, the corrected mass losses (in mg) after cleaning and the mean mass losses (in mg) and derived corrosion rates (expressed as mm/year) are shown in tables for each of the metals in turn in the two test waters and over the 3 time periods. The mean corrosion rates are displayed in the histograms.

Aluminium

The mean corrosion rate in base-exchange softened water was found to decrease from 0.21mm/yr after 30 days to 0.084mm/yr after 90 days to 0.052mm/yr after 188 days. However, when one looks at the plots of mass loss after testing and after cleaning (which are shown after the histogram), it is apparent that the initial mass loss was constant at between 40 and 50 mg, i.e. did not increase with exposure time in softened water. The cleaning of these coupons in inhibited chromic/phosphoric acid showed that the solution formed film became thicker over time and removal of this on cleaning contributed to more than half of the total mass loss. Since this film was compact and coherent, it could be argued that the film was protective and its formation did not contribute to increased corrosion of the aluminium.

In the hard water, the mean corrosion rates for aluminium decreased from 0.11mm/yr after 30 days to 0.022 mm/yr after 90 days. However, there was a slight increase to 0.026mm/yr after 188 days.

What is striking, however, is the shape of the mass loss curves produced on cleaning and how this differed from those obtained with Al coupons exposed to softened water. Whilst the Al coupons in base-exchange softened water all showed an initial and constant mass loss of 40-50mg after testing, the coupons in hard water all showed a substantial mass gain of over 200mg. The mass gain actually increased from around 240mg after 30 days to around 330mg after 6 months. The mass gain would appear to be due to deposition of magnetite on the aluminium. Nevertheless, cleaning in chromic/phosphoric acid did eventually remove this deposit and then the solution formed film on the aluminium. After 6 months exposure, over 30 minutes of cleaning was required to get back to the aluminium surface, which contrasted to the 4 or 5 minutes usually required.

Therefore, although the corrosion rates for aluminium on softened water were found to be higher than in hard water by a factor of around 2, the longer term behaviour of aluminium in softened water is likely to be better than this. Deposition of a coherent magnetite layer on the aluminium coupons in hard water could also have reduced the amount of corrosion measured on these coupons.

Mild Steel

The mean corrosion rates for mild steel coupons in base-exchange softened water were found to decrease from 0.0079mm/yr after 30 days to 0.0021mm/yr after 90 days to 0.0014mm/yr after 188days exposure. In hard water the corresponding corrosion rates were 2 to 3 x higher at 0.019mm/yr, 0.0061mm/yr and 0.0034mm/yr.

It is considered likely that the initial corrosion of the steel would have come about due to aeration of the system waters in both rigs at the start of the test. Measurements of dissolved oxygen, taken using a Mettler Toldeo M300 DO meter and sensor were initially measured at around 10% saturation in both rigs. However, after 1 month, these levels had dropped to 0.9% saturation for the softened water rig and 1.0% saturation for the hard water rig.

The reason for the higher corrosion rates found for mild steel in hard water above those found in base-exchange softened water is not clear.

Copper

The mean corrosion rates for copper in base-exchange softened water decreased from 0.00036mm/yr after 30 days to 0.00011mm/yr after 90 days and then remained constant at this very low value. In hard water, the corresponding corrosion rates were between 3 and 5 times higher at 0.0014mm/yr, 0.00055mm/yr and 0.00030mm/yr. However, even these higher rates in hard water were low and would not be a problem in a real system.

Brass

The mean corrosion rates for brass in base-exchange softened water decreased from 0.0012mm/yr after 30 days to 0.00038mm/yr after 90 days and then increased slightly to 0.00049mm/yr after 188 days. In hard water, the corresponding corrosion rates were slightly higher after 30 and 90 days at 0.0017mm/yr, 0.00065mm/yr but slightly lower at the end of the 188 test period at 0.00038mm/yr. Therefore, overall, there was little difference in the corrosion rates of brass in hard and softened water. In addition, although the corrosion rates were higher than with copper, the rates were still low and would not be a problem in real systems.

Stainless Steel

Mean corrosion rates were again higher for stainless steel in hard water than in base-exchange softened water for the 30 and 90 day exposures, although by the end of the 188 day test, they were the same at 0.00013mm/yr. Overall, the general corrosion rates in both waters, as expected were insignificant. For austenitic stainless steel in neutral or near neutral pH waters, pitting corrosion can be more of any issue than general corrosion. However, there was no indication of pitting attack on any of the stainless steel coupons.

c) Corrosion of Heat Exchangers

Images of the aluminium heat exchangers before and after sectioning with a band saw are shown in Appendix 3. The heat exchangers were sectioned into several parts to enable close inspection of the water ways for any signs of deposits and pitting.

The heat exchanger from the base-exchange softened water rig is shown in figures 8 to 16. All the waterways inspected were covered with a thin layer of brown deposit, most likely iron oxide from some corrosion of the steel radiators. None of the water channels showed any signs of pitting or significant wall thinning. On part 7, on the upward facing waterway on the bottom of the heat exchanger,were 3 small mounds of alumina or aluminium hydroxide above small pit sites. A typical one is shown in Figs 15 and 16, before and after cleaning with phosphoric/chromic acid. The dimensions of the pits underneath the mounds were all <1mm across by 0.07mm deep. Hence, they were very shallow and only a tiny fraction of the wall thickness of 5mm.

The heat exchanger from the hard water rig is shown in figures 21 to 27. Like the corrosion coupons removed from this rig, the waterways in the heat exchanger were all coated with a black magnetite layer. In some parts, the magnetite had spalled off in small areas revealing bright aluminium underneath, as shown for part 3 in figure 23. Again, no pitting was found in the internal waterways of this heat exchanger.A solitary pit was found in part 7 in the bottom waterway. On cleaning, this pit was found to be 0.5mm wide and 0.08mm deep. Hence, like the pits found in the heat exchanger from the softened water rig, this pit was of insignificant size.

d) Corrosion of Steel Radiators

A radiator from each of the two rigs was sectioned with a band saw, as shown in figures 17 and 28 in Appendix 3, in order to inspect the top, bottom and vertical waterways. The appearance of the waterways from the base-exchange softened water rig are shown in figures 18 to 20 and from the hard water rig in figures 29 to 31. All of the waterways exhibited some slight general corrosion with light deposits of iron oxides but there was no significant thinning or pitting corrosion observed.

e) Water Analysis Results

Water analysis results from samples taken at the start, 30 day, 90 day and at the end of the test are given in Appendix 4.

The key parameters are shown below in table 2.

	Water	Start	1 month	3 month	6 month
pH	HW	7.8	7.2	7.7	7.9
	ASW	8.4	8.5	7.9	8.8
Total hardness	HW	302	135	75	65
	ASW	2.4	2.8	1.8	1.3
Conductivity	HW	655	367	305	267
	ASW	735	746	793	773
Chloride	HW	31	34	25	23
	ASW	31	34	27	14
Iron (total)	HW	8.9	0.5	0	0.28
	ASW	8.9	0.07	0	0.21
Aluminium (total)	HW	0.02	0	0	0.04
	ASW	0.01	1.9	0.31	2.53
Copper (total)	HW	0.3	0.01	0	0.02
	ASW	1.0	0.01	0	0.04

HW = hard water. ASW = base-exchange softened water.

Table 2 **Key Water Analysis Parameters**

The water analyses, confirmed that the Attleborough base-exchange softened water was virtually totally softened to about 2mg/L $CaCO_3$. The Attleborough hard water initially had a total hardness of 302mg/L $CaCO_3$. This though decreased steadily throughout the test, so that by the end of the 6 months it was down to 65 mg/L $CaCO_3$. This is consistent with precipitation of limescale in the heat exchangers.

The decrease in hardness was also reflected in the decrease in conductivity of the hard water from 665µS to 267µS. Of course, no precipitation of limescale would have occurred with the softened water and the conductivity of this was also fairly constant at 735 to 793µS. The higher conductivity of this water is due to the much higher sodium levels brought about by base-exchange softening.

The pH of the hard water was fairly constant and did not rise above 7.9 over the 6 month's test. The pH of the base-exchange softened water was somewhat higher and fluctuated between 7.9 and 8.8 over the test. Although the last reading after 6 months was the highest, there was no clear trend here.

The chloride concentrations in both waters were similar at around 20-35 mg/L, although there was an unexplained drop in the base-exchange softened water at the end of the test. The chloride results showed that there was no chloride carry-over from the water softener used.

Although the iron, aluminium and copper levels were reported as Total, the values measured were almost certainly all dissolved ions. Iron started off quite high in both rigs at 8.9 mg/L. This decreased sharply to less than 0.5mg/L in both rigs within one month and then continued to drop. This can be explained by precipitation of solid iron corrosion products and indicates that corrosion of steel was highest at the start of the tests when the waters were the most aerated.

Aluminium concentrations were low in the hard water rig throughout the test. However, in the base-exchange softened water rig this showed a general increase and was measured at 2.5mg/L at the end of the test. Despite the increase in dissolved aluminium in base-exchange softened water, a level of 2.5mg/L is not especially high and does not indicate high corrosion rates on aluminium.

Copper concentrations were very low for both rigs throughout the test indicating very low corrosion rates of copper pipework or brass fittings.

4) Summary of Findings

Examination of the corrosion coupons, mass loss measurements and determination of corrosion rates has shown basically that in base-exchange softened water the corrosion rate for aluminium was slightly higher than in hard water but the corrosion rate for mild steel, copper, brass and stainless steel was lower, at least over the first 3 months. However, several observations need to be made to qualify the above:

- In the hard water rig, all of the coupons were coated with a magnetite layer from corrosion of steel components in the rig. This could have formed a protective layer on some of the coupons in this rig, especially for aluminium.
- The corrosion of aluminium in softened water took place via an initial metal loss and then growth of a coherent aluminium oxide or hydroxide layer. The corrosion rate in softened water was then decreasing continually with time whereas in hard water it did not decrease further after 3 months.
- The corrosion of mild steel in both waters was very high initially but decreased significantly and continually with time, as dissolved oxygen levels decreased. Measurements of dissolved oxygen were initially high in both rigs (normal for mains water). However, after 1 month, these levels had dropped to below 1.0% saturation for the both rigs. Since DO readings were not regularly taken, it is possible that differences in corrosion rates between the two rigs could be due to small difference in DO levels.
- Although there were some differences in the corrosion rates for brass, copper and stainless steel between the two rigs, overall the rates were so low that it would have made little practical difference.

The aluminium primary heat exchangers are made from cast Al-Si alloy (grade LM6). The waterways would be protected from corrosion by the formation of a thick air formed film (millscale). Examination of the heat exchangers from both rigs showed no discernible thinning and very little pitting corrosion. A few isolated pits were found in the bottom water way in the heat exchangers from both rigs but measurements of the pits after cleaning showed them to be extremely shallow. Therefore, any risk to the boilers from corrosion over the longer term would have been insignificant.

Examination of the radiators showed the presence of some iron oxide corrosion products in all of the water ways but the general corrosion of the steel was slight.

Signed.............................. Phillip Munn

Date.............................. 20/11/12

Appendix 1

IMAGES of COUPONS after TEST in SOFTENED WATER

Fig 2 After 30 days

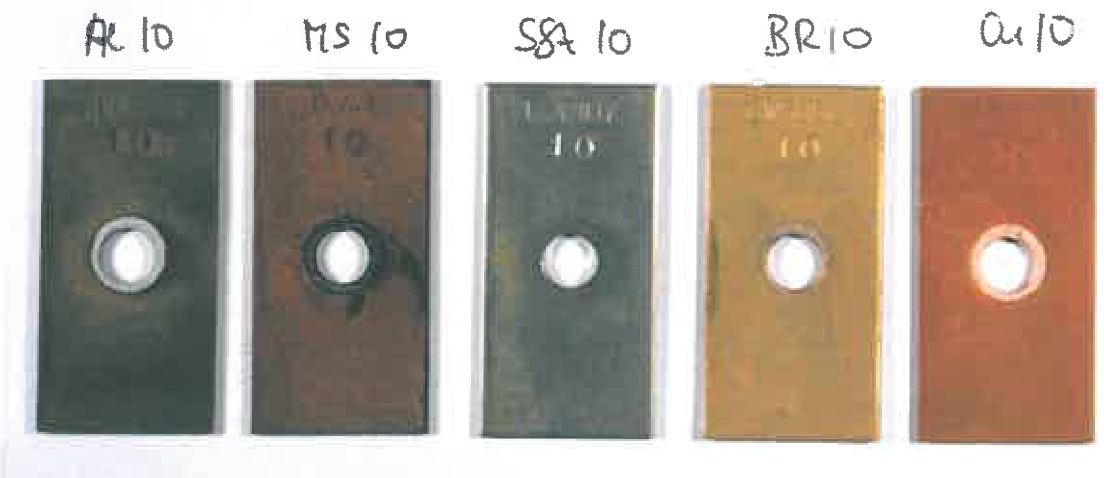


Fig. 3 After 90 days

Fig 4 After 188 days

IMAGES of COUPONS after TEST in HARD WATER

Fig 5 After 30 days

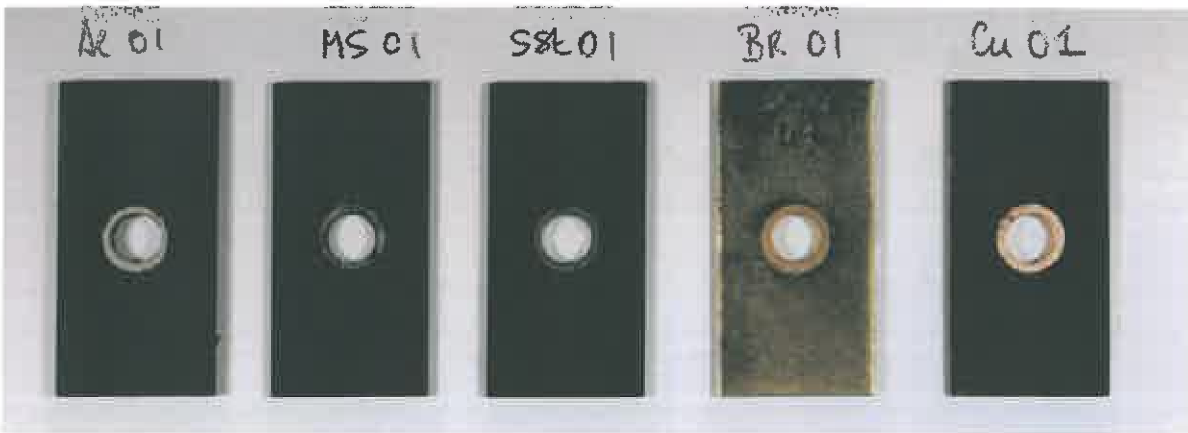


Fig 6 After 90 days

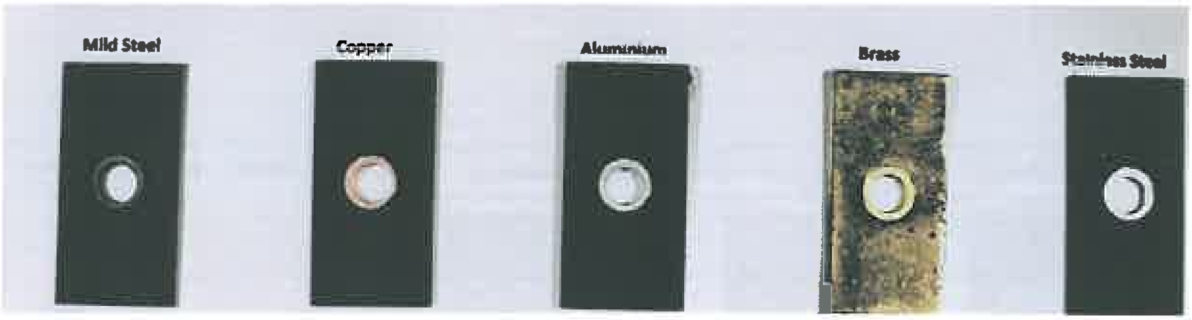
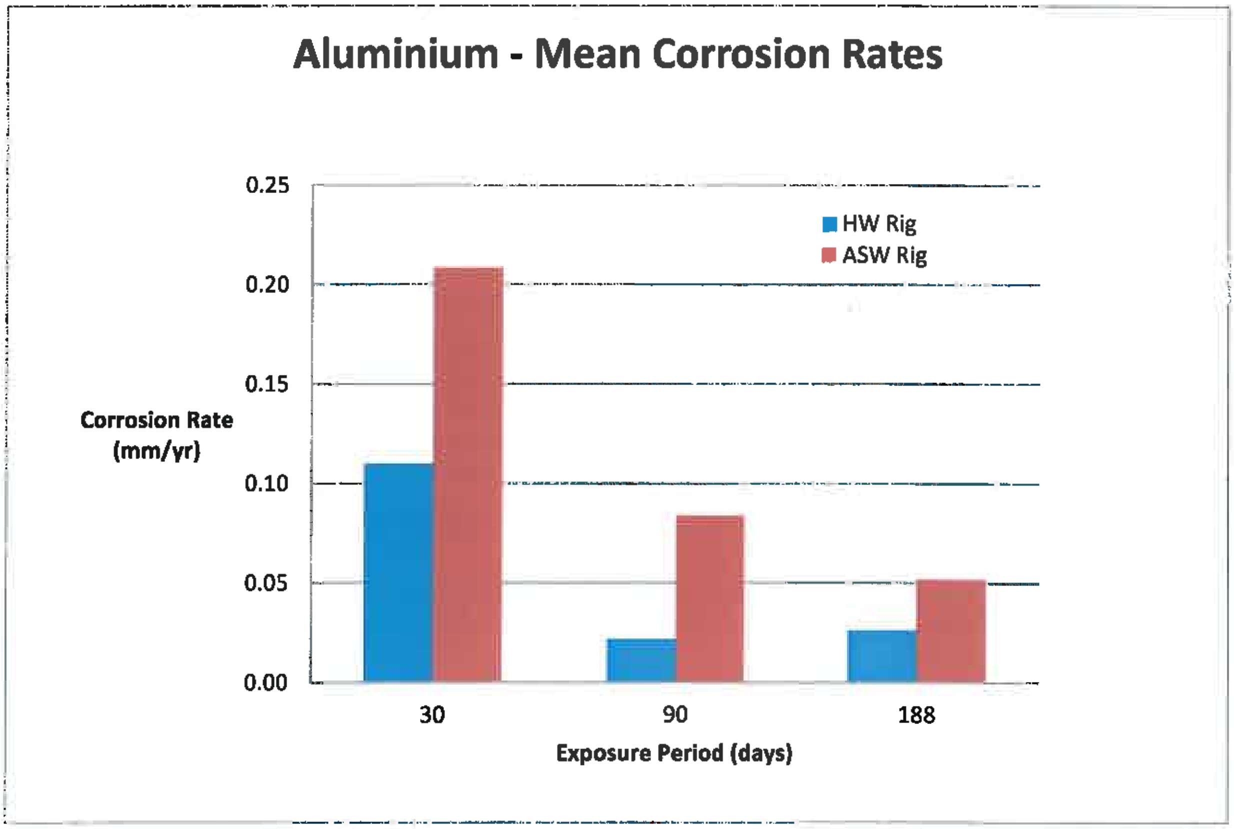


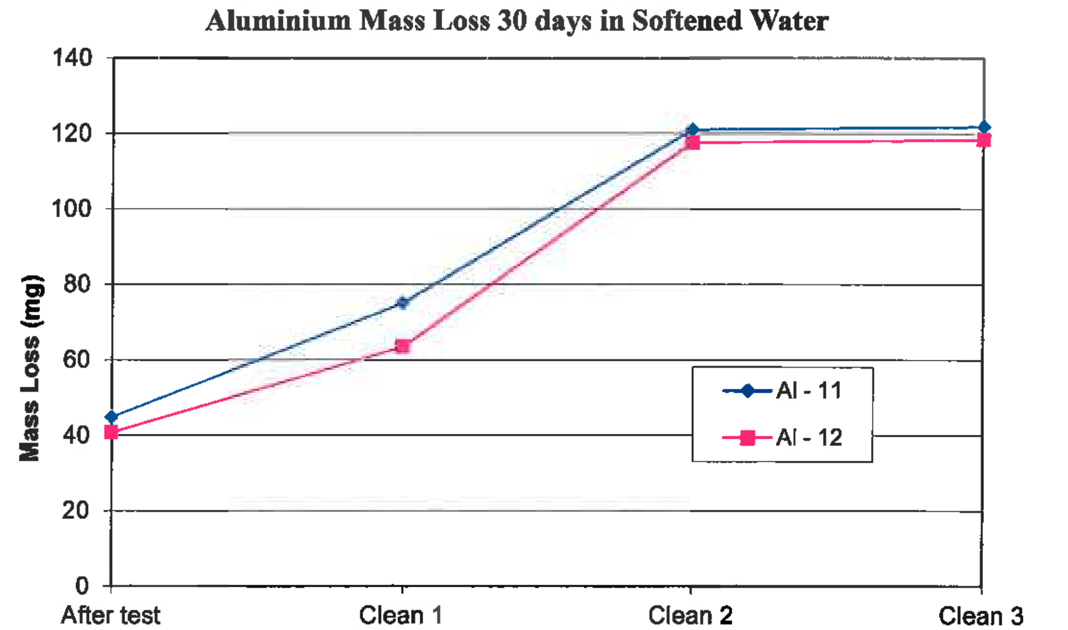
Fig. 7 After 188 days

Appendix 2 Mass Losses and Mean Corrosion Rates of Metal Coupons

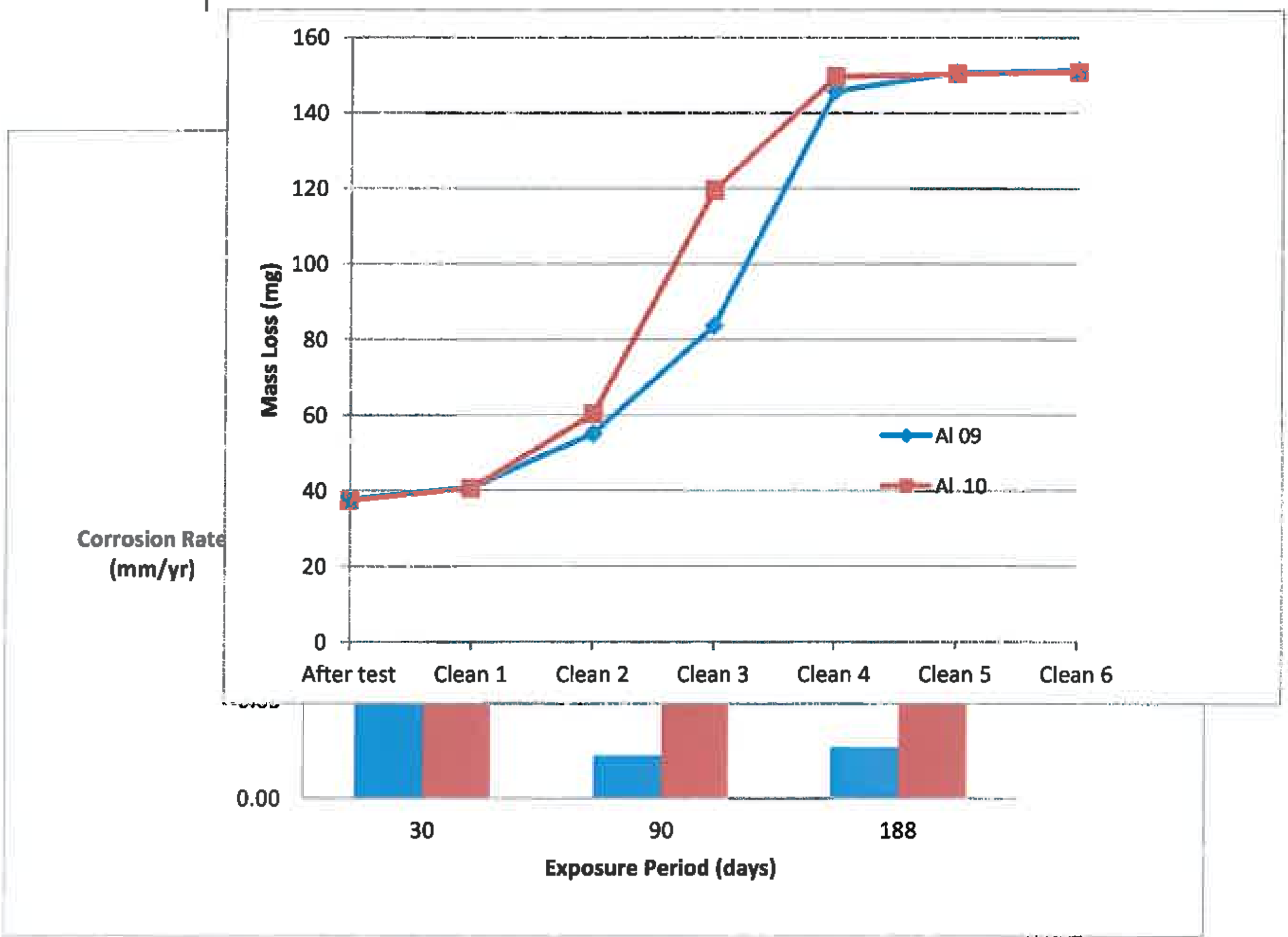
Aluminium Coupons

Water	Days	Mass loss	Mean mass loss	Corrosion rate
HW	30	71.88	60.94	0.11
		50		
ASW	30	119.43	117.77	0.21
		116.1		
HW	90	31.95	36.1	0.022
		40.28		
ASW	90	146.18	140.3	0.084
		134.42		
HW	188	92.86	92.86	0.026
		92.86		
ASW	188	180.0	184.5	0.052
		189.0		

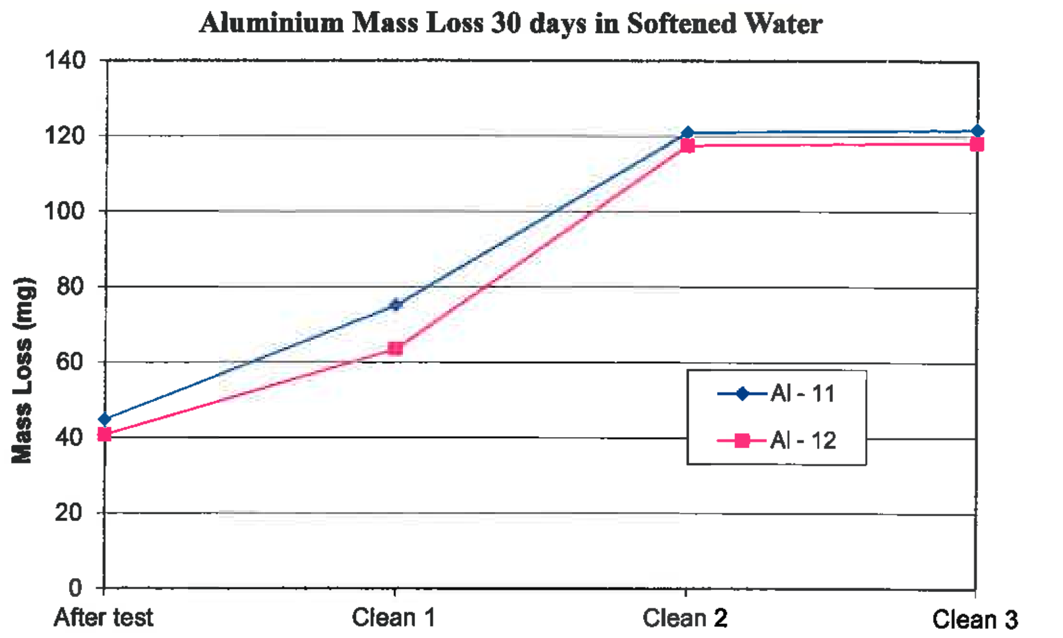


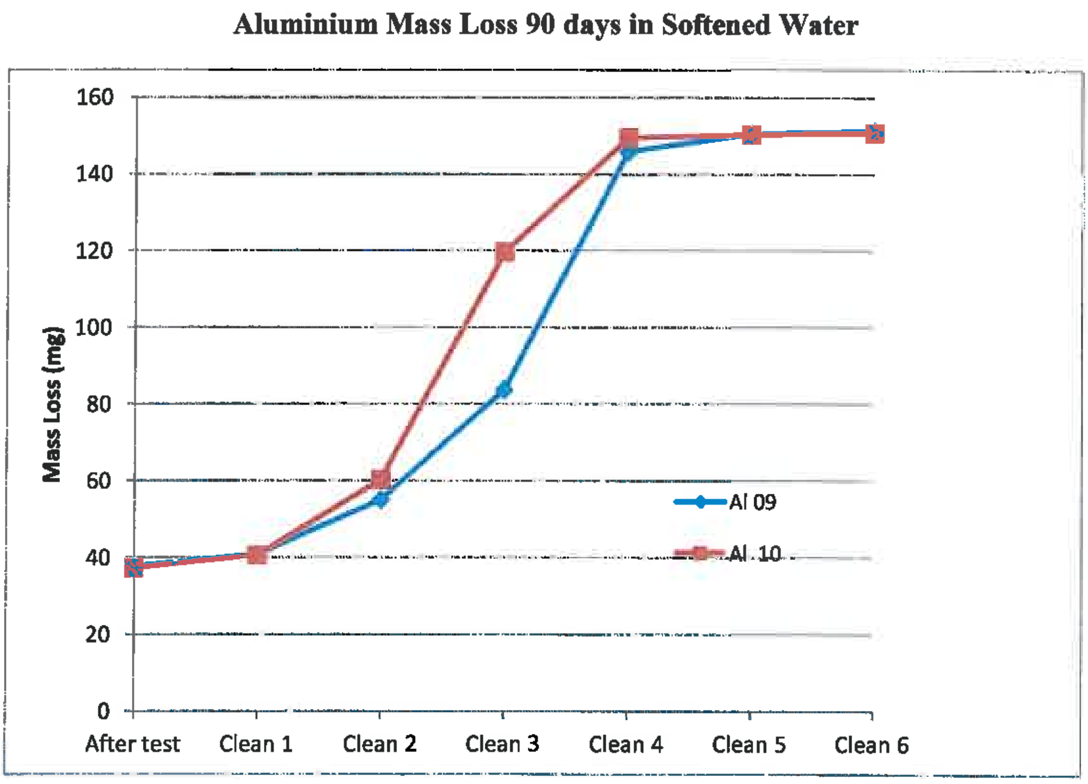


Aluminium Mass Loss 30 days in Softened Water
Mass Loss (mg)
140
120
100
80
60
40
20
0
After test
Clean 1
Clean 2
Clean 3
Al - 11
Al - 12

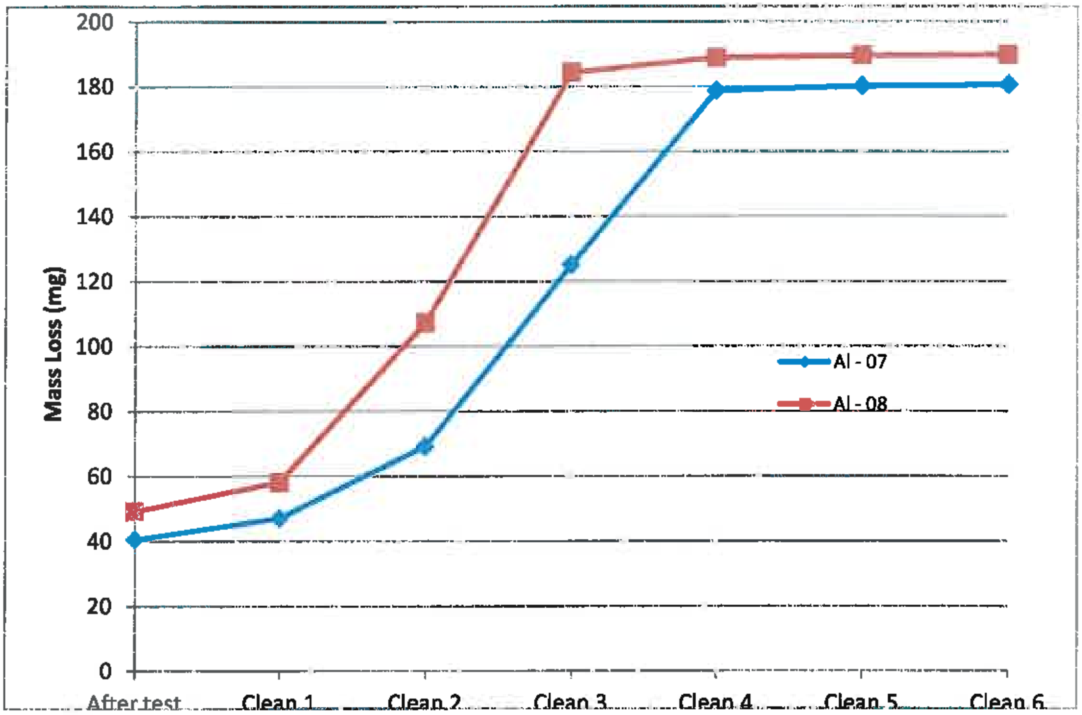


Mass Loss (mg)
160
140
120
100
80
60
40
20
0
After test
Clean 1
Clean 2
Clean 3
Clean 4
Clean 5
Clean 6
Al 09
Al 10
Corrosion Rate
(mm/yr)
0.00
30
90
188
Exposure Period (days)

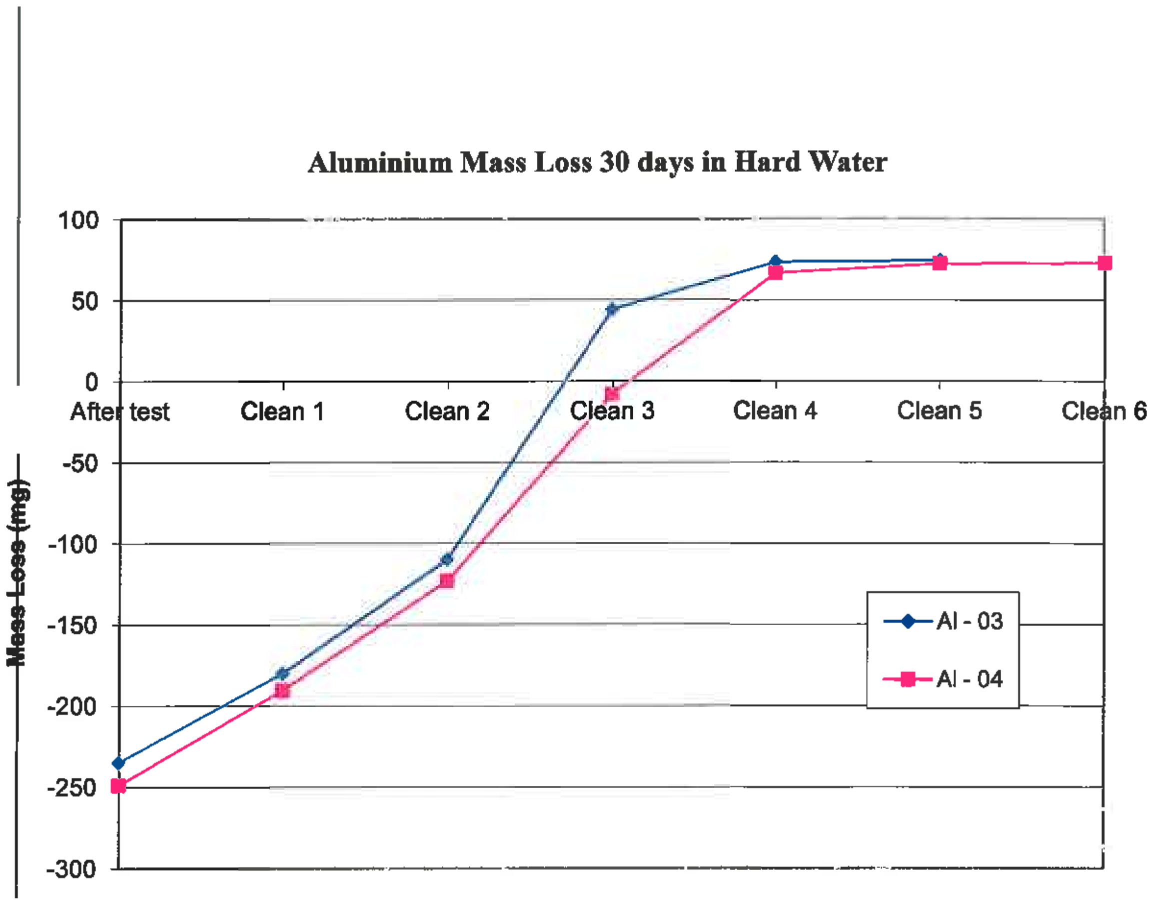

Aluminium Mass Loss 30 days in Softened Water
140
120
100
80
60
40
20
0
Mass Loss (mg)
After test
Clean 1
Clean 2
Clean 3
Al - 11
Al - 12

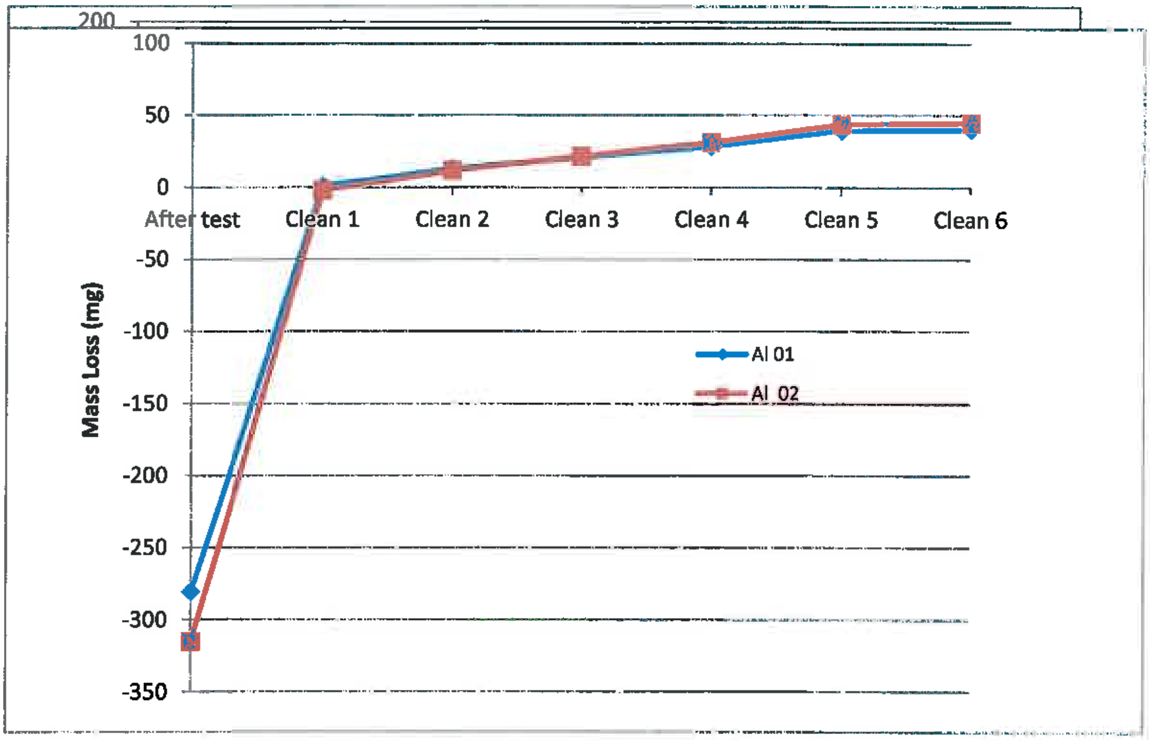

Aluminium Mass Loss 90 days in Softened Water
160
140
120
100
80
60
40
20
0
Mass Loss (mg)
After test
Clean 1
Clean 2
Clean 3
Clean 4
Clean 5
Clean 6
Al 09
Al 10

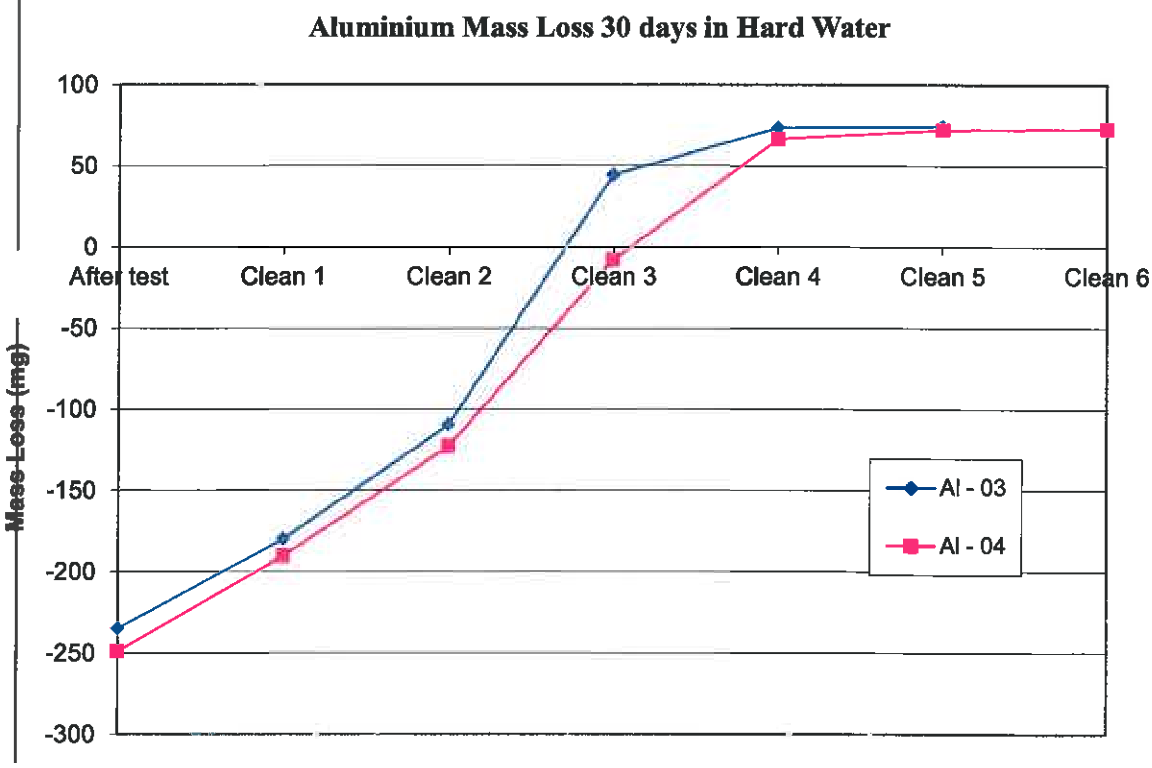
Aluminium Mass Loss 188 days in Softened Water



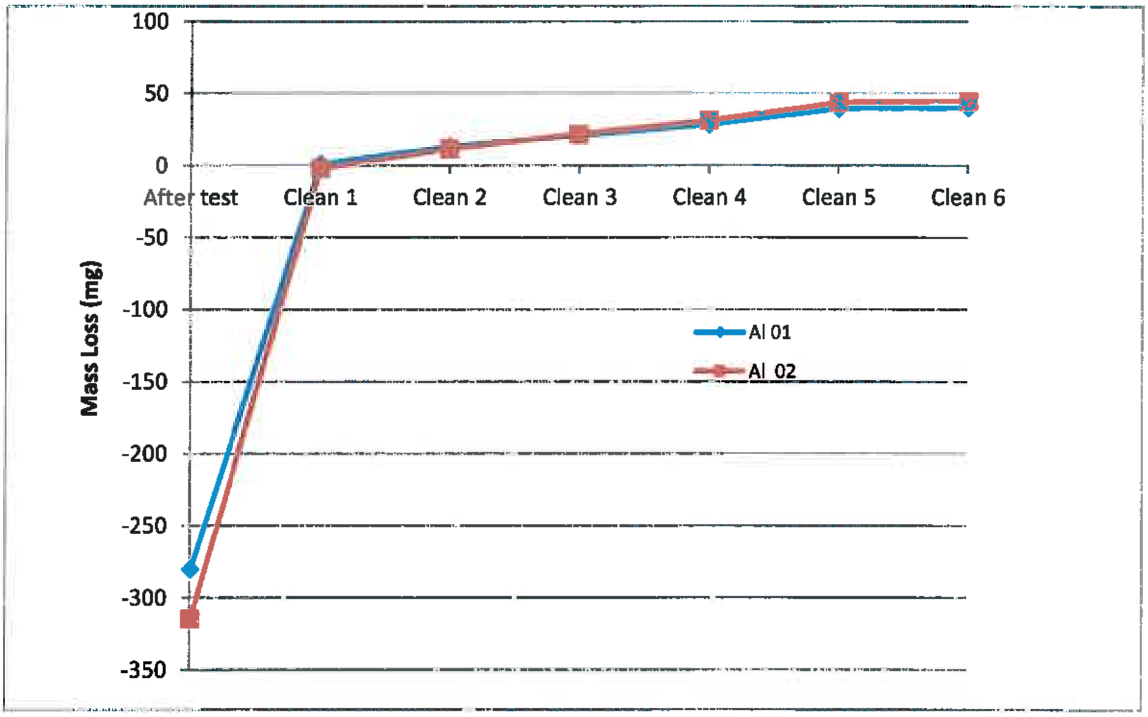
Aluminium Mass Loss 30 days in Hard Water



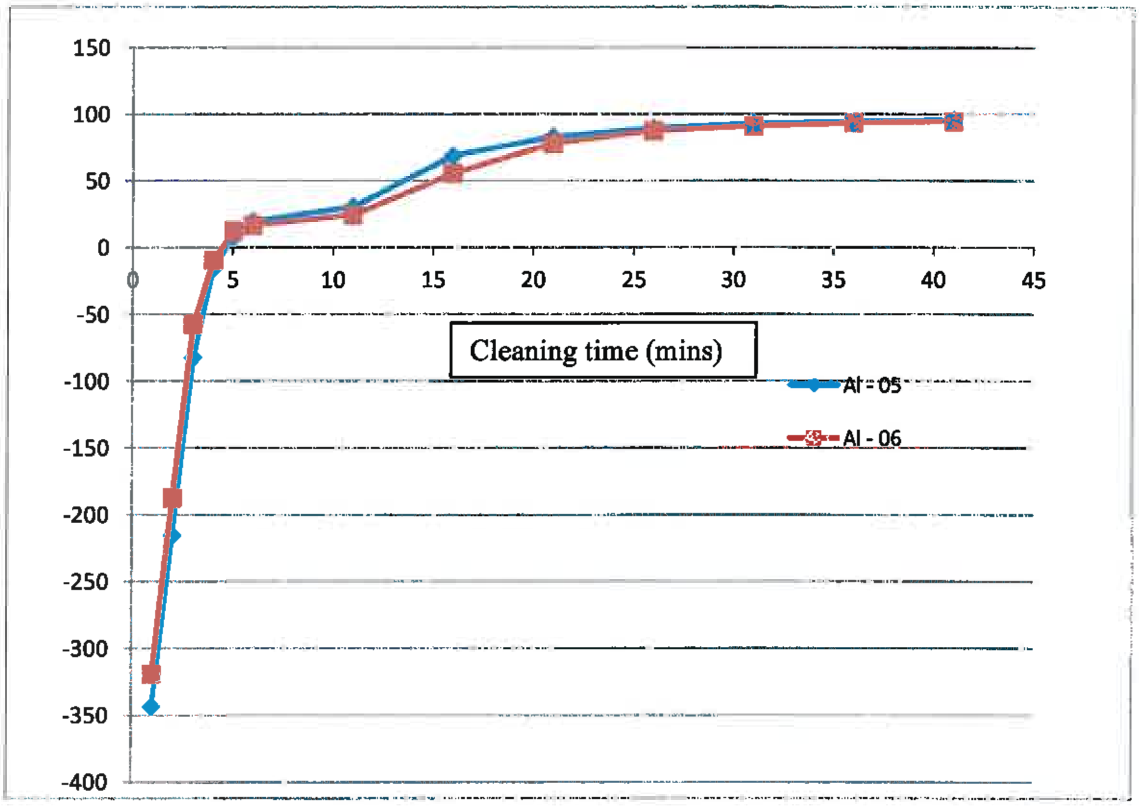

200
100
50
0
-50
-100
-150
-200
-250
-300
-350
After test
Clean 1
Clean 2
Clean 3
Clean 4
Clean 5
Clean 6
Mass Loss (mg)
Al 01
Al 02


Aluminium Mass Loss 30 days in Hard Water
100
50
0
-50
-100
-150
-200
-250
-300
After test
Clean 1
Clean 2
Clean 3
Clean 4
Clean 5
Clean 6
Mass Loss (mg)
Al - 03
Al - 04

Aluminium Mass Loss 90 days in Hard Water

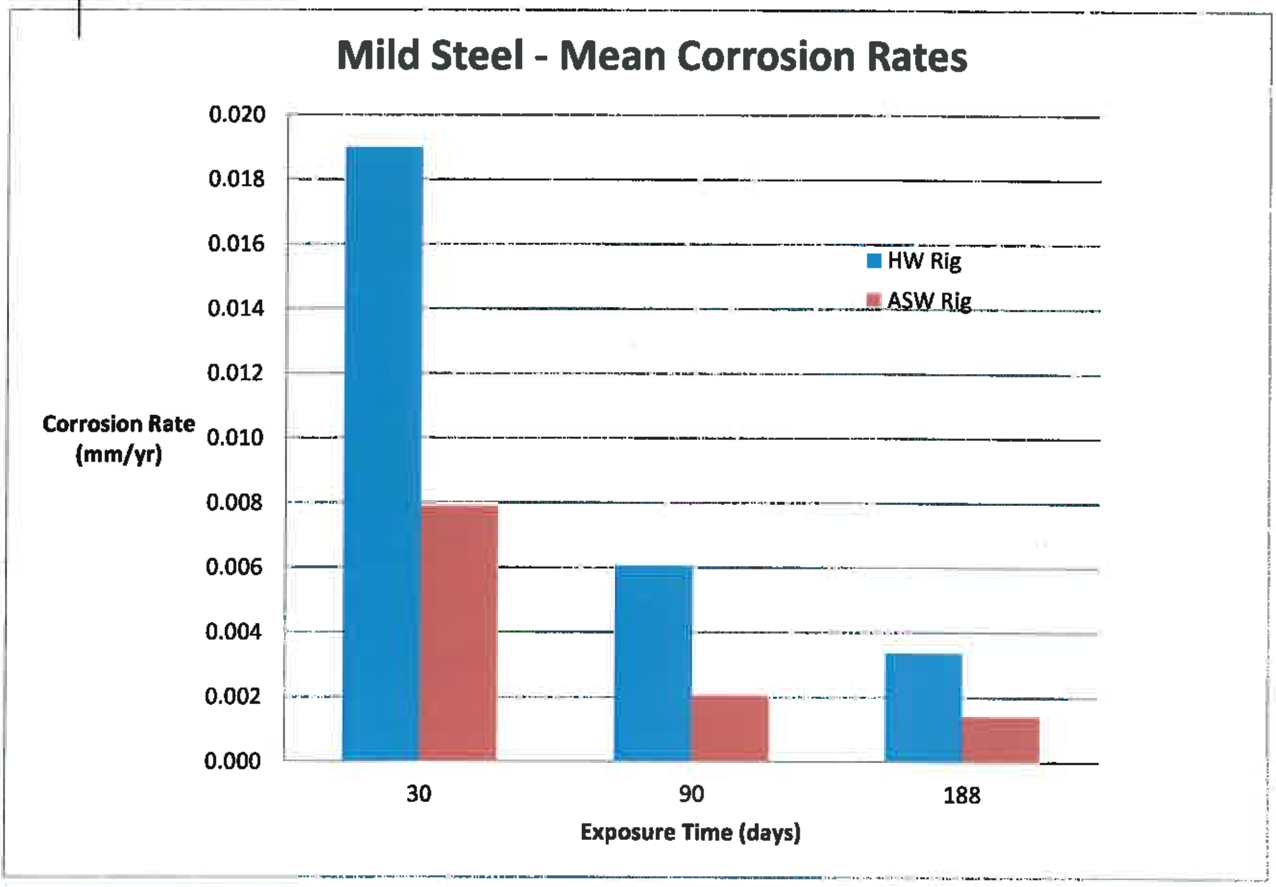


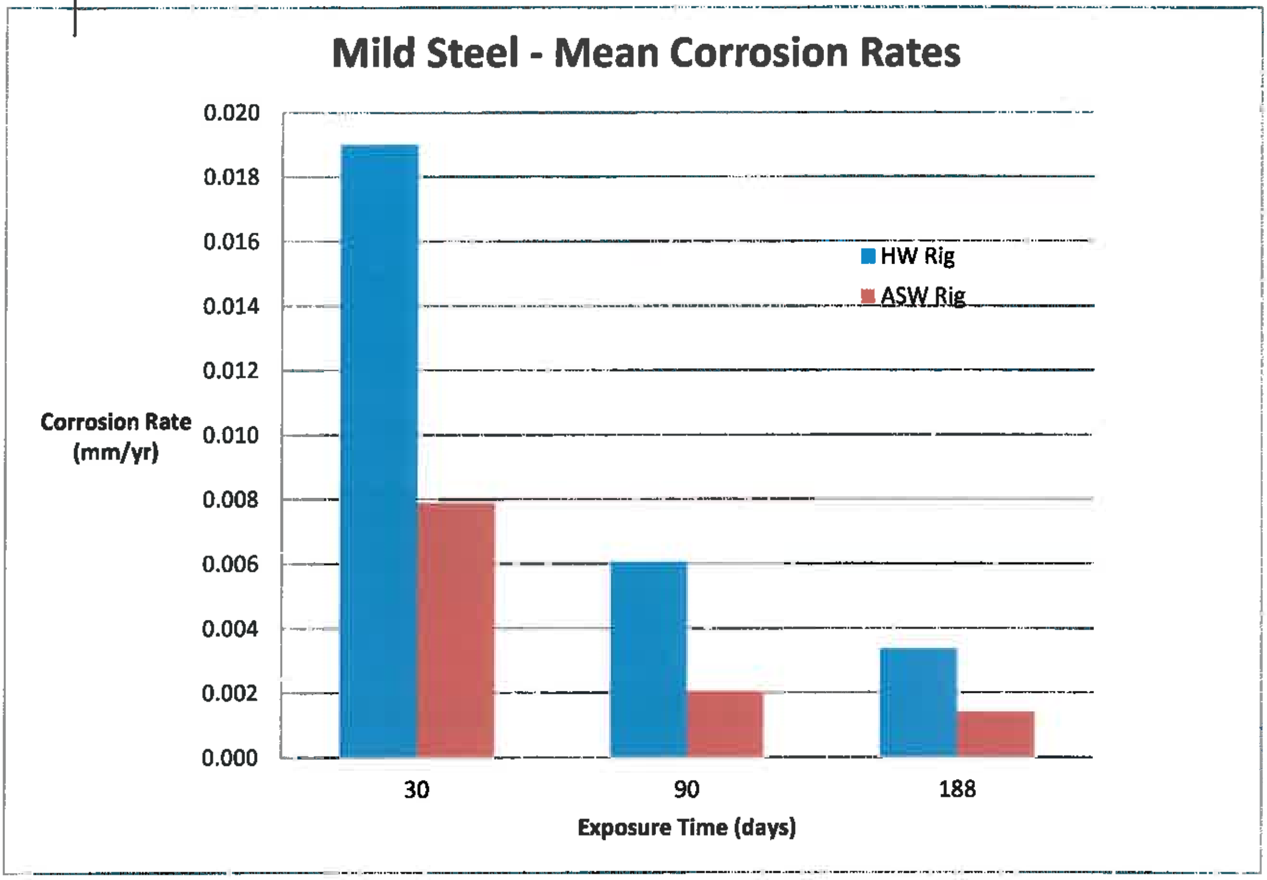
Aluminium Mass Loss 188 days in Hard Water



Mild Steel Coupons

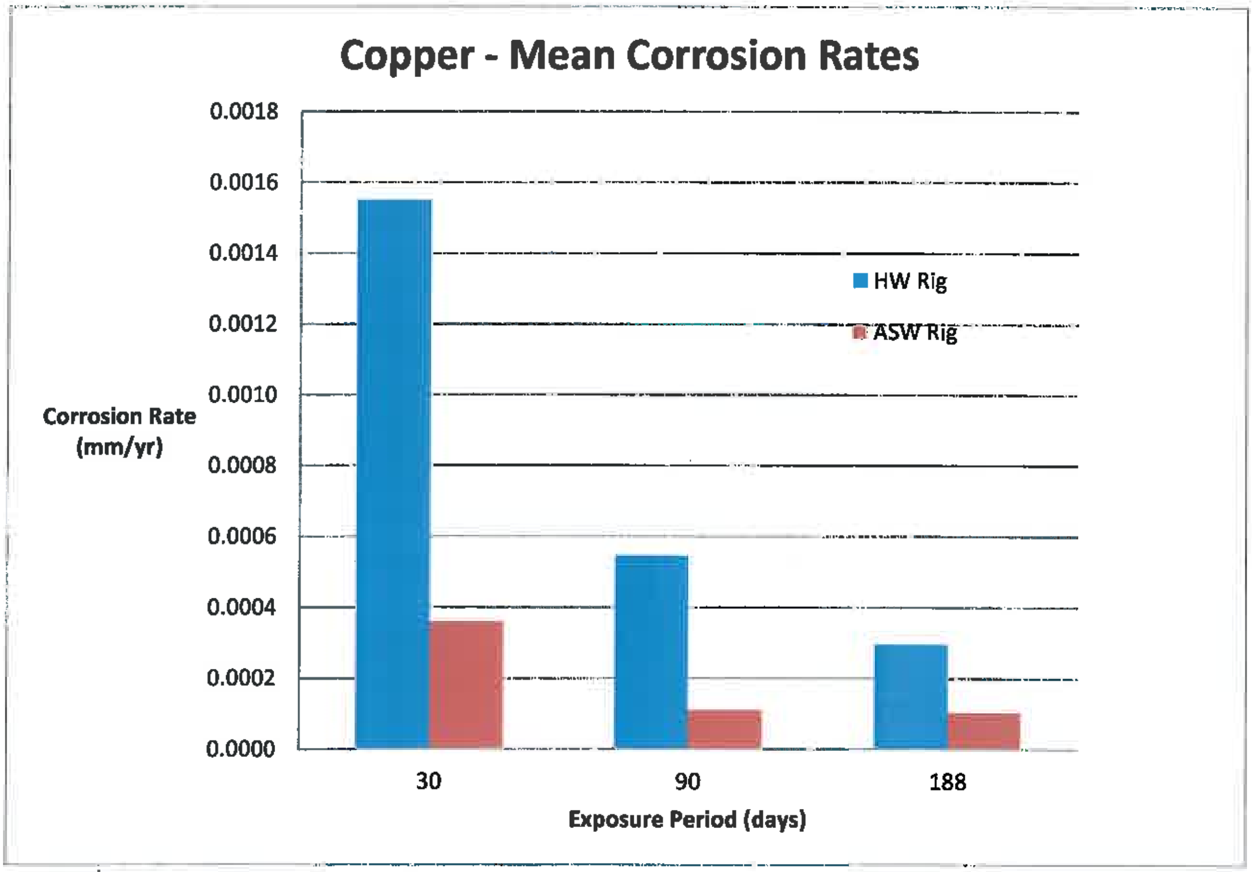
Water	Days	Mass loss	Mean mass loss	Corrosion rate
HW	30	31.11	30.42	0.019
		29.73		
ASW	30	13.88	12.77	0.0079
		11.66		
HW	90	27.5	30	0.0061
		32.5		
ASW	90	9.14	10.18	0.0021
		11.21		
HW	188	34.67	34.7	0.0034
		34.67		
ASW	188	11.25	14.5	0.0014
		17.81		




Mild Steel - Mean Corrosion Rates
Corrosion Rate (mm/yr)
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
HW Rig
ASW Rig
30
90
188
Exposure Time (days)

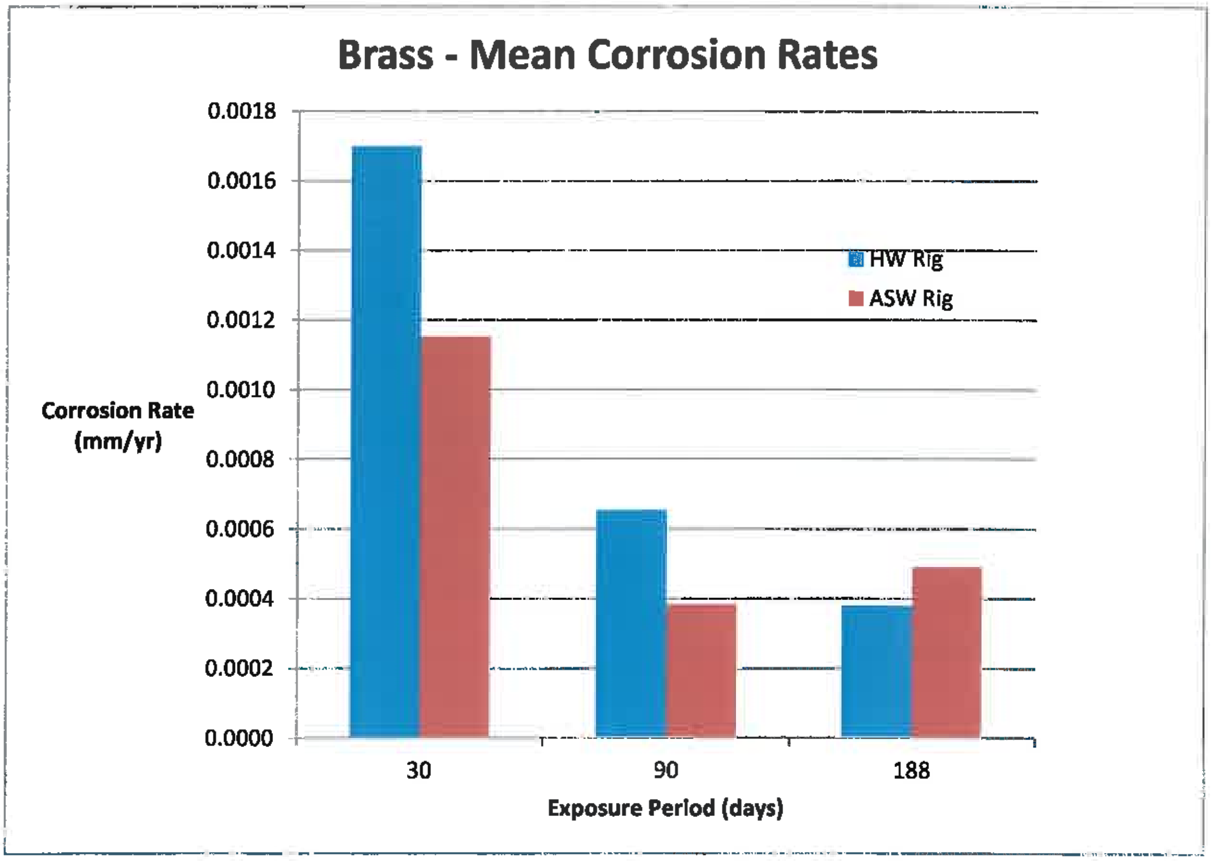
Copper Coupons

Water	Days	Mass loss	Mean mass loss	Corrosion rate
HW	30	2.98	2.74	0.0014
		2.50		
ASW	30	0.65	0.7	0.00036
		0.75		
HW	90	2.5	3.19	0.00055
		3.88		
ASW	90	0.60	0.65	0.00011
		0.70		
HW	188	3.33	3.61	0.00030
		3.89		
ASW	188	0.55	1.26	0.00010
		2.00		



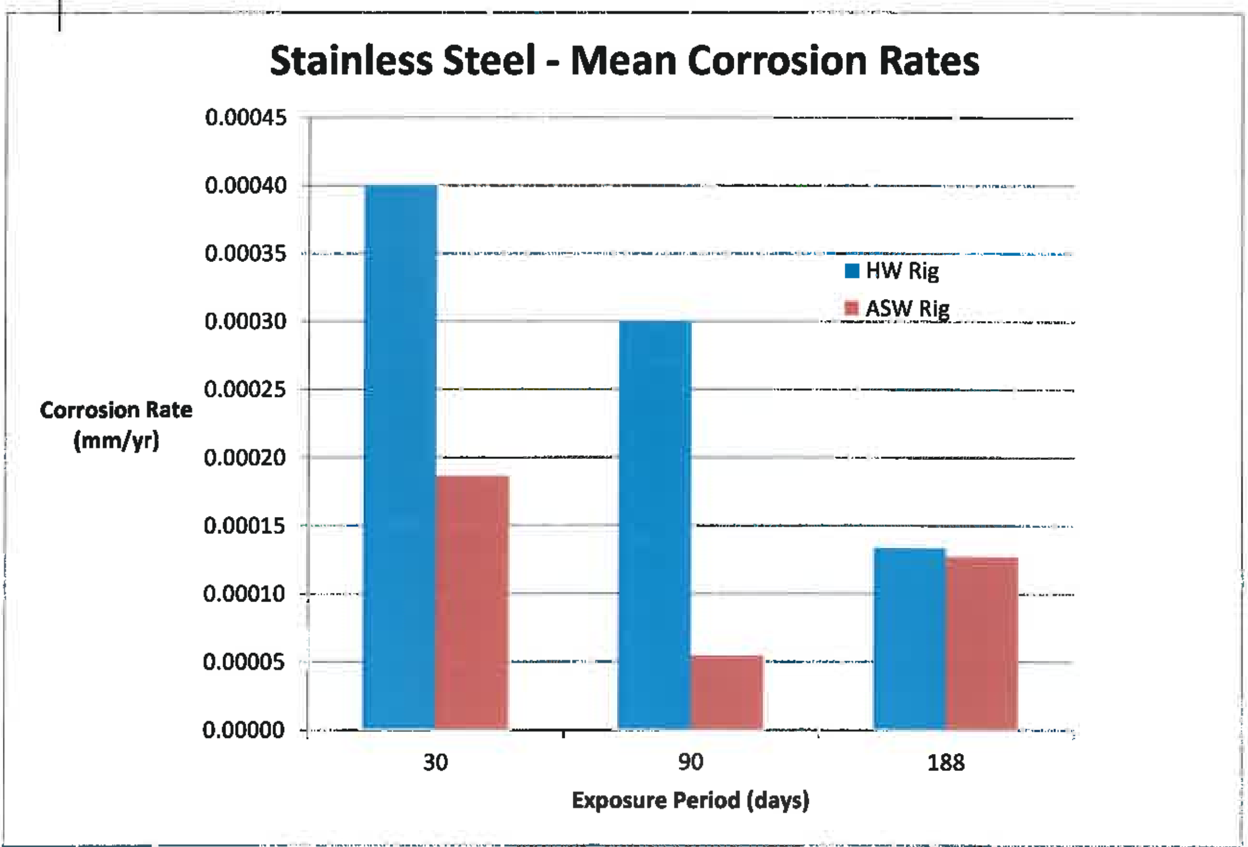
Brass Coupons

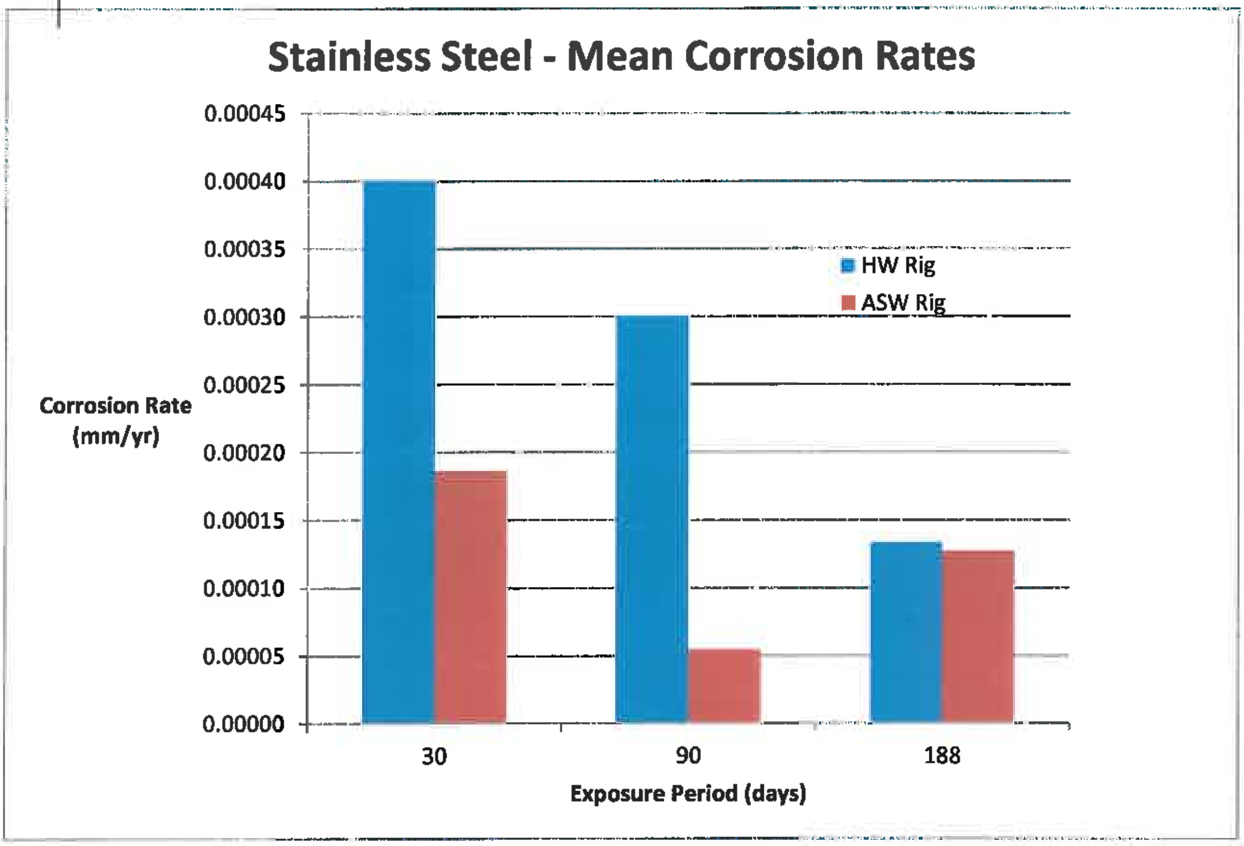
Water	Days	Mass loss	Mean mass loss	Corrosion rate
HW	30	3.14	3.00	0.0017
		2.86		
ASW	30	2.01	2.06	0.0012
		2.10		
HW	90	3.80	3.5	0.00065
		3.20		
ASW	90	1.81	2.05	0.00038
		2.28		
HW	188	4.30	4.25	0.00038
		4.20		
ASW	188	3.83	5.48	0.00049
		7.13		



Stainless Steel Coupons

Water	Days	Mass loss	Mean mass loss	Corrosion rate
HW	30	1.11	0.65	0.00040
		0.19		
ASW	30	0.177	0.31	0.00019
		0.437		
HW	90	1.72	1.51	0.00030
		1.30		
ASW	90	0.37	0.27	0.000055
		0.18		
HW	188	1.11	1.38	0.00013
		1.65		
ASW	188	1.54	1.32	0.00013
		1.09		




Stainless Steel - Mean Corrosion Rates
Corrosion Rate (mm/yr)
0.00045
0.00040
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
HW Rig
ASW Rig
30
90
188
Exposure Period (days)

Appendix 3 Images of Heat Exchangers and Radiators after Tests

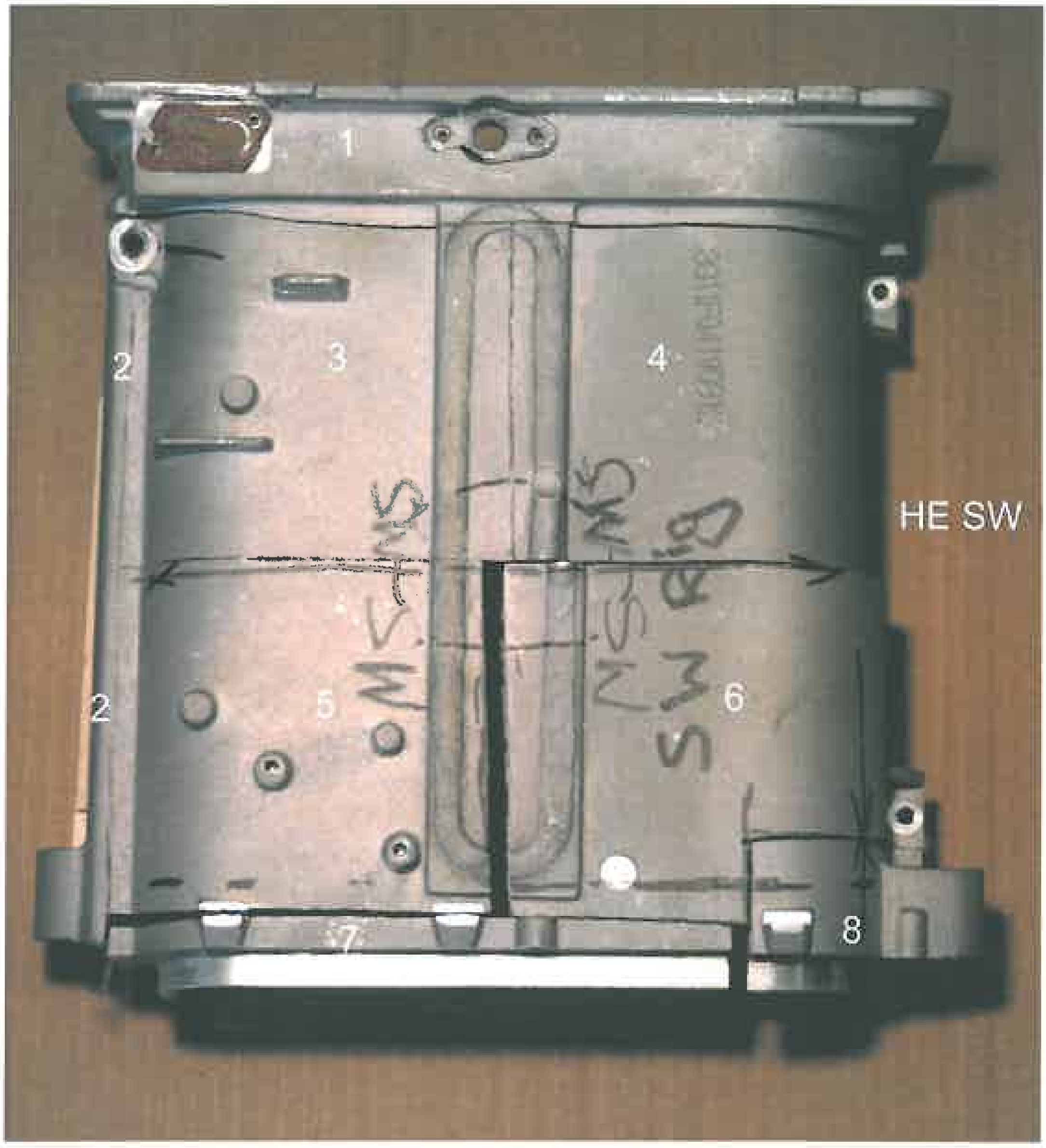


Fig 8 Whole Heat Exchanger from a Soft Water System with labelled sections

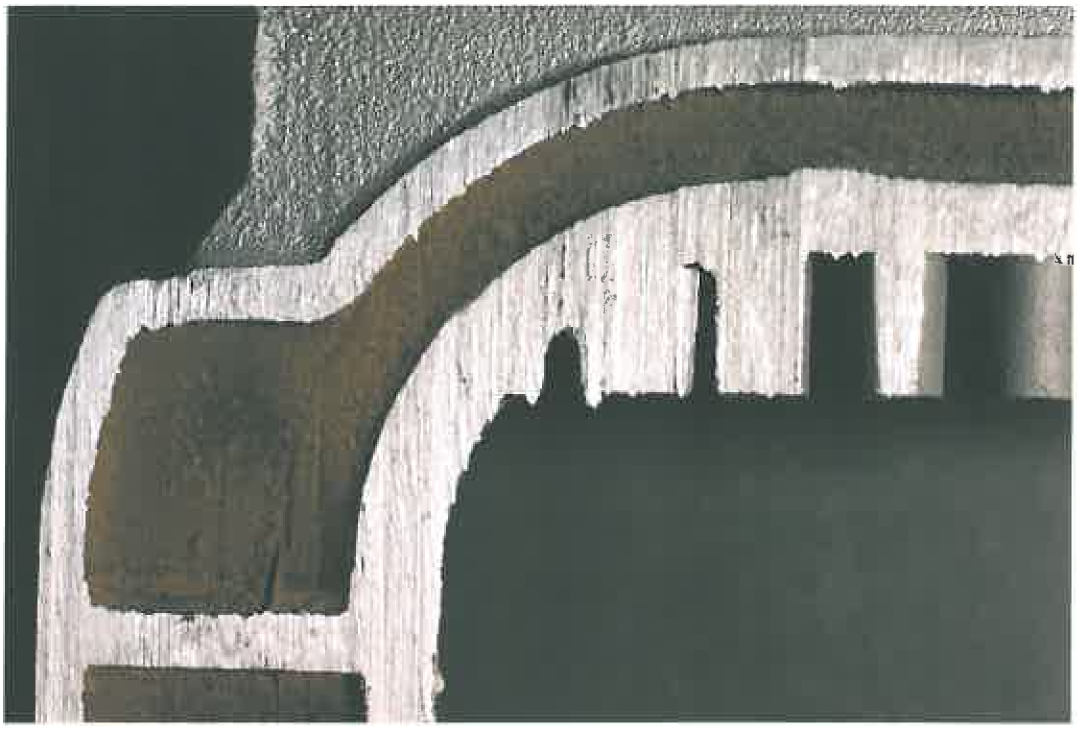


Fig 9: Waterway in pt 1

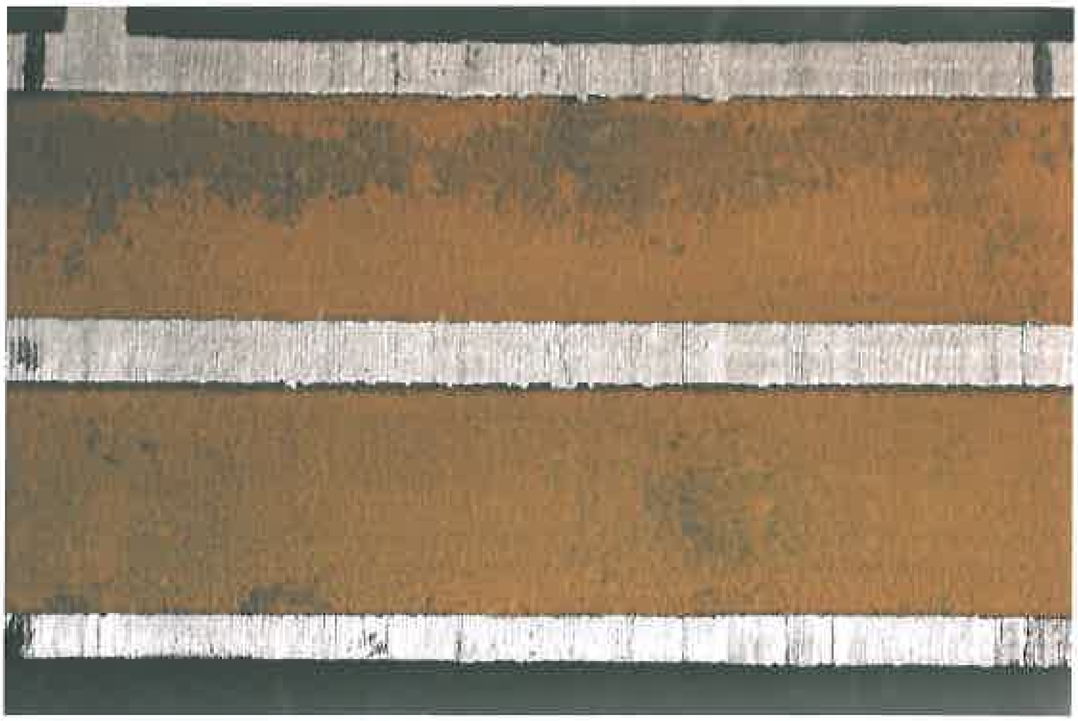


Fig 10 Waterways in pt 2

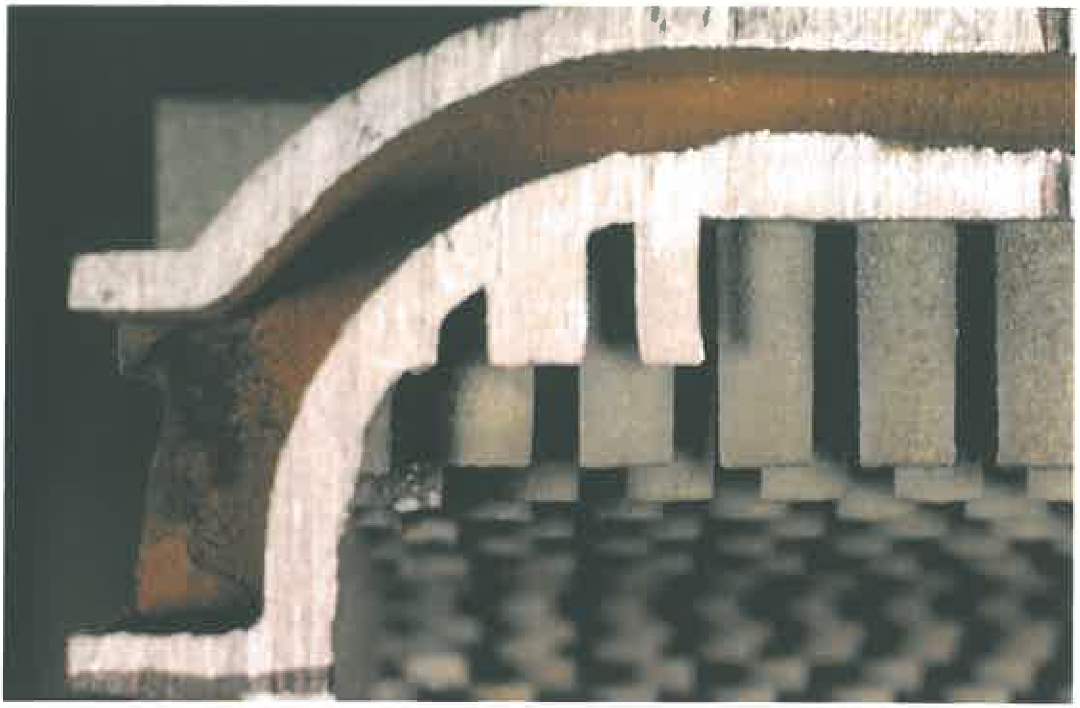


Fig 11 Waterway in pt3

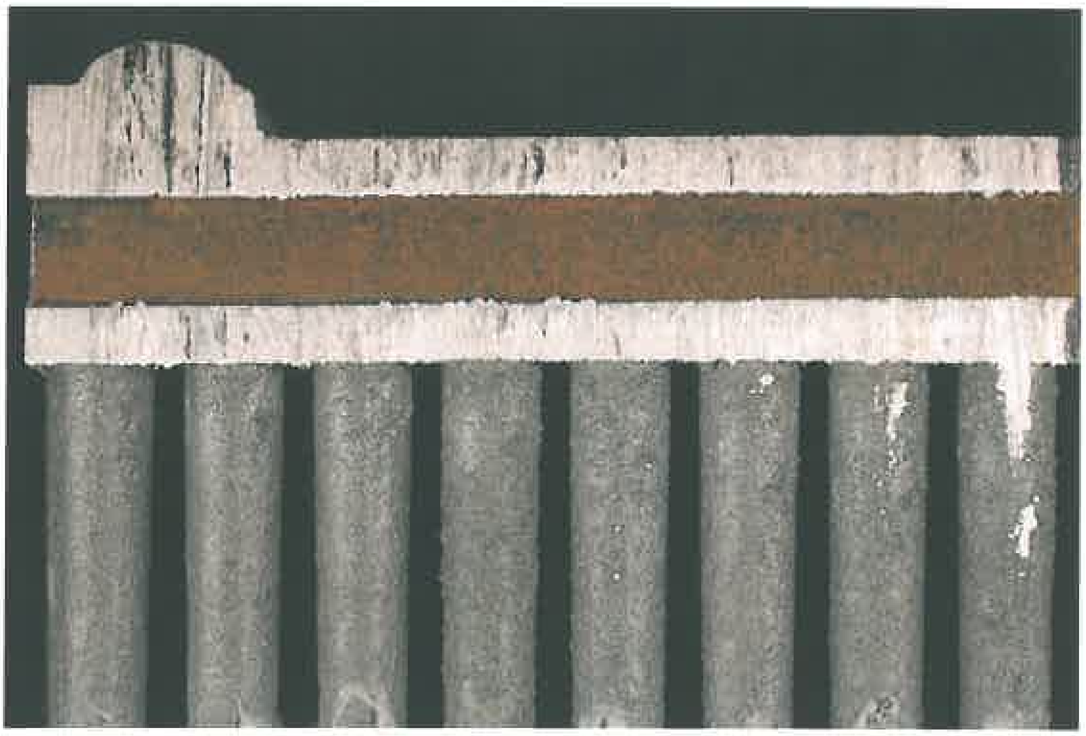


Fig 12 Waterway in pt 4

Fig 13 Waterways in pt 5

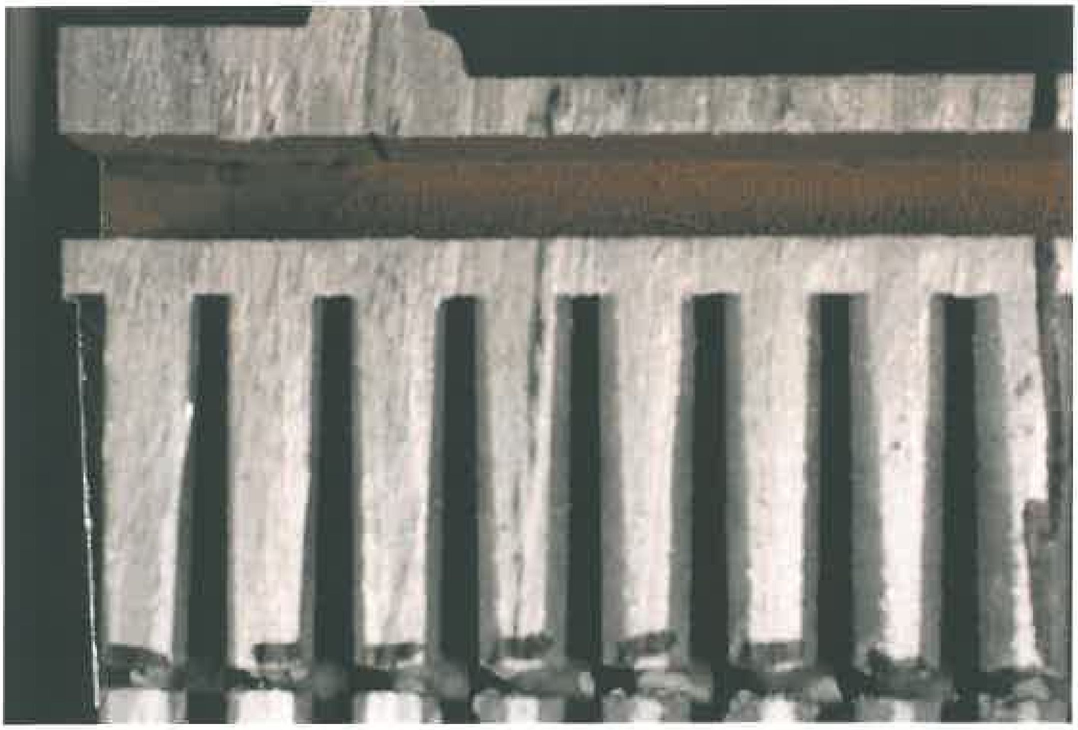


Fig 14 Waterway in pt 6

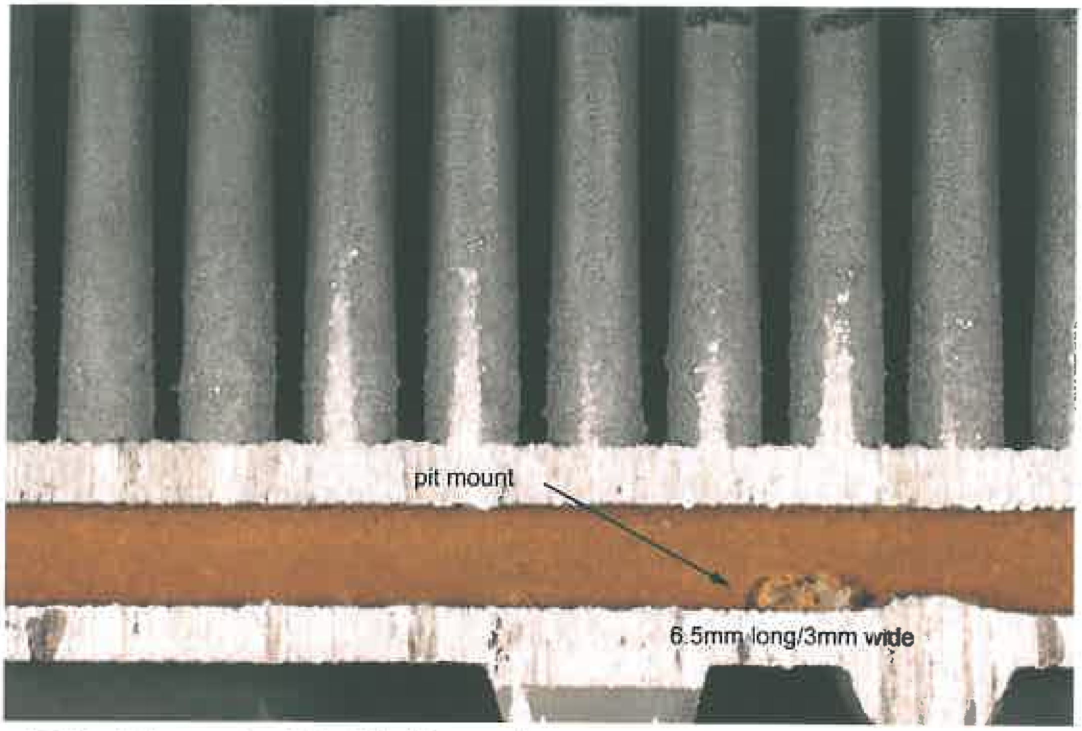


Fig 15 Waterway in pt 7, with pit mound

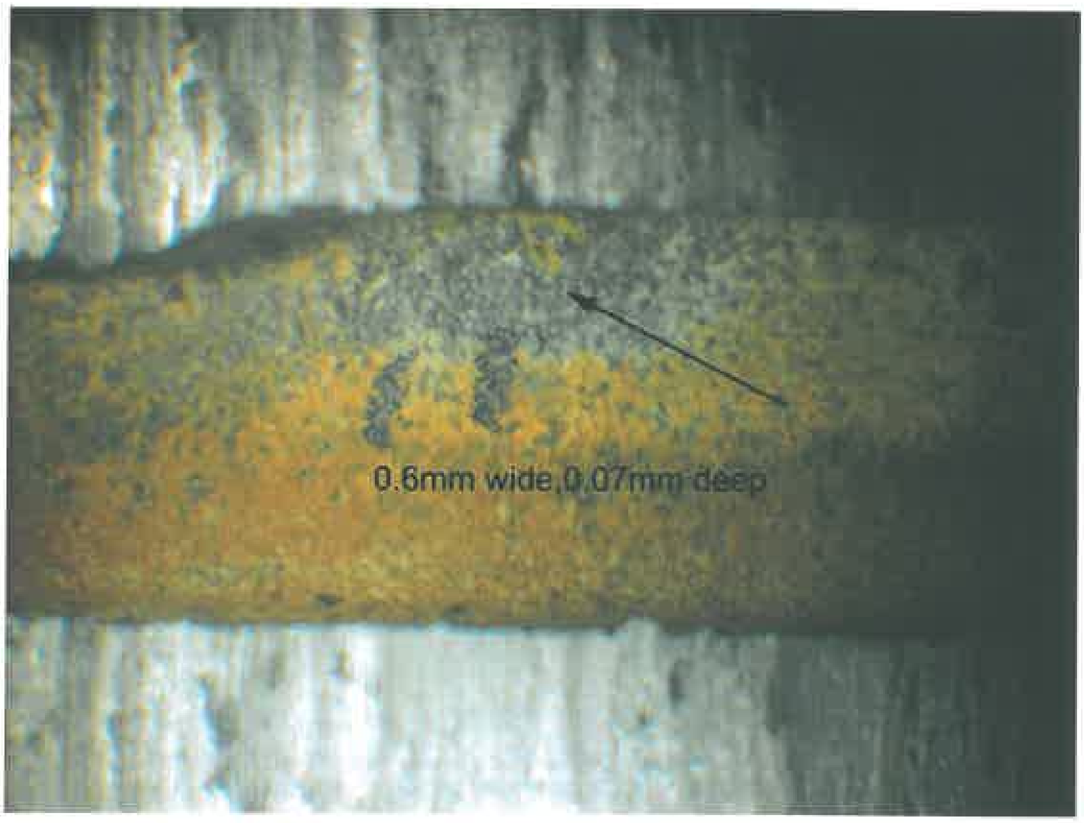


Fig 16 Pit after clean, pt7

Fig 17 Soft Water Radiator cut marks

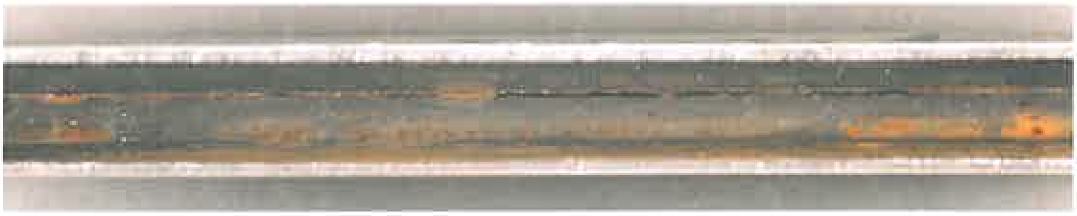


Fig 18 Radiator top waterway

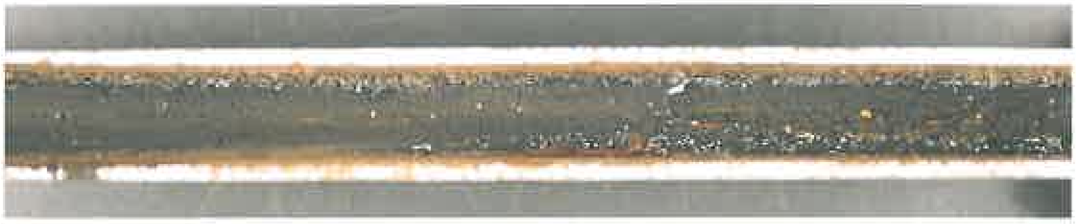


Fig 19 Radiator bottom waterway

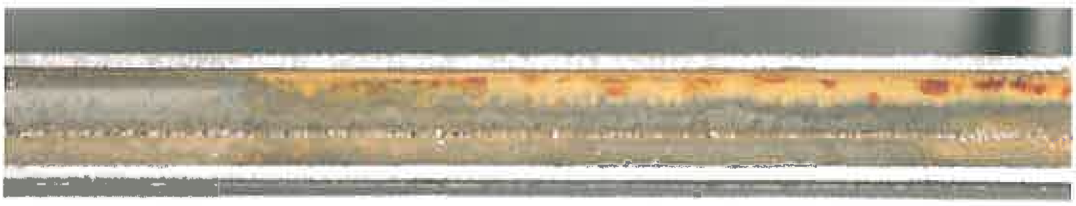
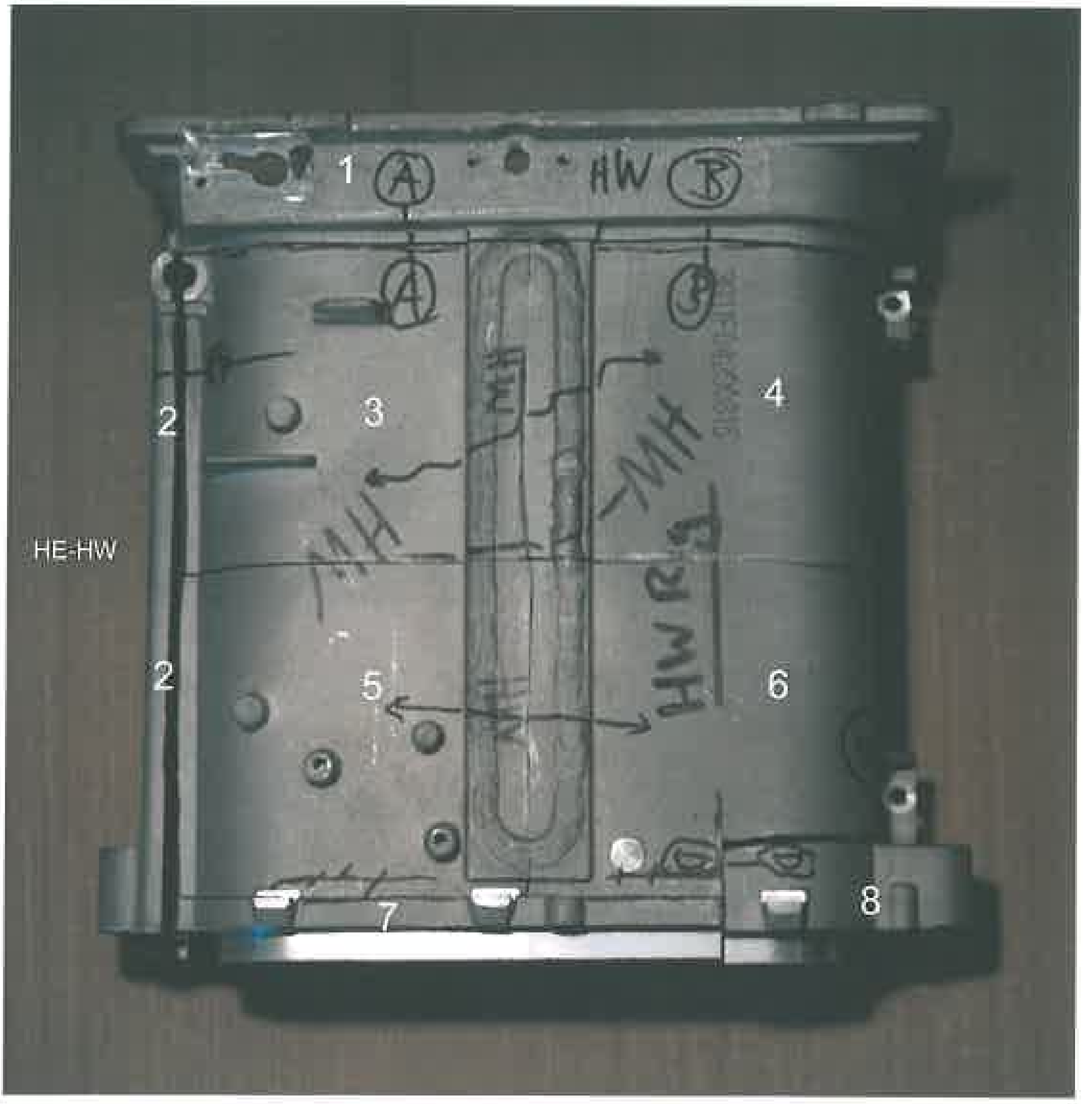


Fig 20 Radiator vertical waterway

Fig 21   Whole Heat Exchanger from a Hard Water System



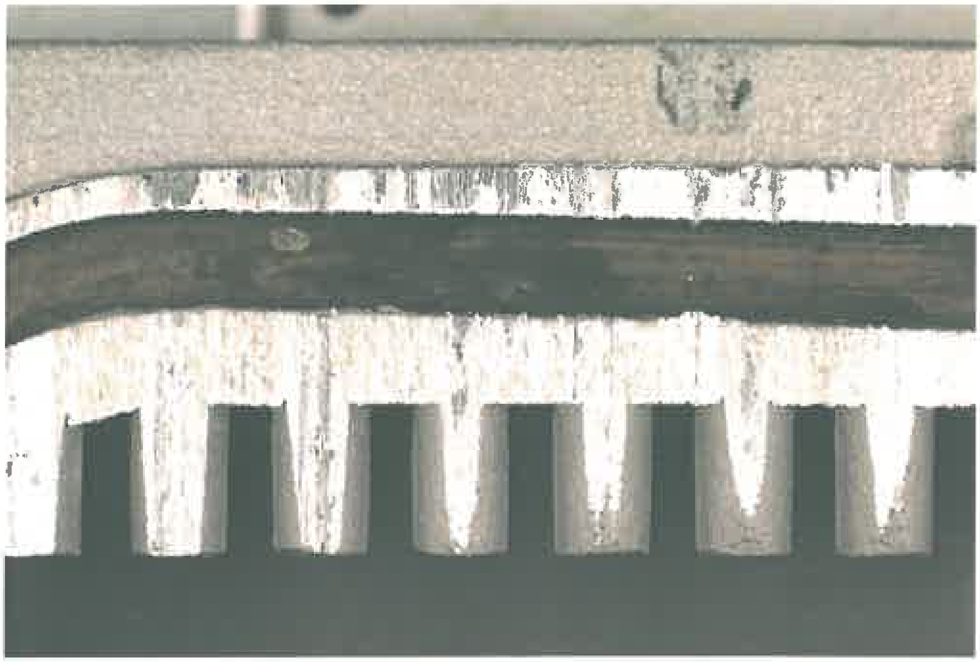


Fig 22 Water way in pt 1

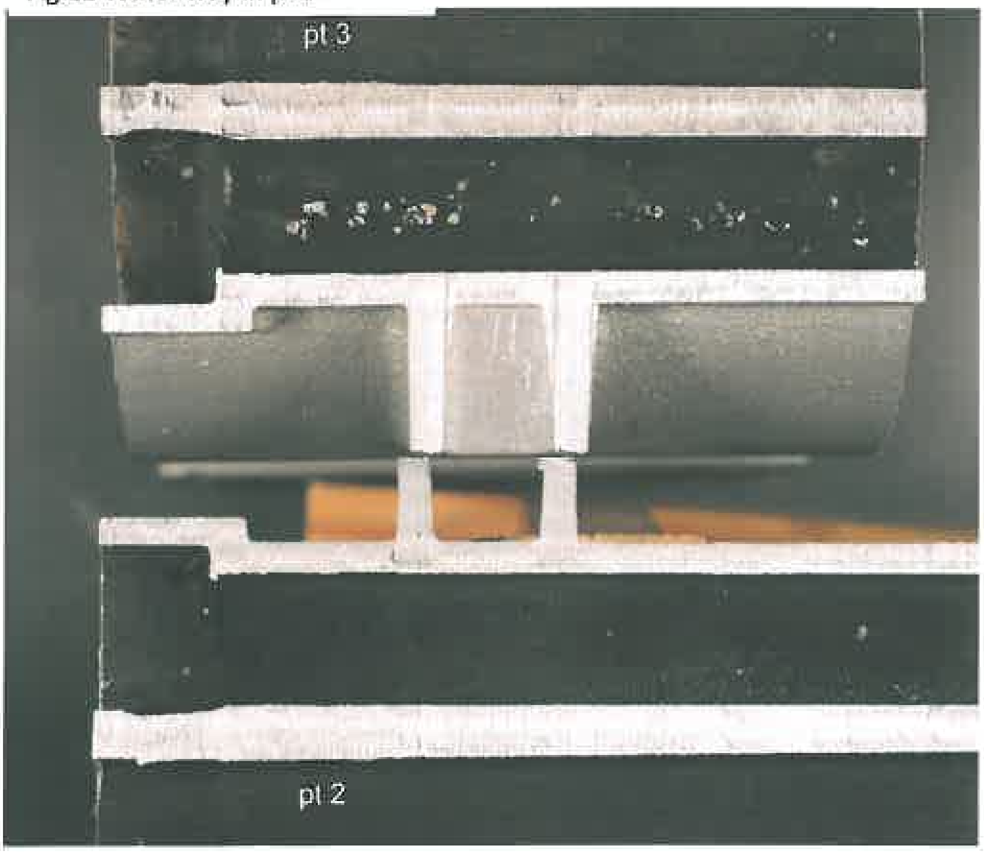


Fig 23 Waterways in pts 2 and 3

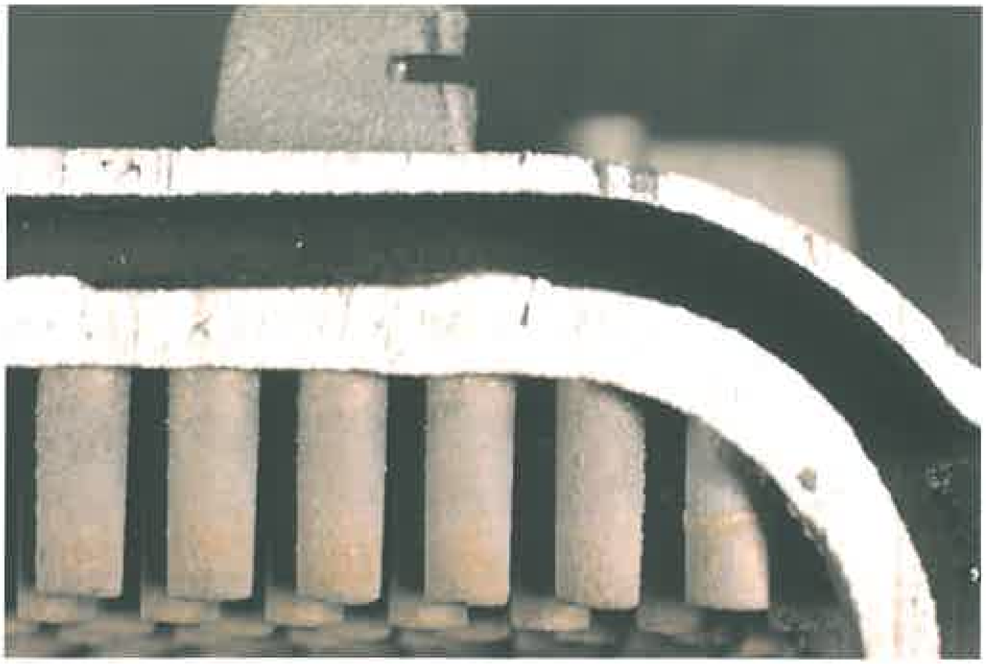


Fig 24 Waterway in pt 3

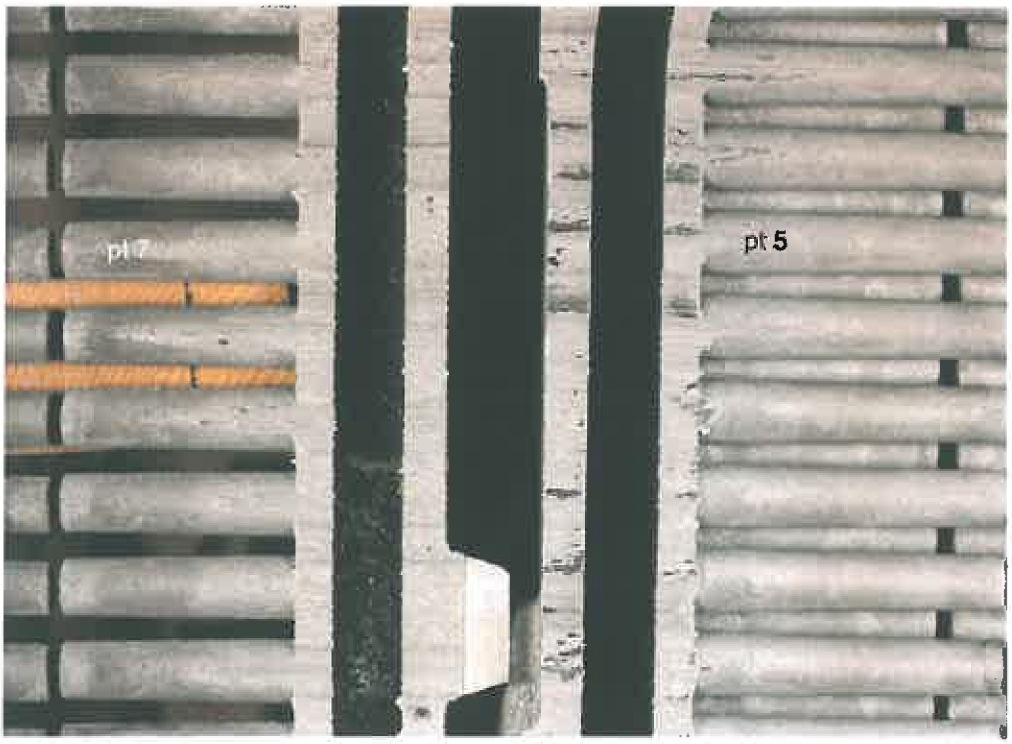


Fig 25 Waterways in pts 5 and 7

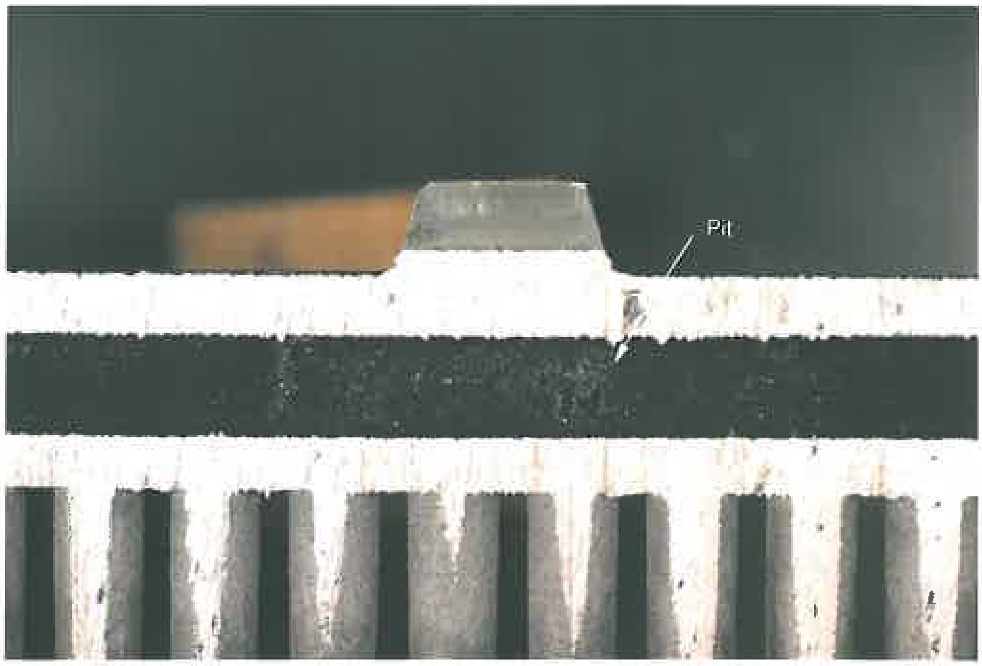


Fig 26 Waterway in pt 7 with location of pit mound

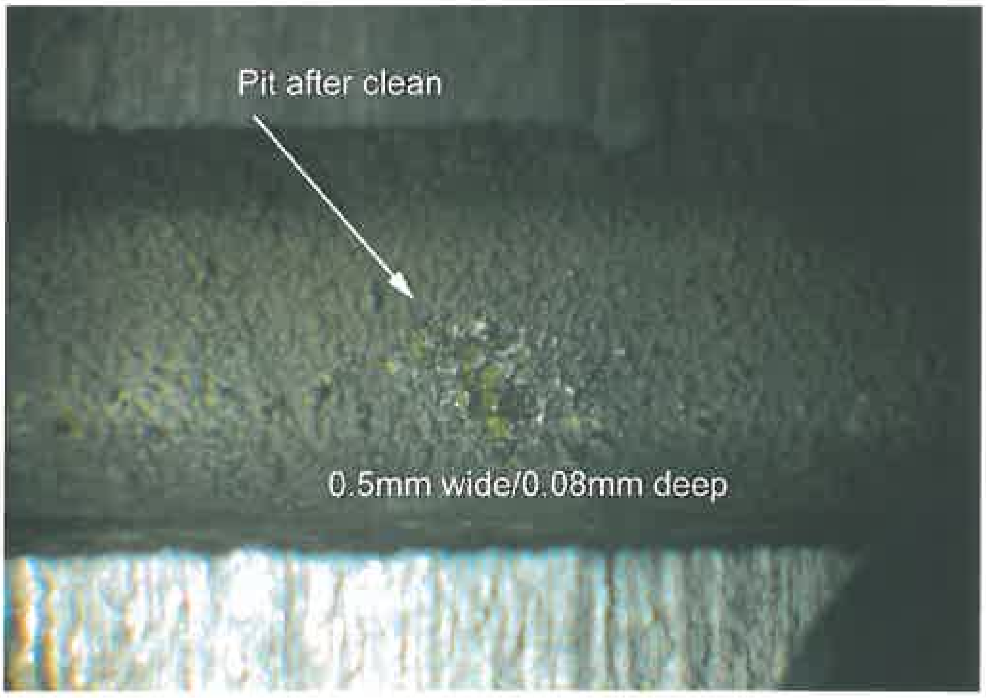


Fig 27 Pit in pt 7 after cleaning

Fig 28 Radiator Hard Water with saw marks

Fig 29 Radiator top waterway

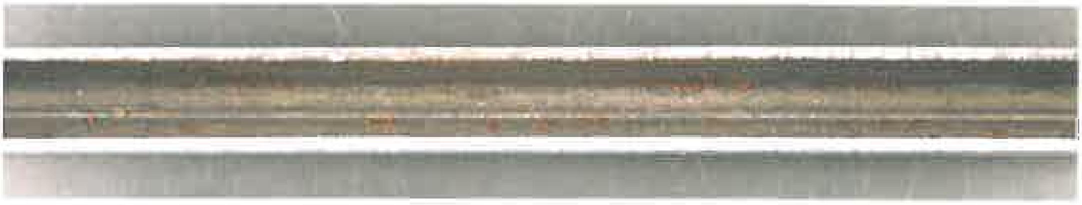


Fig 30 Radiator bottom waterway

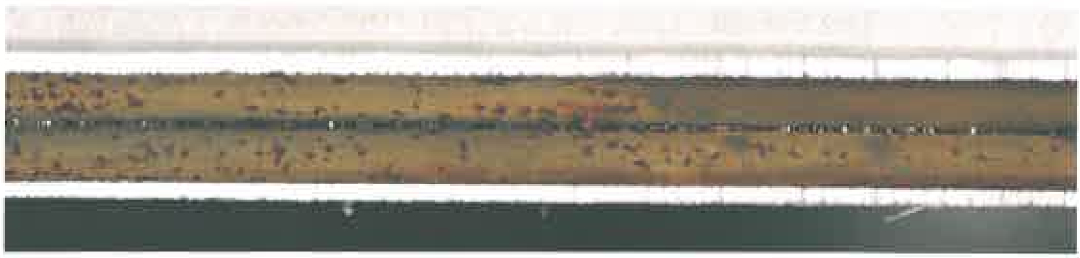


Fig 31 Radiator vertical waterway

Appendix 4 Water Analyses

Water Analysis Results

Sample Date: 21.03.12
Received Date: 26.03.12
Date Completed: 27.03.12

Report Number: 3574
Customer: Midland Corrosion

Site: BSI Loughborough

Sample 1: Soft water Rig Start

Qualitative Analysis

Colour	Slight straw
Turbidity NTU's	74.3
pH	8.4
Conductivity / µS	735
Refractive Index / % Sugar	0
Debris	n/d

Quantitative Chemical Analysis

	mg/L
Total Hardness as $CaCO_3$	2.4
M-alkalinity as $CaCO_3$	300
Boron as B	0
Chloride as Cl	30.7
Sulphur, Total as SO_4	35.8
Nitrite as NO_2	0
Nitrate as NO_3	2.4
Phosphorous, Total as P	0
Molybdenum as Mo	0
Silicon as Si	4.4
Sodium as Na	170.4
Potassium as K	0.2
Magnesium Total as Mg	0.1
Calcium Total as Ca	0.8
Iron, Total, as Fe	8.65
Copper, Total, as Cu	1.04
Zinc, Total, as Zn	0.13
Aluminium, Total as Al	0.01

Sample 2: Hard water Rig Start

Qualitative Analysis

Colour	Slight straw
Turbidity NTU's	101
pH	7.9
Conductivity / µS	535
Refractive Index / % Sugar	0
Debris	Trace magnetite fines

Quantitative Chemical Analysis

	mg/L
Total Hardness as $CaCO_3$	302.2
M-alkalinity as $CaCO_3$	223
Boron as B	0
Chloride as Cl	31.3
Sulphur, Total as SO_4	36.3
Nitrite as NO_2	0
Nitrate as NO_3	2.8
Phosphorous, Total as P	0.1
Molybdenum as Mo	0
Silicon as Si	4
Sodium as Na	13.1
Potassium as K	1.1
Magnesium as Total as Mg	4.2
Calcium Total as Ca	114
Iron, Total, as Fe	8.89
Copper, Total, as Cu	0.3
Zinc, Total, as Zn	0.14
Aluminium, Total as Al	0.02

MCS Midland Corrosion Services Ltd.

Water Analysis Results

Sample Date: 20.04.12
Received Date: 23.04.12
Date Completed: 24.04.12

Report Number: 3599
Customer: Midland Corrosion

Site: BSI Loughborough

Sample 1: **Hard water rig**

Qualitative Analysis

Colour	Trace straw
Turbidity NTU's	31.3
pH	7.2
Conductivity / µS	357
Refractive Index / % Sugar	0
Debris	Trace magnetite fines

Quantitative Chemical Analysis	mg/L
Total Hardness as $CaCO_3$	134.8
M-alkalinity as $CaCO_3$	98
Boron as B	0
Chloride as Cl	34.3
Sulphur, Total as SO_4	40.3
Nitrite as NO_2	0
Nitrate as NO_3	0
Phosphorous, Total as P	0
Molybdenum as Mo	0
Silicon as Si	1.1
Sodium as Na	12
Potassium as K	1.1
Magnesium Total as Mg	4.1
Calcium Total as Ca	47.1
Iron, Total, as Fe	0.5
Copper, Total, as Cu	0.01
Zinc, Total, as Zn	0.06
Aluminium, Total as Al	0

Ionic blance sample 1		1.13

QA sample 1		Fail

Sample 2: **Soft Water rig**

Qualitative Analysis

Colour	Water white
Turbidity NTU's	2.55
pH	8.5
Conductivity / µS	748
Refractive Index / % Sugar	0
Debris	n/d

Quantitative Chemical Analysis	mg/L
Total Hardness as $CaCO_3$	2.8
M-alkalinity as $CaCO_3$	341
Boron as B	0
Chloride as Cl	33.9
Sulphur, Total as SO_4	38.9
Nitrite as NO_2	0
Nitrate as NO_3	0
Phosphorous, Total as P	0.9
Molybdenum as Mo	0
Silicon as Si	0.8
Sodium as Na	158.1
Potassium as K	0.2
Magnesium as Total as Mg	0
Calcium Total as Ca	1.1
Iron, Total, as Fe	0.07
Copper, Total, as Cu	0.01
Zinc, Total, as Zn	0
Aluminium, Total as Al	1.9

Ionic balance sample 2		1.00

QA sample 2		Pass

Midland Corrosion Services Ltd.

Water Analysis Results

Sample Date: 19.06.12
Received Date: 26.07.12
Date Completed: 27.07.12

Report Number: 3753
Customer: Midland Corrosion Services Ltd

Site: BSI Loughborough

Sample 1: HW Test rig

Qualitative Analysis

Colour	Water White
Turbidity NTU's	1.41
pH	7.7
Conductivity / µS	305
Refractive Index / % Sugar	0
Debris	n/d

Quantitative Chemical Analysis	mg/L
Total Hardness as $CaCO_3$	75.3
M-alkalinity as $CaCO_3$	70
Boron as B	0
Chloride as Cl	26.3
Sulphur, Total as SO_4	30.8
Nitrite as NO_2	0
Nitrate as NO_3	0
Phosphorous, Total as P	0.2
Molybdenum as Mo	0
Silicon as Si	0.2
Sodium as Na	10.9
Potassium as K	1.3
Magnesium Total as Mg	1.9
Calcium Total as Ca	27
Iron, Total, as Fe	0
Copper, Total, as Cu	0
Zinc, Total, as Zn	0
Aluminium, Total as Al	0

Ionic blance sample 1	0.95

QA sample 1	Pass

Sample 2: SW Test rig

Qualitative Analysis

Colour	Water white
Turbidity NTU's	0.22
pH	7.9
Conductivity / µS	793
Refractive Index / % Sugar	0
Debris	n/d

Quantitative Chemical Analysis	mg/L
Total Hardness as $CaCO_3$	1.8
M-alkalinity as $CaCO_3$	356
Boron as B	0
Chloride as Cl	27.4
Sulphur, Total as SO_4	32.6
Nitrite as NO_2	0
Nitrate as NO_3	0
Phosphorous, Total as P	0.3
Molybdenum as Mo	0
Silicon as Si	0.6
Sodium as Na	183.4
Potassium as K	0.2
Magnesium as Total as Mg	0
Calcium Total as Ca	0.7
Iron, Total, as Fe	0
Copper, Total, as Cu	0
Zinc, Total, as Zn	0
Aluminium, Total as Al	0.31

Ionic balance sample 2	0.96

QA sample 2	Pass

Midland Corrosion Services Ltd.

Water Analysis Results

Sample Date: 25.09.12
Received Date: 27.09.12
Date Completed: 28.09.12

Report Number: 3792
Customer: Midland Corrosion Services

Site: BSI Loughborough

Sample 1: **1 Soft**

Qualitative Analysis

Colour	Trace straw
Turbidity NTU's	15.6
pH	8.8
Conductivity / µS	773
Refractive Index / % Sugar	0
Debris	Trace ferric fungals

Quantitative Chemical Analysis	mg/L
Total Hardness as $CaCO_3$	1.3
M-alkalinity as $CaCO_3$	320
Boron as B	0
Chloride as Cl	14
Sulphur, Total as SO_4	12.3
Nitrite as NO_2	0
Nitrate as NO_3	47.9
Phosphorous, Total as P	0.3
Molybdenum as Mo	0
Silicon as Si	1
Sodium as Na	169.5
Potassium as K	0.3
Magnesium Total as Mg	0
Calcium Total as Ca	0.5
Iron, Total, as Fe	0.21
Copper, Total, as Cu	0.04
Zinc, Total, as Zn	0.01
Aluminium, Total as Al	2.53

Ionic blance sample 1	0.98

QA sample 1	Pass

Sample 2: **3 Hard**

Qualitative Analysis

Colour	Trace straw
Turbidity NTU's	0.75
pH	7.9
Conductivity / µS	297
Refractive Index / % Sugar	0
Debris	Trace magnetite fines

Quantitative Chemical Analysis	mg/L
Total Hardness as $CaCO_3$	64.5
M-alkalinity as $CaCO_3$	103
Boron as B	0
Chloride as Cl	23.2
Sulphur, Total as SO_4	14.1
Nitrite as NO_2	0
Nitrate as NO_3	58.7
Phosphorous, Total as P	0.5
Molybdenum as Mo	0
Silicon as Si	0.3
Sodium as Na	15.4
Potassium as K	1.3
Magnesium as Total as Mg	0.8
Calcium Total as Ca	24.5
Iron, Total, as Fe	0.28
Copper, Total, as Cu	0.02
Zinc, Total, as Zn	0.01
Aluminium, Total as Al	0.04

Ionic balance sample 2	0.97

QA sample 2	Pass