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Materials & metallurgical consulting, testing & research

Document: JDG-2

Project No.: 41204

Report for: Brookfield Multiplex Limited

Level 17, 240 Queen St,
Brisbane Qld 4000

Attention: Mr John Taylor
Commercial Manager

Subject: Leaks in Copper Pipe at Shafston Mansions

Date: 30 October, 2008

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Signed for & on behalf of UQ Materials Performance

Checked by

.....
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PROJECT 41204 — REPORT

Leaks in Copper Pipe at Shafston Mansions

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PROJECT 41204 — REPORT

Leaks in Copper Pipe at Shafston Mansions

1. BACKGROUND

1.1 Introduction

Brookfield Multiplex Limited engaged UQ Materials Performance to investigate the cause of failure of copper piping in the recirculating hot water system of the Shafston Mansions building. There have reportedly been a number of leaks from pinholes in the copper piping. UQMP was provided with a copy of an earlier report prepared by JWP Engineers, included with which was an appended report from MM Kembla in relation to the copper pipe.

UQMP was engaged to undertake a metallurgical failure analysis of the problem, based on pipe samples provided. Hydraulic analysis is outside of the scope of this report.

1.2 System Layout and Reported History

The recirculating hot water system supplies the 11 student accommodation floors of the 18 storey building. There are 8 hot water tanks at the top of the building, which supply the apartments below via 15 lines. Feed water is sourced from the Brisbane Water supply directly to the heaters. Water is in constant circulation in the system even when no water is drawn by the apartments. Unused water is collected in a manifold at the bottom and returns to the hot water tanks via a single 40 mm diameter riser.

Information concerning the history of the leaks was supplied by Mr John Taylor. We have not been provided with a documented history hence the reliability of this verbal information could not be confirmed. However, the following information appears to be pertinent:

- It is alleged that leaks from pinholes started occurring not long after the building was finished in 2001.
- It is alleged that some 12 leaks were recorded between June 2005 and June 2007.
- Leaks have been reported in a wide variety of locations, including branch lines, droppers, the lower manifold and the 40 mm riser.

2. METHODS

UQMP's D. Schonfeld and L. McInnes conducted a site inspection on 10 September 2008, coincident with repair of a recently diagnosed leak. They spoke with and gathered information from a number of people, including John Taylor (Commercial Manager from Brookfield Multiplex), Karim Shehab (a hydraulics engineer from Lincolne Scott) and a number of maintenance plumbers who were on site during the inspection. From these sources I have accepted as accurate matters that seemed to be of a factual and non-contentious nature, but have not relied upon any statements of opinion, especially any that pertain to the cause of the leaks.

UQMP specified the sections of pipe, which included the leak, to be removed for examination. A sample of pipe from a section with no history of leaking was also removed for comparison. The sections were cut in the presence of UQMP staff and taken directly to UQMP's laboratories to ensure no contamination or damage occurred during transport. A short section from the leaking pipe was retained by the building manager.

Outlet temperatures of the seven operating heaters were measured using a contact thermocouple placed in contact with the outer surface of the copper outlet pipe. The calibration of the contact thermocouple was checked using boiling water (100°C). Contact with the outside wall of the metal vessel returned a reading of 98°C. The 2°C error¹ would result in measured temperatures that underestimate the outlet water temperatures by 2°C.

A water sample was collected from the outlet of one of the water heaters and delivered directly to the water analysis laboratory (Simmonds and Bristow Pty Ltd).

In the UQ laboratories the sample tubes were photographed, sectioned and examined using stereo microscopy. Hardness tests were performed by the Vickers method at a load of 5 kg. Samples of the tubes were submitted to Spectrometer Services Pty Ltd for chemical analysis by ICP-AES (inductively coupled plasma – atomic emission spectroscopy).

Two samples of the pitted surfaces were examined at high magnification by SEM (scanning electron microscopy) and selected features chemically analysed by EDS (energy-dispersive X-ray spectroscopy). EDS spectra were quantified using conventional ZAF (atomic number, absorption, fluorescence) corrections.

¹ The 2°C error could be due to any combination of imperfect thermocouple calibration, heat losses across the wall and imperfect thermal contact between the device and the wall. The latter two are expected to very small, since thermal conduction across a thin metal wall is very rapid while heat transfer to the air is relatively slow, and since the device is a contact thermometer and designed for this purpose. An uncertainty of $\pm 2^\circ\text{C}$ is typical for thermocouples at moderate temperatures.

3. RESULTS AND BASIC INTERPRETATION

3.1 Observations from Site Inspection 10 September

The leak to be repaired was located at the lower end of the 40 mm return riser. The leak had been identified some days previously and a pipe clamp was attached to minimise loss of water prior to repair — see Figure 1. The pinhole leak was adjacent to the soldered joint. One of the plumbers advised that most leaks he had attended were close to bends, tees and joints in the pipe work, but I am not aware of documentary records to confirm this statement. The pipe samples removed for inspection included this bend and a piece approximately 500 mm upstream of the bend.

The copper pipe was marked “Crane Copper” and “DN 40B” — see Figure 2.

Figure 3 shows a location where the service duct has been entered previously to replace a section of pipe. A piece was removed from the unused section of remaining pipe (arrowed), for comparison with the leaking pipe.



Figure 1: Location of leak at bottom of 40 mm return line – pipe clamp used to minimise water loss before repair.



Figure 2: Manufacturer's identification markings on copper pipe.



Figure 3: Section of straight pipe on Level 11, remaining from a previous repair/replacement event.

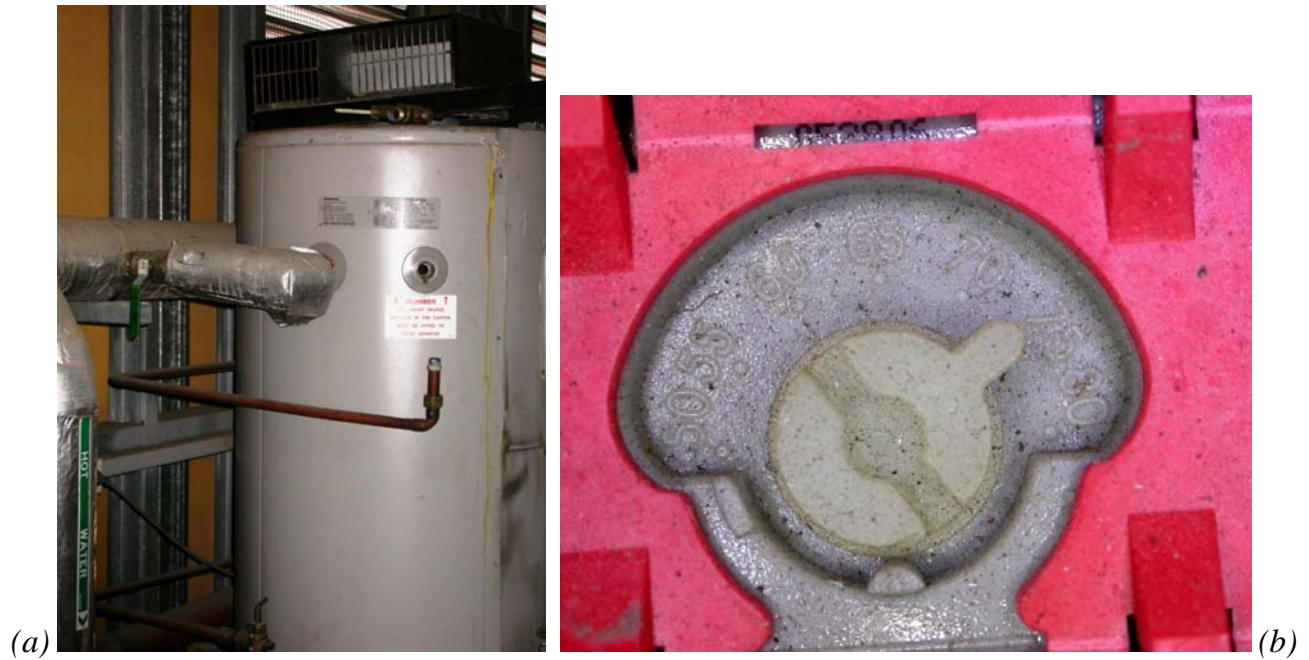


Figure 4: Water heater and temperature controller.

Figure 4(a) shows one of the gas fired water heaters. Of the eight heaters, seven were operational at the time of inspection. Figure 4(b) shows one of the temperature controllers which appears to be set to about 73°C.

The measured outlet temperatures of the operational heaters are listed in Table 1. In view of the small calibration error of the thermocouple, these measured temperatures are believed to underestimate the outlet water temperatures by 2°C.

Table 1: Outlet Temperatures of Water Heaters

Heater #	1	2	3	4	5	6	7	8
Measured Temperature (°C)	—	78	59	54	70	56	80	57

3.2 Copper Composition and Hardness

The chemical composition of the copper pipe as determined by spectrographic analysis is shown in Table 2. The measured composition complies with the requirements of Australian Standard AS 1432 – 2004, Copper tubes for plumbing, gasfitting and drainage applications. It also complies with AS 1432 – 1996, which would have been current at the time the building was being designed in 1999.

The measured hardness of the copper pipe is shown in Table 3. The measured hardness meets the requirements of AS 1432 – 2004 and AS 1432 – 1996 for hard drawn copper tube.

Table 2: Chemical Composition of Copper Pipe Samples

Element	Cu	P	Fe	As	Sb	Others*, each
Level 4 Pipe	Bal	0.02	0.008	<0.01 [§]	<0.01 [§]	<0.005 [§]
Level 11 Pipe	Bal	0.02	0.008	0.01	<0.01 [§]	<0.005 [§]
AS 1432	≥ 99.90	0.015–0.040				

* Si, Zn, Pb, Cr, Ni, Mn, Sn, Al, Be, Cd, Bi, In, Ag, Te, Se, Ti, Zr

§ Below detectable limit.

Table 3: Hardness of Copper Pipe Samples

Readings	1	2	3	4	Average
Level 4 Pipe	112	110	107	118	112
Level 11 Pipe	114	105	113	117	112
AS 1432, Hard drawn tube					≥ 100

3.3 Water Analysis

The full water analysis results are attached as an Appendix A. Some relevant values are shown in Table 4. For comparison, some examples of Brisbane Water Mt.Crosby supply compositions are provided in Appendix B.

There is nothing unusual or noteworthy about this water analysis. The Langelier saturation index of –0.3 indicates balanced water conditions in which calcium carbonate scales neither form nor are dissolved at any significant rate. This can be regarded as normal².

3.4 Visual and Optical Microscope Examination

Sectioning of the pipe samples revealed the distribution and characteristics of the attack which led to leakage of the copper pipe. Figure 5 gives an overview of the samples after sectioning. The “furry” appearance at the cut edges is due to burrs from the cutting process.

Figure 6 shows the pinhole leak, (a) from the outside of the pipe and (b),(c) from the inside of the pipe. It is clear that the leak has occurred as a result of some form of localised

² Calcium carbonate scales can impart some protective effect against corrosion, and soft non-scaling waters (saturation index less than –1.0) may be more corrosive than balanced or scaling waters. However, heavy scaling can create flow problems. Water authorities typically aim for balanced conditions, between –0.5 and +0.5.

corrosion. The attack involves localised loss of the protective oxide scale on the inside surface of the pipe, while the surrounding pipe surface maintains its oxide scale.

Figure 7 shows the early stages of the attack. Some regions have an intact protective copper oxide scale, but in other areas the protective oxide has been lost, exposing bare metallic copper to the flowing water. Attack of the copper then leads to creation of horseshoe-shaped pits. Further details of the progression of attack are shown in Figure 8 and Figure 9, showing how the horseshoe-shaped pits have coalesced to form a larger region of attack, and how the remaining regions of protective oxide become undercut.

The observed characteristics of the attack are fully consistent with the phenomenon of Erosion-Corrosion (otherwise known as Flow-Assisted Corrosion or Impingement Corrosion). The clear observation of horseshoe shaped pits, with their open ends facing downstream, is classically diagnostic of Erosion-Corrosion.

Table 4: Water Composition

Quantity	Conductivity at 25°C	pH at 25°C	pH _s *	Langelier Index	Total Dissolved Solids at 105°C	
Value	540 µS/cm	8.1	8.4	-0.3	300 mg/L	
Quantity	Total Calcium as Ca	Bicarbonate as CaCO ₃	Sodium as Na	Chloride as Cl	Sulphate as SO ₄	Free CO ₂
Value (mg/L)	30	110	49	72	28	1.4
Quantity	Calcium hardness as CaCO ₃	Total hardness as CaCO ₃	Bicarbonate Alkalinity as CaCO ₃	Total Alkalinity as CaCO ₃		Free CO ₂ at pH _s
Value (mg/L)	75	140	91	91		0.70

* pH at CaCO₃ saturation – used to calculate the Langelier saturation index

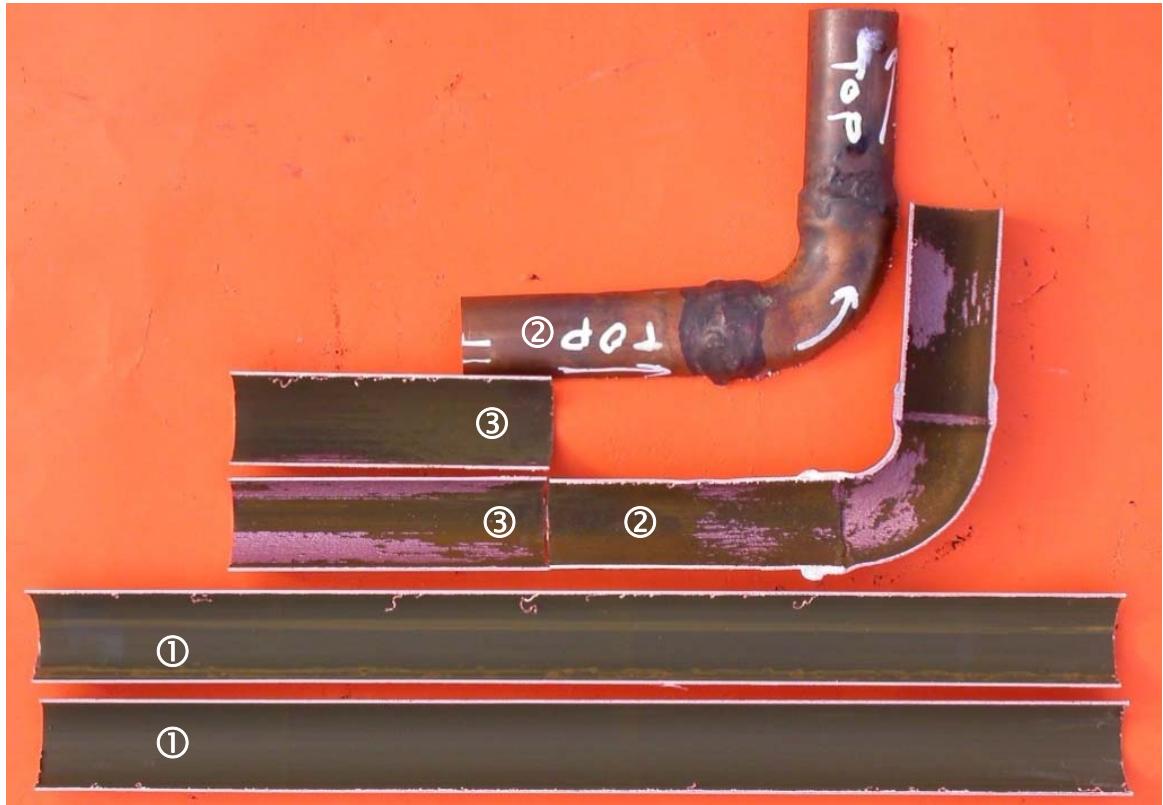


Figure 5: Pipe samples after sectioning. ① From region shown in Figure 3; no attack evident.
② Leak site as shown in Figure 1; severe attack in several locations (pink coloured patches).
③ From approximately 500 mm upstream of the bend (not adjacent as shown).

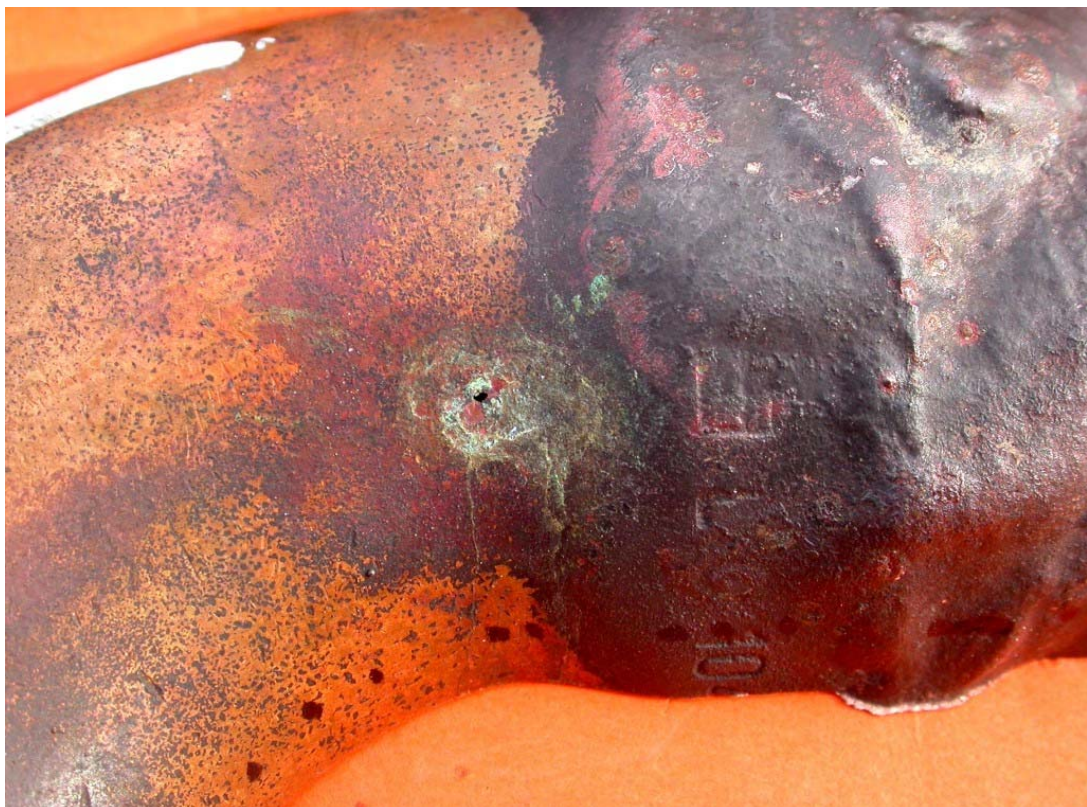


Figure 6(a): Pinhole leak at bend, viewed from outside of pipe.



Figure 6(b): Pinhole leak at bend, viewed from inside of pipe.



Figure 6(c): Detail of pinhole leak at bend, viewed from inside of pipe.

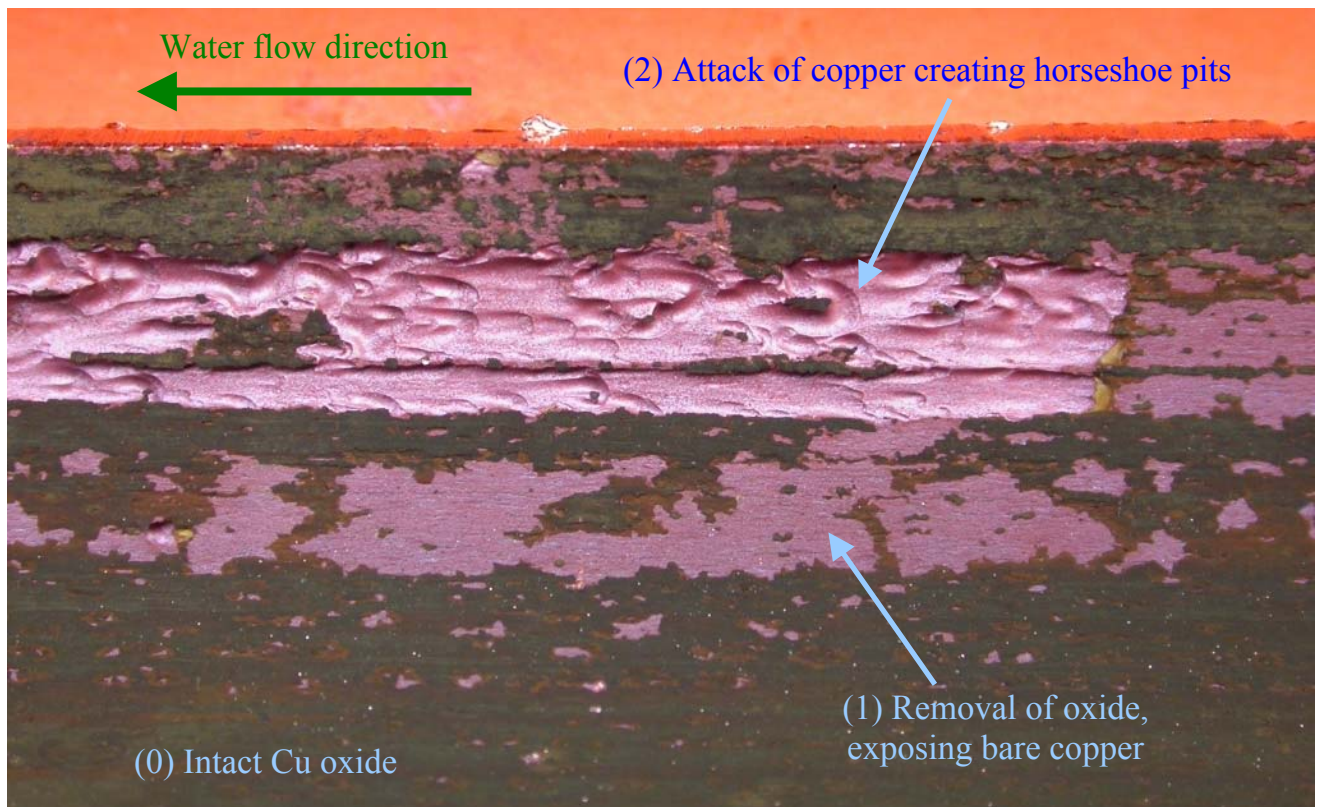


Figure 7: Early stages of Erosion-Corrosion attack. Horseshoe-shaped pits have open end downstream.

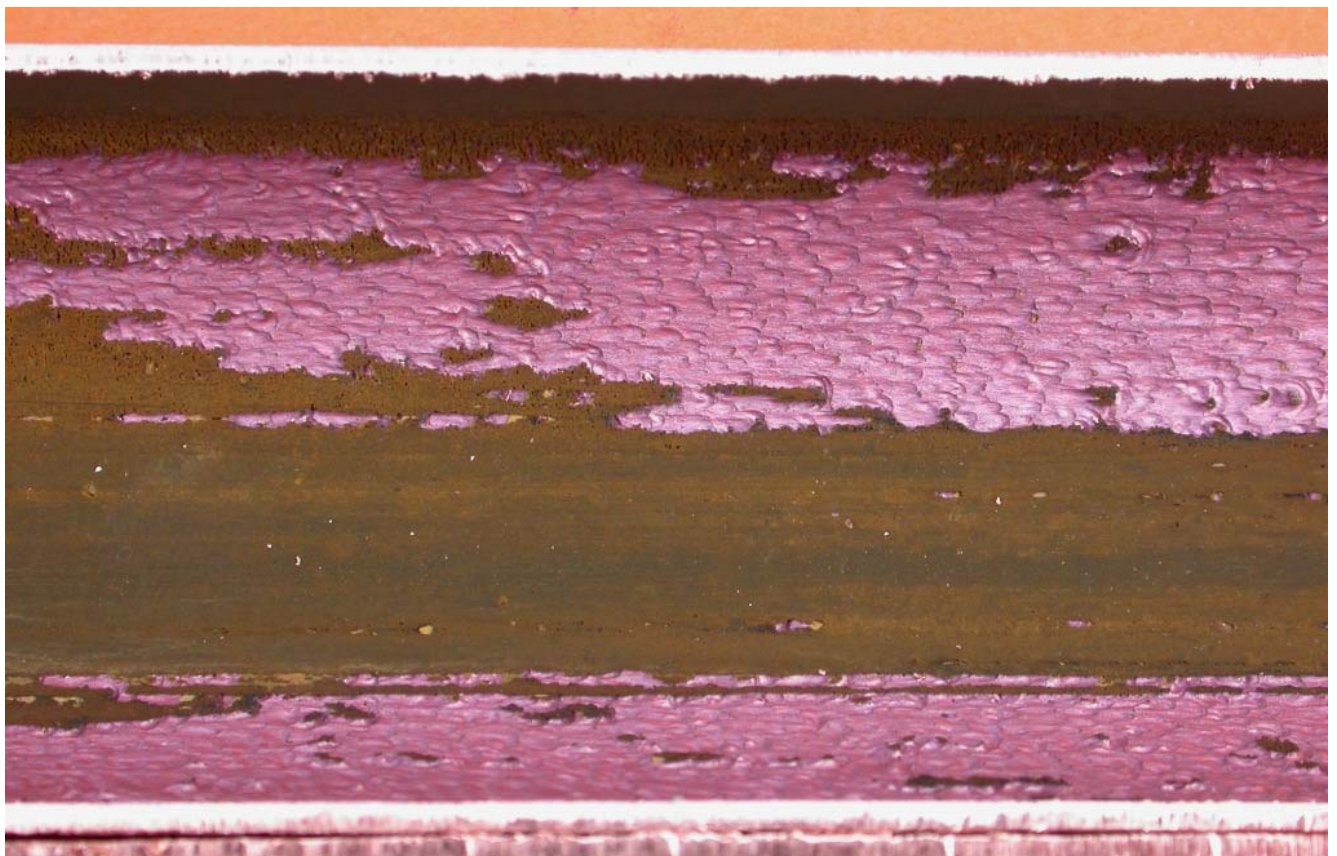


Figure 8: Large region of Erosion-Corrosion in straight section of pipe ~500 mm upstream of the bend. Many horseshoe-shaped pits, coalescing.

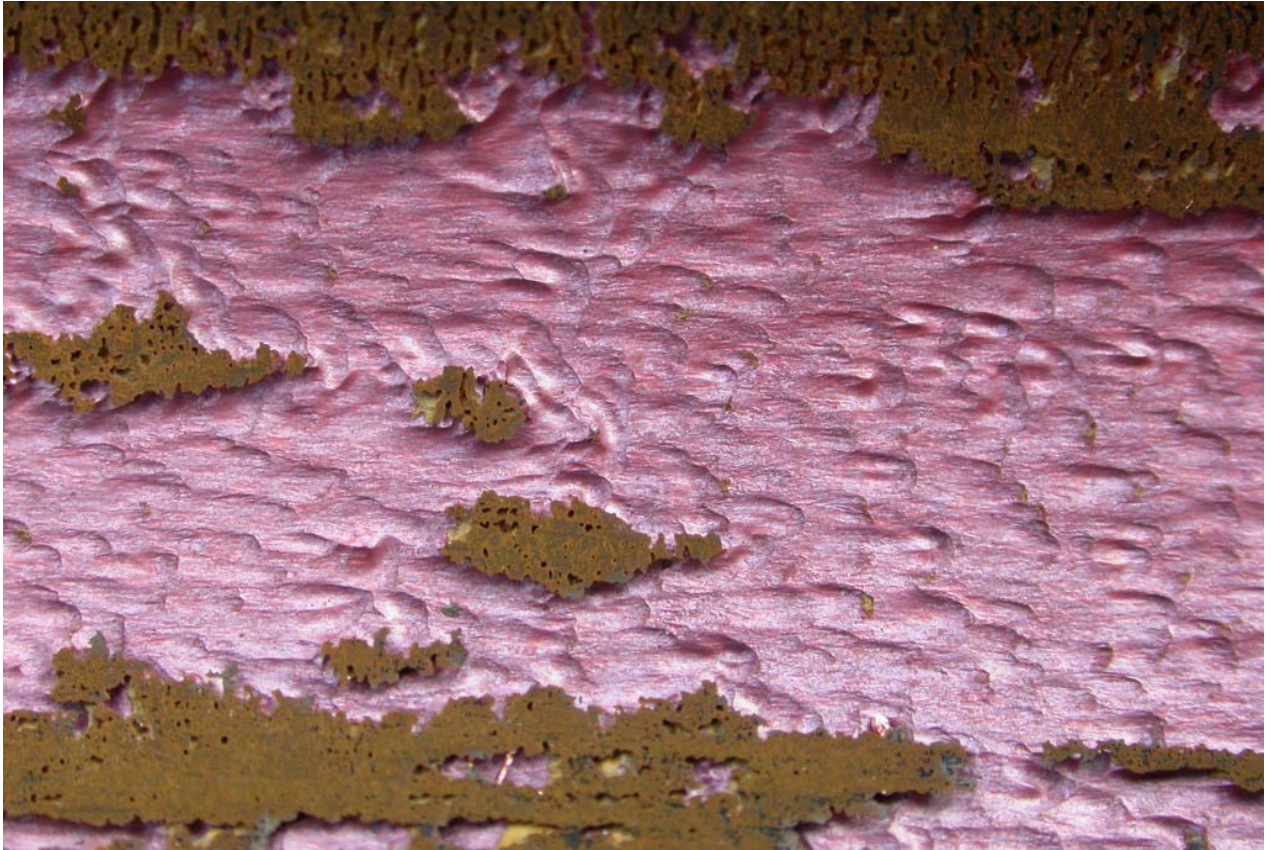


Figure 9(a): Further detail of Erosion-Corrosion, showing coalescence of horseshoe-shaped pits and islands of intact oxide. The latter are deeply undercut.



Figure 9(b): Further view of Erosion-Corrosion and undercut islands of intact oxide.



Figure 10(a): Erosion-Corrosion downstream of joint.



Figure 10(b): Erosion-Corrosion in bend downstream of joint.

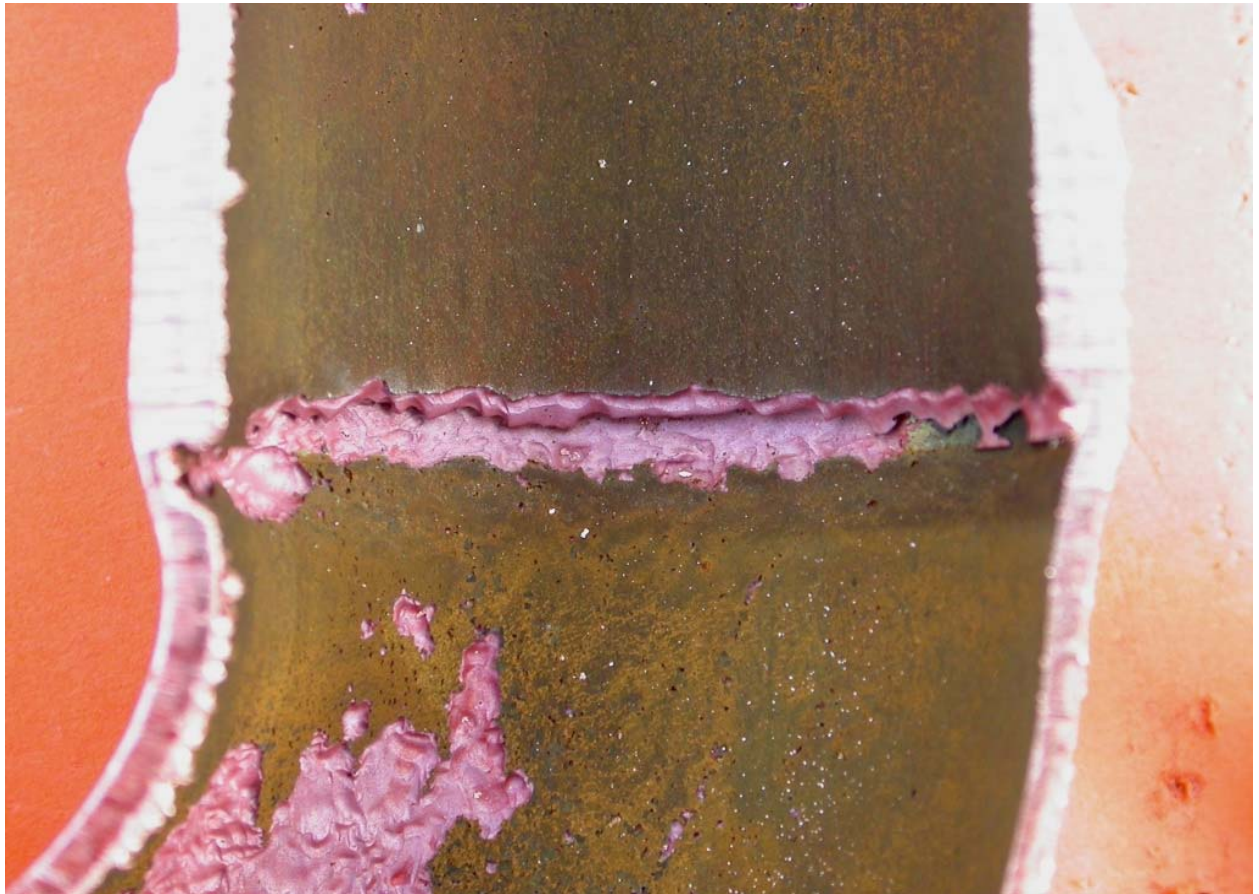


Figure 11(a): Erosion-Corrosion at joint, apparently promoted by turbulence at the joint.



Figure 11(b): Erosion-Corrosion at joint, apparently promoted by turbulence at the joint.

Figure 5, Figure 10 and Figure 11 above show that the Erosion-Corrosion occurs preferentially at and/or downstream of joints in the pipe. This is indicative of the results of turbulence created by the internal step at the joint. However, the attack shown in Figure 8 is not associated with any obvious source of turbulence.

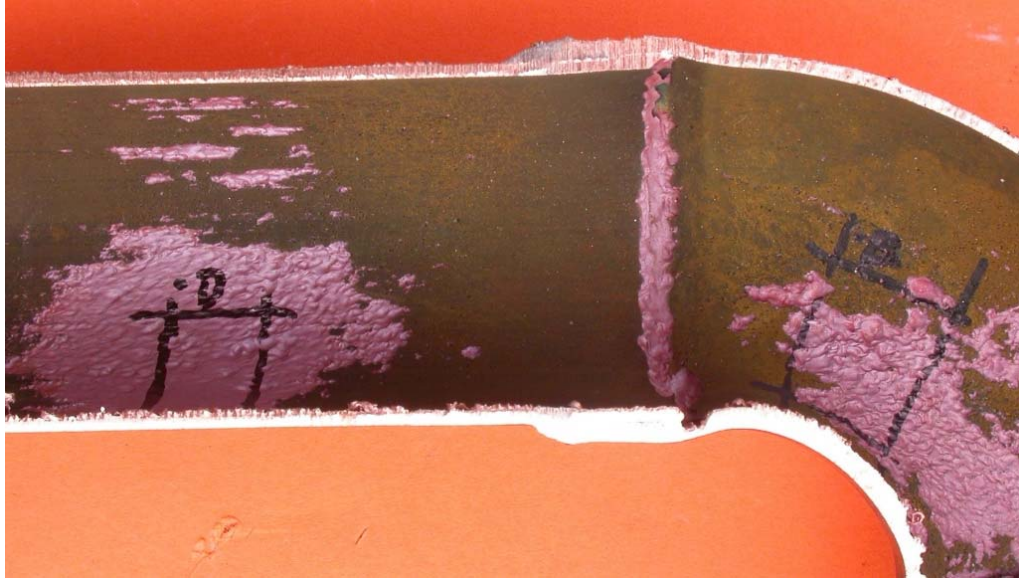


Figure 12(a): Location of samples for SEM examination: (right) sample “B” (Bend) and (left) sample “D” (Downstream of bend).

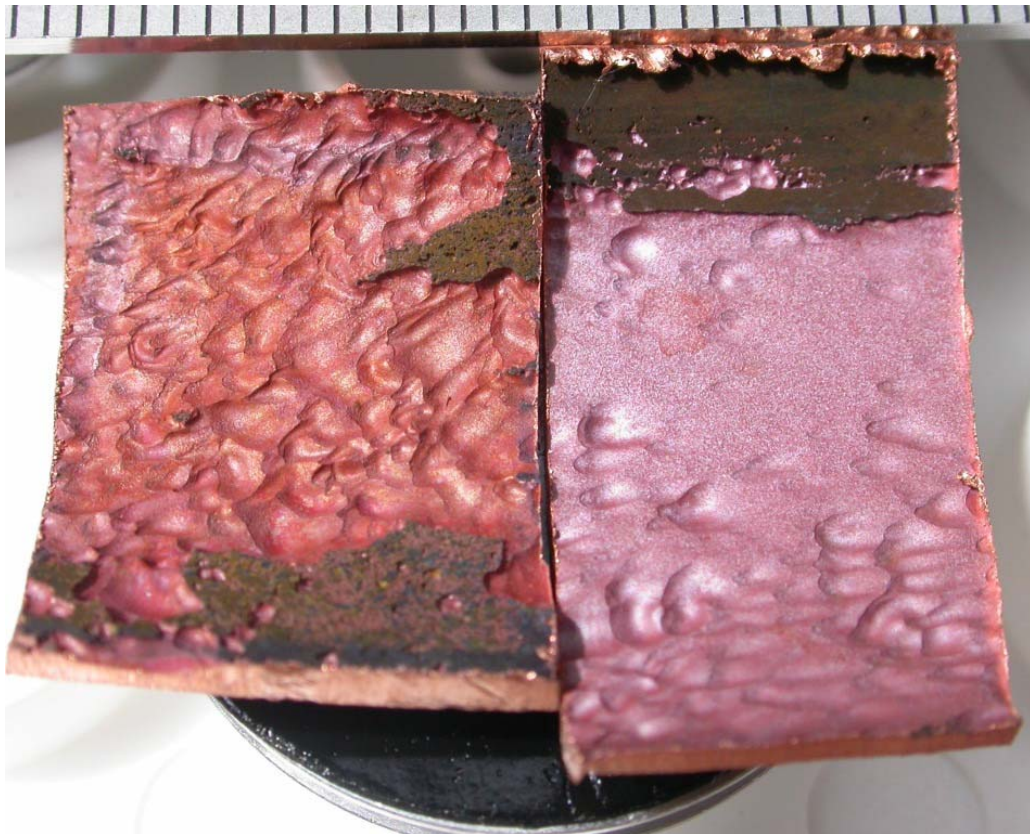


Figure 12(b): SEM samples mounted on SEM stub: (left) sample “B” (Bend) and (right) sample “D” (Downstream of bend).

3.5 SEM Examination

3.5.1 Samples

Scanning electron microscopy was used to provide high-magnification images and chemical composition information about the surfaces in the Erosion-Corrosion region. Two samples were cut, as shown in Figure 12 above:

- Sample “B” (Bend) and
- Sample “D” (Downstream of bend).

Sample B shows the rough scalloped surface typical of the turbulent flow patterns in the bend, while sample D shows a flatter surface typical of more laminar flow.

3.5.2 Oxide Scales and Bare Metal

Figure 13 shows low-magnification SEM images from Sample B. The two images show an island of remaining protective oxide scale, with Erosion-Corrosion pits on either side. Figure 13(a) is a secondary electron image (SEI) and (b) is a backscattered electron image (BEI) of the same field of view. The SEI emphasises the topography, while the BEI gives information about the average atomic number (related to the atomic weight) of the chemical elements in the features on the surface. As a result of this “atomic number contrast”, the BEI in Figure 13(b) enables us to distinguish between oxide and metal. The bare metal in the pits appears brighter than the oxide, because the average atomic number of the oxide is lower than that of the metal. This confirms what has been assumed from the visual and optical microscope examination.

Figure 14 shows two examples of EDS (energy dispersive X-ray spectroscopy) spectra from different regions of the Sample B. Figure 14(a) is from a region of bare metal, while Figure 14(b) is from the oxide scale shown in Figure 13(b).

Table 5: EDS Analysis Results – Bare Metal

	Wt.% Cu	Wt.% O	Wt.% Cl
Average	95.8	3.8	0.5
Std Dev	0.7	0.7	0.1

EDS analysis of the bare metal surface shows predominantly copper (Cu), with a small amount of oxygen (O) and traces of chlorine (Cl). Carbon (C) also shows in the spectra, but carbon is almost always present as a contaminant on the surface of SEM samples and can be ignored. Table 5 above shows quantified EDS data averaged from 7 spectra from different regions of the bare metal (some from sample B and some from sample D). It can be seen that the measured concentrations of oxygen and chlorine were very consistent, suggesting that

these elements are incorporated into an ultra-thin film (not readily visible even at SEM magnifications) on the surface of the metal. This sub-microscopic film of oxide could have formed simply due to exposure of the sample to air after it was removed from the system, and should not be confused with the much thicker scale of corrosion products (visible to the naked eye) that is present outside of the Erosion-Corrosion pits. The original scale of corrosion products consists primarily of copper (Cu) oxides, mixed with oxides of iron (Fe), silicon (Si), aluminium (Al) and some metallic copper.

3.5.3 Surface Features of Bare Metal

Figure 15(a) to (d) is a series of SEM secondary electron images (SEI) at 4-fold increments of magnification from 100× to 6400×, showing the bare-metal surface from sample D. The metal surface appears substantially flat and fairly smooth even at moderately high magnifications. At high magnification (6400×), the scale of surface roughness can be seen to be uniform, with features in the range of about 0.5–2 µm across. There are no obvious signs of either grooves or embedded mineral particles, such as might suggest Solid Particle Erosion at low impingement angles (Abrasive Erosion). The uniform and relatively fine-scale surface roughness could be consistent with active corrosion alone.

Figure 16(a) to (d) is again a series from 100× to 6400×, this time showing sample B. The low magnification image (a) shows the rough scalloped surface resulting from turbulent flow in the bend. Figure 16(b) to (d) show one of the “hill” regions within (a). The surface features are broadly similar to those seen in sample D, except that there are several small patches of smoother material. It is difficult to know what has caused these smoother patches, but they are not suggestive of Solid Particle Erosion.

Figure 17(a) and (b) are from a valley region within Figure 16(a). In the lower portion of the field of view in Figure 17(a) there are some fine roughly linear striations. The striations are some 12–15 µm long, and there are 10 or more of them, approximately parallel to each other. It is difficult to judge what is likely to have caused these linear features. It is conceivable that they might be the remnants of grooves from abrasive particles (subsequently affected by corrosion). Alternatively they could represent preferential corrosion of some directional feature in the copper microstructure, such as twinning. I have some experience with examination of surfaces damaged by Solid Particle Erosion, but am not able to make a confident judgement in this case.

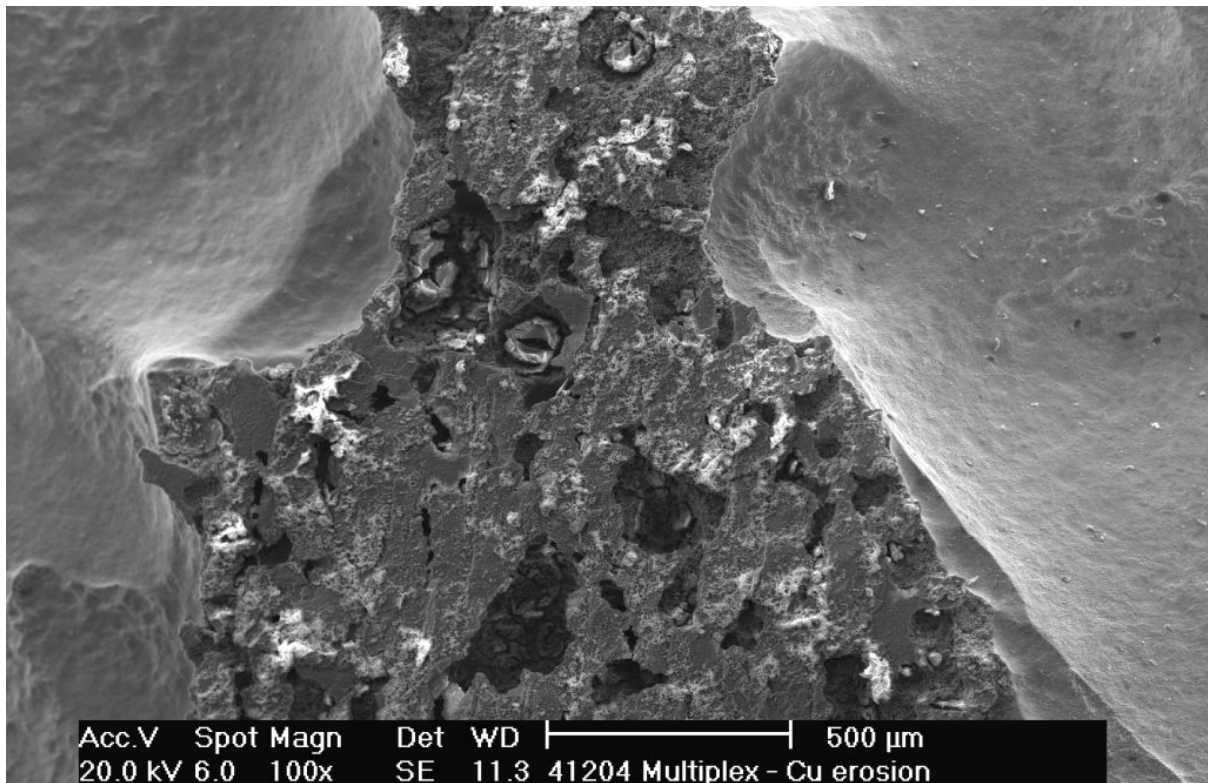


Figure 13(a): Sample “B” (within Bend). Low-magnification (100×) secondary electron image (SEI) of an island of protective oxide scale, with Erosion-Corrosion pits on either side.

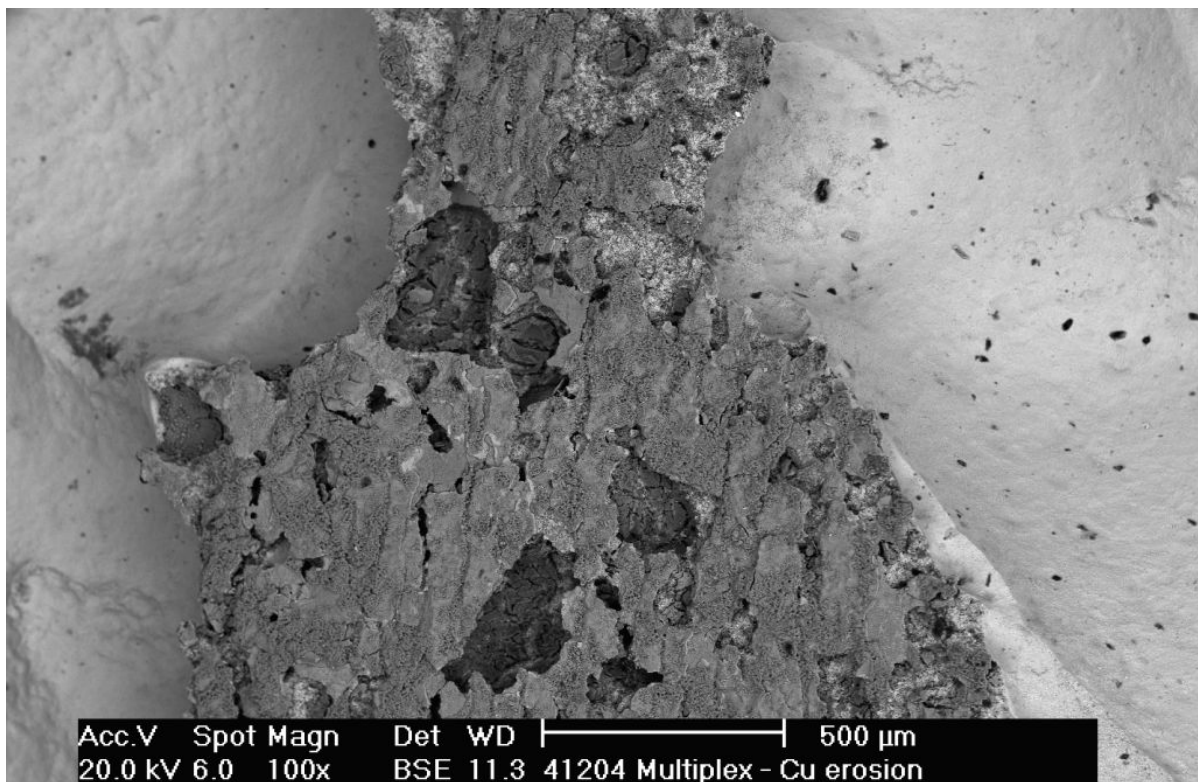


Figure 13(b): Backscattered electron image (BEI) of the same feature as shown in (a). The bare metal in the pits shows brighter than the oxide, because the average atomic number of the oxide is lower than that of the metal.

Label A: UQMP 41204 Multiplex - Cu erosion - Sample B, bare metal

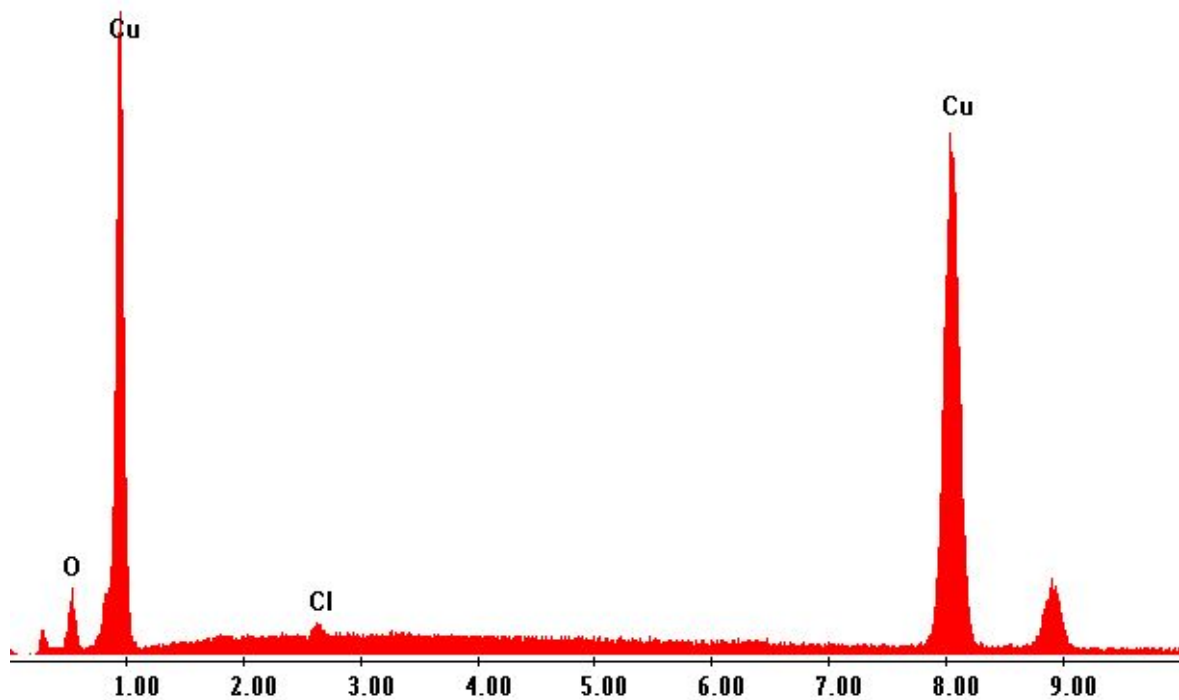


Figure 14(a): Typical EDS spectrum from a bare metal region.

Label A: UQMP 41204 Multiplex - Cu erosion - Sample B, Oxide layer, low-Z region

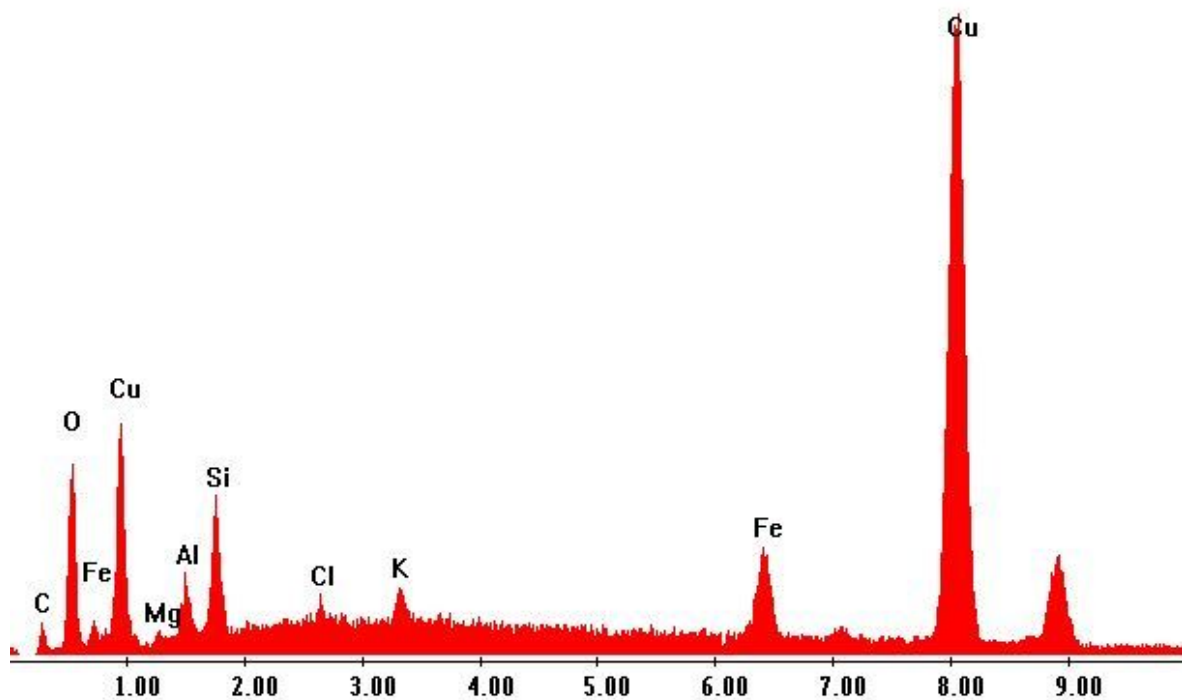


Figure 14(b): EDS spectrum from a region of the original protective scale of corrosion products on the pipe surface.

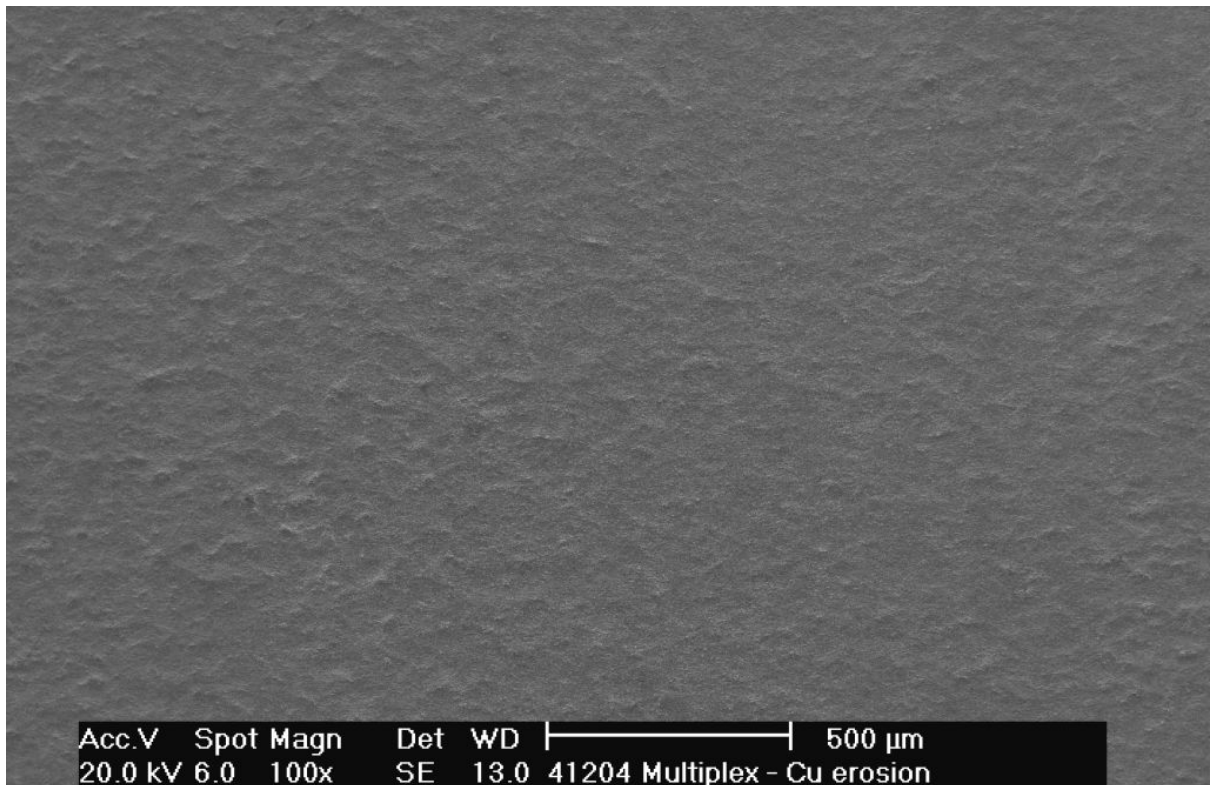


Figure 15(a): Sample “D” (Downstream of bend). Low-magnification (100×) secondary electron image of a flat smooth region of the eroded surface.

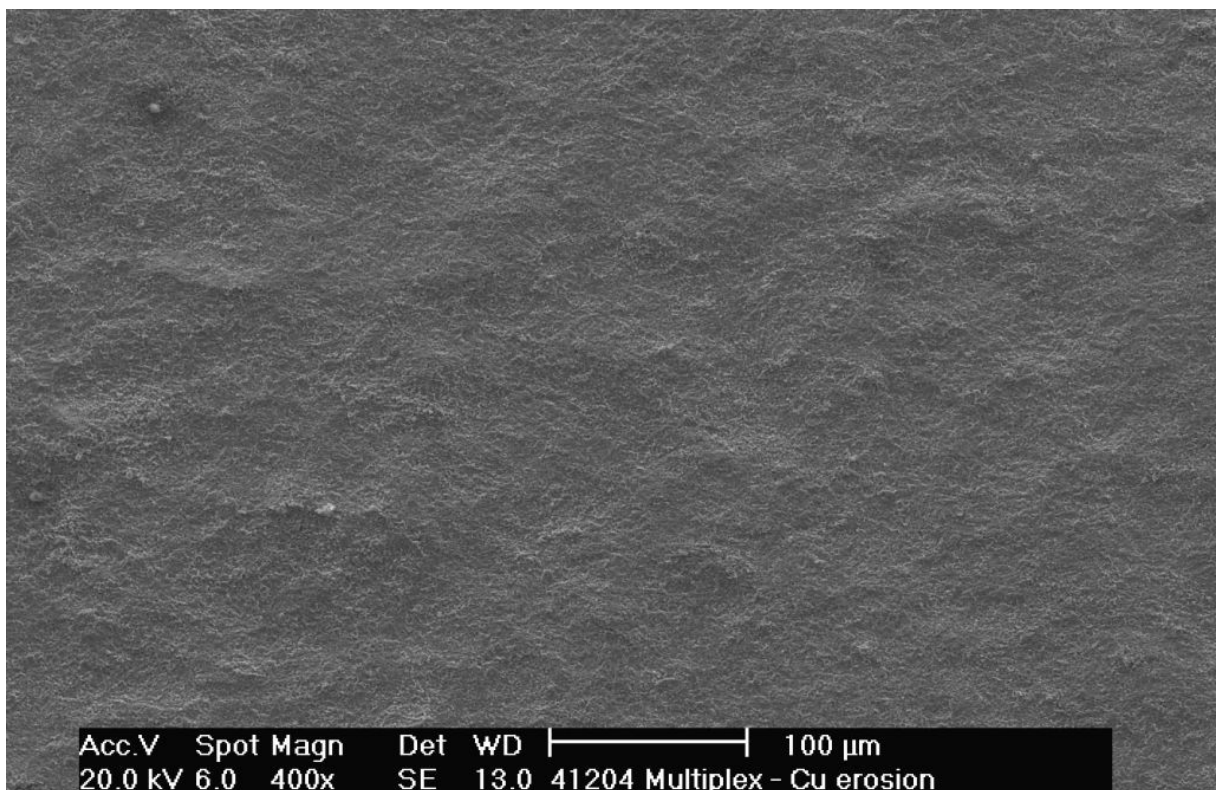


Figure 15(b): As per Figure 15(a) but at medium magnification (400×). Bare metal surface is flat and fairly featureless.

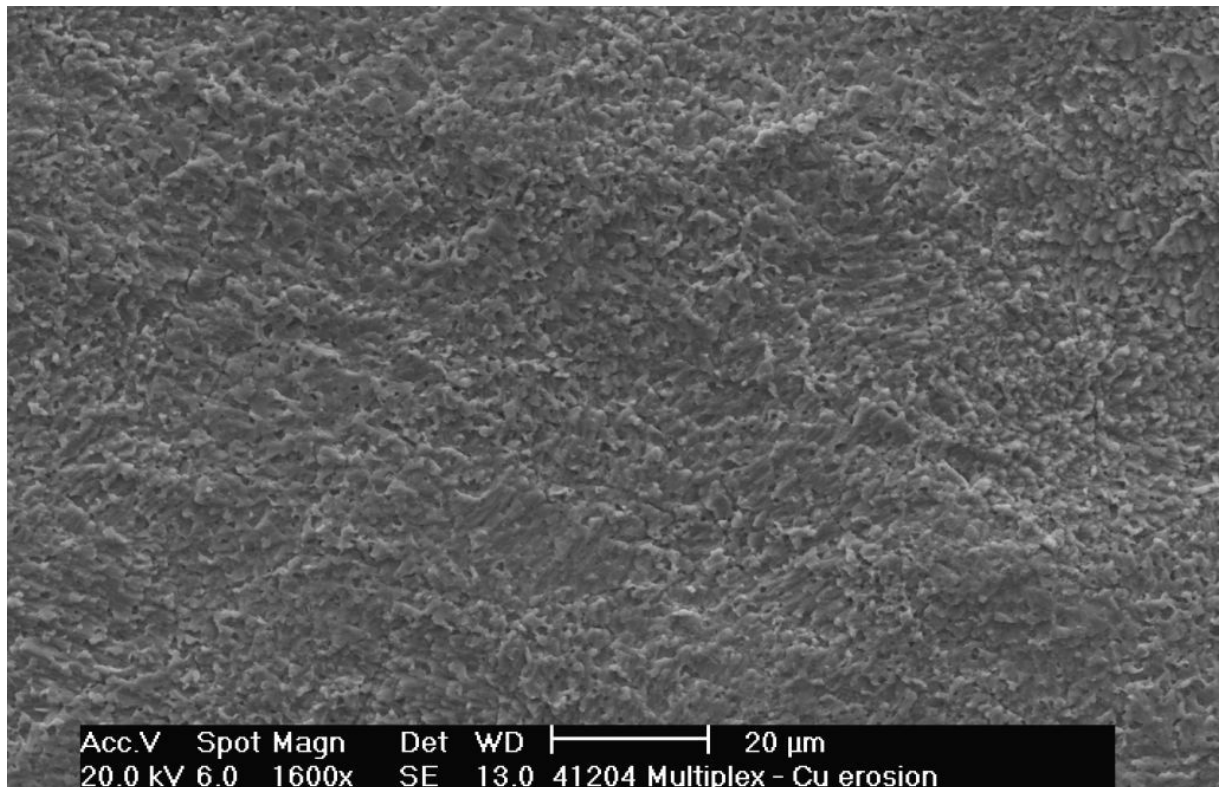


Figure 15(c): Sample “D” (Downstream of bend). As per Figure 15(a) and (b) but at medium-high magnification (1600×).

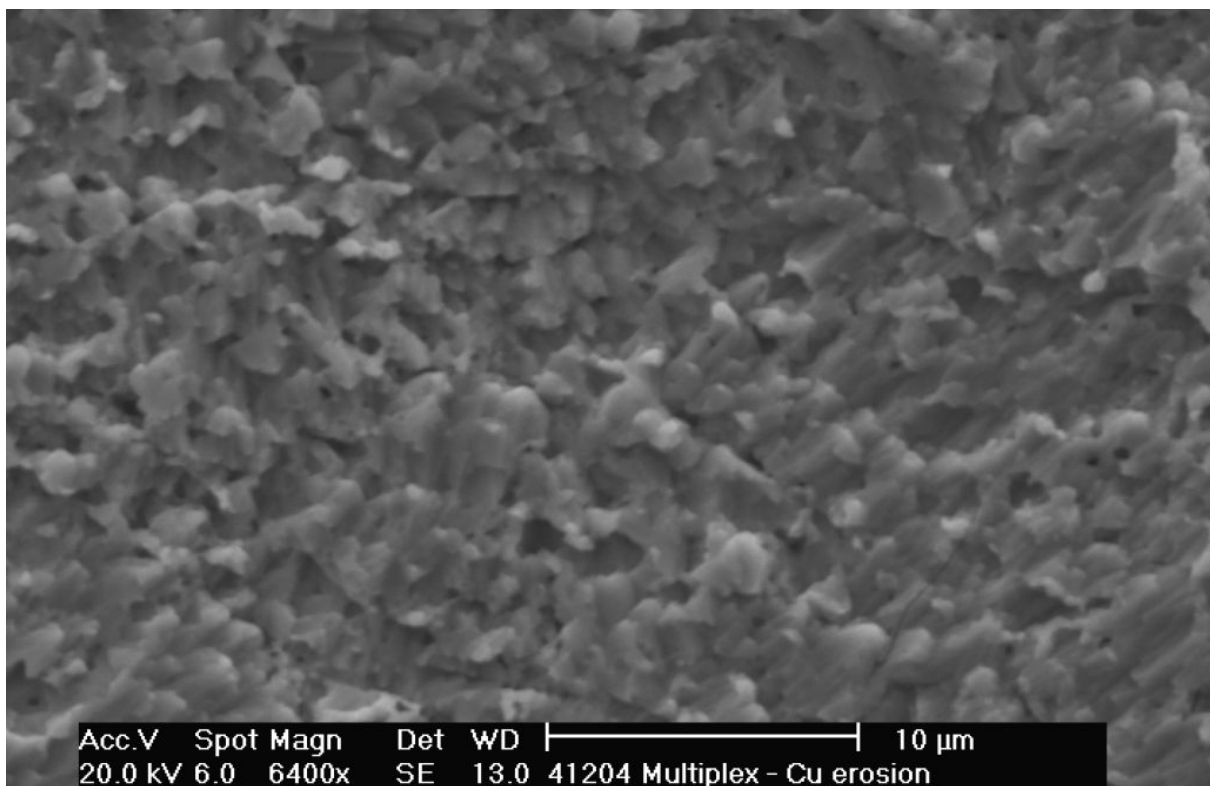


Figure 15(d): As per (a)–(c) but at high magnification (6400×). There are no obvious signs of solid particle erosion at low impingement angles (abrasive erosion), such as grooves or embedded mineral particles. Surface features could be consistent with active corrosion alone.

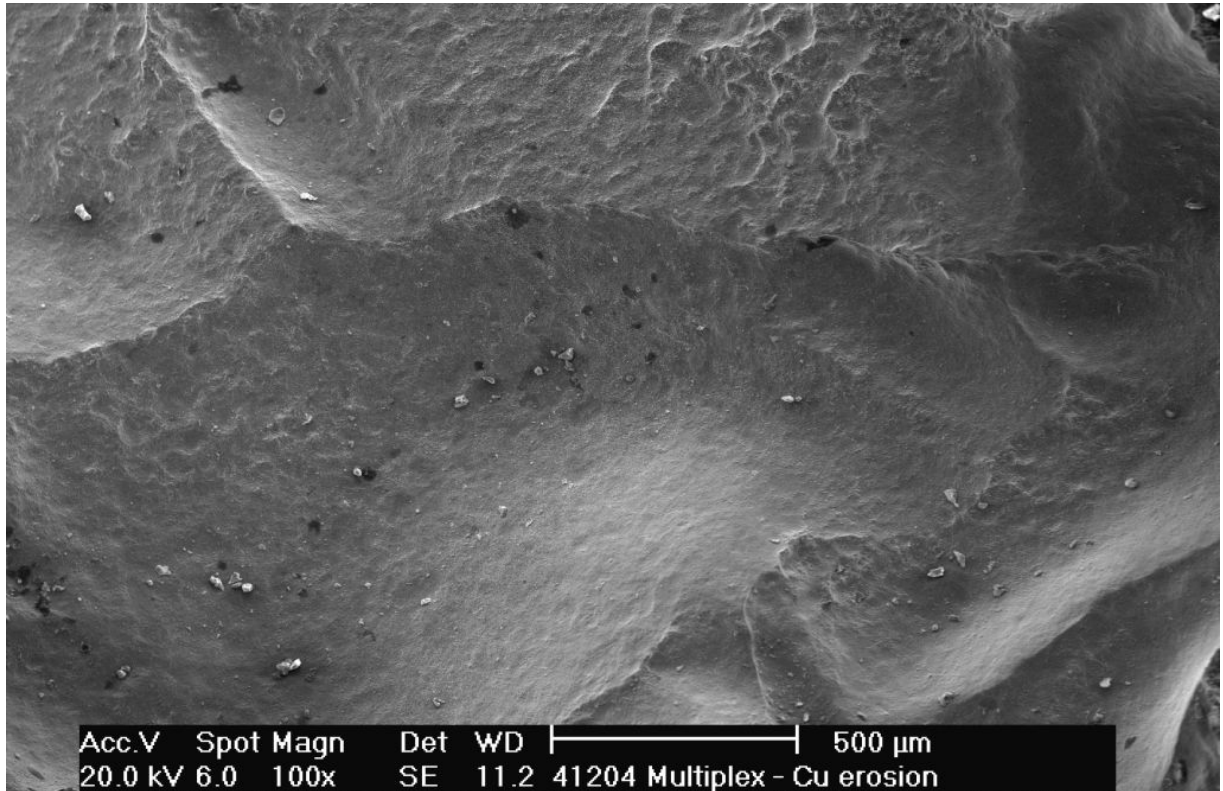


Figure 16(a): Sample “B” (within Bend). Low-magnification (100×) secondary electron image of the rough scalloped surface resulting from turbulence in the bend. Some debris particles.

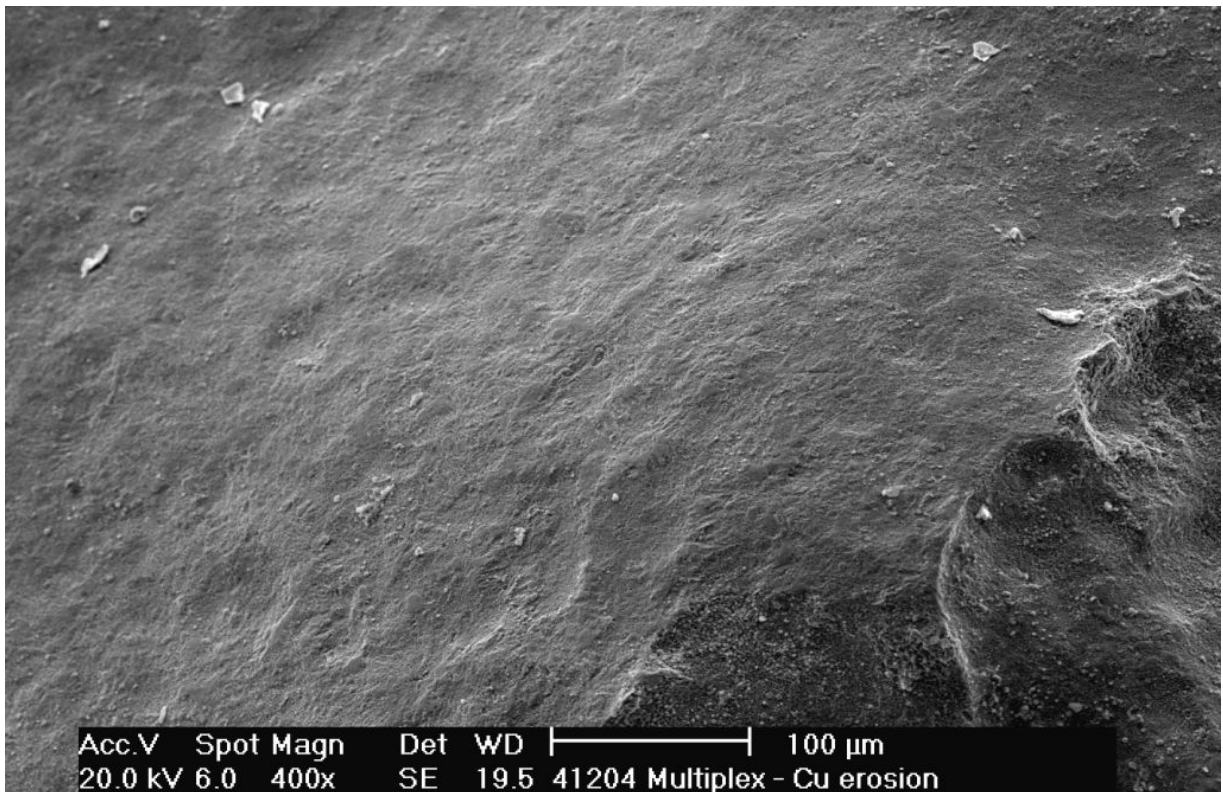


Figure 16(b): As per Figure 16(a) but at medium magnification (400×).

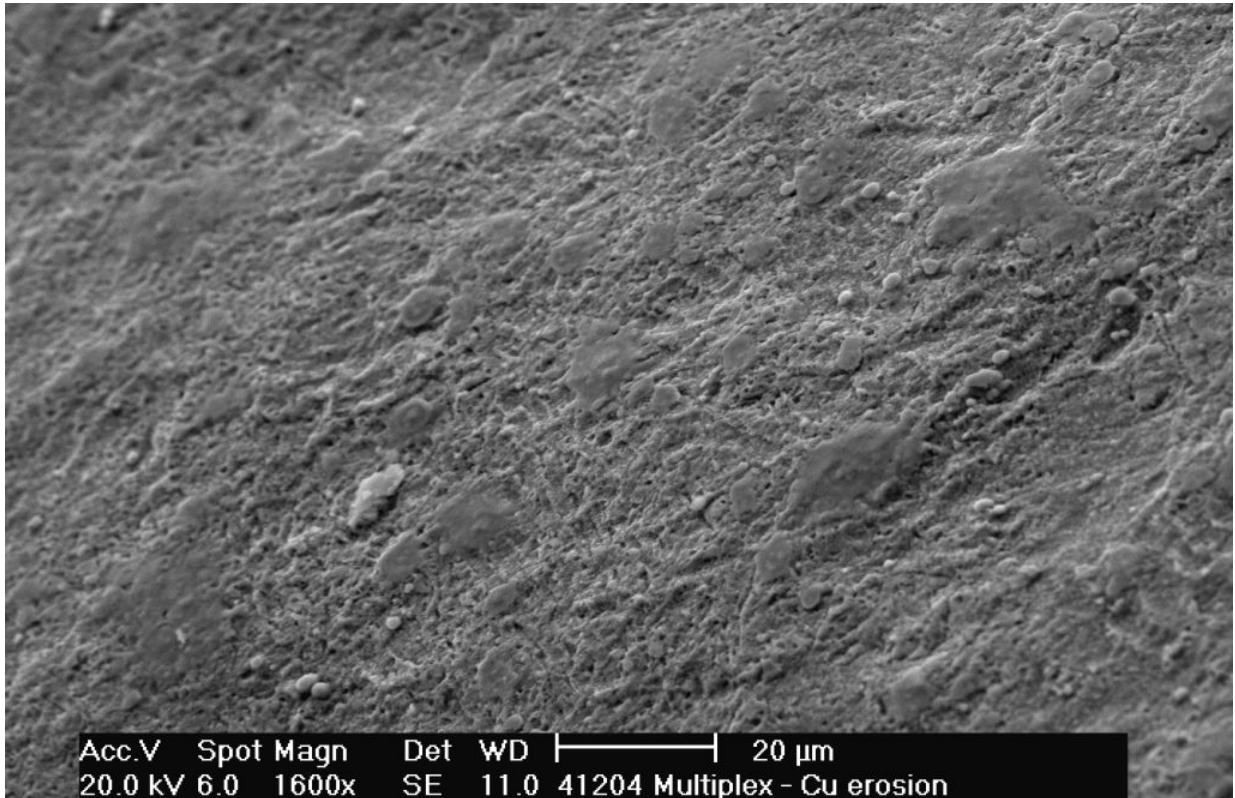


Figure 16(c): Sample “B” (within Bend). As per Figure 16(a) and (b) but at medium-high magnification (1600×)

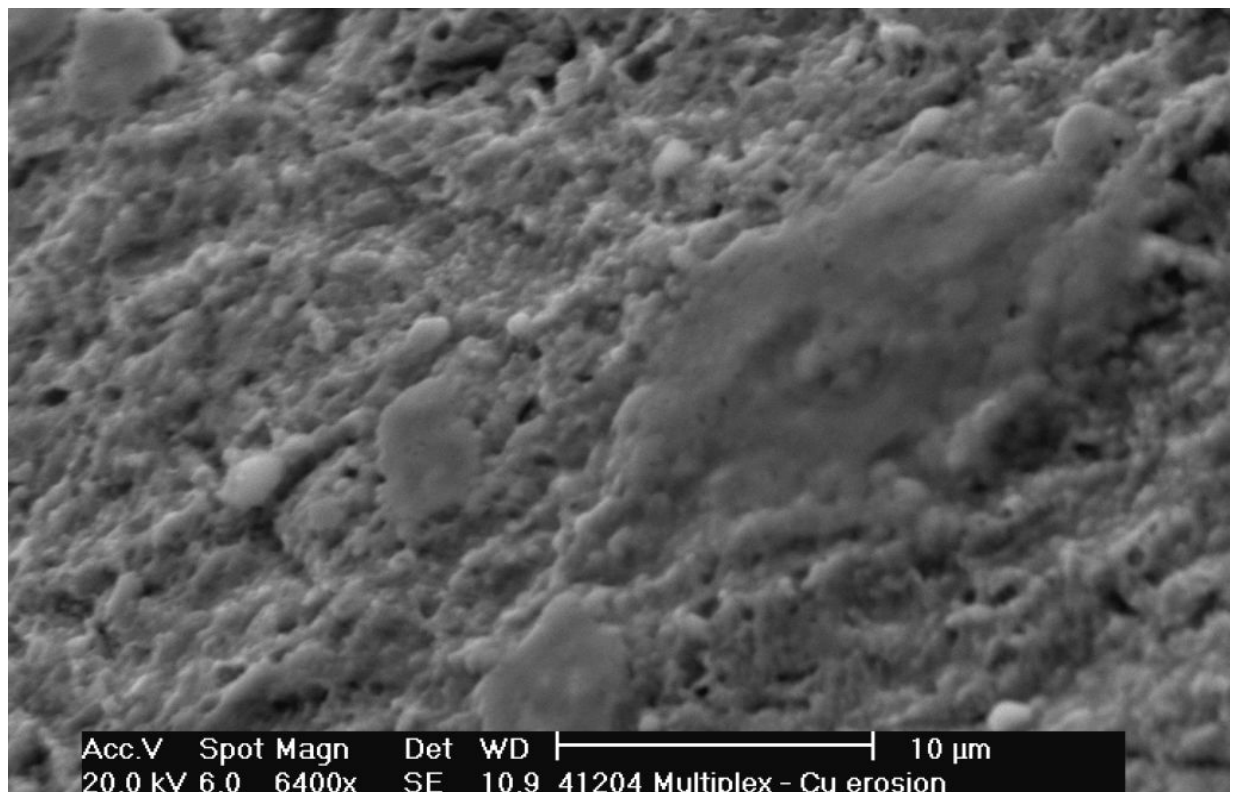


Figure 16(d): As per (a)–(c) but at high magnification (6400×). Once again there are no signs of solid particle erosion. EDS analysis shows that essentially all of the surface (including both rougher and smoother features in this image) is metallic copper.

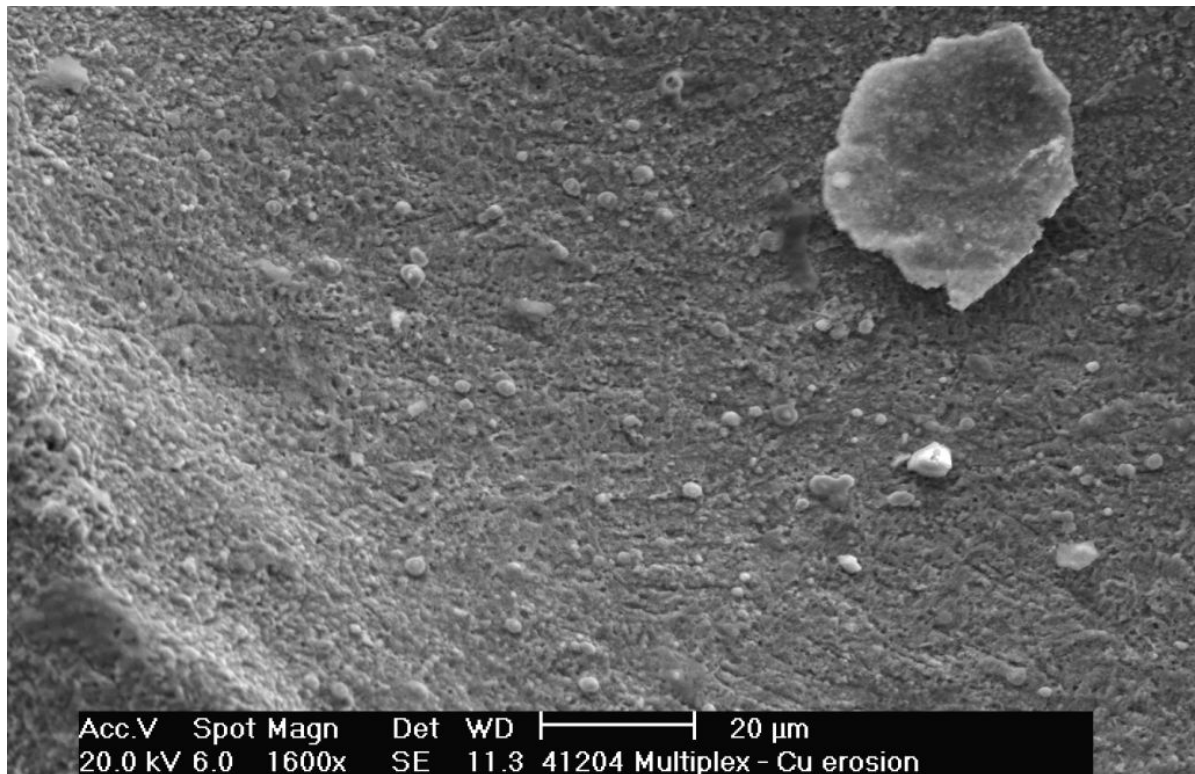


Figure 17(a): Region within valley to left of centre in upper portion of Figure 16(a), at medium-high magnification (1600×). Debris includes some small mineral particles and a ~30 µm flake of metallic copper.

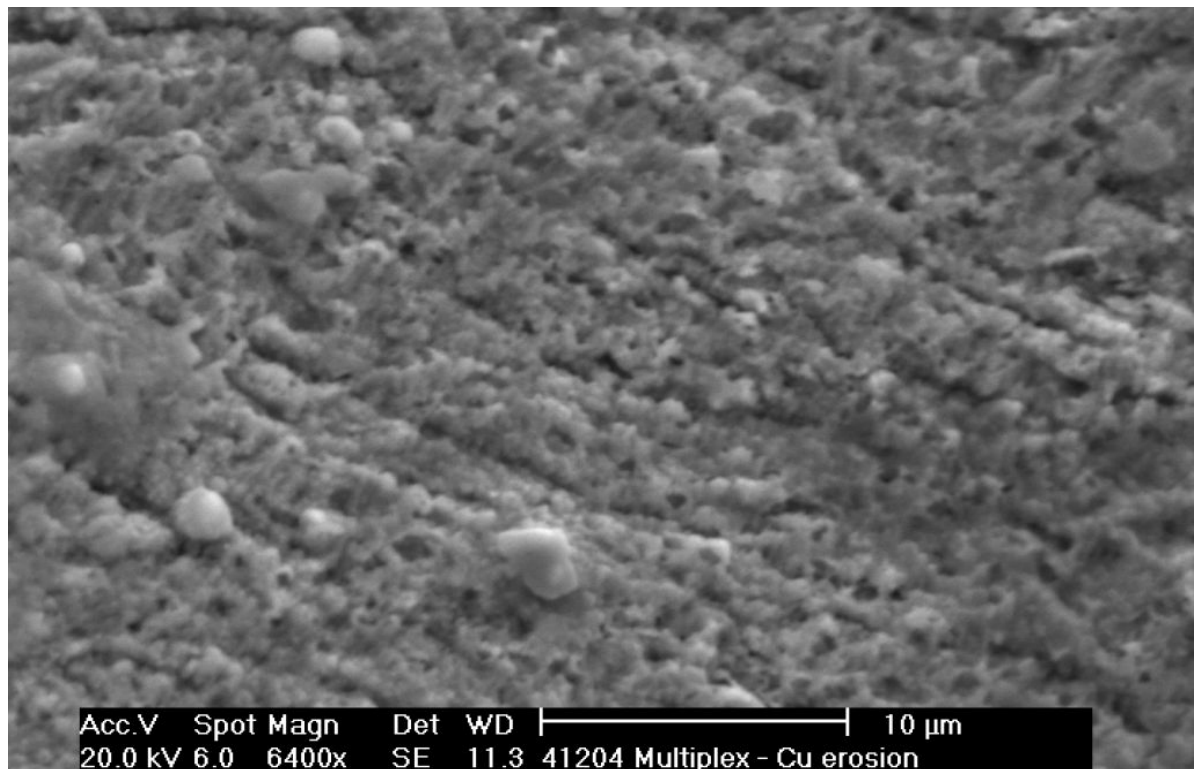


Figure 17(b): High magnification image from lower portion of Figure 17(a). It is difficult to judge whether or not these striations represent evidence for Solid Particle Erosion effects.

4. DISCUSSION

4.1 Mechanism of Leak

4.1.1 Erosion-Corrosion

The features of attack on the samples examined clearly demonstrate that the leak in this pipe occurred by the mechanism of Erosion-Corrosion. This diagnosis is unambiguous, due to the following features which are characteristic of Erosion-Corrosion (both E-C in general and specifically E-C of copper pipes by potable water):

- The corroded regions show bright metal surfaces, free from oxide scales;
- Horseshoe-shaped pits with their open ends facing downstream;
- Preferential occurrence at bends and downstream from any deviations from the smooth internal surface profile of the pipe (due to water turbulence at these features).

Erosion-Corrosion is a mode of material surface damage in which corrosive attack by the chemical environment and mechanical wear by a flowing fluid (with or without entrained solids or gas bubbles) act conjointly to increase the rate of material loss. In general terms, Erosion-Corrosion can occur by a spectrum of mechanisms, from corrosion-dominant (where the fluid flow merely increases the rate of corrosion) to erosion-dominant (where selective corrosion reduces the erosion resistance of the material surface). In the specific case of Erosion-Corrosion of copper pipes in potable water, the mechanisms are as follows:

- The flowing water dislodges portions of the protective copper oxide scale from the surface, exposing patches of bare metal.
- In terms of the electrochemistry of corrosion, the protective oxide scale is “cathodic” (noble) while the exposed metal is “anodic” (reactive). The configuration of small anodic patches surrounded by a larger area of cathodic material gives rise to acceleration of the corrosion rate by “galvanic action”.
- The corrosion rate of the patches of exposed metal remains high because the flowing water provides a continuous supply of dissolved oxygen and flushes away the dissolved copper ions.

A feature of Erosion-Corrosion is the phenomenon of the critical velocity, also known as the breakaway velocity. The critical velocity is the flow velocity at which there is a distinct transition from low corrosion rates (when the protective scale remains largely intact) to high corrosion rates (when the protective scale is dislodged by the flow).

4.1.2 Type 2 Pitting

The JWP report (June 2007 Revision A), in section 2.7 on p.13, states that “The pattern of internal pitting indicates that it is ‘type 2’ pitting”. The first paragraph of Section 3 of the JWP report also refers to the failure being by “type 2 pitting”. This is not correct. Although Type 2 pitting (also known as Hot Water Pitting) and Erosion-Corrosion do have some features in common, the literature indicates that they are quite distinct phenomena. Their similarities are as follows:

- Both show relatively deep narrow pits (relative to those in Type 1 Pitting = Cold Water Pitting);
- In both cases the un-attacked copper surface between the pits has a protective copper oxide scale; and
- Both are accelerated by increasing water temperature.

Diagnostic differences include the following:

- Horseshoe-shaped pits are a classical feature of Erosion-Corrosion, clearly indicating the importance of fluid flow in the mechanism.
- In Type 2 Pitting the pits are usually capped by small greenish-black tubercles of Cu_2O (cuprite) and $\text{CuSO}_4 \cdot 3\text{Cu}(\text{OH})_2$ (brochantite).
- Type 2 Pitting only occurs when the ratio of bicarbonate to sulphate is low ($\text{HCO}_3/\text{SO}_4 < 1.0$). For the current case, Table 4 indicates that the ratio $\text{HCO}_3/\text{SO}_4 \approx 4$.
- Increasing water velocities disrupt the mechanism of Type 2 Pitting, which involves deposition of cathodic substances onto the pipe surface.

The MM Kembla report, which is appended to the JWP report, identifies the mechanism of attack as “erosion corrosion”. I agree with this diagnosis, for the reasons stated in section 4.1.1 above. Moreover, on a worldwide basis Type 2 Pitting is relatively rare (except in Japan). Erosion-Corrosion is more common, and is a well-recognised problem in recirculated hot water systems.

In the body of the JWP report, Section 3, the first paragraph makes reference to the role of water flow velocity, which is consistent with the diagnosis of Erosion-Corrosion. The reference to “type 2 pitting” in the same sentence suggests that the writers of the JWP report have mistakenly equated Erosion-Corrosion and Type 2 Pitting.

4.1.3 Cavitation Erosion

I have been asked whether “Cavitation” should be considered as a possible cause of the leaks.

In this context we should first clarify the terminology. “Cavitation” is a pre-requisite for but is not the same as “Cavitation Erosion”. Cavitation is a well-known phenomenon in fluid dynamics and refers to the creation of vapour bubbles in the liquid. This can occur for

example when pipe diameter increases in such a way that the fluid pressure drops below the vapour pressure for the liquid. When these vapour bubbles subsequently enter a region of higher fluid pressure, they can collapse at supersonic speeds. If this collapse occurs in close proximity to a metal surface, the jets of liquid impinging on the surface can create severe local deformation and wear. This kind of wear is denoted “Cavitation Erosion”. The “cavities” referred to by the term Cavitation are the vapour bubbles in the liquid, not the pits on the metal surface created by the erosion.

For the following reasons, I do not believe that Cavitation Erosion is likely to be a contributing factor in the Shafston case:

- The observable features of the attack are distinctive and fully consistent with those of the common Erosion-Corrosion damage mode, so that there is no need to invoke another more specialised damage mode.
- At the level at which I have examined it, the attack does not display any features that I would regard as characteristic of Cavitation Erosion. Surfaces damaged by Cavitation Erosion typically show deep pitting in an apparently random³ pattern.
- Cavitation is common in high velocity fluid dynamics situations such as marine propellers and high-pressure pumps; I would be somewhat surprised to see cavitation occurring in situations where fluid velocities are only in the order of 2 m/s and where sudden large pressure changes seem unlikely. However I would defer to the advice of a hydraulics expert in this respect.

4.2 Possible Causes

The evidence available to me indicates that there are three contributing factors that have led to this rapid Erosion-Corrosion:

- (a) Excessive water velocity in the pipes;
- (b) Elevated water temperature;
- (c) Turbulence due to the joint profile.

The evidence for the contribution of each of these factors is listed below.

³ Contrary to what is sometimes assumed, the fluted, scalloped patterns typical in the erosion of slurry pumps do not indicate Cavitation Erosion but simply reflect the fluid flow patterns. Cavitation Erosion does not typically show these fluted, scalloped patterns. Cavitation Erosion would certainly not be expected to produce horseshoe shaped pits, which are classically characteristic of Erosion-Corrosion.

4.3 (a) Excessive water velocity

4.3.1 General Considerations

Erosion-corrosion is fundamentally caused by the effect of water flow, disrupting the protective copper oxide scale and accelerating corrosion rates. In a water distribution system there are two factors that can lead to water impinging on and moving across a surface at velocities high enough to disrupt the protective oxide scale:

- High general flow velocity;
- Turbulence, causing high local impingement velocities.

It is possible for turbulence to cause erosion corrosion when the general flow velocity is moderate and within industry guidelines. However turbulence cannot occur under zero-flow conditions, and for a given pipe profile turbulence is more likely when the general flow velocity is high.

4.3.2 Specific Observations

Figure 5 and Figure 8 show unambiguous Erosion-Corrosion in a straight section of pipe remote from bends and joints (some 500 mm upstream of the leaking bend). This observation constitutes compelling evidence that there is a systemic problem, as opposed to a problem restricted to regions of local turbulence. Although the attack does not occur in all parts of the system, it is evident that the conditions are so close to critical that any number of local factors can trigger the Erosion-Corrosion. This is suggestive of excessively high general flow velocity (and/or temperature – see section 4.4 below).

4.3.3 Quantitative Guidelines

In the JWP report (section 3.1.1) it is claimed that the system specification called for a water flow rate of 1.5 L/s, corresponding to a velocity of 1.5 m/s in a 40 mm pipe. The JWP report (section 2.6) cites measured flow rates corresponding to water velocities of ~1.4 m/s for low pump speed setting and ~2.1 m/s for high pump speed setting. The JWP report (section 3.1.2) further claims that simultaneous operation of two pumps at high speed settings might have led to velocities in the order of 2.8 m/s.

UQMP is not in a position to judge whether these figures are to be regarded as reliable. If they are, then they can be considered in the light of various published information about the effects of water velocity and temperature on the tendency for Erosion-Corrosion. In particular it is useful to compare these figures with published recommendations for maximum water velocities.

- J.E. Singley, B.A. Beaudet & P.H. Markey 1984 – *Corrosion Manual for Internal Corrosion of Water Distribution Systems*, U.S. Environmental Protection Agency, EPA 570/9-84-001 ORNL/TM-8919, April 1984, section 3.3, pp.11–12

This publication warns of the risk of Erosion-Corrosion in copper pipes, and recommends a maximum flow velocity of 1.2 m/s. This recommendation is made without qualification regarding water temperature.

- H. Cruse, O. von Franqué & R.D. Pomeroy 1985 – Corrosion of copper in potable water systems, in *Internal Corrosion of Water Distribution Systems*, American Water Works Association Research Foundation, Chapter 5, pp.317–416 (esp. pp332–336). This detailed publication provides a graph of corrosion rate as a function of temperature, for softened water at a range of velocities between 0.5 and 4.0 m/s. At the higher velocities the corrosion rate peaks at about 80°C. At temperatures below 60°C, a velocity of 1.2 m/s appears acceptable. To avoid Erosion-Corrosion in cold water the usual recommendation is a maximum velocity of 1.8 m/s, a velocity for which no failures have been reported. Many of the reported cases of Erosion-Corrosion occur in continuously recirculating hot-water systems, and for such systems it is recommended that water velocity not exceed 0.5 m/s.
- BS 6700 : 1987 – *British Standard Specification for Design, installation, testing and maintenance of services supplying water for domestic use within buildings and their curtilages*, p.33, Section 8, Table 5.

The table gives values for maximum permissible water velocities in pipework as follows:

Water temperature (°C):	10	50	70	90
Maximum velocity (m/s)	3.0	3.0	2.5	2.0

A footnote to the table states “The subject of maximum water velocities is currently under investigation and the velocities specified will be amended if the results of this investigation so require”. I do not currently have access to either of the subsequent (1997 and 2006) editions of BS 6700, to see whether any amendments have been made.

- N.W. Polan, F.J. Ansuini et al. 1987 / 1992 – Corrosion of copper and copper alloys, in *ASM Metals Handbook⁴ 9th Edition Volume 13, Corrosion*, American Society for Metals, 1987 (and reprinted in *ASM Handbook⁴ Volume 13, Corrosion*, ASM International, 1992), pp.621–624.
Hot- and cold-water distribution lines in homes and other buildings is the largest single application of copper tube. The protective oxide scale formed under most normal circumstances limits corrosion rates to 5–25 µm/yr, or up to 125 µm/yr in very soft waters, depending on oxygen and carbon dioxide levels in the water. No mention is made of velocity effects or Erosion-Corrosion in the context of fresh water. Only in the context of seawater are velocity effects mentioned. For seawater (at room temperature), accepted maximum design velocities are listed as 0.6–0.9 m/s.

⁴ See footnote ⁶ on page 29 below.

- A. Cohen 1993 – Corrosion by potable waters in building systems, *Materials Performance* (NACE⁵), Vol.32, No.8, pp.56–61.
Cohen states that Erosion-Corrosion can be expected to occur when water velocity exceeds 1.2–1.5 m/s, when water pressure exceeds 550 kPa and/or when water temperature exceeds 60°C. The paper does not make clear how velocity and temperature might interact, but the apparent implication is that 1.2–1.5 m/s is the likely critical velocity for temperatures above room temperature but less than 60°C.
- J.F. Ferguson, O. von Franqué & M.R. Schock 1996 – Corrosion of copper in potable water systems, in *Internal Corrosion of Water Distribution Systems, 2nd edition*, American Water Works Association Research Foundation, Chapter 5, pp.231–268.
For cold water the “usual recommendation” of “national standards and codes of practice” is a maximum velocity of 1.8 m/s, a velocity for which no failures have been reported. (The possibility of velocities of up to 4.6 m/s is mentioned, but it is not clear under what circumstance such high velocities might be permissible.) NACE⁵ is cited as recommending a maximum design velocity of 1.2 m/s, but no particular reason or circumstances are cited for this more conservative recommendation (conceivably it might take account of possible elevated temperatures up to 60°C). Many of the reported cases of Erosion-Corrosion occur in continuously recirculating hot-water systems, and for such systems it is recommended that water velocity not exceed 0.5 m/s.
- AS/NZS 3500.4 : 2003 / 2005, *Plumbing and drainage, Part 4: Heated water services*, pp.8–9, sections 1.8 and 1.9.
Maximum water velocity in piping shall be 3.0 m/s. There is no explicit mention of Erosion-Corrosion. Temperature is only discussed in terms of minimum temperature of 60°C to inhibit growth of Legionella bacteria, and maximum delivery-point temperatures of 45–50°C to prevent scalding.
- A. Cohen 2005 – Corrosion of copper and copper alloys in specific environments, in *ASM Handbook Volume 13B, Corrosion: Materials*, pp.125-163; citing Copper Development Association 2004, *Understanding Copper Tube*.
To avoid excessive system noise and the possibility of Erosion-Corrosion, recommends that water velocity be limited to 2.4 m/s for cold water; 1.5 m/s for water up to 60°C; 0.6 to 0.9 m/s for water above 60°C.
- Copper Development Association 2006 – *The Copper Tube Handbook*, CDA, New York, Document A4015-04/06, p.11
To avoid excessive system noise and the possibility of Erosion-Corrosion, recommended maximum design flow velocities are: Cold water, 2.4 m/s; Hot water up to 60°C, 1.5 m/s; Hot water where temperatures routinely exceed 60°C, 0.6–0.9 m/s.

⁵ National Association of Corrosion Engineers

There is significant variation between the guidelines given in the various publications listed above. It is important to bear in mind the difference between a *critical* velocity (also called breakaway velocity), above which Erosion-Corrosion can be expected to occur, and a *recommended maximum* velocity, which provides some factor of safety. Note also that the requirements for continuously recirculating systems are more stringent than those for intermittent-use systems, since in the latter there might be time for protective scales to reform. Table 6 attempts to provide a historical perspective on the guidelines.

Table 6: Summary of Guidelines for Maximum Design Velocity (m/s) at Temperature

	< 25°C	?	25 – ≤60°C	> 60°C	Hot Recirc
US-EPA 1984		1.2			
AWWA 1985	1.8		1.2 ?		0.5
BS6700 1987 [†]	3.0		3.0	2.0–2.5	
ASM 1987/1992	No mention of velocity or temperature effects in potable water				
Cohen 1993 [‡]	1.5		1.2		
AWWA 1996	1.8	1.2–1.8			0.5
AS3500.4 2003/2005		3.0			
ASM 2005	2.4		1.5	0.6–0.9	
US-CDA 2006	2.4		1.5	0.6–0.9	

[†] For BS6700 1987, the table interpolates between the temperatures mentioned.

[‡] For Cohen 1993, the table makes assumptions about the likely relationship between design velocity and critical velocity.

It seems likely that the importance of limiting water velocity is more widely appreciated now than it was in 1999 when the Shafston building was being designed. This general historical trend is seen for example in the widely-used ASM Handbook⁶, which in 1992 made no mention of Erosion-Corrosion problems in copper in hot water, but which in 2005 gave clear guidelines. Among researchers in the area the importance of velocity and temperature was well known and published by the mid-1980s, but this information did not fully penetrate more general references and national standards until later. Notably, the damaging effects of velocity for hot water (and especially recirculating hot water systems) have not been recognised in even the most recent (2005) revision of the Australian Standard.

⁶ The 21-volume ASM Handbook, published by the U.S.-based ASM International (formerly the American Society for Metals) is widely regarded as the preeminent reference work for data on the microstructure, properties and performance of engineering materials.

4.3.4 Conclusions Regarding Water Velocity

The unambiguous observation of the physical manifestation of Erosion-Corrosion, in a section of pipe remote from bends and joints (as shown in Figure 5 and Figure 8), is direct evidence that the general conditions of water velocity and/or temperature are or have been too high. The above quantitative considerations (if we assume the alleged specified and measured velocities are correct) appear to provide an explanation as to why Erosion-Corrosion is likely to occur, or at least is a significant risk, in this system.

There are sections of the return pipe that are free from attack. From the presence of attack in some straight sections but not others, I conclude that the specified and/or current velocities and temperatures must be at the margins of the critical conditions for Erosion-Corrosion; or otherwise that conditions have been more severe during some periods than others.

4.4 (b) Elevated Water Temperature

The quantitative guidelines presented in section 4.3.3 above indicate that water temperature has a significant influence on the tendency for Erosion-Corrosion to occur. Several of the guidelines imply that for a given velocity, water temperatures above 60°C are more likely to cause Erosion-Corrosion than are temperatures below 60°C. Equivalently we may say that increasing temperature causes a significant decrease in the critical velocity for Erosion-Corrosion to occur. The elevated water temperatures measured for the Shafston system (up to 80°C at the heater outlet) have very probably contributed significantly to the severity of the Erosion-Corrosion.

The literature cited above provides only approximate relationships between critical velocity and temperature. It is unclear whether or not there is a marked acceleration of Erosion-Corrosion in the vicinity of 60°C, but I do not believe that it should be considered a “critical” temperature. Unquestionably Erosion-Corrosion can be a problem at 50°C, for example. The frequent reference to 60°C is more likely to relate to the temperature required to prevent proliferation of *Legionella* bacteria^{7,8}.

The roles of velocity and temperature are difficult to separate, since both contribute to a systemic propensity for Erosion-Corrosion (allowing attack to occur in straight sections remote from bends or joints). I have not located sufficient quantitative information to indicate the relative sensitivities of corrosion rate to velocity and temperature. For example, would a 20% reduction in temperature (e.g. from 80 to 64°C) have the same, less or more effect than a 20% reduction in water velocity (e.g. from 1.5 to 1.2 m/s)? I do not have the information on which to base such a judgement. However, from the viewpoint of *Legionella*,

⁷ B. Lévesque, M. Lavoie & J. Joly 2004: Canadian Journal of Infectious Disease, Vol.15, No.1, pp.11-12, Residential water heater temperature: 49 or 60 degrees Celsius?

⁸ AS/NZS 3500.4 : 2003, Section 1.9.1.

it is unlikely that any more than a 20% reduction in temperature is permissible. By comparison, it might be feasible to reduce water flow velocities by considerably greater factors, e.g. to 0.5 m/s — perhaps without detriment to the hydraulic operation of the system.

It is conceivable that the severe Erosion-Corrosion at Shafston might not have occurred had the temperature been set to 65°C and returned at 60°C. However, on the balance of evidence available to me, it is suggested that at least some cases of Erosion-Corrosion would probably still have occurred in a 60–65°C temperature regime. In order to minimise the risk of future cases of Erosion-Corrosion, it is recommended that both temperature and velocity can beneficially be reduced somewhat. If temperature and velocity are both reduced as far as is consistent with health and hydraulic constraints, then it seems likely that Erosion-Corrosion problems can be eliminated or at least greatly reduced.

4.5 (c) Turbulence Due to the Joint Profile

Figure 11 and to a lesser extent Figure 10 show evidence of the promotion of Erosion-Corrosion by turbulence at the step in the inner wall profile at a joint.

It is well publicised that turbulence created by rough joint profiles can promote Erosion-Corrosion, in systems otherwise free from this problem. In the 1993 paper previously cited, A. Cohen states the opinion that “Too often, erosion-corrosion is the direct result of improper workmanship. Unreamed cut tube ends, globules of solder ... dents/dings in tube ...”. In respect of prevention, Cohen finishes by stating that “Above all, proper workmanship must be used during installation of the copper tubing system”.

I am uncertain whether the words “above all” should be taken as a rigorous statement to the effect that turbulence has been shown to be the most important single factor in promoting Erosion-Corrosion. However, in the Shafston system, as explained earlier, we have direct evidence that Erosion-Corrosion has occurred in response to the general water velocity and temperature, in a straight section of pipe where there are no turbulence-promoting features. Accordingly I judge that, regardless of the probable contribution of rough joint profiles to a majority of leak sites, it remains true that the Shafston system has a systemic susceptibility to Erosion-Corrosion due to excessive water velocity and elevated temperature.

It would be difficult to apportion blame between these two factors. What is clear is that in at least one case, the systemic high velocity and temperature have been sufficient to cause Erosion-Corrosion in the absence of turbulence. I do not know for certain whether or not the Shafston system has shown any converse cases, where turbulence has caused Erosion-Corrosion despite general velocities known to be low. It has been reported that leaks have occurred in branch lines (which might be supposed to have lower velocities), but I have not been provided with samples for examination. I would need to undertake physical examination of relevant samples before I could form a firm judgement about the causative factors in such alleged cases.

4.6 Other Factors of the Corrosive Environment

Apart from the copper pipes, several other components of the hot water reticulation system have suffered corrosion, including (to my knowledge) two valves and a small pump. It has been suggested that such corrosion might indicate the presence of some other factor promoting corrosion, such as especially aggressive water chemistry, or stray current.

I have not performed a thorough failure analysis on these other corroded components. On cursory inspection, these components appear to be made from carbon steel (the valves) and aluminium (the pump). If these are not electrically isolated from the copper pipework, then galvanic corrosion (dissimilar metal corrosion) can be expected in both carbon steel and especially aluminium components. Such circumstances would not accelerate the corrosion of the copper.

The water analysis performed on a sample taken during the UQMP inspection does not suggest unusually aggressive water chemistry. The analysis performed on a water sample taken from Shafston is fully consistent with Brisbane Water Mt.Crosby supply. It is conceivable that water chemistry could have been more aggressive at some period in the past, but it is unclear why this should be so.

We have not performed an investigation of a type that would be needed to eliminate the possibility of stray current corrosion. If such investigation is required, corrosion-control companies should be able to provide such services. However, the evidence suggests we have a sufficient explanation for the severe attack of the copper pipes, in terms of Erosion-Corrosion under the conditions of temperature and flow velocity in the pipes. Therefore there does not seem to be any need to invoke other causative factors such as stray current effects.

One factor that can accelerate Erosion-Corrosion is particulate matter (suspended solids) in the water. Such particulate matter can help to erode the protective oxide scale on the pipe surface, and thus reduces the velocity threshold at which Erosion-Corrosion commences. The SEM examination of the bare-metal surfaces does not reveal evidence of extensive Solid Particle Erosion, although it would be difficult to rule out the possibility of some influence from this mechanism. I have not found any published literature giving quantitative guidelines for levels of suspended solids expected to give rise to a significant reduction in critical velocity. Once again, I believe we have a sufficient explanation for the Erosion-Corrosion in terms of the operating temperature and flow velocity in the pipes. Therefore there does not seem to be any strong need to identify other causative factors.

5. CONCLUSIONS

The examination of copper pipe samples from the Shafston hot water reticulation system has led to the following findings:

- The chemical composition and hardness of the copper pipe comply with AS 1432 – 1996, the Australian Standard current at the time the building was being designed.
- In the pipe sample examined, the leak is due to Erosion-Corrosion.
- Turbulence at joints has contributed to the Erosion-Corrosion, and the leak examined is associated with such turbulence. However, there is also clear evidence of Erosion-Corrosion occurring as a result of general (systemic) excessive water velocity and/or elevated temperature, independent of turbulence effects.
- From the variation between samples examined, I conclude that the specified and/or current conditions must be at the margins of critical velocity and temperature for Erosion-Corrosion, or that conditions have been more severe during some periods than others.
- Based on available guidelines, it appears likely that at temperatures in excess of 60°C, a water velocity of 1.5 m/s (said to be the velocity resulting from the specified flow rate in the 40 mm return line) is in the vicinity of the critical velocity for Erosion-Corrosion.
- A brief historical survey of published guidelines suggests that the importance of limiting water velocity is more widely appreciated now than it was in 1999 when the Shafston building was being designed. Research indicating the critical importance of velocity and temperature had been published by the mid-1980s, but in 1999 the then-current editions of some authoritative publications (including the ASM Handbook and Australian Standards) lacked guidelines reflecting this research. Even the latest (2005) revision of AS3500.4 permits water velocities up to 3.0 m/s in hot water.
- There is sufficient explanation for the severe attack of the copper pipes, in terms of Erosion-Corrosion under the conditions of temperature and flow velocity in the pipes; I therefore do not see a need to search for other causative factors, such as stray current, suspended solids or cavitation.

6. APPENDICES

6.1 Appendix A – Full Water Analysis



P/O Box 3160 Yeronga 4104
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Rocklea, Qld 4106

Attention: Lenny McInnes

Client Order No.:

Ph: 3365 6123

Client: UQ Materials Performance
Frank White Building Cooper Road University of Qu

Batch Reference No.: J-0809-238

Fax: 3365 6124

Job Description: Hot Water System Analysis

St Lucia, QLD 4072

Chemical Analytical Results

Page 1 of 2

Sample Reference		J-0809-238-01 Water System Overflow
Sample Point		Hot Water System Overflow Pipe
Date Collected		10/09/2008
Date Received		10/09/2008
Date Testing Completed		24/09/2008
* CA090.	pHs	8.4
* CA090.1	Langelier Index	-0.30
* CA105.	Residual Alkali	0.64 meq/L
* CA110.	Total Dissolved Salts (calc'd)	310 mg/L
* CA130.	Sodium Adsorption Ratio - Water	1.8
* CA205.1	Hydroxide Alkalinity as CaCO ₃	0.076 mg/L
* CA205.11	Hydroxide as OH (mg/L)	0.024 mg/L
* CA205.2	Carbonate Alkalinity as CaCO ₃	1.4 mg/L
* CA205.21	Carbonate as CO ₃ mg/L	1.7 mg/L
* CA205.3	Bicarbonate Alk'y as CaCO ₃	91 mg/L
* CA205.31	Bicarbonate as HCO ₃ mg/L	110 mg/L
* CA215.1	Free Carbon Dioxide	1.4 mg/L
* CA215.2	Free Carbon Dioxide at pHs	0.70 mg/L
* CA215.3	Aggressive Carbon Dioxide	< 1 mg/L
* CA247.1	Total Hardness as CaCO ₃	140 mg/L
* CA247.2	Calcium Hardness as CaCO ₃	75 mg/L
* CA247.3	Magnesium Hardness as CaCO ₃	66 mg/L
* CALC.003	Actual Sum [Anions-Cations]	-0.60 meq/L

Authorised for release:

 **SEAN HINTON**
Water Chemistry Supervisor

Date: 24/09/2008

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Attention: Lenny McInnes

Client Order No.:

Ph: 3365 6123

Client: UQ Materials Performance
Frank White Building Cooper Road University of Qu

Batch Reference No.: J-0809-238

Fax: 3365 6124

Job Description: Hot Water System Analysis

St Lucia, QLD 4072

Chemical Analytical Results

Page 1 of 2

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* CA205.11	Hydroxide as OH (mg/L)	0.024 mg/L
* CA205.2	Carbonate Alkalinity as CaCO ₃	1.4 mg/L
* CA205.21	Carbonate as CO ₃ mg/L	1.7 mg/L
* CA205.3	Bicarbonate Alk'y as CaCO ₃	91 mg/L
* CA205.31	Bicarbonate as HCO ₃ mg/L	110 mg/L
* CA215.1	Free Carbon Dioxide	1.4 mg/L
* CA215.2	Free Carbon Dioxide at pHs	0.70 mg/L
* CA215.3	Aggressive Carbon Dioxide	< 1 mg/L
* CA247.1	Total Hardness as CaCO ₃	140 mg/L
* CA247.2	Calcium Hardness as CaCO ₃	75 mg/L
* CA247.3	Magnesium Hardness as CaCO ₃	66 mg/L
* CALC.003	Actual Sum [Anions-Cations]	-0.60 meq/L

Authorised for release:

 **SEAN HINTON**
Water Chemistry Supervisor

Date: 24/09/2008

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6.2 Appendix B – Brisbane Water Composition

For comparison with the measured water composition values in Table 4, Table 7 gives some examples of published compositions for Brisbane Water Mt.Crosby supply. The values given are average values for the months of June 2007, December 2007 and June 2008. It can be seen that there is good agreement between the Shafston measurements and the typical spread of Brisbane Water data.

Table 7: Water Composition – Mt.Crosby Supply; Shafston 10-Sep-2008

	Quantity	Conductivity at 25°C	pH	Langelier Index	
Value	BW June 2007	521 µS/cm	8.0	0.0	
	BW Dec 2007	805 µS/cm	8.0	0.1	
	BW June 2008	526 µS/cm	7.8	-0.3	
	Shafston	540 µS/cm	8.1	-0.3	
	Quantity	Calcium as Ca	Sodium as Na	Chloride as Cl	Sulphur as SO ₄
Value (mg/L)	BW June 2007	24	47	85	27
	BW Dec 2007	31	83	155	28
	BW June 2008	24	52	97	30
	Shafston	30	49	72	28
	Quantity	Calcium hardness as CaCO ₃	Total hardness as CaCO ₃	Total Alkalinity as CaCO ₃	Total Dissolved Salts
Value (mg/L)	BW June 2007	59	133	102	333
	BW Dec 2007	77	182	108	515
	BW June 2008	59	123	73	336
	Shafston	75	140	91	300

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