UQMP
UQ Materials Performance
Materials engineering consultancy, expert opinion, evaluation and research

Phone +61 7 3365 6123
Fax +61 7 3365 6124
Email uqmp@uq.edu.au
Web www.uqmp.com

Lvl 4 Frank White Bldg, Cooper Rd,
The University of Queensland
St Lucia Qld 4072 Australia

A registered business of UniQuest Pty Limited (ABN 19 010 529 898)

Project No. **41587-02**

Report for: **Aquatherm**

PO Box 2038, Rockdale
Sydney NSW 2216

Attention: **Mr Bryce Christian**

Subject: **Erosion-Corrosion of Copper Pipes in Hot Water Reticulation Systems**

Date: **25 January 2012**

Prepared By: **J.D. Gates,** BSc, PhD, MIEAust, CPEng, CMP

Signed for & on behalf of UQ Materials Performance

....
Dr Jeff Gates

UniQuest

PROJECT 41587-02 — REPORT

Erosion-Corrosion of Copper Pipes in Hot Water Reticulation Systems

TABLE OF CONTENTS

REVISION HISTORY

Revision	Date	Authorised
Draft Only	16-Dec-2011	JDG
0	25-Jan-2012	JDG

UQMP
UQ Materials Performance
Materials engineering consultancy, expert opinion, evaluation and research

Phone +61 7 3365 6123
Fax +61 7 3365 6124
Email uqmp@uq.edu.au
Web www.uqmp.com

Lvl 4 Frank White Bldg, Cooper Rd,
The University of Queensland
St Lucia Qld 4072 Australia

A registered business of UniQuest Pty Limited (ABN 19 010 529 898)

PROJECT 41587-02 — REPORT

Erosion-Corrosion of Copper Pipes in Hot Water Reticulation Systems

1. BACKGROUND

Aquatherm Australia Pty Limited is the Australian distributer of a polypropylene (PP-R) hot and cold water piping system manufactured in Germany by Aquatherm GmbH.

It has been suspected that erosion-corrosion of copper pipes may be causing copper to be dissolved into (or otherwise carried by) the water. It is suspected that such copper can be deposited into the surfaces of polypropylene pipes located downstream, with consequent degradation of the polymer.

Aquatherm have approached UQMP to provide expert opinion in regard to:

- The phenomenon of hot-water erosion-corrosion of copper pipes;
- Analysis of technical literature, national standards and trade guidelines regarding the effects of water velocity and temperature on the tendency for erosion-corrosion.

2. EROSION-CORROSION

2.1 Corrosion Pitting and Erosion of Copper Pipes

Copper pipes used for water reticulation in domestic and commercial buildings can suffer from a variety of forms of corrosion, pitting and erosion. The recognised damage phenomena potentially relevant to hot water reticulation systems are as follows:

- Erosion-Corrosion;
- Type 2 Pitting Corrosion;
- Cavitation Erosion.

Of the above three damage phenomena, the phenomenon of Erosion-Corrosion seems to be the most common in Australian conditions. In order to understand this and the other two phenomena, it is necessary first to define the individual terms “Corrosion”, “Pitting” and “Erosion”. In the context of damage to copper pipes used in water reticulation, these three terms can be defined as follows:

- ***Corrosion***: Removal of metal from the surface of the pipe by the mechanism of a chemical reaction between the metal pipe wall and the fluid in the pipe. The chemical reaction results in direct dissolution of metal ions into the fluid and/or formation of a film of reaction products (e.g. oxides, carbonates, sulphates etc).
- ***Pitting***: A form of Corrosion in which the metal removal is localised (rather than uniformly distributed over the surface), resulting in development of distinct depressions (pits) in the surface, surrounded by relatively flat, relatively un-attacked surface.
- ***Erosion***: Removal of metal from the surface of the pipe by a mechanism of physical/mechanical wear, under the influence of the flowing fluid and of any particulate matter carried in the fluid stream. Small (possibly microscopic but larger than atomic sized) fragments of solid material are physically removed from the surface and carried away by the fluid stream.

The phenomenon of Erosion-Corrosion will be explained in section 2.2 below, while sections 2.3 and 2.4 will briefly describe the other two phenomena and indicate how the three may be distinguished from each other.

2.2 The Phenomenon of Erosion-Corrosion

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, between the extremes of:

- Corrosion-dominant — where the fluid flow merely aids ion transport so as to increase the rate of corrosion; and
- Erosion-dominant — where for example selective corrosion might reduce 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 copper initially undergoes some general (uniform) corrosion, forming a layer of corrosion products, known as scale. The scale may be comprised of copper oxides, carbonates, sulphates etc. This scale has the effect of limiting transport of oxygen and other aggressive species to the metal substrate, hence may have a protective effect, reducing the rate of subsequent corrosion.
- The flowing water dislodges portions of the protective 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, and possibly also because of galvanic action.

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 significant portions of the protective scale are dislodged by the flow).

2.3 Type 2 Pitting

Although Type 2 pitting (also known as Hot Water Pitting) and Erosion-Corrosion do have some features in common, the scientific 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 (with their open ends facing downstream) 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 tubercules of Cu_2O (cuprite) and $CuSO_4.3Cu(OH)_2$ (brochantite). In Erosion-Corrosion such tubercules would not withstand the flow conditions.
- According to at least some well-respected published literature, Type 2 Pitting only occurs when the ratio of bicarbonate to sulphate is low ($HCO_3/SO_4 < 1.0$). By contrast, Erosion-Corrosion is largely independent of water composition and is driven primarily by velocity and turbulence issues.
- Increasing water velocities disrupt the mechanism of Type 2 Pitting, which involves deposition of cathodic substances onto the pipe surface.

Occasionally, inspectors and investigators may mistakenly equate Erosion-Corrosion and Type 2 Pitting. Such confusion is understandable given the similarities, but authoritative literature on the subject clearly indicates the two to be distinct phenomena.

2.4 Cavitation Erosion

In order to discuss the mechanism and characteristics of Cavitation Erosion, it is necessary first to clarify the term “Cavitation”. Cavitation is a well-known phenomenon in fluid dynamics and refers to the creation of vapour bubbles when the fluid pressure drops below the vapour pressure for the liquid. This can occur for example when pipe diameter increases in such a way that pressure drops sharply. Cavitation is a pre-requisite for but is not the same as Cavitation Erosion.

When the vapour bubbles created by Cavitation 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 have sufficient momentum and energy to create severe local deformation and wear of the metal. This kind of wear is denoted Cavitation Erosion. By way of disambiguation, 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.

Cavitation is common in high velocity fluid dynamics situations such as marine propellers and high-pressure pumps. It would be fairly unusual 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, the possibility of Cavitation (which causes noise as well as Erosion) is one of the reasons why water velocities are recommended to be less than 3.0 m/s even in cold water.

Contrary to what is sometimes assumed, the fluted, scalloped wear patterns commonly seen 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. Instead, surfaces damaged by Cavitation Erosion typically show a closely spaced array of deep, steep-sided pits, separated by sharp peaks, in an apparently random pattern.

Cavitation Erosion would certainly not be expected to produce horseshoe shaped pits, which are classically characteristic of Erosion-Corrosion.

2.5 Incidence of Erosion-Corrosion in Australian Buildings

In the last decade UQMP has investigated at least two cases of premature failure (leakage) of copper pipes in hot water reticulation systems in commercial buildings in Australia. In both cases the observed features of the attack on the pipes indicated that Erosion-Corrosion was the operative phenomenon. This diagnosis was 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) and not consistent with the other two phenomena:

- The corroded regions (pits) showed bright metal surfaces, free from oxide scales;
- Numerous examples of horseshoe-shaped pits with their open ends facing downstream;
- The remaining surface covered with oxide scale, under-cut at the boundary with the corroded areas;
- Preferential occurrence at bends and downstream from non-smooth joints (due to water turbulence at these features);
- Relatively high ratio HCO_3/SO_4, of approximately 4 — hence unlikely to cause Type 2 Pitting.

The photographs reproduced in Figure 1 to Figure 7 below are from a case investigated in 2008, from a building constructed in 2000.

Figure 1: Overview of pipe samples suffering from Erosion-Corrosion. In this light the attacked bare metal areas show as bright pink while the darker brown regions are the oxide scale.

Figure 2: Pinhole leak at bend, viewed from outside of pipe.

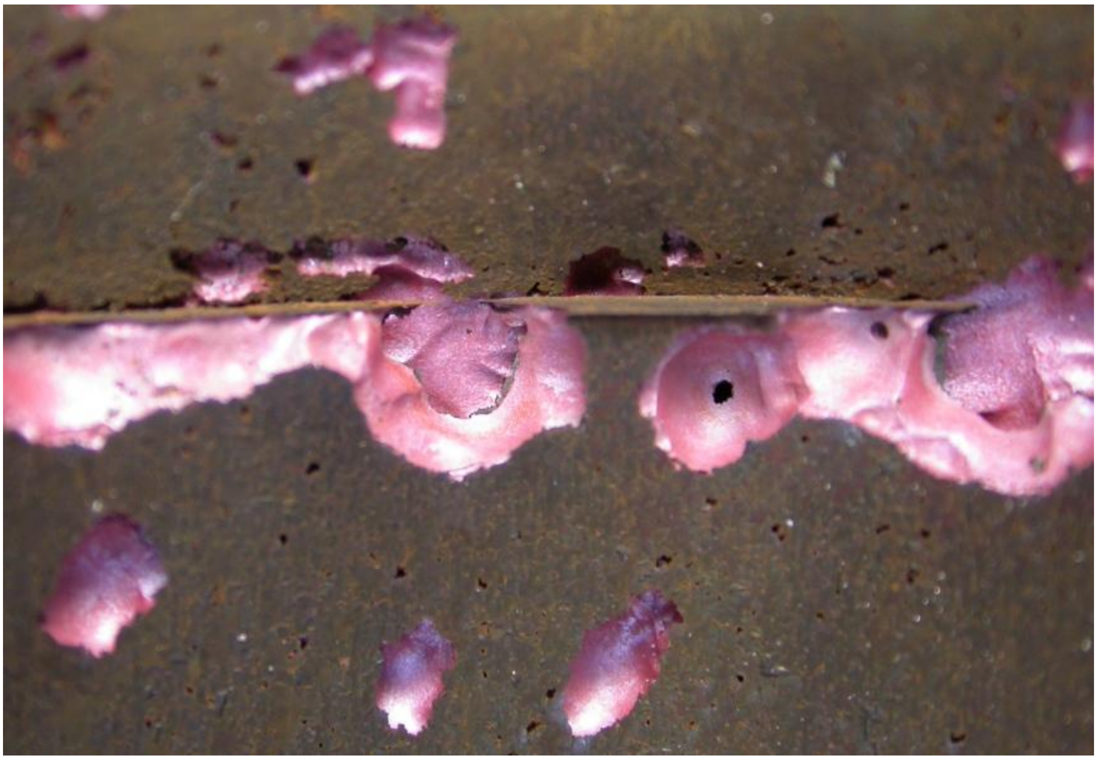

Figure 3: Pinhole leak at joint, viewed from inside of pipe.

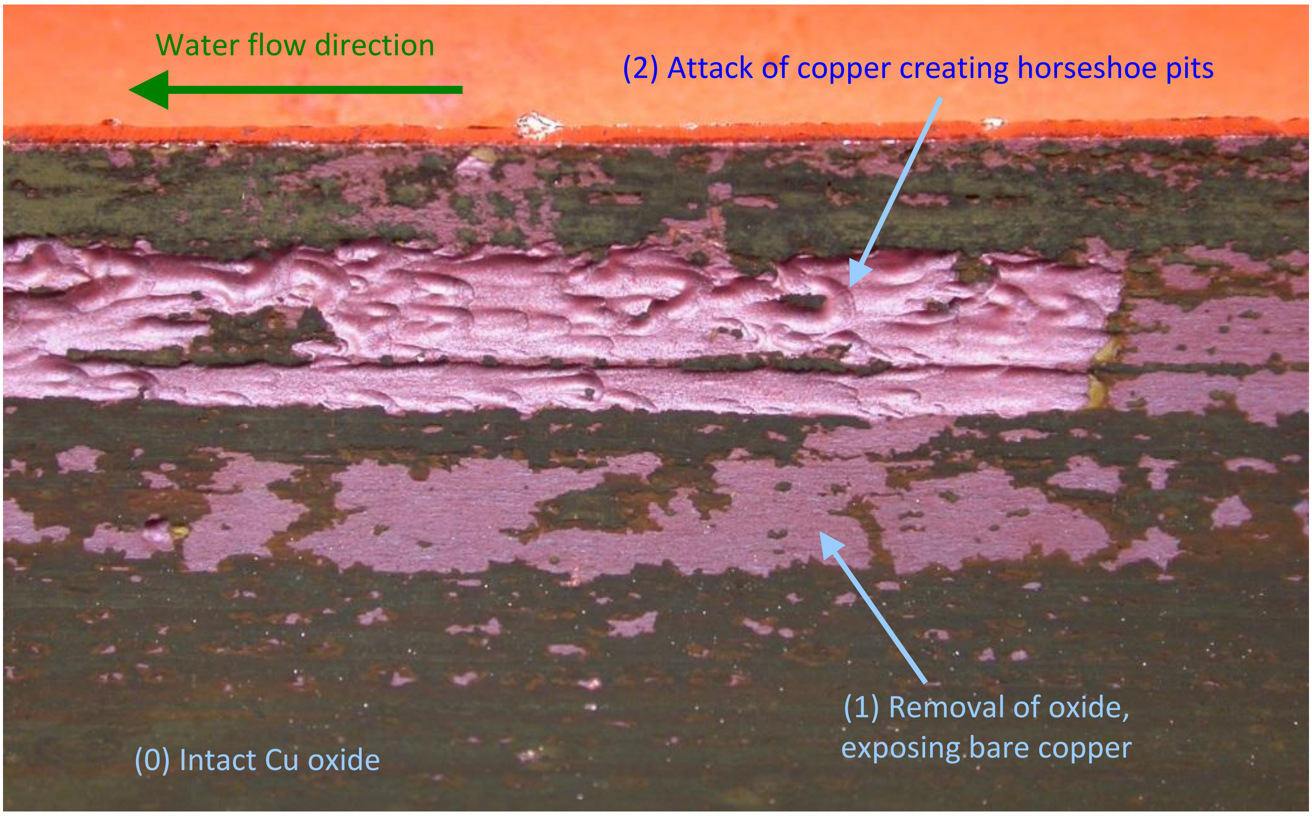

Figure 4: Early stages of Erosion-Corrosion attack. Horseshoe-shaped pits have open end downstream.

Figure 5: Erosion-Corrosion showing coalescence of horseshoe-shaped pits, with islands of intact oxide between. The latter are deeply undercut.

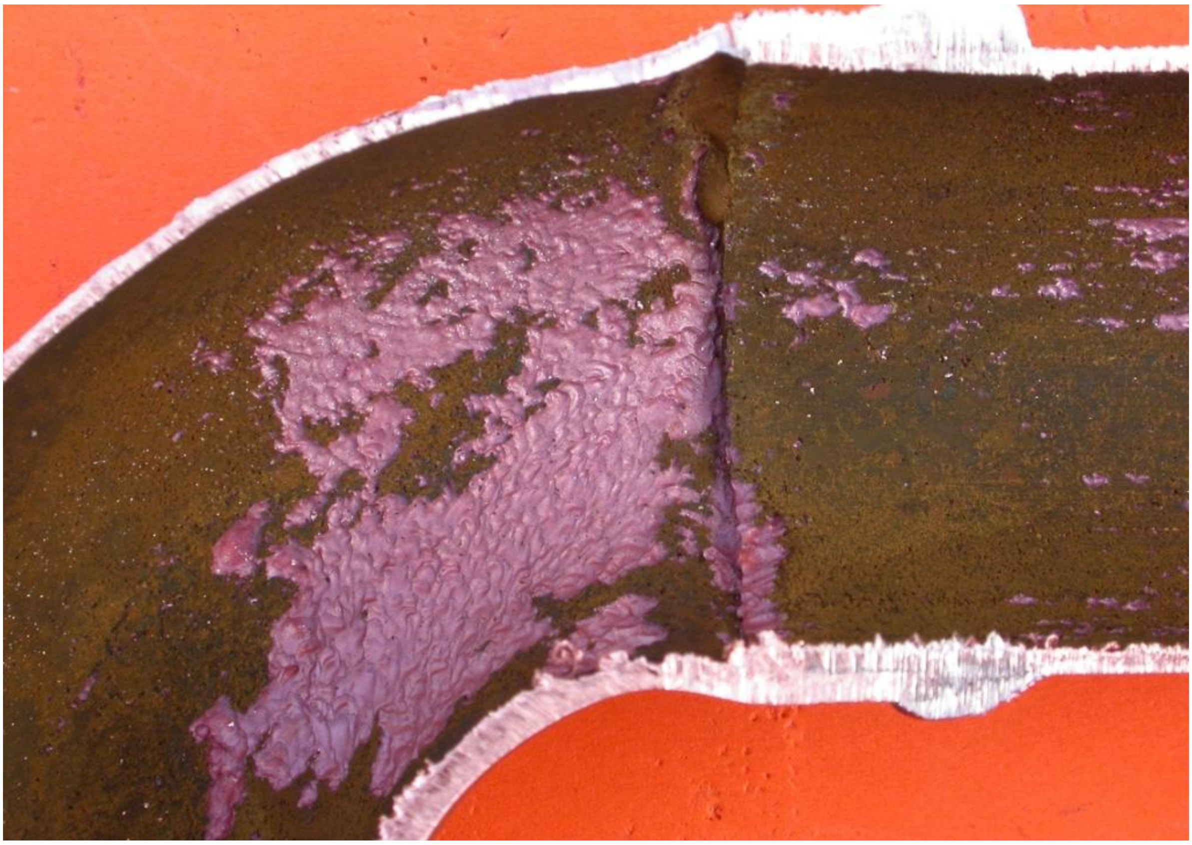

Figure 6: Erosion-Corrosion downstream of a joint, apparently due to turbulence at the joint.

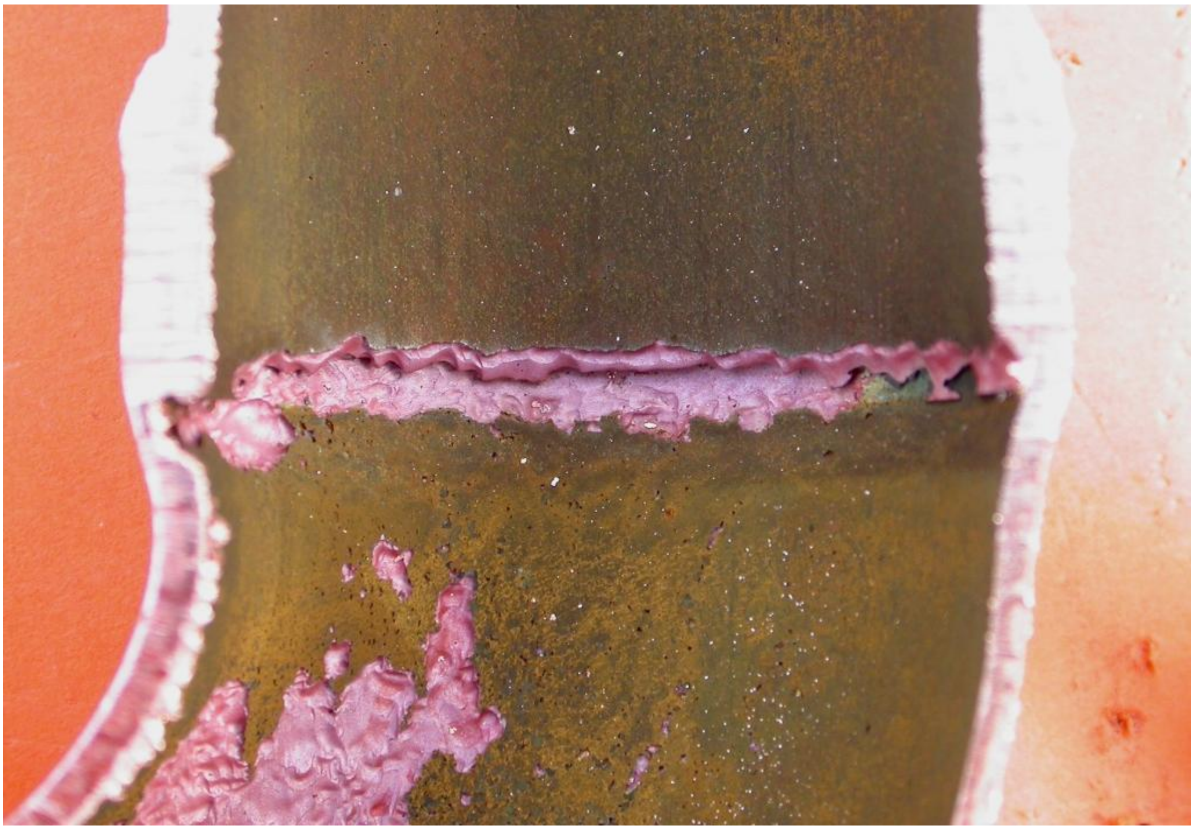

Figure 7: Erosion-Corrosion at a joint, apparently due to turbulence at the joint.

2.6 Possible Causes of Erosion-Corrosion

A systematic analysis of the evidence in the above-described cases of Erosion-Corrosion indicated that there were three contributing factors that led to the premature failures:

(a) Excessive water velocity in the pipes;

(b) Elevated water temperature;

(c) Turbulence due to the joint profile.

The roles of each of these factors are discussed in sections 3.1, 3.2 and 3.3 below.

2.7 Relative Commonness of Erosion-Corrosion and Type 2 Pitting

Erosion-Corrosion is quite common, and is a well-documented problem in recirculating hot water systems.

Most published literature indicates that on a worldwide basis Type 2 Pitting is relatively rare (except in Japan). However, recent anecdotal accounts suggest that Type 2 Pitting might be becoming more common than it was. At present one could only speculate on what might be causing such increasing frequency of Type 2 pitting, but it may be relevant to note that both phenomena are accelerated by increasing water temperature. It is conceivable that the frequency of both phenomena might have increased due to increasing system temperatures being used in view of increasing concern with Legionella control. It is also conceivable that the two could occur in nearby portions of a given system, further adding to potential confusion.

UQMP does not have any statistical information from which to judge the relative commonness of these two phenomena, though other water industry corrosion specialists might have such statistical information. Of the three cases of failure of copper pipes UQMP has investigated over the last decade:

- Two were leaks that were clearly and unambiguously due to Erosion-Corrosion — see section 2.5 above;
- One was ductile bulging associated local annealing (softening) around a brazed joint, in a pipe with wall thickness below that recommended for the water pressure;
- None were Type 2 Pitting.

3. GUIDELINES

3.1 (a) Water Velocity

3.1.1 General Considerations

A necessary condition for Erosion-Corrosion is water velocity sufficient to disrupt the protective copper oxide scale and hence permit active corrosion of exposed bare metal surfaces. 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 significant turbulence is more likely when the general flow velocity is high.

3.1.2 Specific Observations

In one of the investigations described above, unambiguous Erosion-Corrosion was observed in a straight section of pipe remote from bends and joints (some 500 mm upstream of the leaking bend) — see sample in upper-right of Figure 1. This observation constituted compelling evidence that there was a systemic problem, as opposed to a problem restricted to regions of local turbulence. Although the attack did not occur in all parts of the system, it was evident that the conditions were so close to critical that any number of local factors could trigger the Erosion-Corrosion. This was suggestive of excessively high general flow velocity (and/or temperature – see section 3.2 below).

In the above case the system specification called for a volume flow rate of 1.5 L/s, corresponding to a velocity of 1.5 m/s in a 40 mm pipe. Measurements using an ultrasonic flow meter indicated water velocities of about 1.4 m/s for low pump speed setting and about 2.1 m/s for high pump speed setting.

At face value these observations and system specifications indicated that a water velocity of 1.5 m/s was sufficient to cause:

- Some Erosion-Corrosion in straight sections (borderline conditions);
- Severe Erosion-Corrosion, sufficient to cause pipe perforation in a relatively short time, in the vicinity of pipe features promoting turbulence (local conditions clearly exceeding breakaway velocity).

3.1.3 Published Literature

There exists a considerable amount of published information about the effects of water velocity and temperature on the tendency for Erosion-Corrosion. The original research in this area has led to various industry guidelines and national standards. Some relevant publications are listed below, with recommendations for maximum water velocities where given.

- M.F. Obrecht & L.L. Quill, 1960: Tests show effects of water quality at various temperatures, velocities, *Heating Piping and Air Conditioning*, Jan 1960 pp. 165–169; Mar 1960 pp.109–116; Apr 1960 pp.131–137; May 1960 pp.105-113; Jul 1960 pp.115–122; Sep 1960 pp 115–133; Apr 1961 pp. 129–134
  → Original paper not obtained, but citations of this paper indicate that the paper reported the fact temperature interacts with velocity, increasing corrosion attack, especially at temperatures above 60°C. Specific guidelines for maximum permissible velocity not given.
- R.W. Lane, C.H. Neff & S.W. Schilksy, 1971: Silicate treatment to inhibit corrosion of hot potable water systems Phase I, *Air Force Weapons Laboratory Technical Report AFWL-TR-71-58*
  → It was observed that at "high" flow rates (0.9–1.7 m/s), erosion-corrosion was more serious at 82°C than at 60°C. Specific guidelines for maximum permissible velocity not given, but it is clear that velocities in the range 0.9–1.7 m/s are high enough to be problematic when at the upper end of typical temperature ranges for hot water distribution.
- 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 Handbook 9th Edition Volume 13, Corrosion*, American Society for Metals, 1987 (and reprinted in *ASM Handbook 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.

- A. Cohen 1993: Corrosion by potable waters in building systems, *Materials Performance* (NACE[1]), 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.
  → 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. 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

[1] National Association of Corrosion Engineers

under what circumstance such high velocities might be permissible.) NACE1 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).

- 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 injuries.
- 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.
- Plumbing-Heating-Cooling Contactors – National Association 2006: *National Standard Plumbing Code*, PHCC, Falls Church, VA, Section 10.14.1 (Maximum Velocity) and Appendix B.6 (Limitation of Velocity)
  → Lists several reasons for the need to limit water velocity, including noise, shock damage, and accelerated corrosion. In section B.6.3 the term Erosion/Corrosion is used explicitly. Mentions recent research showing that turbulence accompanying even relatively low flow velocities can promote erosion/corrosion, especially where water has high CO_2 (≥10 ppm), very low hardness (non-scaling), and temperature above 43°C. The quantitative guidelines for maximum velocity are:
  - Cold water, pH ≥6.9, positive scale-formation tendency: 2.4 m/s
  - Cold water, pH ≥6.9, positive scaling, with rapid closure devices: 1.2 m/s
  - Cold water, pH <6.9 or very soft (non-scaling): 1.2 m/s
  - Hot water 43–60°C: 1.5 m/s
  - Hot water >60°C: 0.6 – 0.9 m/s
  - Hot water (>43°C?), continuous flow (recirculating systems): 0.6 m/s
- Anonymous (Wikipedia) 2008: *Erosion corrosion of copper water tubes* http://en.wikipedia.org/wiki/Erosion_corrosion_of_copper_water_tubes, last modified 30 August 2008.

Cited an un-named Swedish publication containing the same data as in BS 6700 : 1987 but qualifying these values as being “for pipes that can be replaced”; while “for pipes that cannot be replaced” the guidelines were said to be as follows:

Water temperature (°C):	10	50	70	90
Maximum velocity (m/s) for pipes that cannot be replaced	2.0	1.5	1.3	1.0

These more conservative figures correspond reasonably closely to the majority of more authoritative guidelines cited above. The phrase “for pipes that can be replaced” implies that Erosion-Corrosion is a significant risk if one uses the higher velocities. It seems a rather dubious guideline, since apart from the cost of replacement, the risk of water damage in buildings due to leaking pipes would seem a powerful motivation to use the more conservative figures regardless of the ability or otherwise to replace the pipes. We have no way of knowing whether replaceability was a consideration in the choice of the guidelines in BS 6700 : 1987. [More recent Wikipedia article, last modified 16 September 2011, has unchanged guidelines with respect to “pipes that cannot be replaced”]

- J.L. Villalobos 2007 – *CSEmag* (Online version of *Consulting – Specifying Engineer* magazine), http://www.csemag.com/article/CA6434235.html.
  Villalobos cites a number of guidelines, including the following:
  - Copper Development Association 2006: Maximum velocity for circulating systems (temperature not specified): 1.2–1.5 m/s.
  - Canadian Copper & Brass Development Association (publication details not specified): Maximum velocity for recirculating hot water systems at ≤60°C: 1.5 m/s.
  - National Association of Corrosion Engineers (unspecified “recent” publication): Maximum velocity for water at >60°C: 0.9–1.2 m/s.
  - Based on his own experience of over 12 copper pipe failures due to flow-accelerated corrosion, Villalobos recommends velocity be kept below 0.9 m/s.

3.1.4 Historical Development of Guidelines

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 re-form.

Table 1 attempts to provide a historical perspective on the guidelines.

It seems likely that the importance of limiting water velocity is more widely appreciated now than it was in the late 1990s, when many of the buildings that are now experiencing Erosion-Corrosion problems were being designed. This general historical trend is seen for example in the widely-used ASM Handbook[2], which in 1992 made no mention of Erosion-Corrosion problems in copper in hot water, but which in 2005 gave clear guidelines.

Among researchers 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.

Table 1: 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	
PHCC NSPC 2006	**+ve Scaling**	**<25°C, Non-Scaling**			
	2.4	1.2	1.5	0.6–0.9	0.6

† This table interpolates between the temperatures mentioned in BS6700 1987.

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

3.2 (b) Elevated Water Temperature

The quantitative guidelines presented in section 3.1 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.

[2] 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 composition, manufacture, microstructure, properties, performance and failure of engineering materials.

In one of the failures investigated by UQMP, elevated water temperatures (up to 80°C at the heater outlet) were measured. This very probably contributed significantly to the severity of the Erosion-Corrosion which occurred.

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[3,4].

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*, 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 — without major detriment to the hydraulic operation of the system.

In order to minimise the risk of future cases of Erosion-Corrosion, both temperature and velocity must be controlled. 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.

3.3 (c) Turbulence Due to the Joint Profile

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 …*".

Figure 1, Figure 6 and Figure 7 show clear evidence of the promotion of Erosion-Corrosion by turbulence at the step in the inner wall profile at a joint. On the other hand, there was direct evidence that Erosion-Corrosion had occurred in response to the general water velocity and temperature, in a straight section of pipe where there were no turbulence-promoting features. It follows that, regardless of the probable contribution of rough joint profiles to a majority of leak sites, it was clear that this system had a systemic susceptibility to Erosion-Corrosion due to excessive water velocity and elevated temperature.

---

[3] 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?

[4] AS/NZS 3500.4 : 2003, Section 1.9.1.

It would be difficult to apportion blame between these two factors; they can both contribute.

4. CONCLUSIONS

- UQMP has investigated failures of copper pipes in hot water reticulation systems in Australian commercial buildings, in which the failure was unambiguously due to the phenomenon of Erosion-Corrosion.
- In the failed installation described in section 2.5 of this report the water velocity was believed to be 1.5 m/s, well within the limit of 3.0 m/s specified by AS/NZS 3500.4.
- It has been known and published in water distribution industry literature since the mid 1980s that, in recirculating hot water systems, in order to prevent Erosion-Corrosion of copper pipes the water velocity should not exceed 0.5–0.6 m/s.
- In principle it is quite plausible that Erosion-Corrosion of copper pipes upstream from a polypropylene pipe could be the source of copper found to have deposited on the polypropylene.
- This hypothesis could be verified by one or both of two means:
  - Physical examination of copper pipes from the affected installation, especially at joints and bends (assuming the affected copper pipes have not already been replaced);
  - If it is a recirculating hot water system with water temperatures above 60°C and water velocities known to exceed about 1.2 m/s in any of the copper pipes, then Erosion-Corrosion is almost inevitable.
- There would seem to be an urgent need for AS/NZS 3500.4 to be updated with respect to its specifications for maximum permissible water velocities, in order to conform with known principles of corrosion protection and to come into line with international standards.

5. TERMS OF REPORT

UniQuest, University staff and consultants operating with UniQuest will make all reasonable efforts to ensure an accurate understanding of client requirements. The information in reports is based on that understanding and UniQuest strives to be accurate in its advice and to engage suitably qualified consultants with requisite skills of the highest order.

While all reasonable care will be taken in the preparation of reports, all information, assumptions, and recommendations therein are published, given, made, or expressed on the basis that:

(a) any liability of any nature which would otherwise exist or arise in any circumstances by reference to any part or any omission from this report is excluded to the maximum extent permitted by law;

(b) any liability which is unable to be excluded is limited to the minimum sum permitted by law;

(c) these provisions bind any person who refers to, or relies upon, all or any part of a report;

(d) these provisions apply in favour of UniQuest and its directors, employees, servants, agents and consultants.

The client shall indemnify UniQuest and its directors, employees, servants, agents, consultants, successors in title and assigns against any claim made against any or all of them by third parties arising out of the disclosure of reports, whether directly or indirectly, to a third party.

A laboratory certificate, statement, or report may not be published except in full, unless permission for publication of an approved abstract has been obtained, in writing from the Chief Executive of UniQuest.

Samples will be destroyed within thirty (30) days unless collected by the client, or alternative arrangements have been agreed to by UniQuest Pty Limited.