Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252
DOI: 10.51501/jotnafe.v38i2
Vol. 38 No. 2 December 2021

Forensic Issues that Arise from Recirculating Hot Water Systems

By Stephen R. Jenkins, CPEng (NAFE 11)

Abstract

There has been a significant increase in the failure of pipes used for recirculating hot water systems installed in hospitals, apartment blocks, and hotels in recent years. The rise has occurred as these systems have increased in popularity, and thermostatic mixing valves have made the higher operating temperatures in recirculating systems safe. A common theme tends to be the continuous flow of water above 65°C (150°F) at velocities that have been found acceptable for non-continuous flow. Failures have been experienced in pipes made from both copper and polypropylene random copolymer. Explanations have been slow to emerge and are still subject to debate, particularly as to the initiating causes of pin-hole corrosion (one of the more common modes of failure). Since it is not possible to view the initiation of the pin hole, proof of the cause of the initiation is still unknown. There are indications from consistent correlations between operating conditions and the onset of pin-holing corrosion that are used by authorities as the basis of modifications to design and installation standards to minimize occurrence. This paper will cover some of the background, myths, and current thinking on the causes of the problem in both copper and polypropylene from the point of view of a forensic engineer trying to make sense of uncertain science and the complications of a problem that is trans-disciplinary in nature.

Keywords

Recirculating hot water, pin-hole corrosion, erosion corrosion, installation faults, polypropylene cracking, copper pipes, forensic engineering

Introduction

The widespread use of copper pipes began in the mid-1800s — formed from copper sheets with longitudinal lap joints and screw thread connections. Around 1900, pipes began to be drawn or extruded but were still either joined by fine screw threads or push fit joints, incorporating O-ring seals. In 1936, the first British standard was published, allowing capillary brazing for joints[1]. Since then, the use of copper pipes has been normal practice and is covered by a range of engineering standards.

Copper piping has long been the favored material selection for plumbing systems for domestic water, having been used for water piping successfully from the days of early civilizations to the present day. Copper pipes to drain water from the ceremonial areas in the pyramids of Abusir around 2750 BC in Egypt were discovered by archeologists in 1994 (these were still functional). Copper began to be used as a roofing and water proofing material in around 650 BC. Copper pipes have been in regular use in the Western world for more than 100 years as evidenced by standards for manufacture and use[1,2,3].

However, copper has not been without occasional problems — generally appearing as accelerated corrosion, resulting in leaks or blue water staining on sanitary fittings. These problems have tended to arise in concentrated areas, or, at particular times, followed by research on the problem that has identified and generally resolved the immediate problem — often without finding more general solutions or the actual root cause. For example, an area of a community may experience an outbreak of pin-hole corrosion, which (after investigation) is found to be related in time to the introduction of a water softening system with an associated change in the chemical ions present in the water, but the mechanism of failure may not be clear[4].

In parallel with the use of copper, alternative piping systems based on plastics have developed and generally been successful for cold water applications. The extension

Stephen Jenkins, CPEng, P.O. Box 1591, Wellington, New Zealand, 6140, +64 21 325998, stephen.jenkins@aurecongroup.com
DOI: 10.51501/jotnafe.v38i2.156

of service conditions for plastic piping into hot water systems have often not been successful with some systems having a short commercial life before being withdrawn (author's observation).

With the rise of reliable and economic point-of-use thermostatic mixing valves, recirculating hot water systems have become popular in large facilities (such as large hospitals or apartment blocks) where peak usage patterns and the length of the reticulation system make the use of higher temperatures a practical engineering solution to maintaining satisfactory water temperatures for users as well as microbiological hygiene, in some instances. In parallel with the growth of this engineering solution, there has been a significant increase in pin-hole corrosion in copper pipes and unexpected failures in random polypropylene random copolymer used in hot water recirculating systems[5].

Most hot water used for personal hygiene (e.g., showers and basins) is used at between 38°C and 43°C (100 to 110°F). Tests by the author indicate users prefer the lower end of this range. To reduce storage volumes, it is held at higher temperatures and reticulated generally in the 60°C to 65°C (140 to150°F) range. This is also the temperature where legionella cannot colonize the water reticulation — just below the temperature copper is prone to develop failures. Unfortunately, where high peak demand occurs, a simple solution is to raise the water storage temperature. In the author's experience, temperatures of 75°C to 80°C (167 to 176°F) are not unknown in hotels and other buildings with high peak demands.

This paper is based on the author's experience in trying to understand the reasons for persistent pin-holing. The investigation included the collection of data and examination of samples from a large building over the course of five years — where he was leading a team of experts, metallurgists, and tradespersons.

The Use of Copper

Copper is a soft and reasonably reactive material. When used in water reticulation systems, it typically develops a protective coating either through the formation of copper oxide or copper carbonate films or a layer of minerals precipitated from the water being carried by the pipe. In essence, the copper becomes the mechanical support for a contact surface that is not metallic copper (**Figure 1**).

This both protects the copper and preserves the chemical quality of the water. However, there are circumstances

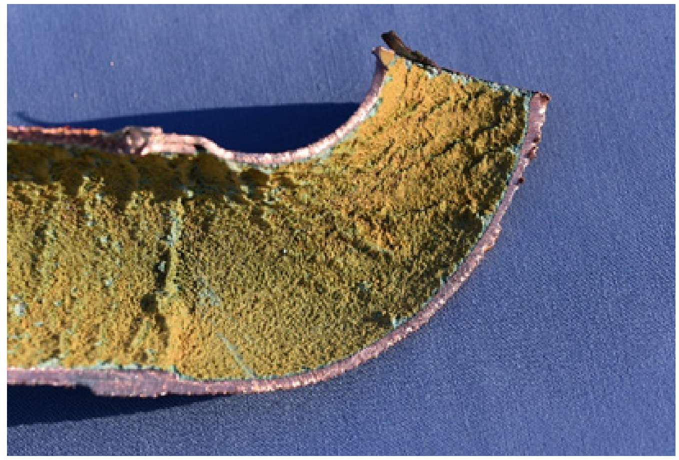

Figure 1
Copper pipe after 30 years of service with an internal coating.

where the formation of these films is imperfect, and reactions between the water and the copper pipe can create problems that fall into reasonably well-recognized classes. These classes of problems include: blue water, where dissolved copper gives the water a characteristic blue tinge and often results in blue stains on sanitary fittings; pinhole pitting in relatively short time frames of two to five years; microbially induced corrosion; erosion corrosion; and leaks generated by deposits of flux or debris on the inside pipe surface.

There is a wide range of research in published literature, much of which concentrates on trying to relate the chemical characteristics of the water carried by the pipe and the type of failure observed that inevitably leads to much confusion and contradiction amongst reports of research with words like "suggested," "proposed," and "likely" common[4,6].

There is no doubt that water chemistry (particularly the pH and softness/hardness of the water) plays a part in the problem. However, the author's review of some of the published research and investigations carried out over the last 20 or 30 years emphasizes the fact that water is an amazingly versatile compound with a wide range of characteristics and a high ability to absorb small amounts of other materials. This has led to many papers identifying a unique aspect of water chemistry apparently associated with a particular problem, often superseded by other research proposing an entirely different chemical cause for a similar problem.

This, coupled with what appears to be quite complex chemical and electrochemical behavior of copper and the variable conditions of temperature and velocity in the pipes, makes the problem a transdisciplinary issue that does not lend itself to a single path to resolution[7,8,9].

Characterizing Copper Corrosion

Because there are distinctly different circumstances associated with corrosion of copper pipe, types of corrosion have been described and classified by industry associations such as the Water Services Association of Australia[10,11]:

- Type I pitting (largely eliminated by better manufacturing processes), which occurs in cold water reticulation systems.
- Type II pitting (the current problem), which occurs in hot water systems, often soft waters with a pH of around seven.
- Type III pitting initially associated with stagnation particularly early in the life of the pipe.
- Microbially induced corrosion generally arising from the development of a biological film in cold or warm soft waters able to support biological activity.
- Erosion corrosion from high-velocity water, particularly in hot water systems or because of cavitation at any temperature.
- Flux induced corrosion or poor workmanship during construction or repairs.
- Concentration or differential aeration cell corrosion arising from debris and deposits in the pipes often because of inadequate flushing after construction or an accumulation of solids delivered in the supplied water.

Although these characterizations are still commonly referred to in discussions of copper pipe corrosion, research and experience have modified the classifications.

Type I pitting is rarely (if ever) seen in current installations. This is because the root cause was identified as being a thin carbon film left on the inside of the pipe during the manufacturing process as a result of oxidation of drawing lubricants[12,13] (**Figure 2**). This film was generally imperfect, and accelerated electrochemical pitting took place at breaks in the film. This happened in cold water, and initial perforations typically appeared after about two years. Tests were devised, and manufacturing processes were adjusted some 20 years ago to eliminate the formation of this film. It is unlikely that any installed pipe networks with this problem remain in service (as they would have failed many years ago).

Type II and Type III pitting (**Figure 3**) are now recognized as similar processes with a high probability that both originate or are associated with periods of stagnation during construction or use, although other processes are suggested in the literature[14,15]. Installation standards now recognize this problem and recommend procedures to avoid it.

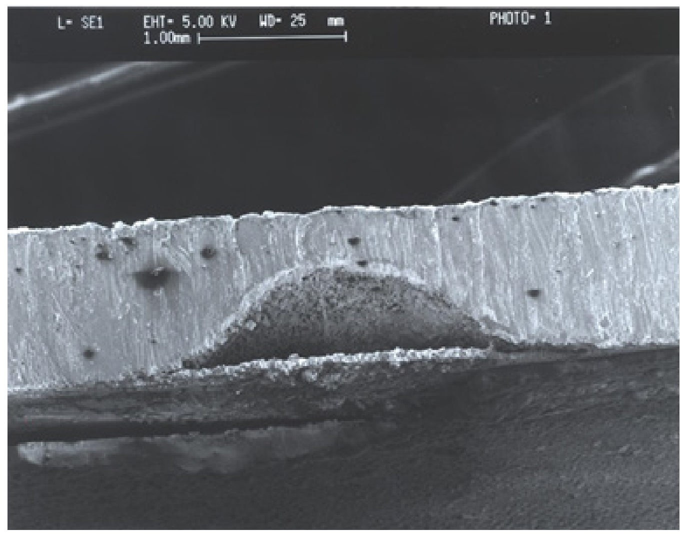

Figure 2
Scanning electron micrograph of a Type 1 pit.

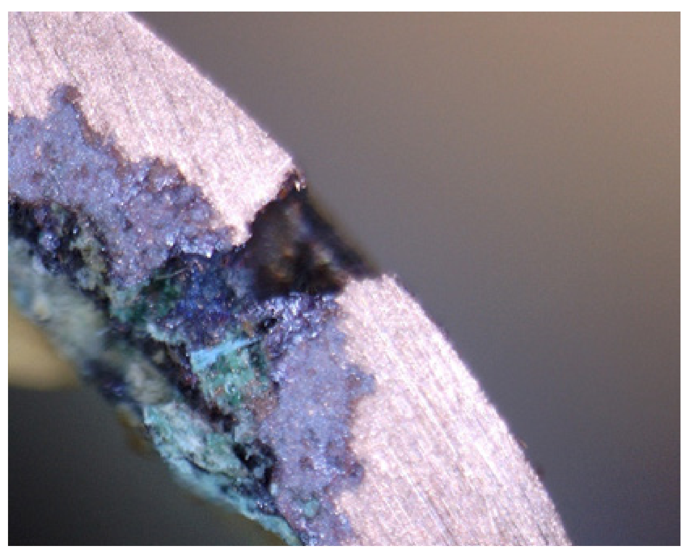

Figure 3
Polished section through a Type II pit from a system that was subject to stagnation.

Pits caused by debris on the bottom of the pipe can be easily identified by the inclusion of large debris in the corrosion cap (**Figure 4**). It should be noted that a Type II corrosion cap can contain finely divided copper released by the corrosion process. This type of corrosion, which involves differential access to oxygen caused by the presence of the debris, is not limited to copper pipe.

Research into the Causes and Characteristics of Copper Corrosion

In an analysis of some 48 published water analyses from a range of literature, the author found references to 61 compounds and elements and five characterization tests with little consistency in the conclusions drawn relating to the proposed causative chemical for any particular type of failure.

Comparison across the published water analyses show cause being allocated to a particular element. Chlorine, silica, iron, and manganese have all been identified as having an effect coupled with pH and temperature in particular circumstances, but there is contradictory evidence in other research reviewed by the author. For example, where an element is claimed to be causative in one investigation, it is present in other investigations where cause is allocated to different elements present in the analytical results. Therefore, conclusions drawn from a single water analysis are likely to be unreliable.

Temperature and pH are common factors in the speed and intensity of observed corrosion. This is an area where, as forensic engineers, we need to be both cautious and skeptical. Senior metallurgists who have spent a lifetime working with copper corrosion in water pipes advise that while many proposed causes have been eliminated, there is still some uncertainty as to the actual processes that initiate corrosion in copper pipe[9]. Many technical papers use terms such as "provides insight" or "indicating," suggesting caution in accepting the conclusions of a single research paper. Much of the knowledge is based on correlating suspected issues with known results. So, for example, pin-hole corrosion is frequently experienced where copper pipes are left stagnant for long periods, typically greater than eight weeks[11]. pH seems to have an effect in a certain range. Temperatures above 65°C appear to accelerate the process.

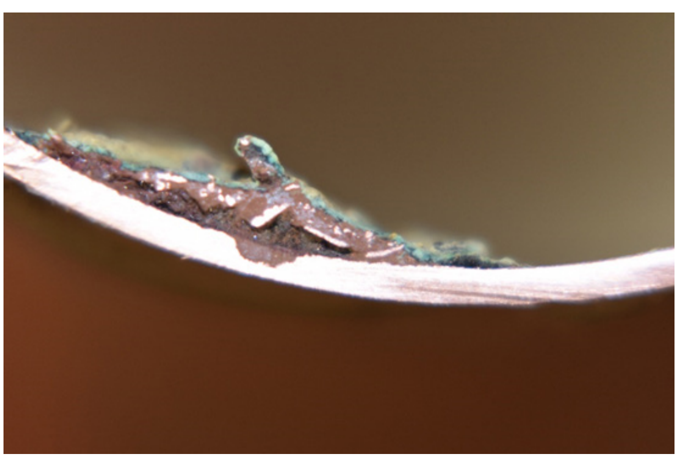

Figure 4
Pit caused by an accumulation of debris at the bottom pf the pipe.

It is often maintained that the corrosion relates to, or is initiated by, a "bad batch" of pipe or a particular manufacturer. This tends to be reinforced for lay persons by the fact that these problems are either localized in a community on a single water supply or occur in a large installation. The extent of the problem can often be traced to a consistent construction method where there are a limited number of tradesmen in a local community or a large installation where all pipes have been subject to similar treatment. Occasionally, the water chemistry is the cause of widespread but similar issues, particularly where a new water supply is introduced from a source with different characteristics (i.e., hard, soft, surface, deep well, artesian.)

Despite extensive testing, no repeatable research has managed to establish a difference in performance between copper pipes from different manufacturers that have good quality assurance and comply with manufacturing standards (as most do) or between different batches from the same manufacturer[1].

It is also often suggested that electrical currents arising from the use of copper pipe networks for electrical earthing promotes or accelerates corrosion processes[1]. Again, there is no repeatable research that demonstrates or proves stray currents or impressed voltages have a discernible effect on pin-hole corrosion rates. Indeed, research concludes there is no effect on rates or origination of corrosion from this cause.

When copper pipes are recovered and opened after periods of service, they often exhibit characteristic linear blue-green deposits (**Figure 5**), which, to an observer, suggest a logical connection between linear surface defects arising from the extrusion or drawing process and pin-hole leaks or corrosion. However, no research has found a definite correlation, although there is still some unproven suspicion that there is a connection between them.

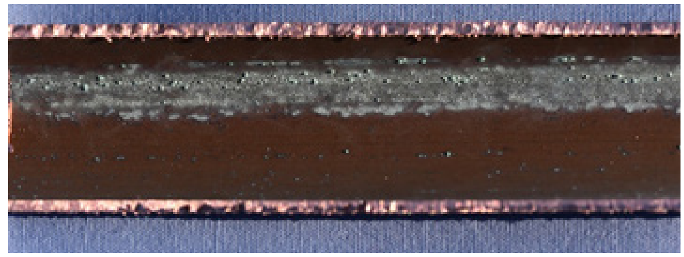

Figure 5
Normal linear markings inside copper pipes removed from service at around 10 years.

What is generally agreed by research metallurgists is that pitting corrosion is an electrochemical process that is initiated by small sites associated with defects in the normally protective oxide or carbonate coatings that form on the inside of the pipe. The cause of these defects — and their relationship to the initiation of pitting — is still a subject for research.

Microbially Induced Corrosion (MIC)

For many years, it was thought that microbes could not exist in a copper-rich environment; therefore, microbially induced corrosion could not be a cause of problems in copper pipe. Experience and research have shown that microbes are often present in cold water systems reticulated in copper pipe[16,17]. They certainly contribute to (and may be the primary the cause of) blue water, and appear to possibly play a part in the initiation of pitting corrosion. One of the problems of establishing a firm connection is that pitting corrosion is clearly an electrochemical process and is only detected when pipe wall penetrations occur. No one sees the start of the process.

In most operating hot water systems, microbial activity is not present because temperatures are too high — and legionella does not survive temperatures greater than 50°C (122°F)[18,19]. In cold water systems, if microbes are detected in corrosion pits, it is not clear whether they have been there from the start, or simply found a convenient place to live — sheltered from the water flow and possible disinfectants.

When the ability of microbes to survive in copper piping systems was firmly established, it was, for a while, regarded by many as the answer to copper corrosion problems — and certainly was raised as a defense in litigation. It now appears to be better understood as a potential contributor rather than an unavoidable natural root cause.

Problems in Recirculating Hot Water Systems

Currently in New Zealand, Australia, and Europe, the failure of piping systems in recirculating hot water systems has become a regularly reported problem. It's also the subject of wide discussion in the building design profession because the issue is creating problems in hospitals, hotels, and apartment buildings. (This geographical concentration is most likely to be because these countries have common engineering design standards. The problem is likely to arise elsewhere in the world where recirculating hot water systems are becoming common — there are no particularly local characteristics to either the design or the failure process.)

Typically, systems in large facilities that fail begin to experience pin-hole corrosion after four to five years in their hot water system if they have used copper pipe, or they experience splits in polypropylene random copolymer pipe apparently appropriately rated for the operating temperatures. Both failures appear to be continuing after the initial appearance with pin-holing, in particular showing little sign of reducing over time if no corrective action is taken. Some mitigations (such as precise temperature control below 65°C) can slow the process. However, metallurgists tell us that once pinholes have started, the only thing that can be controlled is the speed with which they penetrate the pipe wall.

One common factor in both these types of failure is a water temperature above 65°C, but the nature of the failure obviously is different in different materials. Some failures as observed in polypropylene random copolymer are related to stress or joints that appear to have been moved during fabrication while the joint is still hot and occur in both hot and cold services (**Figure 6**, on page 58).

In terms of the failures investigated by the author in polypropylene random copolymer systems, the problem appears to be a combination of temperature and pressure, particularly in high-rise buildings as the failures tend to occur at a level where the static pressure is high, and the recirculating water has not lost much temperature.

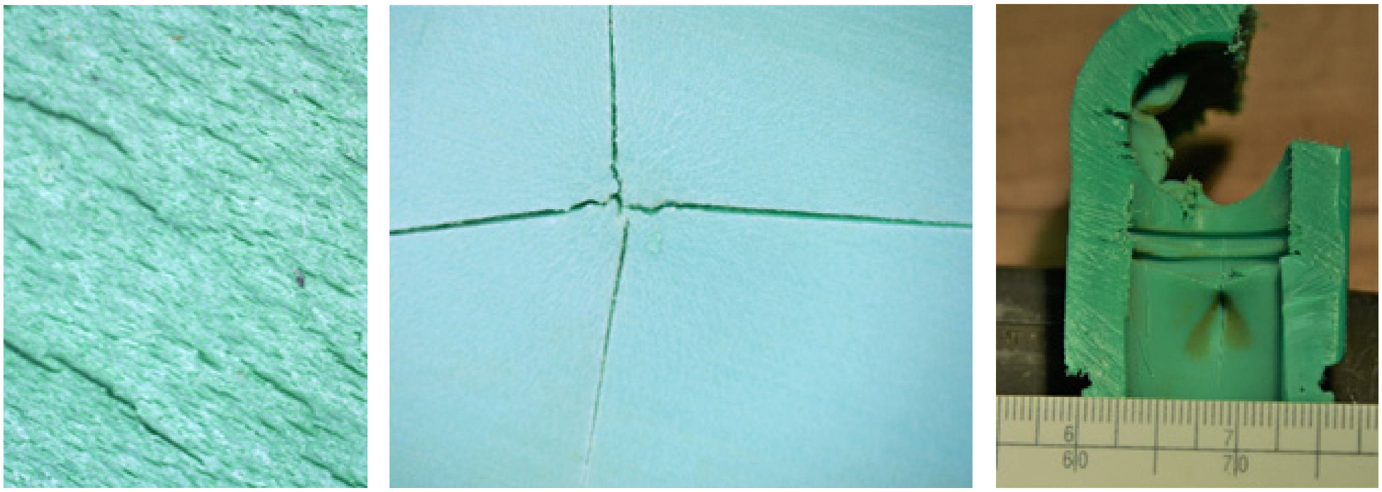

Figure 6
Typical failures in PPr piping in hot and cold systems. Left: internal surfacing cracking; center: cracking from point stress; right: cracking from poorly formed joints.

Examination of the rating tables supplied by pipe manufacturers suggest that the life of polypropylene random copolymer at the combinations of temperatures and pressures that are being seen is relatively short.

One of the suggested causes is that a mixture of polypropylene random copolymer and copper in a hot water system results in dissolved copper attacking the plasticizers in polypropylene random copolymer. Manufacturers claim this is a cause, and recommend that polypropylene random copolymer should not be used in a system with any copper piping or fixtures[20].

Causes Proposed for Copper Pipe Corrosion

There is no doubt when the fundamentals of reactions between copper and water are examined scientifically that there is a region where a combination of temperature around 65°C and pH around 7.0 result in a change in the processes that are taking place[21,22]. However, there is not a full understanding of what these processes are and how they can be controlled, apart from moving either the temperature or the pH out of the critical region.

Temperature is obviously the easiest parameter to control. Unanticipated consequences are likely if dosing to adjust pH is undertaken, given the fact that many of the systems fed by the reticulation in health or industrial installations are likely to be tuned to the current water chemistry.

In copper recirculating hot water systems, we are seeing both pitting and erosion. The rate at which these processes are damaging the copper pipes appears to be closely related to the combination of temperature and velocity in the pipes. Since 2000, engineering standards around the world have been steadily reducing design velocities for hot water in recirculating systems from the original standard based on non-recirculating systems of 3 m/s (10 ft/s) to figures as low as 0.5 m/s (less than 2 ft/s). There are also strong recommendations that temperatures should not exceed 65°C (150°F) and should preferably be in the order of 60°C (140°F). These are reinforced by recommendations in health facility specifications to maintain the temperatures in recirculating hot water systems between 60°C (140°F) in the flow lines and 50°C (122°F) in the return lines for control of legionella species[23].

Standards also require that during construction and commissioning copper pipe systems should not be allowed to stand with stagnant water for extended periods (AS4809 recommends no more than eight weeks)[11]. The standard requires either routine flushing on a regular basis or draining and drying the piping systems. This creates a practical problem as normal construction sequencing generally leaves pressurized water in the pipes between the first and second plumbing fix to ensure any pipe damage during the fitting of wall linings is detected. (First fix is installing concealed pipework before the wall linings are installed. Second fix is connection of the fittings and fixtures.) This can be overcome by testing with air (taking care to test in steps to avoid burst incidents) and leaving a low residual pressure that can be monitored for sudden drops that will indicate pipe damage has occurred.

The recommendations are essentially practical, based

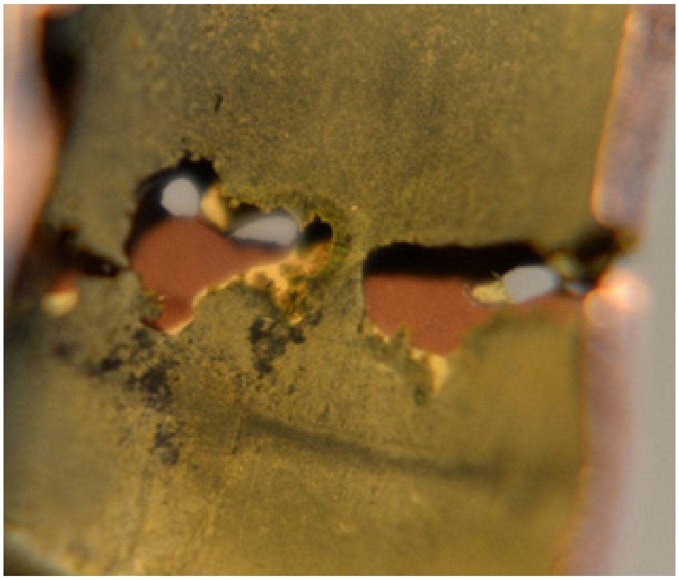

Figure 7
Erosion penetrations at poorly formed joints.

on observation and experience, although some consistent opinion (rather than hard research) on the cause is beginning to emerge.

Observations to date are:

- Systems that are not subject to periods of stagnation and are put into service soon after construction do not have pin-hole corrosion problems.
- Similar systems that have had periods of stagnation exceeding eight weeks, particularly during construction, are often subject to pin-hole corrosion.
- The rate of pin-hole corrosion appears to be reduced if water temperature is reduced.
- Erosion corrosion is observed less frequently in areas of reticulation systems where velocities and temperatures are lower.

It is suggested, but not proven, that during early stagnation the formation of protective oxide or carbonate layers can be disrupted by naturally occurring microbes in the water. This creates defects in the protective layer, which become sites that allow aggressive high temperature water to initiate pin-hole corrosion processes when the microbe colonies die. This suggests a connection between microbial-induced corrosion as an initiator with the electrochemistry of pin-hole corrosion as the driving mechanism.

Hot water above 65°C is an aggressive material with a high capacity to damage copper through erosion, particularly as a result of cavitation, which can be originated by poor joints (**Figure 7**) or partially closed valves used for flow control (**Figure 8**). It can also erode apparently smooth surfaces most likely starting at a small surface imperfection[3] (**Figure 9**, on page 60).

Recognizing Different Corrosion Types

There are many references, some of which are quoted in this article, that assert blue water is a result of microbial colonization and can generally be controlled by either shock dosing with chlorine disinfectant followed by

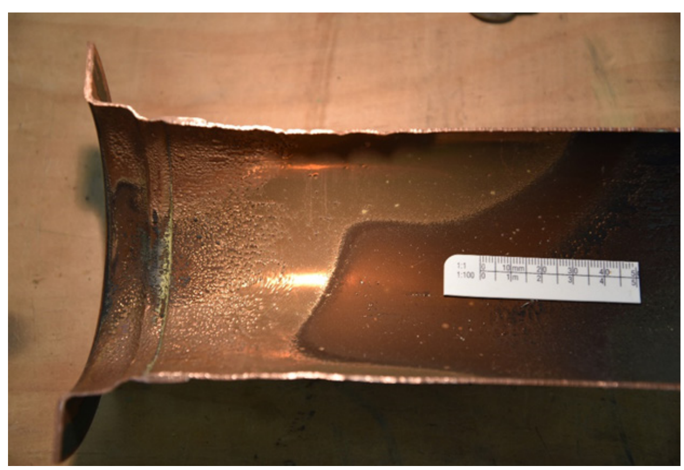

Figure 8
Copper pipe removed from service showing
erosion and surface polishing where a butterfly valve
was used to throttle flow rates. Flow left to right.

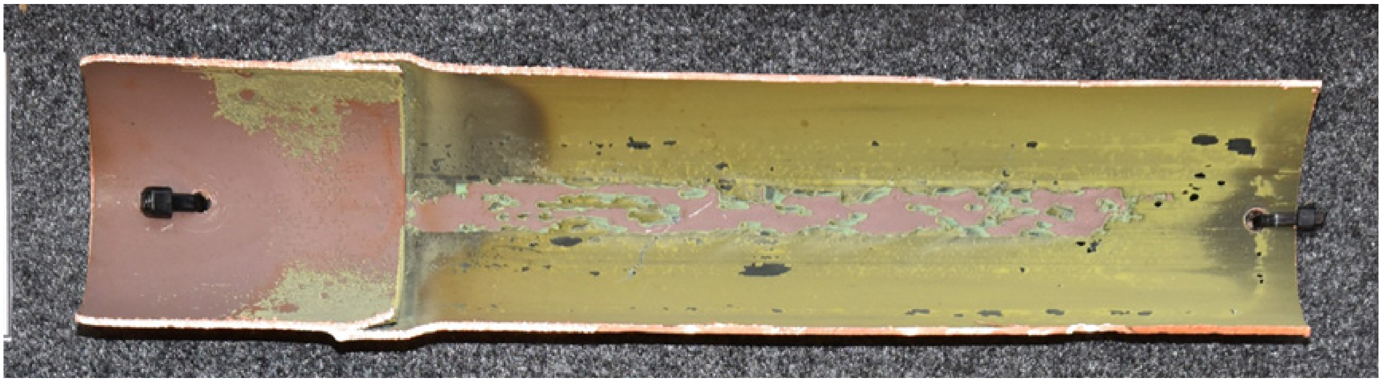

Figure 9
Left-hand end general material removal from surface with gross erosion extending from a burr measured at 0.1 mm high at the joint coupled with a poorly formed joint. Flow left to right. (Bend in joint at bottom was caused when the section was cut.)

subsequent normal levels of chlorination or by flushing the system with hot water typically at 60°C (140°F)[10,11,16,17]. Care must be taken to ensure that temperature-sensitive elements are not present and people are prevented from using the fixtures if hot water treatment is the chosen alternative.

Tests can be performed, if necessary, to prove microbial colonization. These typically involve recovering pipe samples aseptically and providing them to specialists who will use staining followed by microscopic examination[17]. Gross colonization can often be recognized as a slimy surface on the inside of the pipe.

Pin-hole corrosion in hot water systems can be recognized from the outside of the pipe, as it will either weep or spray from a relatively regular small hole. The leak rate may be low enough that initially the water will evaporate from the hot pipe surface before it flows away, leaving a mass of corrosion, adhered insulation material, and mineral deposits on the outer pipe surface. Examined internally, it will have a mound of corrosion product often with a comet tail extending downstream of the deposit (**Figure 10**).

In cold water systems (Type 1 corrosion), the external appearance of the pin-hole will be the same (although with less mineral and adhered materials). But internally the corrosion site will more likely appear flat or slightly depressed with raised corrosion material around the edge. Type 1 corrosion does not occur in hot pipes and is unlikely to be observed in current cold systems. Erosion leaks tend to be irregular in shape woprihen examined from the outside of the pipe and will often appear in groups or in a circumferential pattern around an artifact, such as a brazed joint (**Figure 7**).

Gross erosion is identified by large areas of material removal often with small peaks surrounded by a bright

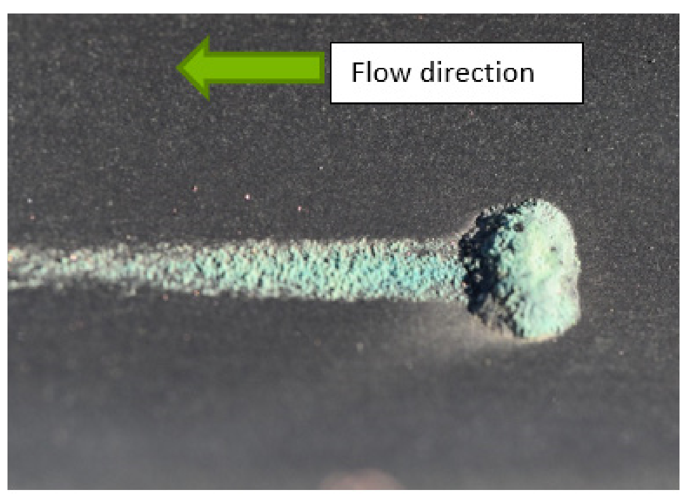

Figure 10
Typical active pin-hole leak and internal corrosion tubercule.

Figure 11
Gross material erosion. Flow from left to right cut from a section of pipe about 3 meters (10 feet) long.

horseshoe shape (**Figure 11**). The direction of flow can be identified using the mnemonic that horses walk upstream. It may be difficult to find an origination for this kind of erosion, which can extend for significant distances along the inside surface of the pipe.

Rough internal surfaces (**Figures 8** and **9**) or highly polished areas are both indications of surface material loss as a result of local cavitation or high-velocity flow fields.

When carrying out investigations into leaks in copper pipes, the location of the leak (top, bottom, or side), the direction of the flow, and the orientation of the pipe are important to record as they provide clues as to the cause. Pitting proposed to be caused by stagnation typically is observed at the top of the pipe and can be present on vertical sections of the reticulation — pitting caused by debris is almost always on the bottom of the pipe, and erosion can be at any orientation.

Conclusions

The current apparently sudden increase in pin-hole corrosion in hot water systems using copper pipes appears to be closely correlated to the appearance of high temperature recirculating hot water systems.

Although much has been written about the relationship between corrosion in copper pipes, and the composition and stability of the water flowing in them, it appears that temperatures above 150°F (65°C), velocity in the region of 6 to 10 ft/sec (2 to 3 meters per second), and possibly a water pH of around 7.0 appear to be the critical factors — probably coupled with periods of stagnation during construction or commissioning. The problem appears to be controllable by ensuring that the new design criteria appearing in standards for temperature and velocity are adopted, and stagnation during construction is avoided. Tests have not found any root cause associated with the manufacture or the material of copper pipe.

Other failures occurring in systems using polypropylene random copolymer pipe appear to be related to the ability of the material to withstand combinations of temperature and pressure that occur in the recirculating system. Polypropylene random copolymer manufacturers do not recommend the use of this material in association with copper in hot water systems[20]. Polypropylene random copolymer pipes have an entirely satisfactory service history at cold temperatures, but many designers are justifiably reluctant to use them for hot water reticulation based on industry experience, although manufacturers claim the product has been improved.

References

1. D. M. Nicholas, "Corrosion of Copper in Australasian Drinking Waters: A Historical Review," Corrosion and Prevention, no. Paper 21, p. 14, 2014.

2. C. A. Copper Development Association, "Copper Through the Ages." [Online]. Available: https://copperalliance.org.uk/about-copper/copper-history/copper-through-the-ages/#:~:text=The%20Sumerians%20and%20Chaldeans%20Copper%20first%20came%20into,others%20somewhere%20between%205000%20and%206000%20years%20ago.

3. Copper Tube Handbook Industry Standard Guide for the Design and Installation of Copper Piping Systems, Handbook A4015-02/16, C. D. A. I. C. Alliance, New York, 2016.

4. Z. Jia, C. Du, D. Zhang, and X. Li, "Analysis of Copper Pitting Failure in Drinking Water Distribution System," Journal of Failure Analysis and Prevention, vol. 11, no. 2, pp. 152-157, 2011/04/01 2011, doi: 10.1007/s11668-010-9415-y.

5. S. R. Jenkins, "Personal observations and commissioned investigations," ed, 2016 -2020.

6. D. A. Lytle and M. R. Schock, "An Investigation of Copper Pitting Corrosion and Pinhole Leaks," presented at the World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat, Tampa, Florida, 2007. [Online]. Available: https://ascelibrary.org/doi/

abs/10.1061/40927(243)592.

7. D. A. Lytle and M. R. Schock, "Pitting corrosion of copper in waters with high pH and low alkalinity," Journal AWWA, vol. 100, no. 3, pp. 115-129, 2008, doi: https://doi.org/10.1002/j.1551-8833.2008.tb09586.x.

8. B. D. Custalow, "Influences of Water Chemistry and Flow Conditions on Non-Uniform Corrosion in Copper Tube," Master of Science, Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2009. [Online]. Available: https://vtechworks.lib.vt.edu/handle/10919/34388

9. J. C. Rushing, "Advancing the understanding of water distribution system corrosion: Effects of chlorine and aluminium on copper pitting, temperature gradients on copper corrosion, and silica on iron release." Master of Science in Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, 2002. [Online]. Available: https://vtechworks.lib.vt.edu/bitstream/handle/10919/34235/RushingETD.pdf?sequence=1&isAllowed=y.

10. Corrosion of Copper Pipe in Australian Drinking Waters, Technical W. S. A. o. Australia, June 2015.

11. Copper pipe and fittings-Installation and commissioning, A. Standards, Sydney, 2003.

12. H. S. Campbell, "PITTING CORROSION IN COPPER WATER PIPES CAUSED BY FILMS OF CARBONACEOUS MATERIAL PRODUCED DURING MANUFACTURE," J. Inst. Metals, vol. 77, p. 14, 1950.

13. G. J. Schafer, "CORROSION OF COPPER AND COPPER ALLOYS IN NEW ZEALAND POTABLE WATERS," New Zealand Journal of Science, vol. Dec 1962, p. 10, 20 August 1962 1962. [Online]. Available: file:///D:/Corrosion%20of%20Copper%20and%20Copper%20Alloys%20in%20New%20Zealand%20Potable%20Waters.pdf.

14. W. S. Holden, Ed. Water Treatment and Examination. London: J. & A. Churchill, 1970, p. 513.

15. R. J. Oliphant, "A Review of Current Knowledge CAUSES OF COPPER CORROSION IN PLUMBING SYSTEMS," Foundation for Water Research, Marlow, September 2010 2010.

16. J. T. Walker, D. Wagner, W. Fischer, and C. W. Keevil, "Rapid detection of biofilm on corroded copper pipes," Biofouling, vol. 8, no. 1, pp. 55-63, 1994/04/01 1994, doi: 10.1080/08927019409378260.

17. P. J. Bremer, B. J. Webster, and D. B. Wells, "Biocorrosion of Copper in Potable Water," AWWA, p. 10, August 2001 2001.

18. N. A. o. S. E. a. Medical, Management of Legionella in Water Systems. Washington, DC: The National Acadamies Press, 2020.

19. B. J. Webster, S. E. Werner, D. B. Wells, and P. J. Bremer, "Microbiologically Influenced Corrosion of Copper in Potable Water Systems—pH Effects," Corrosion, vol. 56, no. 9, pp. 942-950, 2000, doi: 10.5006/1.3280598.

20. OPNA, "COPPER IONS AFFECT ON PP-R," ed: Pestan North America, 2021.

21. B. Beverskog and I. Piugdomenech, "Revised Pourbaix Diagrams for Copper at 5-150ºC," Swedish Nuclear Power Inspectorate (SKi), SKi Report 95:73, October 1995 1995. Accessed: 27/5/2016.

22. J. D. Gates, "Erosion-Corrosion of Copper Pipes in Hot Water Reticulation Systems - Case Studies and Wider Implications," The University of Queensland, St Lucia, 7 July 2014 2014. Accessed: 30/5/2016.

23. Scottish Health Technical Memorandum 04-01: Water safety for healthcare premises Part A: Design, installation and testing, N. N. S. Scotland, 2014.