Controlling corrosion in drinking water distribution systems: a grand challenge for the 21st century

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Abstract It is argued that the water distribution system will be a key public health battlefield of the 21st century. Corrosion in private plumbing is deserving of special attention, since the health and economic impacts are probably of equal or greater magnitude compared to public systems, and there has not been an advocate working on behalf of the consumer to solve these problems. To better serve society in this endeavour we will need educational programs, aggressive research to minimize the unsustainable costs of corrosion, and to consider our legacy to future generations when making decisions on materials use.

Keywords Consumer; corrosion education; cost; policy; private plumbing; public health

A weakening pillar of civilization

The water and wastewater distribution system, transporting clean water into and sewage away from concentrated populations, is the foundation upon which human civilization is built. Indian, Babylonian and Roman engineers who first realized the importance of water distribution and developed the first functioning systems collectively made one of the greatest scientific contributions in the history of man (George, 2001). More recent advances made in water treatment, supply and distribution, which still ranked 4th on a list of noteworthy engineering achievements of the 20th Century as compiled by the US National Academy of Engineering, must be considered incremental by comparison.

Over the last half century the US has made relatively small investments in distribution system research and repair, since we inherited a system engineered to last more than one hundred years. Many are shocked to learn that our plumbing legacy will not be nearly as long-lived, and that recent studies point to problems that pose a direct threat to the public health, finances and well-being. As we stand at the “The Dawn of the Replacement Era” where an unprecedented investment in public infrastructure is required of us (AWWA, 2001), it is instructive to pause, consider our present circumstance, and attempt to make decisions that will be viewed favourably in the hindsight of future generations.

The war comes to us

“Suppose they gave a war, and nobody came? Why then, the war would come to you!”

Bertolt Brecht.

The overall costs of corrosion are astronomical. A study conducted by the Federal Highway Administration (2002) estimated that the direct cost of corrosion in the US was $276 billion per year, or 3.1% of the gross domestic product. Of this total, direct costs of corrosion in public drinking water and sewage represented $36 billion of the total, with $22 billion attributed to drinking water and $14 billion attributed to sewage systems (Brongers, 2002). This is consistent with studies in Australia, Great Britain, Japan and other countries where it has been estimated costs of corrosion are approximately 3–4% of the GNP (Uhlig and Revie, 1985). Much has also been made of the fact that required upgrades to the public
water transmission system alone are expected to cost utilities between $77–325 billion (US dollars) in the United States over the next 20 years, or $1.02 trillion over 20 years if operations, maintenance and financing are included (WIN, 2000). The estimates for public water infrastructure needs are about twice the anticipated costs of all water treatment over the same time period (Davies et al., 1997).

There are also costs of corrosion in public systems that are not so obvious. For instance, unaccounted for water at utilities ranges from < 10 to 32% of the total production (Kirmeyer et al., 2001), and it is believed that a significant portion of this water is attributable to leaks due to corrosion. Ascribing a retail price of $0.35/m³ to the 15% of unaccounted for water in the US would add another $3 billion dollars in potential direct costs likely attributable to corrosion each year (Brongers, 2002). It is also estimated that 2–3% of energy use in the world is due to pumping and treating water, and 15–20 per cent of the total energy demand in the US is consumed in treating, pumping and heating water (Watergy, 2002). Scale and corrosion directly impact those costs since they decrease efficiency of pumps and heat transfer, while increasing energy loss in pipes. There are also unspecified property damages that result from failures of water pipes due to corrosion, and as in the case of the oil and gas industry, these costs are typically larger than the direct costs (Hausler, 1978; Brongers, 2002). It is also understood that corrosion failures in hydrants and sprinkler systems can lead to unquantified loss of property and life from fires (e.g. Farrell and Sharockman, 2002).

While society collectively bears the cost of public infrastructure corrosion as rate-payers/taxpayers, the costs of corrosion in US home and business plumbing fall directly on individual property owners with the noteworthy exception of lead and copper leaching to drinking water. Obvious costs of corrosion to the homeowner include water damages from leaking pipes, costs of accessing, repairing/replacing failed pipes, higher insurance premiums or refused renewal of insurance after reporting one leak, aesthetic problems arising from distasteful/discolored water, and hot water heater repair and replacement. The high potential public health costs are detailed in a later section, and if they prove to be significant, would have an indirect cost of many billions of dollars per year (e.g. Hudson and Gilcrea, 1976). While the total costs of all these corrosion problems to the homeowner have never been rigorously assessed nationally, a case study in Seattle estimated they were about 10–20 times higher than those for public plumbing infrastructure in the same system (Ryder, 1980). Other studies have found that corrosion damages in residences are about twice those of the corresponding public water supply (Levin et al., 1989).

Several other factors tend to increase the importance of privately owned plumbing systems relative to the much better studied public systems. First, we note that 16 million US households are not connected to public water supplies (EPA, 1999), and after considering the extra treatment, pumps and infrastructure present in such cases, these homeowners likely have an investment in plumbing that far exceeds that for the other 96 million housing units in the US. Secondly, society and industry maintain a substantial private plumbing infrastructure separate from that found in residential housing units. We do not yet know how to quantify the relative net present value of all industrial and community owned drinking water plumbing versus that for privately owned housing, but it seems reasonable to expect it is of similar or equal magnitude. Considering that a typical complete replumb costs about $5,000 per housing unit, the net present replacement value of privately owned plumbing tube alone is in the range of $1.0 trillion dollars in the US (112 million housing units × $5,000/housing unit × 2 total privately owned units/housing unit). This is about twice the estimated value of publicly owned drinking water transmission infrastructure in the US at $0.6 trillion dollars [$6,300/household (WIN, 2000) × 96 million housing units]. These ballpark estimates are close to the 1:2 ratio for public infrastructure versus private infrastructure cited in the earlier paragraph on costs of corrosion control.
We further note that consumers and businesses have nearly no control over the corrosivity of the water supplied to their homes, even though they must directly bear the cost of such problems. Water utilities have historically been responsible only for corrosion problems up to the consumer’s service connection. Because all materials corrode differently, it is quite possible that a water supplied by a utility could be very non-corrosive to public infrastructure (e.g. iron and concrete-lined pipe) yet remain very corrosive to private infrastructure (e.g. copper).

Despite the obvious costs of private plumbing corrosion mentioned above, such costs were not included in the most recent national assessment of corrosion impacts (i.e. Brongers, 2002), perhaps because no one is charged with the direct responsibility of overseeing this valuable national asset. The very high investment that will be required for public plumbing infrastructure over the next 20 years has been deserving of its high profile recent discussion, but what about private plumbing corrosion issues? No one yet speaks for the consumer, who could be subject to an unexpected bill at any time for several thousands or tens of thousands of dollars. It is also clear that no one is directly responsible for controlling costs of corrosion in private systems, funding basic research to develop answers to questions that consumers have, or even serving as an unbiased centralized source of existing knowledge. In this vacuum, consumers must make critical decisions with the input of whoever will listen and give them advice. Thus, consumers are routinely taken advantage of by vendors who will listen to their problem, purchasing expensive products purported to stop corrosion (i.e. magnetic water treatment and other devices) even when clear scientific evidence has shown that many such devices are outright frauds (e.g. Alleman, 1985; Wisconsin Department of Justice, 1993; Utah Department of Commerce, 1995).

**Plumbing and public health**

“There is no question that our health has improved spectacularly in the past century…it did not happen because of medicine or medical science…much of the credit should go to the plumbers and engineers…”

*Lewis Thomas*, Chancellor of the Memorial Sloan-Kettering Cancer Center, 1984

The preceding section highlighted the high economic costs attributed to degradation of our public and private potable water distribution systems. All of these costs can be well understood by the average citizen. More recently, discoveries have been made regarding the impact of degraded plumbing systems on public health. Indeed, in the very near future if not the present, the public health benefits achievable from enhanced understanding of corrosion and distribution system dynamics will far exceed those attainable from further improvements to treatment. Subsequent paragraphs illustrate why this is the case from the perspective of contaminant intrusion, permeation, contaminant leaching from pipes, and waterborne disease outbreaks from the distribution system in general.

**Intrusion**

The work of Payment et al. (1997) provided data that strongly suggest, for at least one treatment plant and distribution system in Canada, that factors contributing to consumer gastrointestinal upset were not present in treated drinking water as it left the treatment plant, but were somehow introduced to the water as it passed through the distribution system. To explain this result, hypotheses were developed, and extraordinary recent progress has been made to verify that contaminants can be drawn into distribution systems through holes in pipes during pressure transients caused by surge or water hammer (LeChevallier et al., 2002; Boyd et al., 2002). This phenomenon is termed “intrusion.”
Estimates as to the volume of untreated soil pore water that may enter a distribution system through holes in pipes during transient events range from a few mls to hundreds of gallons (Kirmeyer et al., 2001). Since a wide variety of pathogens are present and active in all soil samples collected next to pipelines (total fecal coliform levels were as high as 10^4 per 100 grams of soil), and the pipe is occasionally submerged or located close to leaking sewage conduits, it is reasonable to believe that consumers are directly exposed to pathogens with nearly no disinfection if such events are significant (Kirmeyer et al., 2001).

The catastrophic consequences to human health when low pipeline pressures occur without an adequate distribution system residual are all too easily quantified. For instance, in a case study in Tajikistan where this deadly combination was present, at least 95 deaths were attributed to typhoid. Fecal coliforms increased an average of about 300% from the time water left the treatment plant to the time it arrived at consumers’ houses (Mermin et al., 1999). In some respects, it can be argued that our own declining infrastructure will force us to re-learn the most basic plumbing lessons of earliest times; that is, treatment is irrelevant if the clean water subsequently mixes with or is exposed to sewage before reaching the consumer. The intrusion problem would not be significant if leaks in plumbing were not present.

Permeation/leaching

Problems associated with leaching of lead and copper to potable water are relatively well understood and will not be elaborated on in this paper, except to say that a significant percentage of waterborne GI has been attributed to excessive copper leaching under some circumstances (Craun and Calderon, 2001). However, recent evidence has also been gathered that other substances also leach to drinking water at levels that might be of interest to public health, including aluminium from cement mains, and vinyl chloride, organotin/organolead from plastics.

The issue of aluminium leaching from cement is deserving of increased scrutiny. In 1996, 9 dialysis patients in Curacao died from acute toxicity due to aluminium leaching from a factory installed cement lining (Berend and Trouwborst, 1999). Aluminium concentrations were as high as 700 ppb and remained elevated for years. Use of a relatively high aluminium content cement and long detention times in the affected area were deemed at least partly responsible. In contrast, a rigorous study of pipes in circumstances favoring leaching in Holland found levels of aluminium always < 11 ppb in distribution system samples (KIWA, 1996), a trend consistent with general expectations in the US (AWWA, 1996). However, since US monitoring is designed to detect aluminium carryover leaving the treatment plants, we actually have very little experience monitoring aluminium in the distribution system. In recent cases when such monitoring was conducted to determine the source of aluminium deposits present on copper pipes (i.e. Rushing et al., 2002), we have frequently discovered that aluminium is leaching at levels that can exceed the secondary maximum contaminant level even at detention times considered relatively short.

Organic plumbing materials have also caused concern in relation to leaching – many of these incidents were only detected after consumer complaints regarding taste and odors. For instance, in 1989 the city of Calgary found a problem with steel pipe that had an improperly cured epoxy coating and which was leaching benzene, toluene, ethylbenzene and xylene (BTEX) at levels of up to 300 ppb (Satchwill, 1998). This led to coupon testing of NSF and AWWA epoxy resins, which illustrated that tens of mg/L BTEX and hundreds of mg/L TOC were leached to water over a 72 hour exposure. Calgary then implemented their own testing, inspection and sampling program before putting any water main or reservoir into service. Other complaints of a “mothball” odor led to detection of more than 5,000 ppb polyaromatic hydrocarbons leached from a coal tar enamel in water. Other utilities could benefit by following the Ottawa example.
Leaching of a variety of organics from PVC pipe has long been of concern. These concerns found public support in June of 1992, when the Kansas Department of Health and Environment discovered up to 8.9 ppb vinyl chloride during a non-routine sampling of distributed water (Flourney et al., 1999). This event led to testing of the PVC pipe in question, which was determined to leach excessive vinyl chloride to water (up to 280–410 ppb) if temperatures were above 50°F, pipe was less than 2 inches diameter, water pipe contact times were more than one day, and pipes were manufactured using technology commonplace before 1977. Subsequent risk analysis based on vinyl chloride monitoring data collected from 1992–1998 (after more than 20 years of leaching from most of the PVC pipe in question) demonstrated that the leaching would still exceed a $10^{-4}$ cancer risk by both inhalation and ingestion routes over a lifetime exposure. Given this, it is somewhat perplexing we are not carefully monitoring vinyl chloride monomer within consumers’ homes.

Leaching of organotin and organolead stabilizers from PVC/CPVC should also be of greater concern. One occurrence study in Canada found organotin in drinking water samples taken from distribution systems with PVC pipes (Sadiki, 1998). That study included seven Canadian provinces and sampled the water at three points in the distribution system: influent to the water treatment plant, effluent from the water treatment plant, and at the point-of-use. The study was the first to show that organotin concentrations increased as they passed through the distribution system, and the researchers concluded that PVC pipes are a likely source of significant organotin in drinking water. Disturbing levels of organotin have recently been discovered in human blood and liver tissue (Takahashi, 1999). The United States Environmental Protection Agency (USEPA) has listed organotin on the Drinking Water Contaminant Candidate List (CCL). Alternative stabilizers such as Ca/Zn do not perform as well, but it appears that European pipe manufacturers are likely to go directly from organolead stabilizers in pipe directly to Ca/Zn stabilizers (Tullo, 2000). Lead stabilizers in PVC were scheduled for phaseout after December, 2003 (Greenpeace International, 2001).

Permeation of contaminants through plastic pipe from the local environment has caused more than 100 incidents of drinking water contamination in the US (Glaza and Park, 1992). In at least a few instances the level of drinking water contamination exceeded the benzene MCL by 100–260 times (Holsen et al., 1991). Understandably, permeation of contaminants has never been a problem for metallic pipe, and this is an important consideration in selection of materials.

**Overall waterborne disease and the distribution system**

According to one study and classification system, water distribution system deficiencies were the cause of 45% of all US waterborne disease outbreaks in community water systems since 1995 (Craun and Calderon, 2001). Moreover, close examination of the classification system itself as compiled by the Centers for Disease Control (CDC, 2002) suggest that the existing classification system is probably strongly biased towards finding failures with water treatment, as opposed to the newly acknowledged yet hard to detect public health risks such as intrusion, permeation and leaching described above. Specifically, to be classified as an outbreak, two or more people must become sick, and it cannot be from a specific source such as a single faucet – this eliminates sickness from first draw sampling. Likewise, it would be nearly impossible to trace a waterborne disease to intrusion or permeation, since this phenomenon could occur at any leak or plastic pipe in the system, is a transient event, and the hole cannot be directly examined. Also specifically excluded from consideration are the 4% of the US population relying on private water systems. These private systems are probably the least likely to treat their water to mitigate corrosion impacts, and therefore, could be more susceptible to problems with degrading
infrastructure noted above. Residents of private systems, who suffer from and otherwise meet criteria for a waterborne disease outbreak, might be surprised to learn that CDC “statistics exclude outbreaks associated with these sources because they are not intended for drinking and are not considered to be public water systems (CDC, 2002).”

Recent forward thinking articles summarizing the drinking water challenges for the US in the 21st Century have noted the poor state of public US drinking water infrastructure, the fact that 6–40% of gastrointestinal illness in the US and Canada may be water related, and recent data suggesting a link between carcinogens and disinfection (Levin et al., 2002). However, the authors do not even mention the issue of contaminant intrusion through holes in declining infrastructure, leaching of contaminants to water from modern plumbing materials, permeation, or the economic and public health challenges posed by private plumbing systems. This is further evidence that the most pressing issues related to potable water that are facing consumers are being totally overlooked, even in efforts expressly made to define such problems – those of us who study corrosion problems must take some responsibility for allowing these problems to remain essentially undetected.

**Our legacy to future generations: doing better**

“If a builder builds a house for a man and do not make its construction firm and the house which he has built collapse and cause the death of the owner of the house – that builder shall be put to death. If it cause the death of the son of the owner of the house – they shall put to death a son of that builder.”

*Code of Hammurabi, 2200 B.C.*

Though we live in a time of unprecedented prosperity, it is worthwhile to ponder whether we have become bankrupt of common sense. Given the enormity of the investment before us, it would seem obvious that every drinking water and wastewater pipe replaced in the years ahead should be designed to last for generations to come. And yet, we remain focussed on the cheapest, fastest, and lightest…not the best. Even in the public system where decision-makers are educated in the economics of such problems, we are installing pipe that may not withstand the test of time. In fact, there is a very good chance the very thin walled materials we are currently installing will not last as long as the thick grey cast iron installed by our forefathers in the 19th century. Highly respected materials scientists at US utilities lament the poor quality of the tube made available to them. The above quote from the King of Babylon today obviously could not be applied in the present, where firms can go bankrupt and escape legal liability for shoddy products and workmanship, but it does give us pause to consider our current short-sightedness in the 20/20 hindsight of our grandchildren.

Society has also long perceived corrosion problems as tolerable, and our profession has done little to change that mentality since the extraordinary costs of corrosion are somehow deemed unavoidable or acceptable (or overlooked completely). Members of the corrosion profession are largely ignorant of the basic processes that govern corrosion in water systems, their complexity, and range of environmental impacts. Indeed, contributions to fundamental understanding of internal drinking water corrosion from within organizations such as the National Association of Corrosion Engineers (NACE) are noteworthy only by virtue of their absence. However, the great corrosion scientist Evans at least elevated the “dirty” science of corrosion to relative respectability (Hoar, 1974). While respectable people have studied internal corrosion problems in drinking water, the study of corrosion and scaling is most certainly not yet respectable. Rather, our colleagues tend to view our endeavours in the same light as the general public:
“Plumbing is one of the easiest do-it-yourself activities, requiring only a few simple tools and a willingness to stick your arm into a clogged toilet.”

Dave Barry, 2000 in The Taming of the Screw.

The reality is that we have done little to change this perception. To the authors’ knowledge, no schools offer courses in corrosion engineering as applied to the field of water supply, and a comprehensive instructional textbook on the subject does not exist. This is inexcusable given the costs, future employment potential for students, and public health threats. Indeed, if anything is taught in the classroom at all, it is often principles discredited for more than a decade such as use of the Langelier index as a viable guide to corrosion control (AWWA, 1996). Fundamental change is obviously necessary, in many areas, if we are to leave a worthy legacy to future generations.

Acknowledgements

The author owes inspiration and wisdom to fellow corrosion researchers worldwide including Mark LeChevalier, Anne Camper, Laurie McNeill, Darren Lytle, Vern Snoeyink, Bob Ryder, Rhodes Trussell, John Ferguson, Steve Reiber, Gregory Korshin, David Nicholas, Russell Taylor, and especially Michael Schock. This work was supported by the National Science Foundation under grant BES-0223992: Towards a Sustainable Potable Water Infrastructure – Ecology, Aesthetics and Economics of Corrosion. The opinions, findings, conclusions, or recommendations are those of the author and do not necessarily reflect those of the National Science Foundation. Some ideas in this manuscript were previously presented at the Association of Environmental Engineering Professors Education and Research Conference in Toronto, Canada (2002), and during a keynote address at the Australasian Corrosion Association Annual Conference in Newcastle, Australia (2001).

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