

*The situation in Flint underscores the need for change in the handling of complex technological problems with high risk.*

# The Corrosion Crisis in Flint, Michigan

## A Call for Improvements in Technology Stewardship



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**T**he water contamination crisis in Flint, Michigan, vividly demonstrates that the current approach to technology stewardship in the face of problems that may lead to calamity is not working. Lessons often are tragically *not* learned or used during decision making.

A more proactive approach to technology stewardship, risk assessment, and public policy practice is recommended, drawing on lessons from previous experiences and supporting timely, data-driven decisions and actions by well-informed authorities. Without such cultural and behavioral change, there is the risk of repeating technological mistakes and encountering disasters again and again with enormous costs in public health and public trust and at great taxpayer expense (Koch et al. 2016).

This article suggests tools for anticipating and managing potential problems before they produce a calamity.

### **The Flint Water Crisis: A “Perfect Storm”**

The situation in Flint can be traced to the original decision to use lead piping and then a series of unfortunate choices and missed opportunities, starting with the switch to Flint River water followed by a failure to follow federally recommended corrosion control measures.

It has been noted that the location of the lead pipe in Flint’s water supply and distribution system cannot be readily ascertained. Documentation

of lead pipe use in the city is recorded on 45,000 index cards and stored in a public utility building, making it difficult to determine which end consumers are connected to lead pipe (Fonger 2015).

The city's drinking (potable) water supply was switched in 2014 from Lake Huron to the Flint River to save money while the city was under state emergency management (Adams 2014). The significantly more corrosive Flint River water chemistry caused faster lead release into the city's potable water as well as rampant iron corrosion (Edwards 2015a,b; Edwards et al. 2015). The iron corrosion led to brown water and may have helped to trigger the growth of *Legionella* bacteria via an established pathway (State et al. 1985).

In June 2015 an EPA memorandum to the Michigan Department of Environmental Quality (MDEQ) noted that maximum contamination levels for coliform were exceeded 5 times (Del Toral 2015). It pointed out violation of a federal guideline (the LCR<sup>1</sup>) based on high lead levels measured in selected Flint homes, and reminded the MDEQ of the requirement to provide corrosion control for all water systems serving more than 50,000 customers in order to limit lead release (Del Toral 2015).

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It appears, however, that the MDEQ was uninformed about LCR sampling guidance (40 USC. Sec 141.86<sup>2</sup>) and/or used questionable sampling methods to produce results that would not exceed the maximum

<sup>1</sup> In the 1991 Lead and Copper Rule (LCR) the EPA defined a maximum concentration for lead in water at an action level of 0.015 mg/L (15 ppb) (40 USC. Sec 141), although the EPA acknowledges that sampling techniques might “miss the worst case lead concentrations” in water (Edwards et al. 2015).

<sup>2</sup> 1996 Safe Drinking Water Act (SDWA) 42 United States Code (USC) §300f, Section 1417, Prohibition on Use of Lead Pipes, Solder, and Flux, p. 652.

lead levels requiring action. Practices alleged include the exclusion of samples with high lead, claims that the homes themselves (even those with plastic pipes) were the source of lead, and the flushing of faucets before lead sampling (Del Toral 2015; Edwards 2015c; Edwards et al. 2015). Independent lead sampling was criticized and its results even ridiculed as equivalent to “pulling a rabbit out of a hat” (Edwards 2015c). Two 6-month study periods were claimed to be necessary (Edwards 2015c).

The problems added up to a perfect storm of corrosive water, lack of corrosion control, and nonconservative water testing that failed to either detect or report the corrosion, and they were compounded by a classic series of calamity-related behaviors, described below (DemocracyNow! 2016; Eclectablog 2015; Erb 2015a; Hulett 2015).

### **Characteristics of Corrosion-Related Calamities**

What happened in Flint is typical of corrosion-related calamities such as those associated with Chinese drywall (CDW) and the San Francisco–Oakland Bay Bridge (SFOBB).

In the CDW case, the purchase order for the Taishan drywall company's product was reissued after removal of the requirement to meet an ASTM standard of lower sulfur levels after Taishan reported that it could not meet the standard (Fallon and Wilkinson 2010). In the SFOBB case, standards and journal papers warned of hydrogen embrittlement of high-strength zinc-coated alloys in water but were not heeded (Gorman et al. 2015). In all three cases, the calamity could be traced to fatal decisions in design, improper materials selection, failure to adhere to standards, denial or failure to recognize emerging problems, and missed opportunities to implement midcourse corrections.

Moreover, corrosion immunity is assumed or misunderstood (Scully 2015), and when a problem starts to become apparent, it is often met with denial that corrosion happens (Eclectablog 2015; Erb 2015b; Hulett 2015; Smith 2015), a focus on issues other than the root cause (Carmody 2015; Fonger 2014a), criticism of the whistleblowers who report corrosion or its consequences, misplaced emphasis on assigning blame instead of making improvements, begrudging and late admission of corrosion problems and recognition of the real cause, scapegoating of select individuals, and reactionary emergency funding, which often is not adequate and quickly evaporates (figure 1).

For the authorities and decision makers in Flint, adequate technical information was available about risks associated with lead pipe and water-based corrosion, together with lessons from previous incidents and standards-based guidance, to enable wise, data-based, informed decisions before the problem became a calamity. Yet *almost no opportunity was missed to miss an opportunity* for corrective action.

### Materials Used in US Public Water Systems

Over a million miles of pipes, treatment plants, water mains, and service lines in the United States connect water sources to points of consumption (e.g., homes, places of business). Pipes may be made of copper (Cu), galvanized steel, cast iron, or plastic (e.g., polyvinyl chloride, high-density polyethylene), but a large number are lead (Pb).

Installation of lead pipes in the United States began in the 1800s and continued into the 1900s in most major cities based on the justification that lead was malleable and lasted longer than cast iron from a corrosion standpoint (Brodeur 1974; Rabin 2008; Troesken 2006). Industry associations lobbied heavily for lead use. Yet concerns about lead in connection with drinking water have been known for centuries (e.g., Brous 1943; Hodge 1981; Troesken 2006). The decision to use lead has been called one of the most serious environmental disasters in US history (Troesken 2006).

Moreover, lead pipe and lead solder are often galvanically coupled to copper and iron piping, and much of the Flint distribution system is old unlined iron (Hu et al. 2012; Winkless 2016). Together with lead-tin solders used to connect pipes and leaded brasses or other copper

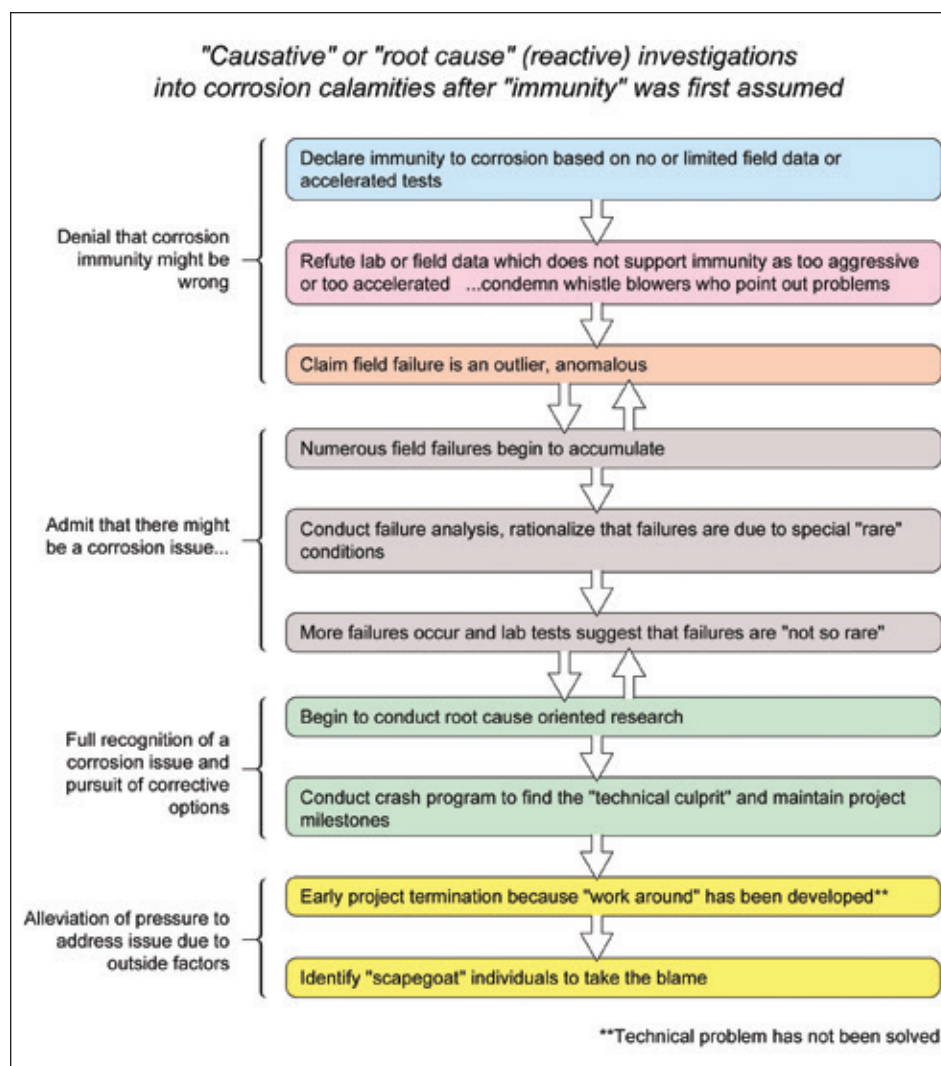


FIGURE 1 Flow chart depicting the stages of doubt and “corrective” actions often encountered during technology stewardship for an engineering problem involving a corrosion-related calamity.

alloys used in fittings and household fixtures, lead pipes are the main contributor to large amounts of lead contamination in drinking water all over the country (Paige and Covino 1992). A recent report identified almost 2,000 US water systems with lead, affecting up to 6 million people (Young and Nichols 2016).

Unfortunately, partial replacement of lead pipes has no health benefits (Triantafyllidou and Edwards 2011). The “upstream-downstream” transmission sequence of copper (service line) → lead (service line) → copper (pipe to house) after partial replacement can cause long-range deposition corrosion on lead across remaining lead pipes as well as galvanic corrosion of lead where copper and lead are in close proximity (St. Clair et al. 2012). Both can actually accelerate lead release.

## Corrosion

### *The Hidden Threat*

Corrosion often involves a time, age, or condition-based dependency that triggers problems down the road. The problems may be a function of poor engineering design, improper materials selection, poor upkeep, improper practice, and/or human error. The controlling factors and effects of corrosion are often hidden from public view and poorly understood.

The long time periods before corrosion problems become evident may lead to a false sense of security for technologists and officials until there is a serious problem. Also because of the long time dependency—and corresponding perception that the risk is not immediate—many managers defer allocation of resources to corrosion problems that cost much more to repair later.

The challenge for managers is an inability to (1) decide which technical issues can be deferred and which cannot, and (2) know what the return on investment will be from intervention before there is a problem.<sup>3</sup> Protection from known corrosion problems therefore often requires reliance on standards or best practices that must be followed faithfully and conservatively even if they are not understood. For this reason management of many complex corrosion issues has been distilled into easy to implement standards and practices, sometimes with justifications cited in the references at the back of such standards.

### *Lead Corrosion in Water*

Lead corrosion is typically anodically controlled and is governed by the insolubility and other attributes of the mineral scales and lead (II) corrosion deposits formed at the lead anode (Smith 1987). Anion content and ionic mobility are key. For example, lead sulfates are relatively insoluble while lead chlorides are soluble. Therefore, the chloride-to-sulfate mass ratio (CSMR) governs the intrinsic corrosion of lead and galvanic corrosion of lead to copper in water (Nguyen et al. 2011).

The lead corrosion rate also depends on the degree of water hardness. Hardness is caused by calcium and magnesium salts, which at levels >125 ppm can lead to the formation of deposits that can limit corrosion (Smith 1987). For soft waters, the lead corrosion rate depends on pH and oxidizers (e.g., O<sub>2</sub>, Cl<sub>2</sub>) and can be partially mitigated by CO<sub>2</sub> yielding bicarbonates and forming lead (II) carbonates, which also enjoy modest

insolubility (Smith 1987). It is often assumed that such scales are good enough to limit lead release.

Figures 2a and b indicate that protection against lead corrosion by formation of Pb(II) carbonate species is ineffective until a pH above 7. Cerussite (PbCO<sub>3</sub>) and hydrocerussite (Pb<sub>3</sub>(CO<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>) cannot reduce lead levels below 0.020 mg/L (the regulatory maximum) (Boffardi and Sherbondy 1991). Figure 2b shows thermodynamically stable soluble lead species at all pH levels even in the presence of these carbonate films. Lead is not recommended for use for components in soft potable waters (Smith 1987).

Cast iron mains can release iron when waters are corrosive and copper is deposited on iron (Hatch 1955), causing further deposition-induced galvanic corrosion of lead pipe downstream. Plastic pipe eliminates deposition corrosion and galvanic corrosion, but the self-corrosion of any remaining lead pipe in corrosive waters remains an issue (Hu et al. 2012).

Flint River water was 19 times more corrosive than Lake Huron water and contained over 8 times more chloride (Cl<sup>-</sup>), which increased the CSMR from 0.45 to 1.6 (Edwards et al. 2015); a CSMR of 0.77 or greater is reported to be highly detrimental (Nguyen et al. 2011). Moreover, the Larson ratio (a measure of iron corrosivity; Larson and Shold 1958) increased from 0.5 to 2.3 upon the switch to Flint River water (Edwards et al. 2015).

One doesn't have to be a corrosion specialist to raise the red flag here, especially when the local automobile manufacturers stopped using Flint River water owing to its corrosive effects on new metal auto parts (Fonger 2014b).

### *Regulations, Standards, and Research*

Standards developed by technical societies and standards-writing organizations represent the consensus guidance of many stakeholders including producers, end users, decision makers, and owners. Standards produced by nonprofit organizations such as the National Association of Corrosion Engineers (NACE International) are designed for the safe use of systems, corrosion control, and public safety.

Other standards and regulations result from government legislation.<sup>4</sup> The 1986 EPA Safe Water Drinking

<sup>3</sup> For discussion of approaches to return on investment, see Koch et al. (2016) and Jacobson (2016).

<sup>4</sup> Materials acceptance standards specify minimum properties for acceptance and should not be confused with those designed to safeguard against materials failures.



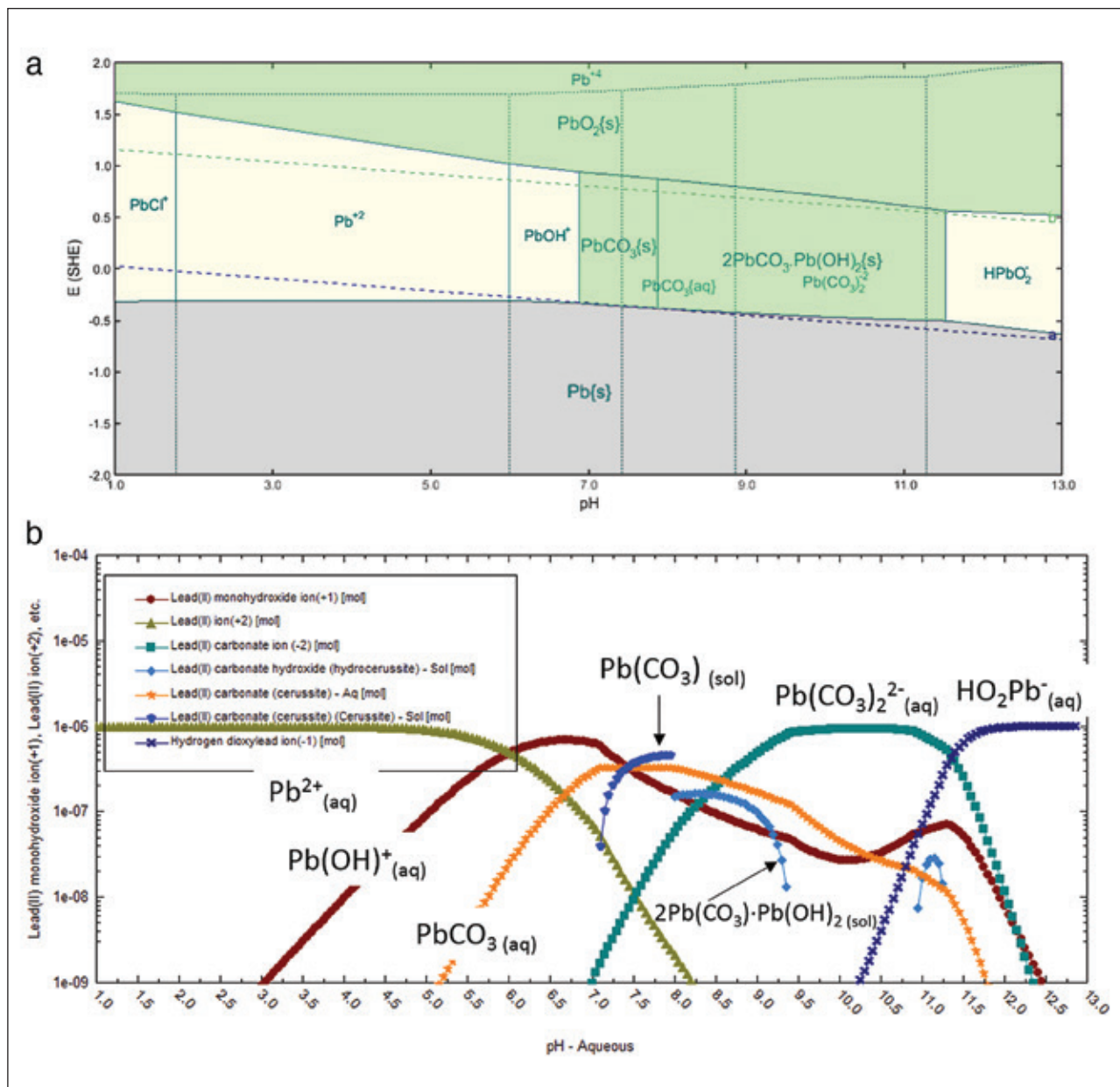


FIGURE 2 (A) E-pH equilibrium diagram for the Pb-H<sub>2</sub>O system showing the predominance of various lead species in the presence of carbonate. The vertical axis reports the electrochemical potential versus a standard hydrogen electrode (SHE). The horizontal axis is the range of solution pH. Green designates the region of stability of solid Pb oxides or compounds, cream represents the E-pH region for soluble Pb(II) stability, and grey shows the E-pH region for unoxidized Pb or immunity from corrosion. Most drinking water is at a bulk pH of 6–8. It can be seen that lead carbonate hydroxides may only protect over a narrow pH from about 7 to just over 11. During corrosion, Pb anode sites can become acidified to a lower pH. Assuming the pH may decrease from 6–8 to lower levels over time, it can be seen that lead carbonate hydroxides may not be protective to lead at lower pH levels. The conditions for the construction of the diagram were ambient air, [Pb] = 10<sup>-6</sup> molar, [CO<sub>3</sub><sup>2-</sup>] = .01 molar, and 25°C. (The equilibrium species depicted are unlikely to exactly represent all the metastable species present in real applications.) (B) Lead Pb(II) species stability diagram showing concentrations of various lead species as a function of pH. The vertical axis reports the electrochemical potential versus a standard hydrogen electrode. The horizontal axis is the range of solution pH. The concentrations assumed to construct the diagram were [Pb<sup>2+</sup>] = 10<sup>-6</sup> molar; [PO<sub>4</sub><sup>3-</sup>] = 0 molar; [CO<sub>3</sub><sup>2-</sup>] = .01 molar; open to the atmosphere. The ionic Pb<sup>2+</sup> concentration responsible for lead poisoning begins to decrease from very high levels at a pH of approximately 5.5 and falls to low levels at a pH of >8 in the presence of Pb(II) carbonate films. However, some dissolved species, such as Pb(CO<sub>3</sub>)<sub>2</sub><sup>2-</sup>, are thermodynamically stable. aq = aqueous or dissolved species; mol = molar; sol = solid.

Act (SWDA) prohibited use of materials that were not lead free. Although the act limits the use of lead pipes, solders, and fixtures in new installation or repair after June 1986, it left in place miles of lead pipe or solder that are vulnerable to corrosive waters and depend on chemical inhibitors.

But standards often are not considered, are misunderstood, or are “gamed” to avoid corrective action. Indeed, adherence to standards may simply seem excessively burdensome when the risks are not known or understood.

In addition to guidance from standards, much can be learned about corrosion problems from published information, new science, and previous experience (Scully 2015). Research on lead corrosion and release and on lead/copper galvanic corrosion issues in freshwater was published well before 2014 (Nguyen et al. 2011). Several notable articles warned of the dangers of lead corrosion and release as a function of water chemistry in fresh water and about the role of water chemistry in triggering lead release (Hu 2012; Nguyen et al. 2011; St. Clair et al. 2015).

Standards must be updated based on new science, but gaps persist in scientific knowledge. For instance, changes in the Pb release rate after complex sequence changes in water chemistry (e.g., intermittent or on/off orthophosphate treatment) are unknown, as are residual release rates under different scales and corrosion products as a function of water chemistry and deposit type (Gerke et al. 2016). Such information is of immense practical importance for the management of water systems with lead pipe.

### Water Chemistry and Treatment

Clean water is threatened by natural and anthropogenic factors such as drought, climate change, aging infrastructure, and, more specifically, higher  $\text{Cl}^-$  content in water due to rising sea levels and the use of road salts. Chloride and other factors also affect the corrosion of public water infrastructure components, further compromising water quality. In addition, the corrosiveness of drinking water sources differs around the world and can change with time, creating the risk that a dormant or low-level corrosion problem can be triggered by seemingly mundane changes in water chemistry (Nguyen et al. 2011; St. Clair et al. 2012).

Water chemistry control and the production of drinking water thus present complex tradeoffs: it is necessary to manage water hardness to prevent flow restrictions

due to excessive deposits, remove contaminants by treatments, add chlorine or chloramines to control biological toxins, and add lime or orthophosphates to limit lead corrosion. The efficacy of corrosion control must be monitored carefully.

Disinfectants like chlorine, whose use is justified given that contamination of drinking water can be fatal, are well-known electrochemical oxidants that provide a potent cathodic half-cell reaction that increases the corrosion rate of lead, steel, and copper (Ha et al. 2011; Jones 1996). Instead of recognizing and addressing the corrosion, officials in Flint added chlorination in an attempt to disinfect the water, significantly enhancing corrosion rates. The higher rates of iron corrosion, in turn, consumed the chlorine disinfectant and likely triggered the *Legionella* growth.

The need for orthophosphate as a chemical inhibitor to control lead corrosion is well known (Boffardi and Sherbondy 1991; Ha and Scully 2013). The protection provided by a covering lead orthophosphate film  $\text{Pb}_3(\text{PO}_4)_2$  ranges from about pH 4–6 to 11.5 (figure 3a). However, as the potential pH (figure 3a) and Pb(II) species stability (figure 3b) diagrams indicate, decreased  $\text{Pb}^{2+}$  thermodynamic stability above pH 4.5 is not equivalent to immunity to lead corrosion. Even when the dominant thermodynamic species over a range of neutral pH is solid  $\text{Pb}_3(\text{PO}_4)_2$ , there is still a nonzero equilibrium concentration of aqueous or dissolved  $\text{Pb}^{2+}$  (shown as  $\text{Pb}^{2+}$  and  $\text{Pb}(\text{OH})^+$ ) from about pH 3.5 to 12.5 (figure 3b) under the conditions explored.

The human tolerance level for lead is now recognized to approach zero (Edwards 2014). Therefore, while some hard waters and lime treatments can “passivate” somewhat (figures 2 and 3), this can hardly be a strategy for public safety. Corrosion inhibitors such as orthophosphate could have dramatically reduced the lead corrosion rate (Boffardi and Sherbondy 1991) in Flint and would reportedly have cost the state of Michigan about \$100/day (Gosk et al. 2016). But when the City of Flint switched from Lake Huron to Flint River water, corrosion control with orthophosphate was discontinued despite the river’s greater known corrosivity.

### Impact of Government Inquiries and Congressional Hearings

In the wake of calamities, federal hearings are often held to investigate and assess responsibility. But the impacts of these investigative efforts are variable. For example, the hearings and report of the Presidential

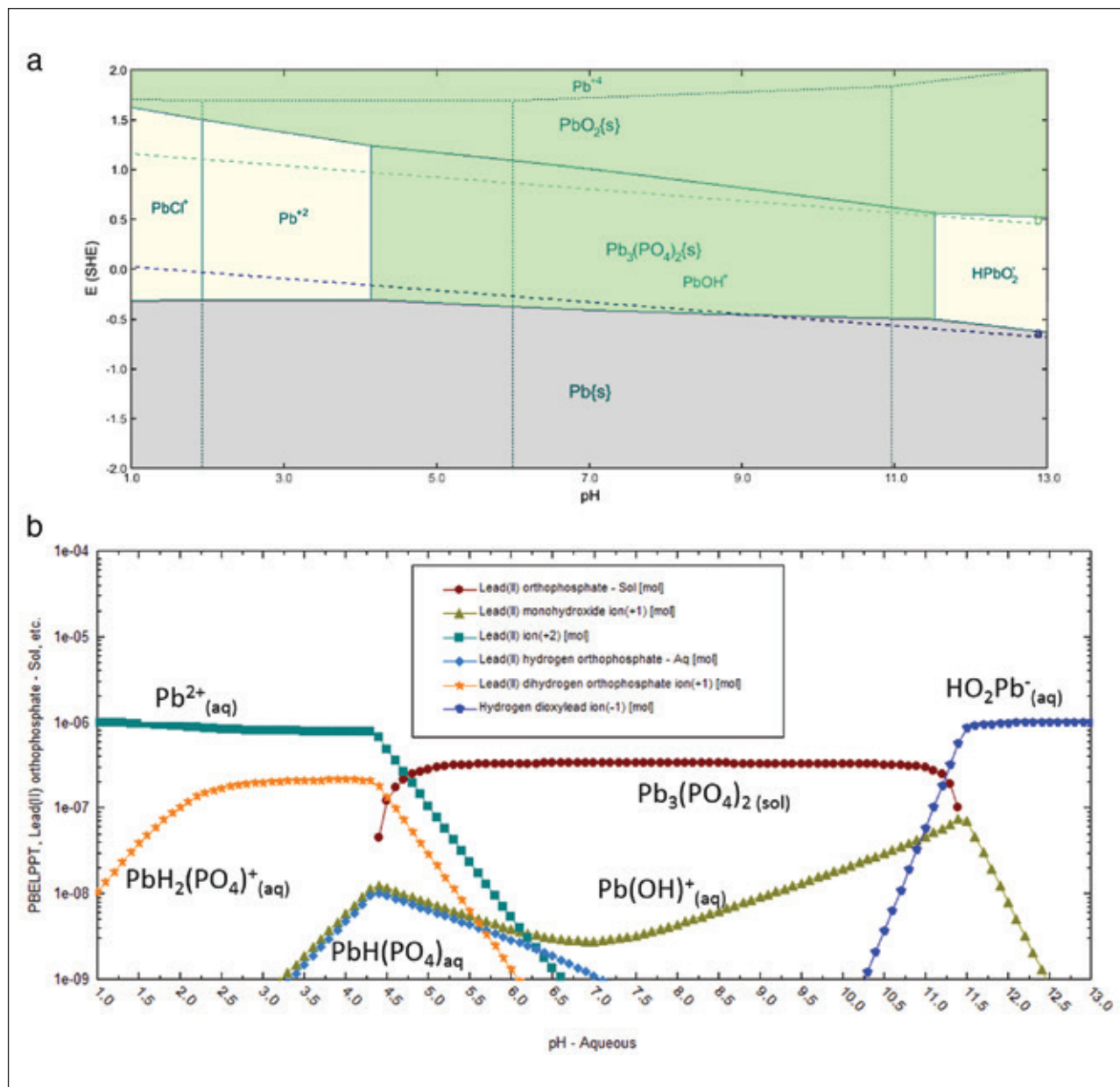


FIGURE 3 (A) E-pH equilibrium diagram for the Pb-H<sub>2</sub>O system showing the predominance of various lead species in the presence of phosphate. The conditions for the construction of the diagram were ambient air, [Pb<sup>2+</sup>] = 10<sup>-6</sup> molar, [PO<sub>4</sub><sup>3-</sup>] = .01 molar. Green designates the region of stability of solid Pb oxides or compounds, cream represents the E-pH region for soluble Pb(II) stability, and grey shows the E-pH region for unoxidized Pb or immunity from corrosion. Pb(II) phosphates shown in green are protective. (The equilibrium species depicted are unlikely to exactly represent all the metastable species present in real applications.) Most drinking water is at a bulk pH of 6–8, but Pb anode sites can become acidified over time to a lower pH. The Pb(II) phosphates are stable to a lower pH than Pb(II) carbonates. The range of protection by a covering lead orthophosphate film Pb<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> is about pH 4.5–11.5, illustrating the benefits of orthophosphate inhibitor over the pH range of 4.5–8 compared to natural carbonates. (B) Lead Pb(II) species stability diagram showing concentrations of various lead species as a function of pH. The species concentrations assumed to construct the diagram were [Pb<sup>2+</sup>] = 10<sup>-6</sup> molar; [PO<sub>4</sub><sup>3-</sup>] = .01 molar; [CO<sub>3</sub><sup>2-</sup>] = 0.0 molar; open to the atmosphere. The ionic Pb<sup>2+</sup> concentration responsible for lead poisoning begins to decline at a pH above about 4.5 and falls to low levels at a pH of >6.5 in the presence of Pb(II) phosphate films such as lead(II) orthophosphate. This illustrates the benefits of phosphate inhibitor over the pH range of 4.5–8 compared to natural carbonates. However, this treatment only reduces Pb(II) stability, indicating that some soluble lead will be thermodynamically stable even after use of a corrosion inhibitor. aq = aqueous or dissolved species; mol = molar; sol = solid.

Commission on the Space Shuttle *Challenger* Accident<sup>5</sup> in 1986 did not prevent the *Columbia* orbiter disaster in 2003<sup>6</sup> (NASA 2003; Rogers Commission 1986).

Congressional hearings on Flint may be just as ineffective. The issue was immediately politicized: the political right blamed the EPA while the left blamed the state of Michigan. Environmental racism was even suggested (House of Representatives Committee on Oversight and Government Reform 2016).

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## *Why are calamities not averted even after careful review of the root causes, actions taken, and missed opportunities?*

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Why are calamities not averted even after commissions carefully review the time line, root causes, actions taken, and missed opportunities? Hearings and commission reports do not change the *underlying culture, lack of understanding of risks, and habits* that lead to such calamities. Similarities between a current situation and past experiences are not recognized, time is limited, financial pressures exist, other problems clamor for attention, and complex technologies have massively parallel failure scenarios and many potential root causes.

During the March 2016 House of Representatives Oversight and Government Reform Hearing about the Flint Water Drinking Contamination Issue (2016), Michigan governor Rick Snyder said that the state would “try to learn from this mistake.” Indeed, *one of the main lessons from the Flint calamity is that past lessons were not learned.*

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<sup>5</sup> The Rogers Commission Report observed that lack of failure after each launch was taken as evidence of 0 percent risk of failure, an approach likened to a game of Russian roulette where each successful orbiter launch gave a false sense of security.

<sup>6</sup> NASA and contractors were said to have unjustified optimism. In its report on the *Columbia* space shuttle disaster the Columbia Accident Investigation Board listed over 1,000 paths in the fault tree analysis conducted after the fact, but noted that 33 foam strikes were dismissed as not critical to flight safety (NASA 2003).

### **Tools to Avoid Future Corrosion Calamities**

The path forward does not likely involve more standards and legislation. Ample evidence indicates the adequacy of standards in many cases, although customized standards may be needed when new technology, knowledge, or complexities emerge.

But technologists and policymakers may be too quick to rule out related standards that could help. Decision makers lack basic corrosion education to know when to seek expert advice. Technologists and public officials lack tools to weigh risks quickly rather than relying on lengthy studies.

Corrosion education is part of the solution, as identified in a recent study (NRC 2009). Managers can also benefit from a variety of accessible tools and resources that facilitate risk assessment and decision making, as explained in the following sections.

#### *Big Data*

One way to anticipate and manage potential corrosion calamities might be to implement the revolution occurring in biomedical data sciences using big data. Data on lead release could be collected in a database of drinking water systems covering a number of materials, water chemistry, corrosion inhibitor use, and physical variables as well as historical factors. Major advances in data integration, fusion, modelling, and analytics might be required. Technologists must be trained in methods to identify important trends in massive amounts of data. What are the common attributes of a water system experiencing high lead levels? Conditions that produce a likelihood of high lead release rates would become evident. A database with such information could be queried by decision makers and technology stewards, and the data could help avoid recurrence of Flint-type issues in other water systems. Reported experiences with lead pipe could yield data on water chemistry factors correlated with high lead releases.<sup>7</sup>

The Flint authorities might have thought that lead levels would decline over time of exposure. But a quick check of the proposed database would have revealed that there was no reasonable hope of a decline in lead levels sufficient to achieve less than 15 ppb given the

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<sup>7</sup> Use of big data is the opposite of computer prognosis and deterministic multiscale modelling; in the latter, governing laws and properties are known well enough to take inputs to prediction of lead levels through a quantitative scientific model. In big data the exact deterministic model is not known.



high corrosivity of the Flint River water and the high lead levels seen so far (Edwards 2015c).

### *Simulation*

Another tool would be a simulator game that outputs relative levels of lead release in water infrastructure (e.g., supply, treatment, plant, pump, distribution line, service line) under various scenarios. The simulation could also feature other parallel failure scenarios such as biotoxin release due to lack of disinfection.

The purpose is to illuminate sensitivities to various decisions and the risks (or consequences) of various actions (or inaction) by reporting the impacts of various scenarios. The player selects combinations of lead, copper, iron, and plastic pipe, and also picks water chemistries, disinfectants, and corrosion inhibitors. The resulting game gives a running concentration of lead and levels of biotoxins as a function of each factor. For instance, “superchlorination” might disinfect but lead release would become intolerable due to accelerated corrosion.

A similar tool to recognize the dangers of corrosion is *CorrSimulator* (Greenwood 2012), a DOD-funded online corrosion game in which the player acts as a plant manager to make corrosion-related decisions that have an impact on equipment operation and longevity. Even at this very simplistic stage such a lead risk assessment game is useful and important enough to be distributed to thousands of water utility managers. For example, the effects of the orthophosphate inhibitor would be immediately clear if programmed into the game. Technologists and policymakers could use these tools to anticipate and manage potential risks.

### *Systemic Sampling vs. Real-Time Online Sensing*

Cyberphysical systems are another new technology that could help. There is much uncertainty and error in manual lead sampling. Such sampling could be automated with thousands of lead sensors at many points in a water system as part of a smart cities initiative. Data would ideally be acquired by computers and sent to decision makers. Why wait for a 6-month study via batch analysis of lead concentration? Sample in real time, send wireless data, and observe the downstream consequences of actions in upstream water management.

Progress is required in sensing, communication, energy harvesting, low-power electronics, and data analysis.

### *Financial Management*

Corrosion management financial tools (perhaps with a health assessment or public safety risk calculator) are desperately needed so that a compelling case can be made about the benefits of corrosion control (Jacobson 2016; Koch et al. 2016).

With these tools, beleaguered technologists and policymakers might be able to make a more compelling argument to decision makers in a timely manner about the need for corrosion control so that action can be taken and calamities averted.

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