How Lead Ended Up In Flint's Tap Water

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When Virginia Tech researchers tested the water in LeeAnne Walters's home in Flint, Mich., this past summer, one sample had lead levels that reached a staggering 13,200 parts per billion.

That's almost 900 times as high as the 15-ppb regulatory limit set by the Environmental Protection Agency. When lead levels exceed that threshold, water utilities must act to reduce concentrations of the toxic element.

"What was so scary about LeeAnne's house was not one sample," says Marc A. Edwards, the Virginia Tech environmental engineer who led the team. "We took 30 samples over 20 minutes, and the average was over 2,000 ppb. And even after 20 minutes of flushing, it never got below 300 ppb."

In terms of sustained high levels of lead in a home, Edwards had seen nothing like it before. "It was in a league of its own."

Lead contamination is the most troubling in a series of water problems that have plagued Flint since the summer of 2014. All of them were caused by corrosion in the lead and iron pipes that distribute water to city residents. When the city began using the Flint River as its water source in April 2014, it didn't adequately control the water's ability to corrode those pipes. This led to high lead levels, rust-colored tap water, and possibly the growth of pathogenic microbes.

Flint isn't the only city susceptible to these problems. The pipes in its old distribution system had seen the same water for decades. Switching water supplies in 2014 changed the chemistry of the water flowing through those pipes. When a switch like this happens, the water system is going to move toward a new equilibrium, says Daniel Giammar, an environmental engineer at Washington University in St. Louis. "It could be catastrophic as it was in Flint, or it could be a small change."

Before 2014, Flint was getting its water from the Detroit Water & Sewerage Department, which would draw water from Lake Huron and then treat it before sending it to Flint. Looking to lower the city's water costs, Flint officials decided in 2013 to instead take water from the Karegnondi Water Authority, which was building its own pipeline from the lake. Shortly after that, Detroit told Flint it would terminate their original long-term water agreement within a year and offered to negotiate a new, short-term agreement. Flint declined the offer. As an interim solution, while waiting for the new pipeline to be finished, Flint began taking water from the Flint River and treating it at the city's own plant.

Problems with the city's tap water started the summer after the switch. First, residents noticed foul-tasting, reddish water coming out of their taps. In August and September, the city issued alerts about Escherichia coli contamination and told people to boil the water before using it. A General Motors plant stopped using the water in October because it was corroding steel parts. In December, the Michigan Department of Environmental Quality notified Flint that its water was in violation of national drinking water standards because it contained high levels of trihalomethanes, toxic by-products of chlorine disinfection.

Then, in early 2015, reports of high lead levels started making news. In January, it was Flint's University of Michigan campus; in February, it was the Walters home.

By early September, Edwards and his Virginia Tech team had sampled water from 252 homes and reported on their website, flintwaterstudy.org, that the city's 90th percentile lead level was 25 ppb. EPA's action limit is based on a 90th percentile calculation, meaning that if 10% of homes exceed the agency's 15-ppb threshold, then action is required.

That same month a team led by Mona Hanna-Attisha, a pediatrician at Hurley Children's Hospital, in Flint, released data showing that the number of Flint children with elevated levels of lead in their blood had increased since the water change. The percentage of affected kids went from 2.4% to 4.9%, according to a paper they published recently (Am. J. Public Health 2016, DOI: 10.2105/ajph.2015.303003). In areas with the highest lead concentrations in the water, about 10% of the children had elevated blood levels of the element. Lead is neurotoxic and can disrupt children's development, leading to behavioral problems and decreased intelligence.

With evidence of lead contamination mounting, Flint switched back to the Detroit water in October.

So why did the switch to Flint's river water cause this catastrophe?

To understand the problem, consider that as water travels through the miles of pipes in a city's distribution system, molecules in the water react with the pipes themselves. "The distribution system acts like a geochemical reactor," says Haizhou Liu, an environmental engineer at the University of California, Riverside. "There are miles and miles of pipes—some iron, copper, and lead—that get corroded." This corrosion occurs when oxidants, such as dissolved oxygen or chlorine disinfectant, react with elemental iron, lead, or copper in the pipes.

Cities no longer install lead pipes. But older cities such as Flint still rely on them, usually as service lines that connect water mains in the street to a home's water meter. A 1990 report from the American Water Works Association estimates there are millions of lead service lines in the U.S. To limit how much lead leaches into the water from these pipes and some homes' plumbing, EPA's Lead & Copper Rule requires water utilities serving more than 50,000 people to establish a plan to monitor and control corrosion.

As part of these plans, utilities treat their water to maintain a mineral crust on the inside surfaces of their pipes. This so-called passivation layer protects the pipes' metal from oxidants in the water. The coatings consist, in part, of insoluble oxidized metal compounds produced as the pipe slowly corrodes.

If the water's chemistry isn't optimized, then the passivation layer may start to dissolve, or mineral particles may begin to flake off of the pipe's crust. This exposes bare metal, allowing the iron, lead, or copper to oxidize and leach into the water.

Environmental engineers that C&EN contacted say that, on the basis of how Flint treated the river water, the water chemistry was not optimized to control corrosion.

Most important, the treated Flint River water lacked one chemical that the treated Detroit water had: phosphate. "They essentially lost something that was protecting them against high lead concentrations," Giammar says. Cities such as Detroit add orthophosphate to their water as part of their corrosion control plans because the compound encourages the formation of lead phosphates, which are largely insoluble and can add to the pipes' passivation layer. By press time, C&EN was unable to get a comment from Flint city officials about why a corrosion inhibitor wasn't added to the river water.

The entire Flint water crisis could have been avoided if the city had just added orthophosphate, Edwards says. He bases his opinion, in part, on experiments his group ran on the treated Flint River water. The researchers joined copper pipes with lead solder and then placed the pieces in either treated Flint River water or treated Detroit water. After five weeks in the Flint water, the joined pipes leached 16 times as much lead as those in the Detroit water, demonstrating just how corrosive the treated Flint water was. But when the scientists added a phosphate corrosion inhibitor to the Flint water, the factor went down to four.

Still, orthophosphate isn't the only corrosion solution. Some water utilities treat water so it has a high pH and high alkalinity, Giammar says. Such conditions decrease the solubility of lead carbonates, which also contribute to the pipe's protective mineral layer.
The treated Flint River water had a relatively low pH that decreased over time. According to monthly operating reports from the Flint treatment plant, the city's water had a pH of about 8 in December 2014, but then it slowly dropped to 7.3 by August 2015. Environmental engineers say that if water pH drifts too low in the absence of orthophosphate, the water can start to leach high levels of lead from pipes.

The pH drop over time seems to indicate that plant operators in Flint didn't even have a target pH as part of a corrosion plan, Edwards says. Water utilities usually find a pH that's optimal for preventing corrosion in their system. For example, in Boston, another city with old lead pipes, average water pH held steady around 9.6 in 2015, according to reports from the Massachusetts Water Resources Authority. By press time, C&EN wasn't able to get a comment from Flint city officials about whether they had a target pH for the water.

Another chemical factor that contributed to the treated river water's corrosiveness was its chloride concentration. The treated Detroit water's average chloride level was 11.4 parts per million in 2014, according to an annual water quality report from the Detroit Water & Sewerage Department. Meanwhile, the treated Flint water had 85-ppm chloride in August 2015, according to a monthly operating report from the Flint treatment plant. The plant may have contributed to these high levels when it tried to address high levels of toxic trihalomethanes.

Disinfection by-products such as trihalomethanes can form through reactions between organic matter in water and chlorine disinfectant added at treatment plants. The Flint plant had increased the amount of chlorine it used in the summer of 2014 to combat the E. coli contamination problem. To reduce levels of trihalomethanes that formed, the plant removed organic matter from the water by adding ferric chloride, which coagulates organic matter, making it easier to filter out. Even though the treatment took care of the trihalomethanes problem, it increased the water's chloride levels.

Environmental engineers worry about high chloride levels because studies have shown that lead corrosion is more likely when the ratio of chloride to sulfate concentrations is greater than 0.58. Researchers at Virginia Tech calculated the ratio for treated Detroit water as 0.45 and for treated Flint River water as 1.6.

Corrosion of lead pipes caused Flint's most serious water issue, but corrosion of the city's iron pipes also created problems. The chemistry that controls iron pipe corrosion is a little more complicated than the chemistry surrounding lead pipe corrosion, but some of the same factors play a role.

Problems with Flint's iron pipes started early: The rust color and bad taste of the water coming out of residents' taps in the summer of 2014 was a sign that the passivation layer on iron pipes was dissolving into the water.

But the issue that worries environmental engineers most about iron corrosion is that it could encourage the growth of pathogens in the distribution system. As the mineral layer in iron pipes falls off, it exposes bare iron that can reduce free chlorine added to the water as a pathogen-killing disinfectant. Walters's home—the one with lead levels that were almost 900 times as high as the EPA limit—had no detectable chlorine levels over 18 days of monitoring by the Virginia Tech team.

Susan J. Masten, an environmental engineer at Michigan State University, points out that the Flint water distribution system has another issue that could have worsened both the corrosion and disinfection problems. Much of the distribution system was built when the city's population was about 200,000 and Flint was a major manufacturing center. But the city now has less than half the population, and much of the industry, which used a lot of Flint's water, has left town. As a result, water usage has dropped significantly, while the system's capacity has remained the same.

"That means water is residing in the distribution system for very long periods of time," Masten says. In some places, the water sits in pipes for more than six days before use, providing more time for reactions that corrode pipes and break down chlorine.

Although they acknowledge that they won't ever be able to directly prove it, the Virginia Tech researchers think that the E. coli contamination in 2014 could have been due to problems with maintaining sufficient chlorine levels in the water. Bolstering their case are two outbreaks of Legionnaires' disease, a waterborne respiratory infection caused by Legionella bacteria, in and around Flint—one starting in June 2014, and another in May 2015.

Now that Flint has switched back to the Detroit water, it may take months to a year for pipes to regain their passivation layers, for corrosion to slow to normal levels, and for lead concentrations to drop back into an acceptable range, say the environmental engineers that C&EN contacted. The lesson from Flint, they say, is to continually monitor water chemistry, especially when switching between water supplies.

"What we learned here is when we collect data, we need to use those data," Masten says. She points out that the water utility officials were already collecting all the data they needed—pH, alkalinity, chloride levels—to determine if the water was too corrosive.

"Learning from Flint, I think the key message is to consider the connections between the stability of the water infrastructure and the chemistry of the water flowing through that infrastructure," UC Riverside's Liu says. "That will inevitably control the water quality at the tap."