PUBLIC WATER SUPPLIES: PROPOSED NEW
35 ILL. ADM. CODE 604
R2018-017 (RULEMAKING – WATER)

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STATE OF ILLINOIS
Pollution Control Board

PRE-FILED TESTIMONY
SUBMITTED BY:

Capt. Michael D. Curry, P.E.
As an individual
803 South Paul Street
Nashville, IL 62263
Work Ph. 618-327-8841
mcurry@curryassociates.com

SUBMITTAL DATE: 14 OCTOBER 2017

A summary statement of my qualifications and experience is attached.

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Preface

I have referenced temporary page numbers for Part 604 for my convenience.

PART 604
DESIGN, OPERATION AND MAINTENANCE CRITERIA

General Comment 1

Definitions are not provided for terms contained in this part; addition of definitions would be helpful to the public entities that will be using this part for guidance.

General Comment 2

Traditionally, the Board's regulations have used the term "shall" for mandatory compliance items and the term "should" for recommendations.

This part departs from the traditional format, and frequently uses the term "must".

604.105 (d) 3) (Curry temporary page no. 5)

… duplicate units for water treatment facilities must be provided … when treatment unit is installed … for … removal of carcinogenic volatile organic compounds.

Question:

East Alton, Illinois has a single aerator and intermittently detects troublesome concentrations of regulated VOCs (volatile organic chemicals). Will East Alton be required to install a second aerator?

604.120 (Curry temporary page no. 6)

… piping identification …

Respectfully recommend that use of painted labels be permitted.

Many existing plants do not use color coding, and the individual pipes bear painted labels identifying the contents.

I personally know Water Operators that are "color blind"; color-coding of piping may cause those persons to not correctly identify pipes and contents?

Questions:

If this proposed requirement remains "as-is", will existing plants that use painted labels be required to re-paint and color code all piping?

If re-painting is required to comply with this proposal, would the Board and Agency grant at least a 12 month grace period to accomplish the re-painting?

604.130 (c) (Curry temporary page no. 9)

… measuring chlorine residual …

Respectfully recommend add additional requirements for systems that use chloramines for disinfection and as a secondary disinfectant: "… test equipment to measure free chlorine residual, total chlorine residual, monochloramine residual, dichloramine, free Ammonia-N, total Ammonia-N (including reagents to dechlorinate samples containing chloramines)."

It is essential that systems using chloramination have the capability to speciate the form and concentration of the chloramine residuals, and to be able to analyze products of chloramine decay in distribution systems (i.e., dichloramine, ammonia or ammonium); measurement of Ammonia-N in raw water is required to select the correct Ammonia or Ammonium dosage to form monochloramine; measurement of total and free Ammonia-N is necessary to monitor the treatment process and distribution system to minimize potential for nitrification … and to help identify water quality parameters if nitrifying bacteria are present.

Dichloramine concentration can be determined with an amperometric titrator. Otherwise, dichloramine can be estimated using the following relationship:

mg/L dichloramine = mg/L total chlorine residual – (mg/L free residual + mg/L monochloramine)

604.130 (d) (Curry temporary page no. 9 and 10)

At (2) … Respectfully recommend re-phrase: "iron removal – test equipment for measuring ferrous and total iron".

Effectiveness of conventional iron removal processes relies upon oxidation of ferrous iron (Fe^{+2}) to ferric iron (Fe^{+3}). Process monitoring should include the capability to measure the "un-oxidized" ferrous iron. Ferrous iron is soluble and will not be removed with filtration; ferric iron is insoluble and can be removed with filtration.

(Ferrous and total iron testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

Total iron = ferrous iron (Fe^{+2}) + ferric iron (Fe^{+3})

At (3) …Respectfully recommend add equipment for measuring CHLORIDE.

Cation exchange softeners use sodium chloride to regenerate the ion exchange resin. The sodium is "exchanged" with the divalent metallic cations (calcium and magnesium) to accomplish softening, and the Chloride remains in solution. The fast rinse and slow rinse portions of ion exchange resin regeneration cycle remove excess Chloride. If excess Chloride is not 100% removed from cation exchange vessel, Chloride concentration is increased in treated water and corrosivity of the water would increase.

(Chloride testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

At (4) … Respectfully recommend add Nitrite-N to list of parameters.

MCL for Nitrate-N is 10 mg/L; MCL for Nitrite-N is 1 mg/L; MCL for Nitrate-N plus Nitrite-N is 10 mg/L; if nitrification is occurring, the Nitrite-N is formed first, followed by oxidation of Nitrite-N to Nitrate-N. In most instances, concern about Nitrite-N formation is out in the distribution system. The capability to measure Nitrite-N is necessary to assure that the MCL is not exceeded.

(It will be necessary to have the capability to monitor for Nitrite-N and Nitrate-N to comply with the NAP (Nitrification Action Plan) proposed at 604.140.)

(Nitrite-N and Nitrate-N testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

At (4) … <u>Respectfully recommend eliminate "alkalinity" and replace with "total and phenolphthalein["P"] alkalinity forms."</u>

The coagulation process is affected by the type of metal (aluminum and iron are most common) coagulant used, and their effectiveness is dependent upon pH and the form of alkalinity.

(Total and phenolphthalein ["P"] alkalinity testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

(Please, also see (5) below.)

At)(4) … <u>Respectfully recommend adding "Total and Insoluble Aluminum" to list of parameters.</u>

At plants using coagulants that contain aluminum (particularly aluminum sulfate, colloquially referred to as alum), if coagulation occurs outside the pH zone of least solubility for aluminum, there is potential for soluble aluminum to pass through the filters and precipitate in solid form (aluminum hydroxides) after filtration and increase turbidity of the filtered water to the extent that the turbidity MCL may be exceeded. This actually occurred at Hillsboro, IL and resulted in a prolonged citywide boil order … which could have been prevented if the plant had checked for aluminum in the filtered water.

If soluble aluminum passes through the filters, it is likely to precipitate in the distribution system and appear in the form of "white floc particles" which is objectionable and can cause the public to mistrust the safety of the water.

If soluble aluminum passes through the filters and orthophosphate is used as a corrosion inhibitor, it can result in detrimental scale formation in treated water mains. (DuPage County Water Commission experience?)

AWWA and others recommend that total aluminum not exceed 0.05 mg/L in drinking water.

(Aluminum testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

(Soluble aluminum can be measured by first passing the sample through a 0.2 micron membrane filter using commercially available equipment for this procedure.)

At (5) … Respectfully recommend eliminate "alkalinity" and replace with "total and phenolphthalein alkalinity forms." (It is important to be able to differentiate forms of alkalinity.)

When total and phenolphthalein alkalinity values are known, the specific forms of alkalinity can be identified (bicarbonate, carbonate, hydroxide) … and the chemical precipitation softening processes are directly related to the form of alkalinity present within known pH ranges.

Alkalinity is "buffering capacity" or "resistance to change in pH". Alkalinity is expressed as equivalent to $CaCO_3$ (Calcium Carbonate) since its molecular weight is 100 and simplifies calculations.

Alkalinity is comprised of:

HCO_3	bicarbonate	(when pH is below 8.3, all alkalinity is bicarbonate)
CO_3	carbonate	(pH must be above 8.3 for carbonate to be present)
OH	hydroxide	(pH must be above 9.3 for hydroxide to be present)

At lime softening plants, the Operator typically tests for "P" (phenolphthalein) alkalinity and for "Total" alkalinity.

The indicator solution for "P" alkalinity is phenolphthalein; pH at endpoint of titration is 8.3.

The indicator solution for "Total" alkalinity is bromcresol green. pH at endpoint of titration is:

4.9	if alkalinity is 30 mg/L as $CaCO_3$
4.6	if alkalinity is 150 mg/L as $CaCO_3$
4.3	if alkalinity is 500 mg/L as $CaCO_3$

pH at endpoint is often taken as 4.5 for routine analyses.

Alkalinity Relationships

Result of Titration	Hydroxide Alkalinity As $CaCO_3$	Carbonate Alkalinity As $CaCO_3$	Bicarbonate Alkalinity As $CaCO_3$
P = 0	0	0	T
P < ½ T	0	2 P	T – 2 P
P = ½ T	0	2 P	0
P > ½ T	2 P – T	2 (T – P)	0
P = T	T	0	0

(Total and phenolphthalein alkalinity testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

At (9) … ***Respectfully recommend eliminate "hardness" and replace with "calcium hardness and total hardness, expressed as calcium carbonate".***

Calcium hardness (as $CaCO_3$) is used in calculations to determine Calcium Carbonate Precipitation Potential … used to estimate the tendency of water to form or dissolve calcium carbonate scale; excessive scale formation can clog piping and household plumbing systems; an acceptable amount of scale can help to prevent "red water" problems associated with corrosion of iron piping materials.

(Calcium hardness and total hardness testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

At (9) … Respectfully recommend add "temperature".

Temperature is used in calculations to determine Calcium Carbonate Precipitation Potential… used to estimate the tendency of water to deposit, or dissolve, calcium carbonate scale. Please see preceding item.

At (9) … ***Respectfully recommend adding Chloride and Sulfate to list of parameters.***

Marc Edwards [Virginia Tech] et al. has documented the importance of the Chloride:Sulfate ratio with respect to corrosivity. (Mark Edwards and Simoni Triantafyllidou (July 2007) "Chloride to sulfate mass ratio and lead leaching to water", Journal AWWA (Peer Reviewed).

Edwards article @ ATTACHMENT 1.

USEPA has documented that the Chloride:Sulfate Mass Ratio (OCSMR) is an important parameter in evaluating potential for lead release into water. (USEPA Office of Water (March 2016) Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, (EPA 816-B-16-003; Office of Water (4606M)).

The Larson-Skold "The Larson-Skold index was developed to evaluate the potential for the corrosion of cast-iron pipes transporting water from the Great Lakes." (Roberge 2006, cited at Masten et al., 2016). *Chloride and sulfate concentrations are required (in addition to alkalinity) to calculate this index.* **This index was used to analyze and explained the reasons for water discoloration at Flint, MI during the lead crisis**. (Masten et al.)

Masten article @ ATTACHMENT 2.

Larson-Skold Index information @ ATTACHMENT 3.

Larson & Skold (1957) T.E. Larson, and R.V. Skold, "Corrosion and tuberculation of cast iron", Journal AWWA, 49(10), 1294-1302.

Larson & Skold (1958) T.E. Larson, and R.V. Skold, "Laboratory studies relating to mineral water quality of water to corrosion of steel and cast iron", Corrosion, 14(6), 285-288.

Masten et al.(2016) Susan Masten, Simon H. Davies, and Shawn P. McElmurry "Flint Water Crisis: What Happened and Why", Journal AWWA, 108.12, December 2016. ATTACHMENT 2

> Roberge (2006) P. Roberge, "Corrosion Inspection and Monitoring", s.I., Wiley Online Library (cited at Masten et al., 2016).

Respectfully recommend add:

(10) manganese removal – test equipment for measuring the concentration of total Manganese and soluble Manganese.

Many groundwater and surface water supplies operate treatment processes to remove Manganese, which causes discoloration of water and staining of laundry and plumbing fixtures. Manganese has now come to the forefront as a potential public health concern.

Successful operation of Manganese removal processes depends on measurements of total and soluble Manganese.

AWWA and others recommend that total Manganese not exceed 0.05 mg/L in drinking water.

(Manganese testing methods are contained in "Standard Methods" and equipment and reagents are commercially available.)

(Soluble Manganese can be estimated* by first passing the sample through a 0.2 micron membrane filter using commercially available equipment for this procedure.)

> * Manganese dioxide (insoluble) is colloidal and the majority is retained on a 0.2 micron membrane filter, and it is presumed that Manganese in the filtrate represents the "soluble" fraction not oxidized/removed in the treatment process. Many Water Operators successfully employ filtration with 0.2 micron membrane filter as a process monitoring technique; the academic community uses "molecular scale" filtration – which is not considered practical for most water treatment plants.

Respectfully recommend add:

(11) "treatment with chlorine dioxide – equipment for measuring chlorine dioxide residual and chlorite ion concentration."

Other regulatory guidance limits chlorine dioxide residual to 0.8 mg/L. There is a 1.0 mg/L MCL for chlorite ion … so monitoring is necessary.

Question:
Perhaps this provision would better be incorporated at (c)?

604.135 (d) (Curry temporary page no. 12)

… Emergency Operations Plan …

Question:
Are "templates" available from IEPA, USEPA, or any other source? Many small systems do not have in-house staff capable of writing this type of plan. If the Agency and/or Board desires specific content, would it be possible to include a sample "table of contents" for the plan?

The concept of having an Emergency Operations Plan is in the best interest of the public, but the logistics are daunting for preparation of individual plans for approximately 1700 individual systems in Illinois. Small systems in particular could benefit from additional guidance.

604.140 (a) (Curry temporary page no. 12)

… Nitrification Action Plan …

Question:
Will "consecutive systems" that purchase treated water from another source be required to comply with 604.140? Please, can a clarification be added?

TKN (Total Kjeldahl Nitrogen) = Ammonia-N + Organic N

Question:
Anticipate that there is no TKN data for Illinois community water systems? If Organic N is present, it may pose water quality problems? And, if it is present, but not monitored, the nitrogen balance may be inaccurate?

An annual test for TKN could be beneficial … to determine if organic N is present.

At (a) … respectfully recommend re-phrase as follows, with addition of total ammonia (after dechlorinating samples containing chloramines) and dichloramine.

"a) contain a plan for monitoring total Ammonia-N, free Ammonia-N, Nitrite-N, Nitrate-N, monochloramine residual, dichloramine residual, and total chlorine residual."

Performing a nitrogen balance can be useful in evaluating occurrence of nitrification in water distribution systems, and it is necessary to know total Ammonia-N concentration. In surface waters, Nitrate-N concentration can vary in source water with subsequent treated water Nitrate-N variation in distribution systems. Monitoring of Nitrate-N is nevertheless important.

Total Nitrogen = Ammonia-N + Nitrite-N + Nitrate-N + (0.27 x monochloramine residual)

Expressing nitrogen compounds in terms of "N" equivalence is conventional in the field. The MCLs for Nitrite-N and Nitrate-N are expressed as "N" equivalents.

As chloramine residual decays, Ammonia-N (and Ammonium-N) is released into the water. As nitrification progresses, oxidation of Ammonia-N occurs and the Ammonia-N concentration decreases. IT IS CONSIDERED ESSENTIAL TO MONITOR TOTAL AMMONIA-N IN ADDITION TO FREE AMMONIA-N TO IDENTIFY NITRIFICATION OCCURRENCE.

Nitrification is also accompanied by:

- ✓ Alkalinity decrease.
- ✓ pH decrease.
- ✓ D.O. (dissolved oxygen) decrease (and even depletion in some cases) due to oxygen uptake by the Ammonia and Nitrite oxidizing bacteria.

Decay of chloramine residual and D.O. concentration decrease will be accompanied by a decrease in ORP (Oxidation Reduction Potential) … which can potentially increase potential for leaching of lead from solder, lead service lines, and plumbing materials that contain lead.

In critical chloramine decay and/or nitrification circumstances, it will be advisable to monitor alkalinity (with a high degree of accuracy), pH, D.O., and ORP … and increased monitoring for lead may be necessary in sensitive systems.

Rationale for monitoring dichloramine
The NAP requires monitoring for total chlorine residual and monochloramine residual. If they are not equal, then dichloramine is present.

Total chlorine residual = free residual + combined residual

Combined residual = monochloramine + dichloramine + trichloramine
(gaseous nitrogen trichloride)

The difference between total residual and monochloramine residual will consist of dichloramine.

The following information is from: Russell et al. (2017) "Practical Considerations for Implementing Nitrosamine Control Strategies", (Peer Reviewed), Journal AWWA; Caroline G. Russell, Richard A. Brown, Katie Porter, and David Reckhow; June 2017 – 109:6. ATTACHMENT 4.

"USEPA included five nitrosamines on the fourth Contaminant Candidate List and also considered nitrosamines (including N-nitrosodimethylamine [NDMA] as part of the third Six-Year Review of the Microbial and Disinfection Byproducts (M/DBP) regulations (USEPA 2016). If the USEPA decides to regulate nitrosamines, affected water systems will need to explore strategies to reduce concentrations in their finished water and in their distribution systems. More than one out of every 10 chloraminated water systems could be affected by an NDMA MCL equivalent to the current California notification level of 10 mg/L (Russell et al. 2012).

NDMA, the nitrosamine detected most frequently in drinking water, is a chloraminated disinfection by-product (DBP) that forms from reaction of dichloramine with amine-based precursors (Schreiber & Mitch 2006).

Nitrification in the distribution system could also contribute to NDMA formation in the distribution system. (Zeng & Mitch 2016)."

Nitrification in the distribution system can cause decay of monochloramine residual … resulting in formation of dichloramine.

Dichloramine is objectionable because it reacts with precursors to form NDMA … a known carcinogen … which is under consideration for regulation by USEPA.

Nitrosamines and/or NDMA are not yet regulated by USEPA, but a proactive approach is recommended … to minimize formation of dichloramine. Dichloramine should be measured.

With respect to the NAP … TCEQ (Texas Commission on Environmental Quality) has published extensive guidance documents and a template for use by systems in Texas that are required to create a NAP. TCEQ has granted permission to use their documents so long as TCEQ is identified as the source. Until such time that Illinois develops its own guidance documents and templates, it is recommended that community water supply systems distributing water without a free chlorine residual should be informed of the availability of the TCEQ documents.

604.155 (b) Curry temporary page no. 14

… standby power …

Respectfully recommend revise to include: Systems that do not have standby power on the date this part is adopted shall install standby power supply within 24 months of the date of adoption of this part.

It could take up to 24 months for a community public water supply system to obtain financing, complete engineering design, utilize a public bidding procedure for procurement of equipment and installation, and to complete construction and startup of a standby power system.

604.160 (a) Curry temporary page no. 15

… chemical safety plan …

Question:
Are "templates" available from IEPA, USEPA, or any other source? Is there available guidance identifying the contents desired by the Board? If the Agency and/or Board desires specific content, would it be possible to include a sample "table of contents" for the plan?

604.165 (d) Curry temporary page no. 15

… operating report records …

Question:
How long do the copies of records need to be maintained and stored?

604.170 Curry temporary page no. 15

(a) … protection …

Respectfully recommend revising to read as follows:
"Each community water supply well, well house, raw water intake structure, pumping stations, treatment plant buildings, and treated water storage reservoirs shall be protected to prevent vandalism and entrance by animals or unauthorized persons."

(b) **… fencing …**

Respectfully recommend clarifying where fencing is specifically required.

It is not feasible to fence raw water reservoirs/lakes or river sources to prevent trespassing etc.

There are many treatment plants that have open-top clarifiers and/or settling basins, but the properties are not fenced. What timeframe will be allowed to construct fencing in order to comply with this requirement?

Respectfully recommend specifying the type of protective fencing, minimum height, and configuration.

For instance? Chain link fence equal to Illinois Dept. of Transportation (IDOT) Standard 664001-02 …, minimum 6 ft. height with 3-strands of barbed wire above minimum fence height, with locking devices provided for all gates.

604.200 (b) (2) Curry temporary page no. 15

604.200 references raw water source … the requirements described at (b)(2) are more specifically described in various parts of 35 IAC.

Redundant?

604.245 Curry temporary page no. 24-27

… well records …

Respectfully recommend adding the following requirements at the end of 604.245:

"g The owner of each well shall be responsible for submitting record information for each well to the Illinois State Water Survey and Illinois State Geological Survey, including:

1) items listed at 604.245 (d).

2) full description of gravel pack material configuration, if used, including results of gradation tests to identify effective size and uniformity coefficient, thickness, and depth interval, and relationship to screen slot size opening.

3) well pump, discharge piping, and appurtenances information listed in 604.255.

h The owner of each well shall be responsible for submitting driller's log and drill cuttings to the Illinois State Geological Survey."

The Illinois State Water Survey and Illinois State Geological Survey have been the "keeper-of-records" for wells in Illinois. The first place that we check for well records is at the Illinois State Water Survey.

604.315 (a) (4) (A) Curry temporary page no. 33

Respectfully recommend … add list of parameters that are to be tested … for wells … and for surface water sources.

Guidance is available from the Agency for initial raw water quality parameters for well construction?

Raw water quality parameter guidance is needed?

604.510 (f) Curry temporary page no. 41

… flocculation …

(f) states: "Superstructure – A superstructure over the flocculation basins may be required."

Questions:

1. ***What is meant by the term "superstructure"?***
2. ***What criteria govern the determination whether or not a "superstructure" is required?***

I have personally been involved with "open-air" flocculation basins at the Carlyle plant from the mid-1960s through the early 1980s prior to their new plant, Nashville plant from 1969 to 1997 prior to their new plant, Salem plant from 1974 to date, Kaskaskia Water District plant from 1977 to date. These basins and treatment plants have operated satisfactorily.

604.515(h) Curry temporary page no. 42

... mechanical sludge removal equipment required in sedimentation basin.

Respectfully recommend revise to read as follows:
"h) Mechanical sludge removal equipment may be used in the sedimentation basins."

Or "h) Mechanical sludge removal equipment shall be used in sedimentation basins constructed after the date of adoption of this part."

There are numerous Illinois treatment plants that obtain satisfactory results using "plain" sedimentation basins without mechanical sludge collectors … including the Illinois American Water Company Mississippi River plant at East St. Louis, City of Salem, etc.

I have firsthand familiarity with the Salem water treatment plant, and the plant operates very efficiently and treated water quality has historically complied with regulatory requirements. Requiring installation of mechanical sludge collectors in their sedimentation basins would not result in improved treated water quality and could be "economic waste".

604.520 (c) Curry temporary page no. 43

… rapid mix device … with solids contact unit

What criteria will the Agency use in determining that a particular installation will require a separate rapid mix basin?

Solids contact upflow clarifiers having different configurations are commercially available and are used in Illinois. The solid contact upflow clarifiers that are equipped with upflow draft tubes for high-rate sludge recirculation intermixed with raw water containing selected chemicals (for coagulation etc.) do not, in my opinion, require a separate rapid mix.

604.600 (a) Curry temporary page no. 47

… filtration … pilot study …

604.600 (a) states that the Agency "may" require pilot treatment studies.

What criteria will the Agency use in determining whether or not a pilot treatment study is to be performed?

The types of filter configurations listed at 604.600 (b) are considered to be conventional and in widespread use in North America.

If pilot studies will be required … the duration and protocol (including treatment methods used preceding filtration) will need to be identified?

604.600 Curry, temporary page no. 47

…filtration …

Criteria for membrane filtration?

604.605 (g) (1) Curry, temporary page no. 49

… rapid gravity filters …

This provision limits the filter media depth to 30 inches unless otherwise approved by the Agency pursuant to Section 604.145(b). Section 604.145(b) indicates that the Agency "may" approve … alternate designs.

What criteria will the Agency use for approving filter media depth greater than 30 inches? The 30 in. depth limitation is not objectionable in itself … but the necessity for obtaining Agency approval is burdensome and criteria for the Agency's approval are not stated.

The Nashville, IL water treatment plant utilizes 48 in. filter media depth (24 in. of GAC over 24 in. of sand). Will the City be required to obtain an "exception" from the Agency?

The City of Springfield water treatment plant utilizes filter media with 32 in. depth. Will the City be required to obtain an "exception" from the Agency?

Deep bed filter media depth may vary from 48 to 72 in. according to Figure 8.5, Water Quality and Treatment, A Handbook of Community Water Supplies, American Water Works Association, 1999.

Lake County Water Action Agency's treatment plant uses approximately 60 in. of filter media. (Personal communication with Bill Soucie.)

604.605(i)(5) Curry temporary page no. 52

Respectfully recommend revise to read as follows: a continuously recording Nephelometer capable of measuring and recording filter effluent turbidity at maximum 15 minute intervals, and with an alarm to notify the Operator if filtered water turbidity exceeds 0.3 NTU (Nephelometric Turbidity Units).

The "surface water treatment rule" requires continuous recording Nephelometers for filters treating surface water.

604.605 (i) (6) Curry temporary page no. 52

Gravity filters … filter flow rate controller …

Respectfully recommend revise to read as follows: "(6) provide an adjustable valve to allow the Operator to gradually control the flow rate increase when placing each filter back into operation;"

Gravity filters are used for surface water sources, and must deliver filtered water with turbidity less than 0.3 NTU at least 95% of the time.

604.605(i)(4) appropriately requires provisions for "filter to waste" (also referred to as "re-wash") prior to placing a filter back into service.

The requirement for a "flow rate controller" implies that some type of automatic valve or controller must be installed to provide gradual (flow) rate increase when placing the filter back into operation? I am not aware of any plants that have some type of automated flow rate controller that provides gradual rate of increase.

Most plants manually control the filter effluent valve* to select the desired filtration rate during the filter-to-waste portion of the cycle and/or to allow gradual increase of filtration rate following backwash. An Operator is in attendance during the backwash and return-to-service and the Operator manually sets the filter effluent valve in a position to deliver the desired production flow rate.

* The valve can be controlled by the Operator with a manual hand wheel, or it can be manually controlled via an electric or pneumatic actuator.

"Slow starting of a filter consists of starting the filter at a low filtration rate and gradually increasing the rate over a period of time, such as 15 minutes. To slow-start a filter, the filter should be equipped with rate control ***valve*** *(emphasis added)* that can be gradually increased." (USEPA (2004) Long Term 1 Enhanced Surface Water Treatment Rule Turbidity Provisions Technical Guidance Manual, (EPA 816-R-04-007).

604.605 (i) (7) Curry temporary page no. 53

… Operator-attended backwash cycle … rapid rate gravity filters

Stipulates that backwash is to be "operator initiated" and "automated systems" shall be "operator-adjustable".

Respectfully recommend … revise to read as follows: "7) An Operator shall be in attendance to initiate the backwash cycle and to control the return-to-service procedure to assure that the effluent turbidity is less than 0.3 NTU when the filter is placed back into operation for discharge to the clearwell."

What constitutes an "automated system"? It has been my experience that an Operator needs to be present to initiate the backwash cycle, and to terminate the backwash cycle (including filter-to-waste) when the filter can be returned-to-service with turbidity less than 0.3 NTU.

604.620 Curry temporary page no. 56

Respectfully recommend revise 6th sentence in first paragraph to read as follows: " … synthetic organic chemicals, oxidation of ammonia-nitrogen, iron, and manganese."

Ammonia-N is biochemically "oxidized", not biochemically reduced. Nitrate and perchlorate can be biochemically "reduced" for removal.

604.620 (a)(2) Curry temporary page no. 56

Respectfully recommend revise to read as follows: "2) The pilot study shall establish empty bed contact time, surface filtration hydraulic loading rate, substrate loading rate per unit filter media volume, and treatment efficiency for removal or reduction of concentration of parameters targeted for the pilot study."

Substrate (such as Ammonia-N for example) loading per unit volume is usually the controlling factor for sizing attached growth (fixed film) bio-reactors. (Ref. Personal communication, Professor Bruce E. Rittmann, Arizona State University (formerly at Northwestern University and University of Illinois).

604.700 (b) Curry temporary page no. 56

This provision prohibits use of chloramines as a primary disinfectant, unless approved by the Agency pursuant to Section 604.145(b).

Comment:
I am aware of at least one surface water treatment plant that does NOT use free chlorine residual in its process and completely relies on chloramine disinfection to achieve required log inactivations for Giardia and viruses. That particular community has chosen this treatment technique to minimize potential formation of DBPs (THM4 and HAA5) and for control of manganese.

Question:
If the specific community treatment plant has not had any water quality violations and has a record of attaining required log inactivations for Giardia and viruses, will the Agency approve continued use of chloramines? **Should the community file a formal request for approval?**

604.700(d) Curry temporary page no. 57

Respectfully recommend … clarify intent? … to notify the public (particularly hospitals, kidney dialysis facilities, and fish breeders) … prior to changing the form of chlorine residual or type of disinfectant.

Intent is to give notice prior to changing form of chlorine residual from free residual to chloramines, and prior to changing from chloramines to free residual, in addition to type of disinfectant (including use of chlorine dioxide).

604.715 (a) Curry temporary page no. 58

… contact time … carry-over from IEPA Technical Policy Statements

<u>Question:</u>
Reference is made to a 0.3 baffling factor.

How is the 60 minute minimum contact time to be determined? (Reference to the 0.3 baffling correction factor implies that my Potential Method B is to be used?)

<u>Potential Method A (historically used in Illinois to evaluate compliance with this requirement)</u>

$$\textit{Hydraulic retention time} = \frac{\underline{\textit{water volume in basin, gallons}}}{\textit{flow rate, gpm}} = \textit{minutes}$$

Or,
<u>Potential Method B (modified for use with baffle correction factor)</u>

$$\textit{Effective retention time, } T_{10}\ {}^{*} = \frac{\textit{water volume in basin, gal. x 0.3}}{\textit{flow rate, gpm}} = \textit{minutes}$$

**** "Baffle correction factor" is the ratio of the time taken for 10% of a tracer to reach the outlet (known as T_{10}) to the system's theoretical average detention time; the theoretical average detention time is equal to the basin volume divided by the flow rate expressed in gpm. (Ref: USEPA)***

<u>Comment:</u>
There are likely many communities in Illinois that have facilities designed, constructed, and operated based on <u>Potential Method A</u> for calculating minutes detention time based on the 60 minute requirement. <u>Potential Method A</u> has historically been used in Illinois to determine compliance with the 60 minute contact time requirement.

<u>Questions:</u>
If <u>Potential Method B</u> will be required for calculating effective retention time, how many community systems will be in violation?

Expanding contact basin capacity if required in order to use this method for determining compliance could be costly, have the costs been estimated?

If filtration is employed and at least 0.5 log Giardia inactivation and at least 2 log Virus inactivation are achieved with disinfection in the clearwell after the filters, is the 60 minute contact time still required?

IF POTENTIAL METHOD B MUST BE USED TO DETERMINE COMPLIANCE … Respectfully recommend revise to include: Existing systems that do not comply with this requirement on the date this part is adopted shall make necessary modifications (baffling, increased volume, etc.) within 24 months of the date of adoption of this part.

It could take up to 24 months for a community public water supply system to obtain financing, complete engineering design, utilize a public bidding procedure for procurement of equipment and installation, and to complete construction and startup of a standby power system.

604.720 (d) Curry temporary page no. 59

… inactivations …

Comment:

The "baffle correction factor" selection procedure was elusive for a number of years. I do not know of any specific instances where a community expended funds to perform a tracer study, but some may have been performed. (Perhaps …???... many of us are fearful that the tracer study may produce a baffle correction factor that is lower than the value being used for calculating inactivations … because it could require either capacity-down-rating for a plant, or it could require major expenditures to improve the effective contact time.?????)

In the interest of public health protection … should we "bite the bullet" and undertake statewide tracer studies? We are not aware of any disease outbreaks caused by inadequate inactivations at treatment plants … but we do not know if isolated illnesses have been caused by inadequate inactivations? Are the "safety factors" already sufficient?

Respectfully recommend that the Board and Agency consider revising to read as follows: "d) Factors to be considered in determining inactivation include, but are not limited to: pH, temperature, form of disinfectant residual, disinfectant residual concentration, flow rate, volume of basins/piping, and baffling factors. Baffling factor shall be determined in accord with "Improving Clearwell Design for CT Compliance"* or a tracer study approved by the Agency."

"Improving Clearwell Design for CT Compliance, Gil F. Crozes and James P. Hagstrom (Carollo Engineers); Mark M. Clark, Joel Ducoste, Catherine Burns (University of Illinois); AWWA Research Foundation, 1999.

604.725 Curry temporary page no. 59

THIS INCREASES MINIMUM FREE CHLORINE RESIDUAL FROM 0.2 TO 0.5 MG/L AND INCREASES MINIMUM CHLORAMINE RESIDUAL FROM 0.5 MG/L TO 1.0 MG/L.

I RESPECTFULLY ACKNOWLEDGE THAT THE AGENCY HAS OBSERVED WATER QUALITY PROBLEMS THAT ADVERSELY AFFECTED PUBLIC HEALTH, AS A RESULT OF INADEQUATE DISINFECTANT RESIDUAL. THE AGENCY HAS INDICATED THE BELIEF THAT INCREASING THE MINIMUM RESIDUAL VALUES WILL IMPROVE PROTECTION OF PUBLIC HEALTH.

Respectfully recommend consider that this provision take effect 90 days (or a time period acceptable to the Board and Agency) after adoption of 604. It will take some time for Operators throughout the state to become informed of this change and to modify their treatment and operational practices.

Comment:

I and others in the field will need to remind Operators of the provisions contained in 35 IAC 611.313, 611.380(d), and 611.383(c)(1)(A) … which allows considerable flexibility in disinfectant residual concentration leaving the treatment plant … in order to sustain a higher residual in the distribution system if necessary.

604.730 Curry temporary page no. 59

… automatic shutdown …

Comment:

I am not aware of any treatment plants that now comply with the "automatic shutdown" provision. To attain compliance will require that a low level alarm from a continuous recording chlorine residual analyzer be electrically interconnected to shut-down:

Pumps at raw water source.
Each individual pre and post chemical treatment system.
Each individual clarifier sludge blowdown valve.
Each individual filter effluent valve.
Each treated water high service pump.

At present, the low-level condition causes a visual and/or audible alarm that notifies the Operator of the problem, and the Operator manually shuts down the plant.

An indeterminate amount of time and money will be required for each community to comply with this requirement.

If this requirement is adopted "as-is" …
Respectfully recommend consider that this provision take effect 180 days (or a time period acceptable to the Board and Agency) after adoption of 604. It will take some time for Operators throughout the state to become informed of this change and to modify their treatment plant electrical controls and operational practices.

604.900 Curry temporary page no. 63

THIS IS A DISCUSSION THAT WARRANTS INPUT FROM EXPERT WATER QUALITY PROFESSIONALS … SUCH AS VERNON L. SNOEYINK, PROFESSOR EMERITUS OF ENVIRONMENTAL ENGINEERING, UNIVERSITY OF ILLINOIS, CHAMPAIGN-URBANA.

The valuable USEPA publication titled: Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, March 2016 (USEPA Office of Water (4606M) EPA 816-B-16-003) contains nine (9) flow charts that provide guidance for corrosion control. Each individual flow chart contains alternative treatment techniques to select from.

Regardless of which treatment method is used for corrosion control, I respectfully recommend that all systems measure …

Chloride:Sulfate Ratio and the Larson-Skold Index, initially once monthly for 6 consecutive months and then once annually if stable conditions are demonstrated to exist. If stable conditions exist for 6 consecutive months, annual measurement shall be performed.

SEE ATTACHMENT 1 FOR CHLORIDE:SULFATE RATIO INFORMATION. (Edwards et al.)
SEE ATTACHMENT 2 FOR IMPACT OF DETRIMENTAL LARSON-SKOLD INDEX INFORMATION. (Masten et al.)
SEE ATTACHMENT 3 FOR LARSON-SKOLD INDEX INFORMATION.

For systems that rely on adjustment of pH and other water quality parameters for corrosion control: CCPP (Calcium Carbonate Precipitation Potential) once weekly.

The treatment process should be controlled to prevent excessive calcium carbonate scale deposition by assuring that the CCPP does not exceed + 4 mg/L.

[See discussion below for evaluation of calcium carbonate scale-forming tendency at systems that feed orthophosphate corrosion inhibitor.]

CCPP BACKGROUND INFORMATION:

> "The prediction of the threshold for calcium carbonate formation is important for several reasons. First, it can create a constraint on the ability to adjust pH, **by forming a detrimental deposit**. *(emphasis added)* Second, for some materials such as cement linings, it is a consideration for adjusting water chemistry to arrest deterioration. Third, it can be used to monitor the consistency of treatment processes such as lime softening or neutralization with limestone or dolomitic materials." (Schock and Lytle, 2011)
>
> Schock, Michael; Lytle, Darren A. (2011); "Chapter 20. Internal Corrosion and Deposition Control", Water Quality & Treatment, A Handbook on Drinking Water, 6th ed., James K. Edzwald, Editor; American Water Works Association.

Here, the "detrimental deposit" is excessive calcium carbonate that is deposited because of improper equilibrium of water quality parameters. These deposits can reduce the carrying capacity of water mains and household piping systems, fire suppression piping, and can cause clogging of household plumbing systems.

Marc Edwards (Virginia Tech) et al. have documented the importance of the Chloride:Sulfate ratio with respect to corrosivity. (Mark Edwards and Simoni Triantafyllidou (July 2007) "Chloride to sulfate mass ratio and lead leaching to water", Journal AWWA (Peer Reviewed). ATTACHMENT 1.

USEPA has documented that the Chloride:Sulfate Mass Ratio (CSMR) is an important parameter in evaluating potential for lead release into water. (USEPA Office of Water (March 2016) Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, (EPA 816-B-16-003; Office of Water (4606M)).

The Larson-Skold "The Larson-Skold index was developed to evaluate the potential for the corrosion of cast-iron pipes transporting water from the Great Lakes." (Roberge 2006, cited at Masten et al., 2016). ***Chloride and sulfate concentrations are required (in addition to alkalinity) to calculate this index.*** **This index was used to analyze and explain the reasons for water discoloration at Flint, MI during the lead crisis**. (Masten et al.) ATTACHMENT 2.

Larson & Skold (1957) T.E. Larson, and R.V. Skold, "Corrosion and tuberculation of cast iron", Journal AWWA, 49(10), 1294-1302.

Larson & Skold (1958) T.E. Larson, and R.V. Skold, "Laboratory studies relating to mineral water quality of water to corrosion of steel and cast iron", Corrosion, 14(6), 285-288.

Masten et al.(2016) Susan Masten, Simon H. Davies, and Shawn P. McElmurry "Flint Water Crisis: What Happened and Why", Journal AWWA, 108.12, December 2016.

Roberge (2006)P. Roberge, "Corrosion Inspection and Monitoring", s.I., Wiley Online Library (cited at Masten et al., 2016).

See ATTACHMENT 3 for information about Larson-Skold Index.

CCPP (Calcium Carbonate Precipitation Potential) is "quantitative", so results are meaningful.
I believe that there is consensus for monitoring the scale-formation tendency using CCPP (Calcium Carbonate Precipitation Potential), except at systems that use orthophosphate for corrosion control.

The $CaCO_3$ Indices Modeling Spreadsheet can be used to estimate CCPP (Calcium Carbonate Precipitation Potential), and is available as a FREE download from Trussell Technologies, Inc., Pasadena, CA. Contact www.trusselltech.com, select "downloads", select "tools", select $CaCO_3$ Modeling Spreadsheet. This is a useful tool for predicting quantitative estimates of calcium carbonate scale forming tendencies.

The TetraTech (RTW) Model is available for purchase from AWWA (AWWA catalog number 53052), at a cost $274. for members and $421. For non-members, as of May 2016. In addition to predicting CCPP (Calcium Carbonate Precipitation Potential), the Excel spreadsheet software is useful for monitoring water quality parameters using different chemicals for coagulation, pH adjustment, and alkalinity adjustment. (Rothberg et.al., 2011)

Rothberg, Michael R., Liang, Hong-Chang "H.C.", Tabatabaie, Sarvin, Tamburini, Joseph R. (2011) TetraTech (RTW) Model for Water Chemistry, Process, and Corrosion Control, AWWA.

CCPP is referenced in "Standard Methods". Parameters required as input for the spreadsheet models referenced above are:

TDS (Total Dissolved Solids) … conductivity is easier to measure and is considered sufficient for estimating TDS after confirmation of the multiplier factor.

pH

Temperature (deg. C.)

Alkalinity (expressed as $CaCO_3$)

Calcium hardness (expressed as $CaCO_3$)

****

Monitoring calcium carbonate scale forming tendency for systems that feed orthophosphate corrosion inhibitor:
If phosphates are present, preference is given to the *Marble Test* over the Trussell Technologies spreadsheet or the TetraTech (RTW) Model spreadsheet for estimating CCPP. (Schock & Lytle, 2011)

Schock, Michael; Lytle, Darren A. (2011); "Chapter 20. Internal Corrosion and Deposition Control", Water Quality & Treatment, A Handbook on Drinking Water, 6th ed., James K. Edzwald, Editor; American Water Works Association.

The Marble Test (Larson, 1971)

"The marble test is a rapid method of determining if a water is in balance with solid calcium carbonate. The test procedure is given in detail in the AWWA publication "Simplified Procedures for Water Examination". Essentially, the test consists of determining the alkalinity on one portion of the sample being tested and adding an excess of finely powdered calcium carbonate to another portion of the same sample in a 300-ml glass-stoppered (and water sealed) BOD bottle. This sample is mixed by shaking at frequent intervals for at least 3 hr., settled overnight, and filtered. The alkalinity is then determined on the filtered sample. If the alkalinity has increased, it indicates that the water was not saturated with calcium carbonate and could not deposit any protective scale. In fact, it might dissolve any previously deposited scale and would then be corrosive. If the alkalinity has decreased, the water is supersaturated with calcium carbonate and may deposit protective scale or maintain a coating already deposited. It should not dissolve any previously deposited protective scale, but neither will it maintain or improve such a coating."

Larson, Thurston E. ("Doc") (1971); "Chapter 8. Corrosion Phenomena – Causes and Cures", Water Quality and Treatment, A Handbook of Drinking Water, 3rd ed., Paul D. Haney, Revision Committee Chairman, American Water Works Association.

The procedures for "Calcium Carbonate Saturation" are similar to the *marble test* described by T.E. "Doc" Larson, and are described at Simplified Procedures for Water Examination, Manual of Water Supply Practices M12. (AWWA, 2002)

Special attention must be given to equipment and procedures used to measure alkalinity for the Marble Test (Calcium Carbonate Saturation) in order for results to be meaningful.

ALKALINITY TEST

TITRATION ENDPOINT WITH pH METER

mg/L alk as $CaCO_3$	end point pH for total alk
30	4.9
60 estimated	*4.8*
100 estimated	*4.7*
150	4.6
245 estimated	*4.5*
350 estimated	*4.4*
500	4.3

COLOR CHANGE FOR IDENTIFYING THE ALKALINITY TEST TITRATION ENDPOINT IS INDIVIDUALLY SUBJECTIVE … WHICH IS WHY USING A pH METER IS PREFERRED FOR MAXIMUM ACCURACY.

Accurate alkalinity values are required for input into the $CaCO_3$ Indices Modeling Spreadsheet to estimate CCPP (Calcium Carbonate Precipitation Potential), TetraTech (RTW) Model to estimate CCPP, and for alkalinity measurements using the Calcium Carbonate Saturation … "Marble Test".

	End point pH for total alkalinity
Silicates or phosphates known or suspected	4.5
Routine or automated analyses	4.5

(Estimated alkalinity values for endpoint pH 4.8, 4.7, 4.5, and 4.4 are not listed in "Standard Methods", and were estimated for use here using graphical method.)

ALKALINITY TEST

The customary sample volumes for "routine" alkalinity tests are listed below (AWWA):

Alkalinity Range mg/L as $CaCO_3$	Sample Volume ml	Multiplication Factor "A" (a)	Estimated Accuracy
0-250	100	10	± 1 mg/L (b)
251-500	50	20	± 2 mg/L (b)
501-1000	25	40	± 4 mg/L (b)

(a) Based on:

$$\text{Alkalinity as mg } CaCO_3/L = \frac{\text{“A”} \times N \times 50{,}000}{\text{ml sample}}$$ (APHA, AWWA, WEF)

"A" ml of standard acid titrant used.
N normality of standard acid, 0.02N H_2SO_4

(b) Assume can read burette graduations to nearest 0.1 ml of acid titrant used.

The sample volumes shown in the above table may be acceptable for "non-critical" alkalinity determinations, but are not considered suitable for alkalinity determinations to be used for CCPP calculations or for the "marble test".

ALKALINITY TEST VALUE ACCURACY CAN BE IMPROVED BY USING A LARGER BURET VOLUME WITH GRADUATION MARKINGS SHOWN ON THE FOLLOWING TABLE.

ALKALINITY TEST

Commercially available "automatic" burets that can be utilized to disperse the titrant for the alkalinity test include:

Buret Volume, ml	Subdivision for Graduation Markings	Sample Volume, ml	Maximum Alkalinity (a)	Estimated Accuracy
50	0.1 ml	100	500 mg/L	± 1 mg/L (b)
50	0.1 ml	150	333 mg/L	± 0.66 mg/L (b)
25	0.05 ml	100	250 mg/L	± 0.5 mg/L (c)
25	0.05 ml	150	166 mg/L	± 0.33 mg/L (c)
10	0.02 ml	100	100 mg/L	± 0.2 mg/L (d)
10	0.02 ml	150	66 mg/L	± 0.13 mg/L (d)

(a) Using 0.02N H_2SO_4 titrant.
(b) Assume can read burette graduations to nearest 0.1 ml of acid titrant used.
(c) Assume can read burette graduations to nearest 0.05 ml of acid titrant used.
(d) Assume can read burette graduations to nearest 0.02 ml of acid titrant used.

WE HAVE A HISTORY OF RELYIING ON THE LANGELIER SATURATION INDEX TO MONITOR TENDENCY TO DEPOSIT CALCIUM CARBONATE SCALE

IT HAS SHORTCOMINGS … AND IS NOT “QUANTITATIVE”

IT REMAINS TO BE A VALUABLE “TOOL”, BUT CCPP IS THE PREFERRED METHOD FOR EVALUATING THE TENDENCY TO FORM CALCIUM CARBONATE SCALE EXCEPT IN WATER CONTAINING PHOSPHATES, WHERE THE MARBLE TEST IS PREFERRED.

“The Langelier saturation index (Langelier,1936) is the **most widely used and MISUSED index** *(emphasis added)* in the water treatment and distribution field.” (Schock & Lytle, 2011)

The Langelier Saturation Index (LSI), and other calcium carbonate-related indices such as the Ryznar Index and calcium carbonate precipitation potential (CCPP), can be used as indicators of scaling conditions (Schock and Lytle, 2011)[13]. **It is important that the LSI and other $CaCO_3$ related indices *not* be used to evaluate lead or copper control**. The LSI is only important insofar as it provides information regarding the amount of pH adjustment that can be employed without causing precipitation. (Schock & Lytle, 2011)

“The Langelier Saturation Index (LSI) was used historically as an indicator of water’s corrosivity. **It is ineffective** as an indicator because it’s based on inhibition that’s solely by carbonate species (carbonate, bicarbonate, and hydroxide ions) and calcium, and incorrect from the perspective of dissolved inorganic carbonate, which is a measure of all dissolved carbonate-containing species. Other compounds can complex with metals, including phosphate and silicate among other anions, so **the LSI may not correlate well with the water’s corrosivity.**” (Snoeyink et al., 2014)

In 1994, in recognition that the LSI was frequently misused as a corrosion index and that inappropriate treatment approaches were being adopted and used in different parts of the United States, the **USEPA repealed the section of the 1980 amendment to the National Interim Drinking Water Regulation that required all community water supply systems to determine either the LSI or an even more approximate version, the aggressiveness index (AI),** and report these values to the state regulatory agencies (USEPA, 1980, 1994). **Although the LSI tends to predict if $CaCO_3$(s) will precipitate or dissolve, it does not predict how much $CaCO_3$(s) will precipitate or whether its structure will provide resistance to corrosion (Larson, 1975).** “ (Schock and Lytle, 2011))

Schock, Michael; Lytle, Darren A. (2011); “Chapter 20. Internal Corrosion and Deposition Control”, Water Quality & Treatment, A Handbook on Drinking Water, 6th ed., James K. Edzwald, Editor; American Water Works Association.

Snoeyink et al. (2014) “Developing Corrosion Control for Drinking Water Systems”, OPFLOW, American Water Works Association (AWWA), November 2014. Quirien Muylwyk (with CH2M Hill), Anne Sandvig (with Cadmus Group), and Vern Snoeyink (Professor Emeritus of Environmental Engineering at University of Illinois).

604.900(a) Curry temporary page no. 63

Respectfully recommend that alkalinity, total hardness, and calcium hardness be expressed equivalent to calcium carbonate ($CaCO_3$).

Respectfully recommend that temperature be added as a water quality parameter, especially because it impacts CCPP (Calcium Carbonate Precipitation Potential) and potential for nitrification increases at higher temperature.

604.900(b) Curry temporary page no. 63

Respectfully recommend revising as follows:

Under 3) … list orthophosphate and sodium silicate as corrosion inhibitors?

Under 5 … list calcium hydroxide, soda ash (sodium carbonate), and sodium bicarbonate as alkali chemicals?

604.905 Curry temporary page no. 63

Proprietary systems, such as TOMCO, provides carbon dioxide addition in the form of a carbonic acid/water solution fed under pressure … which does NOT require a separate recarbonation basin having detention time of 20 minutes or more.

Respectfully recommend alter this provision to permit use of proprietary carbonic acid feed systems that can be used for lowering pH of lime softened water before it enters the filters.

604.1010(b)(2)(A) Curry temporary page no. 67

Respectfully recommend revise to read as follows: "A minimum detention time of 30 minutes shall be provided following aeration to insure that the oxidation reactions are complete prior to filtration. This minimum detention time may be modified only where a pilot plant study indicates completion of oxidation reactions in less time. For new treatment plants, the time required for complete oxidation of iron after being aerated should be determined by bench scale pilot studies."

> *Justification for recommending bench scale pilot studies:*
>
> *Ref. O'Connor John T. (1971) "Iron and Manganese", Water Quality and Treatment, A Handbook of Public Water Supplies, American Water Works Association*
>
> *"A survey of the performance of 31 plants practicing iron removal in Illinois was made in 196. The results of this survey provide some indication of the effectiveness of aeration and filtration for iron removal. ... Although 1 hr. of detention was normally provided following aeration, frequently a large fraction of the iron in the filter influent appeared to be in the ferrous form* [SOLUBLE … NOT REMOVED BY FILTRATION]. *Much of this unoxidized iron appeared in the filter effluent, indicating that complete oxidation might have resulted in more complete iron removal."*
>
> *"The survey indicated that design deficiencies may exist when insufficient reaction time is provided for the complete oxidation and agglomeration of iron and manganese. The amount of time required apparently must be determined by measuring the kinetics of precipitation for each individual water."*

I believe that the O'Connor's lessons from 67 years ago remain valid today. Performing a bench scale study to evaluate reaction time for complete oxidation of iron is a relatively simple procedure.

Recommendation for consideration for "iron removal using groundwater source":

… add provision as follows: "When raw water iron and manganese concentration is expected to exceed 10 mg/L, consideration should be given to use of a clarification unit or settling basin prior to filtration in order to reduce the solids loading to the filters and minimize potential for excessive water usage for backwashing the filters.

Most small "iron removal plants" utilize aeration, a detention/reaction basin, and pressure filters that employ "direct filtration". When the raw water iron concentration reaches the 8 to 10 mg/L range, the solids loading to the filters causes very short filter runs and a considerable amount of water (and plant capacity) is taken up by the increased frequency of filter backwash.

> "When concentrations in the source water are above 8 to 10 mg/L combined iron and manganese, a clarification step is typically required before filtration. The clarification process reduces the amount of solids that must be removed by the filters, which results in longer filter run times before backwashing is required." *(AWWA (2015) Iron and Manganese Removal Handbook, Second Edition, American Water Works Association.)*

> "Alum flocculation and sedimentation are generally required after aeration. These processes are then followed by filtration, especially in cases where the iron concentration of the raw water exceeds 5 mg/L." *(Kawamura, Susumu (2000) Integrated Design and Operation of Water Treatment Facilities, Second Edition)*

604.1020 (f) Curry temporary page no. 70

… powdered activated carbon feeders …

Respectfully recommend … eliminate the 0.1 mg/L minimum dosage.

The 0.1 to 40 mg/L dosage range represents (40/0.1) = 400 to 1 feed ratio. Commercially available volumetric feeders normally have a 10:1 feed range, and some of the newer motor/drive systems can expand to 50:1 feed range if the Operator can change the size of the feed screws and spouts. It is not considered practical to feed powdered activated carbon at dosage as low as 0.1 mg/L, and it is not considered to be practical to determine the impact on water quality at dosage as low as 0.1 mg/L.

I have personally experienced T&O situations where **80 mg/L PAC dosage** was required. That particular system's experience of feeding large amounts of PAC resulted in installation of GAC filter media (overlying sand media) … which resulted in overall cost reduction and a dramatic water quality improvement and consistent absence of objectionable T&O.

604.1020(g) Curry temporary page no. 70

... powdered activated carbon storage …

Respectfully recommend delete (g) and insert the following requirements taken from the current edition of "10-State Standards":

g. Powdered activated carbon must be handled as a potentially combustible material.

1) ***A separate room shall be provided for carbon feed equipment, including a door to allow isolation of the room.***
2) ***The separate room shall be as nearly fireproof as possible.***
3) ***Other chemicals shall not be stored in the same room as powdered activated carbon.***
4) ***Carbon feeder rooms shall be equipped with explosion-proof electrical outlets, lights, and motors.***

The General Carbon Corporation (Calgon) manufactures powdered activated carbon and their Safety Data Sheet includes the following information:

- ✓ Hazard classification … combustible dust.
- ✓ All powdered activated carbons are classified as weakly explosive.
- ✓ Fine carbon dust may penetrate electrical equipment and cause electrical shorts [Curry addition …which can result in fires].

The recommendation is considered necessary as a safety measure to protect Operators and other personnel.

604.1010(d)(2) Curry temporary page no. 69

… phosphate solution storage …

Respectfully recommend incorporate additional provision contained at 604.910.

604.1110(b) Curry temporary page no. 77

… deluge shower …

Respectfully recommend add after (b):

"The deluge shower and eye/face wash device shall be located in close proximity to the potentially hazardous material. Comply with:

1) *OSHA regulations contained at 29 CFR 1910.151.*
2) *ANSI Z358.1-2014.*
    - *a. Within 10 seconds walking time from the location of the hazard (approximately 55 ft.).*
    - *b. Installed on the same floor level as the hazard (i.e. access shall not require going up or down stairs or ramps).*
    - *c. The path of travel shall be free of obstructions and as straight as possible.*

The water supply for the deluge shower shall comply with:

3) *OSHA regulations contained at 29 CFR 1910.151.*
4) *ANSI Z358.1-2014.*
    - *a) Water temperature between 60 and 100 deg. F., except in circumstances where a chemical reaction is accelerated by flushing fluid temperature if determined by consultation with product manufacturer safety advice to determine the optimum water temperature for each application.*
    - *b Deliver at least 20 gpm for 15 minutes.*

The water supply for the eye/face wash device shall comply with:

"The water supply for the deluge shower shall comply with:

5) *OSHA regulations contained at 29 CFR 1910.151.*
6) *ANSI Z358.1-2014.*
    - *a) Water temperature between 60 and 100 deg. F., except in circumstances where a chemical reaction is accelerated by flushing fluid temperature if determined by consultation with product manufacturer safety advice to determine the optimum water temperature for each application.*
    - *b Deliver at least 3 gpm for 15 minutes.*

Reason:

The recommended additional provisions are intended to provide adequate safety provisions for Operators and other personnel, and to comply with OSHA and standards of good practice.

If a distressed Operator is suddenly exposed to extremely cold water for up to 15 minutes duration, after a bodily exposure to a hazardous chemical, cardiac arrest can occur.

It is my recollection that IDPH has a regulation governing deluge shower and eye/face wash devices … but I was unable to research their regulations.

604.115(c)(11) Curry temporary page no. 78

… provisions to chemically neutralize chlorine gas …

Comment:
I am not aware of any treatment plant in the southern part of Illinois that has provisions for neutralization of chlorine gas. This is not to say that some or all of the plants need to install this type of equipment in order to protect public health.

Question:
Is there a certain distance between the chlorine gas storage area and residential or developed areas that the Board and Agency feel should trigger installation of equipment to chemically neutralize chlorine gas?

Respectfully recommend revise to include: Existing systems that do not have provisions for neutralization of chlorine gas, but are required to provide this capability, on the date this part is adopted, shall install equipment for neutralization of chlorine gas within 24 months of the date of adoption of this part.

It could take up to 24 months for a community public water supply system to obtain financing, complete engineering design, utilize a public bidding procedure for procurement of equipment and installation, and to complete construction and startup of a chlorine gas neutralization system.

604.1140(b)(1) Curry temporary page no. 80

… ammonium sulfate mixer …

Respectfully recommend … delete the last sentence … "Provision should be made for removal of the agitator after dissolving the solid."

Question:
What is the reason to require removal of the agitator/mixer each time the ammonium sulfate solution is batched?

Comment:

I am familiar with numerous installations where the agitator/mixer remains in the day tank after re-batching the solution and have never experienced any problems with leaving the mixer in the tank. I am not aware of any reason for needing to remove the agitator/mixer.

Respectfully recommend add the following: "(b)(3) The submerged portion of the mixer shaft and propeller shall be made of 304 or 316 stainless steel that is resistant to corrosion by ammonium sulfate solution.

Comment:
Use of stainless steel mixer shafts and propellers is considered to be common practice.

604.1145 Curry temporary page no. 81

… potassium permanganate …

Comment:
I have been involved with numerous potassium permanganate feed systems that have successfully operated without using heated water for dissolving potassium permanganate. I discussed this proposed requirement with John Boll, an employee for nearly 40 years with Carus Chemical Company at LaSalle-Peru, and he does not feel that it is necessary to have a heated water source.

From my experience, if potassium permanganate is batched at solution strength compatible with the solubility at the temperature of water being used, and taking into account the temperature in the feed line environment, the potassium permanganate remains in solution (dissolved). It my experience that 1 to 3% solution strength is suitable for most applications, with higher solution strength permissible during summer months.

From my experience, clogging problems have occurred in the feed piping because:

- ✓ ***The amount of permanganate added exceeded the solubility limits based on temperature of the water being used.***
- ✓ ***"free-flowing" grade was used instead of "technical grade", and the "free-flowing" grade is meant for use with gravimetric feeders … and is coated with a hydroxide-type coating that causes localized elevation of pH resulting in precipitation of calcium carbonate that "clogs" the piping system.***

Questions:
As now written, this section appears to be applicable only to-batched solutions fed from day tanks?

Does this section take into account that many (larger) treatment plants feed potassium permanganate with gravimetric (dry) feeders?

604.1150(c)(1) Curry temporary page no. 82
… fluoride incompatible with aluminum coagulants …

Respectfully recommend revise (c)(1) to read as follows: "1) Fluoride compound shall not be added prior to filters at plants that lime soften and/or coagulate for turbidity removal, and shall not be added prior to ion exchange softeners."

Reason … should add fluoride after coagulation:
Coagulant chemicals used for lime softening and/or turbidity removal may reduce the concentration of fluoride. Alum, in particular, will remove fluoride.

Fluoride dosage needs to produce a specific fluoride concentration in the water being delivered to customers, so chemical interference should be avoided.

604.1225(c)(1)(C) Curry temporary page no. 86
… redundant flow meter …

Respectfully recommend delete (C) … a meter for measuring flow rate for each individual pump.

Reason:
A meter for measuring flow rate is required at 604.1225(c)(2). Customary piping arrangements allow a single meter to be used to check/monitor flow rate from individual pumps. Installation of redundant meters is not necessary for pump stations and would unnecessarily increase the cost of piping and the size of the building to house the pumping and piping equipment.

If this requirement would remain "as-is", many existing facilities would have to be retrofitted, and the cost for compliance could be significant.

604.1225(e)(3) Curry temporary page no. 86
… electrical controls above grade …

Respectfully recommend delete (3) requiring that electrical controls be located above grade.

Comment:
There are numerous "package" underground water pumping stations located in Illinois, many of which are manufactured by Engineered Fluid, Inc. at Centralia, IL. Many entities prefer an underground pump station to lessen exposure of above-ground buildings in residential areas and for other reasons. From my experience, all (or nearly all?) of the underground pump stations have controls located underground in the pump room chamber.

It has been my experience that some communities prefer above-ground pump; stations, and some prefer underground pump stations. Underground pump stations have been in service for many years in Illinois (including since 1967 at Dix-Kell Water & Sewer Commission in Jefferson County).

If the controls for underground pump stations would have to be located above ground:

a. Operators would be required to access 480 Volt control panels during all weather conditions … rain, lightning, snow, etc. This could result in hazardous exposure for the Operator; or

b. The controls would be in a separate building, which would significantly add to the cost and perhaps defeat the purpose/advantage of an underground pump station.

Below-ground pump stations customarily have a master electrical disconnect above-ground at the service meter, and the National Electric Code requires a disconnect for each pump motor within view of the pump motor … so it is necessary to have the disconnects underground at underground pump stations.

Question:
If this provision is adopted, a large number of community systems would be in violation, and considerable expense would be incurred to modify the controls for existing underground pump stations.

If this provision must be adopted by the Board, respectfully recommend that it not take effect for 24 months to allow communities ample time to obtain funding for modifications to existing control systems for existing underground pump stations.

604.1440(a)(1) Curry temporary page no. 101

Question:

1. What is the definition of "existing or proposed **drain**"?

Respectfully recommend revise to incorporate the following:

The ten ft. horizontal separation is not required between water mains and open-ended culvert pipes intermittently conveying storm water runoff in response to precipitation events, and interconnected with open ditches upstream and downstream.

End written testimony.

Statement of Qualifications and Experience: Capt. Michael D. Curry, P.E.

I am 75 years of age, and I am a Registered Professional Engineer in Illinois by examination, in Missouri by reciprocity, and formerly in Iowa as a Civil Engineer by reciprocity and as a Sanitary Engineer by examination. I chose to allow my Iowa registrations to lapse in good standing because I did not intend to do further work in Iowa. I am an Illinois Class *A* Certified Water Operator. I attended Parkland College and University of Illinois at Champaign-Urbana but did not obtain a degree.

I served on the Water Supply Operators Advisory Board from 1982 to 2000, an appointment made by the Governor of Illinois, based on a recommendation from Illinois EPA. I was Chair of the Illinois Section of the American Water Works Association in 1983-84. In 1983, I received the Clifford E. Fore Award from Illinois Section American Water Works Association. In 1985, I received the Fuller Award from Illinois Section American Water Works Association. I received an "award of excellence" from Illinois Potable Water Supply Operators Association in 2000.

I was the recipient of a national award from American Water Works Association for the "Best Paper of the Year" in the Water Quality Division of Journal AWWA in 1984. I have published various papers in Journal AWWA, OPFLOW, Water & Sewage Works, Journal of Water Supply: Research and Technology (with Vernon L. Snoeyink et al.), and other publications. I have presented technical papers pertaining to water treatment and water quality topics at numerous conferences sponsored by Illinois Section American Water Works Association, Illinois Potable Water Operators Association, Southwest Central Water Operators Association, and Southern Illinois Water Operators Association on nearly an annual basis from 1977 to 2017.

In 1979, at the request of IEPA, I prepared the Outline for Advanced Waterworks Operator Courses offered at community colleges statewide, on a voluntary basis. In 1983, I and Sandy Moldovan prepared the Task Analysis for the IEPA Division of Public Water Supply Operator Certification Section, covering Classes *D*, *C*, *B*, and *A* certification examinations, on a voluntary basis. I was an instructor for water supply operator courses between 1970 and 1999 at Greenville College, John A. Logan College, Rend Lake College, Kaskaskia College, Southeastern Illinois College, Environmental Resources Training Center at Southern Illinois University-Edwardsville, and an advanced water operator class for Missouri DNR at the City of St. Louis Missouri Howard Bend Water Treatment Plant (Missouri River source). Under contract with the Illinois Dept. of Conservation (now IDNR), I conducted various waterworks operations seminars at Starved Rock State Park and at Allerton House (Monticello) for statewide Park Rangers and Park Employees.

In 1980, I served as a "subject matter expert" and was a member of a five person panel from the U.S. and Canada to validate waterworks operator education and certification material for the Association of State Boards of Certification. This one week project at Upland, California was funded by USEPA.

Between 1961 to 1979, I was employed by Sherman Smith & Associates Engineers in Burlington, Iowa; Des Moines County Engineers in Burlington, Iowa; Clark Dietz Painter & Associates in Urbana, Illinois; HMG Engineers in Carlyle, Illinois (including assignments in their St. Louis, Missouri and Libertyville, Illinois offices); Lawrence Lipe & Associates Engineers in Benton, Illinois; Group III Consultants in Salem, Illinois (including assignments in their Washington, Illinois and Effingham, Illinois offices).

I have been employed by Curry & Associates Engineers, Inc. at Nashville, Illinois from 1979 to date. My duties include design of water supply and wastewater treatment facilities, water distribution systems, pumping stations, water storage reservoirs, sewage collection systems, storm water management systems and storm sewers, mainline railroad track alignments and interconnects, industrial railroad spurs and runaround tracks, streets, and roads. We routinely assist Water Operators and other engineers to address water quality and treatment problems.

At the request of IEPA in May 2008, I served as coordinator and member of a four person team that performed a Comprehensive Performance Evaluation (CPE) of the Macomb, Illinois water treatment plant that was experiencing persistent violations of the turbidity regulations for drinking water. The team identified performance-limiting factors and recommended corrective action. The CPE is the first step in a two-step process developed by USEPA, known as "Composite Correction Program (CCP)", which was adopted by the Illinois Pollution Control Board as a regulatory requirement to address chronic violations of drinking water standards.

In 2010, the City of Carbondale requested that I serve as Technical Advisor for the interview process to select a person to fill the position of Water Operations Manager. Assistance included preparation of standardized questions on how to solve water treatment process operational problems, to be answered by all applicants during the interview process. I participated in all interviews and assisted with evaluation of each applicant's qualifications and responses to the standardized questions.

At the request of IEPA in 2016, I served as coordinator and member of a four person team that performed a Comprehensive Performance Evaluation (CPE) of the South Sangamon Water Commission (Sangamon County, Illinois) water treatment plant and satellite systems where persistent customer complaints about water quality were being registered. The team identified performance-limiting factors and recommended corrective action. The CPE is the first step in a two-step process developed by USEPA, known as "Composite Correction Program (CCP)", which was adopted by the Illinois Pollution Control Board as a regulatory requirement to address chronic violations of drinking water standards.

I am a Life Member of the American Water Works Association and a Life Member of the American Society of Civil Engineers. I am a member of the Illinois Potable Water Operators Association, Southwest Central Water Operators Association, Southern Illinois Water Operators Association, and the Missouri Water & Wastewater Conference.

I hold a Merchant Marine 50 Ton Master's license issued by the United States Coast Guard, with a sailing endorsement. I earned a separate United States Coast Guard certification, by written examination, for Celestial "Ocean" Navigation 500/1600 Gross Tons.

… end … qualifications and experience …

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Pollution Control Board

Attachment 1

PUBLIC WATER SUPPLIES: PROPOSED NEW
35 ILL. ADM. CODE 604
R18-17 (RULEMAKING – WATER)

SECOND HEARING, THURSDAY, NOVEMBER 16, 2017 AT 9:00 A.M.
CHICAGO AND SPRINGFIELD BY VIDEOCONFERENCE
IPCB SPRINGFIELD HEARING ROOM
CONFERENCE ROOM 1244 N, 1ST FLOOR
1021 N. GRAND AVE. E.
NORTH ENTRANCE

PRE-FILED TESTIMONY
SUBMITTED BY:

Capt. Michael D. Curry, PE.
As an individual
803 South Paul Street
Nashville, IL 62263
Work Ph. 618-327-8841
mcurry@curryassociates.com

distribution systems

Experimental tests and utilities' practical experience highlighted the importance of chloride-to-sulfate mass ratio (CSMR) in the control of lead leaching to potable water. The effect of higher CSMR was demonstrated in bench-scale experiments using brass coupons and lead solder–copper pipe joints, with the amount of lead leaching to water increasing by factors of 1.2–2.7 and 2.3–40.0, respectively. Anion exchange treatment, a switch in coagulant type, and other seemingly innocuous treatment steps can result in significant changes in CSMR. Practical data collected at three US utilities confirmed that alterations in CSMR can trigger serious lead contamination incidents.

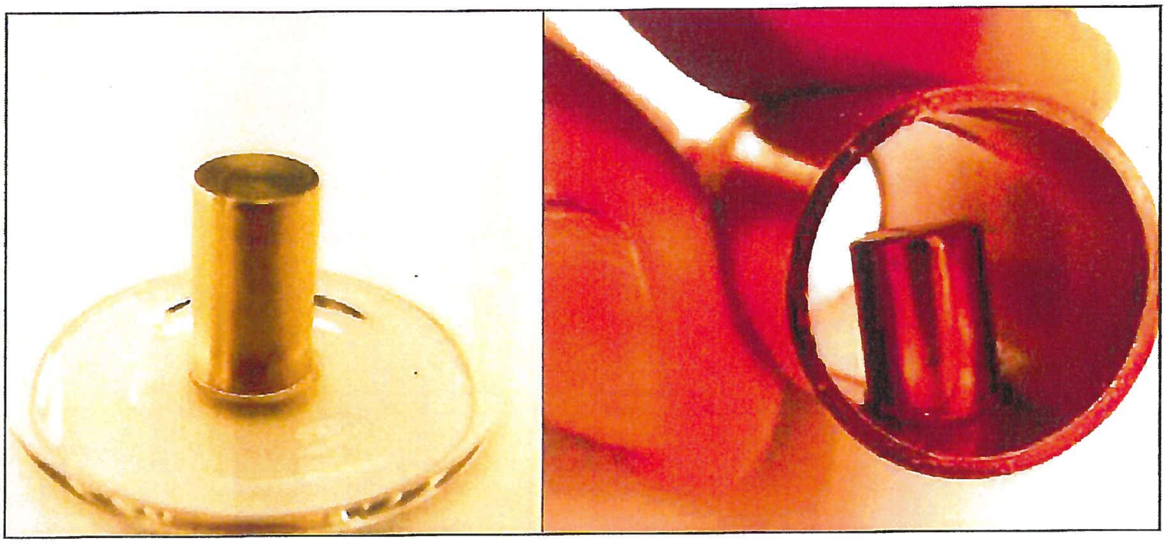
$FeCl_3$
PACl

Chloride-to-sulfate mass ratio and lead leaching to water

BY MARC EDWARDS AND
SIMONI TRIANTAFYLLIDOU

Increasing evidence indicates that lead and copper corrosion can be strongly influenced by seemingly innocuous changes in water treatment. It has long been understood that removal of natural organic matter can sometimes increase the likelihood of copper pitting (Edwards et al, 1994). More recently, research established that in Washington, D.C., a switch from free chlorine to chloramine disinfection caused serious problems with lead leaching to water from lead pipe, solder, and brass materials (Lytle & Schock, 2005; Edwards & Dudi, 2004).

Conceptually, modern corrosion control attempts to reduce leaching from lead pipe, solder, and brass materials by encouraging formation of low-solubility lead hydroxyl-carbonate and phosphate films on the plumbing material surface (e.g., Schock et al, 1996; Schock, 1989). Practically, it is understood that this is an oversimplification of reality. Changes to water that alleviate leaching for one lead-bearing material can worsen leaching in others, and issues such as galvanic corrosion require specialized understanding suspected to be important in some instances (Edwards & Triantafyllidou, 2006; Dudi, 2004; Lytle & Schock, 1996; Britton & Richards, 1981). Thankfully (and in spite of the gaps in current fundamental understanding), lead leaching in the majority of systems has responded favorably to stock cures such as raising pH, increasing alkalinity (i.e., dissolved inorganic carbon), or adding orthophosphate corrosion inhibitors. Recently, however, the authors encountered some unconventional lead corrosion problems that did not respond favorably to stock cures, instigating a literature review of galvanic corrosion and chloride-to-sulfate mass ratio (CSMR) to provide potential insights to the problems.



In the experimental setup for 5% leaded brass, a nongalvanic brass coupon was epoxied to the bottom of a glass vial (left) to study corrosion of brass by itself. A brass coupon was galvanically connected to a type-M copper tube (right) to study galvanic corrosion of the brass and copper connection.

LITERATURE REVIEW

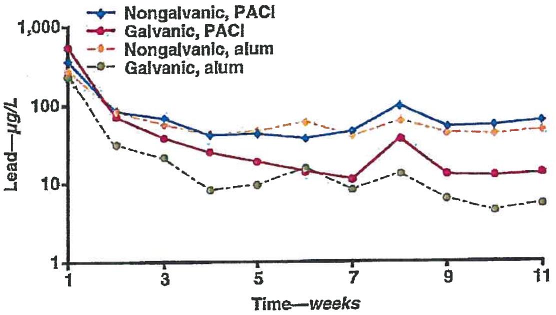
Galvanic corrosion of solder–brass and solder–copper connections. The literature is not in agreement on the potential importance of connections between dissimilar metals as a cause of problems with lead contamination. As background to the debate, Dudi (2004) asserted that in the absence of a connection to copper, corrosion of pure lead pipe is a relatively straightforward phenomenon. It proceeds with lead oxidation (anodic reaction) and oxygen reduction (cathodic reaction) occurring in relatively close proximity over the pipe surface. The OH^- produced via the cathodic reaction is at least partly neutralized by the acid produced via the anodic reaction, resulting in a slight increase or no change in the pH of water contacting the lead pipe. When lead pipe is connected to copper, the anodic and cathodic reactions are separated. The lead material becomes anodic and is sacrificed, whereas the cathodic reactions occur over the surface of the copper. In this situation, lead leaching to water could increase because of a higher corrosion rate and/or a lower pH at the surface of the lead material. Because lower pH tends to prevent passive film formation on lead surfaces, high galvanic currents could be somewhat self-perpetuating.

A high chloride-to-sulfate mass ratio attributable to coagulant change can trigger galvanic corrosion of lead solder and cause hazardous levels of lead in drinking water.

It is instructive to examine the studies that investigated galvanic corrosion of leaded plumbing materials in relation to drinking water contamination. The work of Reiber and Dufresne (2006) and Reiber (1991) concluded that galvanic effects are short-lived and of relatively little consequence. These studies never took direct measurements of lead leaching to drinking water but relied on electrochemical measurements that were imperfect predictors of potential lead contamination. Moreover, both sets of experiments were conducted using Seattle (Wash.) tap water or Seattle tap water amended with extra sulfate, which is not representative of the range of US drinking water. Furthermore, the Reiber work was conducted under continuous turbulent flow conditions (velocity of 0.25 m/s in the 1991 study). The constant flow eliminated buildup of acidic pH values at lead surfaces during stagnation, a factor deemed critical to galvanic problems occurring in practice (as described by Dudi, 2004).

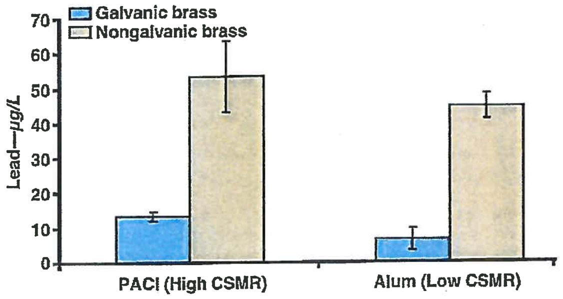
Earlier research suggested that the consequences and longevity of galvanic corrosion are highly dependent on many of the factors thought to be important by Dudi (2004). An English study that examined various synthetic waters noted the importance of chloride and sulfate levels (Oliphant, 1983). Chloride stimulated attack on lead when the lead was galvanically connected to copper, whereas chloride tended to protect leaded materials when they were not connected to copper. Sulfate, on the other

FIGURE 1 Lead release (log scale) versus time for galvanic and nongalvanic brass samples when no inhibitor was added to the water (control condition)



PACl—polyaluminum chloride

FIGURE 2 Effect of galvanic connection on lead release from brass in PACl-treated water versus alum-treated water when no inhibitor was added to the water (control condition)



CSMR—chloride-to-sulfate mass ratio, PACl—polyaluminum chloride

The values reported are averaged from weeks 5 through 11 of the experiment. Error bars represent 95% confidence intervals.

hand, was found to inhibit corrosion of lead-bearing materials both in isolation and in galvanic connections to copper. Analysis of the corroded surfaces by scanning electron microscopy showed that sulfate had a profound effect on the physical form of the corrosion product layer, changing it from needlelike crystals to flat platelets that were deemed more protective. Formation of the more protective layer required sufficient sulfate to overcome the negative effects of chloride. As with Reiber's work, the Oliphant research never measured lead leaching directly but based conclusions on galvanic current measurements under continuous flow conditions.

CSMR. Followup studies by Gregory (1985) using the Oliphant apparatus for 38 real waters in England reinforced the importance of the relative amount of chloride to sulfate in producing sustained, high-galvanic voltages that sacrificed lead plumbing when connected to copper. Gregory developed a concept of CSMR to explain this dependency, with a formula and illustrative calculation for a water containing 10 mg/L Cl^- and 20 mg/L SO_4^{-2} as shown below:

$$\text{CSMR} = \frac{[\text{Cl}^-]}{[\text{SO}_4^{-2}]} = \frac{10 \text{ mg/L Cl}^-}{20 \text{ mg/L SO}_4^{-2}} = 0.5 \qquad (1)$$

In this example, the CSMR is equal to 0.5. Gregory verified Oliphant's previous finding that high chloride relative to sulfate (yielding CSMRs > 0.5) tended to increase galvanic corrosion of lead solder connected to copper pipe. Gregory also studied the effect of inhibitors and determined that zinc (alone or with orthophosphate) was most effective in reducing the voltage of galvanic connections, whereas orthophosphate was relatively ineffective in stopping this type of attack. If waters were highly conducive to sustained galvanic voltages because of an elevated CSMR and other factors, however, the benefits of zinc were not always adequate in reducing corrosivity (Gregory & Gardiner, 1985). Again, no measurements of actual lead leaching to water were made, and the experiments were conducted under continuous flow (100 mL/min).

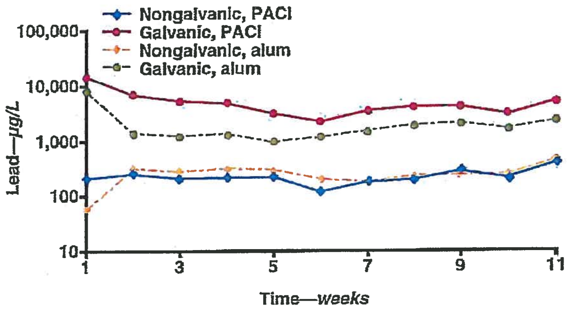
In a utility survey during the initial rounds of the US Environmental Protection Agency (USEPA) Lead and Copper Rule (LCR), Dodrill and Edwards (1995) independently determined that as the relative concentration of chloride to sulfate increased in a water supply, a utility was more likely to have a higher 90th-percentile lead concentration. In fact, for a subset of utilities studied in depth, 100% of utilities (12 out of 12) with CSMRs below 0.58 met the lead action limit of 15 µg/L, whereas only 36% of utilities (4 out of 11) with CSMRs above 0.58 were in compliance. The critical CSMR level cited for adverse effects on lead leaching in the Dodrill and Edwards study (0.58) was remarkably similar to the level identified as causing galvanic corrosion of lead (0.5 mg Cl^-/mg SO_4^{-2}). Other laboratory experiments (Dudi, 2004; Himdi et al, 1994) as well as anecdotal evidence from specific US utilities (AWWA, 2005; Kelkar et al, 1998) supported the hypothesis that lead release was affected by higher ratios of Cl^- to SO_4^{-2} (Table 1).

Study objectives. This literature review uncovered substantial data on the potential importance of the CSMR but found that well-controlled experimental studies and mechanistic insights were limited. In order to provide more insight and overcome some limitations of prior work, the current study had five objectives:

- conduct well-controlled experiments of several weeks' duration to rigorously test the longevity of galvanic corrosion relative to lead contamination,
- assess the relative effects of chloride and sulfate by directly measuring lead release into drinking water at different CSMRs,

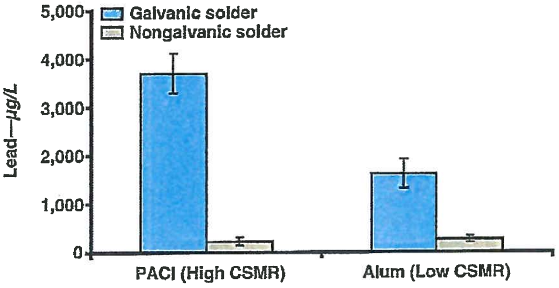
- evaluate the role of inhibitors in mitigating lead leaching,
- test the hypothesis of Dudi (2004) regarding very low pH at the surface of the lead anode as a potential mechanistic explanation of the galvanic acceleration in corrosion, and
- conduct field investigations demonstrating the serious potential public health implications when elevated CSMRs are present in water.

FIGURE 3 Lead release (log scale) versus time for galvanic and nongalvanic solder samples when no inhibitor was added to the water (control condition)



PACl—polyaluminum chloride

FIGURE 4 Effect of galvanic connection on lead release from solder in PACl-treated water versus alum-treated water when no inhibitor was added to the water (control condition)



CSMR—chloride-to-sulfate mass ratio, PACl—polyaluminum chloride

The values reported are averaged from weeks 5 through 11 of the experiment. Error bars represent 95% confidence intervals.

MATERIALS AND METHODS

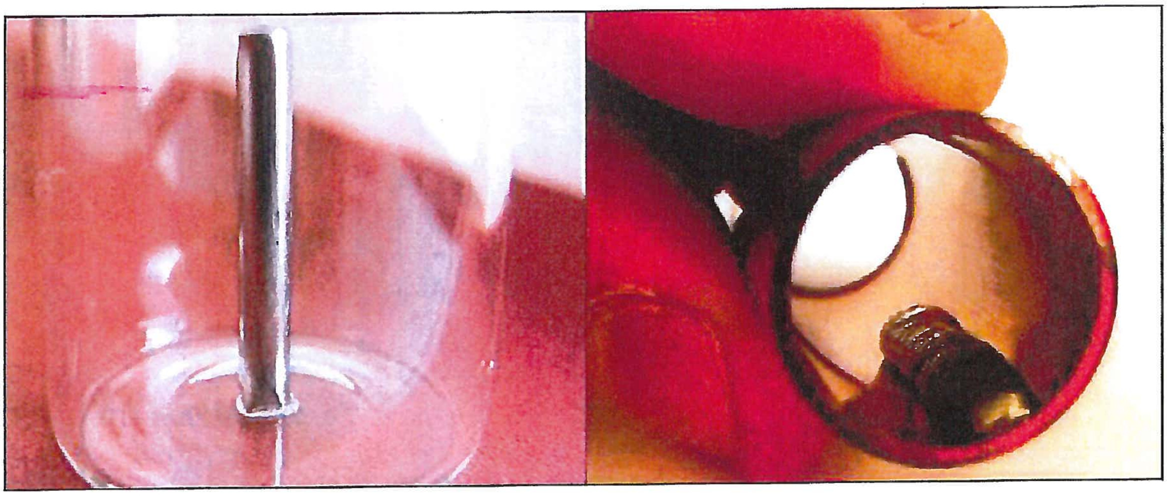
To address the first four goals, bench-scale experiments were undertaken for 11 weeks. Real waters originating from the same raw source and treated with polyaluminum chloride (PACl) or alum were compared head to head in terms of lead leaching from brass (5% lead content) and 50:50 lead–tin solder. Both leaded materials are present in home plumbing as well as in the publicly owned distribution system, where they typically are in direct electrical connection to copper pipe.

Material content. New brass fixtures, such as faucets, are considered major contributors to lead contamination of tap water (Kimbrough, 2001; Lytle & Schock, 1996; Mariñas et al, 1993). One of the most common types of brass used in faucets is C83600, an alloy with a lead content of 5% by weight. In this test, small C83600 brass coupons of 0.64-cm (0.25-in.) diameter and 0.97-cm (0.38-in.) height were fabricated from brass rods. The coupons were epoxied to the bottom of a 46-mL glass vial to study corrosion of brass by itself (see photo on page 97). This vial was filled halfway with test water in order to achieve a ratio of brass surface area to water volume of 1.4×10^{-2} sq in./mL. To simulate brass galvanically connected to copper, identical brass coupons were squeezed into a hole machined into a copper type M pipe coupon of ¼-in. nominal diameter and 2.0-in. height. All other aspects of exposure were the same for this sample. If anything, the brass galvanically connected to the copper had 14% more surface area exposed to the water because no epoxy was used on the bottom surface.

Solder wire (50:50 lead–tin) pieces of 3.2-mm (0.125-in.) diameter and 22-mm (0.854-in.) height were epoxied to the bottom of a 46-mL vial (see photo on page 100), which was then filled halfway with 25 mL of test water. To simulate the galvanic connection between copper pipe and solder at joints, an identical piece of solder wire was melted onto the inside surface of a copper tube. It is estimated that the solder connected to the copper pipe had approximately 40% more surface area exposed to the 25 mL of test water compared with solder by itself.

Test water. Test water was obtained by weekly shipment of raw water from the Greenville (N.C.) Utilities Commission (GUC) treatment plant. Collected water was separated and subjected to two simulated treatments. Treatment involved coagulation with either PACl or alum, ozonation, filtration, fluoride addition, chloramination, and final pH adjustment. The pH for both treatments was adjusted to pH 7.7 ± 0.1. The two waters were identical, except that one had been treated with PACl and the other had been treated with alum (see illustration on page 107). Because PACl adds chloride to the water, it increases the ratio of chloride to sulfate, whereas alum adds sulfate, thereby decreasing the ratio. The two CSMR values obtained in the lab were identical to those obtained for finished GUC water (GUC currently uses alum coagulation but in the past used PACl coagulation). The two CSMR ranges are reported later in the case study section.

With the exception of ozone, which was produced on site, all chemicals were provided by the Greenville treat-



In the experimental setup for 50:50 lead–tin solder, a nongalvanic solder coupon was epoxied to the bottom of a glass vial (left) to study corrosion of the solder by itself. A solder coupon was galvanically connected to a type-M copper tube (right) to study galvanic corrosion of the solder and copper connection.

ment plant. Doses, timing of addition, and duration of treatments were selected to simulate (to the extent possible at bench scale) the full-scale treatment practice. Tests of finished water ultraviolet absorbance at 254 nm (UV_{254}) at bench scale compared favorably with those at full scale, providing some reassurance that the simulated treatment was similar to that at full scale. Slightly more UV_{254} was removed by alum coagulation because of the lower coagulation pH inherent for that chemical, relative to PACl.

Each water was subjected to four levels of corrosion control: (1) no inhibitor, (2) orthophosphate dosed at 1.0 mg/L as P (current Greenville treatment), (3) orthophosphate dosed at 1.0 mg/L as P and zinc dosed at 0.5 mg/L as Zn^{+2}, and (4) zinc dosed at 0.5 mg/L as Zn^{+2}.

Number, protocol, and frequency of tests conducted. In summary, two leaded materials (solder and brass) under two connections to copper (galvanic versus nongalvanic connection) were exposed to two water conditions (PACl versus alum treatment) under four inhibitor options. Each test was performed in triplicate (2 × 2 × 2 × 4 × 3) for a total of 96 tests (inside 96 glass vials) conducted overall. All glass vials were kept at room temperature and out of light throughout the testing period.

Exposure of the plumbing materials to water was via a static "fill-and-dump" protocol three times per week (Monday/Wednesday/Friday). The water from each test condition was collected throughout the week, and the unfiltered composite was analyzed for metals. Metals analysis was performed via inductively coupled plasma mass spectrometry. In addition to metals analysis, pH measurements were taken for water near the brass and copper surfaces using a flat membrane pH microelectrode.[1]

TABLE 1 Key water quality parameters, CSMR, and LCR lead monitoring (where applicable) for selected case studies

Study	Water pH	Alkalinity *mg/L as $CaCO_3$*	Corrosion Inhibitor	CSMR Range Before/After Coagulant Change	90th-Percentile Lead Before/After Coagulant Change *µg/L*	Reference
Bay City, Mich.*	9.1–9.3	30–40	Data not available	1.0–2.0/0.4–0.6	> 15/< 15	Kelkar et al, 1998
Columbus City, Ohio	7.7–7.9	30–45	Zinc orthophosphate	0.82–1.50/0.29–0.49	33/3	AWWA, 2005
Virginia Tech study	8.5	38.6	One condition with orthophosphate, all others with no inhibitor	0.79 versus 19.8 in experiments	NA	Dudi, 2004
University of Colorado study	7.8	Two conditions: 45 and 90	No inhibitor	Varied from 0.02 to 0.2 in experiments	NA	Himdi et al, 1994

$CaCO_3$—calcium carbonate, CSMR—chloride-to-sulfate mass ratio, NA—not applicable, LCR—Lead and Copper Rule

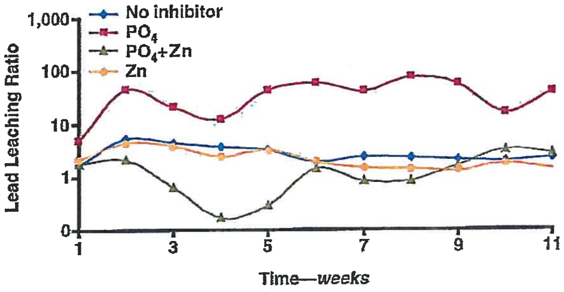
*Finished water quality parameters for Bay City reflect past conditions, at the time of high CSMR.

RESULTS AND DISCUSSION

Role of galvanic connection and exposure time. A comparison of lead release from samples with and without a connection to copper pipe provides direct insight into galvanic effects. For brass, the enhancement to lead leaching resulting from the galvanic connection was 52% in the water with high CSMR only during the first week of testing. Surprisingly, under all other conditions and times, the galvanic connection reduced lead leaching from the brass (Figure 1). Brass is close to copper in the electrochemical series, and, in exceptional circumstances, brass can even be cathodic to copper, in which case the galvanic connection reduces lead leaching both in theory and practice (Triantafyllidou, 2006; Dudi, 2004). This might have been the case here, because the galvanic connection between brass and copper reduced lead leaching by a factor of 4 at high CSMR and by a factor of 7 at low CSMR, for average data from weeks 5–11 of the experiment (Figure 2). It is also possible that the higher monitored levels of copper in the water with the galvanic connection to copper pipe somehow acted to reduce lead leaching from the proximate brass (copper, zinc, lead) alloy. After the first week of exposure, lead release from brass dropped markedly (by a factor of 3–8) in both the presence (galvanic) and absence of copper pipe (nongalvanic connection). However, the drop was more pronounced in the presence of copper pipe (Figure 1).

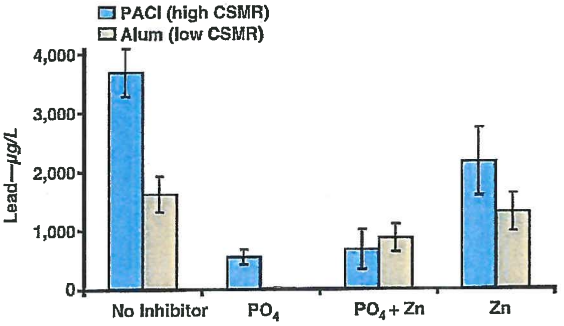
In the case of solder alone, the galvanic connection increased lead leaching by 6 times (low CSMR) to 16 times (high CSMR) over the duration of the study (Figures 3 and 4). The greatest enhancement to leaching from the connection to copper (66 times) occurred during week 1 and for the high CSMR water, with 14,400 µg/L lead released in the galvanic connections versus 220 µg/L in solder alone. Indeed, the water exposed to the solder galvanically connected to copper became very turbid, whereas turbidity was not visually observed for solder alone (see the photo on page 106). By week 2, the galvanic enhancement was 27 times for the high CSMR condition (low sulfate) and only 4 times for the low CSMR (high sulfate). This was consistent with the observation of others (Gregory, 1985; Oliphant, 1983) that waters with high sulfate passivate galvanic attack for lead. It may also explain the rapid passivation that was observed in a previous study (Reiber, 1991) because extra sulfate was added to that water. In the current study, however, the galvanic effect was much more sustained in the water with high CSMR; the lowest observed enhancement to lead leaching was 14 times during weeks 5 and 9 of the experiment.

FIGURE 5 Lead leaching ratio versus experimental time for galvanic solder



PO_4—phosphate, Zn—zinc

FIGURE 6 Lead release versus corrosion control treatment for galvanic solder in PACl-treated water and alum-treated water, averaged from weeks 5 to 9 of the experiment



CSMR—chloride-to-sulfate mass ratio, PACl—polyaluminum chloride, PO_4—phosphate, Zn—zinc

Error bars denote 95% confidence intervals.

Effect of CSMR and inhibitors on lead leaching from solder galvanically connected to copper. In order to directly compare the relative effect of higher CSMR for each test water, a lead-leaching ratio, $R_{(Pb)}$, was calculated. $R_{(Pb)}$ was defined as the amount of lead released in PACl-treated water (high CSMR), divided by the amount of lead released in alum-treated water (low CSMR):

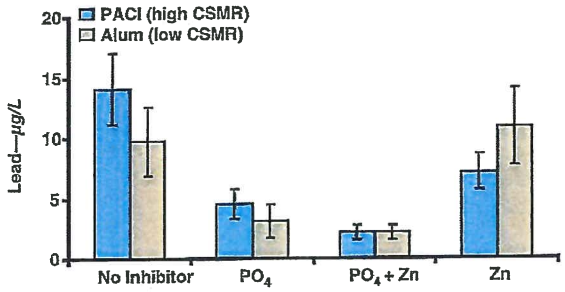
$$R_{(Pb)} = \frac{\text{Pb release}_{\text{in PACl water}}}{\text{Pb release}_{\text{in alum water}}} \tag{2}$$

From this perspective, PACl-treated water typically increased lead leaching by 1.5 to 3 times, relative to alum-treated water for the case with no inhibitor.

When orthophosphate was added to the water, however, a much more dramatic difference of approximately 40 times (on average) was noted for the duration of the study (Figure 5). For instance, with orthophosphate, during week 1 of the experiment, more than 19,000 µg/L lead was released in the PACl-treated water. Use of the same inhibitor in alum-treated water released only 490 µg/L lead. By week 7, solder released just 11 µg/L in the alum-treated water, whereas it released 460 µg/L lead in the PACl-treated water.

In general, the inhibitors were ineffective in countering the adverse effects of higher CSMR in PACl-

FIGURE 7 Lead release versus corrosion control treatment for galvanic brass in PACl-treated water and alum-treated water, averaged from weeks 5 to 9 of the experiment



CSMR—chloride-to-sulfate mass ratio, PACl—polyaluminum chloride, PO_4—phosphate, Zn—zinc

Error bars denote 95% confidence intervals.

treated water. The exception was the condition with zinc orthophosphate, for which alum-treated water had higher lead leaching in 5 out of 11 weeks of testing ($R_{(Pb)}$ <1 in Figure 5).

Indeed, in weeks 5 through 9, the higher CSMR did not increase average lead leaching when zinc orthophosphate was used (Figure 6). Among the inhibitors tested, orthophosphate alone was most effective in reducing the concentration of lead leached, regardless of CSMR (Figure 6). Zinc orthophosphate was the second most effective corrosion inhibitor, whereas zinc alone was the least effective corrosion inhibitor.

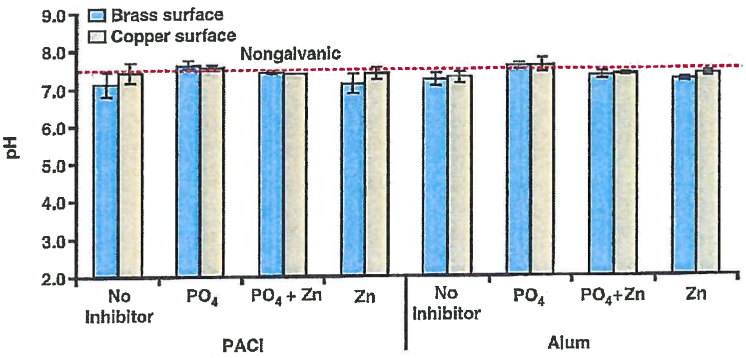
These findings were not consistent with expectations based on prior work (Gregory & Gardiner, 1985; Oliphant, 1983), which measured galvanic corrosion but did not measure lead leaching. These previous studies found orthophosphate ineffective and zinc effective in reducing galvanic current/voltage. This may reinforce the importance of directly measuring lead leaching to water. Future research should consider this potential discrepancy in greater detail.

Effect of CSMR and inhibitors on lead leaching from brass galvanically connected to copper. In a comparison of PACl and alum treatments for both the no-inhibitor and orthophosphate cases, PACl-treated water was generally more aggressive toward lead release by approximately 50% in the long term (Figure 7). When Zn^{+2} was the inhibitor, the exact opposite effect was observed, i.e., the water treated with alum proved to be more corrosive, as evidenced by an average of 50% more lead in the water versus PACl treatment. For the case of zinc orthophosphate, no difference between PACl and alum treatments was observed (Figure 7). Even though these trends were observed for the case of lead leaching from galvanic brass in PACl and alum treatments, they were not significant at 95% confidence (error bars plotted, Figure 7).

A comparison of the different corrosion inhibitors (regardless of coagulation chemical) indicates that addition of zinc orthophosphate was the most effective lead corrosion control strategy for brass connected to copper. Addition of orthophosphate alone was the second most effective condition, whereas addition of zinc alone was the least effective. The control condition without inhibitor was the most aggressive (Figure 7).

Mechanistic insights via pH microelectrode measurements. Measurement of pH provided mechanistic insight into the observed trends. All pH measurements were taken after 48 h of exposure to the test waters during week 11. Measurements of pH were taken near the surface of brass and solder (within 1 mm of the surface), near the surface of the copper tube in the galvanic samples, and in the bulk water for all conditions.

FIGURE 8 Local pH measurements after 48 h of exposure for the 5% leaded brass samples galvanically connected to copper pipe



PACl—polyaluminum chloride, PO_4—phosphate, Zn—zinc

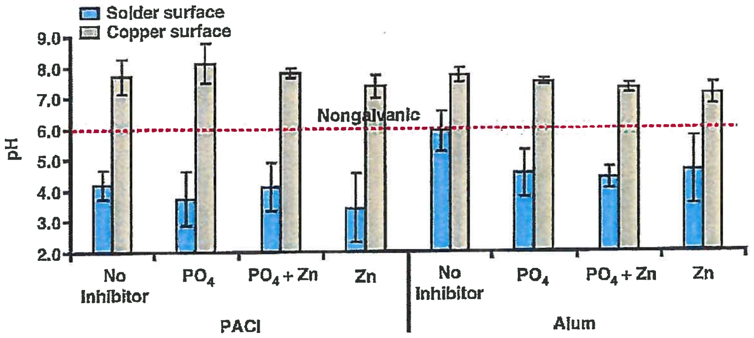
Error bars denote 95% confidence intervals. The red line represents the average pH for the nongalvanic brass samples after 48 h of exposure.

For brass, the galvanic connection reduced or had no effect on lead leaching for all the waters tested. Not surprisingly, measurements of brass and copper surface pH showed little difference. Most differences were not significant at 95% confidence, and the largest difference was only 0.3 pH units (Figure 8). In addition, for the one type of brass tested in this study (C83600, lead content of 5%), little difference was observed in the pH on the surface of brass with and without a galvanic connection to copper (Figure 8). In general, measurements of pH at the surface of the brass detected lower pH than at the surface of copper, which tended to support the fact that the brass was slightly anodic to copper at this point of the experiment.

In the case of solder, dramatic differences were apparent, consistent with the hypothesis of Dudi (2004). In every case, the pH near the surface of the solder anode was lower than that near the surface of the copper cathode at >95% confidence (Figure 9). From an initial bulk water pH of 7.6–7.8, the pH near the surface of the solder without copper present dropped to 6.1, whereas the pH near the solder surface in galvanic samples dropped to as low as 3.4 for PACl treatment (zinc inhibitor) and as low as 4.4 for alum treatment (zinc orthophosphate inhibitor) (Figure 10). These lower pH values would markedly decrease galvanic passivation and enhance lead leaching.

Aside from the contribution of drop in pH to lead leaching, other factors obviously are involved because the trend in pH, e.g., lowest for all inhibitors tested and highest for no inhibitor in the case of alum (Figure 10), was inconsistent with the trend expected on the basis of lead leaching. These other factors probably include (1) the type of solids formed at the anode and cathode, (2) differential formation of soluble lead Cl^- complexes at the anode, and (3) the magnitude of the galvanic current between the anode and cathode. In any case, the preliminary pH measurements reinforced the key role of pH reduction near the anode and suggest that further investigation of this phenomenon is warranted.

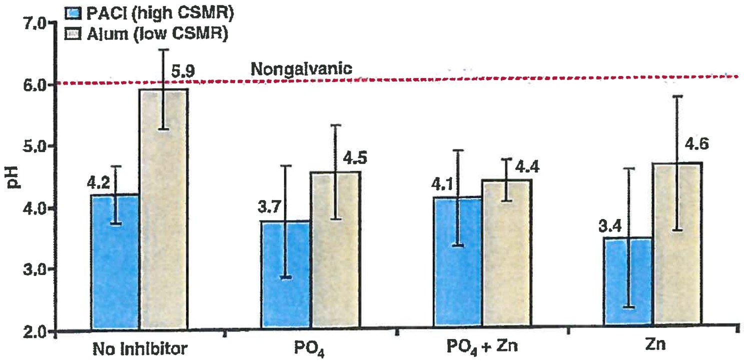
FIGURE 9 Local pH measurements after 48 h of exposure for the solder samples galvanically connected to copper pipe



PACl—polyaluminum chloride, PO_4—phosphate, Zn—zinc

Error bars denote 95% confidence intervals. The red line represents the pH of water close to the solder surface of the nongalvanic sample after 48 h of exposure.

FIGURE 10 Local pH measurements close to the surface of solder galvanically connected to copper



CSMR—chloride-to-sulfate mass ratio, PACl—polyaluminum chloride, PO_4—phosphate, Zn—zinc

Measurements were taken after 48 h of exposure to PACl-treated and alum-treated waters. Error bars denote 95% confidence intervals. The red line represents the average pH of water close to the solder surface of the nongalvanic samples after 48 h of exposure.

REAL-WORLD IMPLICATIONS AND CASE STUDIES

The knowledge and insights derived from the literature review and the experimental results were applied to cases of lead spiking in US drinking water. In all of these instances, changes in water treatment causing the lead spikes had resulted in a higher CSMR.

Stafford, Va. The county of Stafford has two water treatment facilities that have successfully used phosphate corrosion inhibitors since 1984. All homes in the utilities' monitoring program under the LCR were built with lead solder. The 90th-percentile lead was below the detection limit of 2 µg/L in LCR monitoring in 1998 and 2000, allowing the utilities to easily meet the 15-µg/L action level. The highest first-draw sample collected in 1998 was 4 µg/L, and every sample collected in 2000 was below the detection limit for lead.

To comply with new disinfection by-product (DBP) regulations, the utilities instituted treatment changes. Specifically, in April 2003, one of the treatment plants switched from alum to ferric chloride coagulant; the other plant continued to use alum. Both treatment plants changed from free chlorine to chloramine in February 2004. For LCR monitoring conducted in the summer of 2003, 38% of samples (12 of 32) contained detectable lead, 90th-percentile lead was 40 μg/L, and lead concentrations in 16% of samples were >15 μg/L, thereby exceeding the LCR action level. The highest first-draw lead was 68 μg/L. All of the samples with detectable lead came from the part of the distribution system served by water from the treatment plant that had switched from alum to ferric chloride.

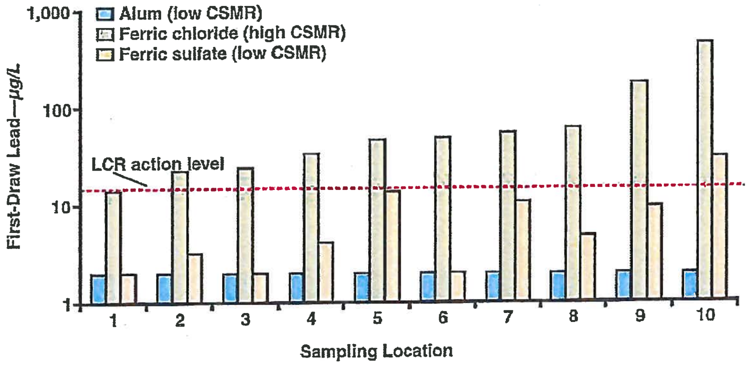
> ***Chloride stimulated attack on lead when the lead was galvanically connected to copper, whereas chloride tended to protect leaded materials when they were not connected to copper.***

The utility increased its orthophosphate inhibitor dose. Even so, in summer 2004, 46% of samples had detectable lead, and 90th-percentile lead was 54 μg/L, significantly above the 15-μg/L action level. At that point the highest sample in the LCR monitoring pool contained 441 μg/L lead. As before, all samples with detectable lead were from parts of the distribution system served by water treated with the ferric chloride coagulant.

The seemingly innocuous change in coagulant type clearly triggered a lead problem in part of the distribution system. The coagulant shift from alum (aluminum sulfate) to ferric chloride decreased the sulfate concentration of finished water from approximately 30 to 8 mg/L and increased the chloride concentration from 10 to 38 mg/L. More specifically, the CSMR of the water supply was 0.29–0.38 in 2001–02 with alum and rose to 4.75 in 2003 with ferric chloride, an increase of 12.5 times. In other words, when alum was used, the CSMR was well below the threshold of 0.58 reported by Dodrill and Edwards (1995) to be relatively nonaggressive to lead leaching; following the utility's conversion to ferric chloride, the CSMR was far above the threshold. Analysis of the problem strongly suggested that the increase in CSMR had triggered the lead problem.

A change in coagulant from ferric chloride to ferric sulfate was recommended in order to reduce the CSMR in the water while maintaining a high-level removal of DBP precursor material (Edwards, 2004). The recommended change was made in August 2004, and test samples collected that October found lead at levels below the detection limit at all but two sites in the distribution system. One sample with detectable lead of 11 μg/L came from a tap that had produced water with lead concentrations of 441 and 718 μg/L when ferric chloride was used. When LCR testing was conducted in December 2004, the 90th-percentile lead dropped to 11 μg/L, and Stafford was again under the action level. More significantly, every sampled home that had first-draw lead levels >10 μg/L before the change from ferric chloride to ferric sulfate had lower lead after the ferric sulfate treatment was instituted (Figure 11). The 90th-percentile lead dropped to 3 μg/L by the first half of 2005.

FIGURE 11 First-draw lead sampling under the LCR in Stafford County, Va., for different coagulants used in treatment



CSMR—chloride-to-sulfate mass ratio, LCR—Lead and Copper Rule

Lead measurements for alum-treated water and for all locations are actually below the 2-μg/L detection limit reported on this figure.

Durham, N.C. The city of Durham is supplied with potable water from two facilities: the Brown Water Treatment Plant (WTP) and the Williams WTP. On the basis of USEPA LCR monitoring, Durham would be classified as a city without a lead corrosion problem, as evidenced by a 90th-percentile lead level of <3 μg/L in 2004. However, an environmental assessment in the apartment of a child diagnosed with lead poisoning found 837 μg/L lead in a 100-mL water sample (Biesecker, 2006; Clabby, 2006; Gronberg, 2006). High levels of lead were detected throughout the apartment complex and in other nearby buildings. Specifically, water from 13 of 51 apartments in the complex and 11 of 19 locations within a half-mile radius of that location had lead concentrations above the action level.

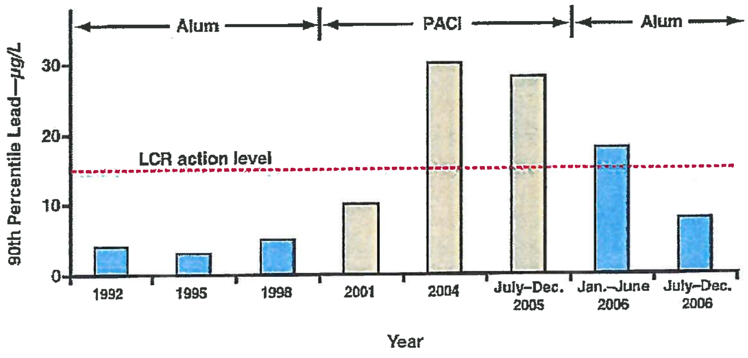
A specialized sampling protocol was used during a site visit to the apartment building and other nearby buildings, and water samples collected during the site visit showed a high CSMR of 5.0. That work demonstrated that lead solder particles trapped in the aerator were a key source of lead (as was the case for Greenville, discussed in detail subsequently). Depending on how samples are collected (e.g., flow rate, with or without the faucet aerator), potentially serious lead problems could be missed (Triantafyllidou, 2006).

In 2002, the Brown WTP, which supplied water to the apartment complex, had changed its coagulant chemical from alum to ferric chloride. This new treatment practice increased the chloride level of finished water from 9.8 mg/L in 2000 to 35.6 mg/L in 2005 while simultaneously decreasing the sulfate level from 22 mg/L in 2000 to 5 mg/L in 2005. The resulting CSMR of finished water was increased 16 times (from 0.44 before the switch to as high as 7.1 after the change) and exceeded the threshold level identified by Dodrill and Edwards (1995) and Oliphant (1983) necessary to trigger galvanic corrosion of solder. In addition to the change in coagulant, chloramines had been introduced as a secondary disinfectant in 2002.

The site visit confirmed that all other aspects of water corrosivity, including pH and orthophosphate dose, were in an acceptable range. Although earlier samples collected by the health department indicated pH < 7.0, these low pH values were not confirmed on the day the site visit was conducted. At least some nitrification was occurring in the pipes, as indicated by nitrite > 0.02 mg/L and a positive test for culturable nitrifiers. Although there was legitimate debate about the extent of the lead problem in the city and the effectiveness of the utility sampling protocol in detecting it, the Brown WTP switched from ferric chloride back to alum in July 2006 (Clabby, 2006). Durham's monitoring data indicated that lead levels in some affected homes decreased markedly within a few months, and by early 2007 only 1 of 157 samples collected were over the USEPA action limit (Baker, 2007).

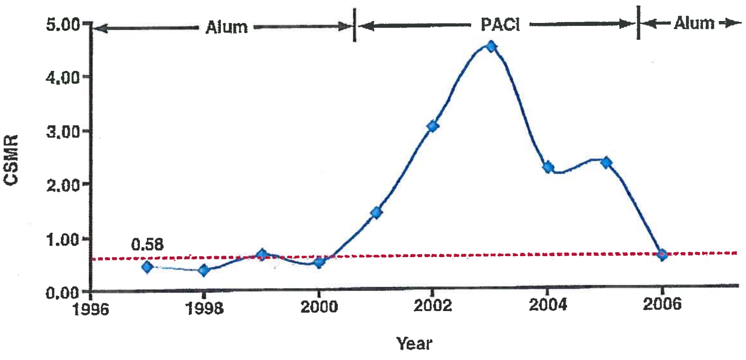
Greenville, N.C. The city of Greenville receives its potable water from the single treatment plant operated by the GUC. Sampling under the LCR from 1992 to 2001 showed that the plant was easily meeting the lead action limit throughout this period (Figure 12). However, sampling in 2004 indicated a problem with lead leaching, which was reinforced by two cases of elevated lead blood levels attributed to lead from potable water (Landers, 2006; Allegood, 2005; Renner, R., 2005; Norman et al, 2005). When tap water from an affected individual's faucet was tested, lead was measured as high as 400 µg/L (although lead was more commonly detected from this faucet at levels of 40–60 µg/L). Greenville's main distribution system does not include lead pipes; therefore, the key sources of lead in the water were leaded solder and leaded brass.

FIGURE 12 Greenville, N.C., compliance history with the LCR action level for lead



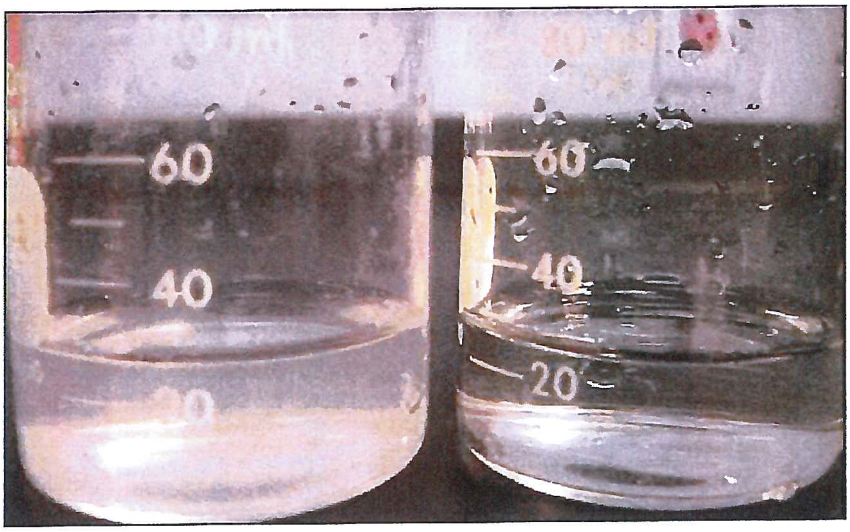
LCR—Lead and Copper Rule, PACl—polyaluminum chloride

FIGURE 13 Historical plant data for the CSMR in Greenville, N.C., finished water



CSMR—chloride-to-sulfate mass ratio, PACl—polyaluminum chloride

Numbers reported are the averages for any given year.



For the no-corrosion-inhibitor condition, water treated with polyaluminum chloride (PACl) showed turbidity after exposure to galvanic solder during week 1 of the experiment (left), in contrast to the clear condition of PACl-treated water after exposure to solder alone (right).

For the year 2004, about 22% of LCR samples contained lead above the action level. This percentage increased to 27% for the year 2005. The 90th-percentile lead concentration was relatively constant at 28–30 µg/L in 2004 and 2005.

Like many other utilities across the United States, the GUC made a series of changes in its treatment process in order to better comply with stringent federal regulations. Theoretically, any of these changes, alone or in combination, could have contributed to the change in the water's aggressiveness to lead. The utility began using chloramines rather than free chlorine as a secondary disinfectant in December 2002 in order to comply with USEPA regulations regarding DBP formation. At the same time (and because of the introduction of chloramines), finished water pH was increased from about 7.2 to 7.7 in order to optimize monochloramine formation. In August 2003, the utility instituted another treatment change and switched from chlorine to ozone as its primary disinfectant. Throughout these shifts in disinfection treatment, the plant continued to follow optimal corrosion control (as required under the LCR) using a polyphosphate/phosphate blend. After exceeding the LCR action level for lead in August 2004, the GUC started dosing an orthophosphate corrosion inhibitor to try to mitigate the lead corrosion problems.

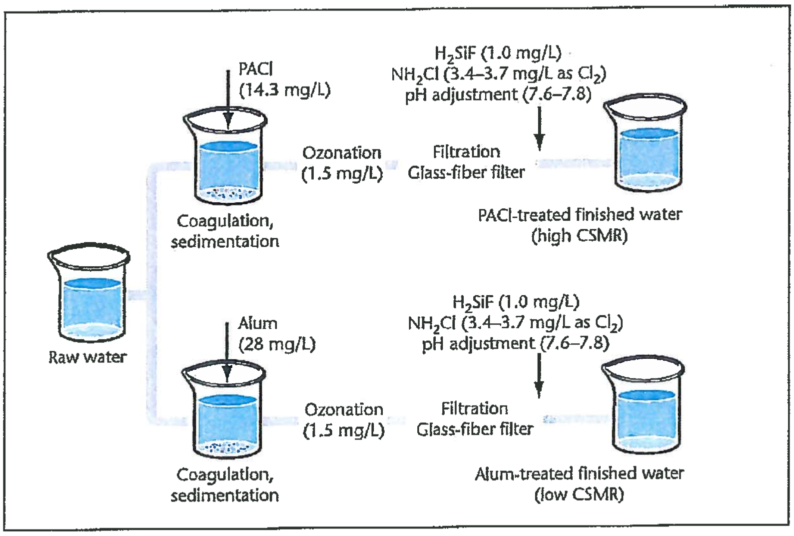
Thankfully (and in spite of the gaps in current fundamental understanding), lead leaching in the majority of systems has responded favorably to stock cures such as raising pH, increasing alkalinity (i.e., dissolved inorganic carbon), or adding orthophosphate corrosion inhibitors.

In January 2001, the facility had made another change and switched its coagulant from alum (aluminum sulfate) to PACl as a means of achieving better removal of turbidity and organic matter. The new treatment triggered an increase in the CSMR of finished water leaving the treatment plant, as demonstrated by historical data (Figure 13). After the coagulant switch, the CSMR increased to well above the threshold of 0.58 cited in the Dodrill and Edwards study; for the year 2000 (just before the change), the CSMR averaged 0.50 but increased by a factor of 9 to 4.50 during the year 2003 (Figure 13).

After considering recommendations from the bench-scale experiments reported earlier in this article, the utility returned to using alum as its coagulation chemical in April 2006. This change dropped the CSMR to 0.55 (Figure 13) and reduced the 90th-percentile lead level to 18 µg/L (a 38% reduction) during the first half of 2006 (Figure 12). The next LCR sampling, conducted during the second half of 2006, showed further reduction in the 90th-percentile lead concentration to 8 µg/L, below the action level (Figure 12).

CASE STUDY FINDINGS AND LARGER LESSONS LEARNED

A high CSMR attributable to coagulant change can trigger galvanic corrosion of lead solder and cause hazardous levels of lead in drinking water. In many cases, galvanic corrosion of lead often passivates quickly and is of little consequence (Reiber & Dufresne, 2006), but this is not always the outcome. The work described here demonstrated that specific changes in water chemistry can cause hazardous lead leaching from galvanic lead–copper connections, even in systems that had been passivated for decades at utilities practicing optimal corrosion control.



In the experimental setup for water treatment performed in the lab, half of the raw water was treated with polyaluminum chloride (PACl) as the coagulant, and the remainder was treated with alum, resulting in two finished waters with different chloride-to-sulfate mass ratios (CSMRs). Other treatment included ozonation, filtration, fluoride addition (H_2SiF), chloramination (NH_2Cl), and final pH adjustment to a range of 7.6 to 7.8.

In light of earlier work by the authors and others in Washington, D.C. (e.g., Lytle & Schock, 2005; Edwards & Dudi, 2004), it is clear that dangers of lead leaching from plumbing to water do not invariably decrease with time but can reemerge almost overnight if certain aggressive conditions occur. For CSMR, future research might demonstrate that the hazardous effects on lead leaching occur only in waters below approximately 50 mg/L alkalinity as calcium carbonate (Table 2) or that have other as yet unspecified preconditions.

It is troubling that in some North Carolina cases, the lead hazards from water were not detected by utilities but by health officials investigating cases of children with elevated levels of lead in their blood. North Carolina is one of the few health departments to implement commonsense testing of water when investigating cases of elevated blood lead in children, in marked contrast to the Centers for Disease Control and Prevention (CDC) policies that do not recommend testing of lead in potable water if the utility is meeting the LCR (Edwards & Dudi, 2004). Testing of water as a possible cause of elevated blood lead is not always straightforward; in this research, for example, work for the case studies sometimes found no lead problem at the kitchen tap, yet high lead levels (> 1,000 µg/L) were detected at a bathroom tap also used for drinking.

Although all of the case studies described in this article cite changes in CSMR that resulted from switching the coagulant chemical, recent evidence suggests that problems with CSMR are not limited to these situations. For example, anion exchange for arsenic removal replaces sulfate in the water with chloride. In a recent case in Maine, a small apartment complex started to use anion exchange for arsenic treatment and soon experienced first-draw lead values in the hundreds and thousands of micrograms per litre (Bolduc, 2006). The building had not experienced any problems with first-draw lead compliance before the anion exchange treatment was introduced. Serious health problems were avoided, in large part because of the vigilance of local health officials and regulators (Smith, 2007) but also because of the fortunate happenstance that routine LCR monitoring

TABLE 2 Summary of key water quality parameters, CSMR, and LCR lead monitoring for the three US utilities examined in depth in this study

Utility	Finished Water pH	Alkalinity *mg/L as $CaCO_3$*	Corrosion Inhibitor	CSMR Range Before/After Coagulant Change	90th-Percentile Lead Before/After Coagulant Change *µg/L*
Stafford, Va.	7.8	20	Orthophosphate	0.29–0.38/4.75	BDL/40–54
Durham, N.C.	7.1–8.2	17–34	Orthophosphate	0.44/7.1	< 3 after, but cases of lead poisoning occurred
Greenville, N.C.	7.5–8.0	12–35	Orthophosphate	0.50/1.42–4.50	< 10/28–30

BDL—below detection limit, $CaCO_3$—calcium carbonate, CSMR—chloride-to-sulfate mass ratio, LCR—Lead and Copper Rule (scheduled a month after anion exchange treatment was introduced) detected a serious problem. Even though exposure to hazardous levels of lead occurred for only a short duration, the residents' blood lead concentrations were affected and in one case exceeded CDC levels of concern (Bolduc, 2006). The authors' analysis of samples from the apartments proved that much of the lead was associated with tin-containing particles, consistent with the previous utility case studies and galvanic corrosion of lead–tin solder. It is clear that the Maine case was influenced by other water chemistry problems associated with this particular anion exchange treatment, including lower pH and lower alkalinity attributable to frequent regeneration. It is also clear that numerous anion exchange treatments for arsenic have been installed in the United States without triggering serious lead problems. Nevertheless, this incident reinforces the need for caution whenever significant changes in water treatment and CSMR are made.

CONCLUSIONS

A series of well-controlled experiments lasting 11 weeks yielded several significant findings.

- Waters with high CSMR were consistently more aggressive in increasing lead leaching from solder galvanically connected to copper. Although orthophosphate reduced the extent of lead leaching, the adverse effects of higher CSMR were dramatic (e.g., 40 times higher lead) even when phosphates were present. Zinc orthophosphate countered the adverse effects of higher CSMR, whereas zinc alone had little effect.
- Waters with higher CSMR resulted in increased lead leaching from brass. Dosing of phosphate did not mitigate the adverse effects of higher CSMR for lead leaching from brass, whereas zinc orthophosphate or zinc alone did.
- Regardless of the CSMR, orthophosphate was the most effective treatment in the case of solder galvanically connected to copper pipe, and zinc orthophosphate was most effective in the case of brass galvanically connected to copper.
- The galvanic connection of solder to copper markedly increased lead release to the water under all conditions tested for a period of almost three months in the lab. The pH close to the solder surface dropped significantly from the neutral range to as low as 3.4 for the high CSMR water and 4.4 for the low CSMR water. This finding underscores the importance of the pH drop at the anode in sustaining galvanic corrosion and increasing lead leaching, although other factors may be involved as well.
- The galvanic connection of brass to copper markedly decreased lead leaching over the long term for the one type of brass tested. The extent of the pH drop at the surface of brass (connected to copper) was relatively low.

Analysis of the extensive case studies led to the following observations:

- A switch from sulfate-containing coagulants to those containing chloride can increase CSMR, which in turn can create a lead hazard in water. Problems can arise even in systems in which solder has been passivated over a

REFERENCES

Allegood, J., 2005. Pitt Probes Boy's Lead Poisoning. *Raleigh News & Observer,* May 6.

AWWA, 2005. Managing Change and Unintended Consequences: Lead and Copper Rule Corrosion Control Treatment. AWWA, Denver.

Baker, P., 2007. Durham Lead Problems. Press conference, City of Durham, N.C., Jan. 31.

Biesecker, M., 2006. Durham Lead Fear Widens. *Raleigh News & Observer,* June 13, http://www.newsobserver.com/150/story/450089.html (accessed July 6, 2006).

Bolduc, G., 2006. Lakehurst Acres Residents' Tests Indicate Lead in Blood. *Kennebec Journal/Maine Today,* Sept. 20, http://kennebecjournal.mainetoday.com/news/local/3147510.shtml (accessed Jan. 25, 2007).

Britton, A. & Richards, W.N., 1981. Factors Influencing Plumbosolvency in Scotland. *Jour. Inst. Water Engrs. & Scientists,* 35:5:349.

Clabby, C., 2006. Durham Switches to New Water Treatment. *Raleigh News & Observer,* July 10, http://www.newsobserver.com/1170/story/458514.html (accessed July 22, 2006).

Dodrill, D.M. & Edwards, M., 1995. Corrosion Control on the Basis of Utility Experience. *Jour. AWWA,* 87:7:74.

Dudi, A., 2004. Reconsidering Lead Corrosion in Drinking Water: Product Testing, Direct Chloramines Attack and Galvanic Corrosion. Master's thesis, Virginia Polytechnic Institute & State University, Blacksburg, Va.

Edwards, M., 2004. Final Report and Recommendation. Stafford County, Va.

Edwards, M. & Dudi, A., 2004. Role of Chlorine and Chloramine in Corrosion of Lead-bearing Plumbing Materials. *Jour. AWWA,* 96:10:69.

Edwards, M.; Ferguson, J.F.; & Reiber, S.H., 1994. Pitting Corrosion of Copper. *Jour. AWWA,* 86:7:74.

Edwards, M. & Triantafyllidou, S., 2006. A Critical Evaluation of the NSF Standard 61, Section 9 Test in Relation to Lead Leaching. Proc. AWWA 2006 Ann. Conf., San Antonio, Texas.

Gregory, R., 1985. Galvanic Corrosion of Lead in Copper Pipework: Phase I, Measurement of Galvanic Corrosion Potential in Selected Waters. Water Research Centre Engineering, Swindon, England.

Gregory, R. & Gardiner, J., 1985. Galvanic Corrosion of Lead in Copper Pipework: Phase II, Effects of Treatment on Galvanic Corrosion Potentials. Water Research Centre Engineering, Swindon, England.

Gronberg, J., 2006. City Water Lead Levels Alarming Regulators. |*Herald Sun,* June 26, http://www.herald-sun.com/durham/4-747728.html (accessed June 29, 2006).

Himdi, L.; Gladwell, D.; & Edwards, M., 1994. Water Quality and Lead, Copper, and Iron Corrosion in Boulder Water. Rept. to the City of Boulder, University of Colorado, Boulder.

Kelkar, U.; Schulz, C.; DeKam, J.; Roseberry, L.; Levengood, T.; & Little, G., 1998. Mitigating Lead and Iron Corrosion Using the

period of decades with orthophosphate inhibitor. Preliminary data and theory suggest that lead leaching is most sensitive to coagulant type in treating waters with relatively low Cl^- and SO_4^{-2}, because potential shifts in CSMR are more significant in these situations. Lower alkalinity might also be an important factor, because a low buffering capacity is expected to increase the magnitude of the pH drop at the lead anode.

- The negative effects of changing CSMR are triggered not only by coagulant selection but also by other water treatment practices, such as anion exchange for arsenic removal.
- The effects of the CSMR on lead release into drinking water are currently underappreciated and understudied. The work presented here constitutes a first step in filling some of these research gaps. Additional work is needed to determine factors in water that might ameliorate adverse effects of higher CSMR, such as alkalinity and natural organic matter.

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ABOUT THE AUTHOR

Marc Edwards (to whom correspondence should be addressed) is the Charles Lunsford Professor of Civil Engineering at Virginia Polytechnic Institute & State University (Virginia Tech), 407 Durham Hall, Blacksburg, VA 24061; e-mail edwardsm@vt.edu. He has a BS degree in biophysics from the State University of New York in Buffalo and MS and PhD degrees in environmental engineering from the University of Washington in Seattle. His areas of interest include drinking water treatment, corrosion, arsenic removal, and applied aquatic chemistry. Edwards is the recipient of JOURNAL AWWA *outstanding publication awards in 1994, 1995, and 2005. Simoni Triantafyllidou is a research assistant at Virginia Tech.*

FOOTNOTES

[1] MI-406 flat membrane pH microelectrode, Microelectrodes Inc., Bedford, N.H.

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Chloride-to-Sulfate Mass Ratio Approach: A Utility's Bench-scale and Full-scale Experience. Proc. AWWA Ann. Conf., Dallas.

Kimbrough, D., 2001. Brass Corrosion and the LCR Monitoring Program. *Jour. AWWA*, 93:2:81.

Landers, J., 2006. Getting the Lead Out. *Public Works*, April 1, http://www.pwmag.com/industry-newsprint.asp?sectionID=775&articleID=284925 (accessed June 22, 2006).

Lytle, D. & Schock, M., 2005. Formation of Pb(IV) Oxides in Chlorinated Water. *Jour. AWWA*, 97:11:102.

Lytle, D. & Schock, M., 1996. Stagnation Time, Composition, pH, and Orthophosphate Effects on Metal Leaching From Brass. USEPA National Risk Management Research Laboratory, Ofce. of Res. & Devel., EPA/600/R-96-103, Cincinnati.

Mariñas, B.J.; Bogard, C.L.; & Lan, H.-T., 1993. Control of Drinking Water Lead Contamination Contributed by Brass Plumbing Fixtures. Proc. AWWA Ann. Conf., San Antonio, Texas.

Norman, E.; Robertson, E.; & Rudo, K., 2005. Elevated Blood Lead Levels in Two Children From a Possible Sole Source of Lead in Drinking Water in Greenville, N.C. Epi Notes, Vol. 2005-2, North Carolina Dept. of Health & Human Services, Div. of Public Health, Raleigh, N.C.

Oliphant, R.J., 1983. Summary Report on the Contamination of Potable Water by Lead From Soldered Joints. Water Research Centre Engineering, External Rept. 125-E, Swindon, England.

Reiber, S., 1991. Galvanic Stimulation of Corrosion on Lead–Tin Solder Sweated Joints. *Jour. AWWA*, 83:7:83.

Reiber, S. & Dufresne, L., 2006. Effects of External Currents and Dissimilar Metal Contact on Corrosion From Lead Service Lines. Rept. to US Environmental Protection Agency Region III, contract 68-C-02-069, work assignment 47. http://www.epa.gov/dclead/Grounding_Effects_Study_Final_November_2006.pdf (accessed May 4, 2007).

Renner, R., 2005. Chloramines Again Linked to Lead in Drinking Water. *Envir. Sci. & Technol.* http://pubs.acs.org/subscribe/journals/esthagw/2005/jun/science/rr_chloramines.html (accessed Jan. 11, 2006).

Schock, M.R., 1989. Understanding Corrosion Control Strategies for Lead. *Jour. AWWA*, 81:7:88.

Schock, M.R.; Wagner, I.; & Oliphant, R.J., 1996 (2nd ed.). *Corrosion and Solubility of Lead in Drinking Water in Internal Corrosion of Water Distribution Systems.* AwwaRF/DVGW-Technologiezentrum, Denver.

Smith, A.E., 2007. Personal communication.

Triantafyllidou, S., 2006. Addressing and Assessing Lead Threats in Drinking Water: Nonleaded Brass, Product Testing, Particulate Lead Occurrence, and Effects of the Chloride-to-Sulfate Mass Ratio on Corrosion. Master's thesis, Virginia Polytechnic Institute & State University, Blacksburg, Va.

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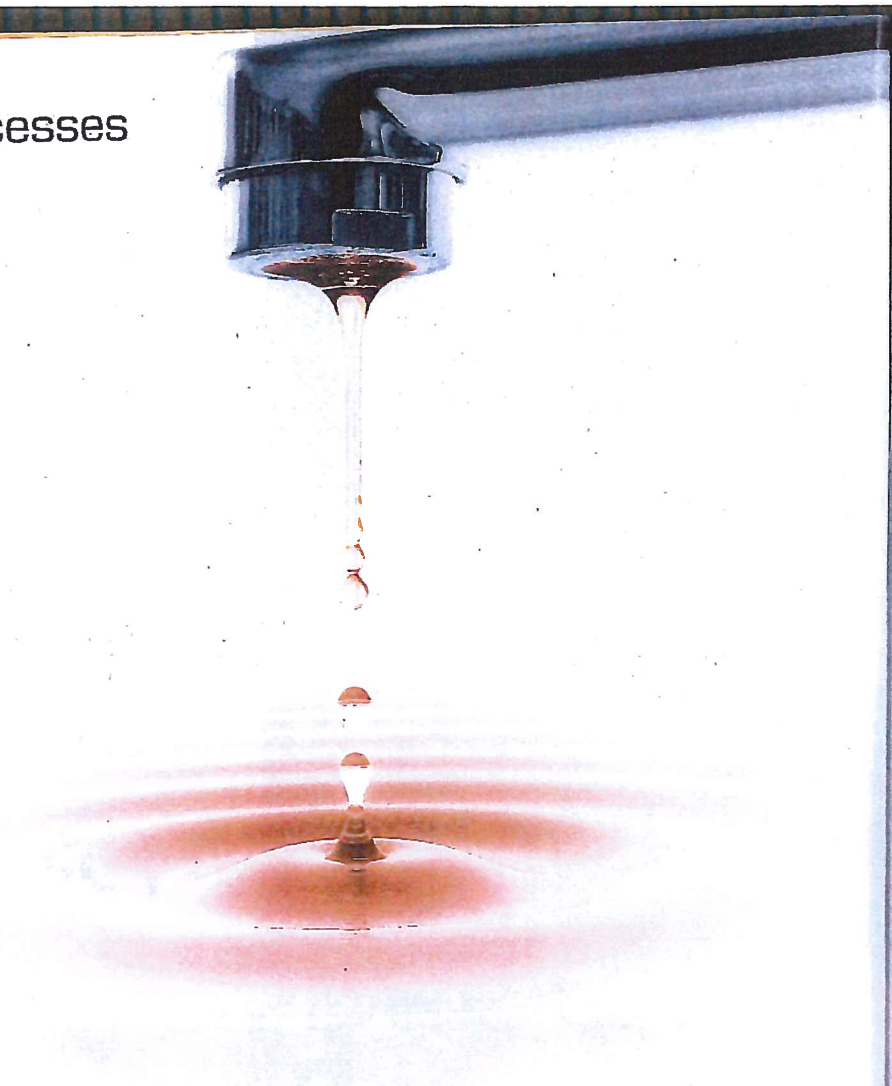
Attachment 2

PUBLIC WATER SUPPLIES: PROPOSED NEW 35 ILL. ADM. CODE 604 R18-17 (RULEMAKING – WATER)

SECOND HEARING, THURSDAY, NOVEMBER 16, 2017 AT 9:00 A.M.
CHICAGO AND SPRINGFIELD BY VIDEOCONFERENCE
IPCB SPRINGFIELD HEARING ROOM
CONFERENCE ROOM 1244 N, 1ST FLOOR
1021 N. GRAND AVE. E.
NORTH ENTRANCE

PRE-FILED TESTIMONY
SUBMITTED BY:

Capt. Michael D. Curry, PE.
As an individual
803 South Paul Street
Nashville, IL 62263
Work Ph. 618-327-8841
mcurry@curryassociates.com



SUSAN J. MASTEN, SIMON H. DAVIES, AND SHAWN P. McELMURRY

Flint Water Crisis:

What Happened and Why?

THE FLINT RIVER IS A VARIABLE WATER SOURCE AND THUS A CHALLENGE TO TREAT; OVERSIGHTS AND MISSTEPS COMBINED WITH INHERENT CHEMICAL CONDITIONS SET THE STAGE FOR THE HISTORIC WATER CRISIS IN FLINT, MICH.

There has been much in the news about the water crisis that began in 2014 in Flint, Mich., and the length of time it took for government officials to react. The elevated levels of lead found in the drinking water of residences in Flint have had a profound effect on the level of trust within the community and the state, the economy of the region, and the health and well-being of the residents of Flint and the surrounding communities. As Eric P. Rothstein so aptly stated, "Flint matters because the water utility industry can do better. The crisis, tragic in so many respects, also presents an opportunity for lasting benefit—benefit from recognizing that we are Flint" (Rothstein 2016). We have investigated the chemistry and engineering behind what happened to Flint's water, why it was corrosive, and the extent to which the system appears to be recovering. This analysis is based on an extensive review of the monthly operating reports (MORs) and other reported documents from the water treatment facilities, and from personal communications with plant operators and managers.

HISTORICAL PERSPECTIVE

The first water distribution system in Flint was privately owned and incorporated as the Flint Water Works Company in 1883 (Dunbar & May 1995). On July 8, 1897, the City of Flint passed an ordinance requiring lead pipes: "all connections with any water mains shall be made with lead pipe" (Anon. 1897).

The City of Flint purchased the Flint Water Company in 1912. By 1930, Flint River water was being treated using alum coagulation before sand filtration, with the plant rated at 28 mgd (Hardin 1932). Construction on a new treatment plant for the City of Flint began in 1952 and was completed in 1954. At that point, treatment of the Flint River included prechlorination, coagulation with alum, lime–soda ash softening, recarbonation, filtration, the addition of polyphosphate for corrosion control, and postchlorination. Taste-and-odor-causing compounds were removed using activated carbon, along with the addition of ammonia and sodium chlorite. The plant was rated at a capacity of 59 mgd, with a maximum overload capacity of 86 mgd. The 50th percentile pH, color, and turbidity of the finished (tap) water were 10.3, 2, and 0.1 ppm (silica scale; approximately equivalent to 0.02 Jtu), respectively. The total and noncarbonate hardness were 86 and 49 mg/L as $CaCO_3$ (calcium carbonate), respectively (Wiitala 1963).

In 1967, Flint began purchasing wholesale treated water from the Detroit Water and Sewage Department (DWSD). While the water quality of the Flint River was poor as a result of unregulated discharges by industries and municipalities (Leonardi & Gruhn 2001), the principal reason for the switch was to ensure a sufficient quantity of water for the growing population (Carmody 2016). After 1967, the Flint Water Service Center (FWSC) was maintained as a backup water treatment facility, treating Flint River water two to four times a year for periods of only a few days. The National Pollutant Discharge Elimination System permit allows the treated water to be discharged back into the Flint River. In 2012, the Board of Water Commissioners for the City of Detroit approved a resolution that would allow the DWSD director to enter into contractual arrangement to allow blending of treated Flint River water with that purchased from DWSD as a cost-saving measure (City of Detroit 2012). While DWSD and the City of Flint never entered into a contractual agreement, it is unclear whether blending of these two different waters actually occurred.

With the goal of reducing the costs for treated water (Felton 2016), Flint officials decided in 2013 to join the newly formed Karegnondi Water Authority (KWA), which was constructing its own pipeline to transmit raw water from Lake Huron. In the interim, the City of Flint had the option to continue to purchase treated water from DWSD (whose source was Lake Huron) or treat Flint River water at its own facility. After failing to come to an agreement on a short-term contract with DWSD, Flint decided to use water from the Flint River and treat it at the FWSC.

Many warnings and concerns were voiced regarding the use of the Flint River as a community water source. For example, Brian Larkin, then associate director of the (Michigan) Governor's Office of Urban and Metropolitan Initiatives, foretold the crisis in a Mar. 14, 2014, e-mail message to several others in the governor's office: "The expedited timeframe is less than ideal and could lead to some big potential disasters down the road." Mike Glasgow, laboratory and water quality supervisor at the plant, warned in an Apr. 25, 2014, e-mail to the State of Michigan Department of Environmental Quality (MDEQ), "I do not anticipate giving the OK to begin sending water out anytime soon. If water is distributed from this plant in the next couple weeks, it will be against my direction." Despite concerns, the FWSC switched from purchasing and distributing water from DWSD to treating water at its facility in Flint. In doing this, the source water changed from Lake Huron to the Flint River.

> Many warnings and concerns were voiced regarding the use of the Flint River as a community water source.

Within a few weeks of the switch, residents started complaining about the color, taste, and odor of their drinking water. In May 2014, they informed officials that the water was causing rashes, especially in children (MDEQ e-mail records). During this time, red water and discoloration were observed throughout the distribution system (Veolia North America 2015, Felton 2014), and there was an unusually large number of water main breaks (Fonger 2015). General Motors Corporation complained about the corrosiveness of the water on its engine parts and in October 2014 switched to using water from Flint Township instead of from Flint.

Starting in summer 2014, a number of violations occurred. *Escherichia coli* (*E. coli*) and total coliform violations resulted in the issuance of three boil-water alerts within a 22-day period during summer 2014 (Emery 2016; Fonger 2014a, 2014b). As shown in Table 1, total trihalomethane (TTHM) concentrations at several sampling locations exceeded the 80 µg/L regulatory limit during May and August 2014 (Lockwood, Andrews, & Newman 2015). As a result, the MDEQ requested a preemptive operational evaluation in September 2014 and notified Flint of an initial quarterly violation of the Safe Drinking Water Act (SDWA) Disinfection/Disinfection Byproducts (D/DBP) Rule in December 2014 (Flint Water Advisory Task Force 2016; Table 1).

In February 2015, the City of Flint sampled Flint resident Lee Ann Walters' home and found lead in her water at a concentration of 104 µg/L (e-mail correspondence between US Environmental Protection Agency [USEPA] Region 5 and MDEQ dated Feb. 26, 2015; Flint Water Advisory Task Force 2016). By Aug. 31, 2015, Marc Edwards, a professor at Virginia Polytechnic Institute and State University, had analyzed 120 samples from Flint homes. He found that 20% of the samples had lead levels that exceeded the 15 µg/L action level and that the 90th percentile was 30 µg/L (Roy 2015a). In September, a team led by a local pediatrician, Mona Hanna-Attisha, published data showing that blood lead levels (BLLs) in children increased significantly after the switch to the Flint River as a water source (Hanna-Attisha et al. 2016; Kennedy et al. 2016). In the area of Flint that had the highest lead levels in the water, the BLLs in children who were tested increased by a factor of about 2.5.

The city was required by the SDWA Lead and Copper Rule to conduct sampling for lead and copper in Tier 1 premise plumbing over six-month periods. Although not all of the homes sampled were Tier 1 sites (City of Flint 2016), the first round of sampling revealed that the 90th percentile lead concentration was greater than that observed during the previous five rounds of testing (Figure 1); by the end of the second six-month sampling period, the 90th percentile lead level was almost three times greater than that observed in the previous 15 years (Figure 1).

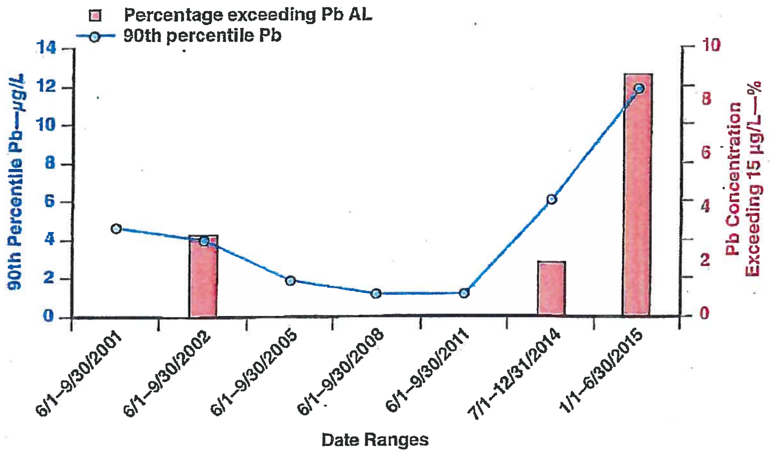
After much publicity regarding the lead problem, on Oct. 16, 2015, the source water for the City of Flint was switched back to treated Lake Huron water supplied by DWSD, with approximately 1 mg/L phosphorus to inhibit corrosion. Because the lead levels measured in the water remained high in some houses, on Dec. 9, 2015, the concentration of the phosphate corrosion inhibitor was increased by adding an additional ~2.5 mg/L phosphoric acid (P) at the FWSC.

Finally, in February 2016, information on the increase in the number of cases of Legionellosis that occurred in Flint in the summers of 2014 and 2015 was released. Ninety-one cases and 12 deaths have been confirmed in the Flint area, up from six to 13 cases a year before the switch to Flint River water (Anderson 2016). The source of the outbreak has not been definitively determined or directly connected to the Flint water system, but as noted by Anderson (2016), the illnesses began after Flint changed its water supply. Given the low residual disinfectant levels (chlorine in this case) and the presence of iron in the water in the distribution system (Veolia North America 2015, Felton 2014), along with high concentrations of assimiliable organic carbon that would have likely formed during the

TABLE 1 Total trihalomethane (TTHM) concentrations in the Flint distribution system

	TTHM concentration *µg/L*			
Location	**May 21, 2014**	**Aug. 21, 2014**	**Nov. 21, 2014**	**Aug. 18, 2015**
1	162.4	145.3	58.6	67.9
2	75.1	112	36.2	53.6
3	111.6	127.2	33.3	60.2
4	79.2	181.3	33.9	72.0
5	106.4	196.2	93.6	93.5
6	82.2	112.4	50.1	65.9
7	88.2	144.4	53.6	69.4
8	96.5	118.3	41.1	54.9

FIGURE 1 Historical data for lead concentrations in the Flint distribution system



Sampling and analyses were required for compliance with the Lead and Copper Rule.

AL—action level, Pb—lead

ozonation of the high total organic carbon (TOC) Flint River water, conditions could have been conducive to biological growth and the propagation of *Legionella* in the distribution network.

WATER TREATMENT AT THE FLINT WATER TREATMENT PLANT

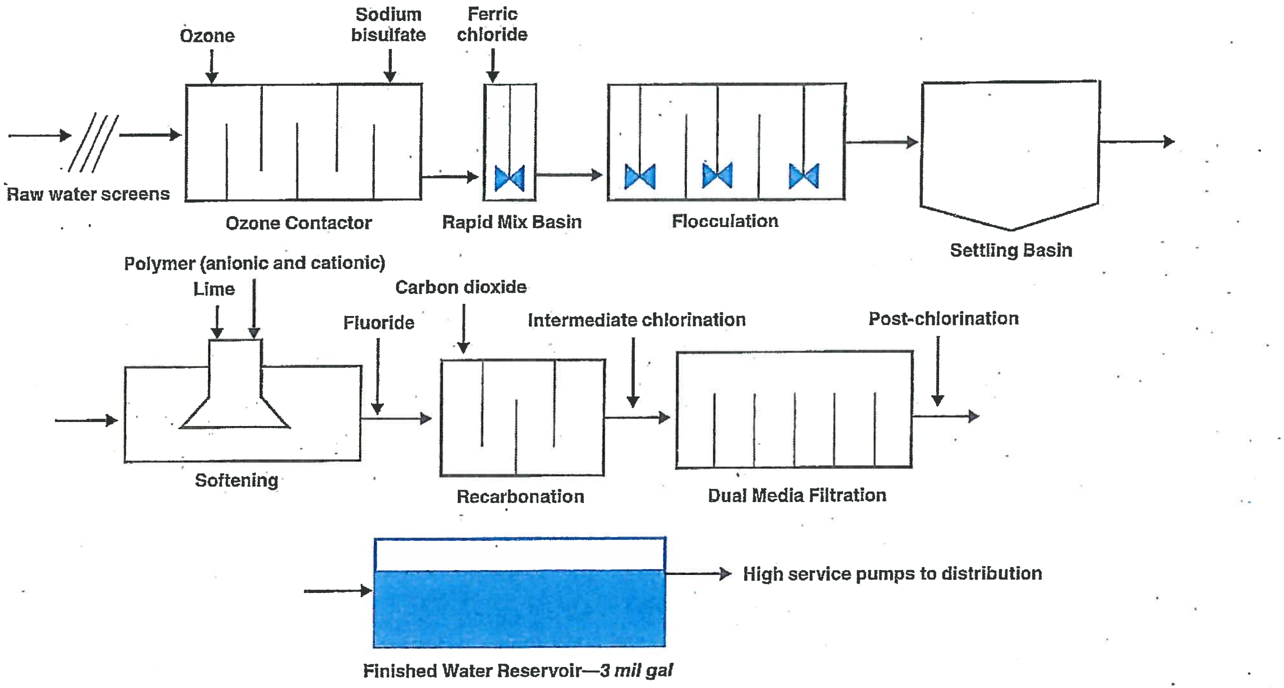
During the period from April 2014 to October 2015, the turbidity of the raw Flint River water at the FWSC plant ranged from 1.5 to 45.2 ntu (according to the MORs). The chloride level in the raw water ranged from 38 to 82 mg/L, with the monthly average values ranging from 38 to 54 mg/L. The TOC of the Flint River was reported to be 10.3 mg/L on May 22, 2014 (Lockwood, Andrews, & Newman 2014). The FWSC raw water intake is upstream of most development in Flint, but there is still some concern about industrial contaminants and sewage (Fonger 2014c).

Although numerous changes were made to the treatment process over the course of the 1.5 years of treatment, as of November 2014, when the draft Operational Evaluation Report (OER) was published, the treatment train was as shown in Figure 2 (Lockwood, Andrews, & Newman 2014). Water was drawn from the Flint River through raw water screens, then pumped into the ozonation basin. Sodium bisulfate was added in the last cell of the ozone contactor to destroy any residual ozone left in the water. The water then flowed into a rapid mix tank, where ferric chloride was added. From there, the water entered a three-stage flocculation unit followed by plate settlers. From the settling unit, water flowed into an upflow clarifier, where lime and anionic and cationic polymers were added. Fluoride was added at the outlet of the clarifier. From there, water moved into the recarbonation unit, where carbon dioxide was added to lower the pH. Chlorine was added just before dual media (sand/anthracite) filtration and again before flowing into a 3-mil-gal clearwell (Figure 2).

> It is unclear what ozone dosage was used over the majority of the treatment period because it was not recorded in the MORs until March 2015.

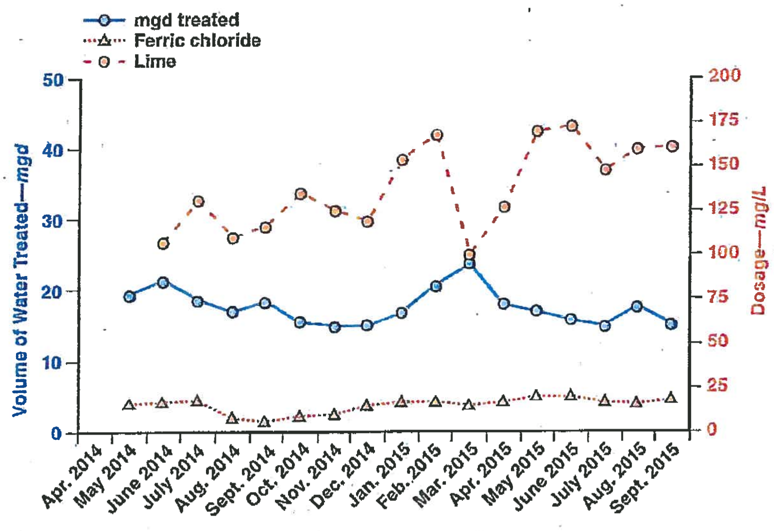
Before the switch to Flint River water, Laboratory and Water Quality Supervisor Mike Glasgow sent MDEQ staff engineers an e-mail message on Apr. 17, 2014, stating, "I do not anticipate giving the OK to begin sending out water anytime soon." While the message sounded the alarm that staffing and monitoring plans were inadequate, it has not been reported how poorly equipped

FIGURE 2 Schematic of the Flint Water Treatment Plant



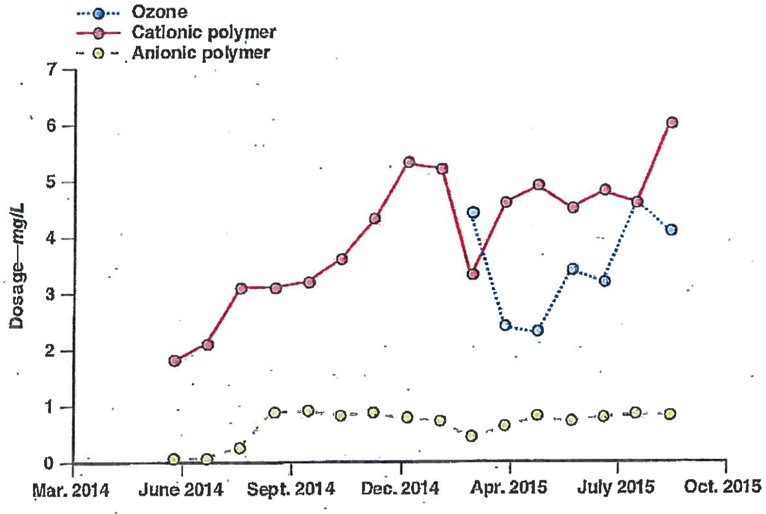
the plant was. It is clear from the MOR that the plant was woefully unprepared for full-time operation on Apr. 25, 2014. The May 2014 MOR reveals that the plant had only four to five days of polymer available to "use as a trial on two different occasions." Supervisory control and data acquisition (SCADA) upgrades were incomplete and out for bid. Filter headloss meters were not operational on the SCADA system. Also, chlorine residual monitoring equipment at the point of entry into the distribution system had not been installed, so chlorine levels would have had to have been measured by taking grab samples from the clearwell as well as from a tap in the laboratory. It appears that, on the basis of the MORs, chlorination after filtration was not used until May 17, 2014. Fluoridation was not implemented until July 2, 2014. The water utility did not have a corrosion-control plan, and it had not installed corrosion control equipment when the water was switched back to DWSD on Oct. 16, 2015. On the basis of the comments in the MORs, the filter headloss meters were never made operational.

FIGURE 3 Variability in the monthly average ferric chloride (as Fe^{3+}) and lime dosages used at the Flint water treatment plant for 1.5 years



The volume of water treated (mgd) is given for comparative purposes.

FIGURE 4 Variability in the monthly average ozone and polymer dosages used at the Flint water treatment plant for 1.5 years



The maximum dosage of the anionic polymer (P-142PWG) is 1.0 mg/L as recommended by NSF International.

Figures 3 and 4 illustrate the variability in the chemical dosages that were used during the treatment process. Bench-scale jar testing for trihalomethane (THM) removal was not completed until sometime between January and August 2015 (City of Flint 2015). Without any treatability studies on which to determine chemical dosages until late August 2015 (City of Flint 2015), it appears that plant personnel were left to attempt to address the plethora of complex water quality issues and complaints by trial and error. Significant changes were made to chemical dosages, and the reasons for these changes were often not apparent. For example, the dosage of the anionic polymer (P-142PWG) added to the lime softening process to enhance settling was initially 0.05 mg/L; the anionic polymer dosage was later increased significantly, with concentrations approaching or exceeding the maximum dosage of 1.0 mg/L as recommended by NSF International (2016). The OER issued in August 2015 (Lockwood, Andrews, & Newman 2015) states that "feeding coagulation/flocculation polymer aids" do not have "a meaningful benefit." However, while there was a slight decrease in polymer use in March 2015, both anionic and cationic polymers were used continuously until the plant was shut down in October 2015. The reasons for the increase in the lime dosage in November 2014 and then the decrease in February and March 2015 are unknown.

It is unclear what ozone dosage was used over the majority of the treatment period because it was not recorded in the MORs until March 2015. The OER (Lockwood, Andrews, & Newman 2015) states that the ozone system was not feeding optimally until "corrective modifications" were made in January 2015. The corrective modifications appear to have been "repairs to gauges and programming" to produce "proper ozone under manual operation." Repairs were planned for the first quarter of 2015 to "allow automatic operation," but it is unclear if those were made.

Bromate is a disinfection by-product formed by the reaction of bromide ion with ozone. Monthly bromate monitoring for the first year of operation was required by the D/DBP Rule and were ordered by MDEQ staff on Sept. 11, 2014. The first bromate sample was to be taken by the end of that month. The 2014 consumer confidence report (City of Flint 2014) states that the bromate levels varied from 0 to 23 µg/L, and that no violation occurred. However, as the reporting limit for bromate was 5 µg/L (Stark 2016), the bromate levels actually varied between <5 and 23 µg/L.

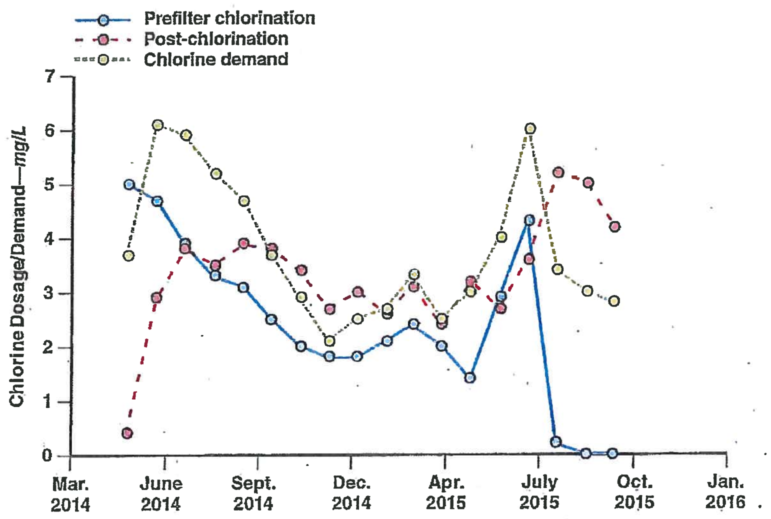
The maximum contaminant level (MCL) for bromate is 10 µg/L, as a running annual average (RAA), determined at the point of entry. No data for bromate concentrations are provided in the 2015 consumer confidence report (City of Flint 2016); however, e-mail correspondence on Apr. 6, 2015, between MDEQ staff members indicate that the RAA was "hovering just above the MCL of 10 ppb." E-mail correspondence between FWSC staff and MDEQ staff indicates that bromate results were not reported for five of the 13 months after September 2014, even though ozone was used continuously at the plant.

Disinfection was accomplished using gaseous chlorine which, as shown in Figure 2, was to be added both before and after filtration. The total chlorine dosage varied from ~5 mg/L in the winter months to >7 mg/L in the summer months (Figure 5). Not surprisingly, the chlorine demand, calculated by subtracting the chlorine residual leaving the treatment plant from the applied chlorine dosage, increased during the summer and decreased during the winter. The location of chlorine application varied significantly during the treatment period, with no post-filtration chlorination until May 17, 2015, and then no prefilter chlorination after Aug. 3, 2015. No justification for these changes was documented in the MORs. The softening bypass stream had been reduced to no greater than 20% in November 2014 in an attempt to reduce chlorine demand. The minutes of the Nov. 7, 2014, TTHM Response Planning Meeting (MDEQ e-mail correspondence) state that the bypass was discontinued "and it appears that the chlorine demand has dropped by 0.5–1.0 mg/L." However, as shown in Figure 5, this drop appears to be a part of a downward trend that occurred before this change. In summer 2015, the chlorine demand was somewhat lower than in summer 2014, but it is not clear whether this is due to eliminating the softening bypass stream or to other causes.

Since the Flint plant had not been fully operational in almost 50 years, was understaffed, and some of the staff were undertrained, it is not surprising that it was difficult to achieve effective treatment.

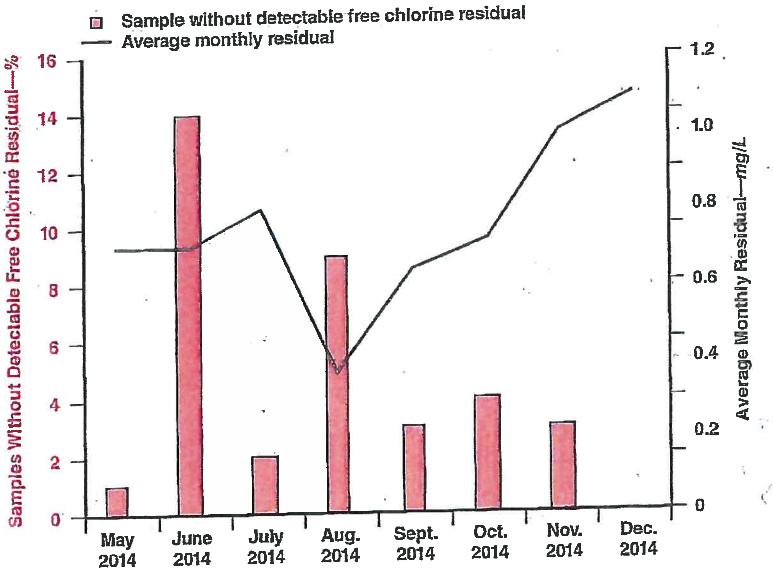
Difficulties were encountered in maintaining chlorine residuals throughout the distribution system throughout the 1.5 years of treatment and continues to be problematic, even after the change back to DWSD water. As shown in Figure 6, chlorine residuals in the treated Flint River water were low during the first few months of operation. In response to

FIGURE 5 Applied chlorine dosages and chlorine demand of treated Flint River water



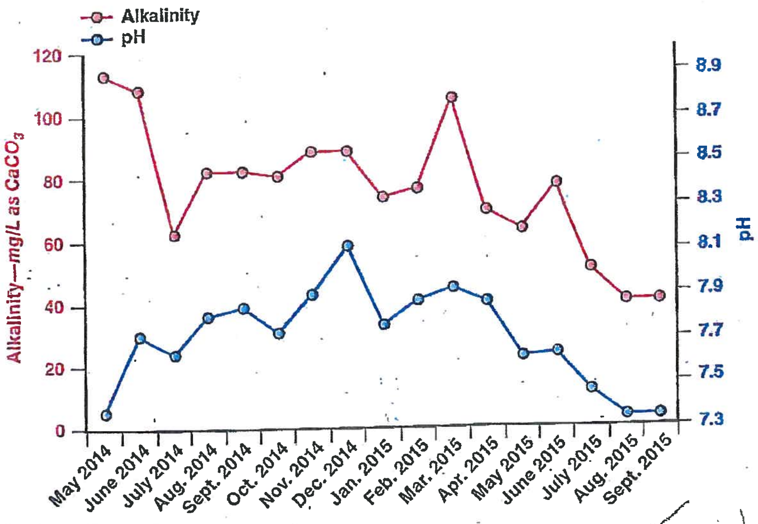
this and the detection of *E. coli*, the post-filtration chlorine dosages were increased from 0.0 to 2.9 mg/L in June 2014 and then to ~3.8 mg/L in July–October 2014, resulting in a decrease in the number of distribution system samples with no detectable chlorine residual. However, as shown in Table 1, increasing the chlorine dose resulted in increased concentrations of TTHMs. Although the FWSC reported increases in chlorine residuals after Oct. 2014, Marc Edwards reported that in August 2015, 41% of the samples his group collected had no detectable chlorine (Roy 2015b).

FIGURE 6 Chlorine residuals at monitoring sites in the Flint distribution system



Source of data: City of Flint monthly operating reports

FIGURE 7 Monthly average pH and alkalinity in the treated Flint River water



Source of data: City of Flint monthly operating reports

$CaCo_3$—calcium carbonate

This team's sampling and analysis in late October 2015 revealed that 16 of the 30 samples collected had chlorine residuals less than 0.2 mg/L and 10 had chlorine levels less than 0.1 mg/L. The US Environmental Protection Agency (USEPA) Safe Drinking Water Task Force remains concerned about chlorine residual levels in Flint's water (Emery 2016).

The 24-month source water sampling for *Cryptosporidium*, *E. coli*, and turbidity to determine bin placement required by the SDWA Long-Term 2 Enhanced Surface Water Treatment Rule was not done before the switch to Flint River water, apparently because MDEQ staff believed the Flint River was only a temporary source (MDEQ e-mail conversations), despite the fact that construction on the 80-mi KWA pipeline had not even begun in April 2014.

Attempts to address the TTHM exceedances included first eliminating the softening bypass stream in an attempt to increase TOC removal (Lockwood, Andrews, & Newman 2014). However, TTHM exceedances continued, so the anthracite media in the filters was replaced with granular activated carbon, and the ozonation system was repaired in summer 2015 (MDEQ Construction Permit W151055). TTHM levels were finally reduced, and in August 2015, only one of the eight samples taken exceeded the 80 µg/L TTHM limit (Table 1).

QUALITY OF TREATED FLINT RIVER WATER

In attempting to understand what happened in Flint, it is necessary to look not only at specific contaminants but also the general quality of the treated water. As shown in Figure 7, the pH and alkalinity of the finished water varied significantly over the 1.5 years of treatment, and for much of the time, both were quite low, especially in summer 2015. The decreases in alkalinity from June to July 2014 and over the course of the period from March to May 2015, both correspond to increases in the lime dosage (Figure 3). The reason for the change in alkalinity and pH after June 2015 is unknown, as the lime and ferric chloride dosages were fairly constant during this period. The carbon dioxide dosage may have changed during recarbonation, but the carbon dioxide dosages were not provided in the MORs.

Treatment for softening and turbidity removal, along with disinfection, reduced the alkalinity by as much as 204 mg/L as $CaCO_3$ and the pH by up to one log unit. The Langelier saturation index (LSI) is a measure of calcium carbonate solubility described as

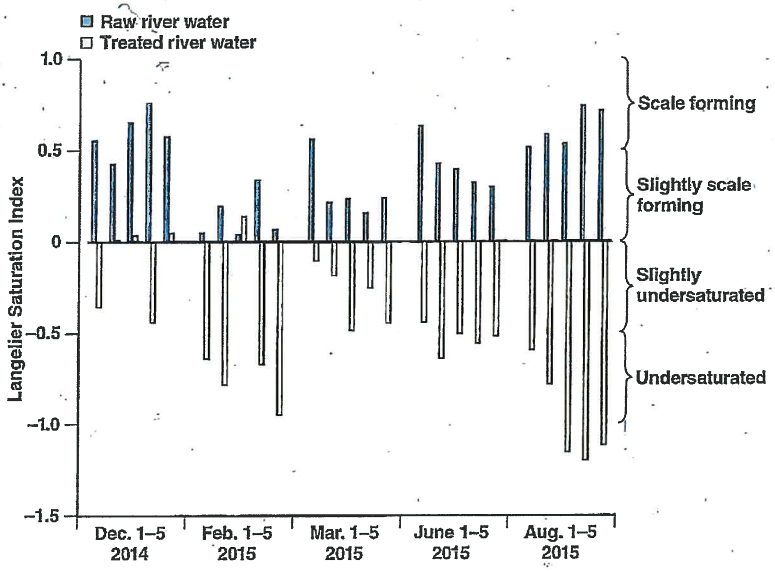
$$\mathrm{LSI} = \mathrm{pH} + \log \left(\frac{K_a \cdot \gamma_{Ca^{2+}} \cdot [Ca^{2+}] \cdot \gamma HCO_3^{-} \cdot [HCO_3^{-}]}{\gamma_{H^+} \cdot [K_{sp}]} \right)$$

where K_a is the acid dissociation constant for bicarbonate, γ is the activity coefficient, [ ] denotes the molar concentration, and K_{sp} is the solubility product of $CaCO_3$. An LSI value greater than zero indicates that the solution is supersaturated and the precipitation of calcium carbonate is favored and that corrosion is less likely. An LSI value less than zero indicates that the solution is undersaturated and calcium carbonate dissolution is favored, and that the water could be corrosive if no other measures were taken to control corrosion. As a result of reductions in pH, alkalinity, and hardness during treatment, the finished water was undersaturated with respect to calcium carbonate (Figure 8). As the temperature of the water is likely to change in the distribution system (warms during winter, cools during summer), the LSI is also likely to change, suggesting that the water became more undersaturated during summer and less undersaturated during winter. The LSI would have approached –1.5 during August 2015, when the water temperature was predicted to be 15°C in the distribution system.

As shown in Table 2, the chloride content of the treated water ranged from 62 to 95 mg/L (median of 83 mg/L). The chloride level in the treated water was significantly higher than in the river water, predominantly due to the addition of ferric chloride as a coagulant. Calculations using dosing data show that the chloride levels in the treated water increased by 28–100% as a result of the addition of ferric chloride.

The turbidity of the raw Flint River water varied seasonally (Figure 9). The turbidity of the finished water did not vary greatly (0.08–0.16 ntu), demonstrating that the filters were operating successfully. However, it can be observed that the turbidity of the water applied to the filters varied greatly, indicating the challenges plant operators had in achieving consistent performance in the upflow clarifiers. The changes in lime and polymer dosages, shown in Figures 3 and 4,

FIGURE 8 Langelier saturation index of the treated Flint River water at various times during the treatment period



The temperature used is that of the raw water as provided in the treatment plant monthly operating reports.

TABLE 2 Parameter concentrations used to characterize the likelihood of corrosion and associated CSMR and Larson–Skold indexes in the treated Flint River water

	Concentration *mg/L*		Concentration *mg/L as* $CaCO_3$		
Sample Date	**Cl^-**	**SO_4^{2-}**	**Alkalinity**	**CSMR**	**Larson–Skold Index**
May 22, 2014	85	25	118	3.8	1.24
Aug. 6, 2014	65	23	60	2.8	2.31
Oct. 28, 2014	62	22	76	2.8	1.45
Feb. 16, 2015	95	25	47	3.8	3.40
May 12, 2015	90	31	56	2.9	2.84
Aug. 11, 2015	81	21	36	3.8	3.78

$CaCO_3$—calcium carbonate, Cl^-—chloride, CSMR—chloride-to-sulfate mass ratio, SO_4^{2-}—sulfate likely reflect attempts to optimize the removal of turbidity.

CORROSIVE INDEXES

Although a number of indexes have been developed to provide an indication of the likelihood that corrosion or deposition will occur, none are able to predict the rate at which corrosion might occur. Nevertheless, they can be used to assess the potential effects of water quality changes on the likelihood of corrosion.

The Larson–Skold index was developed to evaluate the potential for the corrosion of cast-iron pipes transporting water from the Great Lakes (Roberge 2006). It can be used to determine the effect of chloride, sulfate, and bicarbonate/carbonate ions on the corrosivity of the treated water toward iron pipes in the distribution system. The Larson–Skold index is calculated as

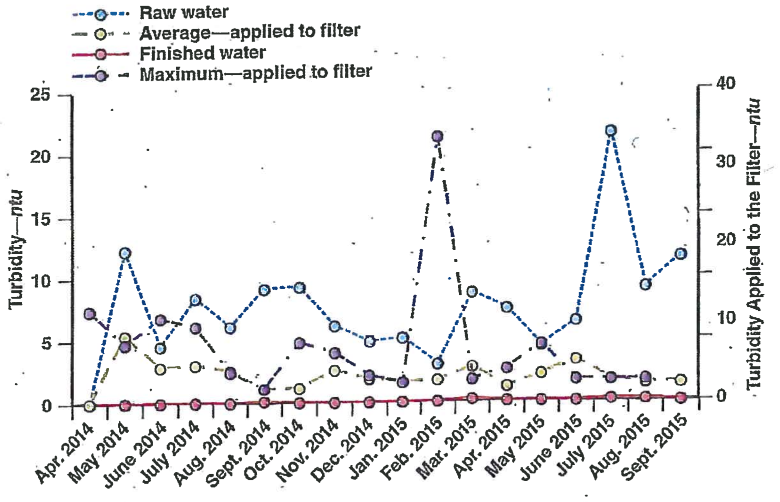
$$\text{LSI} = \frac{(\text{Cl}^-) + (\text{SO}_4^{2-})}{(\text{HCO}_3^-) + (\text{CO}_3^{2-})}$$

where the concentrations are given in units of equivalents per liter. A Larson–Skold index of (1) less than 0.8 suggests that chloride and sulfate levels are unlikely to cause corrosion, (2) between 0.8 and 1.2 suggests higher than desired corrosion rates may occur, and (3) greater than 1.2 is indicative of high corrosion rates (Roberge 2006).

Unfortunately, as the sulfate concentrations were determined on only six occasions, the Larson–Skold index can be calculated only for those six days (Table 2). Of those six days, the Larson–Skold index suggests that high (sometimes very high) rates of iron corrosion should have been expected. While the number of dates are limited, the sulfate concentration was fairly constant over the 1.5 years; therefore, the values of the Larson–Skold index shown in Table 2 are likely to be indicative of the treated water during the time when the Flint River supplied the FWSC plant.

The chloride-to-sulfate mass ratio (CSMR) has been shown to be an effective tool to identify where corrosion is likely (Hill & Cantor 2011). An extensive survey of water utilities showed that 100% of utilities with a CSMR <0.58 met USEPA action limit for lead (15 µg/L) (Edwards 1999). On the contrary, only 36% of utilities with a CSMR >0.58 met the USEPA action limit (15 µg/L). If the alkalinity is less than 50 mg/L as CaCO_3, then Nguyen et al. (2010) suggested that the goal should be to achieve a CSMR in the finished water of less than 0.2. Table 2 shows that the CSMR for the treatment period was very high in all six samples. The high values of the CSMR and Larson–Skold indexes of water entering the Flint distribution system should have raised serious concerns about the possibility of corrosion, especially given prior experience by water utilities. For example, in Columbus, Ohio, the 90th percentile lead levels in the water increased by almost 360% after a change in coagulant from alum to ferric chloride, which resulted in an increase in the CSMR by up to 170% (Hill & Cantor 2011).

FIGURE 9 Variability in turbidity within the Flint water treatment plant



SO WHAT WENT WRONG IN FLINT?

The previous discussion demonstrates the complexity of treating a variable water source. Flint River water was considered to be a challenge to treat, with "high bacteria and high carbon concentrations" that "fluxuate [sic] depending on rain events" (Mar. 20, 2012, meeting minutes, MDEQ meeting on KWA water issues). The only pilot testing that appears to have been completed before the switch was in 2002—a treatability study by Alvord, Burdick, and Howson LCC (AB&H)—and is mentioned in the OER (Lockwood, Andrews, & Newman 2015). The author of the study describes the water source as "particularly difficult to treat with seasonal variation between high organic load and high magnesium hardness" (Lawrence 2012). The treatment train recommended in the AB&H report differs significantly from that used at the Flint water treatment plant, which meant that in 2014 the plant operators lacked important information about the treatability of the water that was necessary for proper plant operation.

AWWA (Muylwyk et al. 2014) recommends that "if a municipality is considering changing how its source water is treated, the potential effects on the corrosivity of the treated water and the need for corrosion control should be evaluated." However, sufficient pilot testing and corrosion studies were not commissioned and completed before the April 2014 switch of source waters. Furthermore, since the Flint plant had not been fully operational in almost 50 years, was understaffed, and some of the staff were undertrained, it is not surprising that it was difficult to achieve effective treatment.

Muylwyk et al. (2014) warn that any of the following treatment changes could affect corrosion or corrosion control in the distribution system:

- Process changes that result in pH or alkalinity changes
- Process changes that affect the CSMR
- Change in coagulant (the Lake Huron plant uses alum)
- Introduction of a new acid to the process (the Lake Huron plant does not use recarbonation; the Flint plant did)
- Introduction of a new base (the Lake Huron plant does not use lime; the Flint plant did)

These changes were made when Flint switched to treating the Flint River water; however, as mentioned previously, corrosion control was not used at the plant, and there was no plan for corrosion control.

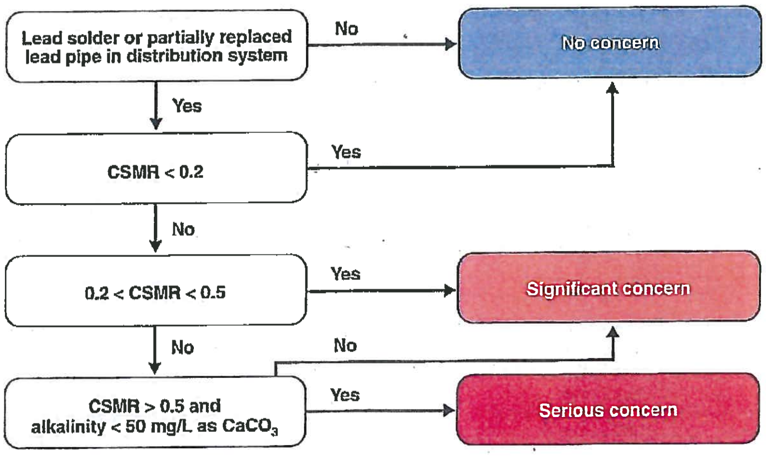
As shown in Figure 7, the monthly average pH and alkalinity of the treated water were highly variable. Not shown in the figure are the changes on a daily basis. The daily pH measurements varied from 7.00 to 8.46 over the first three months of treatment. Daily fluctuations often varied between ±0.2 to 0.3 pH units, and as high as 1.1 log units in late April 2014. By contrast, the pH of the DWSD water varied no more than 0.34 log units over the course of a month. Changes in pH more than 0.2 units per week are ~~not~~ recommended (Hill & Cantor 2011), as such rapid changes in water chemistry (as experienced in the Flint system) may adversely affect system equilibrium and the passivation layer and scales on the insides of the pipes.

The red color of the water observed by Flint residents is evidence of the corrosion of iron distribution pipes. While FWSC flushed the mains by opening fire hydrants, it never seemed to address the root cause of the colored water, namely the corrosion of the iron pipes. Changes in pH and alkalinity can result in the softening of iron tubercles and therefore result in increased iron corrosion (Hill & Cantor 2011). As discussed previously, in all six samples, the Larson–Skold index was close to or greater than 1.2, indicating potentially high iron corrosion rates should have been expected. On the basis of this and the fact that no corrosion inhibitor was used, it is not surprising that significant iron corrosion was observed. In addition, bacteria are known to contribute to the corrosion of iron pipes, so it is possible that the corrosion problem was exacerbated by bacterial regrowth as a result of low chlorine residual and the likely presence of low molecular weight/easily metabolized compounds formed from the reaction of ozone with naturally occurring organic matter.

> Even after all the lead pipes are replaced, it may take years for the lead levels in Flint to reach a point at which the concentrations of all samples are below the action level.

Commonly used indexes could have predicted that the treated Flint River water would likely corrode lead pipes. For example, the decision tool shown in Figure 10 uses the CSMR to predict the corrosivity of water toward lead piping. As shown in Figure 7, before July 2015, when the alkalinity of the water was greater than 50 mg/L as $CaCO_3$, the CSMR values of the

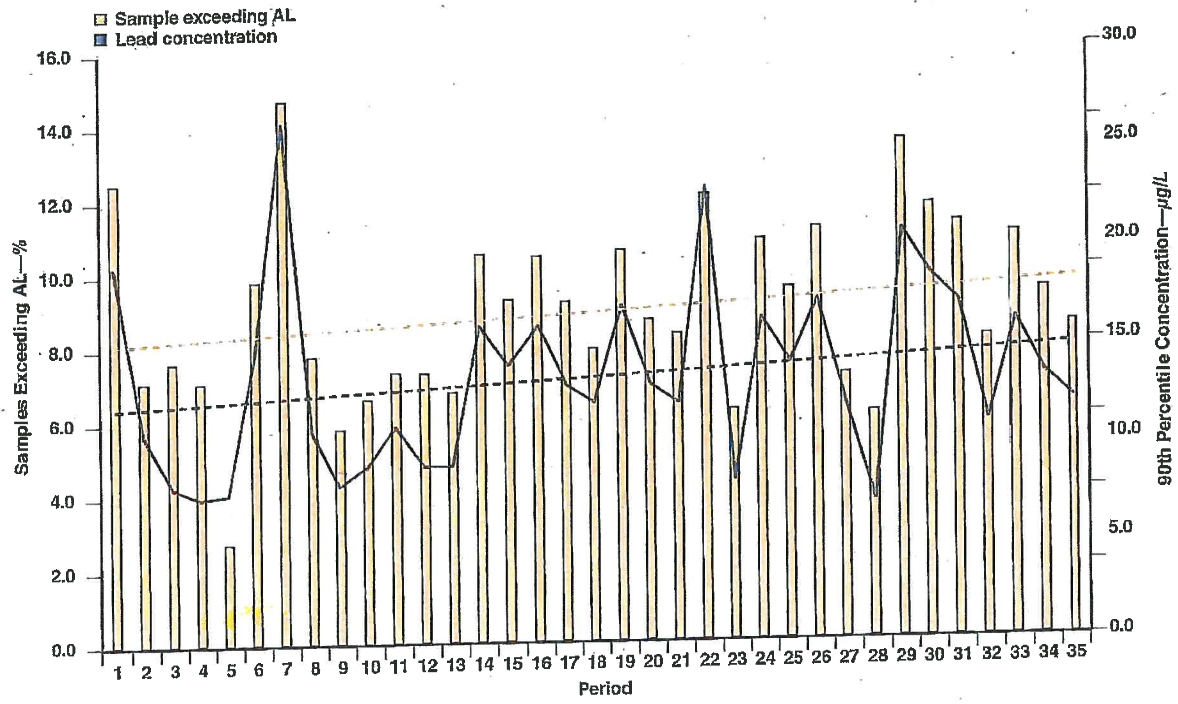
FIGURE 10 Decision tool to assess corrosion potential based on CSMR



Adapted from Nguyen et al. 2010

$CaCO_3$—calcium carbonate, CSMR—chloride-to-sulfate mass ratio treated Flint River water exceeded the 0.5 cutoff, so the corrosivity of water would have been a significant concern. After this time, the alkalinity of the water was less than 50 mg/L and the CSMR greatly exceeded 0.2, indicating that lead corrosion was an even more serious concern than earlier. The addition of phosphate as an inhibitor to prevent lead corrosion is commonly used in the industry (Hill & Cantor 2011), and while the possible use of phosphate as a corrosion inhibitor was suggested (WadeTrim 2009), the reason corrosion control was not implemented is still unknown. No preliminary corrosion estimates using simple indexes appear in any of the engineering reports, and they do not appear to have been considered during the design process. Journalistic reports of the Flint disaster have often stated that the failure to add phosphate was the primary cause of the lead corrosion problem. However, it should be recognized that the CSMR of the treated Flint River water was so high that, even with the addition of phosphate, the water may have been so corrosive that lead levels in the system might have still exceeded the action level. The

FIGURE 11 Percentage of samples exceeding the lead AL of 15 µg/L and the 90th percentile lead concentration[a]



AL—action level

[a]Determined from the Michigan Department of Environmental Quality sampling efforts from Sept. 1, 2015, through July 23, 2016

Period	Date
	2015
1	September
2	Oct. 1–15
3	Oct. 16–31
4	November
5	Dec. 1–10
6	Dec. 11–31
	2016
7	Jan. 3–9
8	Jan. 10–16
9	Jan. 17–23
10	Jan. 24–30
11	Jan. 31–Feb. 6
12	Feb. 7–13
13	Feb. 14–20
14	Feb. 21–27
15	Feb 28–Mar. 5
16	Mar. 6–12
17	Mar. 13–19
18	Mar. 20–26
19	Mar. 27–Apr. 2
20	Apr. 3–9
21	Apr. 10–16
22	Apr. 17–23
23	Apr. 24–30
24	May 1–7
25	May 8–14
26	May 15–21
27	May 22–28
28	May 29–June 4
29	June 5–11
30	June 12–18
31	June 19–25
32	June 26–July 2
33	July 3–9
34	July 10–16
35	July 17–23

failure to recognize the corrosivity of the water and to add a corrosion inhibitor had devastating effects.

In the wake of the lead exposure, the MDEQ finally conducted extensive sampling and analysis of the Flint water. As of June 28, 2016, a total of 23,119 samples have been collected and analyzed for lead since September 2015. The highest lead levels measured exceeded 23,100 µg/L. On the basis of the Sentinel samples and this more extensive data set collected by the MDEQ, it appears that a significant number of premises still have high lead levels in their water (Figure 11). It has been suggested that in many cases, the high lead levels now seen in homes are due to the presence of particulate lead (USEPA 2016). This may be the case, although at this time there appears to be limited publicly available evidence to support this supposition.

There are plans to replace all lead pipes in the Flint system. As of July 2016, lead pipes have been replaced in about 30 premises (Thomas 2016). In the case of Madison, Wis., the utility and homeowners worked together for several years to fully replace the lead service lines in every home in their service area (Corley 2016). High lead levels were found in a number of samples four years after all of the lead pipes were replaced in Madison, Wis. (Cantor 2006), suggesting that even after all the lead pipes are replaced, it may take years for the lead levels in Flint to reach a point at which the concentrations of all samples are below the action level. Clearly there is much to be done before the water crisis in Flint is over.

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ABOUT THE AUTHORS

Susan J. Masten (to whom correspondence may be addressed) is a professor in the Department of Civil and Environmental Engineering at Michigan State University, 428 Shaw Ln., East Lansing, MI 48824 USA; masten@egr.msu.edu. She has 35 years' experience in water treatment and 27 years at Michigan State University. She holds a patent on a hybrid ceramic membrane filtration system and has conducted extensive research on the use of this technology for the control of disinfection by-products, nanoparticles, bromate, and pharmaceuticals in drinking water. Masten earned a BS degree in biochemistry from Fairleigh Dickinson University, Teaneck, N.J.; an MSE degree in environmental engineering from West Virginia University in Morgantown, W.V.; and a PhD degree in environmental engineering from Harvard University, Cambridge, Mass. Simon H. Davies is a research engineer in the Department of Civil and Environmental Engineering at Michigan State University. Shawn P. McElmurry is an associate professor in the Department of Civil and Environmental Engineering, Wayne State University, Detroit, Mich.

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REFERENCES

Anderson, E., 2016. Legionnaires'-Associated Deaths Grow to 12 in Flint Area. *Detroit Free Press*, April 11. www.freep.com/story/news/local/michigan/flint-water-crisis/2016/04/11/legionnaires-deaths-flint-water/82897722/ (accessed July 2016).

Anon., 1897. *Charter and Ordinances of the City of Flint, Michigan and Rules of the Common Council*, Section VI, p.142). Authority of the Common Council of the City of Flint, Flint, Mich.

Cantor, E., 2006. Diagnosing Corrosion Problems Through Differentiation of Metal Fractions. *Journal AWWA*, 98:1:117.

Carmody, T., 2016. How the Flint River Got So Toxic. *The Verge*, Feb. 26. www.theverge.com/2016/2/26/11117022/flint-michigan-water-crisis-lead-pollution-history (accessed July 2016).

City of Detroit, 2012. *Proceedings of the Board of Water Commissioners*. www.dwsd.org/downloads_n/announcements/bowc_2012_calendar/minutes/bowc_approved_minutes_10242012.pdf (accessed July 13, 2016).

City of Flint, 2016. *Flint 2015 Annual Water Quality Report*. s.l., Flint, Mich.

City of Flint, 2015. *Water Improvements*. s.n., Flint Mich.

City of Flint, 2014. *2014 Annual Water Quality Report*. s.n., Flint, Mich.

Corley, C., 2016. Avoiding a Future Crisis, Madison Removed Lead Water Pipes 15 Years Ago. *National Public Radio*, March 31. www.npr.org/2016/03/31/472567733/avoiding-a-future-crisis-madison-removed-lead-water-pipes-15-years-ago (accessed July 2016).

Dunbar, W. & May, G., 1995 (3rd ed.). *Michigan: A History of the Wolverine State*. Wm B. Eerdsman Publishing Co., Grand Rapids, Mich.

Edwards, M.; Jacobs, S.; and Dodrill, D., 1999. Desktop Guidance for Mitigating Pb and Cu. *Journal AWWA*, 91:5:66.

Emery, A., 2016. EPA Concerned About 'Urgent' Situation With Chlorine Levels in Flint Water. *MLive*, June 4. www.mlive.com/news/flint/index.ssf/2016/06/epa_expresses_concerns_of_chlo.html (accessed July 2016).

Felton, R., 2016. How Flint Traded Safe Drinking Water for Cost-Cutting Plan That Didn't Work. *The Guardian*, Jan. 23. www.theguardian.com/us-news/2016/jan/23/flint-water-crisis-cost-cutting-switch-water-supply (accessed July 2016).

Felton, R., 2014. Flint Residents Raise Concerns Over Discolored Water. *Detroit Metro Times*, Aug. 13. www.metrotimes.com/detroit/flint-residents-raise-concerns-over-discolored-water/Content?oid=2231724 (accessed July 12, 2016).

Flint Water Advisory Task Force, 2016. *Final Report*, s.n., Lansing Mich.

Fonger, R., 2015. Flint DPW Director Says Water Use Has Spiked After Hundreds of Water Main Breaks. *MLive*, Apr. 22. www.mlive.com/news/flint/index.ssf/2015/04/flint_dpw_director_says_water.html (accessed July 2016).

Fonger, R., 2014a. Second Positive Coliform Bacteria Test Means Flint's West Side Water Boil Notice Still in Effect. *MLive*, Aug. 18. www.mlive.com/news/flint/index.ssf/2014/08/second_postivie_ecoli_test_mea.html (accessed July 2016).

Fonger, R., 2014b. Tests Positive for Total Coliform Again in Water-Boil Area on Flint's West Side. *MLive*, Aug. 19. www.mlive.com/news/flint/index.ssf/2014/08/water_boil_area_in_flint_gets.html (accessed July 2016).

Fonger, R., 2014c. State Says Two Discharges in 10 Days Sent 16 Million Gallons of Sewage Into Flint River. *MLive*, Aug. 21. www.mlive.com/news/flint/index.ssf/2014/08/state_says_two_discharges_in_1.html (accessed July 2016).

Hanna-Attisha, M.; LaChance, J.; Sadler, R.; & Schnepp, A., 2016. Elevated Blood Lead Levels in Children Associated With the Flint Drinking Water Crisis: A Spatial Analysis of Risk and Public Health Response. *American Journal of Public Health*, 106:2:283. http://dx.doi.org/10.2105/AJPH.2015.303003.

Hardin, E., 1932. Design and Operation Data on Large Rapid Sand Filtration Plants in the United States and Canada. *Journal AWWA*, 24:8:1190.

Hill, C. & Cantor, A., 2011 (1st ed.). *Internal Corrosion Control in Water Distribution Systems*. AWWA, Denver.

Kennedy, C.; Yard, E.; Dignam, T.; Buchanan, S.; Condon, S.; Brown, M.J.; Raymond, J.; Schurz Rogers, H.; Sarisky, J.; de Castro, R.; Arias, I.; & Breysse, P., 2016. *Blood Lead Levels Among Children Aged <6 Years—Flint, Michigan, 2013–2016*, Centers for Disease Control, Atlanta.

Lawrence, C., 2012. *Special Rules Meeting of the Board of Trustees, Village of Park Forest, Will, and Cook Counties, IL.* www.vopf.com/ArchiveCenter/ViewFile/Item/496 (accessed July 8, 2016).

Leonardi, J. & Gruhn, W., 2001. *Flint River Assessment.* State of Michigan Department of Natural Resources, Lansing, Mich.

Lockwood, Andrews, & Newman Inc., August 25, 2015. *Trihalomethane Formation Concerns: Operational Evaluation Report.* City of Flint, Mich.

Lockwood, Andrews, & Newman Inc., November 26, 2014. *Draft Operational Evaluation Report: Trihalomethane Formation Concerns.* s.n., Flint, Mich.

Lockwood, Andrews, & Newman Inc., 2011. *Analysis of the Flint River as a Permanent Water Supply for the City of Flint. Appendix 8: Technical Memorandum Cost of Service Study.* s.n., Flint, Mich.

Muylwyk, W.; Sandvig, A.; & Snoeyink, V., 2014. Developing Corrosion Control for Drinking Water Systems. *Opflow*, 40:11:24. http://dx.doi.org/10.5991/OPF.2014.40.0073.

Nguyen, C.; Stone, K.; Clark, B.; Edwards, M.; Gagnon, G.; & Knowles, A., 2010. *Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water.* Water Research Foundation, Denver.

NSF International, 2016. *NSF/ANSI 60 Drinking Water Treatment Chemicals—Health Effects.* http://info.nsf.org/Certified/PwsChemicals/Listings.asp?Company=09630& (accessed July 13, 2016).

Roberge, P., 2006. *Corrosion Inspection and Monitoring.* s.l., Wiley Online Library.

Rothstein, E., 2016. Why Flint Matters. *Journal AWWA*, 108:7:36. http://dx.doi.org/10.5942/jawwa.2016.108.0136.

Roy, S., 2015a. Analysis of Water Samples From an Additional 72 Flint Homes Are Concerning. *Flint Water Study Updates.* http://flintwaterstudy.org/2015/08/analysis-of-water-samples-from-an-additional-72-flint-homes-are-concerning-as-well/ (accessed Jan. 11, 2016).

Roy, S., 2015b. *Results From Field Sampling in Flint (Aug 17–19 2015): No Fecal Bacteria in Water But Low Chlorine Residuals a Problem.* http://flintwaterstudy.org/2015/08/field-sampling-results-fecal-bacteria-chlorine/ (accessed July 12, 2016).

Stark, B., 2016. Business unit manager, NSF International, Ann Arbor, Mich. Personal communication, July 6.

Thomas, R., 2016. Pipe Replacements Hitting Stumbling Blocks, Water Safety Guarantees Uncertain, City and State Officials Report. *East Village Magazine*, July 8. www.eastvillagemagazine.org/2016/07/08/pipe-replacements-hitting-stumbling-blocks-water-safety-progress-uncertain-city-and-state-officials-report/ (accessed July 10, 2016).

USEPA (US Environmental Protection Agency), 2016. EPA, DEQ and City of Flint Recommend Flushing Water to Speed Recovery of System [news release]. www.epa.gov/newsreleases/epa-deq-and-city-flint-recommend-flushing-water-speed-recovery-system (accessed July 10, 2016).

Veolia North America, 2015. *Water Quality Report: Flint, MI.* s.l., Veolia North America.

WadeTrim, 2009. *Appendix 9: Lake Huron Water Supply Study—Technical Memorandum City of Flint Water Treatment Plant*, Feb. 20, Flint, Mich.

Wiitala, S.A.; Vanlier, K.E.; & Krieger, R.A, 1963. *Water Resources of the Flint Area Michigan.* US Department of the Interior, Washington.

AWWA RESOURCES

- Lead Resource Community. AWWA webpage. www.awwa.org/resources-tools/water-knowledge/lead.aspx.
- Law & Water—The Failure of Cooperative Federalism in Flint, Michigan. Fewell, B., 2016. *Journal AWWA*, 108:3:12. Product No. JAW_0083222.
- Roundtable—The Flint Crisis. McGuire, M.J.; Beecher, J.A.; Hanna-Attisha, M.; Masten, S.J.; & Rose, J.B., 2016. *Journal AWWA*, 108:7:26. Product No. JAW_0083783.
- Statement From AWWA CEO David LaFrance Concerning Flint Water Quality Crisis. Press release, Jan. 19, 2016. www.awwa.org/resources-tools/public-affairs/press-room/press-release/articleid/3993/statement-from-awwa-ceo-david-lafrance-concerning-flint-water-quality-crisis.aspx.

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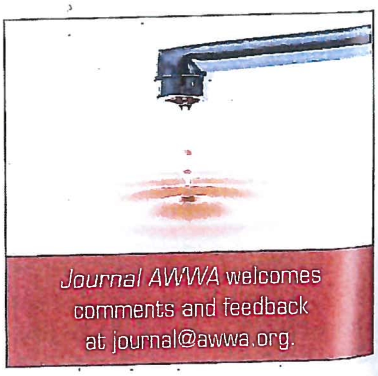

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PUBLIC WATER SUPPLIES: PROPOSED NEW 35 ILL. ADM. CODE 604
R18-17 (RULEMAKING – WATER)

SECOND HEARING, THURSDAY, NOVEMBER 16, 2017 AT 9:00 A.M.
CHICAGO AND SPRINGFIELD BY VIDEOCONFERENCE
IPCB SPRINGFIELD HEARING ROOM
CONFERENCE ROOM 1244 N, 1ST FLOOR
1021 N. GRAND AVE. E.
NORTH ENTRANCE

PRE-FILED TESTIMONY
SUBMITTED BY:

Capt. Michael D. Curry, PE.
As an individual
803 South Paul Street
Nashville, IL 62263
Work Ph. 618-327-8841
mcurry@curryassociates.com

Larson-Skold Index
For Evaluating Corrosion of Iron Pipes

December 2016

Preface

Well-remembered are the television pictures of "reddish-brown" water from the taps at Flint, MI during the 2014-2015-2016 water quality crisis when high levels of lead were released into the water from household plumbing. Based on analysis of Larson-Skold index for 6 water samples collected between May 22, 2014 and August 11, 2015, the Larson-Skold index varied between 1.24 and 3.78 (Masten et al., 2016). The high index coincided with distinct water discoloration problems associated with release of iron into the water from tubercules in unlined cast iron pipe. It is unfortunate that the Index was not being measured even though it was known that the raw water from the Flint River had much higher concentration of chloride than the water previously purchased from Detroit.

The Larson-Skold Index relates to potential corrosion of iron and steel pipe, but it does ***not*** *relate to corrosive conditions that can cause release of lead (and copper) into drinking water. Presence of iron discoloration in drinking water, in absence of iron in the source water, signals a warning that corrosive conditions likely exists in the distribution mains.*

The work by Masten, Davies, and McElmurry (Masten et al., 2016) has revived new interest in the Larson-Skold Index for use as an additional "tool" in evaluating and protecting water quality.

****

"The Larson-Skold index was developed to evaluate the potential for the corrosion of cast-iron pipes transporting water from the Great Lakes." (Roberge 2006, cited at Masten et al., 2016).

> *Here, the Larson-Skold Index is expressed as L-SI, to differentiate it from the customary expression of Langelier Saturation Index ... "LSI".*

L-SI < 0.8	Suggests that chloride and sulfate levels are unlikely to cause corrosion.
L-SI 0.8 to 1.2	Suggests higher than desired corrosion rates may occur.
L-SI > 1.2	Indicative of high corrosion rates (Roberge 2006, cited at Masten et al., 2016)

A similar but slightly different approach.

"It is well known that the neutral salts chloride and sulfate influence the corrosion of ferrous metals drastically. This corresponds to the practical experience of many water utilities. The German regulations (DIN 50930, Teil 2, 1980) that deal with the behavior of plumbing materials in contact with drinking water consider this influence in terms of a "neutral salt/alkalinity ratio:

$$\frac{[Cl^{-1}] + 2\,[SO_4^{-2}]}{[HCO_3^{-1}]}$$

where the brackets denote the molar concentration of the ion. If this ratio is smaller than 1, the probability of *(ferrous material)* corrosion problems in negligible. This is based on the work by Larson and Skold (1957). There are no equivalent requirements in the United States, although Larson and Skold (1957) recommended that the **neutral salt/bicarbonate ratio should be less than 5**." *(emphasis added) (AWWARF/DVGW 1985, p. 47)*

$$\text{MDC comment: } \frac{[Cl^{-1}] + 2\,[SO_4^{-2}]}{[HCO_3^{-1}]}$$

This is different from Larson-Skold Index because this expression contains 2 SO_4^{-2}.

"Larson and Skold (1957) studied the effects of Cl^{-1} and SO_4^{-2} on iron and mild steel corrosion and found that the effects are primarily related to their concentration relative to HCO_3^{-1}. They proposed the relationships

$$LI_1 = \frac{[Cl^{-1}] + 2\,[SO_4^{-2}]}{[HCO_3^{-1}]}$$

(Different from Larson-Skold Index.)

and

$$LI_2 = \frac{[Cl^{-1}]}{[HCO_3^{-1}]}$$

where the brackets indicated concentration in units of equivalents/L. Observations of corrosion in water of different quality showed the rate of corrosion of mild steel to increase significantly if LI_2 was greater than 0.1 to 0.2 (Larson 1957). "*(AWWARF/DVGW 1985, p. 25-26)*

Notes:

1 *The denominator is intended to represent total alkalinity concentration, including (CO_3^{-2}). When pH is < 8.3, all alkalinity will be HCO_3^{-1}.*

2 *All concentrations are to be expressed in units of equivalents.*

The traditional approach.

It is accepted that the Larson-Skold Index is expressed as:

$$LSI = (Cl + SO_4)\ /\ \text{Alkalinity}$$

Where all parameters are expressed in terms of equivalents/L. (Larson & Skold, 1958; Masten et al., 2016; Masten, 2017).

THIS IS DIFFERENT FROM TETRA TECH (RTW) MODEL …. ALK / (Cl + SO_4) … where ALK is expressed as mg/L equivalent $CaCO_3$, Cl is expressed as mg Cl/L, SO_4 is expressed as mg SO_4/L. Dr. H.C. Liang suggests calling the "Larson-Type Index or Ratio". (Liang, 2016)

A later, alternative interpretation for determining the Larson-Skold Index.

"The Larson Index, unlike both the LSI *(Langelier Saturation Index)* and AI *(Aggressiveness Index),* is **not** *(emphasis added)* related to the solubility of calcium carbonate. The Larson Index is an empirically derived ratio of specific ions which expresses the corrosive nature of a particular water sample with regard to the rate of metal corrosion. The Larson Index is

$$\text{Larson Index} = (Cl + SO_4) \ / \ \text{Alk.}$$

Where chloride (Cl), sulfate (SO_4), and total alkalinity (Alk.) concentrations all are expressed as mg/L of **equivalent $CaCO_3$**. *(emphasis added) (Singley and others, 1985, p. 116; Larson, 1975, cited at Barringer et al, 1993).*

All Larson Index values greater than 0.5 indicates potential water corrosiveness (Singley and others, 1985, p. 116). The Larson Index emerged from work with experimental solutions containing bicarbonate, chloride, and sulfate ions (Larson, 1975), and is not designed to be applied to waters with low hardness and small concentrations of dissolved solids (Singley and others, 1985, p. 116). The Larson Index may be applicable to waters containing dissolved solids ranging from 250 to 1000 mg/L (the range of dissolved solids in Larson's experimental solutions). As a ratio, it compares the corrosion-enhancing properties of chloride and sulfate to the corrosion-inhibiting effect of alkalinity. Schock and Neff (1982) point out that the Larson Index is not based on chemical kinetic expressions or mass-action expressions, and does not accurately predict whether metal concentrations in drinking water will exceed drinking-water standards." *(Barringer et al., 1993)*

"The presence of aggressive anions, such as chloride, sulfate, and fluoride, can greatly increase corrosion rates, especially pitting corrosion. Larson (1975) has shown that the ratio of ***equivalents* (emphasis added… do not confuse the 0.2 value below with the Larson and Skold Ratio)** of chloride to bicarbonate or chloride plus sulfate to bicarbonate can be directly related to corrosion rate, at least for steel in waters of relatively high alkalinity. Anions diffuse toward the anodic site in a corrosion cell. Values above about 0.2 are associated with increased corrosion rates. The strong acid anions have no neutralizing capacity to the acidity of the corroding metal ions. Hence, low pH values and high concentrations may develop corroding pits. It is believed that the aggressive effects of sulfate and chloride are due to their chemisorption to the iron surface, where they interfere with the formation of a protective oxide film or alter the properties of the film that forms. Since fluoride is also a strong acid anion and has similar sorption properties at low concentrations, it is hypothesized that the ratio of sulfate plus chloride plus fluoride to bicarbonate can be used as an index of corrosion susceptibility. Such a ratio has not been tested …" *(AWWARF/DVGW 1985, p. 631-633)*

Calculating Larson-Skold Index

L-SI = $(Cl + SO_4)$ / Alkalinity

All parameters expressed as mg/L of equivalent $CaCO_3$.
Barringer et al. (1993)

THIS IS A DIFFERENT FORM OF EXPRESSION FOR THE LARSON-SKOLD INDEX SINCE IT UTILIZES Cl and SO_4 EXPRESSED AS EQUIVALENT TO $CaCO_3$.

THIS IS DIFFERENT FROM RTW MODEL .... ALK / $(Cl + SO_4)$ ... where ALK is expressed as mg/L $CaCO_3$, Cl is expressed as mg Cl/L, SO_4 is expressed as mg SO_4/L ... which Dr. H.C. Liang suggests calling the "Larson-Type Index or Ratio". (Liang, 2016)

****

Definition:
Equivalent weight = atomic wt./valence

Molecular weight of $CaCO_3$ = 40.078 + 12.011 + 3 (15.999) = 100.086

Equivalent weight of $CaCO_3$ = (100.086)/2 = 50.043

Equivalent wt. of Cl^{-1} = 35.453/1 = 35.453

mg/L Cl^{-1} expressed as $CaCO_3$ = mg/L Cl^{-1} x 50.043/35.453
= mg/L Cl^{-1} x 1.4115

Molecular wt. of SO_4^{-2} = 32.066 + 4 (15.999) = 96.062

Equivalent wt. of SO_4^{-2} = 96.062/2 = 48.031

mg/L SO_4^{-2} expressed as $CaCO_3$ = mg/L SO_4^{-2} x 50.043/48.031
= mg/L SO_4^{-2} x 1.0419

Example:

Given … $Cl^- = 65$ mg/L
$SO_4^{-2} = 23$ mg/L
Alk. = 50 mg/L as $CaCO_3$

****

Professor Susan Masten calculation procedure …(Masten 2017)
All values expressed as "equivalents", which is based on the original work by Larson and Skold.

	Cl^-	SO_4^{-2}	Alk
mg/L	65	23	50 as $CaCO_3$
mg/mmol	35.453	96.0626	
n	1	2	
mg/meq	35.453	48.0313	50 mg/meq (for $CaCO_3$)
meq/L	(65/35.453) 1.833413	(23/48.0313) 0.478854	 1

$$\text{L-SI} = \frac{(1.833413 + 0.478854)}{(1)} = \boxed{\mathbf{2.31226}}$$

Professor Masten developed an Excel spreadsheet for this calculation , and kindly granted permission to share the spreadsheet to assist waterworks professionals, and C&A will be happy to forward it to interested persons.

****

Alternative calculation procedure … (after Barringer et al, 1993)

$$\text{L-SI} = (Cl + SO_4) \;/\; \text{Alkalinity}$$

All parameters expressed as mg/L of equivalent $CaCO_3$.
Barringer et al. (1993)

$$\frac{(65\text{ mg/L } Cl^- \times 1.4115) + (23\text{ mg/L } SO_4^{-2} \times 1.0419)}{50\text{ mg/L alk}} = \boxed{\mathbf{2.314}}$$

References

AWWARF/ DVGW (1985)	Internal Corrosion of Water Distribution Systems, Cooperative Research Report, AWWA Research Foundation, DVGW-Forschungsstelle (Federal Republic of Germany) *(U.S. section authors include Vernon Snoeyink, Michael Schock, J. Edward Singley, Henry Cruse, John Ferguson, Robert Ryder, R. Rhodes Trussell)*
Barringer et al. (1993)	Julia L. Barringer, George R. Kish, and Anthony J. Velnich; "Corrosiveness of Ground Water in the Kirkwood-Cohansey Aquifer System of the New Jersey Coastal Plain"; U.S. Geological Survey Water-Resources Investigations Report 90-4180, prepared in cooperation with the New Jersey Dept. of Environmental Protection and Energy, West Trenton, New Jersey, 1993.
Larson & Skold (1957)	T.E. Larson, and R.V. Skold, "Corrosion and tuberculation of cast iron", Journal AWWA, 49(10), 1294-1302.
Larson & Skold (1958)	T.E. Larson, and R.V. Skold, "Laboratory studies relating to mineral water quality of water to corrosion of steel and cast iron", Corrosion, 14(6), 285-288.
Liang (2016)	Personal communication (10 March 2016), H. C. Liang, Ph.D., Senior Engineer/Water Chemistry and Process Technical Lead; Tetra Tech, Denver, CO.
Masten et al.(2016)	Susan Masten, Simon H. Davies, and Shawn P. McElmurry "Flint Water Crisis: What Happened and Why", Journal AWWA, 108.12, December 2016.
Masten (2017)	Personal communication (1 January 2017), Susan Masten, Professor of Civil and Environmental Engineering, Michigan State University, East Lansing, MI.
Roberge (2006)	P. Roberge, "Corrosion Inspection and Monitoring", s.I., Wiley Online Library (cited at Masten et al., 2016).

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Attachment 4

PUBLIC WATER SUPPLIES: PROPOSED NEW 35 ILL. ADM. CODE 604 R18-17 (RULEMAKING – WATER)

SECOND HEARING, THURSDAY, NOVEMBER 16, 2017 AT 9:00 A.M.
CHICAGO AND SPRINGFIELD BY VIDEOCONFERENCE
IPCB SPRINGFIELD HEARING ROOM
CONFERENCE ROOM 1244 N, 1ST FLOOR
1021 N. GRAND AVE. E.
NORTH ENTRANCE

PRE-FILED TESTIMONY
SUBMITTED BY:

Capt. Michael D. Curry, PE.
As an individual
803 South Paul Street
Nashville, IL 62263
Work Ph. 618-327-8841
mcurry@curryassociates.com

Peer Reviewed

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Practical Considerations for Implementing Nitrosamine Control Strategies

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CAROLINE G. RUSSELL,[1] RICHARD A. BROWN,[2] KATIE PORTER,[3] AND DAVID RECKHOW[4]

[1]Carollo Engineers, Austin, Tex.
[2]Cornwell Engineering Group, Newport News, Va.
[3]Brown and Caldwell, Los Angeles, Calif.
[4]University of Massachusetts–Amherst, Amherst, Mass.

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The US Environmental Protection Agency included five nitrosamines, including *N*-nitrosodimethylamine (NDMA), on the fourth Contaminant Candidate List, indicating its consideration of these contaminants for potential regulatory determination. If nitrosamines are regulated, affected water systems and regulators will need to consider simultaneous compliance, risk balancing, operational, and cost impacts of implementing control strategies. This study showed that site-specific data are lacking on the source(s) of NDMA, hindering the ability of a water utility to identify optimal control strategies for their system. A framework is presented to guide water systems through initial steps to assess nitrosamine sources, control strategies, and unintended consequences as they plan for potential regulations.

Keywords: *NDMA control strategies, NDMA sources, practical considerations, unintended consequences*

The US Environmental Protection Agency (USEPA) included five nitrosamines on the fourth Contaminant Candidate List and also considered nitrosamines (including *N*-nitrosodimethylamine [NDMA]) as part of the third Six-Year Review of the Microbial and Disinfection Byproducts (M/DBP) regulations (USEPA 2016). If the USEPA decides to regulate nitrosamines, affected water systems will need to explore strategies to reduce concentrations in their finished water and in their distribution systems. More than one out of every 10 chloraminated water systems could be affected by an NDMA maximum contaminant level (MCL) equivalent to the current California notification level of 10 ng/L (Russell et al. 2012).

② NDMA, the nitrosamine detected most frequently in drinking water, is a chloraminated disinfection by-product (DBP) that forms from reaction of dichloramine with amine-based precursors (Schreiber & Mitch 2006). Effluent organic matter has been identified through several studies as an important source of NDMA precursors in wastewater-affected waters (Krasner et al. 2009, Mitch et al. 2005, Mitch & Sedlak 2004). Soluble microbial products from biological wastewater treatment plants, the pharmaceutical ranitidine, quaternary amines found in shampoos, dyes in laundry water, and the herbicide diuron have all been identified as nitrosamine precursors that can occur in wastewater- or agriculturally affected source waters (Zeng & Mitch 2015, Kemper et al. 2010, Le Roux et al. 2011, Krasner et al. 2008, Sacher et al. 2008).

Cationic amine–based polymers, such as polyDADMACs or polyamines used as coagulant or dewatering aids have also been identified as NDMA precursors (Kohut & Andrews 2003, Wilczak et al. 2003, Najm & Trussell 2001). Mitch et al. (2009) found that finished water NDMA concentrations at chloramine plants generally increased with increasing polyDADMAC dose. Cornwell et al. (2017) observed similar trends; however, the increase in NDMA formation with increasing polyDADMAC dose was more pronounced in some water sources than others. Park et al. (2009) showed that the NDMA formation potential of polymers generally follows the trend of polyamine > polyDADMAC > cationic polyacrylamide, regardless of which oxidant or nitrosifying agent was involved.

NDMA can also be present as a source water contaminant from liquid rocket fuels production or upstream wastewater discharge, an impurity in ion exchange resins (Kemper et al. 2009, Najm & Trussell 2001), or a contaminant of materials (e.g., rubber gaskets) used in distribution systems (Morran et al. 2011). However, review of Unregulated Contaminant Monitoring Rule 2 (UCMR 2) data (Russell et al. 2012) and additional NDMA occurrence studies

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A full report of this project, *Unintended Consequences of Implementing Nitrosamine Control Strategies* (#4491), is available for free to Water Research Foundation subscribers by logging on to www.waterrf.org.

implications associated with unregulated contaminants (e.g., emerging DBPs) and regulated contaminants within compliance with existing rules (e.g., increased formation of bromate, but at levels below the 10-µg/L MCL). This article presents information on unintended consequences to provide practical guidance to water utilities and inform regulatory discussions.

APPROACH

This approach to identify and document unintended consequences of implementing nitrosamine control strategies included a literature review, desktop analysis of 14 water systems, and a project workshop. For the literature review, peer-reviewed articles and reports focused specifically on NDMA control strategies, and documented consequences were reviewed (e.g., Krasner et al. 2015, 2012a; Shah et al. 2012), along with general guidance documents on the consequences of implementing the strategies that could be considered to reduce NDMA concentrations (e.g., USEPA 2007). This review formed the basis for developing site-specific considerations for further discussions with water systems participating in the desktop studies.

Desktop studies were developed for 14 water systems representing a range of system size and source water, treatment, and distribution system characteristics (Table 1). All participating water systems are located in the continental United States: one in the Northeast, four in the South, five in the Midwest, and four in the West. Eight of the 14 water systems operate more than one water treatment plant (WTP), resulting in 27 WTPs being reviewed in total. Because basic treatment characteristics of the WTPs for a given water system were generally consistent, Table 1 focuses on overall characteristics of the water systems themselves.

All participating water systems use chloramines as a disinfectant, and most had average distribution system NDMA concentrations >10 ng/L based on UCMR 2 data. Most of the water systems use some form of cationic amine–based polymer; however, the type varies.

TABLE 1 Characteristics for participating utilities

Water System	System Size[a]	Geographic Region	NDMA LRAA[b]	Polymer Addition	Oxidation	Treatment Type	Secondary Disinfectant
A	XL	South	15	PolyDADMAC	Ozone	Conventional; converting to biological filtration	Chloramines
B	XL	South	30	PolyDADMAC	None	Conventional	Chloramines
C	XL	South	16	PolyDADMAC	Chlorine	Conventional	Chloramines
D	VL	Midwest	NA	PolyDADMAC	Chlorine	Conventional	Chloramines
E	XL	West	3	PolyDADMAC	Ozone/chlorine	Conventional	Chloramines
F	XL	Midwest	35	PolyDADMAC (seasonal use)	None	Softening, clarification, membrane filtration	Chloramines
G	VL	West	NA	PolyDADMAC	Chlorine/ozone	Conventional with biologically active carbon	Chloramines
H	XL	Midwest	11	PolyDADMAC	Chlorine	Lime softening, year-round PAC	Chloramines
I	S	Northeast	26	Polyamine (epichlorohydrin-dimethylamine)	Chlorine	Conventional	Chloramines
J	VL	Midwest	30	PolyDADMAC	None	Conventional	Chloramines
K	VL	Midwest	20	PolyDADMAC	Chlorine	Conventional	Chloramines
L	VL	South	10–20[c]	Polyacrylamide	Chlorine dioxide	Conventional	Chloramines
M	XL	West	NA	PolyDADMAC	Ozone/chlorine	Direct filtration, UV disinfection	Chlorine and chloramines[d]
N	XL	West	3	PolyDADMAC	Chlorine	Conventional	Chloramines

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LRAA—locational running annual average, NA—not available, NDMA—N-nitrosodimethylamine, PAC—powdered activated carbon, S—small, UV—ultraviolet, VL—very large, XL—extra large

[a] Small: 501–3,300; medium: 3,301–10,000; large: 10,001–50,000; VL: 50,001–100,000; XL: >100,000.
[b] Based on Unregulated Contaminant Monitoring Rule 2 data unless otherwise noted.
[c] One-year range from Water Research Foundation Project 4444 using monthly data for approximately a year (Uzun et al. 2016).
[d] Converting to chloramines; a portion of the system was on chlorine at the time of this study, whereas other portions of the system were on chloramines.

(Krasner et al. 2016) illustrate that NDMA in finished water and distribution system samples is foremost attributed to chloramines disinfection.

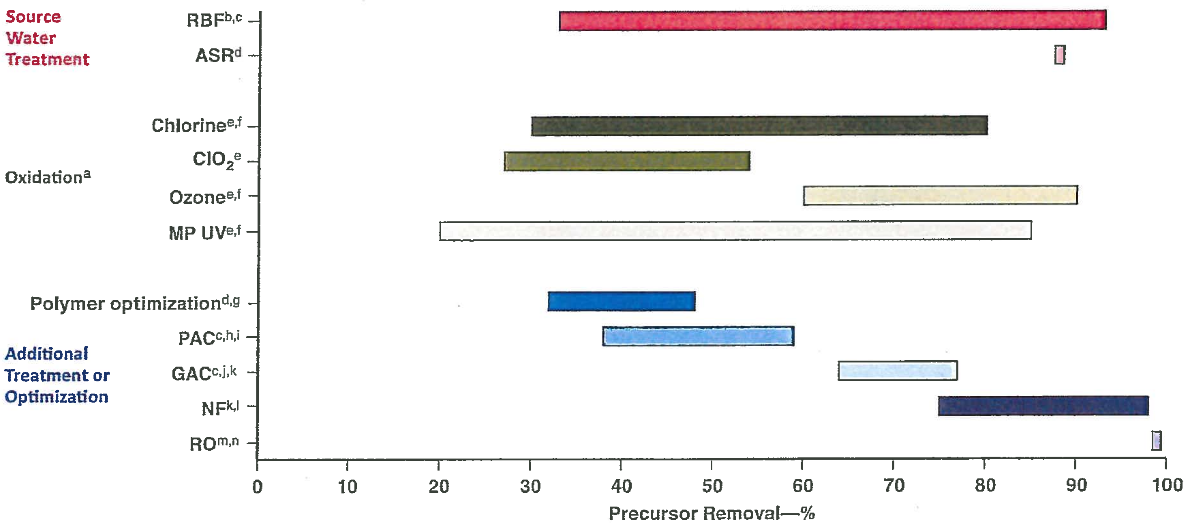
NDMA control strategies targeting precursor removal (Figure 1) include

- biodegradation during riverbank filtration (Krasner et al. 2015);
- oxidation with chlorine, chlorine dioxide, ozone, or medium-pressure ultraviolet photolysis (McCurry et al. 2015, Shah et al. 2012);
- adsorption onto powdered activated carbon (PAC) or granular activated carbon (GAC) (Hanigan et al. 2012);
- membrane desalination (i.e., nanofiltration and reverse osmosis) (Wang et al. 2015, Sedlak & Kavanaugh 2006); and
- polymer optimization (Labernik et al. 2010).

The latter can include replacement of polyDADMAC polymers with natural starch-based polymers (Cornwell et al. 2015). Notably, the best available technologies to reduce formation of currently regulated halogenated DBPs (i.e., enhanced coagulation and softening as well as moving the point of chlorine addition to later in the treatment train) are not effective for reduction in NDMA formation. Krasner et al. (2013) provide a summary of NDMA sources, formation mechanisms, and control strategies.

Practical guidance on unintended consequences associated with implementing changes to reduce NDMA or nitrosamine concentrations has been lacking. Several of the control strategies that could be implemented to reduce NDMA (e.g., oxidation, polymer optimization) could result in simultaneous compliance issues with the M/DBP rules. Strategies to reduce nitrosamines could also have operational and cost effects and potential health-risk

FIGURE 1 Impact of treatment on NDMA precursor removal



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ASR—aquifer storage and recovery, ClO_2—chlorine dioxide, GAC—granulated activated carbon, MP—medium pressure, NDMA—*N*-nitrosodimethylamine, NF—nanofiltration, PAC—powdered activated carbon, RBF—riverbank filtration, RO—reverse osmosis, UV—ultraviolet

[a] Percent NDMA precursor removal for chlorine, ClO_2, and ozone is based on doses typically applied for *Giardia* inactivation ranging from 14 to 60 mg-min/L chlorine and 0.2–1.0 mg-min/L ozone per McCurry et al. (2015) and from 4 to 20 mg-min/L ClO_2 per Shah et al. (2012). NDMA precursor removal for UV is based on 186–1,000 mJ/cm^2 MP per McCurry et al. (2015).

[b] Schmidt et al. 2006

[c] Krasner et al. 2015

[d] Sacher et al. 2008

[e] Shah et al. 2012

[f] McCurry et al. 2015

[g] Labernik et al. 2010

[h] Percent removal for PAC doses ranging from 4 to 21 mg/L at two full-scale wastewater-affected plants (Krasner et al. 2015). Percent removal depends on PAC dose and type and site-specific NDMA precursor characteristics (e.g., wastewater- or polymer-derived).

[i] Hanigan et al. 2012

[j] Percent removals for two full-scale wastewater-affected plants, with GAC filters in various stages of exhaustion. Percent removal may depend on degree of GAC exhaustion and site-specific NDMA precursor characteristics.

[k] Miyashita et al. 2009

[l] Wang et al. 2015

[m] Sedlak & Kavanaugh 2006

[n] Farré et al. 2010

Information packages based on UCMR 2 data and other available survey and research data were assembled for each water system. The information packages included the data listed in Table 2 to the extent available. Table 2 can be used as a checklist for other utilities seeking to evaluate potential NDMA sources and control strategies for their own systems. Consecutive systems will need to partner with their wholesale providers to collate information to assess NDMA sources and evaluate corresponding control strategies, which could be challenging absent a regulatory driver.

On the basis of the water system information, one to four potential nitrosamine control strategies were proposed

profiling

TABLE 2 Information to compile for review of nitrosamine sources, control strategies, and consequences

Data Category	Parameter	Sample Location	Recommended Number and Frequency of Data Points for Review	Other Information
Source water characteristics	Ammonia	All source water supplies for a given WTP	≥monthly samples for past 1–2 years	Description of source water type (e.g., surface, groundwater); upstream point and nonpoint source impacts (number of WWTPs and distance upstream, type of agricultural and industrial activities within watershed) Information of seasonal events (e.g., rainy seasons) and corresponding changes in plant operations (e.g., PAC addition, change in coagulant or polymer dose)
	TOC		≥monthly samples for past 1–2 years	
	Bromide		≥quarterly samples for past 1–2 years	
	Sucralose		≥quarterly samples	
Nitrosamine and NDMA concentrations	Nitrosamine concentrations	Source water(s), recycle stream(s), settled water, finished water, distribution system maximum residence time location[b]	≥quarterly samples	Descriptions of any nitrosamine control strategies that have been implemented, tested, and/or are under consideration for analysis
	NDMA precursor concentrations[a]		≥quarterly samples	
General water treatment plant characteristics	Average flow	High-service pump stations	≥monthly data for past 1–2 years	WTP process flow diagram and rated capacity Information on site-specific approach to meet Stage 1 D/DBPR TOC removal requirements
Polymer addition	Polymer dose	Each application point	Daily data for past 1–2 years	Information on polymer application point(s), polymer type for each application point, and location relevant to chlorine and ammonia addition
PAC addition	PAC dose	Application point	Weekly data for past 1–2 years	PAC application point, carbon type, and water quality goals prompting use
Oxidant/primary disinfectant addition	Oxidant dose	Each application point	Monthly data for past 1–2 years	Oxidant type and application point(s), contact time including description of any seasonal variation
	Oxidant residual at $C \times T$ monitoring location	For each oxidant type and corresponding disinfection zone	Monthly data for past 1–2 years	
Plant recycle protocols	Recycle flow	Each recycle stream	Weekly data for past 1–2 years	Information on which residuals streams are recycled, any polymers used for residuals handling before recycle, and disinfectant residual in the recycle stream
Chloramine dosing procedures	Chlorine residual	Entry point and DS	Entry point: weekly for past 1–2 years DS: monthly for past 1–2 years	Information on chloramine application points, target chlorine residual concentration at the entry point and in the distribution system, Cl_2:NH_3-N mass ratio, pH
	Cl_2:NH_3-N ratio	Entry point	Weekly for past 1–2 years	
Distribution system data	TTHM and HAA5 speciation and concentrations	DS	Quarterly for past 2 years	Information on water age (average and maximum)

$C \times T$—product of disinfectant concentration determined before or at the first customer and the corresponding disinfectant contact time, Cl_2:NH_3-N—chlorine to ammonia mass ratio, D/DBPR—Disinfectants and Disinfection Byproducts Rule, DS—distribution system, HAA5—five haloacetic acids, NDMA—*N*-nitrosodimethylamine, PAC—powdered activated carbon, TTHM—total trihalomethane, TOC—total organic carbon, WTP—water treatment plant, WWTP—wastewater treatment plant

[a] Any available NDMA formation potential, uniform formation conditions, or simulated distribution system data should be collated to review sources of precursors at the different sample locations. See Krasner et al. (2012b) for information on methods to assess NDMA concentrations following chloramine addition at bench scale as an indicator of the presence of precursors.

[b] See Water Research Foundation 4491 for Guideline on Source-to-Tap NDMA/Nitrosamine profiling (Russell et al. 2017).

TABLE 3 NDMA control strategies and considerations (example prepared for utility H)[a]

Compliance Strategy (1)	Origin of NDMA			Site-Specific Considerations (5)
	Preformed in Source (2)	Watershed-Derived (3)	Polymer-Derived (4)	
Change in source water	X	X	X[b]	Water rights New surface water source would require monitoring for LT2ESWTR compliance, which may result in bin reclassification and additional treatment Changes in treatability of plant influent water and impacts to distribution system stability
Riverbank filtration or soil aquifer treatment	X	X	X[b]	Depends on geology and land availability Changes in treatability of plant influent water
Oxidation with chlorine[c]		**X**	**X**[d]	**Tests and/or desktop analysis of data using empirical models needed to assess feasibility of achieving longer $C \times T$ while complying with Stage 1 and 2 D/DBPR, particularly maintenance of 40/30 TTHM/HAA5 certification**
Oxidation with ozone		**X**	**X**[d]	**Testing needed to understand seasonal impacts on NDMA precursor removal, bromate formation, and assimilable organic carbon concentrations** **Potential beneficial impact on taste and odor issues and Stage 2 D/DBPR compliance** **Relatively high capital and O&M cost compared with alternate oxidants**
Oxidation with chlorine dioxide		X	X[d]	ClO_2 only effective in some cases Could be included in bench tests if ClO_2 is considered for other purposes such as zebra mussel control or Mn oxidation Testing should include evaluation of chlorite formation
Change in polymer dose/type			**X**	**Sampling needed to assess nitrosamine precursor contribution by polymers** **Bench and pilot- or full-scale testing to determine impact on settled water turbidity, filter run times, and residuals handling**
PAC addition		**X**	**X**[e]	**PAC feed system already in place for use in spring and summer to remove atrazine** **Testing would be needed to assess impact of increased dose or frequency of application and carbon type on NDMA precursor removal**
GAC contactors		X	X[e]	GAC filter adsorbers included as potential future process in long-range facility plan Beneficial impact on taste and odor issues Impact on polymer-derived precursors would need to be assessed
UV photolysis	X	X[f]	X[f]	Included as potential future treatment process in long-range facility plan Could remove NDMA from finished water but reformation would need to be assessed
Dichloramine minimization		X	X	Chlorine added first, with ammonia added to achieve a chlorine-to-ammonia-nitrogen mass ratio as close as possible to 5:1
Distribution system management	Continued reaction of chloramines with precursors in finished water; distribution system materials (in some cases)			Further testing recommended to assess the seasonal impact of water age on continued NDMA formation in the distribution system

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ClO_2—chlorine dioxide, $C \times T$—product of disinfectant concentration determined at the end of a disinfection zone and the corresponding disinfectant contact time, D/DBPR—Disinfectants and Disinfection Byproducts Rule, GAC—granulated activated carbon, HAA5—five haloacetic acids, LT2ESWTR—Long Term 2 Enhanced Surface Water Treatment Rule, Mn—manganese, NDMA—*N*-nitrosodimethylamine, O&M—operations and maintenance, PAC—powdered activated carbon, TTHM—total trihalomethane, UV—ultraviolet

[a] Boldface text is used to indicate the four potential NDMA mitigation strategies identified for utility H.
[b] Could help reduce polymer dose at plant.
[c] Increased NDMA precursor removal can be achieved by increasing the free chlorine contact time and optimizing pH (Krasner et al. 2015).
[d] For polymer-derived precursor degradation, the oxidation step should occur after sedimentation.
[e] Hanigan et al. (2015) showed that activated carbon could not remove polyDADMAC-derived precursors, but could potentially remove polyamine-derived precursors. More research is needed on the degree to which polymer-derived precursors can be adsorbed to activated carbon and the conditions influencing adsorption (e.g., polymer type, carbon type).
[f] Precursor removal is observed in some waters (Shah et al. 2012); however, testing is required to assess the impact under site-specific conditions. McCurry et al. (2015) showed that medium-pressure UV is more effective than low-pressure UV.

using the decision tree provided in Krasner et al. (2015) as a guideline. Control (compliance) strategies that were considered are listed in Table 3 (column 1), and those that were selected for a given water system were indicated in boldface text for further discussion with the utility.

Table 3 highlights the identified control strategies (boldface text) for utility H. Similar tables were prepared for each of the 14 participating water systems and are available in Russell et al. (2017). Nanofiltration and reverse osmosis were not included in the desktop evaluation because they would likely be considered only by systems seeking to address additional water quality concerns and/or if no other strategy proved effective to meet target finished water NDMA concentrations. The control strategies focus on removal of NDMA and/or NDMA precursors rather than other nitrosamines because NDMA is detected at much greater frequency (approximately 1 in 10 UCMR 2 samples) than other nitrosamines (<1 in 1,000 samples for each of the other five nitrosamines included in UCMR 2). Nitrosamines other than NDMA were detected only in a few UCMR 2 samples for two of the 14 participating water systems.

Columns 2–4 in Table 3 illustrate which sources of NDMA the respective compliance strategies are effective at addressing on the basis of the literature. For example, an "X" in column 2 indicates that riverbank filtration is a demonstrated technology to remove NDMA in source waters (Schmidt et al. 2006). If no "X" is shown, the compliance strategy is assumed to have limited effectiveness in reducing NDMA from the indicated source.

Site-specific considerations factoring into selection of the control strategies for utility H are summarized in column 5 of Table 3. Chlorine oxidation was selected for discussion as a potential control strategy because the utility's WTPs have multiple chlorine feed points, thus facilitating potential changes in chlorine oxidation time, and because total trihalomethane (TTHM) and five haloacetic acid (HAA5) concentrations are historically low (i.e., 16 and 17 µg/L average distribution system concentrations, respectively). Ozone oxidation was selected as a potential strategy if other, potentially lower-cost plant optimization techniques were not feasible. Polymer optimization was selected because the plant may be able to achieve lower NDMA formation by altering the polymer dose, type, or chlorine and ammonia feed point. Data comparing NDMA formation after chloramination of settled water have been shown to be lower than the maximum NDMA formation possible by reaction of the whole polymer with chloramines (Cornwell et al. 2015). PAC addition was selected as a potential control strategy because utility H's WTPs already have PAC feed capabilities, but may not have optimized the carbon dose and type for NDMA precursor removal. Dichloramine minimization was not selected because the WTPs currently operate under conditions that would be recommended to minimize dichloramine formation (i.e., chlorine added first, 4.5:1 to 5:1 chlorine-to-ammonia nitrogen mass ratio, pH ~8). Distribution system management was not highlighted because UCMR 2 data did not indicate continued NDMA formation in the distribution system.

The research team discussed the practicality of implementing identified potential control strategies and consequences with each participating water system. Utility input was solicited on site-specific simultaneous compliance, operational, and cost impacts of implementing the respective nitrosamine control strategies. A project workshop was conducted to solicit additional input on unintended consequences of nitrosamine control strategies and feedback on the type of practical guidance that could be developed for utilities as an outcome of the project.

WATER SYSTEM CHARACTERISTICS AND CONSIDERATIONS FOR NDMA MITIGATION

Table 4 summarizes available source water quality data for the 14 participating water systems. Six of the water systems have participated in other Water Research Foundation (WRF) projects or have proactively conducted additional water quality analyses relevant to understanding NDMA sources. For these systems, source water sucralose, NDMA, and NDMA formation potential (FP) data (not shown) provided insight into the potential contribution of watershed-derived NDMA precursors. Sucralose concentrations were reviewed because the artificial sweetener provides an indication of the percent wastewater impact (Oppenheimer et al. 2011), and wastewater effluents have been identified as a source of NDMA precursors (Krasner et al. 2009). The available data indicated a range in source water quality, with some water systems having higher wastewater impacts (i.e., utilities A, D, F, and L; seasonal sucralose concentrations >1,000 ng/L) and others having minimal wastewater impacts (e.g., utility E, with sucralose <200 ng/L). As a reference, Oppenheimer et al. (2011) reported a median concentration of sucralose in US wastewater treatment plant effluents of 27,000 ng/L. NDMA FP data generally reflect expected trends based on sucralose data, with higher NDMA FP concentrations (>30 ng/L) in source waters for utilities A, D, F, and L, and lower NDMA FP concentrations (<10 ng/L) for utility E. A few utilities had detectable levels of NDMA in the source water. Utility J had NDMA concentrations between 4.5 and 5.7 ng/L in its source water, utility K had NDMA ranging from nondetect to 8.8 ng/L, and utility M had NDMA in one of its groundwater supplies up to 40 ng/L. Utility M is located near an area with groundwater contamination from former liquid rocket fuel production. For the eight water systems with no source water nitrosamine or NDMA precursor data, sampling would be needed as an initial step to assess concentrations in the source water and corresponding control strategies.

Other water quality data, such as ammonia, bromide, and total organic carbon, facilitate a review of potential control options, factoring in unintended consequences.

Utilities A, B, F, H, and K have ammonia in the source water based on available data, providing insight into the feasibility of implementing chlorine oxidation or dichloramine minimization to reduce NDMA. Historical bromide concentrations can be used to (1) frame bench test conditions to assess the feasibility of implementing ozone factoring in compliance with the bromate MCL and (2) model the impact of an increase in free chlorine contact time on Stage 1 and 2 Disinfectants and Disinfection Byproducts (D/DBP) Rule compliance, factoring in formation of brominated DBPs. Research has also indicated a threefold increase in NDMA concentrations following chloramine addition in the presence of bromide at pH >8 (Luh & Mariñas 2012); however, the bromide concentrations evaluated (32 mg/L) were several orders of magnitude higher than those typically observed in drinking water supplies (i.e., 100 µg/L) (Amy et al. 1995).

Some WTPs treat water from multiple sources (e.g., utilities L and M). For these water systems, the characteristics for each source will need to be reviewed to assess nitrosamine and NDMA precursor sources and control strategies. Any planned or future changes to the relative

TABLE 4 Source water characteristics for participating water systems

Utility	Upstream Impacts (Reported): Wastewater	Agricultural	Industrial	Ammonia *mg/L as N*	TOC *mg/L*	Bromide *µg/L*
A[a], WTP1	•			ND–0.3	5.3	120
A, WTP2	•			0.11–0.96	6.6	145
A, WTP3	•			0.10	5.9	148
B, WTP1 and 3	•	•		0.18–2.5[b]	3.4–14.3	38–147
B, WTP2 and 4	•	•			5.8–16.1	24–93
C	•	•			2.9–4.7	
D[a]	•		•		8.2–18.4	20–40[c]
E[a], WTP1					4.9	
E[a], WTP2					1.6	
F[a]	•			ND–0.36	7.0–12.7	
G, WTP1[d]	•	•			1.9–6.0	ND–650
G, WTP3[d]	•	•			2.4–5.2	ND–300
H, WTP1	•	•		0.01–0.31	2.7–9.2	<50–210
H, WTP2	•	•		0.01–0.5	3–9.8	<50–150
I				<0.1	6.2	
J[a], WTP1	•		•			
J[a], WTP2	•		•			
K[a]	•	•	•	0.11	6.9	
L[a], WTP source 1[e]	•		•			184–487
L[a], WTP source 2[e]	•					31–56
M[a], WTP source 1[e]		•		ND–0.12	1.6–3.8	40–270
M[a], WTP source 2[e]		•		ND–0.02	1.4–3.8	30–290
M[a], wells			•			
N[a], WTP1	•		•			
N[a], WTP2			•			
N[a], WTP3	•					

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N—nitrogen, ND—not detected, TOC—total organic carbon, WTP—water treatment plant

[a] Sucralose, *N*-nitrosodimethylamine (NDMA) formation potential, and/or source water NDMA data were available from utility sampling and/or other Water Research Foundation projects (4180, 4370, 4461, 4444).

[b] Surface water is chloraminated by a water authority before distribution to the utility's WTPs.

[c] Blend of two supplies; concentrations >300 µg/L are measured in a source that constitutes 20% of the current supply.

[d] Utility G's WTP2 uses a blend of the source for WTP1 and WTP3.

[e] Utilities L and M operate only one surface water treatment plant but had discrete data sets for each of the two sources supplying that WTP.

Shading indicates that information is not available.

blend should also be considered in an evaluation of control strategies and consequences.

Plant schematics and operations data were used to further assess potential NDMA sources and control strategies. For example, if a water system used a polyamine or polyDADMAC polymer, polymer-derived precursors were considered as a potential source of NDMA. If a utility had a long free-chlorine contact time (e.g., >200 mg-min/L), additional chlorine oxidation was not considered a potential control strategy for further reduction in NDMA formation. If a utility had TTHM or HAA5 concentrations approaching the respective MCLs, D/DBP Rule compliance factored into the assessment of potential control strategies and consequences.

Eight of the 14 water systems operate more than one WTP. To respond to a potential nitrosamine regulation, these systems will need to consider NDMA contribution from each entry point and the effect on potential distribution system compliance concentrations, factoring in seasonal variations in plant production and water age.

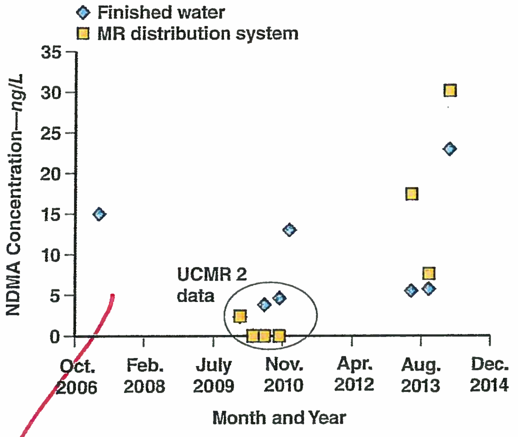
Several of the water systems add PAC either on a seasonal or year-round basis. Other utilities have PAC feed capabilities at their WTPs but report that the feed systems are never or rarely used. For these utilities, PAC addition on a more frequent basis could be a low-capital-cost option to trim NDMA concentrations for compliance with a potential future regulation. PAC has been observed in bench tests to remove wastewater-derived precursors, with better removal achieved using lignite versus bituminous coal carbon for the conditions evaluated (Hanigan et al. 2012). Krasner et al. (2015) reported 38–59% NDMA precursor removal at two full-scale wastewater-affected plants for PAC doses ranging from 4 to 21 mg/L (Figure 1).

NDMA TRENDS AND SOURCES

Figures 2–5 show NDMA data for several of the participating water systems, highlighting the following trends:

- NDMA data for utility A (Figure 2) highlights the need for year-to-year profiling to assess the range of NDMA concentrations that could be observed in the finished water and distribution system. UCMR 2 data collected in 2009 and 2010 were all <5 ng/L. However, grab samples collected in 2007 and 2010 had finished water concentrations >10 ng/L. Samples collected in 2013 (Krasner et al. 2016) also showed higher concentrations.
- On an annual basis, a wide range of NDMA concentrations is observed for some water systems in finished water and distribution system samples. Quarterly distribution system maximum residence time samples varied more than 15 ng/L for utilities A, C, F, I, J (WTPs 1 and 2), and K (Figure 3). For these water systems, seasonal water quality (e.g., percent wastewater impact, source water ammonia concentrations) and/or operational conditions (e.g., polymer use, chloramination conditions, water age) may be leading to periodically high NDMA concentrations. Review of plant operation and water quality data to understand factors contributing to these events could lead to control strategies that lower the peak NDMA concentrations facilitating compliance, which is

FIGURE 2 NDMA concentrations in finished water and distribution system samples from utility A



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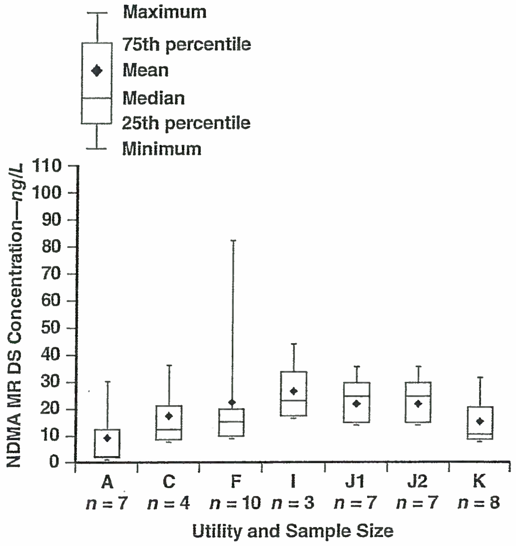
MR—maximum residence time, NDMA—*N*-nitrosodimethylamine, UCMR 2—Unregulated Contaminant Monitoring Rule 2

FIGURE 3 Box and whisker plot illustrating range in NDMA MR DS concentrations over one year



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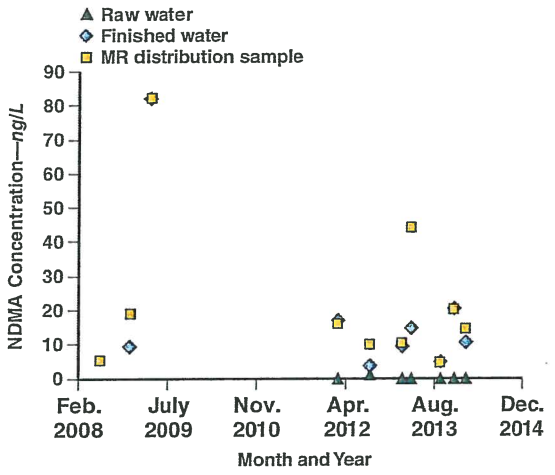
DS—distribution system, MR—maximum residence time, NDMA—*N*-nitrosodimethylamine expected to be based on a locational running annual average (LRAA), if regulated. As an example, utility F (Figure 4) observed high NDMA concentrations on two spring sampling events when ammonia was detected in the source water. For these sampling events, localized breakpoint reactions resulting in dichloramine formation and an absence of free chlorine contact time were identified as the likely causes of the high NDMA concentrations (McCurry et al. 2016a).

FIGURE 4 NDMA concentrations in finished water and distribution system samples from utility F



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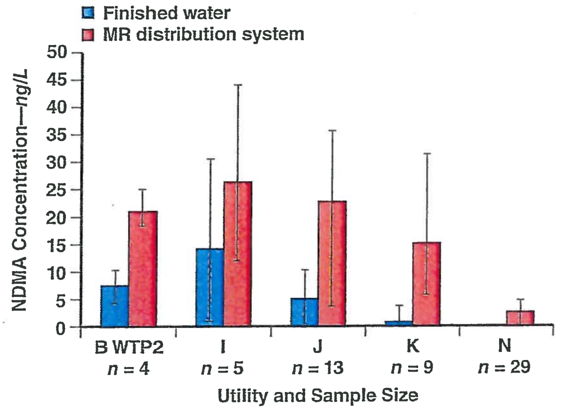
MR—maximum residence time, NDMA—*N*-nitrosodimethylamine

FIGURE 5 Average finished water and distribution system NDMA concentrations for utilities B (WTP2), I, J, K, and N



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MR—maximum residence time, NDMA—*N*-nitrosodimethylamine, WTP—water treatment plant

Whiskers indicate maximum and minimum concentrations.

- Some water systems (Figure 5) had consistently higher distribution system NDMA concentrations compared with finished water concentrations, indicating continued formation or additional NDMA sources in the distribution system that would need to be factored into any control strategy. For utility N, the distribution system NDMA concentrations were above the finished water concentrations, but still low at <10 ng/L.

ASSESSMENT OF POTENTIAL NITROSAMINE SOURCE AND CORRESPONDING CONTROL STRATEGIES

Table 5 lists potential sources of NDMA formation at each water system based on available NDMA data and information on system characteristics (Tables 1 and 4). The potential contribution of source water contamination, watershed-derived precursors, polymer-derived precursors, and distribution system formation is referenced as "high" if considered a likely source of NDMA, "medium" if considered a possible source, and "low" if considered to contribute minimally or not at all. In the absence of quantitative information, the following assumptions were made to provide a qualitative assessment of potential sources of NDMA:

- Concentrations of preformed NDMA were assumed to be minimal in source waters unless data were available to indicate otherwise. This assumption is supported by trends observed in WRF 4461 (Krasner et al. 2016). In a few cases, data were available from other WRF projects and/or the utility to confirm the absence of NDMA in source water samples.
- Source water characteristics (Table 4) were reviewed to assess the likely contribution of watershed-derived precursors. For example, if utilities indicated that their water supply had upstream agricultural or industrial impacts or was wastewater-affected, the source water was identified as a likely source of NDMA precursors. The water supply for utility E is not affected by any municipal, agricultural, or industrial activities. Utility I is located in a rural area and has a pristine source water; however, NDMA formation tests would be needed to confirm the contribution of the source water to NDMA formation.
- The potential contribution of polymer-derived precursors was assessed on the basis of use of polymer at each respective utility and NDMA data, if available. Polymer precursors were indicated as a likely source of NDMA in Table 5 for utilities reporting the use of polyDADMAC and polyamine (epichlorohydrin-dimethylamine). Utility E optimized its use of polyDADMAC in 2003, reducing the dose to <0.5 mg/L as product, and it has since observed finished water NDMA concentrations <2 ng/L minimum reporting level. Utility F uses polymer (polyDADMAC) only a

few months of the year. Utility L applies <0.1 mg/L polyacrylamide. On the basis of bench-scale NDMA FP tests for utility L, the polyacrylamide does not contribute NDMA, consistent with literature findings (Labernik et al. 2010).

- NDMA formation in the distribution system is indicated as a possible source of NDMA for water systems with higher NDMA concentrations in distribution system samples than in finished water samples. For these systems, the distribution system concentration being higher than the finished water NDMA concentration is likely attributed to continued reaction of watershed- or polymer-derived precursors with chloramines and/or reaction of biofilm-derived precursors with chloramines. However, in some cases, distribution system materials have been linked to NDMA (Teefy et al. 2014, Morran et al. 2011). Nitrification in the distribution system could also contribute to NDMA formation in the distribution system (Zeng & Mitch 2016).

Backwash water recycling practices should also be considered in an assessment of potential nitrosamine sources. Eleven of the 14 participating water systems recycle decant or pressate from the sedimentation basin blowdown and/or spent filter backwash water. On the basis of system characteristics for utility I, current backwash recycling practices are a likely source of NDMA; however, sampling data are needed to confirm the contribution from the recycled water.

Table 5 highlights the need for source-to-tap nitrosamine and NDMA precursor profiling to identify and quantify the primary sources of NDMA, which may include source water contamination, watershed-derived precursors, polymer-derived precursors, recycled backwash water, and distribution system components. The relative contribution of those potential NDMA sources may vary under site-specific conditions. Profiling should be conducted at an appropriate frequency to account for potential seasonal and year-to-year variations.

Table 6 summarizes proposed control strategies for all of the participating utilities, developed on the basis of available system information. Dots are used to illustrate the proposed NDMA control strategies for each utility. In some cases, only one control strategy was suggested. For example, utility E has conducted sufficient studies to pinpoint distribution system materials (tank gaskets) as the source of NDMA concentrations >10 ng/L. No other control strategy is suggested because the source of NDMA and prioritized strategy have been identified. In contrast, for most other utilities, testing is required to identify the primary sources of NDMA and assess the optimal NDMA control strategy, taking into account costs, operational impacts, and simultaneous compliance considerations. For these utilities, three or more control strategies may be considered until NDMA sources and control options are better understood.

The variability in proposed NDMA control strategies (Table 6) highlights these key points:

TABLE 5 Summary of potential NDMA sources for case studies

Utility	Source Contaminant	Watershed Precursors	Polymer Precursors	Distribution System Formation
A[a]	Low	High	High	Medium
B	Low	High	High	Medium
C	Low	High	High	Low
D[a]	Low	Medium	High	Medium
E[a]	Low	Low	Low	High[b]
F[a]	Low	High	Low	Medium
G	Low	Medium	Medium	Medium
H	Low	High	High	Medium
I[a]	Low	Low	High	Medium
J[a]	Medium	High	High	Medium
K	Medium	High	High	Medium
L[a]	Low	High	Low	Medium
M[a]	High	Medium	Medium	High
N[a]	Low	Medium	Medium	Medium

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high—a likely source of NDMA, low—an unlikely source of NDMA, medium—a possible source of NDMA, NDMA—*N*-nitrosodimethylamine

[a] Additional NDMA data (besides Unregulated Contaminant Monitoring Rule 2) were available to help clarify nitrosamine sources (e.g., from utility sampling and/or other Water Research Foundation projects).

[b] NDMA in Utility E's distribution system is linked to leaching of NDMA and NDMA precursors from materials in a distribution system storage tank.

- No single best available technology exists for NDMA treatment. The optimal treatment approach will depend on the primary sources of NDMA, the NDMA treatment goal, and other site-specific characteristics, such as source water quality (bromide, turbidity, ammonia, TTHM and HAA5 precursor concentrations), existing treatment processes (e.g., polymer use, current oxidation steps), and distribution system characteristics (e.g., water age, materials).
- Testing is needed to assess the optimal control strategy on the basis of NDMA removal and simultaneous compliance considerations, operational impacts, and costs. Some utilities with lower NDMA concentrations may be able to tweak existing processes, whereas others will need to explore a range of options to get NDMA below a target compliance level.

UNINTENDED CONSEQUENCES

Many of the known consequences of implementing treatment or control strategies considered to minimize NDMA concentrations have been documented. For example, in its simultaneous compliance document for the M/DBP rules, the USEPA lists simultaneous compliance and operational considerations associated with source management, distribution system management, ozonation, chlorine dioxide addition, and addition of GAC (USEPA 2007). Table 7 summarizes consequences documented in that USEPA guideline, along with considerations derived from other literature and those highlighted during discussion with the 14 participating water systems. The tables can be used to facilitate rule development, such as for taking into account the costs associated with the identified consequences (e.g., changes to residuals handling options, increased DBP monitoring if the 40/30 TTHM/HAA5 certification for reduced monitoring is no longer met).

The compilation of consequences documented in the literature and derived from the 14 participating water systems for this desktop study clearly illustrates that changes made at a WTP to reduce NDMA concentrations may

- result in compromised ability for a water system to comply with other regulations;
- result in increased health risk from exposure to other constituents in water while still in compliance with existing regulations; and
- affect operations, with implications for annual operations and maintenance costs.

Discussion with the participating water systems highlighted several consequences of implementing NDMA control strategies that were not immediately apparent from review of the literature or engineering experience. Several utilities were concerned about continued ability to meet Partnership for Safe Water criteria if they made changes to their polymer use. Participation in the Partnership for Safe Water aids in consumer confidence and minimizes pathogen risk beyond levels required by the surface water treatment rules. Two water systems also expressed potential challenges

TABLE 6 Potential NDMA control strategies for participating water systems[a]

Utility (NDMA Range—*ng/L*)	Polymer Optimization	PAC Addition	Chlorine Oxidation	Ozonation	Other Major Capital Project[b]	DS Control/Management
A (ND–30)	•		•		•	
B (4–25)	•	•		•		
C (8–36)	•	•		•	•	
D (3–7)	•	•		•		
E (ND–3)						•
F (5–82)		•	•	•	•	
G (ND–4)						•
H (3–18)	•	•	•	•		
I (10–45)	•	•	•			
J (ND–35)	•	•		•	•	
K (5–32)	•	•		•	•	
L (3–25)		•	•	•		
M (ND–21)	•			•	•	•
N (ND–7.5)	•	•				•

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DS—distribution system, ND—no data, NDMA—*N*-nitrosodimethylamine, PAC—powdered activated carbon

[a] Dots indicate potential NDMA control strategies proposed for different utilities.

[b] Other major capital projects discussed with participating utilities include granulated activated carbon contactors, ultraviolet photolysis (medium-pressure ultraviolet at doses ≥200 mJ/cm²), riverbank filtration, or soil aquifer treatment.

TABLE 7 Simultaneous compliance, risk balancing, and operational considerations for NDMA control strategies

NDMA Mitigation Approach	Simultaneous Compliance[a]	Risk Balancing	Operational Impacts
Change in source water	Changes in DS water quality with impacts on pipe corrosion May affect TTHM and HAA5 formation May change particle and pathogen loading *LT2ESWTR, Stage 1 and 2 D/DBPR, LCR, GWR, RTCR*	Change in DS water quality with impacts on pipe corrosion Changes in pathogen loading balanced with impacts on disinfection requirements and corresponding formation of TTHM and HAA5	A source water change may alter the taste and/or odor of a water or cause water color issues (e.g., from Fe or Mn) Potential impact on residuals quality/quantity Changes in treatability and corresponding plant operations
RBF or SAT	Changes in DS water quality with impacts to pipe corrosion May decrease TTHM and HAA5 formation Potential credit for *Cryptosporidium* removal per microbial toolbox (USEPA 2006a) May reduce particle and pathogen loading *LT2ESWTR, Stage 1 and 2 D/DBPR, LCR*	Change in DS water quality with impacts on pipe corrosion Potential increase in concentrations of minerals/contaminants in the riverbank or aquifer (e.g., arsenic)	Potential impact on residuals quality/quantity Clogging/hydraulic impacts for RBF Changes in treatability and corresponding plant operations
Oxidation with chlorine	Increased formation of TTHM and HAA5 Potential increase in $C \times T$ and improved pathogen control *Stage 1 and 2 D/DBPR, RTCR*	Increased formation of TOX and unregulated halogenated DBPs (Krasner et al. 2006)	Increased sampling if 40/30 certification allowing reduced monitoring no longer applies (see Table IV.F-1 of USEPA 2006b)
Oxidation with ozone	Bromate formation Potential reduction in TTHM and HAA5 formation, particularly when coupled with BAF Potential increase in $C \times T$ and improved pathogen control Degradation of NOM to AOC can affect biofilm growth and stability of pipe scales Potential credit for *Cryptosporidium* inactivation per microbial toolbox (USEPA 2006a) *LT2ESWTR, Stage 1 and 2 D/DBPR, LCR, RTCR*	Increased formation of chloropicrin (McCurry et al. 2016b, Bond et al. 2014, Hoigné & Bader 1988), and acetaldehydes (McKnight & Reckhow 1992) Increased cancer risk from bromate ingestion at levels below the MCL Reduction in haloacetonitriles (McKnight & Reckhow 1992) Potential benefit for algal toxin control Change in DS water quality with impacts on pipe corrosion if AOC is not mitigated	May remove taste-and-odor-causing compounds from water Affects Mn speciation and removal Additional water quality monitoring for bromate, ozone residual, and AOC Discontinued ability to add chlorine for algae control on filters if they are converted to BAF in conjunction with ozone addition
Oxidation with chlorine dioxide	Chlorite formation Potential increase in $C \times T$ and improved pathogen control Potential credit for *Cryptosporidium* inactivation per microbial toolbox (USEPA 2006a) *LT2ESWTR, Stage 1 and 2 D/DBPR*	Chlorate formation potential Benefit for algal toxin control	May remove taste-and-odor-causing compounds from water Can improve Fe and Mn removal Nitrification prevention from release of chlorite ion (McGuire et al. 2006) Requires additional monitoring for compliance with Stage 1 D/DBPR
Change in polymer dose/type	Impact on particulate removal and SWTR compliance including LT2ESWTR *Cryptosporidium* removal credit if IFE or CFE turbidity concentrations change Compliance with Stage 1 and 2 DBPR[b] Potential impact on NPDES permit depending on change in coagulant dose and site-specific permit limits *LT2ESWTR, NPDES*	Impact on pathogen risk reduction Impact on continued ability to meet Partnership for Safe Drinking Water requirements	Plant production efficiency Shorter filter run times Increased backwash frequency Residuals handling Alternate polymers may not be effective for targeted filter loading rates (>10 gpm/ft^2) for a direct filtration plant

TABLE 7 Simultaneous compliance, risk balancing, and operational considerations for NDMA control strategies, *continued*

NDMA Mitigation Approach	Simultaneous Compliance[a]	Risk Balancing	Operational Impacts
PAC addition	Removal of NOM and certain trace organics can reduce DBP formation *Stage 1 and 2 D/DBPR*	Potential benefit for algal toxin control	May remove taste-and-odor-causing compounds from water Maintenance of PAC feed system Increase in residuals loading Impact on chlorine dose depending on point of addition
GAC contactors	Removal of organics can reduce DBP formation Removal of organics can improve control of distribution system biofilms and reduce chlorine demand with beneficial impacts on LCR and RTCR compliance Potential 0.5-log credit for *Cryptosporidium* removal per microbial toolbox (USEPA 2006a) *Stage 1 and 2 D/DBPR, LCR, RTCR*	Potential benefit for algal toxin control Removal of other organic microconstituents	May remove taste-and-odor-causing compounds from water Potential need for low lift pumping Addition of GAC backwash water for residuals handling
UV photolysis	Pathogen inactivation Potential credit for *Cryptosporidium* inactivation per microbial toolbox (USEPA 2006a) *LT2ESWTR*	Chloropicrin formation with medium pressure UV lamps (Reckhow et al. 2010) Degradation of microconstituents	Potential need for low lift pumping
Dichloramine minimization	Optimized formation of monochloramine and improved management of nitrification can provide benefit for RTCR compliance *RTCR*	Careful control over Cl_2:NH_3-N can also help manage nitrification, resulting in better disinfectant residual maintenance	Impact on nitrification control depending on target Cl_2:NH_3-N and pH Minimize taste and odor associated with dichloramine Stringent performance window with implications for process control and staffing
Distribution system management	Potential reduction in TTHM and HAA5 concentrations if water age is reduced Improved chlorine residual maintenance Can reduce corrosion *Stage 1 and 2 D/DBPR, RTCR*	Potentially improved microbial control	Impact on nitrification control if water age is reduced or a change in chlorine boosting is implemented Flushing results in increased water loss

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AOC—assimilable organic carbon, BAF—biologically active filtration, CFE—combined filter effluent, Cl_2:NH_3-N—chlorine-to-ammonia mass ratio, $C \times T$—product of disinfectant concentration and the corresponding disinfectant contact time, DBP—disinfection by-product, D/DBPR—Disinfectants and Disinfection Byproducts Rule, DS—distribution system, Fe—iron, GAC—granulated activated carbon, GWR—Groundwater Rule, HAA5—haloacetic acid, IFE—individual filter effluent, LCR—Lead and Copper Rule; LT2ESWTR—Long Term 2 Enhanced Surface Water Treatment Rule, MCL—maximum contaminant level, Mn—manganese, NDMA—*N*-nitrosodimethylamine, NOM—natural organic matter, NPDES—National Pollutant Discharge Elimination System, PAC—powdered activated carbon, RBF—riverbank filtration, RTCR—Revised Total Coliform Rule, SAT—soil aquifer treatment, SWTR—Surface Water Treatment Rule, TOX—total organic halogen, TTHM—total trihalomethane, USEPA—US Environmental Protection Agency, UV—ultraviolet

[a] Regulations for which compliance could be affected because of proposed NDMA mitigation strategy are listed in italics.

[b] A few participating water systems that tested polymer changes at full-scale observed an increase in TTHM and HAA5 formation as a result of that change; however, it was not clear from discussions whether the coagulant dose was a factor.

associated with meeting National Pollutant Discharge Elimination System (NPDES) permit requirements if a change in polymer application translated to increased coagulant dose. Utility K currently discharges all plant residuals to the Mississippi River under an NPDES permit. That section of the river has established numerical criteria for aluminum; an increase in the alum dose potentially required to facilitate discontinued or reduced use of polymer may result in NPDES permit compliance implications. Utility H also cited concerns regarding the potential impact of a change in polymer dose or type on its residuals permit.

Positive consequences of making changes to address NDMA were also reported. Utility M reported that its efforts to optimize polymer use to reduce chemical costs translated to a reduction in NDMA formation following chloramine addition. Implementation of ozone, chlorine dioxide, PAC, or GAC to address NDMA can also result in improved taste and odor.

Compliance with the existing M/DBP rules (i.e., Revised Total Coliform Rule, Interim Enhanced Surface Water Treatment Rule, Long Term 1 Enhanced Surface Water Treatment Rule/Long Term 2 Enhanced Surface Water Treatment Rule, and Stage 1 and 2 D/DBP Rule) is most frequently at risk from implementing potential NDMA control strategies. Several NDMA control strategies can affect distribution system water quality, with potential impacts to Revised Total Coliform Rule and/or Lead and Copper Rule compliance.

The cost implications of making changes to address NDMA were also discussed with the participating water systems during conference calls and a breakout session at the workshop. Costs associated with implementing NDMA control strategies were brought up as a concern primarily during discussion of major capital improvements such as riverbank filtration, ozone addition, GAC contactors or filter adsorbers, or ultraviolet photolysis. The following key points were discussed:

- For small systems, such as utility I, a very small number of customers would bear the burden of a rate impact. Such systems will be particularly constrained to finance a capital improvement project for nitrosamine control.
- Until regulated, funding for capital improvement projects to reduce NDMA concentrations may be difficult to justify to utility boards or councils and to ratepayers.
- Budgeting should include the costs to conduct source-to-tap nitrosamine and NDMA precursor profiling (see Table 2), and to conduct bench and/or pilot tests to assess the effectiveness of the proposed control strategy, evaluate consequences and any mitigation factors, and develop design criteria.

Costs to implement nitrosamine control strategies will depend on the target NDMA concentration/compliance level. For example, utility L has been able to reduce NDMA LRAA concentrations from 22 to 7 ng/L by adding a small amount (0.4–1 mg/L) of chlorine, in conjunction with chlorine dioxide, before the clearwells. Costs associated with this treatment change are minimal. If utility L needed to reduce NDMA concentrations further, PAC addition could be implemented on a year-round basis (currently only added seasonally, approximately three months per year) to achieve an additional 20% reduction in NDMA to an ~5 ng/L LRAA (based on full-scale data and associated analysis for WRF 4444; Uzun et al. 2016). Capital costs for the PAC feed system were previously incurred by the water system; however, annual chemical costs to increase PAC addition at the utility's 150 mgd WTP to year-round frequency are $230,000 in 2016 dollars (based on PAC cost of $0.63/lb [PAC costs in other regions of the United States may be higher]). Further reduction in NDMA could require implementation of a more costly improvement project.

For many systems using chloramines as the primary or secondary disinfectant, minor, low-cost modifications may only be capable of reducing NDMA to concentrations in the mid-range of where USEPA could consider regulating (e.g., 20 ng/L, twice the California notification level). Major capital changes may be needed to meet more stringent MCLs (e.g., ≤10 ng/L) with significant system-specific cost implications, particularly when factoring in costs to mitigate unintended consequences (Russell et al. 2017).

FRAMEWORK FOR IMPLEMENTING NITROSAMINE CONTROL STRATEGIES ACCOUNTING FOR CONSEQUENCES

In the process of compiling data for each system to assess potential NDMA sources and corresponding control strategies, it quickly became clear that absent nitrosamine and NDMA precursor profiling data, any assessment of consequences (not to mention sources and control strategies) was qualitative at best. As was expected, the more data that were available, the easier it was to identify potential next steps for nitrosamine control. Even when data were available, historical knowledge of operational events, such as seasonal water quality issues or timing of change in polymer used, was critical to help with the appropriate interpretation of the data. Participating utilities recommended the development of tools and processes to help step through decision-making and provide guidance on how to perform in-house assessments.

Figure 6 provides an overarching framework and tools for water utilities to assess nitrosamine sources and control strategies, accounting for simultaneous compliance, operational, and cost impacts. A checklist (Table 2) can be used to identify source water, treatment, and distribution system characteristics to facilitate an initial assessment of nitrosamine sources and potential control strategies that are based on site-specific conditions. In the absence of comprehensive, seasonal nitrosamine data, the Guideline for Source-to-Tap NDMA/Nitrosamine Profiling (Russell et al. 2017) can be followed to identify sample locations and procedures to assess the site-specific source(s) of NDMA. A minimum of quarterly samples is recommended, including seasonal events that are anticipated to affect formation of NDMA (e.g., when polymer doses are high, percent wastewater impact is expected to be high).

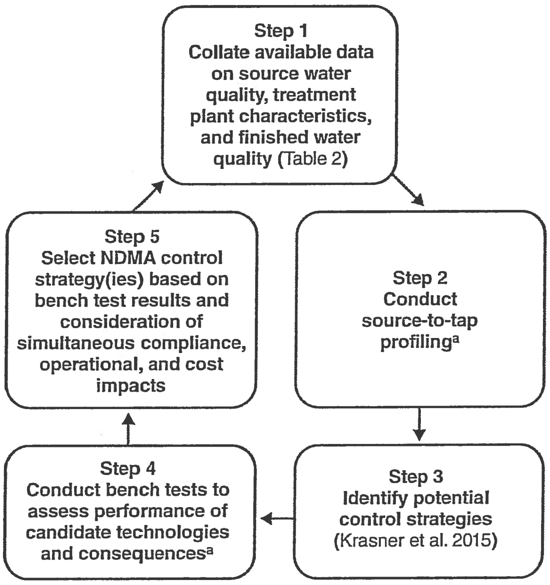
A decision tree (Krasner et al. 2015) that is based on the water system data and source-to-tap profiling can be used to identify potential compliance options and any interim studies that may help inform the decision-making process. Bench tests may be needed to inform decisions on the optimal control strategy to achieve target nitrosamine concentrations while maintaining compliance with other regulations and minimizing detrimental impacts to plant operations and costs.

Actions to reduce concentrations of a contaminant are sometimes challenging in the absence of a final regulation. One approach water systems can take is to integrate planning for a potential NDMA regulation, with ongoing operational or capital improvement program activities and/or long-range facility planning, to better position the utility for future compliance, using the framework (Figure 6) as a guideline.

CONCLUSION

A qualitative assessment of unintended consequences of implementing nitrosamine control strategies was developed on the basis of a literature review, desktop exercise, and expert workshop evaluating potential control strategies for 14 participating water systems. The assessment provided tabulated information on consequences, including simultaneous compliance and operational impacts that are well documented in the literature, along with site-specific considerations elucidated from discussions with the participating water systems. The qualitative information can help inform the regulatory development process by highlighting factors that should be considered in a cost and technology assessment for rule development.

FIGURE 6 Framework for implementing nitrosamine control strategies accounting for simultaneous compliance, operational, and cost impacts



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NDMA—*N*-nitrosodimethylamine

[a] Guidelines are under development for Water Research Foundation Project 4491 (Russell et al. 2017).

Seasonal profiling data are needed to understand nitrosamine and NDMA precursor sources as one of the first steps to assess control strategies and corresponding consequences. UCMR 2 data alone are not sufficient. Most water utilities do not have NDMA profiling data unless they have conducted special studies either within their own utility or via participation in WRF projects.

On the basis of a review of 14 participating utilities, the sources of nitrosamines and NDMA precursors (and relative contribution of those sources) vary between plants. The optimal treatment approach will depend on the primary sources of NDMA, the NDMA treatment goal, and other site-specific characteristics, such as source water quality (e.g., bromide, turbidity, ammonia, TTHM and HAA5 precursor concentrations), existing treatment processes (e.g., polymer use, current oxidation steps), and distribution system characteristics (e.g., water age, materials).

In the absence of robust NDMA data, water quality, plant design, and operational data can be compiled to initiate an assessment of potential nitrosamine sources and to inform development of a source-to-tap profiling plan to quantify sources under different seasonal conditions. Testing is needed to assess the optimal control strategy on the basis of NDMA removal and factoring in unintended consequences. Some utilities with lower NDMA concentrations may be able to make minor adjustments to existing processes to meet a target NDMA goal, whereas others will need to explore a range of options to get NDMA below a target compliance level. The lower the NDMA treatment goal, the more likely it is that high-cost capital projects are needed.

Absent a regulatory determination, most water systems are unlikely to characterize their NDMA sources and plan steps to reduce concentrations unless those steps are taken as part of a broader facility planning exercise in which potential NDMA compliance is factored into planned upgrades to the plant to ensure that the existing plant can accommodate improvements needed to address a nitrosamine regulation if promulgated. A framework was developed to help utilities respond to an NDMA regulation or take the first steps to integrate NDMA control into ongoing near-term capital improvement project activities, and/or long-range facility planning. This process should be initiated early because a minimum of 18 months would be needed to conduct quarterly sampling and test control strategies, followed by an additional two years or more to design and implement NDMA strategies requiring a capital improvement project.

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ABOUT THE AUTHORS

Caroline G. Russell *(to whom correspondence may be addressed) is a principal technologist with Carollo Engineers Inc., 8911 Capital of Texas Hwy. North, Ste. 2200, Austin, TX 78759 USA; crussell@carollo.com. She was the national practice leader for drinking water at ARCADIS U.S. Inc. during the time this project was conducted. She has more than 17 years of experience in the drinking water field, focusing on topics ranging from treatment process and distribution system optimization to planning for future regulations.* ***Richard A. Brown*** *is with Cornwell Engineering Group, Newport News, Va.* ***Katie Porter*** *is with Brown and Caldwell, Los Angeles, Calif., and was with ARCADIS U.S. Inc. at the time of this work.* ***David Reckhow*** *is with the Department of Civil Engineering, University of Massachusetts–Amherst, Amherst, Mass.*

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REFERENCES

Amy, G.; Siddiqui, M.; Zhai, W.; DeBroux, J.; & Odem, W., 1995. *Survey of Bromide in Drinking Water and Impacts on DBP Formation.* AWWA Research Foundation, Denver.

Bond, T.; Templeton, M.R.; Rifai, O.; Ali, H.; & Graham, N.J., 2014. Chlorinated and Nitrogenous Disinfection By-Product Formation From Ozonation and Post-Chlorination of Natural Organic Matter Surrogates. *Chemosphere,* 111:218. https://doi.org/10.1016/j.chemosphere.2014.03.090.

Cornwell, D.; Brown, R.; & Krasner, S., 2017. Evaluating Polymers to Avoid Polymer-Induced NDMA Formation. *Journal AWWA,* 109:6:E197. https://doi.org/10.5942/jawwa.2017.109.0040.

Cornwell, D.; Krasner, S.; Mitch, W.; & Pignatello, J., 2015. *Investigating Coagulant Aid Alternatives to PolyDADMAC Polymers.* Water Research Foundation, Denver.

Farré, M.J.; Keller, J.; Gernjak, W.; Weinberg, H.S.; Lyon, B.; & Poussade, Y., 2010. Fate of Disinfection By-products & Their Precursors Across Reverse Osmosis Membranes When Producing High Quality Recycled Water. AWWA Water Quality Technology Conference, Savannah, Ga.

Hanigan, D.; Zhang, J.; Herckes, P.; Zhu, E.; Krasner, S.; & Westerhoff, P., 2015. Contribution and Removal of Watershed and Cationic Polymer *N*-Nitrosodimethylamine Precursors. *Journal AWWA,* 107:3:E152. https://doi.org/10.5942/jawwa.2015.107.0013.

Hanigan, D.; Zhang, J.; Herckes, P.; Krasner, S.; Chen, C.; & Westerhoff, P., 2012. Adsorption of *N*-Nitrosodimethylamine Precursors by Powdered and Granular Activated Carbon. *Environmental Science and Technology,* 46:22:12630. https://doi.org/10.1021/es302922w.

Hoigné, J. & Bader, H., 1988. The Formation of Trichloronitromethane (Chloropicrin) and Chloroform in a Combined Ozonation/Chlorination Treatment of Drinking Water. *Water Research,* 22:313. https://doi.org/10.1016/S0043-1354(88)90120-0.

Kemper, J.M.; Walse, S.S.; & Mitch, W.A., 2010. Quaternary Amines as Nitrosamine Precursors: A Role for Consumer Products. *Environmental Science & Technology,* 44:1224. https://doi.org/10.1021/es902840h.

Kemper, J.M.; Westerhoff, P.; Dotson, A.; & Mitch, W.A., 2009. Nitrosamine, Dimethylnitramine, and Chloropicrin Formation During Strong Base Anion-Exchange Treatment. *Environmental Science & Technology,* 43:466. https://doi.org/10.1021/es802460n.

Kohut, K.D. & Andrews, S.A., 2003. Polyelectrolyte Age and *N*-Nitrosodimethylamine Formation in Drinking Water Treatment. *Water Quality Research Journal of Canada,* 38:4:719.

Krasner, S.W.; Leavey, S.; Qian, Y.; Li, X.-F.; Marfil-Vega, R.; & Bukhari, Z., 2016. *Nitrosamine Occurrence Survey.* Water Research Foundation, Denver.

Krasner, S.W.; Shirkhani, R.; Westerhoff, P.; Hanigan, D.; Mitch, W.A.; McCurry, D.L.; Chen, C.; Skadsen, J.; & von Gunten, U., 2015. Controlling the Formation of Nitrosamines During Water Treatment. Water Research Foundation, Denver.

Krasner, S.W.; Mitch, W.A.; McCurry, D.L.; Hanigan, D.; & Westerhoff, P., 2013. Formation, Precursors, Control, and Occurrence of Nitrosamines in Drinking Water: A Review. *Water Research,* 47:4433. https://doi.org/10.1016/j.watres.2013.04.050.

Krasner, S.W.; Mitch, W.A.; Westerhoff, P.; & Dotson, A., 2012a. Formation and Control of Emerging C- and N-DBPs in Drinking Water. *Journal AWWA,* 104:11:E582.

Krasner, S.W.; Fen, C.; Lee, T.; Mitch, W.A.; & von Gunten, U., 2012b. *Development of a Bench-Scale Test to Predict the Formation of Nitrosamines.* Water Research Foundation, Denver.

Krasner, S.W.; Westerhoff, P.; Chen, B.; Rittmann, B.E.; Nam, S.N.; & Amy, G., 2009. Impact of Wastewater Treatment Processes on Organic Carbon, Organic Nitrogen, and DBP Precursors in Effluent Organic Matter. *Environmental Science & Technology,* 43:8:2911.

Krasner, S.W.; Westerhoff, P.; Chen, B.; Amy, G.; Nam, S.N.; Chowdhury, Z.K.; Sinha, S.; & Rittmann, B.E., 2008. *Contribution of Wastewater to DBP Formation.* Water Research Foundation, Denver.

Krasner, S.W.; Weinberg, H.S.; Richardson, S.D.; Pastor, S.J.; Chinn, R.; Sclimenti, M.J.; Onstad, G.D.; & Thruston, A.D. Jr., 2006. Occurrence of a New Generation of Disinfection Byproducts. *Environmental Science & Technology,* 40:23:7175. https://doi.org/10.1021/es060353j.

Labernik, S.M.; Liang, S.; Yates, R.; & Yun, T., 2010. Formation and Control of NDMA With Cationic Polymers. AWWA Water Quality Technology Conference, Savannah, Ga.

Le Roux, J.; Gallard, H.; & Croue, J., 2011. Chloramination of Nitrogenous Contaminants (Pharmaceuticals and Pesticides): NDMA and

Halogenated DBPs Formation. *Water Research,* 45:3164. https://doi.org/10.1016/j.watres.2011.03.035.

Luh, J. & Mariñas, B., 2012. Bromide Ion Effect on *N*-Nitrosodimethylamine Formation by Monochloramine. *Environmental Science & Technology,* 46:9:5085. https://doi.org/10.1021/es300077x.

McCurry, D.L.; Krasner, S.W.; & Mitch, W.A., 2016a. Control of Nitrosamines During Non-potable and de Facto Wastewater Reuse With Medium Pressure Ultraviolet Light and Preformed Monochloramine. *Environmental Science & Technology,* 50:2:502. https://doi.org/10.1039/c6ew00044d.

McCurry, D.L.; Quay, A.N.; & Mitch, W.A., 2016b. Ozone Promotes Chloropicrin Formation by Oxidizing Amines to Nitro Compounds, *Environmental Science & Technology,* 50:3:1209. https://doi.org/10.1021/acs.est.5b04282.

McCurry, D.L.; Krasner, S.W.; von Gunten, U.; & Mitch, W.A., 2015. Determinants of Disinfectant Pretreatment Efficacy for Nitrosamine Control in Chloraminated Drinking Water. *Water Research,* 84:161. https://doi.org/10.1016/j.watres.2015.07.024.

McGuire, M.J.; Perarthree, M.S.; Blute, N.K.; Arnold, K.F.; & Hoogerwerf, T., 2006. Nitrification Control by Chlorite Ion at Pilot-Scale. *Journal AWWA,* 98:1:95.

McKnight, A. & Reckhow, D.A., 1992. Chlorine Reactions of Ozonation By-products: Model Compound Studies. American Chemical Society National Conference Preprints, 32:1:722.

Mitch, W.; Krasner, S.W.; Westerhoff, P.; & Dotson, A., 2009. Occurrence and Formation of Nitrogenous Disinfection By-products. AWWA Research Foundation, Denver.

Mitch, W.A.; Oelker, G.L.; Hawley, E.L.; Deeb, R.A.; & Sedlak, D.L., 2005. Minimization of NDMA Formation During Chlorine Disinfection of Municipal Wastewater by Application of Pre-formed Chloramines. *Environmental Science & Technology,* 22:6:882. https://doi.org/10.1089/ees.2005.22.882.

Mitch, W.A. & Sedlak, D.L., 2004. Characterization and Fate of *N*-Nitrosodimethylamine Precursors in Municipal Wastewater Treatment Plants. *Environmental Science & Technology,* 38:1445. https://doi.org/10.1021/es035025n.

Miyashita, Y.; Park, S-H.; Hyung, H.; Huang, C-H.; & Kim, J-H., 2009. Removal of *N*-Nitrosamines and Their Precursors by Nanofiltration and Reverse Osmosis Membranes. *Journal of Environmental Engineering,* 135:9:788. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000043.

Morran, J.; Whittle, M.; Fabris, R.B.; Harris, M.; Leach, J.S.; Newcombe, G.; & Drikas, M., 2011. Nitrosamines From Pipeline Materials in Drinking Water Distribution Systems. *Journal AWWA,* 103:10:76.

Najm, I. & Trussell, R.R., 2001. NDMA Formation in Water and Wastewater. *Journal AWWA,* 93:2:92.

Oppenheimer, J.M.; Eaton, A.; Badruzzaman, M.; Haghani, A.W.; & Jacangelo, J.G., 2011. Occurrence and Suitability of Sucralose as an Indicator Compound of Wastewater Loading to Surface Waters in Urbanized Regions. *Water Research,* 45:13:4019.

Park, S.H.; Wei, S.; Mizaikoff, B.; Taylor, A.E.; Favero, C.; & Huang, C.H., 2009. Degradation of Amine-Based Water Treatment Polymers During Chloramination as *N*-Nitrosodimethylamine (NDMA) Precursors. *Environmental Science & Technology,* 43:1360. https://doi.org/10.1021/es802732z.

Reckhow, D.A.; Linden, K.G.; Kim, J.; Shemer, H.; & Makdissy, G., 2010. Effect of UV Treatment on DBP Formation. *Journal AWWA,* 102:6:100.

Russell, C.G.; Cornwell, D.; Reckhow, D.; Karanfil, T.; Brown, R.; Jackson, J.; Evans, A.; & Porter, K., 2017. *Unintended Consequences of Implementing Nitrosamine Control Strategies.* Project 4491. Water Research Foundation, Denver.

Russell, C.G.; Blute, N.K.; Via, S.; Wu, X.; & Chowdhury, Z., 2012. Nationwide Assessment of Nitrosamine Occurrence and Trends. *Journal AWWA,* 104:3:E205. https://doi.org/10.5942/jawwa.2012.104.0037.

Sacher, F.; Schmidt, C.K.; Lee, C.; & von Gunten, U., 2008. *Strategies for Minimizing Nitrosamine Formation During Disinfection.* AWWA Research Foundation, Denver.

Schmidt, C.K.; Sacher, F.; & Brauch, H.-J., 2006. Strategies for Minimizing Formation of NDMA and Other Nitrosamines during Disinfection of Drinking Water. AWWA Water Quality Technology Conference, Savannah, Ga.

Schreiber, I.M. & Mitch, W.A., 2006. Nitrosamine Formation Pathway Revisited: The Importance of Chloramine Speciation and Dissolved Oxygen. *Environmental Science & Technology,* 40:6007. https://doi.org/10.1021/es060978h.

Sedlak, D. & Kavanaugh, M., 2006. *NDMA and NDMA Precursors During Wastewater Treatment.* WateReuse Foundation Project WRF-01-002 Report, Alexandria, Va.

Shah, A.D.; Krasner, S.W.; Lee, C.F.T.; von Gunten, U.; & Mitch, W.A., 2012. Trade-Offs in Disinfection Byproduct Formation Associated With Precursor Preoxidation for Control of *N*-Nitrosodimethylamine Formation. *Environmental Science & Technology,* 46:9:4809.

Teefy, S.; Chan, C.C.; Wong, W.; & Work, L., 2014. NDMA Formation From Gaskets Used in Water Storage Tanks. *Journal AWWA,* 106:9:E408. https://doi.org/10.5942/jawwa.2014.106.0081.

USEPA (US Environmental Protection Agency), 2016. Six-Year Review 3 Pre-Publication Notice. USEPA-HQ-OW-2016-0627. www.epa.gov/sites/production/files/2016-12/documents/six_year_3_review_frn_12-21-16.pdf (accessed Mar. 9, 2017).

USEPA, 2007. *Simultaneous Compliance Guidance Manual for the Long Term 2 and Stage 2 DBP Rules.* USEPA 815-R-07-017. www.epa.gov/dwreginfo/stage-1-and-stage-2-compliance-help-community-water-system-owners-and-operators (accessed Mar. 9, 2017).

USEPA 2006a. Long Term 2 Enhanced Surface Water Treatment Rule. *Federal Register,* 71:3:653.

USEPA, 2006b. Stage 2 Disinfectants and Disinfection Byproducts Rule. *Federal Register,* 71:2:388.

Uzun, H.; Kim, D.; Beita-Sandi, W.; Ersan, M.S.; & Karanfil, T., 2016. *Seasonal Changes in NDMA Formation Potential and Its Removal During Water Treatment.* Water Research Foundation, Denver.

Wang, X.-M.; Li, B.; Zhang, T.; & Li, X.-Y., 2015. Performance of Nanofiltration Membrane in Rejecting Trace Organic Compounds: Experiment and Model Prediction. *Desalination,* 370:7. https://doi.org/10.1016/j.desal.2015.05.010.

Wilczak, A.; Assadi-Rad, A.; Lai, H.H.; Hoover, L.L.; Smith, J.; Berger, R.; Rodigari, F.; Beland, J.W.; Lazzelle, L.J.; Kincannon, E.G.; Baker, H.; & Heaney, C.T., 2003. Formation of NDMA in Chloraminated Water Coagulated with DADMAC Cationic Polymer. *Journal AWWA,* 95:9:94.

Zeng, T. & Mitch, W.A., 2016. Impact of Nitrification on the Formation of *N*-Nitrosamines and Halogenated Disinfection Byproducts Within Distribution System Storage Facilities. *Environmental Science & Technology,* 50:2964. https://doi.org/10.1021/acs.est.5b05668.

Zeng, T. & Mitch, W.A., 2015. Contribution of *N*-Nitrosamines and Their Precursors to Domestic Sewage by Greywaters and Blackwaters. *Environmental Science & Technology,* 49:22:13158. https://doi.org/10.1021/acs.est.5b04254.