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TECHNICAL MEMORANDUM

To: Sean Greig, Water & Sewer Superintendent File: 2056.08
From: Michael Metcalf, P.E.
cc: Keith Pratt, P.E.
Date: September 29, 2016
Re: **Corrosion Control with Addition of the MacIntosh Well**

BACKGROUND

The Town of Newmarket is currently served by two gravel packed wells, the Bennett and Sewell Wells, with nominal capacities of 185 gpm (266,400 gpd) and 260 gpm (374,400 gpd) respectively. Average daily use for the three year period from 2013 through 2015 was about 390,000 gpd. These numbers indicate that the Newmarket Water System is not in compliance with NHDES source water capacity criteria which require meeting average day demand with the largest well out of service. As a result, the Town was required to complete a Corrective Action Plan (CAP) indicating how the Town would increase its source water capacity. The CAP, which was submitted and accepted by NHDES in May of 2012, provided a proposed schedule for placing a new bedrock groundwater source, the MacIntosh Well, into service.

The MacIntosh Well, which has been permitted at 300 gpm (432,000 gpd), has water with high sodium, chloride, and TDS concentrations that approach or exceed the secondary MCL's (SMCL's), as well as high conductivity, all of which are indicators of potentially corrosive water. In addition, arsenic is close to the MCL and manganese exceeds the SMCL. The Town evaluated treatment, putting the well on-line as is, and blending with the existing wells to try to reduce the concentrations of the previously mentioned contaminants to below the MCL's and SMCL's. Blending was the selected alternative and the Town is in the final phases of completing a blending facility near Durell Drive. Water from the distribution system (i.e. Bennett and Sewell Well water) will be directed into the blending facility and will be mixed with water pumped from the MacIntosh Well. The blend will then be re-pumped into the system. The current proposal is to blend the waters at a ratio of 50 to 60% MacIntosh water and 40 to 50% distribution water.

Given events in Flint, MI, where a switch to a different more corrosive water source and a lack of proper corrosion control led to leaching of lead from existing water system materials and resultant high lead levels in the distribution system, the Town of Newmarket wants to ensure that similar high lead concentrations do not occur in the Newmarket distribution system as a result of the addition of the MacIntosh Well. Therefore, the Town retained Underwood Engineers (UE) to complete a desktop evaluation to assess the potential for corrosion, the effectiveness of existing corrosion control measures and whether a corrosion inhibitor is needed in addition to adjusting pH and alkalinity.

CORROSION & METALS RELEASE

The internal corrosion of water systems causes pipe material to convert from its insoluble state as solid pipe and become dissolved in the passing water which leads to two types of issues:

1. Loss of carrying capacity due to build up of corrosion by-products (i.e. tuberculation) and possible leaks or pipe failure due to metal loss.
2. Leaching of pipe materials into the water effecting water quality. This could be lead as happened in Flint and/or iron leading to colored water, staining of fixtures, etc.

Corrosion is an electrochemical process involving the flow of electrons. For corrosion to occur, all the components of an electrochemical cell must be present as noted below:

- Anode – the location on the pipe from which electrons are transferred and therefore where pipe material is lost
- Cathode – the location on the pipe with a different electrical potential than the anode and where corrosion byproducts are deposited
- External circuit – the connection between the anode and cathode, i.e. the pipe
- Internal circuit – the conducting solution between the anode and the cathode, i.e. the water in the pipe

The theory of corrosion can be represented by the graphic in **Figure 1** which depicts iron corrosion. Of note in this figure is the “$2H^{+}$” at the cathode. For this reaction to occur, the water (internal circuit) must be acidic in order to provide the two hydrogen ions, and two electrons must be supplied from the anode. The loss of these electrons releases the soluble ferrous iron (Fe^{2+}) from the anode which flows to the cathode where it is deposited as iron tubercles, i.e. corrosion. If this is uniform corrosion, there is a relatively uniform loss of metal along the entire pipe. If it is localized corrosion, it can lead to localized metal loss, *i.e.*, pitting, and build up of tuberculation as noted above.

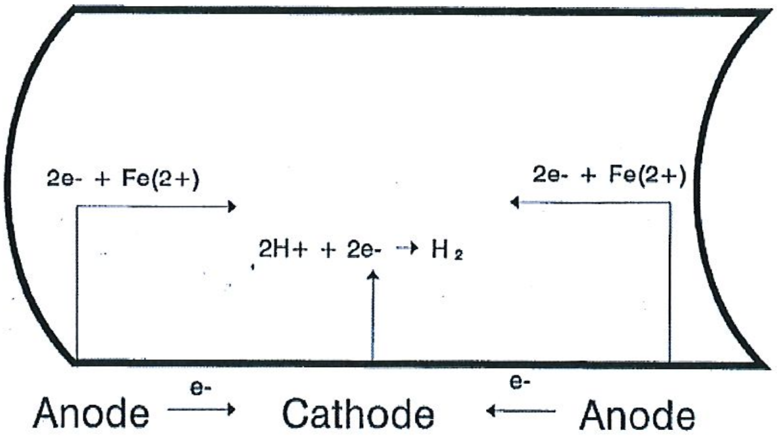


Figure 1 – Corrosion of Iron Pipe in an Acidic Solution

This release of metallic ions is referred to as metals release and is the primary focus of the Lead and Copper Rule (LCR). Metals, including lead and copper, released into the water of a distribution system can be dissolved, colloidal or particulate. Of importance to corrosion control is that these metallic ions combine with other ions in the water to form a scale that naturally builds up on the inside of the pipe. The nature and processes leading to formation of these scales is fairly complex and can result in several types of scales as noted below:

- Passivating films that form when pipe materials and water react directly with each other. (Note: Passivation can be defined as the creation of an outer protective layer of shield material applied as a micro-coating and created by chemical reaction with the base material, i.e. the pipe).
- Deposited scale material that forms when substances in the water such as iron, manganese, calcium or aluminum, precipitate out or adsorb to, and then build up on the pipe surface.

Scales can have layers which are impacted by the treatment history. So, for example, while the Water Treatment Plant (WTP) has been off line for years, there may be aluminum compounds in the existing scales in Newmarket's pipes from the many years that both alum, and later polyaluminum chloride was fed as a coagulant at the WTP. The structure and characteristics of the scale dictate whether and how much metal is released to the water. If conditions favor the formation of an insoluble scale that adheres well to the pipe wall, less metal will be released. If, on the other hand, the scale is more soluble or does not adhere well, there may be a greater metal release.

If any of the electrochemical cell components noted above are missing, corrosion of the piping material will not occur. However, since these components are generally present in a water system, corrosion will usually occur, and the rate of corrosion, as well as metal release, is dependent on a number of water quality parameters as noted below, which impact electron flow and therefore metal release and corrosion.

- pH: pH is the measure of hydrogen ion concentration. The lower the pH value, the higher the hydrogen ion content and the rate of corrosion.
- Alkalinity: Alkalinity is the capacity of water to neutralize acid without a change in pH and is the sum of the carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and hydroxide (OH^-) anions in water. This adds to the buffering capacity of water, or its resistance to changes in pH. A higher alkalinity (at least 30 mg/L as recommended by EPA) will generally reduce the rate of corrosion.
- Dissolved Inorganic Carbon (DIC): DIC is an estimate of the total amount of inorganic carbon, as represented by the following equation: $DIC = CO_2 + H_2CO_3 + CO_3^{2-} + HCO_3^-$. It is closely related to alkalinity. As noted above, most alkalinity comes from carbonate and bicarbonate ions in the water. DIC directly measures the available carbonate species that can react with metals such as iron, lead and copper to form passivating scales.

- Buffer Intensity: Buffer intensity (also called buffer capacity) is a measure of water's resistance to changes in pH and is defined as the concentration of base required to raise the pH one unit. It is dependent on the alkalinity, DIC and pH of the water. **Figure 2** shows the relationship between pH and buffer intensity at various DIC values. Of note in this figure is the low buffer intensity between pH values of 8.0 and 8.5 at all values of DIC. Therefore, waters with pH in this range may be subject to more variable pH within the distribution system. This is important since it is desirable to maintain a stable pH as possible for consistent corrosion control treatment effectiveness throughout the distribution system.

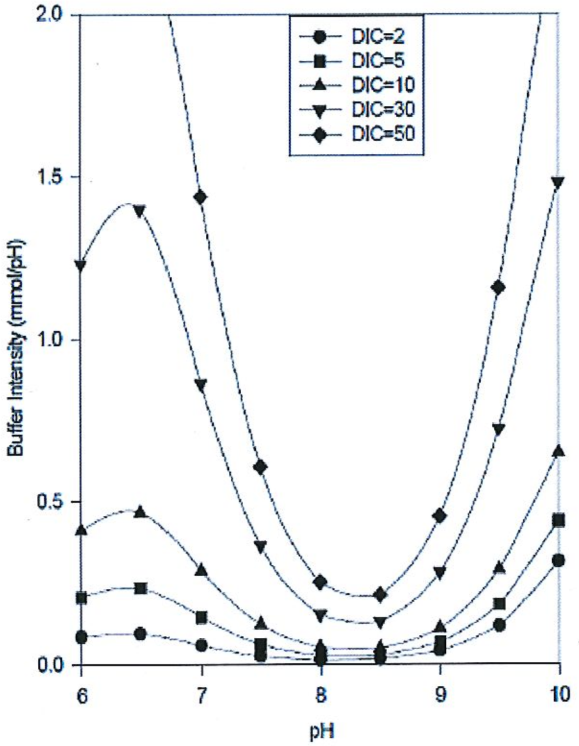


Figure 2 – Buffer Intensity as a Function of pH and DIC

(Taken from *Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agency and Public Water Systems*, EPA, 2016)

- Specific Conductance: Specific Conductance (conductivity) is a measure of water's ability to conduct electrical current. This is directly related to the type and amount of dissolved solids in the water. A higher conductivity implies a greater ability to convey electrons and thus a higher corrosion rate.
- Hardness: Hardness is typically calculated as the sum of calcium and magnesium found in the water and is reported as mg/L as $CaCO_3$ (calcium carbonate). While high hardness may contribute to increased specific conductance, and therefore a higher corrosion rate, it can also cause calcium carbonate precipitation, and therefore a protective scale on the pipe in waters that are being treated to raise the pH.

- Dissolved Oxygen (DO): Oxygen is slightly soluble in water and is impacted by temperature with higher DO concentrations in cold water. DO is lower in groundwater and is likely to be even lower in deeper groundwater such as the MacIntosh Well. The DO concentration affects the solubility of metals. For example waters high in iron can be aerated to oxidize the iron from the soluble ferrous state to the insoluble ferric state so that it can be filtered out and removed. Water higher in DO may have corrosion benefits by facilitating the formation of metal oxides which can form a protective scale.
- Oxidation-Reduction Potential: Also called redox potential or ORP, this is the electrical potential required to transfer electrons from one compound (oxidant) to another compound (reductant). It is measured in volts (V), or millivolts (mV) and is reported as electric potential (E_h). ORP affects how water will interact with solids such as pipe materials. It varies with pH, temperature and DIC, but is primarily impacted by the type and concentration of disinfectant in the water and the DO concentration. Studies have shown that ORP values are highest in systems using free chlorine and that ORP decreases with pH increasing from 7 to 9. For example, one study found an E_h range of 0.51 V (with no disinfectant and pH of 9) to 1.02 V (with chlorine disinfection and a pH of 7) (EPA, 2016).

  ORP has a large impact on lead solubility and therefore potential lead release in water systems. **Figure 3** shows the theoretical E_h and pH conditions favoring different dissolved and solid forms of lead. The hatched areas represent lead solids while the un-hatched areas represent lead complexes in solution. In the range of typical pH levels in water systems, different types of lead solids theoretically exist at both low E_h values (i.e. < -0.5 V) and at higher values (i.e. > 0.7 V). As shown, a drop in pH and/or ORP from a treatment change could cause a change from the solid state to the dissolved state and release lead into the water. For example, the well publicized high lead concentrations that occurred in the water system of the District of Columbia Water and Sewer Authority (DCWASA) between 2000 and 2004 were due in part to a switch from chlorine to chloramines which in turn lowered the ORP.
- Chloride and Sulfate: Both chloride and sulfate can have a two-fold effect on corrosion. Both constituents will increase the conductivity of a solution and therefore increase corrosion. Under low pH conditions chloride and sulfate have the potential to be converted to hydrochloric and sulfuric acid respectively which would add to the corrosiveness of the water.

  With regard to metal release, research has shown that the ratio of chloride to sulfate may be an indicator of potential lead release. Several studies have shown that above ratios of 0.4 to 0.6, lead leaching increased (EPA, 2016). As will be discussed later in this report the ratios in Newmarket far exceed these levels. However the referenced EPA document also notes research which indicated that raising the chloride-to-sulfate mass ratio above 0.7 is not necessarily an indicator of increased lead release.

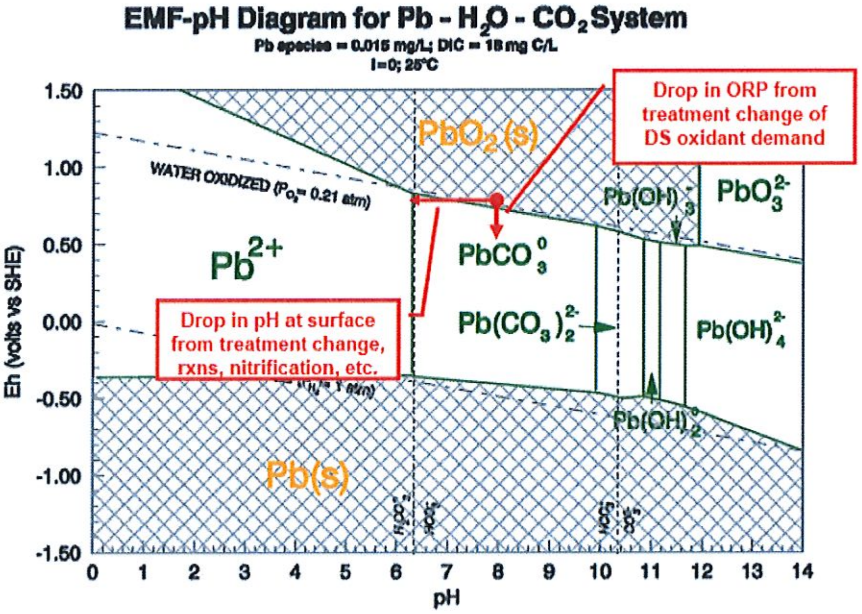


Figure 3 – Effect of ORP and pH on Lead Solubility
(Taken from *Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agency and Public Water Systems*, EPA, 2016)

FLINT, MICHIGAN SITUATION

Due to the high profile nature of elevated lead concentrations in the Flint, Michigan Water System and its possible relation to bringing the MacIntosh Well on line in Newmarket, we have researched what took place in Flint for comparison to Newmarket and to note lessons learned from their unfortunate experience.

Prior to 2014 the City of Flint, Michigan was purchasing treated water from the Detroit Water & Sewage Department (DWSD) whose raw water source is Lake Huron. Due primarily to financial concerns, the City elected to join a new regional water system, the Karegnondi Water Authority (KWA), which also involved the use of treated Lake Huron water but was still under construction. The pipeline which would bring treated water to Flint from the KWA Water Treatment Plant (WTP) was scheduled to be complete near the end of 2016. As an interim measure for the 2 (+/-) year period until completion of the pipeline, a decision was made to start using the Flint River as their sole water source and treat it at the existing Flint WTP. This plant, originally constructed in 1952, received a major upgrade in 2014 prior to the start of using the Flint River. It is a full conventional WTP with pre-ozonation, coagulation, rapid mixing, three-stage flocculation, plate settlers, lime softening, recarbonation, dual media (GAC over sand) filtration and disinfection.

However, other than addition of lime as part of the softening step, no corrosion control was practiced at the WTP. The DWSD water had been dosed with orthophosphate, a corrosion inhibitor, which results in deposition of a passivation layer which physically separates the piping materials from the water and therefore either prevents, or greatly reduces corrosion. Without the feed of this corrosion inhibitor, whatever coating that existed in the Flint Water System broke down. This fact, combined with the more corrosive nature of the Flint River water and the presence of lead service lines, goosenecks and other water system materials containing lead, resulted in the elevated lead concentrations.

Table 1 contains a comparison of some of the water quality parameters effecting corrosion for water from the DWSD system, the Flint system and the MacIntosh Well. Review of this data indicates that the pH and alkalinity of the DWSD water is not all that different from the Flint River. However, the hardness, sodium, chloride, specific conductance and TDS are all higher in Flint River water, all of which point to a more corrosive water than what was received from the DWSD. MacIntosh Well water is higher in pH and similar in alkalinity to both the DWSD and Flint River water which would indicate less corrosive water. However, chloride, sodium, specific conductance and TDS are all significantly, and in some cases, an order of magnitude, greater than the Flint River values which potentially point to MacIntosh Well Water being more corrosive.

Table 1 – DWSD, Flint and MacIntosh Well Water Quality

Parameter	**Units**	**DWSD**[1]	**Flint**[2]	**MacIntosh Well**[3]
pH	S.U.	7.38	7.74	8.2
Alkalinity	mg/L as $CaCO_3$	78	73	79
Hardness	mg/L	101	189	127
Chloride	mg/L	11	86	265
Sodium	mg/L	6	18	206
Specific Conductance	µS/cm	238	390[4]	1158
TDS	ppm	123	250[5]	633

[1] *Based on 2014 Water Quality Report*
[2] *Based on January 2015 Monthly Operations Report*
[3] *Based on the average of data collected during 2010 pump test*
[4] *Reported as " 0.39 mS"*
[5] *Calculated value based on conversion factor of 1 µS/cm = 0.640 ppm TDS*

EXISTING WATER QUALITY, TREATMENT & CORROSION INDEX

Contained in **Table 2** is existing water quality information for the Bennett, Sewell and MacIntosh Wells. The data for the Bennett and Sewell Wells is an average from inorganic sampling and analysis between 2003 and 2015 (conducted every three years). It is noted that this is treated water data based on samples taken after chemical feed. The MacIntosh Well data is from the 56-Day Water Quality Assessment and Pumping Program conducted by Emery & Garrett Groundwater Investigations (EGGI) in 2010. This is raw water quality data since there was no treatment. We have used the maximum value from the 56-day testing to represent the worst case water quality from the MacIntosh Well.

Table 2 – Existing Well Water Quality

Parameter	Units	Bennett Well[1]	Sewell Well[1]	MacIntosh Well[2] Max/(Range)
Sodium	mg/L	32.18	42.46	250/(170-250)
Chloride	mg/L	53.6	69.6	320/(200-320)
Iron	mg/L	ND	ND	0.09/(<0.05-0.09)
Manganese	mg/L	ND	ND	0.10/(0.057-0.10)
Arsenic	µg/L	1.05	1.66	10.0/(6.0-10.0)
Alkalinity	mg/L as $CaCO_3$	38.7	42.05	86/(75-86)
Hardness	mg/L	57.02	55.82	140/(110-140)
pH	S.U.	8.03	8.14	8.2/(8.1-8.2)
Sulfate	mg/L	8.74	9.54	50/(40-50)
Specific Conductance	µS/cm	312.5	389	1300/(1100-1300)
DIC[3]	mg/L	10	10	20
TDS	ppm	150	180	700/(600-700)
Chloride-to-sulfate	N/A	6.13	7.29	6.4

[1] *Values based on averages of data from 2003 through May 2016*
[2] *Values are max and the range of values from the 56 day Water Quality Assessment & Pumping Program*
[3] *Values calculated from Appendix B of Optimal Corrosion Control Treatment Technical Recommendations for Primacy Agencies and Public Water Systems, (EPA, 2016)*

Review of **Table 2** indicates that Bennett and Sewell Well water quality is fairly similar in terms of pH, alkalinity, hardness and DIC. Sewell Well water has higher sodium and chloride than Bennet, most likely due to its proximity to Route 152 and the fact that the well head is downgradient from the road. It is also higher in specific conductance which may be due to the higher sodium and chloride concentrations.

The corrosion control treatment for the Bennett and Sewell Wells is the same; 25% Sodium Hydroxide (NaOH) is fed to increase the pH. This also adds some hydroxide (OH^-) alkalinity and can convert excess carbon dioxide in the water to carbonate alkalinity species. The target is reportedly to raise the pH from about 7 to about 8.3 per the system operators. The current dosage rates for the Bennett and Sewell Wells are respectively 4.4 mg/L and 4.0 mg/L of 25% NaOH.

Compliance sampling for the Lead and Copper Rule (LCR) started in 1992 and was conducted yearly until 1996, after which the sampling frequency was reduced to every three years. For the first two years, 39 sites were sampled. Starting in 1994, this was reduced to 20 sites. The LCR requires that 90% of the sample sites must have lead and copper concentrations below the action levels set by the LCR, which are 0.015 mg/L and 1.3 mg/L for lead and copper respectively. **Table 3** contains a summary of lead and copper compliance sampling results from 1992 to 2014.

Table 3 – Lead & Copper History[1]

Year	Lead 90th %	Copper 90th %
1992	0.01	0.257
1993	0.006	0.340
1994	0.005	0.650
1995	0.003	0.210
1996	0.004	0.410
1999	0.006	0.370
2002	0.008	0.264
2005	0.013	0.227
2008	0.002	0.026
2011	0.002	0.062
2014	0.004	0.106

[1] *Taken from NHDES OneStop Data*

As shown, the Town has been in continuous compliance with the LCR action limits since 1992.

The water from each well is disinfected with calcium hypochlorite tablets (65% available chlorine). The current dosage rates for the Bennett and Sewell Wells are respectively 0.91 mg/L and 0.62 mg/L. The goal is to achieve a chlorine residual of about 0.26 mg/L at the farthest point of the distribution system from the wells.

MacIntosh Well water, with no treatment, is similar in pH and higher in alkalinity and DIC than the treated water being discharged from the Bennett and Sewell Well pump stations. From this perspective, the water is less corrosive and has more scale forming potential with the higher DIC. However, MacIntosh Well water has anywhere from about 3 to 6 times the concentration of sodium, chloride, sulfate, TDS and specific conductance, all of which point toward a more corrosive water.

It was noted earlier that research has shown that a chloride to sulfate ratio above 0.4 to 0.6 may be an indicator of increased lead leaching. The values for all of the Newmarket wells exceed these values by a factor of 10. Since this is the case with the Bennett and Sewell Wells, and the system has been in compliance with lead action levels since 1992, this would not seem to be a true indicator in the Newmarket system.

One way to compare the corrosive tendencies of different waters is to calculate the Langelier Saturation Index (LSI). The LSI is a measure of water's tendency to either dissolve or deposit a calcium carbonate scale. In developing the LSI, Langelier developed an equation for the pH at which water is saturated with calcium carbonate (pH_s). The equation is based on consideration of equilibrium expressions for calcium carbonate solubility and bicarbonate dissociation. It is based on the alkalinity, calcium hardness, TDS, and temperature of the water. The LSI is defined as the difference between the actual measured pH and the calculated pH_s. The expression for this and the meaning of the results are shown below:

- $LSI = pH - pH_s$
  - LSI > 0 The water is oversaturated with $CaCO_3$ and precipitation of $CaCO_3$ scale will occur
  - LSI = 0 The water is in equilibrium with respect to $CaCO_3$ and will neither precipitate or dissolve a $CaCO_3$ scale
  - LSI < 0 The water is undersaturated with $CaCO_3$ and a protective scale of $CaCO_3$ will not precipitate within the distribution system

It should be noted that the LSI should only be used to depict the corrosive tendency of the water and not be used as an absolute indicator of such. The calculated LSI for each of the well sources is shown in **Table 4.**

Table 4 – Langelier Saturation Index

Parameter	Bennett Well	Sewell Well	MacIntosh Well
pH	8.03	8.14	8.2
pH_s	9.19	9.16	8.55
LSI	-1.16	-1.02	-0.35

Based on the calculated LSI, Bennett and Sewell Well water would have greater corrosive tendencies than MacIntosh Well water, which is closer to equilibrium. This is based largely on the higher pH, alkalinity and hardness of MacIntosh Well water, and while TDS is another factor in the calculation, it does not completely account for the high sodium and chloride content and greater specific conductance. All three wells are undersaturated with calcium carbonate, so a protective scale would theoretically not precipitate.

BLENDED WATER QUALITY

As previously noted, the proposed intent is to blend the water from the three wells at a ratio of 50 to 60% MacIntosh water and 40 to 50% distribution (i.e. Bennett and Sewell Well) water. **Figure 4** is a schematic of the proposed blending facility.

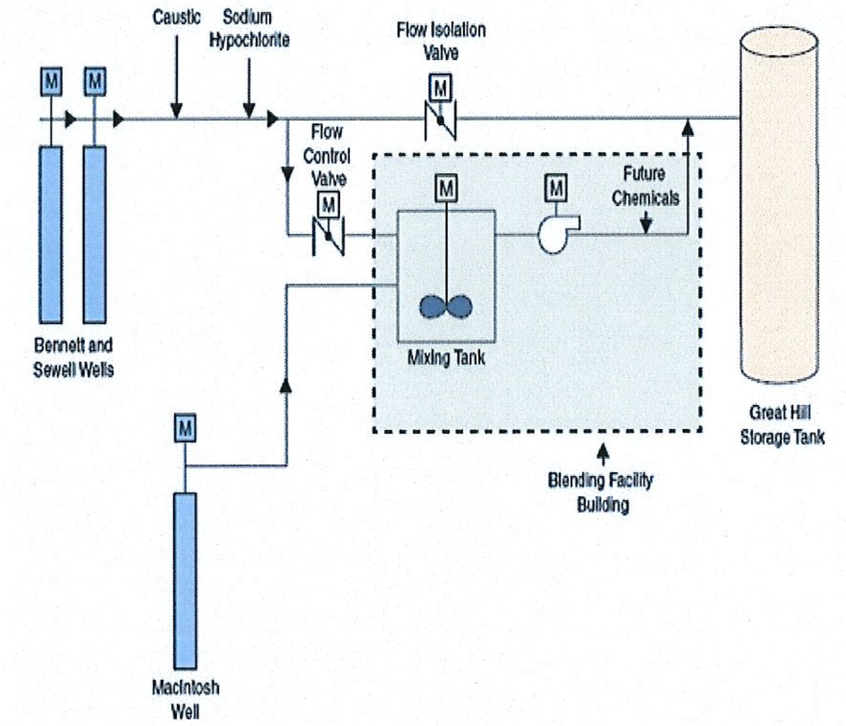


Figure 4 – Schematic of Proposed Blending Facility
(Taken from, *Tasting the Difference-Public Outreach for the Town of Newmarket's New Source,* Hazen & Sawyer)

We looked at three different blending scenarios as noted in **Table 5**.

Table 5 – Blending Scenarios

Scenario/Description	Bennett Flow	Sewell Flow	MacIntosh Flow	Total Flow	% MacIntosh
1-All wells @ 100%	185	260	300	745	40%
2-Sewell & MacIntosh	0	260	300	560	54%
3-Bennett & MacIntosh	185	0	300	485	62%

It is noted that we have used the nominal well capacities (Bennett Well at 185 gpm and Sewell Well at 260 gpm) in our blending calculations. We are aware that the pumping rate of the Bennett and Sewell Wells has been reduced based on declining aquifer level and then increased again to meet demand. It is assumed that with the MacIntosh Well on line, the existing wells will not be pumped as much so that the nominal rates can be used in the future.

Using the water quality results from **Table 2** and the flows from **Table 5**, the expected water quality of the three blending scenarios are given in **Table 6**.

Table 6 – Blended Water Quality for Three Scenarios

Parameter	Units	Scenario 1-All Wells on at 100%	Scenario 2-Sewell and Macintosh Wells	Scenario 3-Bennett and Macintosh Wells
% Macintosh	%	40	54	62
Sodium	mg/L	123.48	153.64	166.91
Chloride	mg/L	166.46	203.74	218.38
Iron	mg/L	0.04	0.05	0.06
Manganese	mg/L	0.04	0.05	0.06
Arsenic	µg/L	4.87	6.13	6.59
Alkalinity	mg/L as $CaCO_3$	58.92	65.59	67.96
Hardness	mg/L	90.02	100.92	108.35
pH	S.U.	8.14	8.17	8.14
Sulfate	mg/L	25.63	31.22	34.26
DIC	ppm	14.03	15.36	16.19
TDS	mg/L	381.95	458.57	490.21
Specific Cond.	µS/cm	736.85	877.04	923.32

The blended water quality in **Table 6**, depending on which scenario used, would be the expected water quality being pumped from the mixing tank shown in **Figure 4**. In terms of minimizing sodium, chloride, hardness, TDS and specific conductance, scenario 1 is the best alternative. This also minimizes the primary contaminant, arsenic, and maintains the manganese concentration just below the SMCL of 0.05 mg/L. Scenario 3, with the highest proportion of MacIntosh Well water, would provide the worst water quality. However, the only exceedance of a standard would be manganese which is just above the SMCL.

TREATMENT TECHNIQUES & DISCUSSION

There are two basic approaches for corrosion control treatment which can be used separately or in combination:

1. Alter the water quality
2. Protect the pipe material with a corrosion inhibitor

Alter Water Quality

The goal of the first approach, addressing the water quality, is to interfere with the electrochemical process of corrosion (i.e. make the water less corrosive) as well as to reduce lead and copper solubility. pH and alkalinity have historically been the usual targeted parameters. Both lead and copper solubility decreases with increasing pH, and increasing alkalinity generally increases the buffering capacity to help avoid swings in pH in the distribution system. This is the treatment technique currently being practiced at the Bennett and Sewell Wells where NaOH is being used to increase the pH to around 8.3 as well as add some hydroxide alkalinity. Lead and copper compliance data indicate this approach has been successful in meeting the action limits.

More recent research also stresses the importance of targeting DIC levels as well as pH and alkalinity. As previously noted, some level of DIC is important in providing carbonate species that can react with metals to form passivating scales. However, too much DIC can result in excessive calcium carbonate deposition that can reduce water main carrying capacity, clog hot water heaters, or cause turbidity. This is especially the case in water with high hardness such as the MacIntosh Well. Research has also shown that lead solubility increases with DIC concentrations approximately above 20 mg/L while minimum lead solubility occurs between a DIC level of 5 to 10 mg/L. The calculated DIC concentrations of the Bennett and Sewell Wells is 10 mg/L while that of the blended water with the MacIntosh Well ranges from about 14 to 16 mg/L. Based on these numbers, it would appear that increasing the DIC of the blended water is not warranted.

Recent guidance from EPA indicates that for control of lead and copper, the target pH should be 8.8 to 10, and that a pH between 8.2 and 8.5 can result in poor buffer intensity, regardless of DIC levels (see Figure 2), which may cause wide swings in distribution system pH. Given that the current practice is to raise pH to about 8.3, we obtained source and distribution system pH data, which the system operators record when they take monthly coliform samples, in order to assess the variation in pH in the system. A summary of that data is contained in **Table 7.** It is noted that the average pH values for the Bennett and Sewell Wells vary slightly from the averages shown in Table 2 due to the different time periods and number of data points.

Table 7 – Distribution System pH (Jan. 2013 – Sept 2016)

	Location							
	Bennett Well	Sewell Well	Lamprey Health Center	Great Bay Racquet Center	L&M Variety	Aubuchon Hardware	Public Works	Town Office
Avg	8.06	8.01	8.00	7.80	7.82	7.85	7.90	7.84
Min	6.81	6.19	6.62	7.01	6.86	6.88	6.83	7.01
Max	8.78	8.87	8.72	8.34	8.39	8.57	8.63	8.36
Delta	1.97	2.68	2.10	1.33	1.53	1.69	1.80	1.35

As shown, the variation in the distribution system is generally between 1 and 2 standard units. However, the variation of the source water pH after treatment is slightly higher and most likely accounts for much of the variation in the system. It is assumed that if the pH of the water entering the system can be held more consistent, the variation in the system will decrease.

Past guidance (Lead Control Strategies, AWWA, 1990) discusses the balance in maintaining a pH near the saturation pH. On one hand it may be desirable to be at or slightly above the pH_s in order to deposit a protective calcium carbonate scale, but on the other hand, raising the pH too much above the pH_s may result in unwanted/excessive precipitation of calcium carbonate causing the problems noted above. Therefore, a generally recommended dosage for pH adjustment would be to achieve a pH one unit below the pH_s. Saturation pH for each well source was calculated to determine the LSI (Table 4). **Table 8** contains calculated pH_s values for each of the blending scenarios in **Table 6** as well as those calculated for the wells. Also shown are the current average pH values for each source and the calculated pH values for the three blending scenarios.

Based on these values, it can be seen that the criteria of adjusting the pH to at least 8.8, as well as staying 1 pH unit below the pH_s are mutually exclusive. However, the high hardness, relatively high DIC, and the assumed ability to achieve a fairly stable distribution system pH by maintaining more consistent pH at the Bennett and Sewell Wells tend to support leaving the pH below the pH_s. It is also noted that the pH_s values in **Table 8** are calculated based on average data and the true value can be impacted by other constituents in the water. A better way to determine the pH_s, and the corresponding proper dosage of pH adjustment chemical is through jar testing. This can be done initially, if desired, with Bennett and Sewell Well water to optimize the NaOH dosage. The basic procedure is to add known incremental dosages of NaOH and measure the pH with each increment, along with the water quality parameters to calculate pH_s (i.e. Temperature, TDS, Ca Hardness and Alkalinity). The pH_s for each increment can then be calculated. The pH and pH_s are then plotted along with the corresponding NaOH dosage. Where the pH and pH_s lines intersect is the optimum pH_s for the water. The dosage can then be set accordingly. This same procedure can be used with blended samples of the well water to determine if pH adjustment is required at the blending facility and if so, what the optimum dosage is.

Table 8 – Calculated pH of Saturation vs. Actual & Estimated pH

Source	pH of Saturation (pH_s)	Actual & Estimated pH
Bennett Well	9.19	8.03
Sewell Well	9.16	8.14
MacIntosh Well	8.55	8.20
Blend #1 (All 3 wells)	8.84	8.14
Blend #2 (Sewell & MacIntosh)	8.73	8.17
Blend #3 (Bennett & MacIntosh	8.69	8.14

Corrosion Inhibitors

The second approach to corrosion control treatment is to add a film-forming corrosion inhibitor with the goal of deposition of a layer of product on the inside of the pipe to physically protect the pipe from the water. The most common corrosion inhibitors are phosphate based and generally are orthophosphate (PO_4^{3-}). These work by reacting with divalent metal ions to form compounds that have a strong tendency to stay in solid form, not dissolve in water, and be electrically attracted to the pipe substrate so they form the desired film. The effectiveness of orthophosphates depend on the their concentration, pH, DIC and the characteristics of the existing corrosion scale, primarily if it contains metals such as iron and aluminum which exert a demand for the orthophosphate. As previously noted, DWSD feeds orthophosphate as a corrosion inhibitor and the discontinuance of feed of this chemical when Flint switched to the Flint River source is attributed as a major cause of the lead problems that occurred subsequently. It is worthy of note that in December of 2015, the City of Flint began feed of orthophosphate to begin re-establishing a protective coating with the expectation of reducing lead levels in the distribution system within 2 to 6 months.

Zinc orthophosphate has been used widely in the past due to the touted positive effect that zinc has on film forming ability as well as adherence to the pipe walls. However, recent research has shown that zinc orthophosphate did not provide any additional lead and copper control over orthophosphate, and in three case studies, it was found that most of the zinc in zinc orthophosphate ends up in the wastewater treatment stream. This can be problematic since zinc can inhibit biological wastewater treatment and particularly denitrification processes which will be an important part of the upgrade to the Newmarket WWTF currently underway.

Polyphosphates are polymers with linked orthophosphate ions in various structures that are used primarily for sequestering iron and manganese. These work by binding the metals into their structure so that they remain dissolved and cannot precipitate out to cause colored water or staining of fixtures or clothes. Research has shown that polyphosphates are not effective for controlling the release of lead and copper in distribution systems.

Blended phosphates which contain a mixture of orthophosphate and polyphosphate can be used for the dual purpose of corrosion control and sequestering. Formulations are available with the orthophosphate fraction ranging from 5% to 70%. Given the manganese content either just under or over the SMCL depending on which blending option is being used, the ability to sequester manganese, as well as iron, which is also present in MacIntosh Well water, would be beneficial. One potential issue with a blended polyphosphate is that polyphosphates can also sequester lead and copper which keeps them in the water and increases the risk of exposure if the complex breaks down, in water heaters for example. Therefore, if a blended polyphosphate were to be used on the blended water, a formulation with a high percentage of orthophosphate would be preferable.

Orthophosphate treatment is most effective within a pH range of 7.2 – 7.8. However, EPA does not recommend immediately lowering pH if it is at 8.0 or higher since orthophosphate may be effective at up to a pH of 9.0. DIC is also a consideration since orthophosphate is more effective at low concentrations (< 10 mg C/L).

Since phosphorus is an important nutrient, a potential issue with use of any phosphate in drinking water systems is the resultant increase in phosphorus loading at the WWTF. This is especially a concern if there is a phosphorus discharge limit or if the increased phosphorus level has any impact on the treatment process. While Newmarket has a nitrogen discharge limitation, it has no phosphorus limitation in its current NPDES discharge permit. However, a future limitation on phosphorus is being considered by EPA and therefore is a possibility. Our understanding is that chemical treatment for possible removal of phosphorus has been included in the WWTF upgrade currently underway in case the need for this arises. This raises the possibility of adding phosphorus for corrosion control and sequestering, and then having to remove it at the WWTF to meet a nutrient limitation. If this were to occur, it would not be a situation unique to Newmarket. In the EPA guidance document, a survey is referenced of 14 utilities that added a phosphate-based corrosion inhibitor, causing on average, a 20% increase in phosphorus load to their respective WWTF's. It was noted that slightly less than half of these facilities removed phosphorus at the WWTF, but that this percentage was expected to increase due to expected increased permit limitations for phosphorus. One example of note is the DCWASA system referenced in the discussion on ORP where a treatment change reduced the system ORP which contributed to elevated lead levels. To resolve this situation, DCWASA instituted an orthophosphate feed system in 2005. As a result, they had to increase their ferric chloride feed at their Blue Plains WWTF to remove phosphorus from the waste stream. It was reported that the additional cost was minor compared to their overall operations budget.

The alternative to phosphate is a silicate based inhibitor. These are mixtures of soda ash and silicon dioxide. The most common form is sodium silicate although potassium silicate is available as well. The mechanisms by which silicates control lead and copper release are a matter of debate. Silicates raise the pH so they may reduce metal release by decreasing their solubility. Silicates also may form an adherent film on the surface of the pipe, as does orthophosphate. Effective creation of this film depends on the pH, DIC and silicate level. Reportedly, pre-existing corrosion products on pipe scales provide a better binding site for the silicate layer. Silicates are also an effective sequestrant and have been used to resolve red water (iron corrosion) complaints in systems. Therefore, as an alternative to adding more phosphorus to the system, silicates can sequester the slightly elevated manganese, elevate pH and provide a film to protect the pipes. There are the issues that feed of sodium silicate will add sodium to the blend which is already quite high, and could raise the pH at the blending facility higher than desired. Silicates have not been widely used due to the fact that higher dosages are required and it is an expensive chemical compared to the alternatives. A startup dose of about 24 mg/L is generally recommended followed by a gradual reduction after about 60 days to a maintenance dose of 8 – 12 mg/L. It is noted that chloride, calcium and magnesium concentrations can affect the optimum dose, so given the level of chloride and hardness in the blended water, these dosage rates may be low. In contrast, orthophosphate may be fed at an initial high dose of 2 – 4 mg/L and then reduced to 1 – 2 mg/L.

As a comparison of the cost of feeding sodium silicates versus a blended phosphate, we assumed maintenance doses of 12 mg/L and 2 mg/L for sodium silicate and blended phosphate respectively to the average daily demand of about 390,000 gpd.

- For silicates, we assumed use of N Sodium Silicate, which is typically used for potable water sources, with a 3.22 SiO_2/Na_2O ratio, and 28.7% SiO_2. At 12 mg/L in 390,000 gpd, about 11.7 gal/day of sodium silicate would be required. According to Harcros Chemical, the cost for sodium silicate is $0.40/lb for bulk deliveries of 1,500-2,000 gallons and $0.70/lb for drum deliveries. At a density of 11.6 lb/gal, this equates to about $4.63/gallon bulk, and $8.33/gallon in drums. Therefore the cost would be $54/day for bulk delivery and $97/day for drum delivery.
- For a blended phosphate, we assumed use of Aquacros HC-2030 with 70% orthophosphate and 30% polyphosphate and overall, 35% total phosphorus. At 2 mg/L in 390,000 gpd, about 6.5 lbs/day as phosphorus would be required. Using the 35% phosphorus content and a density of 11.0 lbs/gal, this equates to about 1.7 gal/day of product. Harcross Chemical indicates that the cost for 30 gallon drums (330 lbs) for this chemical is $1.04/lb or $11.44/gallon. Therefore the daily cost for use of HC-2030 would be about $19/day.
- Therefore, use of sodium silicate would cost 2.8 times as much per day for bulk delivery and 5.1 times as much per day for drum delivery.

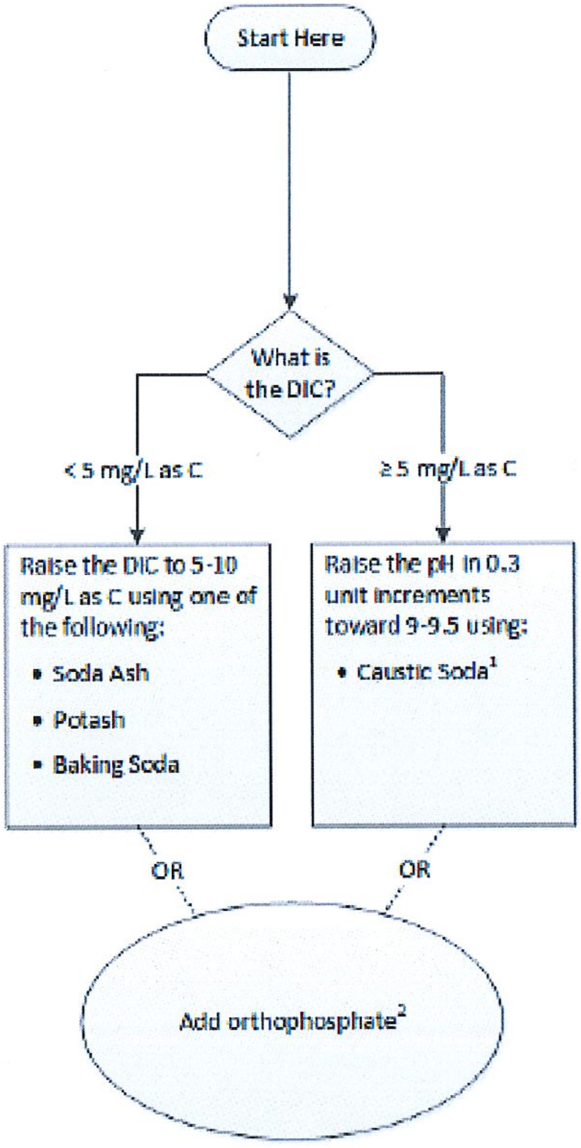
Treatment Flow Charts

Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems (EPA, 2016) contains flow charts which can be used to select corrosion control treatments based on; 1) whether one is treating for lead and/or copper, 2) whether there is iron or manganese in the finished water, and 3) the pH in the distribution system. It is noted that these flowcharts are a screening tool and are not meant to be a substitute for pilot studies or other site-specific investigations. It is also pointed out, as has been discussed herein, that corrosion is impacted by a number of water quality factors. However, these are meant as one tool to help systems make decisions on corrosion control treatment.

We first looked at the flowchart which would be appropriate for the Bennett and Sewell Wells. This would be treatment for lead and copper, with no iron or manganese in the water and pH >7.8 to 9.5 (See **Figure 5**). The calculated DIC for both the Bennett and Sewell Wells is about 10 mg/L so per the flow chart, the recommended treatment would be to raise the pH with sodium hydroxide toward 9-9.5 in 0.3 increments, or to feed an orthophosphate. In terms of pH adjustment, the current treatment matches the flow chart except for the target pH.

We next looked at the flowchart which would be appropriate for the blending scenarios. This would be treatment for lead and copper, with iron and manganese in the water and a pH greater than 7.2 (see **Figure 6**). The calculated DIC for the blending scenarios ranges from 14 to 16 mg/L. The recommended treatment is therefore to add a blended phosphate which would serve to both sequester the elevated manganese and provide corrosion control, or to remove the manganese and feed an orthophosphate.

Flowchart 1c: Selecting Treatment for Lead only or Lead and Copper with pH > 7.8 to 9.5

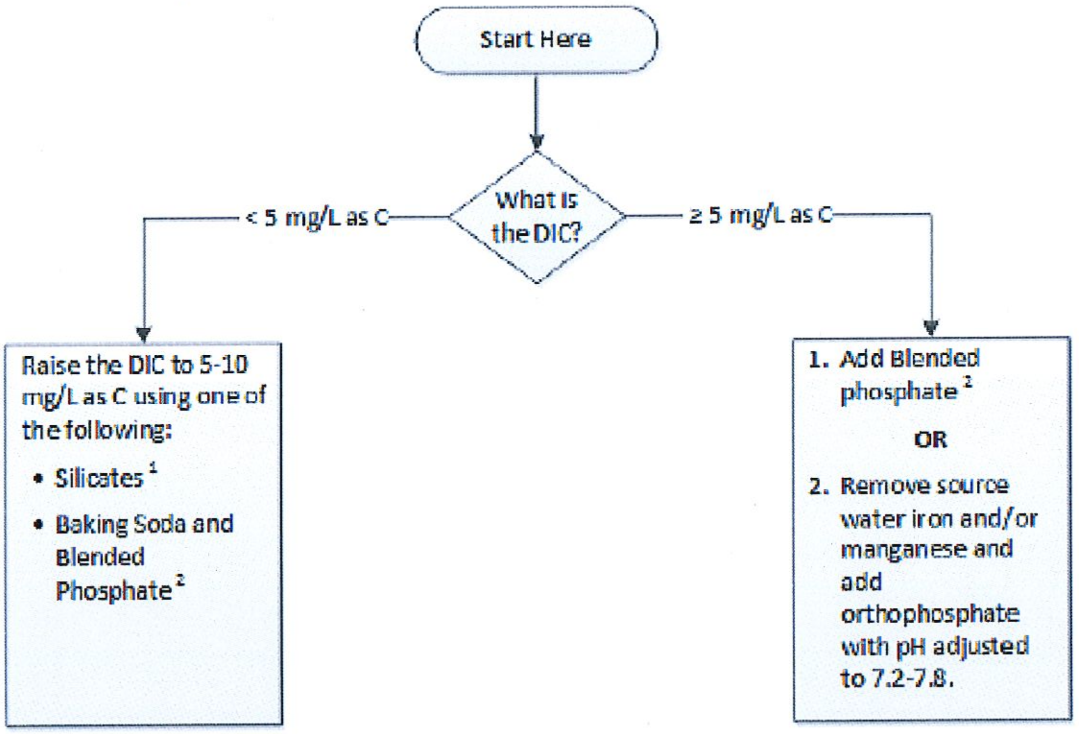


KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes
1. Systems with copper plumbing may experience copper pitting problems when operating at pH 9 – 9.5 and DIC of 5 – 15. Orthophosphate may be a better option for these systems.
2. Optimal pH range for orthophosphate is 7.2 - 7.8 but phosphate may be effective at higher pH depending on dose. Orthophosphate effectiveness is lowest in the pH range of 8 – 8.5. Systems should also avoid this range because of inadequate buffering in the distribution system.

Figure 5 – Flowchart for Treatment for Lead & Copper with pH>7.8-9.5
(Taken from *Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agency and Public Water Systems*, EPA, 2016)

Flowchart 3b: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH ≥ 7.2



KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon

Footnotes:

1. Silicates are most effective when combined iron and manganese concentrations are less than 1.0 mg/L.
2. The effectiveness of blended phosphate varies based on the formulation. Additional evaluation and/or monitoring is recommended. See Section 3.3.2 for additional discussion. Blended phosphates are less effective for controlling copper at DIC greater than 25 mg/L as C.

Figure 6 – Flowchart for Treatment for Lead & Copper with Iron and Manganese in the Finished Water and pH>7.2
(Taken from *Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agency and Public Water Systems*, EPA, 2016)

CONCLUSIONS

Based on our evaluation, we offer the following conclusions:

- Newmarket's current water sources, the Bennett and Sewell Wells do not comply with NHDES water supply criteria of meeting average day demand with the largest well out of service. Addition of the MacIntosh Well will allow this criterion to be met.
- The MacIntosh Well has high levels of sodium, chloride, TDS and conductivity which may be indicative of corrosive water. It also has arsenic levels approaching the 10 µg/L MCL and manganese levels exceeding the 0.05 mg/L SMCL.
- After an evaluation of treatment or blending the MacIntosh Well with the existing sources prior to pumping the water into the distribution system, the Town selected the blending alternative.
- Given events in Flint, MI where a switch to a more corrosive water source and a lack of proper corrosion control led to elevated lead in the water supply, the Town of Newmarket authorized an evaluation of corrosion control in an effort to prevent a similar occurrence.
- Internal corrosion of water systems is an electrochemical process in which the pipe serves as the anode, cathode and external circuit and the water is the internal circuit or conducting solution. Therefore, increasing the levels of TDS and conductivity of the water will increase corrosion rates.
- The result of corrosion is metal release from the piping system materials. Metallic ions released can combine with other ions in the water to form a scale on the pipe interior. These scales can form a passivating (protective) layer on the pipe interior.
- The formation of a passivating layer is dependent on a number of water quality parameters with pH, alkalinity, oxidation-reduction potential (ORP) and the level of dissolved organic carbon (DIC) to combine with metallic ions being key parameters.
- Stability of pH in the distribution system is important for corrosion control and is in part a function of the buffering intensity of the water which in turn is partly dependent on DIC and therefore alkalinity. Buffering intensity is lowest between a pH of 8.0 and 8.5 at all levels of DIC. EPA guidance indicates it is therefore best to maintain the pH in the range of about 7.2 to 7.8 or about 8.8 to 9.5.
- Lead solubility decreases with increasing pH and increasing ORP (at the range of pH generally encountered in distribution systems).
- A comparison of Flint River and MacIntosh Well water quality indicates higher natural pH and alkalinity in the MacIntosh Well water which would tend to make it less corrosive, but much higher chloride, sodium, specific conductance and TDS which tends to make it more corrosive. The comparison of MacIntosh Well water quality to Bennett and Sewell Well water quality is similar.
- The current corrosion control treatment for the Bennett and Sewell wells is a feed of sodium hydroxide to raise the pH from about 7 to 8.3 and add some hydroxide alkalinity. This treatment has resulted in continuous compliance with the lead and copper action limits of the LCR from 1992 to the present.

- Calculation of Langelier Saturation Index (LSI) values as an indicator of the corrosive tendency for water from each well indicates that Bennett and Sewell Well water actually has more corrosive tendency than MacIntosh Well water, and all three are undersaturated with respect to calcium carbonate such that a protective scale would not be deposited.
- Blends evaluated were:
  - All three wells on at 100 % (40% MacIntosh)
  - Sewell and MacIntosh Wells (54% MacIntosh)
  - Bennett and MacIntosh Wells (62% MacIntosh)
- Blending the three wells with 40% MacIntosh Well water provides the best water quality both in terms of factors influencing corrosion as well as arsenic and manganese.
- There are two approaches to corrosion control.
  - Adjust water quality to interfere with the electrochemical process of corrosion, reduce lead solubility and encourage a passivating scale on the pipe interior.
  - Protect the pipe material with a film forming corrosion inhibitor.
- Approach #1 – Adjusting Water Quality
  - Increasing pH and alkalinity, to a point, decreases lead and copper solubility
  - Minimum lead solubility occurs at a DIC level of 5 to 10 mg/L.
  - Lead solubility increases at DIC levels above 20 mg/L.
  - Calculated DIC of both the Bennett and Sewell Wells is about 10 mg/L.
  - Calculated DIC of the three blending scenarios ranges from 14 to 16 mg/L.
  - Increasing DIC of any of the wells is not warranted.
  - EPA guidance suggests;
    - A pH of 8.8 to 10 for lead and copper control.
    - A pH between 8.0 and 8.5 should be avoided if possible due to low buffering intensity in this range.
  - However, with a current average pH of about 8 to 8.1, the measured variability of pH in the system largely mimics the variability of the treated water pH at the Bennett and Sewell Wells. It is assumed that achieving more consistent pH at the sources will lead to more stable pH in the distribution system, even in the 8.0 to 8.5 range.
  - pH at or just above the pH of saturation with $CaCO_3$ (pH_s) can deposit a protective scale of $CaCO_3$. Raising the pH too high above the pH_s however can result in excessive $CaCO_3$ deposition which can reduce hydraulic capacity and cause other problems. A general recommended dose is therefore at pH_s-1.
  - Given calculated pH_s of the three blends at 8.14 – 8.17, it is not possible to both maintain a pH above 8.8 and achieve a pH = pH_s-1.
  - Given the high hardness, relatively high DIC, and the assumed ability to achieve a fairly stable distribution system pH by maintaining more consistent pH at the Bennett and Sewell Wells, it would be best to leave the pH below the pH_s and not raise it to 8.8 or above.
  - The true pH_s can be determined by jar tests/titration to help determine the target pH.

- Approach #2 – Corrosion Inhibitors
    - Inhibitors work by reacting with divalent metal ions to form compounds that have a tendency to stay in solid form, not dissolve, and that are electrically attracted to the pipe substrate.
    - Orthophosphate is the most commonly used corrosion inhibitor.
        - Used by DWSD in water formerly delivered to Flint
        - Used by Flint to counteract elevated lead levels after discovery of high lead levels
        - Used by DCWASA to correct high lead levels after treatment change resulted in high lead levels.
        - Most effective at pH range of 7.2 – 7.8, but is still effective at pH up to 9.0.
        - Also more effective at lower DIC concentration (<10 mg/L C)
    - Zinc orthophosphate has also been widely used.
        - Zinc is supposed to enhance film forming ability.
        - Research indicates no improvement in lead and copper control by using zinc orthophosphate over orthophosphate and that much of zinc ends up in the wastewater treatment stream.
        - Zinc can inhibit biological wastewater treatment, particularly denitrification processes, which will be in use at the Newmarket WWTF.
    - Polyphosphates
        - Used primarily for sequestering iron and manganese.
        - Metal ions are bound into their structure to keep them in dissolved state.
        - Can also sequester lead and copper which can increase exposure risk if compound breaks down.
        - Not effective at controlling lead and copper release in distribution systems.
    - Blended Phosphates
        - Mixture of orthophosphate and polyphosphate for dual purpose of corrosion control and sequestering.
        - Formulations are available with orthophosphate fraction from 5% to 70%.
        - Given manganese content in blended water, a blended phosphate may be appropriate. Since sequestering would be the minor role, and to avoid sequestration of lead and copper, a blended phosphate with a higher fraction of orthophosphate is preferable.
    - Wastewater Issues
        - Feeding phosphate adds to phosphate loading at WWTF.
        - EPA can and has set phosphorus discharge limits in NPDES permits.
        - Newmarket has a nitrogen discharge limit but no phosphorus limit, however, it is possible in the future. Provisions for chemical treatment for phosphorus removal have been included in the upgrade currently underway at the Newmarket WWTF.
        - It is not unusual for utilities to feed a phosphate for corrosion control and also treat for phosphorus removal at the WWTF.

  - Silicates
    - An alternative corrosion inhibitor to phosphates with sodium silicate as the most common form. This would add sodium to the water which is already high.
    - Have the ability to sequester as well as form an adherent film inside pipes.
    - Will also raise the pH.
    - Not widely used due to high required dose and greater expense for chemical.
    - Cost comparison to a blended phosphate
      - Sodium silicate: $54 - $97/day for respectively bulk and drum delivery (12 mg/L in 390,000 gpd)
      - Blended phosphate: $19/day for 30 gallon drum delivery (2 mg/L in 390,000 gpd)
    - Given the higher cost of silicates and no phosphorus limitation at the WWTF, use of silicates is not warranted.
- Treatment Flow Charts
  - EPA has developed screening level corrosion control treatment flow charts based on 1) whether one is treating for lead and/or copper, 2) whether there is iron or manganese in the finished water, and 3) the pH in the distribution system.
  - The appropriate chart for the Bennett and Sewell Wells (treating for lead and copper, no iron or manganese and pH>7.8) suggests raising the pH toward 9 – 9.5 in 0.3 increments, or to feed an orthophosphate.
  - The appropriate chart for the blending scenarios with the MacIntosh Well (treating for lead and copper, iron or manganese in the water, and pH>7.2) suggests feed of a blended phosphate.

RECOMMENDATIONS

Based on our evaluation and conclusions, our primary recommendation is to initiate the feed of a phosphate based corrosion inhibitor to protect the water system piping materials. In order for the corrosion inhibitor to be effective, it will need to be fed at both the Bennett and Sewell Wells in addition to the blending facility so that the entire system is passivated. Due to the presence of manganese at or near the SMCL in the MacIntosh Well, and therefore the blended water, a blended phosphate is recommended to provide some sequestering capability in addition to corrosion inhibition. Secondly, it is important that consistent water chemistry, and particularly pH be maintained, both for maximum protection by the corrosion inhibitor and for optimal corrosion control. Specifically, our recommendations are noted below:

- **pH Adjustment – Bennett and Sewell Wells**

  Historically, the Town has pursued an approach of adjusting pH and alkalinity for corrosion control at the Bennett and Sewell wells. If this treatment approach was to continue, recent EPA guidance would suggest raising the pH even higher. However, as described above, addition of a corrosion inhibitor to protect piping materials is recommended into the future, which necessitates a different pH regime for optimal corrosion control. As it is critical that the corrosion control treatment be as consistent as possible on a system wide basis, we recommend the following:

- Continue to adjust pH with sodium hydroxide to achieve a pH consistent with that of the MacIntosh raw water.
- Monitor the NaOH feed and treated water pH daily and adjust the dose as necessary to maintain a consistent treated water pH and avoid fluctuations in pH.
- Monitor the pH of the MacIntosh Well raw water and if this pH changes with time, adjust the pH of the Bennett and Sewell Wells accordingly.
- Continue to monitor distribution system pH monthly at the existing bacteria compliance testing sites to check on the stability of pH throughout the system. If there is significant variation in pH, even with efforts to maintain a consistent treated water pH at Bennett and Sewell, perform jar tests as described in this report to determine the actual pH_s for each well and adjust the target pH so that it is either just below or above the 8.0 to 8.5 range, but less than the pH_s and consistent with the MacIntosh raw water pH.

- **pH Adjustment – Blended Water**

Blending calculations indicate an expected pH between 8.1 and 8.2 for the scenarios noted in this report. This is consistent with the current treated water pH at both the Bennett and Sewell Wells. As has been noted, it is important to maintain consistent water chemistry throughout the system for optimized corrosion control. Based on these pH values being essentially the same, we have the following recommendations.

- No pH adjustment at the blending facility is recommended at this time.
- Monitor the MacIntosh Well raw water pH and if the pH changes, make corresponding adjustments to the Bennett and Sewell pH adjustments to maintain consistent corrosion control chemistry.
- If the pH drops significantly, make provisions for the feed of sodium hydroxide at the blending facility. Perform jar tests as described in this report to determine the actual pH_s for the blended water and adjust the pH of the blended water, if necessary, to match the target pH of the Bennett and Sewell wells but maintain the pH below the pH_s.

- **DIC Adjustment – All Wells**

The DIC concentrations are already at desired levels in the Bennett and Sewell Wells and a little higher than the desired level, but not excessive, in the blended water based on the calculations conducted for this report. Therefore no DIC adjustment (feed of carbon based compounds) is recommended.

- **Corrosion Inhibition – All Wells**

Feed of a blended phosphate with a high orthophosphate fraction compared to the polyphosphate fraction is recommended at all wells in order to create a protective film throughout the distribution system while also providing some sequestering capability. We recommend a product with 30% polyphosphate and 70% orthophosphate. While this product is available in both dry and liquid form, we recommend a liquid formulation for ease of feeding. This product is available from several manufacturers with total phosphate content in the range of 33 to 36%. The recommended dose, in accordance with both EPA and chemical manufacturer guidance should be set to target a residual concentration throughout the distribution system of 1.0 mg/L as total phosphate. At a maintenance dose of 1.0 mg/L as total phosphate, and depending on the brand, the daily volume used at the average day demand of 390,000 gpd is estimated to be approximately two gallons per day as product.

Since this protective film should be in place prior to startup of the blending facility, feed of the blended phosphate should be instituted as soon as possible at the Bennett and Sewell Wells. Use of the blending facility should begin only when a minimum residual concentration of at least 0.5 mg/L and preferably 0.7 mg/L as orthophosphate can be detected at the extremities of the distribution system. It is noted that monitoring is based on orthophosphate which is much easier to measure than total phosphate. Given the ratio of orthophosphate (70%) to polyphosphate (30%), detection of 0.7 mg/L of orthophosphate should be indicative of about 1.0 mg/L total phosphate.

The usual recommended method of initiating a feed of phosphate is to feed a higher passivation dose, about 2 times the maintenance dose, in order to get the phosphate into the system and build a protective layer more quickly. In most cases, the phosphate will react with existing deposits in the main and cause water quality issues such as red water when the phosphate reacts with iron tubercles. Because of this, flushing of water mains, both to move the phosphate and resolve water quality issues is used with this method. This presents a potential problem given the current drought and low aquifer levels. Newmarket is in a Stage 4 Water Supply Shortage which bans the following:

- All outdoor water usage
- All outdoor irrigation except for hand watering of food crops
- Filling of swimming pools
- Use of automatic sprinkler systems
- Washing or cleaning of streets, driveways or other impermeable surfaces
- Washing of boats and cars

Due to this, use of significant volumes of water for flushing may not only be politically unacceptable, but could potentially jeopardize the Town's ability to continue to meet basic water supply needs.

Another method for initiating a phosphate feed is to start off at a low dose and gradually increase it over several weeks until the desired residual concentration is achieved in the far reaches of the distribution system. While this method may reduce possible water quality issues due to the incremental change in treatment, and reduce or eliminate the need for flushing, it will take longer to build a protective layer and will therefore delay the startup of the blending facility. Based on discussions with chemical manufacturers, this method would use an initial dose of 0.5 mg/L for at least one to two weeks, followed by increases to first 1.0 mg/L, and then 1.5 mg/L and 2.0 mg/L for similar periods until the target residual is reached at the system extremities. The dose would then be cut back to the maintenance dose of 1.0 mg/L.

As discussed, there are pros and cons for each method of initiating the phosphate feed which are not engineering decisions and require the input of the Town based on their priorities. If the priority is to get the blending facility on line as soon as possible to increase the supply, then the first method of feeding a higher dose followed by flushing should be used. If this method is chosen, we recommend that this be preceded by public notification so that residents understand why flushing is occurring when a Stage 4 water ban is in place. If the priority is to minimize water use to conserve supply as well as to minimize water quality upsets, then the second method of a gradual increase should be used.

Regardless of which initiation method is used, preliminary calculations based on the current pumping rates of the Bennett and Sewell wells indicate that the feed rate of undiluted product will be in the range of 5 ml/minute or less, even at the higher passivation dose. Based on space considerations, and the relatively low use, we have assumed use of 30 gallon drums at the Bennett and Sewell Wells. As a general rule, the injection points for the blended phosphate should be upstream of and as far as possible from the disinfection injection points. This is more of an issue with sequestering since chlorine will cause polyphosphate to revert to orthophosphate. Since sequestering is only required at the blending facility, this separation is less important at the Bennett and Sewell Wells.

Our understanding is that the pumping rate at the blending facility will be up to 600 gpm which would seem to necessitate a higher feed rate. However, since the water coming from the Bennett and Sewell Wells into the blending facility will already be dosed with the blended phosphate, the feed rate of undiluted product is expected to be similar to that of the wells. Dilution would allow use of larger metering pump rates if desired. It is important at the blending facility that the phosphate feed be as far upstream of the chlorine feed as possible so that the chlorine does not impact the polyphosphate and sequestering of the elevated manganese.

- **Additional Testing**

The evaluation of the blended water quality in this report relied on water quality data collected during the 56 day pump test which took place over five years ago. Newer data has recently become available since installation of the pump in the MacIntosh Well. We recommend that any new water quality data be compared to the data from the 2010 pump test, and if necessary, new calculations be made of the possible blended water quality to see if the recommendations of this study are impacted.

The recommendations in this report are based on a desktop evaluation of existing water chemistry and treatment, potential water chemistry of the blended water, corrosion theory, experience in other systems and guidance from EPA. One point of guidance from EPA is that if a blended phosphate is recommended for control of lead release, then a demonstration study, additional monitoring, or both is recommended. A demonstration study can consist of coupon studies, pipe loop testing, or analysis of existing scales. Pipe loop testing involves using pipe sections either excavated from the system or representative of the system materials and running system water through them for a set period of time with the proposed treatment to determine what the impact is on pipe scales, water quality, and lead and copper levels. This may be the most appropriate method of simulating what is actually happening in the distribution system. Design of a pipe loop or other demonstration study is beyond the scope of this evaluation but is recommended to check and confirm the recommendations of this study prior to full startup. It is recognized that a pipe loop study can take significant time to get meaningful results and that the blending facility is due to be put into service in the near future. We therefore recommend that the Town work with NHDES to determine what level of demonstration testing is necessary or appropriate.

Once the new corrosion control treatment is in place, we recommend follow up monitoring to determine the effectiveness of the treatment. Sampling and analysis for lead, copper, all the parameters listed in **Table 6,** the disinfectant residual, and the phosphate residual should be conducted at both the entry points to the distribution system (i.e. Bennett, Sewell and blending facility) and at sample taps throughout the distribution system. The distribution sampling points can be the existing lead and copper sampling sites, however, we also recommend that additional sites be selected corresponding to any areas either known or suspected of having piping materials that contain lead. For the first year of operation, we recommend that this sampling be conducted at least quarterly.

After about one year of operation of the new corrosion control treatment, we recommend that an engineering assessment be made on the effectiveness of the treatment. This would be based on the (minimum) quarterly sampling results recommended above.

- **Confirmation of Recommendations**

We recommend that this study be reviewed by Hazen and Sawyer as the engineer of record for the blending facility and the entity that, as we understand it, will be responsible for the implementation of these corrosion control recommendations at the blending facility. Their review should either confirm or modify these recommendations as appropriate.

This study should be submitted to the Drinking and Groundwater Bureau of NHDES so that they can also confirm these recommendations or offer additional recommendations and guidance.