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Metals releases and disinfection byproduct formation in domestic wells following shock chlorination

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DWESD

3, 177–198, 2010

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Shock chlorination is used for rapid disinfection to control pathogens and nuisance bacteria in domestic wells. A typical shock chlorination procedure involves adding sodium hypochlorite in liquid bleach solutions to achieve concentrations of free chlorine of up to 200 ppm in the standing water of a well. The change in pH and oxidation potential may bring trace metals from aquifer materials into solution and chlorine may react with dissolved organic carbon to form disinfection byproducts. We carried out experiments with four wells to observe and determine the persistence of increased concentrations of metals and disinfection byproducts. Water samples from shock chlorinated wells were analyzed for Pb, Cu, As, radionuclides and disinfection byproducts (haloacetic acids and trihalomethanes), immediately prior to treatment, after sufficient contact time with chlorine had elapsed, and at intervals determined by the number of casing volumes purged, for up to four times the well casing volume.

Elevated concentrations of lead and copper dissipated in proportion to free chlorine (measured semi-quantitatively) during the purging process. Trihalomethanes and haloacetic acids were formed in wells during disinfection. In one of two wells tested, disinfection byproducts dissipated in proportion to free chlorine during purging. However, one well retained disinfection byproducts and free chlorine after four well volumes had been purged. Although metals returned to background concentrations in this well, disinfection byproducts remained elevated, though below the MCL, likely because purging volume was insufficient. Simple chlorine test strips may be a useful method for indicating when purging is adequate to remove metals and disinfection by-products mobilized and formed by shock chlorination.

DWESD

3, 177–198, 2010

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



1 Introduction

Shock chlorination is an in-situ method for disinfecting water wells contaminated with pathogens and nuisance bacteria. Much guidance is available for treatment of domestic wells (e.g. Schnieders, 2005; Driscoll, 1986) and <http://www.unce.unr.edu/publications/files/nr/2006/FS0668.pdf>, last access: April 2010). The guidelines recommend contact times (free chlorine concentrations \times resting time of the solution) that are very high relative to those used for public water supply treatment, which is appropriate given that treatments occur sporadically, usually in response to perceived problems with water or the health of those who consume water from a well. The procedure typically involves adding sodium hypochlorite solution directly to a well followed by mixing and a resting period of 12–24 h. The chlorinated water must be purged prior to resuming use. Recommendations for the amount of purging vary significantly, with Schnieders (2005) recommending 10–20 well volumes, and University of Ohio Cooperative Extension and others recommending purging until water no longer smells of chlorine (<http://ohioline.osu.edu/aex-fact/0318.html>, <http://srwqis.tamu.edu/media/2553/shockwells.pdf>, last access: April 2010). The odor threshold for chlorine gas in air is approximately 0.3 parts per million (Amoore and Hautala, 1983). However, the relationship between the amount of chlorine degassing from a solution and the amount that can be detected by smell varies, depending upon the sensitivity of an individual's sense of smell and the degassing rate, which is in turn related to temperature of water, and changes in temperature and barometric pressure associated with obtaining a sample to smell.

Aqueous chlorine (as hypochlorite ion and hypochlorous acid) cleaves carbon-carbon bonds in organic molecules to form disinfection byproducts (DBPs) in two classes: haloacetic acids (HAAs) and trihalomethanes (THMs) (Westerhoff et al., 2004). HAAs and THMs include carcinogenic organic compounds and have Maximum Contaminant Levels (MCLs) of 0.060 mg/L for HAA5 (the sum of concentrations of monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobro-

DWESD

3, 177–198, 2010

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



moacetic acid and dibromoacetic acid) and 0.080 mg/L for total THM, as specified in the Stage 1 Disinfectants/Disinfection Byproducts Rule (40 CFR, Parts 9, 141 and 142). Trihalomethanes include chloroform, bromodichloromethane, dibromochloromethane, and bromoform.

5 Shock chlorination may also increase the concentrations of lead and other trace elements following treatment (Seiler, 2006) and change arsenic concentrations (Gotkowitz et al., 2008). Both lead and arsenic have toxicological effects, with an Action Level and Maximum Contaminant Level of <15 ppb and 10 ppb, respectively.

10 This paper describes the changes in concentration of Pb, Cu, As, U, gross- α and gross- β radiation, HAA5, THM, and free chlorine (semi-quantitatively measured) from shock chlorination of four domestic water wells. The study also sought to demonstrate that simple test strips for semi-quantitative measurement of concentration of free chlorine (used for pool and spa maintenance) can be used to indicate that purging has been sufficient to return concentrations of metals and disinfection byproducts to pre-
15 treatment background levels.

2 Methods and materials

2.1 Study site

20 Four wells (Table 1) were selected in the Lahontan Valley, in Nevada (Fig. 1). Each well was used for domestic supply prior to being retired for water right acquisition by the US Fish and Wildlife Service within the Stillwater National Wildlife Refuge. Three were cased with steel (ASTM A135 SCH40 ERW low-carbon steel, based on inspections at the sites) and one was cased with polyvinyl chloride casing (specifications unknown). These wells were chosen for two reasons. First, they conformed to standards and practices commonly used for domestic water well construction at the time
25 and had well logs available through the Nevada State Engineer's office. Second, because they were no longer in service we did not run the risk of exposing people to

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



metals or disinfection by-products released or created by shock chlorination. Well logs for each indicated that the exteriors of screened intervals on the casing were packed with gravel for wells 182 (PVC-cased), 167N (steel-cased) and 142 (steel-cased). The construction log for well 51 (steel-cased) contained incomplete information about well-completion at the screened interval. The wells pumped water from a stratum of Quaternary valley-fill sands in the inland terminus of the Carson River from depths of less than 15 m (50 ft) from the land surface. Infiltration from irrigation and the Carson River has been identified as the main sources of recharge (Glancy, 1986). Although the groundwater system in the Lahontan Valley is nominally comprised of three geochemically separated systems (shallow (<15.2 m (50 ft) from the land surface); intermediate (15.2–<152.4 m (50–<152.4 ft)); deep (≥ 152.4 m (≥ 500 ft)), aquifer material composition, yields and chemistry vary highly throughout the region (Glancy, 1986). Water in the aquifer has high but spatially variable concentrations of arsenic (as much as 2100 ppb (Walker et al., 2005)) and uranium (as much as 290 ppb (http://www.atsdr.cdc.gov/HAC/PHA/fallonleukemia2/fln_p1.html, last access: April 2010) from contact with sediments and from long-term evapoconcentration (Welch and Lico, 1998). Depth to water (DTW) in the four wells ranged from 1.7 to 5.5 m (5.5 to 18.0 ft) with total well depth ranging from 8.0 to 9.5 m (26.7 to 31.0 ft) (Table 1).

2.2 Well treatment and purging

A 1/2 horsepower portable jet pump fitted with a 7.6 m (25 ft) long, 1.9 cm (0.75 in) interior diameter suction line was used for each trial. The pump and suction line were rinsed with distilled, deionized water between uses and allowed to air dry. Each well was chlorinated and purged as a separate experiment, to avoid cross-contamination of wells. The pump had a fiberglass-reinforced thermoplastic housing and impeller, with Buna-N seals and ceramic bearings. The outflow line was fitted with a GPI electronic inline flow meter, a flow control valve, and a tee that divided flow between a discharge hose and a flow-through chamber for a YSI model 556MPS (Yellow Springs Instruments, Yellow Springs OH), for real-time measurement of temperature (T ($^{\circ}\text{C}$)), pH,

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



oxidation-reduction potential (ORP (mV)), and conductivity (C (mS/cm)). The multi-probe was calibrated immediately prior to each stage of field trials, using pH 4.00, 7.00 and 10.00 standards (Fisher Scientific Buffer-Pac, Cat# SB105), a conductivity standard (1000 mS/cm at 25 °C (Yellow Springs Instrument Co. Cat #3167) and an oxidation-reduction potential reference solution (Equipco Inc., part #3682500).

Prior to conducting trials, each well was purged of stagnant water at a rate of 9.5 to 18.9 l per min (2.5 to 5.0 gpm) until temperature, pH, ORP, and conductivity readings stabilized (<5% variation in continuous readings), then purged an additional four times the well's standing volume of water. The well volume (WV) was estimated as $WV = H \times A$, with H as the measured height of the water column in the well after the level stabilized following pumping and A as the cross sectional area of the interior of the well casing. Pre-chlorination (designated as IP) water samples for all wells were collected for As, Cu, Pb, U, gross- α and gross- β radiation, carbon (as dissolved organic carbon and carbonate), and for a steel-cased well and a PVC-cased well, water samples were collected for HAA5 and THM analyses. Table 1 presents IP conditions in each well.

2.3 Shock chlorination

Following initial purging, each well was chlorinated to an estimated 200 mg/L as Cl using household bleach (unscented, regular strength Clorox[®] labeled as containing 6% sodium hypochlorite) by adding 8.9 ml (0.3 fl oz) bleach per liter (0.26 gallons) of well volume (Table 1). Pump discharge was circulated back into the well casing for 15 min to disperse bleach into solution. Wells were re-capped for a resting period of at least twelve hours.

2.4 Sampling

Immediately prior to and during purging temperature, pH, oxidation-reduction potential, and conductivity were measured. Immediately prior to purging post-chlorination (PC)

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



samples from all wells were tested for As, Cu, Pb, U, and gross- α and gross- β radiation. Samples from two wells (142 and 182) were tested for disinfection byproducts (HAA5 and THM). All metals and disinfection by-products samples were collected using a PTFE dip bailer.

5 Post chlorination purging samples were collected for As, Cu, and Pb at intervals defined by the volume of water purged from each well, including 1/2, 1, 2, 3, and 4 \times WV (designated as 1/2, 1, 2, 3, 4F). After the fourth well volume was pumped, samples were collected for As, Cu, Pb, U, gross- α and gross- β radiation, HAA5 and THM (Table 2).

10 All samples were unfiltered. Samples were collected, immediately placed in a portable cooler with blue ice to avoid exposure to sunlight and changes in temperature and submitted within 24 h to the Nevada State Health Laboratory (University of Nevada School of Medicine, Reno, NV – certified drinking water analysis laboratory) for analysis (Table 3). Samples for arsenic, copper, lead and uranium were collected in
15 500 ml high density polyethylene bottles with 5.0 ml of 15% nitric acid as a preservative in containers provided by the laboratory. After sample collection, the final concentration of nitric acid was 0.15% nitric acid.

2.5 Chlorine test strips

20 Free chlorine was measured semi-quantitatively with test strips for swimming pool and spa maintenance (Arch Chemicals, Inc. – HTH line). The test strips indicated free chlorine concentrations in ranges rather than absolute numbers, similar to pH indicator strips. In order to determine the range, a user dips the strip in a solution and compares colors appearing in segregated rectangles with a key. The ranges reported include undetectable (indicated as 0 on the test strip), >0–1 mg/l, >1–2 mg/l, >2–3 mg/l,
25 >3–5 mg/l, >5–10 mg/l and >10 mg/l. We tested the accuracy of the strips using dilutions of sodium hypochlorite solution and determined that they were adequate for distinguishing between the classes noted above (data not shown).

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



3 Results and discussion

3.1 Conductivity, pH, oxidation-reduction potential and temperature

Post-chlorination conductivity measurements were elevated from initial values, and returned to near initial values following purging four well volumes (Table 4). pH rose in wells 167N and 51 and decreased slightly in wells 182 and 42. Increases in pH conform to observations that concentrations of chlorine of 200 mg/l can be expected to increase pH by up to two units (Schnieders, 2005). Oxidation-reduction potential increased above pre-chlorination levels in all wells, as would be expected with the addition of an oxidizer. Water in well 142 returned to background levels for temperature, pH, conductivity, and oxidation-reduction potential after four well volumes had been purged, though measurements from the other wells indicated that four well volumes of purging was not sufficient to return to background conditions (Table 4). The oxidation-reduction potential in wells 51 and 167 remained above background levels, though temperature and pH were <16% of starting values. This suggests that the oxidizing effects of chlorination led to short-term changes in the immediate vicinity of the well screen, which would have required more purging to eliminate.

3.2 Chlorine concentration

Decreases of free chlorine concentration were hypothesized to be an indicator of purging of mobilized trace metals and disinfection byproducts. The concentration of free chlorine decreased in wells 51, 167N and 142 to >1–2 ppm free chlorine after four well volumes were pumped (Table 5). Site 182 required that five times the well volume be purged before free chlorine decreased to >3–5 ppm.

3.3 Mobilization of trace metals

Concentrations of lead and copper in well water increased following shock chlorination, as previously observed and reported by Seiler (2006). Lead concentrations increased

up to thirteen-fold and copper concentrations increased up to four-fold following treatment. Concentrations of both decreased to initial levels within two well volumes of purging. The return to background levels corresponded with the decline in free chlorine to >3–5 ppm (Table 5).

All wells contained arsenic in concentrations that exceeded the MCL (0.010 ppm) prior to treatment. The decline in arsenic concentration in the chlorine solution prior to purging was similar to results reported by Gotkowitz et al. (2008) and would be expected with the observed changes pH and oxidation-reduction potential. However, the decline was followed by an increase in arsenic above background levels during pumping. After four well volumes, water from one well returned to initial arsenic concentrations, while the others remained elevated by 3–12% higher than initial concentrations.

3.4 Uranium and radionuclides

Samples were analyzed for uranium and gross- α and gross- β radionuclides (Table 6). Uranium concentrations increased at sites 51 and 142 but remained the same or decreased in wells 167N and 187. Concentrations returned to approximately the same as starting levels in all wells after purging four well volumes. Gross- α concentrations changed from the IP to PC sampling steps, increasing in wells 51 and 167N, decreasing in well 142 and remaining approximately the same in well 182. Gross- β concentrations remained approximately the same in all wells at each sampling stage, with concentrations appearing to decrease slightly between the IP and 4F samplings. The maximum change in gross- β concentrations was approximately –9% in well 142.

3.5 Dissolved organic carbon and disinfection byproducts

Dissolved organic carbon (DOC) concentrations in wells 182 and 142, collected prior to treatment, are shown in Table 7. Water from wells obtained after treatment, but prior to purging contained concentrations of THM up to ten times the MCL (Table 7). Following the purging of four well volumes, concentrations in well 142 decreased to below the

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



detection limit, indicating that the increase in concentration was temporary and could be remediated by purging four well volumes after treatment. Well 182 retained disinfection byproducts and free chlorine, with the concentration of free chlorine (indicated by test strips) >10 ppm after purging 4 WV. Testing for free chlorine at the fifth well volume purged indicated a concentration of >3–5 ppm.

4 Conclusions

This study confirmed temporary mobilization and changes in concentration of trace metals from shock chlorination treatment, as previously reported by Seiler (2006) and Gotkowitz et al. (2008). It also demonstrated that disinfection byproducts can be formed and can persist beyond three well volumes of purging. The concentration of disinfection byproducts exceeded drinking water MCLs in the two wells tested. In one well, concentrations decreased to below the detection limits for HAA5 and THM with purging. In the other, concentrations of disinfection byproducts remained elevated, with final concentrations of THM and HAA5 at highest levels after purging four well volumes. Metals, though mobilized by shock chlorination, decreased to near pre-treatment background levels after four well volumes were purged in all wells.

The concentrations of DBP precursors and peak concentrations of HAA5 and THM were substantially higher a steel-cased well than those in a PVC-cased well. Although concentrations of THM and HAA5 were lower in the PVC-cased well, samples collected after four well volumes had been purged indicated that DBPs persisted. This may have been due to differences in well construction and interaction between chlorine solutions and aquifer materials and casing materials. With respect to well construction, the depths of wells and depths to water from the land surface for wells 182 and 142 were similar, but lengths of screened intervals and static volumes differed (Table 1). The screened interval in well 182 spanned 3.3 m (11 ft), compared with the screened interval of 1.5 m (5 ft) in well 142. Although well logs indicated that the screened intervals were set in sands, well yields appeared to be very different based on the discharge

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



rates used for purging and drawdowns observed. In order to maintain a steady discharge rate from well 142, the purging discharge was <20% of the purging rate used in well 182, even though lift distances from the water table to the surface were slightly less for well 142 than well 182. This suggests that the saturated formations in the screened intervals pumped for well 142 were less permeable than those in well 182, which in turn suggests that aquifer materials may have been composed of fine-textured soils including silts and clays. In the absence of significant advective mixing, formation of disinfection byproducts beyond the immediate well volume would be limited to chemical dispersion. Given the low well yield it is likely that disinfection byproducts remained in the well within the saturated formations immediately adjacent to the well screen. In well 182, however, it is likely that a larger volume of saturated soil was exposed to the shock chlorination solution. This hypothesis is, in part, supported by the persistent indication of oxidizing conditions in water withdrawn after completion of four well volumes of purging. A prior study in the region (Fram et al., 2005) demonstrated that free chlorine released significant amounts of carbon from aquifer materials. They concluded that carbon was likely released from clay minerals in proportion to the amount of available chlorine in solution. This suggests that aquifer material and interactions with high concentrations of available chlorine were a source of precursors to HAA5 and THM formation. This also suggests that DBP formation and persistence in well 182 were due to chemical or advective transport of chlorine into aquifer materials during the resting phase.

The mixing procedure used to disperse chlorine throughout the entire well volume was unlikely to have created a gradient that would advect chlorine into aquifer materials, but chemical diffusion through the well screen may have taken place during the resting phase. Given the differences in screened intervals, this may have led to accumulation of DBPS's in aquifer materials in contact with the screened interval of the PVC well, which could have required more thorough purging to remove than those in contact with the shorter screened interval in the steel-cased well. Although purging appeared to be adequate based on number of well volumes removed and stability of

**Metals releases and
disinfection
byproduct formation**

M. Walker and
J. Newman

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

temperature and pH, test strips indicated the presence of free chlorine. Consequently, the chemical reactions that led to metals releases and DBP formation were likely due to chemical diffusion during the resting time following introduction of bleach and likely due to reactions with aquifer materials and gravel packing in the immediate vicinity of the screened interval of the well casing.

Interaction with casing material was unlikely as a source of persistent HAA5 and THM in well 182. PVC polymers may sorb and leach trace metals, organic and phenolic substances, volatile organic chemicals and trihalomethanes (Llopis, 1991; McCaulou et al., 1995). However, the concentrations of THM and HAA5 were at a maximum at the presumed end of purging for this well, rather than at beginning of purging as in the steel-cased well 142, which suggests that leaching from PVC casing was not a significant source of THM and HAA5. Also, sample analyses for disinfection byproduct precursors (dissolved organic carbon, carbonate) indicated that concentrations in well 142 were much higher than in well 182, as were concentrations of HAA5 and THM.

Publications about shock chlorination recommend purging varying numbers of well volumes post treatment and prior to returning a well to service. Guidance for returning a well to service also is based on detecting the scent of chlorine in water. Without metering equipment most domestic well owners have no accurate means of determining when pumping is sufficient to remove a specific number of well volumes. Also, determining the sufficiency of purging by scent is subjective and may not be consistent, especially with respect to avoiding exposure to metals and disinfection byproducts. The use of chlorine test strips shows promise as a simple and accurate means of determining when purging is complete, though this should be verified with further experimental work. This technique has the potential to be a reliable guideline for public health officials and informal educators (including Cooperative Extension), who receive inquiries about proper procedures for shock chlorination, especially when well owners cannot measure discharge rates and discharge volumes.

Metals releases and disinfection byproduct formation

M. Walker and J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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DWESD

3, 177–198, 2010

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Metals releases and disinfection byproduct formation

M. Walker and J. Newman

Table 1. Well characteristics and water physical and chemical characteristics immediately prior to shock chlorination; DTW is depth to water from the land surface, WD is total depth of the well, Static vol. refers to the standing volume of water in a well after water level recovery following the end of pumping. Well diameter, case material, depth to water from the land surface and well depth were recorded at each site. The screened interval length was obtained from well logs available on the Nevada Division of Water Resources (<http://water.nv.gov/>, last access: April 2010).

US Fish and Wildlife Service Site Designation (year finished)	Well dia cm (in)	Case material	DTW from land surface m (ft)	WD from land surface m (ft)	Screened interval length m (ft)	Static vol. l (gal)
182 (1975)	15 (6)	PVC	3.4 (11.1)	9.4 (31.0)	4.6–7.9 (15.0–26.0)	110.6 (29.2)
167N (1996)	15 (6)	Steel	2.4 (8.0)	9.0 (29.6)	8.2–9.1 (27.0–30.0)	120.0 (31.7)
51 (1994)	15 (6)	Steel	1.7 (5.5)	20.4 (67)	18.9–20.4 (62.0–67.0)	171.2 (45.2)
142 (1993)	15 (6)	Steel	3.6 (11.8)	8.1 (26.7)	6.4–7.9 (21.0–26.0)	84.8 (22.4)
US Fish and Wildlife Service Site Designation	pH	Temperature °C	Conductivity mS/cm	Oxidation-reduction Potential mV	Bleach added l (gal)	Treatment duration (h)
182	8.50	14.9	0.740	not taken	1.0 (0.3)	20 h 25 m
167N	7.14	16.9	0.345	114.1	1.1 (0.3)	15 h 10 m
51	7.27	15.57	0.454	269.7	1.5 (0.4)	24 h 20 m
142	7.67	16.86	2.093	–123.3	0.7 (0.2)	17 h 50 m

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[I◀](#)

[▶I](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Table 2. Sampling intervals used, with associated chemical constituents measured.

Sample Type	Initial Purge (IP)	Post-Chlorination (PC)	Post-Chlorination Purging (PCP, for 1/2, 1, 2, and 3 well volumes)	Final (4F: 4 well volumes purged)
gross- α , gross- β , Uranium	✓	✓		✓
Metals (Cu, Pb, As)	✓	✓	✓	✓
HAA5, THM (wells 142 and 182)	✓	✓		✓
Total Organic Carbon (wells 142 and 182)	✓			
Chlorine Test Strips		✓	✓	✓

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 3. Methods used for sample analysis. “EPA” refers to a standard analytic method published by the US Environmental Protection Agency (available at <http://www.epa.gov/sam/index.htm>, last access: April 2010), used by the Nevada State Health Laboratory. “SM” refers to a standard analytic method published in Standard Methods for the Examination of Examination of Water and Wastewater (Clesceri et al., 1998). Dissolved Organic Carbon samples were analyzed using a Shimadzu Spectrophotometer at the University of Nevada.

Analyte	Method	Analytic Detection Limits (mg/l)
Copper	EPA 200.7	0.020, 0.050
Arsenic, Lead, Uranium	EPA 200.8	0.003, 0.002, 0.002
gross- α , gross- β	EPA 900.0	3 pCi/liter
THM	EPA 524.2	0.005
HAA5	SM 6251B	0.001
DOC	SM 5310C	1.0 mg/l*

* The analytic detection limit is based on linear regression analysis of the calibration curve, conducted with three replicates each of 4 standards, ranging from 0.274–20.270 mg/l.

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Table 4. Physical and chemical characteristics of water in test wells observed during post-chlorination purging (*T*: temperature, *C*: conductivity, ORP: oxidation-reduction potential, ND: not measured). Final column displays the percentage difference between values at IP and post-chlorination with 4 well volumes purged.

Well volumes purged→	0	1/2	1	2	3	4	(IP-4)/IP %
182 (discharge rate = 14.4 l per min (3.8 gpm))							
<i>T</i> (°C)	16.68	15.70	15.69	15.67	15.60	15.65	5%
<i>C</i> (mS/cm)	0.680	0.487	0.560	0.558	0.539	0.549	−26%
pH	7.97	7.57	7.70	7.52	7.47	7.58	−11%
ORP (mV)	772.6	817.0	810.5	827.9	837.4	828.9	no IP
167N (discharge rate = 18.9 l per min (5.0 gpm))							
<i>T</i> (°C)	ND	17.1	17.11	17.12	17.1	17.12	1%
<i>C</i> (mS/cm)	2.115	1.225	0.525	0.445	0.420	0.437	27%
pH	8.78	8.38	7.82	7.56	7.27	7.51	5%
ORP (mV)	732.0	786.9	793.2	782.6	791.1	776.9	581%
51 (discharge rate = 14.6 l per min (3.9 gpm))							
<i>T</i> (°C)	16.4	14.83	14.96	15.11	15.32	15.17	−3%
<i>C</i> (mS/cm)	1.945	1.065	1.083	0.787	0.813	0.772	70%
pH	8.65	8.8	8.5	8.27	8.41	8.42	16%
ORP (mV)	866.5	957.0	962.3	958.5	831.0	586.0	117%
142 (discharge rate = 2.5 l per min (0.7 gpm))							
<i>T</i> (°C)	22.40	16.74	16.69	16.63	16.57	16.60	−2%
<i>C</i> (mS/cm)	2.257	1.638	2.067	2.041	1.972	1.942	−7%
pH	7.56	8.48	8.13	7.71	7.74	7.73	1%
ORP (mV)	704.1	719.0	718.9	−108.7	−123.6	−124.4	1%

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Table 5. Trace metal concentrations from pre-treatment (PT) through purging, expressed in number of well volumes pumped. The Maximum Contaminant Level for arsenic is 0.010 mg/l. Action Levels for lead and copper are 1.3 and 0.015 mg/l, respectively. Samples that contained analytes in concentrations less than the reporting limit (RL) are reported as “<RL”. The reporting limit for lead varied according to results of internal laboratory quality control assessments and chemical quality of water samples.

Metals (mg/l)	PT	Well volumes purged					
		0	1/2	1	2	3	4
51							
Arsenic	0.410	0.390	0.380	0.410	0.460	0.460	0.460
Copper	< 0.02	0.08	0.08	0.06	< 0.02	< 0.02	< 0.02
Lead	0.003	0.022	0.016	0.012	0.003	0.002	0.003
Cl	< 1	> 10	> 10	> 10	> 1–2	< 1	< 1
142							
Arsenic	0.580	0.440	0.460	0.750	0.620	0.590	0.600
Copper	< 0.02	< 0.02	0.02	< 0.02	< 0.02	< 0.02	0.02
Lead	< 0.010	0.010	< 0.010	< 0.010	< 0.010	< 0.010	0.010
Cl	< 1	> 10	> 10	< 1	< 1	< 1	< 1
167N							
Arsenic	0.019	0.024	0.018	0.019	0.019	0.019	0.019
Copper	< 0.02	0.03	0.04	< 0.02	< 0.02	< 0.02	< 0.02
Lead	< 0.001	0.013	0.008	< 0.002	< 0.001	< 0.001	< 0.001
Cl	< 1	> 10	> 10	> 10	> 3–5	> 2–3	> 1–2
182							
Arsenic	0.020	0.016	0.016	0.020	0.021	0.021	0.021
Copper	< 0.02	0.04	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Lead	< 0.001	0.011	0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cl	< 1	> 10	> 10	> 10	> 10	> 10	> 3–5

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 6. Uranium, gross- α and gross- β results for three stages of treatment: IP (prior to chlorination), PC (post chlorination but prior to purging) and 4F (after purging 4 well volumes). The Maximum Contaminant Levels for uranium, gross- α and gross- β are 30 $\mu\text{g/L}$, 15 pCi/L and 4 mrem/yr , respectively, (see http://www.epa.gov/safewater/radionuclides/pdfs/qrg_radionuclides.pdf, last access: April 2010).

51	IP	PC	4F
Uranium, $\mu\text{g/L}$	4	29	9
gross- α , pCi/L	13	43	16
gross- β , pCi/L	6	8	5
142			
Uranium, $\mu\text{g/L}$	560	620	580
gross- α , pCi/L	120	92	127
gross- β , pCi/L	173	168	158
167N			
Uranium, $\mu\text{g/L}$	13	13	13
gross- α , pCi/L	8	15	12
gross- β , pCi/L	19	17	19
182			
Uranium, $\mu\text{g/L}$	32	22	35
gross- α , pCi/L	18	21	24
gross- β , pCi/L	18	14	20

Metals releases and disinfection byproduct formation

M. Walker and
J. Newman

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 7. DOC and CO₃ concentrations following initial purging of test wells (IP), and HAA5 and THM concentrations following IP, post chlorination (PC) and after 4 well volumes had been purged (4F).

Site	DOC (IP) mg/L	CO ₃ (IP) mg/L	HAA5 (IP,PC,4F) µg/L	THM (IP,PC,4F) µg/L
182	3.9	49.3	<1.0, 101.0, 128.0	<0.5, 43.7, 70.1
142	15.1	215.8	<1.0, 394.0, <1.0	<0.5, 747.0, <0.5

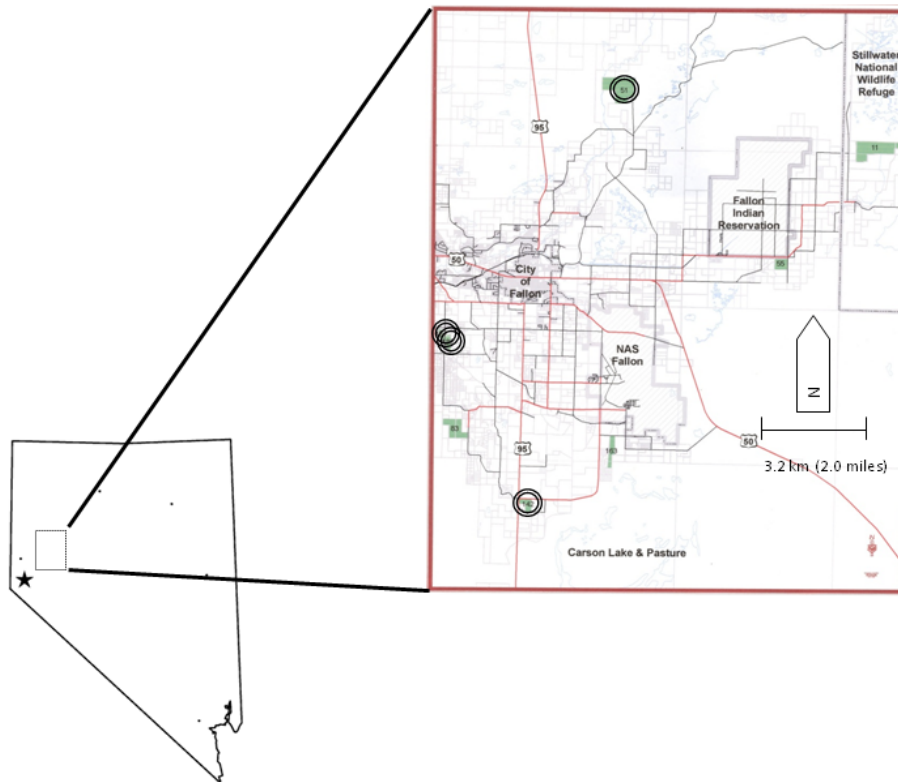


Fig. 1. Location of study area, with locations of test wells indicated in circles.

Metals releases and disinfection byproduct formation

M. Walker and J. Newman

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
⏪	⏩
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	