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PASSIVE REMOVAL OF SELENIUM FROM GRAVEL PIT SEEPAGE
USING SELENIUM REDUCING BIOREACTORS

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EXECUTIVE SUMMARY

Water quality in the lower Colorado and Gunnison Rivers in western Colorado, and many of their tributaries, is impaired by selenium, which originates from the local Mancos shale. Because of the diffuse and widespread nature of this source, there are limited opportunities to reduce selenium (Se) inputs. One option is to treat selenium-contaminated surface water at strategic locations, such as point-source discharges. Gravel extraction is common along these rivers, and treatment of discharges from pit dewatering presents an opportunity for reducing selenium loading.

The goal of this study was to determine: 1) whether a passive selenium-reducing bioreactor can accomplish high-efficiency selenium removal from the basic, saline water typical of the Grand Valley; 2) whether zero-valent iron (ZVI) is beneficial as a bioreactor component; and 3) optimum detention time. To date, bacterial reduction of selenium has been successfully accomplished using power-, and equipment-intensive “active” treatment systems. The passive bioreactors tested can function unattended, ideally by a gravity feed (no pumps), and the "fuel" for the bacteria would be agricultural wastes (e.g., wood chips, hay, cow manure inoculum) and other materials (e.g., quarried limestone) collected locally.

Four 208-liter (55 gallon) bioreactors were constructed with varying amounts of cow manure, hay, sawdust, wood chips, limestone, and zero-valent iron. Influent to the reactors was drawn from a dewatering trench in a gravel pit next to the Colorado River near Grand Junction, Colorado. The reactors were operated, with varying detention times, over a thirteen-month period from July 2006 through September 2007. The results of this study demonstrate that passive bioreactors can accomplish up to 98% removal of Se from surface and ground waters in the Grand Valley of western Colorado. A bioreactor designed to promote microbial processes functioned as efficiently as reactors incorporating ZVI, in spite of the potential of the ZVI to enhance the biological removal process. The highest removal rates were achieved using a detention time of 12 hours, but circumstances prevented optimization of detention time.

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1.0 INTRODUCTION

Selenium in surface and ground water has generated concern since 1982, when selenium was found responsible for mortality of fish and birds inhabiting the Kesterson National Wildlife Refuge in California (National Research Council, 1989). The western United States is susceptible to selenium contamination of ground and surface water due to a combination of geology, climate, and irrigated agriculture. Over 777,000 km² (17%) of the total land area in the western U.S. is composed of seleniferous bedrock, much of which is irrigated (Seiler et al, 2003). Selenium is mobilized as irrigation drainage waters leach it from the bedrock and soils. The arid and semi-arid climates promote high rates of evaporation, which can lead to high concentrations of selenium in surface waters, causing some areas to be out of compliance with water quality standards.

Although selenium forms the active center of certain enzymes and is thus an essential nutrient, in large concentrations it is toxic to invertebrates, fish, birds, and mammals. The oxidation state of selenium determines its bioavailability and toxicity (Amweg et al, 2003). Selenium can occur in its elemental form (Se⁰), as selenate (SeO₄²⁻, Se⁶⁺), selenite (SeO₃²⁻, Se⁴⁺), inorganic selenide (Se²⁻), or organic selenide (organic-Se). Elemental selenium has little effect on living organisms. The inorganic forms selenate and selenite are both water soluble and bioavailable, with selenite being the more toxic of the two. Organic selenide is the most bioavailable form of selenium, and is taken up by algae 1000 times more easily than the inorganic forms. Selenium is also bioaccumulative; its concentration may increase in organisms at successively higher levels in the food chain.

The Grand Valley in western Colorado is underlain by the highly seleniferous Mancos shale. Selenium in surface waters here has been measured at concentrations exceeding 100 µg/L (Spahr et al, 2000), which is well above the U.S. Environmental Protection Agency's criterion of 5.0 µg/L as a maximum continuous concentration of total recoverable selenium for protection of freshwater aquatic life (EPA). Because of the diffuse and widespread occurrence of the Mancos shale, there are limited opportunities to reduce selenium inputs to surface waters. One option is to treat selenium-contaminated surface water at strategic locations, such as point-source discharges (Bureau of Reclamation, 2006). Gravel extraction is common along the Colorado River, and treatment of discharges created by dewatering of groundwater seepage into the pits presents an opportunity for reducing selenium loading to the river.

Various approaches to treatment of selenium-contaminated waters have been investigated (Kapoor et al, 1995). Bioremediation is one such approach (Frankenberger and Arshad, 2001). There are several

selenium removal processes that may occur in typical bioreactors, microbial reduction of soluble selenate and selenite to elemental selenium being the most obvious. Reducing conditions created by the depletion of oxygen from aerobic microbial respiration can result in the chemical reduction of selenate and selenite. If sulfur is present in the water, precipitation of a selenium sulfide is possible. Certain algae and microorganisms have been shown to convert selenium to organoselenium compounds, some of which are volatilized to the atmosphere. The bacterial-algal removal of selenium has been successfully demonstrated at the pilot scale using a power- and equipment-intensive “active” treatment system (Lundquist, 1994).

The goal of this study was to determine: 1) whether a passive selenium-reducing bioreactor can accomplish high-efficiency selenium removal from the basic, saline water typical of the Grand Valley; 2) whether zero-valent iron is beneficial as a bioreactor component; and 3) optimum detention time. If effective, the passive selenium-reducing bioreactor promises to be a low-cost treatment method with the potential to reduce selenium toxicity in waters found throughout western Colorado and at other high-selenium locations. The passive bioreactors described here can function unattended, potentially by a gravity feed (no pumps), and the reactor components would be agricultural wastes (e.g., wood chips, hay, cow manure inoculum) and other materials (e.g., quarried limestone) that may be collected locally. The passive nature of the system and the use of low-cost, locally-derived substrate (that might require replacement on a decade-plus schedule) should combine to reduce the costs.

2.0 MATERIALS AND METHODS

2.2 Site Description

The study was performed in a gravel pit on private land adjacent to the Colorado River in western Grand Junction, Colorado. Groundwater seepage into the gravel pit was collected in a trench extending along the pit perimeter, and then pumped into the Colorado River. This site was chosen because of the significant selenium concentrations in the dewatering trench, which ranged from 31 to 93 µg/L during the year prior to the study (Kerr, 2006). The site was also within a secure area which prevented theft and vandalism of the equipment.

2.3 Materials

Four bioreactors were constructed using 208-liter (55 gallon) polyethylene drums with varying proportions of sawdust, hay, wood chips, agricultural limestone, zero valent iron (ZVI) powder, and manure (Table 1). ZVI (obtained from Connelly Inc., Chicago) was included in varying amounts in order to determine if chemical reduction of selenium would be a significant enhancement to the biological reduction of selenium. Reactor 1, with no ZVI, served as a baseline. Reactors 2, 3, and 4 had increasing weight percentages of ZVI. The materials were weighed out and homogenized manually before transfer into each bioreactor. The manure, which was collected from cows grazing in areas known to have selenium-rich soils, was included as a source of microorganisms acclimated to the presence of selenium. The organic materials were chosen to provide substrate for the growth of the microorganisms. Figure 1 shows the bioreactors at the study site.

2.4 Operation

An automatic sampler (Teledyne Isco, Model 6712) was modified to deliver influent from the dewatering trench to the bioreactors. Power was provided to the sampler by three deep-cycle 12-volt marine batteries connected in parallel and recharged by two 40-watt solar panels. The sampler was programmed to deliver specific volumes to each bioreactor at designated time intervals [e.g., 1.25 liters (L) every 10 minutes]. Upon completion of bioreactor construction on June 27, 2006 the bioreactors were filled with water from the dewatering trench and allowed to sit until July 10, 2006. From July 10 to September 21, 2006 the flow rate was set at 7.5 L/hr to each bioreactor to attain a detention time of 12 hours. Flow sometimes decreased to as low as 6.4 L/hr between site visits; the sampler was recalibrated to re-establish flow to the desired 7.5 L/hr. The flow

rate was changed to 8.8 L/hr on September 21, 2006 and then to 9.6 L/hr on September 28, 2006 to measure bioreactor performance at a shorter detention time of 9.4 hours. Flow rate was decreased on November 16, 2006 to 7.4 L/hr to return to a 12 hour detention time while ambient air and water temperatures were lower. Equipment problems resulted in downtimes of one to five days, particularly during weeks 10 to 19. Operation of bioreactor 4 was suspended in mid-November in order to reduce demand on the storage batteries. Bioreactor 4 was chosen because it was exhibiting decreased permeability due to its high ZVI content. Operation of the remaining bioreactors was suspended on November 27, 2006 (week 20) because of persistent freezing temperatures and malfunctions in the automatic sampler. Routine operation was restored on March 29, 2007 at a flow rate of 7.5 L/hr (12 hour detention time). The flow rate remained at 7.5 L/hr for the remainder of the study.

2.5 Sampling and Analysis

Weekly, unfiltered samples were collected manually from the influent and effluent of each bioreactor from July 18, 2006 (week 1) through November 21, 2006 (week 19), except for weeks when the system was down. Whenever operations were re-started following equipment failures, the reactors were run for at least three days before samples were collected. Filtered samples were collected in addition to unfiltered samples on September 19, 2006 (week 10) and November 21, 2006 (week 19). Samples for selenium speciation were collected on December 27, 2006 by using a small propane heater to thaw enough of the bioreactor to obtain effluent samples. Samples of influent, reactor 1 effluent, and reactor 2 effluent were collected on March 30, 2007 in order to compare the results of analysis both with and without sample digestion. Subsequent monthly samples were collected in May, June, July, and August 2007. In June 2007 bioreactor samples were submitted for toxicity characteristics leaching procedure (TCLP) to evaluate substrate disposal options.

Unfiltered influent and effluent samples were analyzed immediately in the field for temperature, pH, and conductivity using an Oakton pH/CON 10 meter. Dissolved oxygen and oxidation-reduction potential were analyzed immediately using a Hach HQ20 meter. Meters were calibrated and operated according to the manufacturer's instructions.

Analysis for selenium and metals was performed by ACZ Laboratories, Inc. (Steamboat Springs, Colorado). Weekly, unfiltered samples were analyzed for total selenium using EPA method 200.2 for digestion and method 200.8 for analysis by inductively-coupled plasma (ICP) mass spectroscopy. Duplicate samples for selenium analysis were collected on August 8 (reactor 1), September 6 (reactor 3), and October 11 (reactor 1). Once per month, unfiltered samples were

digested using method 200.2 and analyzed by ICP-optical emission spectroscopy for total calcium, iron, and manganese using method 200.7. Unfiltered and filtered sample pairs collected on September 19, 2006 and November 21, 2006 were analyzed for dissolved selenium (no digestion, method 200.8 for analysis by ICP-mass spectroscopy). Samples of influent, reactor 1 effluent, and reactor 2 effluent collected on December 27 were processed using EPA method 3030B then analyzed by atomic absorption-hydride generation for dissolved selenium, selenium(VI), selenium(IV), and organic selenium. Samples of influent, reactor 1 effluent, and reactor 2 effluent collected on March 31, 2007 were split, with one portion analyzed directly by method 200.8 without digestion, and the other portion analyzed by method 200.8 following digestion by method 200.2. All samples collected between July 8, 2006 and November 21, 2006 were analyzed for sulfate by ion chromatography at Mesa State College.

3.0 RESULTS

3.1 Selenium Removal

Selenium (Se) concentrations in bioreactor influent and effluent are shown in Table 2 along with Se removal efficiencies. Selenium results are also presented in Figure 2. Reactor 4 had the highest initial Se removal efficiency; reactor 1 had the lowest initial efficiency. During weeks 4 through 10 of operation, there was no significant difference in Se removal efficiency between the four bioreactors, with each bioreactor averaging either 95% or 96% removal (Figure 3). During this time period, the detention time was 12 hours and average daily temperature varied from 24°C to 11°C. Detention time was shortened to 9.4 hours in week 11. Samples taken in weeks 13 and 14 showed a significant decrease in performance in reactors 2, 3, and 4, with removal efficiencies falling to values between 55% and 85%. The removal efficiency of reactor 1 remained high, with values of 94% and 98%. Average daily temperatures decreased during this period from 11 C to a low of 7.8 °C. Although the longer detention time of 12 hours was restored in week 19, removal efficiencies remained low except in reactor 1. The average daily temperature associated with the week 19 sampling event was only 5.2 °C.

Over the course of the entire study, reactor 1 had the lowest average effluent selenium concentration (2.6 ug/L) and the highest average post-startup removal rate (94%). Reactors 2 and 3 had slightly higher average effluent selenium concentrations of 4.9 and 7.3 ug/L, respectively. The average post-startup selenium removal rates for reactors 2 and 3 were 88% and 80%, respectively.

3.2 Total versus Dissolved Selenium Concentrations

Filtered and unfiltered sample pairs were collected six times in order to determine the proportion of Se in the dissolved form (Table 3). In general, the dissolved analyte concentration determined from the filtered sample should be less than or equal to the total analyte concentration determined from the unfiltered sample. In week 10, this expectation was met only for effluent from reactors 3 and 4, which showed 100% and 95% of Se in the dissolved form, respectively. In week 19, this expectation was met for the influent as well as the effluent from reactors 2 and 3, with 98%, 93%, and 86% of Se in the dissolved form, respectively. Contrary to expectations, dissolved Se was greater than total Se for influent, reactor 1 effluent, and reactor 2 effluent in week 10, as well as for reactor 1 effluent in week 19. In weeks 43, 53, and 60 at least one sample had a greater dissolved concentration than total concentration.

Samples analyzed for total Se are acidified in the field, then digested and analyzed in the laboratory, while samples analyzed for dissolved Se are filtered then acidified in the field, and analyzed without digestion. Given that there is no digestion step in the procedure for dissolved Se, it was hypothesized that a portion of the selenium in the anomalous samples may be occurring in a volatile form that is driven off during digestion, resulting in a lower concentration for a digested sample (total Se) relative to the companion undigested sample (dissolved Se). This hypothesis was tested by having the laboratory analyze the same, unfiltered samples both with and without digestion. The results in Table 4 show that the digested samples have Se concentrations that are higher than in the undigested samples, thus disproving the hypothesis. At this time there is no explanation for the anomalous results in Table 3; this problem should be pursued in a future investigation.

3.3 Selenium Speciation and Toxicity

The variation in toxicity among the different forms of Se (Amweg et al, 2003) provided motivation for determining the speciation of Se in bioreactor effluent. From a toxicity standpoint, the most desirable form of Se in the reactor effluent is Se(0). If the effluent Se has a greater proportion of Se(IV) or organic-Se than the influent Se, there is a possibility that the effluent will be more toxic than the influent even if the total Se is less. Samples collected on December 27, 2006 were analyzed for Se(VI), Se(IV), and organic-Se. The influent had 28 µg/L of dissolved Se, of which 57% was Se(VI), 14% Se(IV), and 29% organic-Se. Unfortunately, all forms of Se in the effluent samples were less than the practical quantitation limit or the method detection limit, and results were inconclusive.

Two substrate samples were collected on June 29, 2007 from Cell 1 and were submitted to ACZ Laboratories for selenium TCLP analysis. Both samples were below the detection limit for selenium. The TCLP results are provided in Appendix B.

3.4 Other Parameters

Results of dissolved oxygen (DO) measurements are shown in Table 5 and in Figure 4. DO in the influent ranged from 6.2 mg/L to 10.4 mg/L over the period of operation. DO in the bioreactor effluents ranged from 0.1 to 3.2 mg/L. These results support the expectation that aerobic microbial respiration was consuming DO in the reactors.

The oxidation-reduction potential (ORP) was monitored to confirm that reducing conditions occurred within the bioreactors (Table 5, Figure 5). The ORPs of the effluents ranged from -393 millivolts (mV) to -79 mV. The ORP of the influent ranged from -185 mV to +143 mV. The effluent ORPs were more negative than the influent ORPs on every date as expected.

With one exception, the pH of the influent ranged from 7.61 to 8.17 (Table 5, Figure 6). The pH of effluent from reactor 1 ranged from 5.8 to 7.7. The pH of effluent from reactor 2 ranged from 6.0 to 8.1. The pH of effluent from reactor 3 ranged from 6.5 to 8.5 and the pH of effluent from reactor 4 ranged from 7.2 to 8.8.

The conductivity of the influent ranged from 0.9 mS/cm to 5.8 mS/cm (Table 5, Figure 7). During weeks 2 through 4, the conductivities of the effluent of all bioreactors were between 5.26 mS/cm and 5.93 mS/cm, which were greater than influent conductivity, which ranged from 3.46 mS/cm to 3.69 mS/cm in that period. Thereafter, the effluent conductivities were generally much more similar to the influent conductivities, ranging from 0.94 mS/cm below the influent conductivity to 1.98 mS/cm above.

In weeks 2 through 4, the sulfate concentrations in the influent ranged from 1,132 mg/L to 1,239 mg/L (Table 5, Figure 8). During that same period, sulfate concentrations in effluent from reactors 1 through 4 were greater, ranging from 1,356 mg/L to 2,293 mg/L, with reactor 4 effluent always showing the highest concentration. Thereafter, the sulfate concentrations in the effluents were always less than the influent sulfate concentration, which ranged from 1,105 mg/L to 1,980 mg/L.

Calcium and iron concentrations were measured in order to monitor the depletion of bioreactor components (Table 5, Figure 9 and 10). The concentration of calcium in the influent ranged from 180 mg/L to 207 mg/L from July through September. With the exception of reactor 1, effluent calcium concentrations were always less than influent concentrations. The effluent from reactor 1 showed calcium concentrations ranging from roughly equal to influent to 30% higher than influent. Influent iron concentrations ranged from 0.19 mg/L to 0.43 mg/L. Effluent concentrations in reactors 2, 3, and 4 were all much higher, ranging from 4.5 mg/L to 96 mg/L, 8.6 mg/L to 116 mg/L, and 5.4 mg/L to 13.5 mg/L, respectively. Two of the three iron concentrations measured in reactor 1 effluent were lower than the influent concentrations. Manganese was monitored to determine if this element was being leached from the bioreactor bed materials. In July, all four bioreactor effluents were greater in manganese (0.61 mg/L to 1.7 mg/L) than the influent (0.31 mg/L). Subsequently all four effluent manganese concentrations were less than the influent concentrations.

4.0 DISCUSSION

During weeks 4 through 10, all four bioreactors achieved selenium removals of at least 92%. These results demonstrate that for a detention time of 12 hours and average daily temperatures between 11 °C and 26 °C, passive bioreactors of the compositions tested here are effective at removing selenium from ground water in the Grand Valley. The reactor with 0% ZVI maintained this high removal efficiency at temperatures down to 5 °C.

The first two sampling events showed a difference in removal efficiencies between the reactors, with reactor 1 having the lowest and reactor 4 having the highest. This suggests that initially the ZVI was responsible for most of the selenium removal. The removal efficiencies of the bioreactors increased as the proportion of ZVI in the reactors increased. By the fourth sampling event, all bioreactors achieved a selenium removal efficiency of 95% to 96%, suggesting that microorganism populations were well developed and that Se removal through reduction by ZVI was not providing a significant enhancement to removal by microbial processes.

Average daily temperature appeared to have no effect on the efficiency of the reactors through week 10. During this period, while the detention time was 12 hr and average daily temperature decreased from 31°C to 11°C, all four reactors maintained over 90% removal efficiency. Detention time was shortened to 9.4 hr in week 11. Shortly thereafter, the temperature dropped from 11°C to 8°C and influent selenium concentration increased from 24.8 mg/L to 68.6 mg/L. These uncontrollable, simultaneous changes in two other factors affecting performance made it impossible to assess the effect of decreased detention time alone. Under these new conditions, the performance of reactors 2, 3, and 4 decreased significantly. Reactor 1 was the only reactor to maintain a removal efficiency over 90%. The detention time was returned to 12 hr prior to the last 2006 sampling event in week 19. The influent concentration (29.4 mg/L) simultaneously returned to roughly its value during the original period of high removal efficiency, while the temperature dropped further to 5°C. Removal efficiencies of reactors 2 and 3 remained low (62% and 52% respectively), while the efficiency of reactor 1 remained high (98%). It is remarkable that reactor 1 continued to perform so well at the lower temperature even though reactors 2 and 3 performed poorly.

DO and ORP measurements confirm that aerobic microbial respiration is taking place and that conditions within the reactors are reducing. Conductivity and sulfate results support the expectation that during the initial period of operation, salts were leached from the reactor materials. Calcium concentrations that are lower in effluent than influent for reactors 2, 3, and 4 indicate that

dissolved calcium is being precipitated as CaCO_3 within these reactors. In contrast, calcium results for reactor 1 suggest that calcium from the agricultural limestone is being lost initially, but is unaffected subsequently. As expected, iron results show that soluble iron(II) was being removed from the reactors by oxidation of the ZVI in reactors 2, 3, and 4. In two out of the three effluent samples from reactor 1 that were analyzed for iron, the iron in the effluent was much less than the iron in the influent. This result is consistent with the absence of ZVI in this reactor, and suggests that iron in the influent may be reduced to an insoluble form and retained within the reactor.

TCLP testing was performed in order to evaluate possible disposal options for bioreactor substrate. Given the non-detect TCLP results for selenium, the substrate from future systems will likely be classified as non-hazardous waste and can therefore be disposed of in a municipal landfill. The Se-negative TCLP results occurred after only 1 year of operation which does not provide a conclusive indication of TCLP results from system which operates for the lifetime of the carbon substrate (approx. 10 to 20 years). However, given the trace concentrations of selenium in the influent water and the limestone content in the substrate, it is likely that 10 year old substrate would pass the TCLP test as well.

5.0 CONCLUSION

The results of this study demonstrate that passive bioreactors can accomplish up to 98% removal of selenium from surface and ground waters in the Grand Valley of western Colorado.

- All four bioreactors performed well with average post-startup effluent selenium concentrations ranging from 1.8 ug/L to 6.1 ug/L. The reactor 1 substrate mixture (30% sawdust, 10% hay, 30% wood chips, 20% limestone, 10% cow manure), which did not contain ZVI, had the lowest average effluent selenium concentration. This substrate mixture is recommended for future passive selenium treatment projects in western Colorado. This mixture is significantly less expensive than the ZVI mixtures due to the high cost of ZVI.
- The highest removal rates were achieved using a detention time of 12 hours, but circumstances prevented optimization of detention time.
- Based on the TCLP results, bioreactor substrate is a non-hazardous material and could be disposed of in a municipal landfill.

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TABLES

TABLE 1 - Bioreactor Components				
Component	Proportion of Each Component by Weight			
	Reactor 1	Reactor 2	Reactor 3	Reactor 4
Sawdust	30%	30%	20%	2.5%
Hay	10%	10%	10%	0%
Wood chips	30%	30%	20%	2.5%
Agricultural limestone	20%	5%	5%	5%
Zero valent iron	0%	15%	35%	85%
Cow manure	10%	10%	10%	5%

TABLE 2 - Selenium Removal in Bioreactors									
Sample Date	Influent	Reactor 1	Removal	Reactor 2	Removal	Reactor 3	Removal	Reactor 4	Removal
	ug/L	ug/L	%	ug/L	%	ug/L	%	ug/L	%
7/18/2006	20.6	9.6	53%	6.1	70%	5.8	72%	0.7	97%
7/25/2006	19.4	2.7	86%	1.5	92%	1.4	93%	0.9	95%
8/1/2006	27.7	7.9	71%	0.9	97%	0.9	97%	0.8	97%
8/8/2006	20.9	1.6	92%	1.0	95%	1.3	94%	1.1	95%
8/16/2006	24.1	1.4	94%	0.9	96%	1.5	94%	0.8	97%
8/24/2006	25.0	0.9	96%	0.9	96%	0.7	97%	0.4	98%
9/6/2006	27.2	0.8	97%	0.7	97%	0.7	97%	1.2	96%
9/13/2006	23.2	0.8	97%	0.7	97%	0.7	97%	1.3	94%
9/19/2006	24.8	0.9	96%	0.9	96%	0.6	98%	2.0	92%
10/11/2006	42.5	0.7	98%	8.4	80%	9.5	78%	6.2	85%
10/18/2006	68.6	4	94%	26.1	62%	30.6	55%	12.7	81%
11/21/2006	29.4	0.7	98%	11.2	62%	14.1	52%	--	--
3/30/2007	25	4.4	82%	3.8	85%	6.7	73%	--	--
5/10/2007	30.5	2.8	91%	2.9	90%	5.5	82%	--	--
7/16/2007	24.9	2.1	92%	1.5	94%	15.4	38%	--	--
8/27/2007	0.7	0.5	29%	42	-5900%	1.2	-71%	--	--
9/5/2007	26.4	1.8	93%	0.9	97%	1.6	94%	--	--
Average	28.8	2.7	89%	4.3	88%	6.1	82%	2.6	93%
Post Startup Average (8/16/06-9/5/07)	31.0	1.8	94%	4.9	88%	7.3	80%	3.5	92%

Note: Results from 8/27/07 are likely erroneous. It appears that the influent and reactor 2 samples were switched. Results from 8/27/07 were not included in the calculations.

TABLE 3 - Comparison of Total and Dissolved Selenium in Bioreactor Influent and Effluent Water					
Week and Date	----- Selenium Concentration (µg/L) -----				
	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4
10	24.8 total	0.9 total	0.9 total	0.6 total	2.0 total
9/19/2006	25.3 diss.	30.7 diss.	4.4 diss.	0.6 diss.	1.9 diss.
19	29.4 total	0.7 total	11.2 total	14.1 total	--
11/21/2006	28.7 diss.	3.6 diss.	10.4 diss.	12.1 diss.	--
37	25.0 total	4.4 total	3.8 total	6.7 total	--
3/30/2007	--	--	3.8 diss.	5.1 diss.	--
43	30.5 total	2.8 total	2.9 total	5.5 total	--
5/10/2007	27.5 diss.	1.8 diss.	2.5 diss.	5.8 diss.	--
53	24.9 total	2.1 total	1.5 total	15.4 total	--
7/16/2007	27.2 diss.	1.4 diss.	1.5 diss.	17.1 diss.	--
60	26.4 total	1.8 total	0.9 total	1.6 total	--
9/5/2007	26.4 diss.	20.7 diss.	0.7 diss.	1.1 diss.	--

Dissolved concentrations greater than total concentrations are highlighted in blue.

TABLE 4 - Comparison of Selenium Analyzed With and Without Sample Digestion (3/30/2007)				
Sample Preparation	- - - Selenium Concentration (µg/L) - - -			
	Influent	Reactor 1	Reactor 2	Reactor 3
Without digestion	21.9	2.8	3.5	6.5
With digestion	25.1	4.1	3.8	7

TABLE 5 - Field Parameters and Analytical Results

Week		0					1					2					3				
Parameter	Units	7/13/2006					7/18/2006					7/25/2006					8/1/2006				
		Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4
Ambient Temperature	deg. C	N/A	N/A	N/A	N/A	N/A	85.3	N/A	N/A	N/A	N/A	87	N/A	N/A	N/A	N/A	78.7	N/A	N/A	N/A	N/A
pH	std. un.	7.6	5.8	6.0	6.5	7.3	7.7	6.6	6.6	6.7	7.2	8.9	7.1	7.0	7.8	8.3	7.8	6.6	7.2	7.2	8.0
ORP	mV	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-50.1	-356.3	-195.9	-213.9	-253.1	-102	-366.1	-243.1	-270.1	-291.8
Conductivity	mS/cm	1.92	6.59	3.00	3.61	4.31	0.90	0.98	0.81	1.12	1.86	3.50	5.93	5.70	5.55	5.33	3.69	5.68	5.46	5.47	5.26
DO	mg/L	7.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Calcium	mg/L	N/A	N/A	N/A	N/A	N/A	180	234	156	161	148	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Iron	mg/L	N/A	N/A	N/A	N/A	N/A	0.4	1.5	95.8	115.0	13.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Manganese	mg/L	N/A	N/A	N/A	N/A	N/A	0.3	0.6	1.1	1.0	1.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sulfate	mg/L	N/A	N/A	N/A	N/A	N/A	1,116	1,042	1,024	1,008	1,145	1,132	1,806	1,626	1,356	2,180	1,239	2,011	1,861	1,910	2,200

N/A = Parameter was not tested for

Week		4					5					6					8				
Parameter	Units	8/8/2006					8/16/2006					8/24/2006					9/6/2006				
		Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4
Ambient Temperature	deg. C	76	N/A	N/A	N/A	N/A	75	N/A	N/A	N/A	N/A	78	N/A	N/A	N/A	N/A	72.7	N/A	N/A	N/A	N/A
pH	std. un.	8.0	6.6	7.9	7.8	8.4	8.2	6.5	7.9	7.8	8.6	7.8	6.9	8.1	7.9	8.8	7.9	6.9	8.0	7.9	8.6
ORP	mV	-21.7	-379.6	-315.8	-310.8	-289.7	-185.1	-371.2	-292.6	-307.6	-289.6	-154.8	-393.1	-311.3	-315.9	-277.7	-152.1	-373.7	-296.8	-288.6	-272.9
Conductivity	mS/cm	3.46	5.77	5.56	5.68	5.52	3.43	3.75	3.36	3.39	3.14	4.05	4.10	3.78	3.88	3.62	4.26	4.26	3.94	4.02	3.77
DO	mg/L	10.1	0.2	0.1	0.1	0.6	9.3	0.4	0.4	0.2	0.2	8.3	0.1	0.2	0.2	0.7	10.4	0.1	0.3	0.8	0.9
Calcium	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	183	185	131	143	85.7	N/A	N/A	N/A	N/A	N/A
Iron	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.2	0.1	4.5	9.2	5.4	N/A	N/A	N/A	N/A	N/A
Manganese	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.4	0.2	0.3	0.2	0.3	N/A	N/A	N/A	N/A	N/A
Sulfate	mg/L	1,162	1,674	1,779	2,012	2,293	1,105	596	940	968	1,063	1,218	873	912	972	1,098	1,407	1,193	1,073	1,094	1,164

N/A = Parameter was not tested for

Week		9					10					13					14				
Parameter	Units	9/13/2006					9/19/2006					10/11/2006					10/18/2006				
		Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4
Ambient Temperature	deg. C	69	N/A	N/A	N/A	N/A	52.3	N/A	N/A	N/A	N/A	52.7	N/A	N/A	N/A	N/A	46	N/A	N/A	N/A	N/A
pH	std. un.	7.7	7.1	8.0	8.0	8.5	7.9	7.2	8.0	8.2	8.3	7.6	7.4	7.7	7.9	8.3	7.6	7.5	7.5	7.7	7.8
ORP	mV	-150	-386.2	-295.6	-287.2	-289.5	79.5	-350.8	-320	-316.7	-280.4	6.1	-246.6	-254	-280.7	-216.6	143	-78.8	-197.5	-228.1	-238.2
Conductivity	mS/cm	4.23	4.31	4.05	4.08	3.88	4.39	4.34	4.10	4.08	3.92	5.12	4.50	4.24	4.29	4.18	5.76	5.50	5.26	5.32	5.06
DO	mg/L	8.6	0.1	0.5	0.6	1	7.7	1	0.7	0.9	0.8	9.6	0.7	0.5	0.5	0.9	7.9	1.7	0.8	0.8	0.7
Calcium	mg/L	N/A	N/A	N/A	N/A	N/A	207	206	153	172	107	N/A	N/A	N/A	N/A	N/A	305	309	232	239	N/A
Iron	mg/L	N/A	N/A	N/A	N/A	N/A	0.3	0.1	10.1	8.6	7.8	N/A	N/A	N/A	N/A	N/A	0.2	1.7	25.2	20.3	N/A
Manganese	mg/L	N/A	N/A	N/A	N/A	N/A	0.4	0.0	0.2	0.3	0.2	N/A	N/A	N/A	N/A	N/A	0.2	0.0	0.3	0.2	N/A
Sulfate	mg/L	1,208	1,050	1,036	1,069	1,100	1,295	1,185	1,134	1,211	1,253	1,607	1,228	1,247	1,230	1,225	1,980	1,830	1,681	1,607	1,598

N/A = Parameter was not tested for

Week		19					24					53					59				
Parameter	Units	11/21/2006					12/27/2006					7/16/2007					8/27/2007				
		Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Influent	Reactor 1	Reactor 2	Reactor 3	Reactor 4
Ambient Temperature	deg. C	41.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
pH	std. un.	7.7	7.7	8.1	8.2	N/A	N/A	N/A	N/A	N/A	N/A	7.69	7.31	7.84	8.05	N/A	7.61	7.28	8.05	8.47	N/A
ORP	mV	-75	-226	-251	-272	N/A	N/A	-320	-290	N/A	N/A	-29.9	-331.4	-299.6	-220.6	N/A	-22.4	-277.8	-139.8	-109.6	N/A
Conductivity	mS/cm	4.21	4.14	4.09	4.05	N/A	N/A	N/A	N/A	N/A	N/A	3.09	5.07	4.91	5	N/A	4.37	3.58	3.56	3.65	N/A
DO	mg/L	7	0.5	0.2	0.1	N/A	N/A	0.2	0.2	N/A	N/A	7.5	0.2	0.3	1.5	N/A	6.2	1.8	2.6	3.2	N/A
Calcium	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Iron	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.1	0.1	3.4	2.3	N/A
Manganese	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sulfate	mg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

N/A = Parameter was not tested for

FIGURES



Denver, Colorado

TITLE

Bioreactors at the Study Site

CLIENT/PROJECT

Grand Junction, CO

DRAWN

EPB

DATE

October-07

JOB NO.

063-2175

CHECKED

TLR

SCALE

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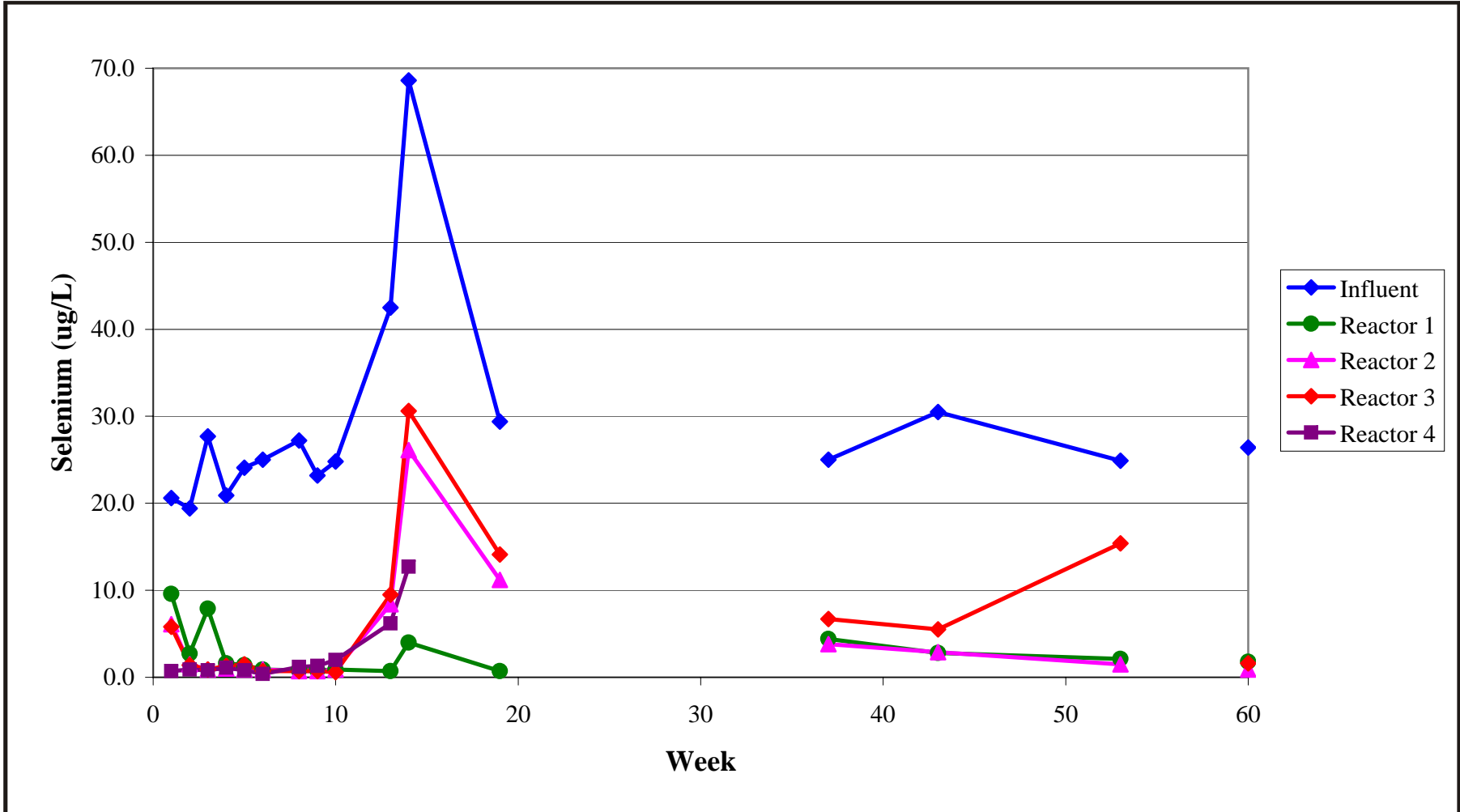
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JJG

FILE NO.

FIGURE NO.

1



Denver, Colorado

TITLE

Total Selenium in Influent Water and Reactor Effluent Waters

CLIENT/PROJECT

Grand Junction, CO

DRAWN

EPB

DATE

October-07

JOB NO.

063-2175

CHECKED

TLR

SCALE

NA

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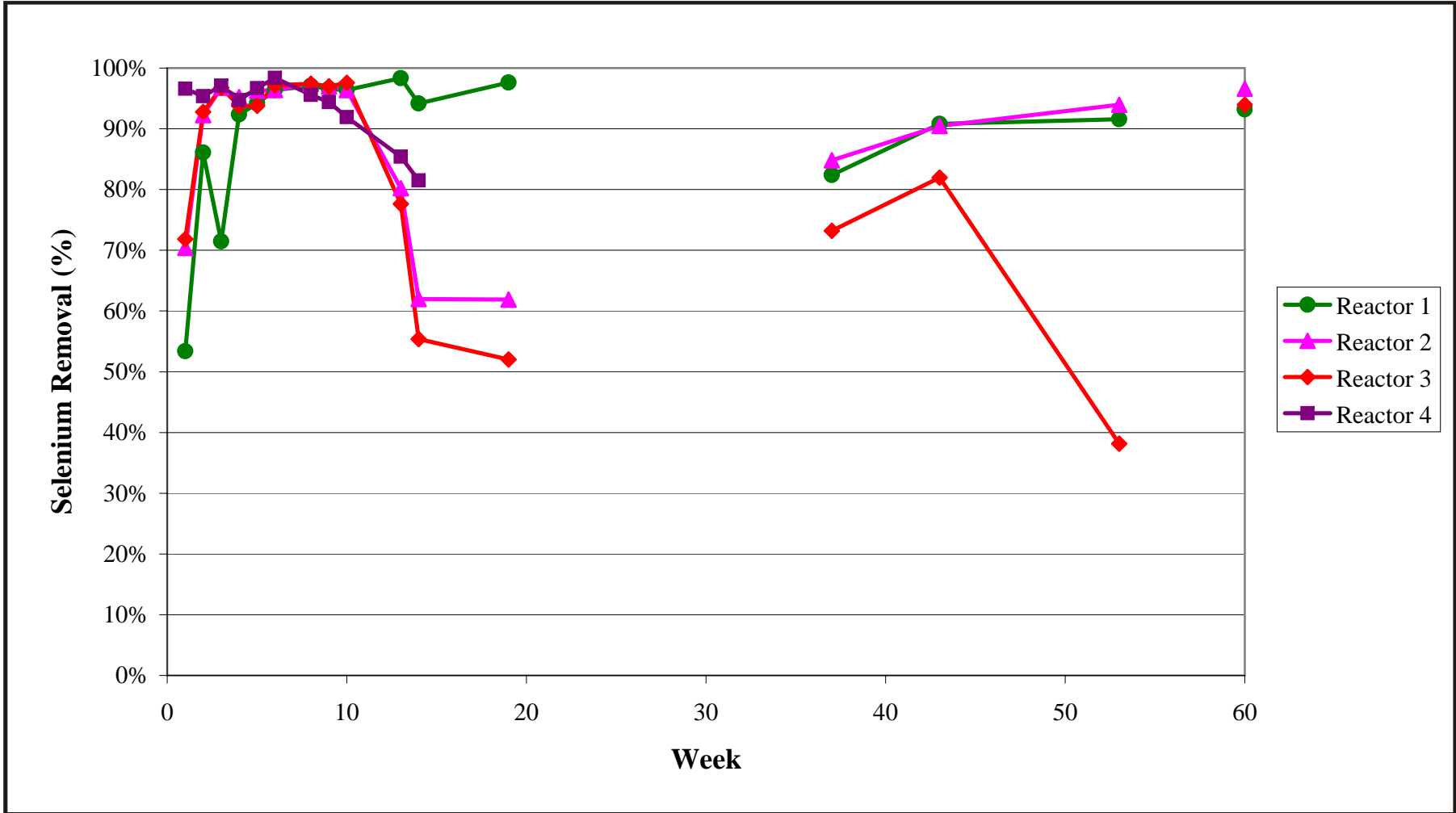
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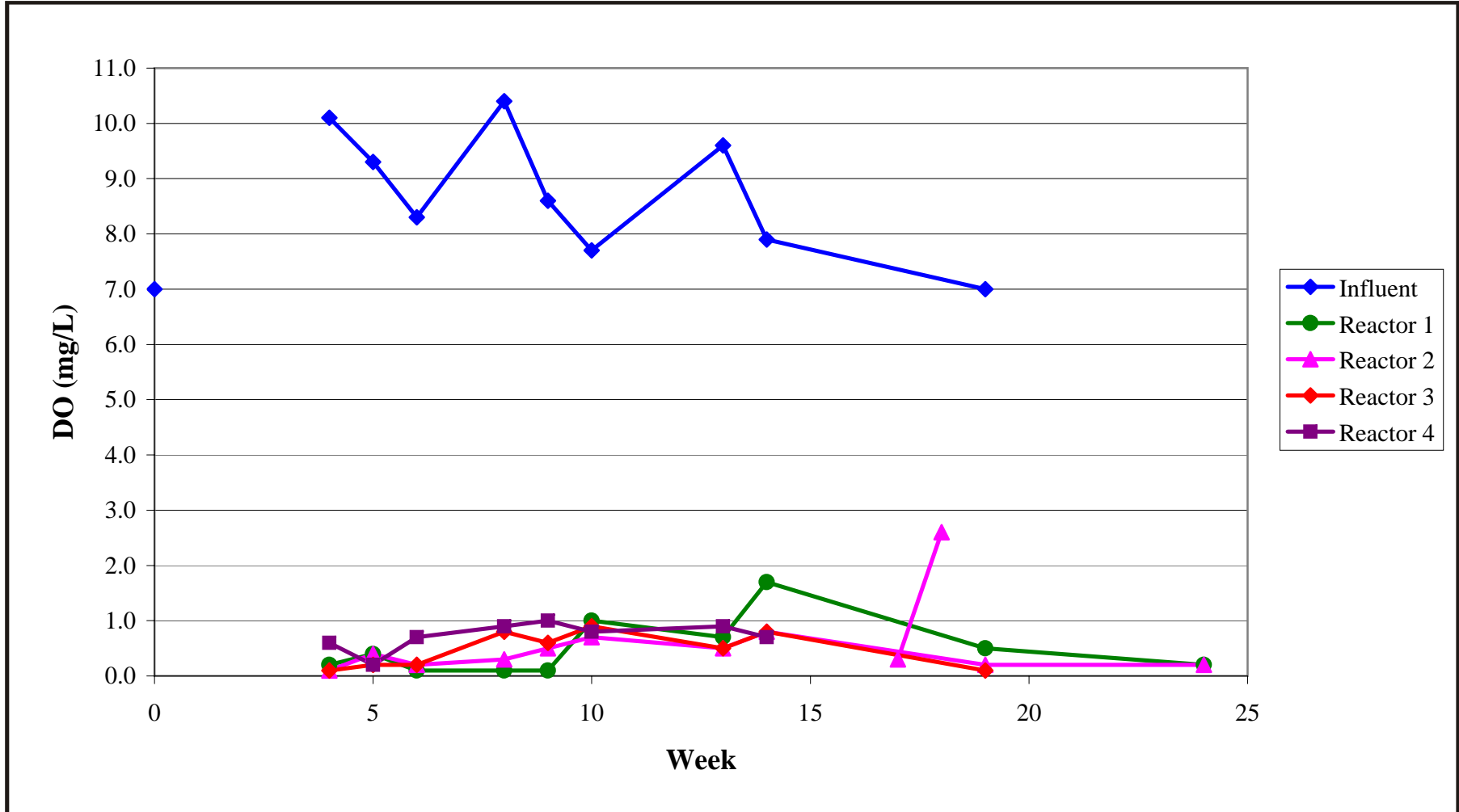
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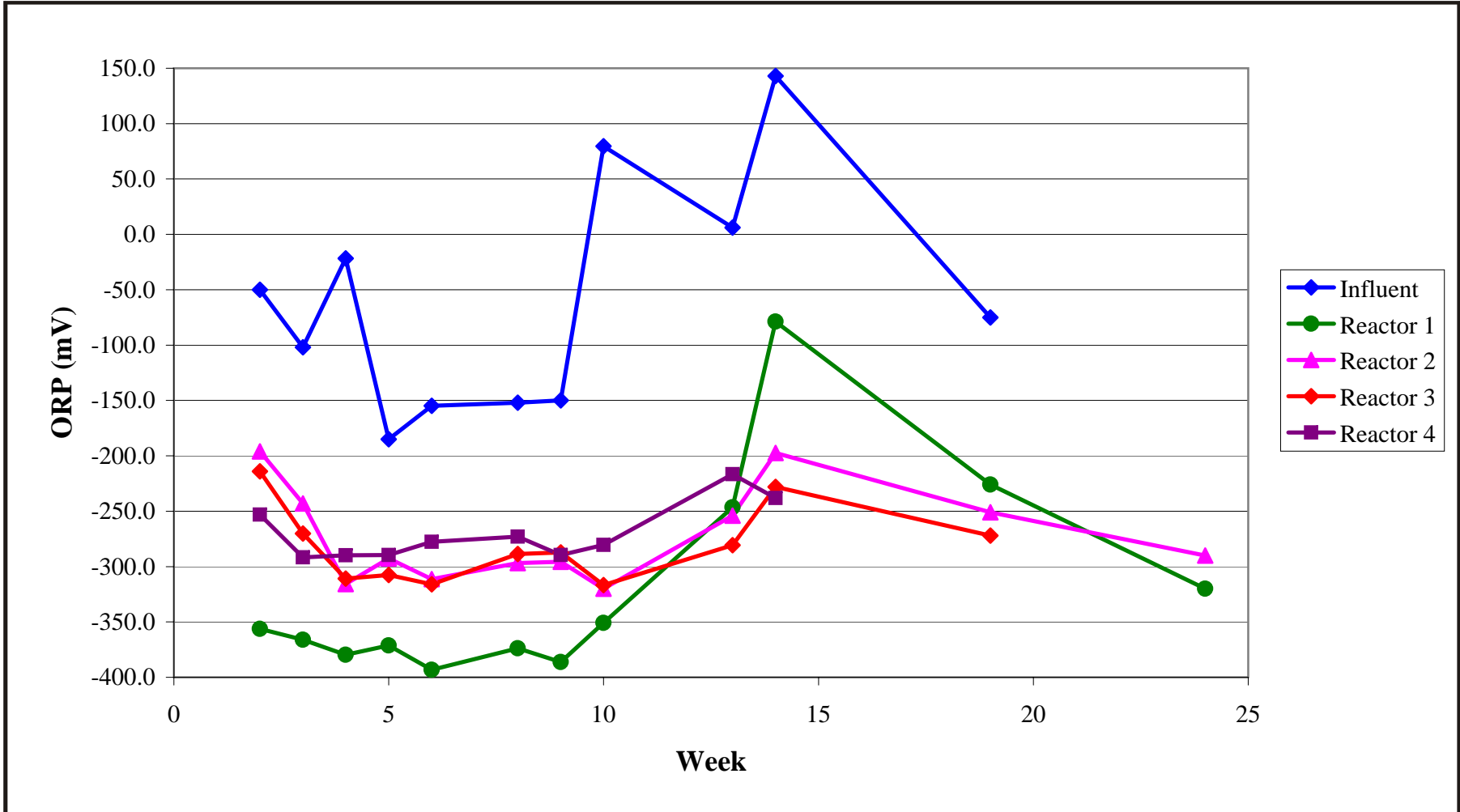
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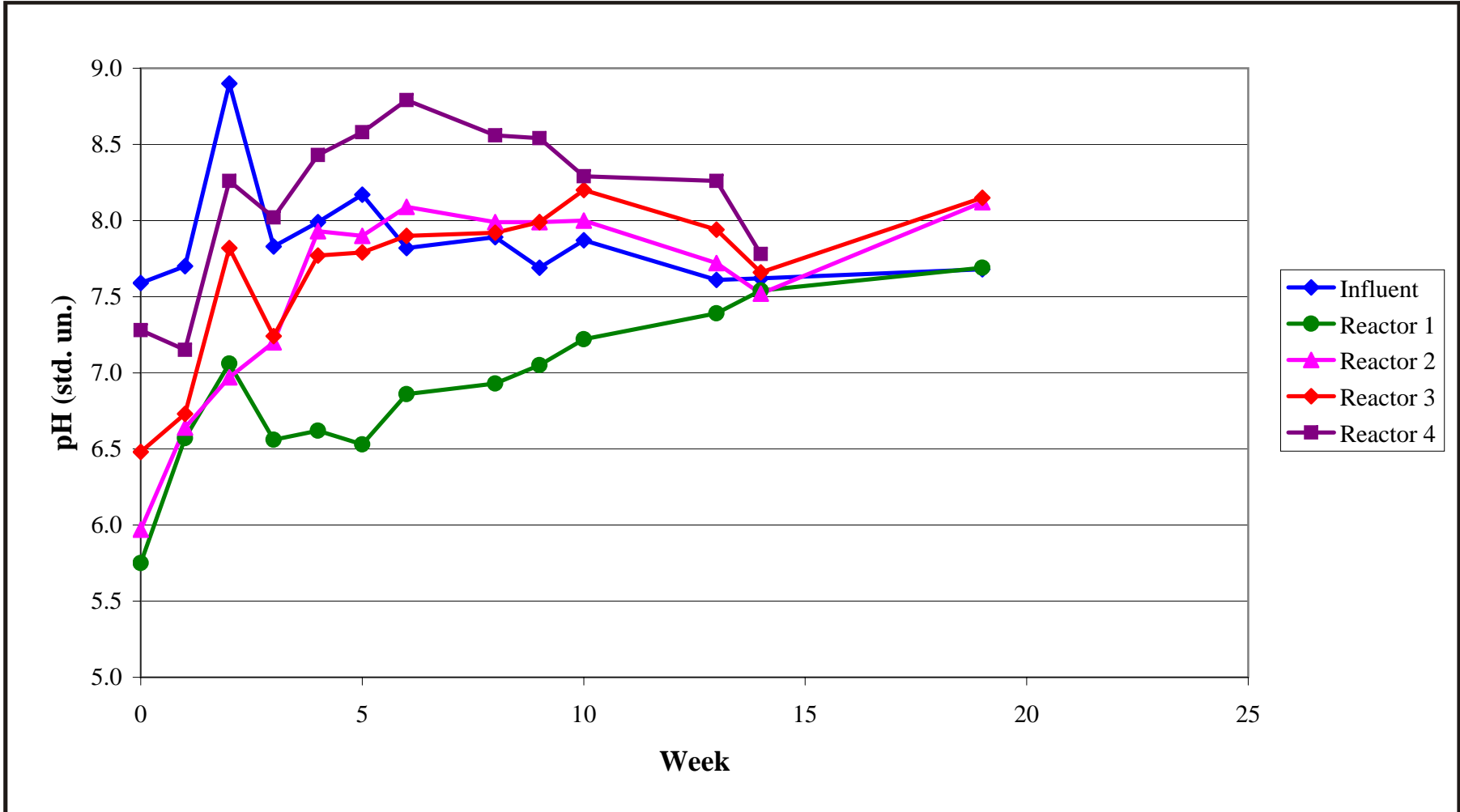
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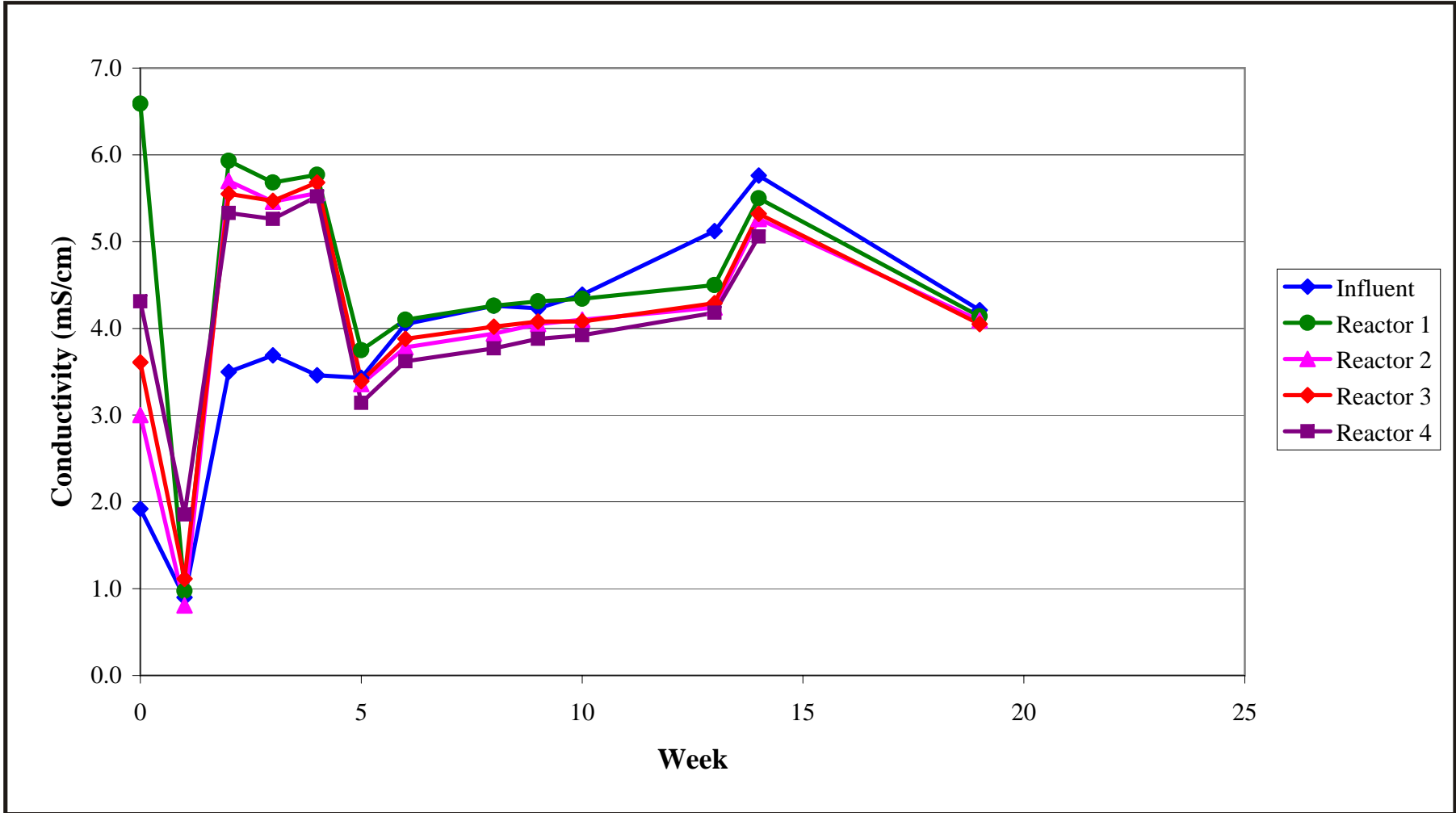
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CLIENT/PROJECT Grand Junction, CO	DRAWN	EPB	DATE	October-07	JOB NO.	063-2175
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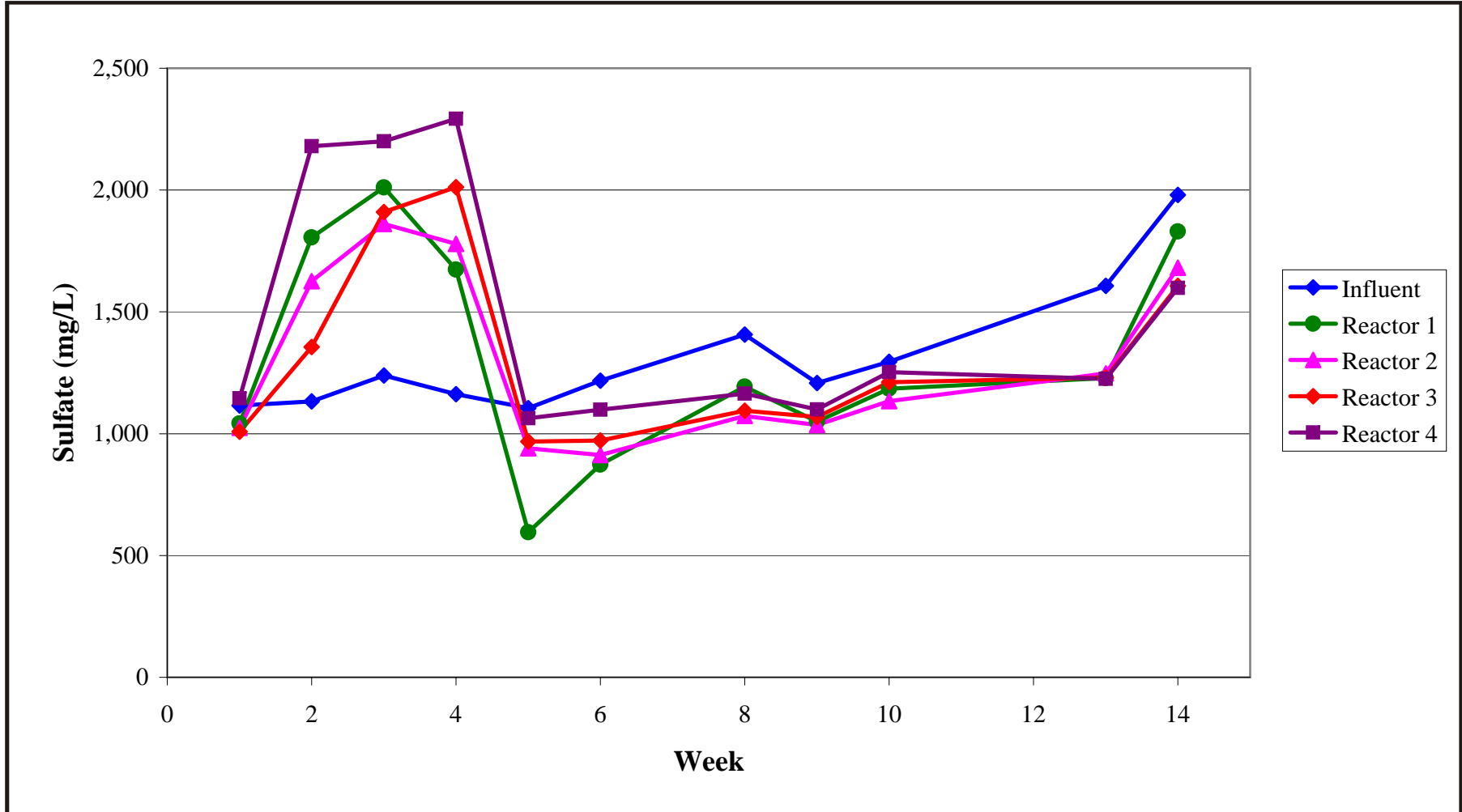
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	REVIEWED	JJG	FILE NO.		FIGURE NO.	5
Grand Junction, CO						




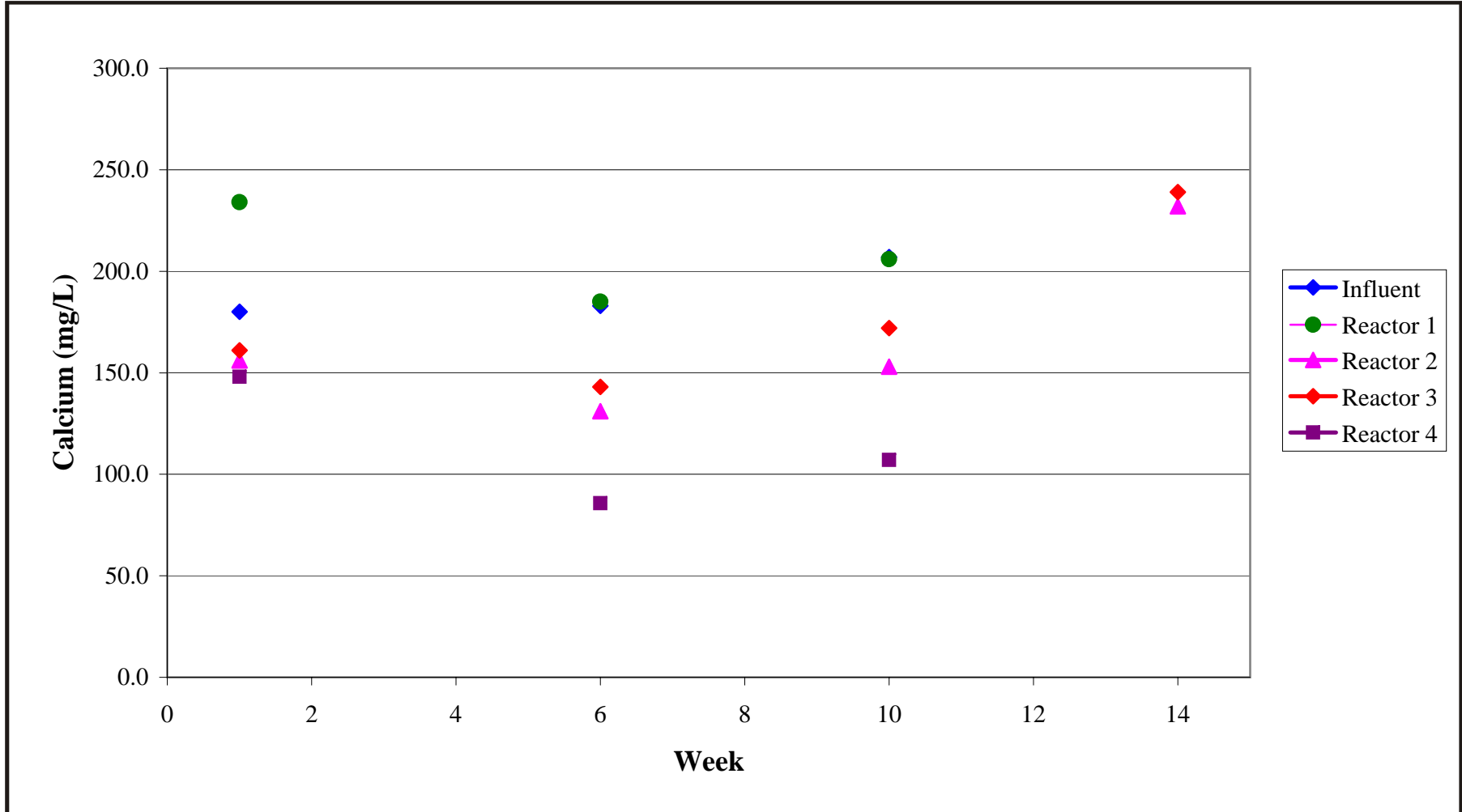
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CLIENT/PROJECT Grand Junction, CO	DRAWN	EPB	DATE	October-07	JOB NO.	063-2175
	CHECKED	TLR	SCALE	NA	DWG. NO.	
	REVIEWED	JJG	FILE NO.		FIGURE NO.	6



 Golder Associates Denver, Colorado	TITLE					
	Conductivity of Influent Water and Reactor Effluent Waters					
CLIENT/PROJECT Grand Junction, CO	DRAWN	EPB	DATE	October-07	JOB NO.	063-2175
	CHECKED	TLR	SCALE	NA	DWG. NO.	
	REVIEWED	JJG	FILE NO.		FIGURE NO.	7



 Golder Associates Denver, Colorado	TITLE					
	Sulfate in Influent Water and Reactor Effluent Waters					
CLIENT/PROJECT Grand Junction, CO	DRAWN	EPB	DATE	October-07	JOB NO.	063-2175
	CHECKED	TLR	SCALE	NA	DWG. NO.	
	REVIEWED	JJG	FILE NO.		FIGURE NO.	8



Denver, Colorado

TITLE

Calcium in Influent Water and Reactor Effluent Waters

CLIENT/PROJECT

Grand Junction, CO

DRAWN

EPB

DATE

October-07

JOB NO.

063-2175

CHECKED

TLR

SCALE

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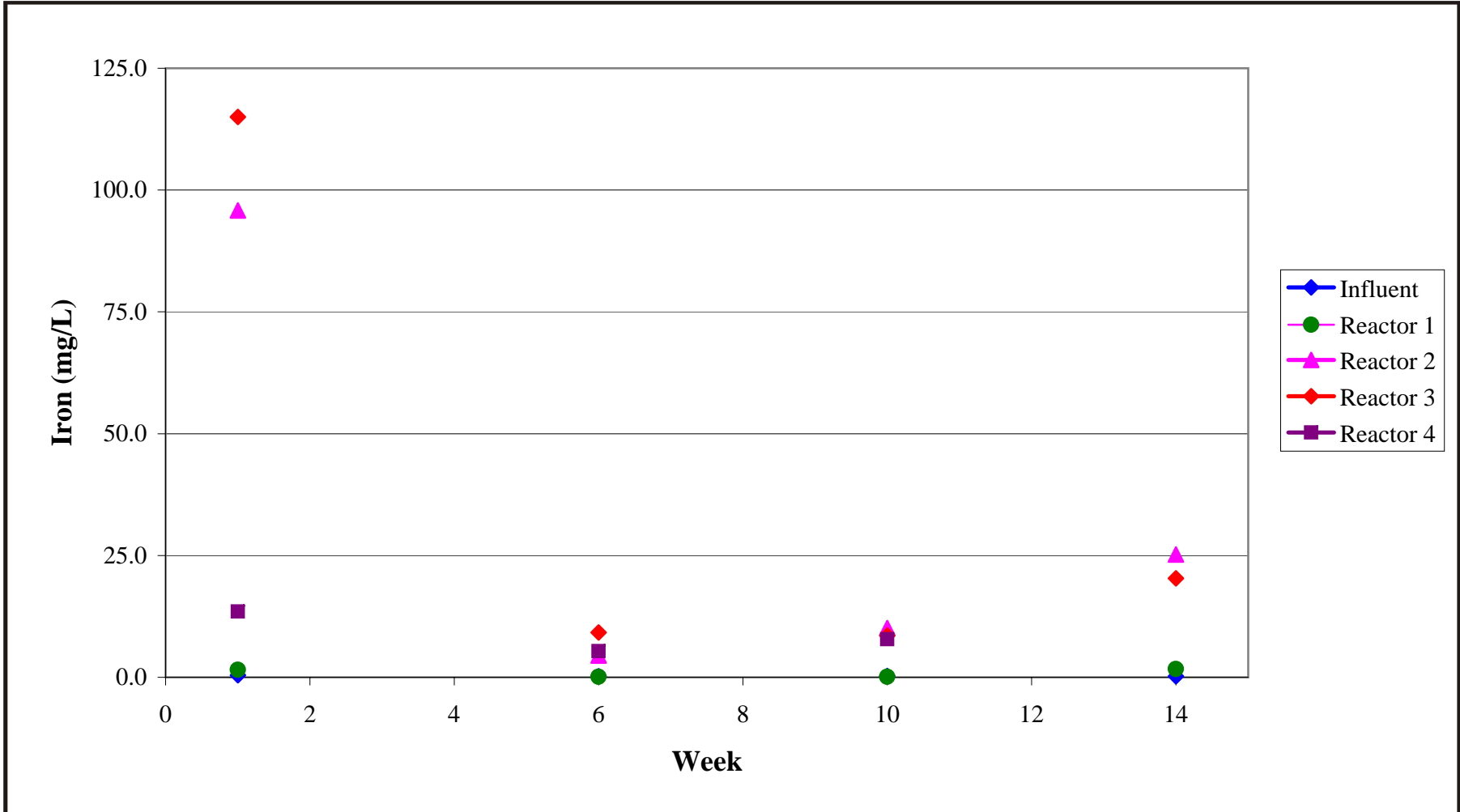
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JJG

FILE NO.

FIGURE NO.

9



 Golder Associates Denver, Colorado	TITLE					
	Iron in Influent Water and Reactor Effluent Waters					
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	CHECKED	TLR	SCALE	NA	DWG. NO.	
	REVIEWED	JJG	FILE NO.		FIGURE NO.	10

APPENDIX A

AQUEOUS ACZ LABORATORY RESULTS

APPENDIX B
TCLP ACZ LABORATORY RESULTS