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December 19, 2007
Project No. 8128.01.12

Mr. Dana Bayuk
Oregon Department of Environmental Quality
2020 SW 4th Avenue, Suite 400
Portland, Oregon 97201-4987

Re: Focused Feasibility Study Coordination
Siltronic Corporation Site (ECSI #183)
NW Natural Gasco Site (ECSI #84
Portland, OR

Dear Dana:

On behalf of Siltronic Corporation (Siltronic), Maul Foster & Alongi, Inc. (MFA) has prepared the following letter to facilitate coordinated implementation of source control measures for impacted soil and groundwater. On October 23, 2007, Siltronic submitted a Focused Feasibility Study (the Siltronic FFS) to the Oregon Department of Environmental Quality (DEQ) that recommended that enhanced *in-situ* bioremediation (EIB) for groundwater impacted by trichloroethene (TCE) and its degradation products be implemented in the source area and at the riverbank. The Siltronic FFS acknowledged potential sequencing issues with the source control measure recommended in the *Groundwater/DNAPL Source Control Focused Feasibility Study* (the NWN FFS) for the NW Natural (NWN) Gasco site, prepared by Anchor Environmental, LLC (Anchor).

Siltronic and its representatives met with DEQ regarding coordination and compatibility issues on December 10, 2007. During that meeting, DEQ concurred that the EIB pilot study successfully demonstrated that EIB is a viable technology for meeting source control objectives consistent with the Joint Source Control Strategy (JSCS). However, DEQ also identified potential implementation risks associated with EIB implementation at the riverbank, and directed Siltronic to evaluate containment (as opposed to treatment) options as part of its FFS.

The objective of this letter is to facilitate DEQ's review of the two parties' respective FFS reports. To that end, this letter provides:

1) Further evaluation of potential secondary downgradient impacts from implementation of EIB at the riverbank (implementation risk)

2) Further evaluation of groundwater extraction as a containment alternative for source control of TCE and its degradation products at the riverbank

3) General comments regarding the recommended alternative in the NWN FFS.

In short, downgradient impacts from implementation of EIB at the riverbank are not a significant implementation risk. EIB implementation is also not likely to pose an implementation risk or delay the schedule for the proposed NWN SCM. Further evaluation of the alternatives shows that groundwater extraction (as a containment alternative) scores lower than EIB at the riverbank, and would leave a significant portion of the aquifer impacted by TCE and its degradation products. Finally, with proper sequencing and relative location to EIB at the riverbank, the recommended alternative in the NWN FFS for the Siltronic property is compatible and can be successfully coordinated.

Siltronic supports NWN's recommended approach for that portion of its SCM to be implemented on Siltronic's property. We believe it is the best approach to avoid potentially catastrophic business impacts to Siltronic, since subsurface barrier technologies carry significant risk with only marginal gain in efficacy to justify implementation. Siltronic further believes that NWN's implementation schedule, if viewed realistically, allows ample time for Siltronic's riverbank EIB to address the TCE-related impacts beneath the river. There are clear limitations inherent in NWN's proposed approach, particularly when viewed as a long-term remedy, and we recommend further evaluation of the modeling assumptions on which it rests and a closer look at other treatment technologies for selection of such a long-term alternative.

Potential Secondary Downgradient Impacts of EIB

During the December 10, 2007 meeting, DEQ identified potential implementation risks that required further evaluation. Specifically, DEQ wondered whether increased concentrations of iron and other redox-sensitive metals in groundwater could potentially migrate downgradient and discharge to surface water in the Willamette River. MFA presented a summary of the data for iron, manganese, and arsenic at that meeting to demonstrate that the potential for mobilization of these metals is low. In fact, those data show that concentrations of these metals decreased to below background conditions during the pilot study.

MFA reviewed concentration data for the other metals in the monitoring program – cadmium, chromium, copper, lead, mercury, nickel, selenium, silver and zinc – which were previously included in the Pilot Study Report (MFA, August 9, 2007). For the most part, these metals were not detected in groundwater samples collected from within or downgradient of the PRB. Exceptions include zinc (decreasing trends were observed in both the PRB and riverbank well) and nickel (low concentrations in the PRB were

detected, but were not detected further downgradient at the riverbank). These additional data are consistent with the data presented at the meeting.

MFA has also reviewed additional technical information regarding the installation of zero-valent iron permeable reactive barriers (ZVI PRBs). As documented in a technical note (from Environmental Technologies, Inc.; Attachment 1), the Eh and pH (the primary controlling factors for metals dissolution and mobilization) are buffered by the aquifer within very short distances downgradient of the PRB. The following text is excerpted:

> Due to potential aesthetic impact on water quality, dissolved iron concentrations downgradient of iron PRBs are often of concern. Monitoring results from existing granular iron PRBs do not show elevated levels of dissolved iron in downgradient aquifers. In fact, monitoring data indicate that aquifer materials downgradient of iron zones have a buffering capacity causing a restoration of background geochemical conditions within a short distance of the PRB. Dissolved iron concentrations ranging from below detection limits to 0.2 mg/L were measured in a monitoring well located 5 ft downgradient of the iron zone at a site in New York, where the PRB treated 1 to 2 mg/L of VOCs (Vogan et al., 1999). A dissolved iron concentration of 0.6 mg/L was reported in a monitoring well located 5 ft downgradient of an iron PRB in Sunnyvale, CA (Warner et al., 1998). About 1 mg/L of total VOCs is treated in this system.
>
> At the three PRB installations, (the Denver Federal Center, the Elizabeth City and F.E. Warren AFB Spill Site 7) iron treatment zones are located within 120, 75 and 40 ft on average of surface water bodies, respectively (McMahon et al., 1999; Puls et al., 1996; Heneman et al., 2001). No elevated iron levels have been detected in downgradient aquifer monitoring wells and no aesthetic surface water problems have been reported at these sites. Recent data from a pilot-scale PRB at a site in Sydney, Australia where groundwater pH is buffered by organic acids at about pH 5 is also encouraging. Groundwater entering this PRB contains 100 to 150 mg/L of VOC, as well as 10 to 50 mg/L dissolved iron. Iron concentrations 1.5 m downgradient of the PRBs, for the most part, are below 5 mg/L.

It is important to note that these data are from sites where pure or mixed granular iron PRBs (i.e., with high concentrations of iron) have been installed. The material and placement for these walls is very different from the EIB PRB recommended for Siltronic, where the concentration of iron to be injected is much lower. ZVI PRBs have been installed throughout the world and approved by state and federal agencies in similar environments, without documentation of downgradient secondary impacts. Downgradient distribution of iron and other redox- and pH-sensitive metals is not a significant implementation risk.

NW Natural's concerns regarding potential iron fouling at its proposed extraction wells are also overstated.[1] Siltronic's FFS recommended installation of riverbank EIB downgradient of those proposed extraction wells. Upgradient increases in iron concentrations are not likely to be an issue. Based on the data from the sites in the Technical Note, an upgradient separation of approximately 10 to 20 feet should be adequate for buffering conditions to prevent iron migration to the extraction wells. Also, at elevations above the pump intake, the aquifer will presumably be dewatered, which would likely create oxidizing conditions lessening the potential for iron to impact the extraction wells.[2] Oxidized iron is relatively insoluble and will likely precipitate in the aquifer before it can reach the well screen.

DEQ also expressed concern about reduced permeability due to precipitation of metals (arsenic, sulfur, and manganese, in the form of pyrites) downgradient of the PRB. As proposed, EHC will be injected at a concentration corresponding to 1% of the soil mass within the PRB area. EHC is approximately 50% iron and 50% hydrophilic organic carbon material, so the amount of iron will be approximately 0.5% of the soil mass. The concentrations of arsenic, sulfur, and manganese are much lower than iron, but even if all of the iron injected turned into pyrite, it would only amount to a permeability reduction of about 0.5%. Reduced permeability due to precipitation is not a significant implementation risk.

Finally, DEQ suggested that Siltronic review metals concentrations in the framework of a Reasonable Potential Analysis (RPA), consistent with DEQ's NPDES regulations for point source discharge. While it is not clear that groundwater discharge to the Willamette River qualifies as a point discharge, MFA reviewed the RPA for Toxic Pollutants Internal Management Directive (IMD) (DEQ, 2005). Meeting the substantive requirements (with respect to characterizing the site and potential "effluent" of the plume) is not compatible with the proposed schedule in the Siltronic FFS, and may not be compatible with the JSCS schedule objectives.

Regardless, MFA calculated dilution factors using the methods in the RPA IMD, using the 7Q10 flow rate (approximately 6,300 cubic feet per second) and the maximum groundwater seepage rate (14 cm/day), as measured by the Lower Willamette Group (LWG). The seepage rate was applied across 2.5 acres, which is conservatively larger than Area 1, for a seepage flow of 0.579 cfs. Using these flow values and dilution equation in the RPA IMD, the dilution factor is approximately 11,000. Any increase in metals from the EIB PRB will, in addition to groundwater attenuation factors, be diluted by a factor of 11,000 upon discharge to the river. The calculated dilution factor is

[1] As stated in Anchor's December 7, 2007 letter to DEQ.
[2] These oxidizing conditions are likely to increase corrosion of a steel sheet pile wall as proposed for the NWN property, and regardless of PRB emplacement.

approximately 40% of the groundwater-surface water attenuation factor (approximately 26,000) calculated by MFA using the in-river data set of paired groundwater and surface water samples.

It is understood that additional analysis of the existing data set may be required to allay DEQ's conceptual concerns regarding theoretical secondary downgradient impacts. In fact, the EIB PRB effectively reduced downgradient concentrations of arsenic and manganese. Zero-valent iron walls are a proven technology, and have been demonstrated throughout the world without attendant downgradient impacts such as those suggested by DEQ. The implementation risk for Alternative 3A is low, and does not require adjustment.[3]

Further Evaluation of Containment Alternative

The Siltronic FFS was prepared consistent with the FFS work plan and DEQ's subsequent directions. DEQ suggested that the Siltronic FFS evaluate containment alternatives. MFA previously submitted the *Draft Source Control Evaluation Work Plan* in January, 2006. Appendix B of the work plan included a detailed screening of potential source control measures, including groundwater extraction and sheet pile wall as containment measures. The screening was completed consistent with DEQ EE/CA guidance, and consistent with the JSCS.

The sheet pile wall alternative was eliminated from consideration for lack of effectiveness due to the depth of the TCE-related impacts. Well-founded concerns about vibration-related impacts suggest that the implementation risk associated with sheet pile wall, or other barriers, is not consistent with Siltronic's business operations. Groundwater extraction was retained and compared to thermal remediation, groundwater circulation wells, chemical oxidation, and bioremediation, but only bioremediation was considered for bench testing, with DEQ's approval.

At DEQ's request, Table 3.1 (Revised Comparison of Alternatives, attached) of the Siltronic FFS has been updated to include groundwater extraction at the riverbank, both with and without source area treatment (Alternatives 5 and 6, respectively). Alternative 6 was included for two reasons. First, monitoring data from the source area indicate that additional treatment may not be required – that is, the pilot study work may represent a sufficient interim remedial action. Second, the effectiveness of groundwater extraction (with respect to meeting the containment goal) will not be improved by source area treatment, which calls into question the need for source area treatment. The revised evaluation of the new and existing alternatives (using the criteria in the FFS:

[3] As discussed in the following section, reduction of the implementation risk score (i.e., increased potential implementation risk) does not change the order of the ranking – Alternative 3A still scores highest.

effectiveness, long-term reliability, implementability, implementation risk, and reasonableness of cost) will be submitted to DEQ under separate cover.

As summarized on Table 3.1, Alternatives 5 and 6 are scored lower than the recommended Alternative 3A. When cost is considered, Alternative 6 scores higher than Alternative 5. Groundwater extraction at the riverbank scored low for effectiveness and long-term reliability because it only meets some requirements with respect to containing or treating the entire plume of TCE and its degradation products.

Alternative 3A remains the highest ranked alternative. The implementation risk (i.e., DEQ's concerns regarding downgradient distribution of metals) was not initially considered in the ranking for Alternative 3A in Table 3.1, but was considered for Alternatives 4A and 4B (EIB implementation at the toe of the slope), due to the potential for daylighting of amendments during injection. The implementation risk for Alternative 4A and B was given a score of 1.0; therefore, the increased distance from the river for Alternative 3A would at most reduce the implementation risk score from 3.0 to 2.0. Even if the implementation risk for Alternative 3A is lowered to 2.0 to account for theoretical concerns about downgradient metals distribution, Alternative 3A would still score higher than the remaining alternatives.

Based on the additional analysis provided herein, Siltronic's recommended alternative represents a proven technology that provides treatment as opposed to containment, with low implementation risk, while maximizing environmental gains. The approach recommended in the Siltronic FFS is an opportunity for DEQ, EPA and the Portland Harbor stakeholders to demonstrate a comprehensive, proactive approach to source control and site restoration that combines upland source control with in-river remediation.

General Comments on NW Natural's FFS

EIB is the most advantageous source control method for groundwater impacted by trichloroethene (TCE) and its degradation products. As discussed in the cover letter for the Siltronic FFS, a properly sequenced, coordinated approach consistent with Siltronic's recommended alternative can occur with minimal impact to the combined schedule for both NWN's and Siltronic's SCMs. The recommended alternative (groundwater extraction with a partial-length sheet pile wall) in the NWN FFS does not change this conclusion.

Based on the information included in the NWN FFS, it appears that the recommended alternative will be effective for containing upland groundwater and MGP DNAPL impacts near the riverbank. Significant transition zone water (TZW) and in-river sediment impacts are located downgradient of the proposed sheet pile wall and/or extraction wells, and may not be captured by the groundwater extraction system. It does

not appear that the recommended alternative will significantly reduce the MGP-related impacts already present in the Willamette River.

The stated primary goal of the action is to minimize or eliminate groundwater discharge to the river, which is consistent with the goals of the Joint Source Control Strategy (JSCS; DEQ and USEPA, 2005). However, the only proposed quantitative performance monitoring is measurement of groundwater elevations at selected wells in the upland portion of the site. The NWN FFS does not include an approach for directly determining if the recommended alternative is successful at achieving the primary goal.

The NWN FFS recommends installation of a subsurface barrier only on the NWN property, approximately 150 feet from the Fab 1 building. If approved, this orientation may mitigate some of the concerns communicated to DEQ and NWN in our letter dated August 30, 2007. However, the need for the vibration study currently in development by Siltronic and NWN is unchanged.

The NWN FFS recommends implementation of hydraulic containment via groundwater extraction for the portion of riverbank in front of Siltronic's Fab 1 building. The capture zones for the extraction system appear to intersect the plume of groundwater impacts from the former Rhone-Poulenc (RPAC) facility located south of Siltronic. The RPAC groundwater constituents of interest (COIs) include dioxins and furans. If selected, the proposed treatment system design may require redesign in order to treat dioxins and furans.

The NWN FFS acknowledges that the interim SCMs are intended to be components of the final remedy for the site. If selected, the groundwater extraction system will likely be a permanent fixture on Siltronic's property, unless it is later found to be ineffective. Accordingly, the decision to implement groundwater extraction requires careful consideration and design, which may not fit within the proposed schedule or be fully compatible with the interim nature of a source control program. Siltronic recommends a phased approach, with implementation on the Siltronic property contingent upon demonstrated effectiveness on the NWN property.

Anchor distributed comments regarding potential compatibility issues on December 13, 2007, noting that implementation of EIB at the riverbank could delay implementation of NWN's recommended alternative. The NWN FFS also identifies other scenarios that could negatively impact the schedule, some of which are similarly likely.

As discussed at the December 10, 2007, meeting and as stated in the Siltronic FFS, the net effect of failure to implement EIB at the riverbank will likely be that natural attenuation is the only feasible alternative for the TCE-related groundwater impacts under the Willamette River. Although natural attenuation of the TCE plume, which has been

well documented in the upland and in-river, will eventually remediate TCE-related impacts that will not be addressed by containment technologies at the riverbank, the time to achieve cleanup levels will be significantly longer than with riverbank EIB.

Please call either of us at (971) 544-2139 if you have questions or comments.

Sincerely,

Maul Foster & Alongi, Inc.

James G.D. Peale, R.G.
Senior Hydrogeologist

James J. Maul, R.G.
Principal Hydrogeologist

Attachments ETI Technical Note 4.02
Table 3.1 – Revised Alternatives Analysis

cc: Matt McClincy, DEQ
James Anderson, DEQ
Tom Gainer, DEQ
Dan Hafley, DEQ
Henning Larsen, DEQ
Tom McCue, Siltronic
Chris Reive, Jordan Schrader Ramis
Alan Gladstone and William Earle, Davis Rothwell Earle & Xochihua, P.C.
Bob Wyatt, NW Natural
Patricia Dost, Schwabe Williamson & Wyatt, P.C.
John Edwards, Anchor Environmental, LLC

enviro**metal**
technologies
inc.

Technical Note 4.02

2007

Groundwater Geochemistry Downgradient of Iron Permeable Reactive Barriers

When granular iron is exposed to groundwater containing dissolved VOCs, several reactions occur, dominated by iron corrosion by water which produces hydrogen and hydroxide ions.

$$Fe^{\circ} + 2H_2O \rightarrow Fe^{2+} + H_{2(aq)} + 2OH^- \quad (1)$$

In most site waters, this reaction causes the pH to increase to about 9 to 10 and the redox potential (Eh) decline to below –200 mV. As pH increases, iron hydroxide ($Fe(OH)_2$) precipitates form in the reactive zone (Odziemkowski et al., 1998). From laboratory and field evidence, the majority if not all the Fe^{2+} will be removed from solution as these precipitates form within the iron zone. In addition, bicarbonate (HCO_3^-) in solution converts to carbonate (CO_3^{2-}) to further buffer this pH increase in the iron zone:

$$HCO_3^- \rightarrow CO_3^{2-} + H^+ \quad (2)$$

At some sites, the carbonate ion may also combine with Fe^{2+} in solution to form siderite ($FeCO_3$).

$$Fe^{2+} + CO_3^{2-} \rightarrow FeCO_{3(s)} \quad (3)$$

The carbonate combines with other cations (Ca^{2+}, Mg^{2+}, etc.) in solution to form other mineral precipitates.

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3(s)} \quad (4)$$

$$Mg^{2+} + CO_3^{2-} \rightarrow MgCO_{3(s)} \quad (5)$$

Sulphate is also commonly removed in the field iron treatment zone.

The potential impact of these precipitates is discussed in ETI technical note (TN) 4.03. The purpose of this memorandum is to discuss the geochemical evolution of groundwater leaving the PRB and moving downgradient into the aquifer system.

From the above reactions, interactions with granular iron in the treatment zone cause groundwater leaving the PRB to have increased pH, decreased Eh, and low inorganic carbon (alkalinity), calcium, magnesium and sulphate concentrations. Similar to other subsurface water systems, the composition of groundwater exiting of the iron zone is influenced by acid-base reactions, mineral dissolution/precipitation, reduction/oxidation reactions and mixing with water unaffected by the iron zone.

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Weak acid-base reactions that originate mainly from gas and mineral dissolution occur as the groundwater leaves the iron zone, enters the surrounding aquifer and equilibrates with the gas and solid phase. As a result of CO_2 dissolution, carbonic acid (H_2CO_3) is formed and its subsequent dissociation lowers the pH of the iron-treated water. Another important weak acid, silicic acid (H_2SiO_3) originates from dissolution of silicate minerals and can also affect water chemistry. The desorption of H^+ from mineral surfaces also causes a decline in pH downgradient of the barrier (Blowes et al, 1999).

As the low Eh iron treated water moves into the aquifer, different redox couples, for example oxygen/water, or sulphate/sulphide, determine the redox potential. In shallow aquifers, dissolution of oxygen and/or dissolution of oxide minerals (Blowes et al., 1999) cause a shift in Eh into the oxidized range under redox equilibrium.

Dissolution/precipitation processes as groundwater proceeds towards chemical equilibrium with respect to various minerals in the aquifer sediments also affect the aqueous carbonate content and other major ion chemistry that compose the aquifer. Low ionic strength and high pH (as observed in the iron-treated water) are conducive especially to the dissolution of silicates and alumino-silicate minerals (Morel and Herring, 1993). The main effect of mineral dissolution is increased alkalinity and some pH buffering.

To show practical effects on water geochemistry, an equilibrium-based geochemical model PHREEQC was used to simulate in water pH, Eh and alkalinity under the above processes, starting with typical composition of groundwater treated with granular iron (Figure 1). The trends were obtained by a sequential equilibration of the iron-treated groundwater with incrementally increasing amounts of dissolving gases and minerals.

Geochemical modeling based on thermodynamic equilibrium is useful in providing insights to general paths of change in the groundwater inorganic chemistry. However, since the natural systems are rarely in equilibrium, the temporal and spatial trends of chemical indicators cannot be determined using this approach. On the other hand, rates of mass transfer are difficult to discern in field conditions due to complexity of the processes and system heterogeneity. For example, CO_2 replenishment in the iron-treated water will probably occur in three ways: CO_2 gas diffusion from the unsaturated zone, mixing of aqueous CO_2 from the formation and recharge water and microbiological production of CO_2 due to oxidation of dissolved hydrocarbons formed during VOC degradation in the iron zone (Warner et al., 1998). The contribution of each of these processes will vary with depth, travel distance, initial groundwater composition and aquifer conditions.

Monitoring results from existing iron permeable reactive barriers indicate that the Eh and pH iron treated groundwater are buffered by the aquifer within a short distance downgradient at most sites (O'Hannesin and Gillham, 1998; Vogan et al., 1999, Warner et al., 1998; Gallant, 1997; Blowes et al, 1999). In downgradient wells usually located within 5 to 10 ft of the iron zone, pH values rebound close to the upgradient levels, alkalinity increases and Eh shifts to the natural aquifer conditions. Major ion chemistry may take a longer travel distance to reach background levels. Over time (10, 20 or 30 years) the "halo" of low Eh, high pH groundwater will move slowly downgradient as the buffering capacity of the aquifer is exhausted, but this should not pose any concern in most aquifer environments.

Due to potential aesthetic impact on water quality, dissolved iron concentrations downgradient of iron PRBs are often of concern. Monitoring results from existing granular iron PRBs do not show elevated levels of dissolved iron in downgradient aquifers. In fact, monitoring data indicate that aquifer materials downgradient of iron zones have a buffering capacity causing a restoration of background geochemical conditions within a short distance of the PRB. Dissolved iron concentrations ranging from below detection limits to 0.2 mg/L were measured in a monitoring well located 5 ft downgradient of the iron zone at a site in New York, where the PRB treated 1 to 2 mg/L of VOCs (Vogan et al., 1999). A dissolved iron concentration of 0.6 mg/L was reported in a monitoring well located 5 ft downgradient of an iron PRB in Sunnyvale, CA (Warner et al., 1998). About 1 mg/L of total VOCs is treated in this system.

At the three PRB installations, (the Denver Federal Center, the Elizabeth City and F.E. Warren AFB Spill Site 7) iron treatment zones are located within 120, 75 and 40 ft on average of surface water bodies, respectively (McMahon et al., 1999; Puls et al., 1996; Heneman et al., 2001). No elevated iron levels have been detected in downgradient aquifer monitoring wells and no aesthetic surface water problems have been reported at these sites. Recent data from a pilot-scale PRB at a site in Sydney, Australia where groundwater pH is buffered by organic acids at about pH 5 is also encouraging. Groundwater entering this PRB contains 100 to 150 mg/L of VOC, as well as 10 to 50 mg/L dissolved iron. Iron concentrations 1.5 m downgradient of the PRBs, for the most part, are below 5 mg/L.

References

Blowes, D.W., Puls, R.W., Gillham, R.W., Ptacek, C.J., 1999. An In-situ permeable reactive barrier for treatment of hexavalent chromium and trichloroethene in groundwater. EPA 600/R-99/095c. Vol. 3.

Gallant, W.A., 1997. Zero valence metal reactive wall demonstration project results and lesson learned. Presented at the HazWasteWorld, Superfund XVIII Conference, Washington, D.C., Dec 2-4.

Heneman, F.C., May, M.R., Powers, B.G. and Perez E.J., 2001. The End of Trilogy: The F.E. Warren AFB Spill Site 7 iron-filings permeable reactive barrier is working. Published in the National Defense Industrial Association 27th Environmental Symposium and Exhibition Proceedings, 2001, Austin, TX, pp. 1-6.

McMahon, P. B., Dennehy K. F. and Sandstrom M. W., 1999. Hydraulic geochemical performance of a permeable reactive barrier containing zero-valent iron, Denver Federal Center. Ground Water. 37(3): 396-404.

Morel, F.M.M. and Herring, J.G., 1993. Principles and applications of aquatic chemistry. John Willey & Sons, New York, pp. 588.

Odziemkowski, M.S., Schuhmacher, T.T., Gillham, R.W. and Reardon E.J., 1998. Mechanism of Oxide Film Formation on Iron in Simulating Groundwater Solutions: Raman Spectral Studies. Corrosion Studies, Vol. 40, No. 2/3, pp. 371-389.

O'Hannesin, S.F., and Gillham, R.W., 1998. Long-term performance of an in-situ "iron wall" for remediation of VOCs. Ground Water, Vol. 36, No. 1, pp. 164-170.

Parkhurst, D.L. and Appelo, C.A.J., 1999. User's Guide to PHRREQC (Version 2) – A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Water-Resources Investigations Report 99-4259. USGS, Denver, CO.

Puls, R.W., Paul C.J. and Powell R.M., 1996. Remediation of chromate-contaminated groundwater using zero-valent iron: Field test at USCG Support Center, Elizabeth City, North Carolina. U.S. Environmental Protection Agency. EPA/600/A-96/07.

Vogan, J.L., Focht, R.M., Clark, D.K. and Graham, S.L., 1999. Performance evaluation of a permeable reactive barrier for remediation of dissolved chlorinated solvents in groundwater. J. Hazard. Mater., Vol. 68, pp. 97-108.

Warner, S. D., Yamane C. L, Bice N. T., Szerdy, F. S., Vogan, J. Major D. W. and Hankins D. A., 1998. Technical update: The first commercial subsurface permeable reactive treatment zone composed of granular zero-valent iron. Designing and Applying Treatment Technologies: Proceedings of the First International Conference on Remediation of Chlorinated and Recalcitrant Compounds, 18-21 May 1998, Monterey, CA, Wickramanayake, G. B., and R. E. Hinchee (Eds.), Battelle Press, Columbus, OH. 1(6) 145-150.

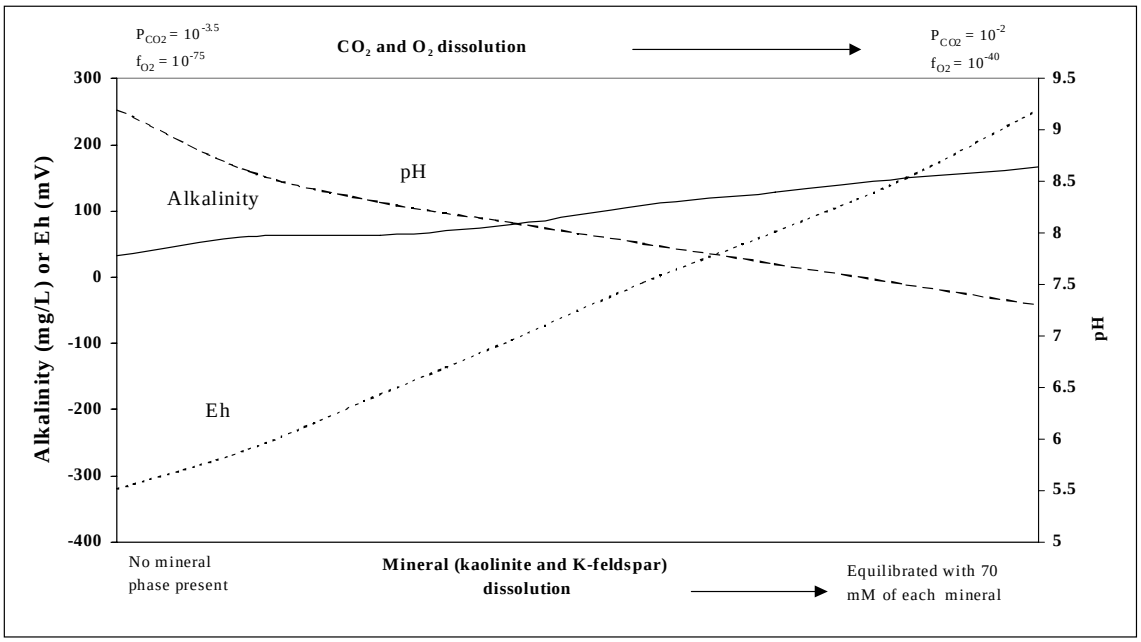

Figure 1. Conceptual illustration of geochemical changes in water treated in an iron PRB as it moves through a shallow aquifer dominated by alumino-silicate minerals. Based on equilibrium modeling using PHREEQC

Table 3-1
Revised Alternatives Analysis
Siltronic Corporation
Portland, Oregon

Alternative		Effectiveness	Long-Term Reliability	Implementability	Implementation Risk	Non-Fiscal Balancing Factors		Cost		All Categories	
						Subtotal	Average	Estimated Cost ($ Million)	Reasonable-ness of Cost	Total	Total Average
Alternative 1: No action		0.0	0.0	3.5	4.0	7.5	1.88	0	0.0	8	1.5
Alternative 2: Source Area Treatment	2A	2.0	3.0	3.0	3.0	11.0	2.75	$5.8M	4.0	15	3.0
	2B	2.0	2.0	3.0	3.0	10.0	2.50	$5.8M	4.0	14	2.8
Alternative 3: Source Area Treatment and Downgradient PRB at Top of Slope	3A[c]	4.0	4.0	3.0	3.0	14.0	3.50	$9.4M	3.0	17	**3.4**
	3B	2.0	1.0	3.0	3.0	9.0	2.25	$9.4M	3.0	12	2.4
Alternative 4: Source Area Treatment and Downgradient PRB at Toe of Slope	4A	4.0	4.0	2.0	1.0	11.0	2.75	$12.8M	2.0	13	2.6
	4B	2.5	1.5	2.0	1.0	7.0	1.75	$12.8M	2.0	9	1.8
Alternative 5: Source Area Treatment and Groundwater Extraction at Riverbank		2.0	2.0	3.0	2.0	9.0	2.25	$15.3M[b]	1.0	10	2.0
Alternative 6: Groundwater Extraction at Riverbank Only		1.0	2.0	3.0	2.0	8.0	2.00	$9.5M[b]	3.5	12	2.3

Alternatives:
2A: No NWN SCM
2B: NWN SCM is installed
3A: No NWN SCM or NWN SCM properly sequenced with EIB - highest ranking alternative
3B: NWN SCM is installed on current DEQ schedule
4A: No NWN SCM or NWN SCM properly sequenced with EIB
4B: NWN SCM is installed on current DEQ schedule
5: Groundwater Extraction at Riverbank by Siltronic (30 yr NPV)
6: Groundwater Extraction at Riverbank by Siltronic, with no source area remedy

Scoring:
0 = To no extent meets criterion
1 = Meets few requirements
2 = Meets some requirements
3 = Meets most requirements
4 = Completely meets criterion

Note:
a Except for Alternatives 5 and 6, estimated cost does not include the cost of the NWN SCM.
b For Alternatives 5 and 6, estimated costs are for implementation by Siltronic, and assume no work by NWN.
c When the implementation risk for this alternative is adjusted (to 2.0) to reflect potential downgradient impacts,

the non-fiscal score is reduced to 3.25, and the total average is reduced to 3.2.