Design, Construction and Installation Verification of a 1200' Long Iron Permeable Reactive Barrier

by

Grant Hocking and Samuel L. Wells
GeoSierra LLC
Atlanta, GA

ABSTRACT: Zero valent iron reactive permeable barriers remediate chlorinated solvent contaminated groundwater by abiotic degradation of the halogenated volatile organic compounds into harmless daughter products. This paper presents the design, construction and field verification tests of a full scale azimuth controlled vertical hydraulic fracture placed iron permeable reactive barrier in silt and sand sequences installed at a Superfund site in Virginia. Pre construction monitoring indicated that the site groundwater was contaminated with chlorinated solvents in the range of thousands of ppb of tetrachloroethene (PCE) and trichloroethene (TCE). The iron permeable reactive barrier (PRB) extends approximately 1,200' in length and was constructed from a depth of 5' down to a total depth of 44'. The iron filings were transported into the ground in a cross linked gel, and the azimuth controlled vertical hydraulic fracturing technology formed a vertical barrier of average thickness of 4" involving the injection of approximately 700 tons of iron filings. The installation of the iron reactive permeable barrier was monitored by precision weight measurement and metering of the iron filings into each frac well casing and the installed geometry of the PRB was monitored in real time by the active resistivity imaging technology. The PRB thickness was verified by inclined profiling at nine (9) locations along the PRB alignment using a soil electrical conductivity probe. High precision hydraulic pulse interference tests were conducted both pre and post PRB installation demonstrating that the PRB did not impede the natural groundwater flow regimes. The PRB's degradation performance is currently being monitored by a series of upgradient and downgradient groundwater monitoring wells.

SITE BACKGROUND

A former manufacturing facility in Virginia, see Figure 1, was contaminated primarily with TCE, PCE and 1,1-dichloroethene (1,1-DCE) in both the soils in the vadose zone and in the groundwater. Groundwater concentrations of TCE were detected up to levels of 50,000 ppb. The record of decision (ROD) was modified to a soil vapor extraction (SVE) system in the vadose zone for the soil remedy and an in situ iron permeable reactive barrier for groundwater remediation. The iron permeable reactive barrier replaced the earlier proposed pump and treat remedy, because the PRB was considered more effective in remediating the groundwater, both in terms of time to remediate and cost. The remnant plume downgradient of the reactive barrier is expected to be in situ remediated by flushing from the clean groundwater emanating from the PRB.

The interbedded upper sands, silts and clays that comprise the Yorktown/Eastover underlie the Site forming the uppermost unconfined aquifer which has a maximum thickness of approximately 45 feet beneath the Site. Underlying the upper aquifer, clays and silts that

comprise the St. Mary's confining unit have an approximate thickness of at least 70 feet. This confining unit is regional in extent and separates the upper aquifer from the underlying confined aquifers contained within the lower (and much deeper) Pamunkey and Potomac Groups. The silt and clay of the St. Mary's create a relatively impermeable hydrogeologic barrier, preventing the downward vertical flow of groundwater.
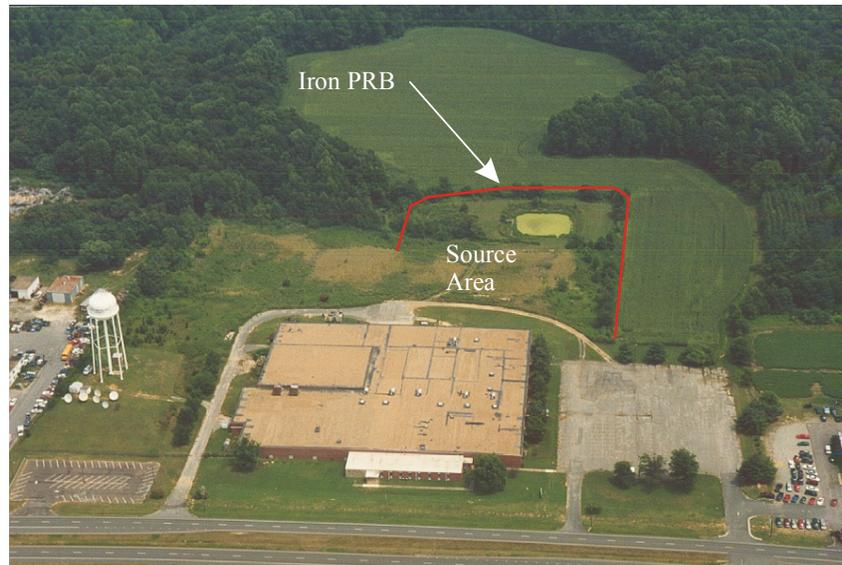
FIGURE 1. Aerial View of Iron PRB and Source Area.

The Site lies just to the northeast of a local topographic high, running northwest-southeast, which acts as a surface water divide, as well as an upper aquifer groundwater divide. Locally, both groundwater and surface water flow to the northeast and southwest of this divide. Horizontal groundwater flow within the upper aquifer immediately beneath the Site is generally to the northeast, where it discharges to the nearby northeast flowing surface water streams. The saturated interbedded sands and silts of the upper aquifer have measured hydraulic conductivities, ranging from approximately $1x10^{-3}$ centimeters per second (cm/sec) to $1x10^{-5}$ cm/sec. This variability in hydraulic conductivity is due to the heterogeneous nature of the thin interbedded fine sands, silts and clays comprising the upper aquifer. The measured vertical hydraulic conductivity of the confining unit beneath the upper aquifer is less than $1x10^{-7}$ cm/sec, as measured in laboratory permeameter tests conducted on Shelby tube samples.

The prime groundwater compounds of concern at the Site are PCE, TCE, 1,1,1-trichloroethane (1,1,1-TCA), 1,1-DCE, 1,2-dichloroethene (1,2-DCE) and 1,1-dichloroethane (1,1-DCA). Groundwater potentiometric and concentration maps indicate that the main VOC migration pathway is to the northeast from the on-site potential source area towards the neighboring north-eastern flowing surface water streams.

The contaminated groundwater plume is a result of downward migration of contaminants from the vadose zone, and a generally north-eastern groundwater flow direction discharging to the neighboring surface water streams. A source control iron permeable reactive barrier and surface impermeable cap system were proposed to be constructed around and over the suspected source area. The surface impermeable cap limits infiltration and thus reduces the hydraulic gradients across the proposed PRB. The PRB alignment was selected to intersect

groundwater flow from the suspected source area to the neighboring surface water streams. The cap system covers an area of approximately 4-1/2 acres, and the PRB extends 1,175 feet in length from a depth of 5 feet below ground surface (bgs) down to a total depth of 44 feet with an average iron thickness of 4 inches.

PROBABILISTIC DESIGN METHODOLOGY & ANALYSIS

The probabilistic design methodology, as outlined in Hocking et. al. (1998a), has been further refined to incorporate both the degradation of VOCs within the PRB and by natural attenuation mechanisms active downgradient of the PRB as illustrated on Figure 2. The iron PRB is designed for influent concentrations that in combination with downgradient natural attenuation (NA) (biodegradation, dispersion, absorption, etc.) mechanisms would meet target concentrations at a pre-determined Site Compliance Point (SCP). The methodology incorporates a probabilistic multi-specie VOC degradation model for degradation within the PRB and a probabilistic fate and transport model for VOC natural attenuation downgradient of the PRB. Deterministic design procedures, whilst adequate for feasibility evaluation, are not sufficient for final iron permeable reactive barrier design because factors of safety from past practices are not available for such systems. Probabilistic methods, on the other hand, can accommodate variability in parameter data and are ideally suited for system design such as an iron permeable reactive barrier. The probabilistic method enables quantification of the degree of confidence that contaminant effluent concentrations are not exceeded. Probabilistic analyses quantify the impact of parameter variability on overall system performance and thus rank the parameter by sensitivity.

FIGURE 2. PRB and Natural Attenuation Probabilistic Design Methodology.

The design criteria for the permeable iron reactive barrier are quantified to ensure the PRB is designed and constructed to meet risk reduction or target effluent levels. These design criteria

address issues regarding impact on groundwater flow regimes, variability of input parameters on system performance, construction quality assurance, long term monitoring and health and safety. The reactive barrier design activity requires additional data over conventional site characterization data; namely, column reactivity data and iron permeability design data. These data are generated from laboratory tests conducted on site groundwater and soils. Laboratory column tests utilizing site groundwater quantify the degradation reaction rates and pathways (daughter products) of the particular contaminant specie in the presence of iron filings, and also address additional issues such as potential precipitation and clogging of the reactive barrier.

VOC degradation half lives and pathways in the presence of zero valent iron are quantified by a column reactivity test conducted using Site groundwater. Zero valent metals abiotically degrade certain compounds; such as, pesticides as described by Sweeny and Fisher (1972), and halogenated compounds as detailed in Gillham and O'Hannesin (1994). The abiotic reduction of TCE, PCE, vinyl chloride (VC) and isomers of dichlorethene (DCE) by zero valent iron metal are shown as mol percent conversion pathways on Figure 3, with ethene and ethane being the final carbon containing daughter compounds. The abiotic reduction of 1,1,1-TCA by zero valent iron metal is also shown as mol percent conversion pathways on Figure 3, with ethene, ethane and chloroethane being the final carbon containing daughter compounds (Pennelly and Roberts, 1998).
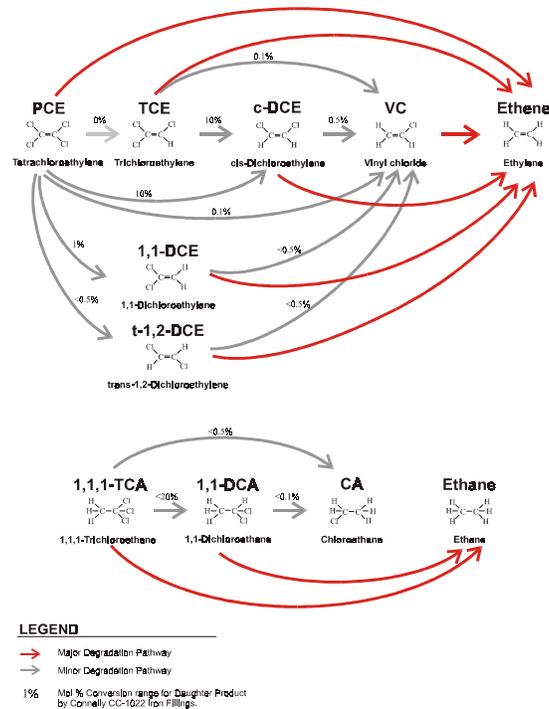
FIGURE 3. Iron Reductive Pathways for Chloroethenes and Chloroethanes

Probabilistic distributions for the design input parameters (formation hydraulic conductivity, groundwater flow gradient, VOCs concentrations, VOCs degradation half lives, iron PRB porosity and iron PRB effective thickness) were developed, resulting in computed probabilistic distributions for PRB effluent VOC concentrations as shown on Figure 4. The PRB probabilistic model 85-percentile VOC effluent concentration levels were used to determine the

minimum iron PRB average-effective thickness required to bring VOC concentrations to below target effluent levels. Degradation rates of the remnant groundwater plume downgradient from the PRB were quantified by the probabilistic fate and transport mode, enabling predictions of PRB downgradient monitoring well performance with time.
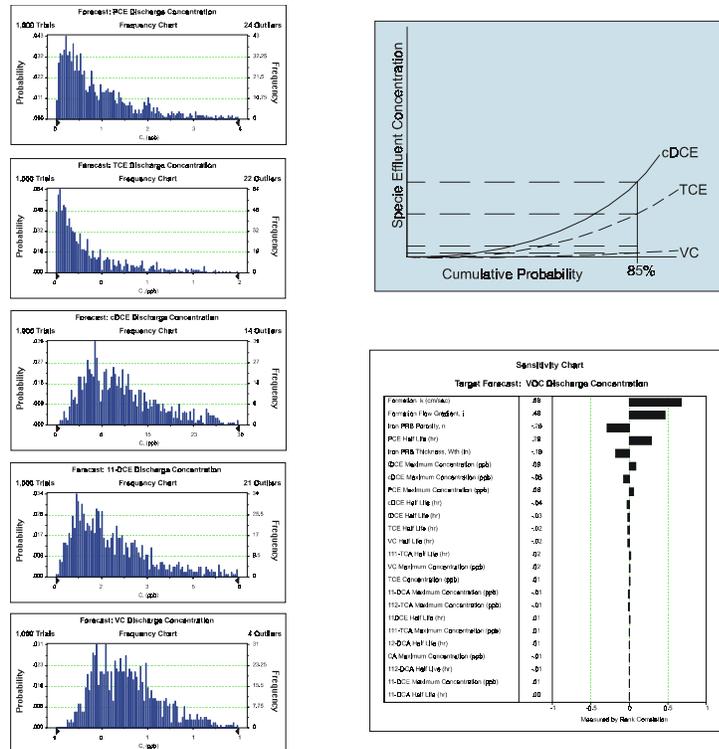
FIGURE 4. PRB Probabilistic Design Analysis Output Data.

PRB CONSTRUCTION

The azimuth controlled vertical hydraulic fracturing placed iron PRB is constructed from conventionally drilled wells installed along the barrier alignment with a specialized frac casing grouted into the boreholes. A controlled vertical fracture is initiated at the required azimuth orientation and depth in each well inside of the specialized frac casing using downhole frac initiation tools. The iron filings are blended and injected in the form of a highly viscous degradable food grade quality gel, hydroxypropylguar (HPG). Multiple well heads are injected with the iron-gel mixture to form a continuous PRB. The PRB is constructed by the injection of the iron filings into these frac casings with real time quality assurance monitoring of the injections to quantify the PRB geometry and iron loading densities. The gel biodegrades into water and sugars by the use of a suitable enzyme, and leaves in situ a permeable iron reactive treatment zone. The azimuth controlled vertical hydraulic fracturing technology has installed full scale iron permeable barriers from 3" to 9" in thickness from moderate ($\sim 50'$) to significant depth ($> 120'$), Hocking et. al. (1998 b, c and 2000).

The iron PRB was constructed from eighty two (82) frac initiation casings installed at approximately twelve (12) to fifteen (15) foot centers along the PRB alignment as shown in plan on Figure 5. Split spoon samples were taken in each alternate boring to ensure the frac casings

were installed down and into the underlying till unit. Downhole resistivity receivers were installed in strings denoted as RR1 through RR39 as shown on Figure 5. Special down hole packer, frac casing and well head system were inserted into each well, F-1 through F-82, and a controlled vertical fracture was initiated at the required azimuth orientation and depth. Upon initiation of the controlled fracture within the well, the gel/iron mixture was then injected to form a continuous permeable iron reactive barrier.

The PRB installation was monitored in real time to ensure mixture consistency, determine volume and weights of iron injected, and to determine the geometrical extent of the barrier thus ensuring it is constructed as designed. The real time monitoring of the PRB geometry involves active resistivity instrumentation equipment and specialized software. During injection, the iron-gel mixture was electrically energized with a low voltage 100 Hz signal. Downhole and surface resistivity receivers were monitored to record the in phase induced voltage by the propagating fracture. From monitoring the fracture fluid induced voltages and utilizing an incremental inverse integral model, the fracture fluid geometry was quantified and displayed during the installation process. The final geometry of the constructed PRB extended approximately 1,175 feet in overall length from a depth of approximately 5 feet down to a maximum depth of 44 feet. The as-built PRB had a cross sectional area of approximately 25,000 sft, an average iron thickness of 4', involving the injection of 700 tons of iron filings.
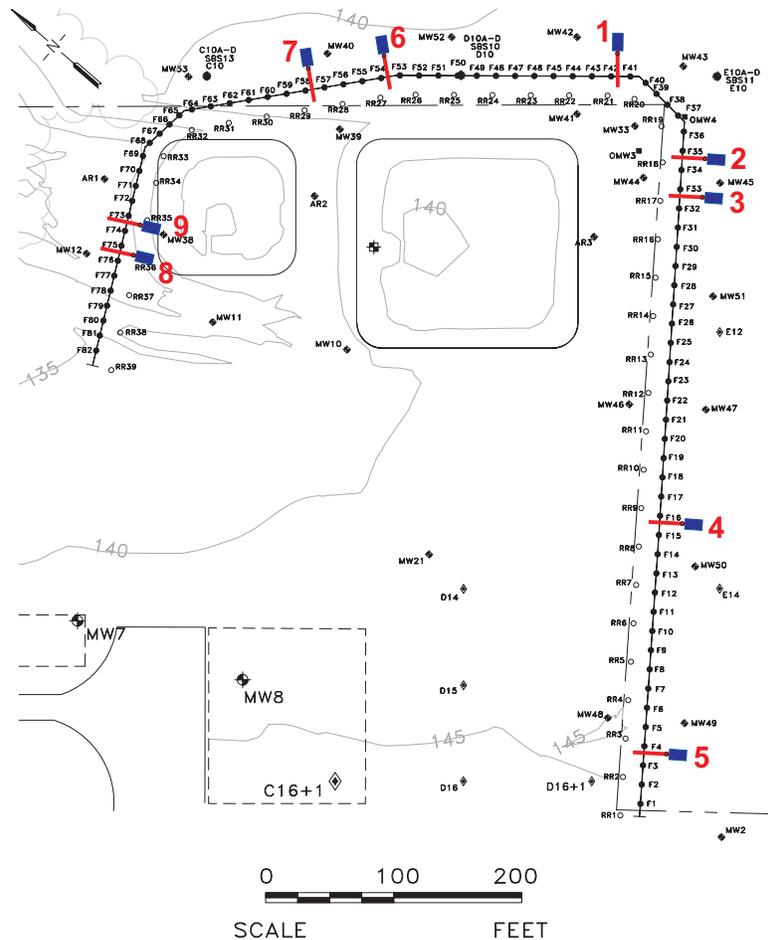
FIGURE 5. Plan of Iron PRB showing Frac Wells and Inclined Profiling Locations.

PRB IN SITU QC VERIFICATION PROCEDURES

Verification procedures of the in situ constructed geometry of the PRB and the impact of the PRB construction on groundwater flow regimes are important for a high confidence in the quality control/quality assurance of the constructed PRB. Difficulties in direct sampling of iron PRBs have been experienced at shallow depth due to the inability to contain the iron filings within the sampler, Beck et. al (2000). At significant depth and/or in flowing ground conditions, direct inclined sampling of undisturbed iron PRBs have been found to be extremely difficult, Hocking et. al. (2001). Under these conditions the ground in front of the sampler flows into the outer protective casing when the sampler is withdrawn and thus disturbs the ground for the next sampling interval. The next sampling attempt then samples disturbed ground consisting of a mixture of native soils and iron filings.

Such direct PRB sampling difficulties have led to the utilization of an inclined direct push soil electrical conductivity/resistivity and magnetometer probes to determine indirectly the iron PRB geometry, Beck et. al. (2000) and Hocking et. al. (2002). The electrical resistivity contrast between native soils and the iron PRB are generally sufficient to clearly identify the iron PRB geometry and thus quantified the iron thickness at various locations along the PRB alignment. The PRB thickness was verified by inclined profiling using a driven electrical conductivity probe at nine (9) locations along the PRB alignment as shown in plan on Figure 5 and in detail on Figure 6. All of the nine (9) incline profiles determined the iron PRB was within the thickness specifications as detailed in the design.
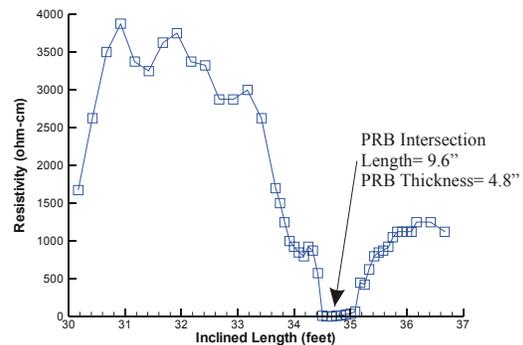
Inclined Resistivity PRB Probing Location #1 Inclination 30 degrees

FIGURE 6. Inclined Thickness Profiling of Iron PRB by a Soil Resistivity Probe.

Permeable reactive barrier systems are being installed as an alternative method to remediate contaminated groundwater. The most significant difference between a permeable reactive barrier and a containment system is the need to ensure the barrier's permeability does not impede or modify the groundwater flow regimes. The issues such as fines, smearing, filter cake clogging, etc. that benefit slurry wall systems as containment structures have major detrimental impacts on a PRB hydraulic performance. In general, such reductions in PRB permeability can not be retroactively removed and in certain construction techniques are difficult to avoid. Since any impediment to flow by a PRB system can have serious consequences to overall system performance, it is imperative to conduct hydraulic integrity testing of such a system to ensure it is constructed as planned. Six (6) hydraulic pulse interference tests, Hocking (2001), were conducted across the PRB's alignment prior and after construction to quantify the barrier's hydraulic characteristics. The hydraulic pulse interference

tests conducted pre and post PRB construction clearly demonstrated that the PRB would not impede or impact groundwater flow at the site.

CONCLUSIONS

Permeable reactive barriers are suitable cost effective remedies for contaminated groundwater, both for plume remediation and as source control. Iron permeable reactive barriers are most efficient in dehalogenating chlorinated solvents in groundwater and are a viable cost effective alternative to pump and treat. The iron reactive barrier system compliments and enhances natural attenuation mechanisms active at the site. The design, construction and performance monitoring of in situ iron permeable reactive barriers warrant special attention due to the functional design requirements of these systems. The design methodology for the PRB incorporated a probabilistic multi-specie VOC degradation model for degradation within the PRB and a probabilistic fate and transport model for VOC natural attenuation downgradient of the PRB.

Azimuth controlled vertical hydraulic fracturing technology constructed the iron PRB 1,175 feet in length down to a total depth of 44 feet. A total of 700 tons of iron filings were injected into the subsurface to create the iron PRB with a cross-sectional area of over 25,000 sft and with an average iron thickness of 4". Verification procedures of the in situ constructed geometry of the PRB and the impact of the PRB construction on groundwater flow regimes are important for a high confidence in the quality control/quality assurance of the constructed PRB. Difficulties in direct sampling of iron PRBs have led to indirect measurements of the PRB geometry by direct push electrical resistivity probes. Nine (9) inclined thickness profiling tests intersected the PRB at depth and quantified that the PRB was constructed within the thickness specifications specified by the design. The hydraulic pulse interference test has considerable merit as an integrity test for quantification of the hydraulic impact of permeable reactive barrier systems. Six (6) pre and post PRB construction hydraulic pulse interference tests across the PRB alignment determined that the constructed PRB would not impede or impact the site's groundwater flow.

REFERENCES

Beck, P. B. Jr., P. J. Clark and R. W. Puls (2000). Location and Characterization of Subsurface Anomalies Using a Soil Conductivity Probe, *Ground Water Monitoring Review*, Spring, pp 55-59.

Gillham, R. W. and S. F. O'Hannesin (1994). Enhanced Degradation of Halogenated Aliphatics by Zero-Valent Iron, *Ground Water*, Vol. 32, No. 6, pp 958-967.

Hocking, G. (2001). Hydraulic Pulse Interference Tests for Integrity Testing of Containment and Reactive Barrier Systems, submitted to the 2001 Int. Containment & Remediation Conf, Orlando, FL, June 10-13.

Hocking, G., S. L. Wells, and R. I. Ospina (1998a). Design and Construction of Vertical Hydraulic Fracture Placed Iron Reactive Walls. 1st Int. Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May.

Hocking, G., S. L. Wells, and R. I. Ospina (1998b). Field Performance of Vertical Hydraulic Fracture Placed Iron Reactive Permeable Barriers. Emerging Remediation Technologies for Soil and Groundwater Cleanup, Florida Remediation Conf., Orlando, FL, November 10-11.

Hocking, G., S. L. Wells, and R. I. Ospina (1998c). Performance of the Iron Reactive Permeable Barrier at Caldwell Superfund Site. RTDF Meeting, Oak Ridge, TN, November 17-18.

Hocking, G., and R. I. Ospina (1999). Construction and Performance Monitoring of In Situ Reactive Barriers. Subsurface Barriers Technologies, IBC's 2nd Annual Env. Technology Symp., Scottsdale, AZ, February 1-2.

Hocking, G., S. L. Wells, and R. I. Ospina (2000). Deep Reactive Barriers for Remediation of VOCs and Heavy Metals, 2nd Int. Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-25.

Hocking, G., S. L. Wells, and R. I. Ospina (2001). Probabilistic Design of Permeable Reactive Barriers, 2001 Int. Containment & Remediation Technology Conf., Orlando, FL, June 10-13.

Hocking, G., S. L. Wells, and M. A. Thurman (2002). Design, Construction and Installation Verification of Deep Iron Permeable Reactive Barriers. 3rd Int. Conf. On Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 20-23.

Pennelly, J. P. and A. L. Roberts (1998). Reaction of 1,1,1-Trichloroethane with Zero-Valent Metals and Bimetallic Reductants. Environ. Sci. Technol., Vol32, pp1980-1988.

Sweeny, K. H. and J. R. Fisher (1972). Reductive Degradation of Halogenated Pesticides. U.S. Patent No. 3,640,821.