

**IN SITU GASEOUS REDUCTION  
LIFE-CYCLE COST MODEL**

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## EXECUTIVE SUMMARY

Many government and private sites contain soils contaminated with heavy metals and/or radionuclides. Many of these contaminants are very mobile and pose a threat to the underlying groundwater.

Historically, soils contaminated with heavy metals or radionuclides have been excavated and disposed in an off-site repository. This baseline remediation technology is costly and subjects cleanup personnel to unnecessary exposure. An innovative technology known as in situ gaseous reduction (ISGR) has been developed to treat soils containing heavy metals and radionuclides in situ. Using this technology, hydrogen sulfide is injected into the ground through injection wells. Extraction wells are used to draw this gas throughout the contaminant plume, which reduces the oxidation state of the contaminant being targeted on contact. While it does not physically remove the contaminant, the objective of this process is to chemically reduce the metal or radionuclide to a less mobile form, which prevents further migration of the contaminants and therefore reduces the risk of contaminating the groundwater. In addition, some metals are less toxic in their chemically reduced form.

Laboratory tests completed by the Pacific Northwest National Laboratory (PNNL) at Hanford have shown 90% or greater immobilization of hexavalent chromium and 50% or greater immobilization of uranium in soil by using this hydrogen sulfide gas treatment. A field test has been completed by PNNL personnel at the White Sands Missile Range (WSMR) in New Mexico to demonstrate the effectiveness of this technology in a large-scale setting. The contaminant of concern was hexavalent chromium, which was the result of an antioxidant compound spilled at this site. The objective of this field test was to reduce the mobile, toxic hexavalent chromium to its immobile, nontoxic trivalent chromium state.

Posttreatment characterization of this WSMR site indicated that approximately 70% of the original hexavalent chromium was reduced to its trivalent state. Sampling and laboratory analysis completed showed the section of soil with the highest concentration of chromium contaminant being decreased by about 86%. This technology was most effective at depths down to 10 feet; however, beyond this depth the contaminant was not significantly reduced. It was concluded that this was due to the treatment gas channeling through the upper zone and bypassing the less permeable lower soil.

A second location where the former 183-DR facility was located at the Hanford Site was chosen for deploying the ISGR during fiscal years (FY) 1999 through 2001. Groundwater at this site has been shown to contain significant amounts of hexavalent chromium. During FY00, two boreholes were drilled to determine the location of the chromium source. Laboratory analysis of soil taken from the two boreholes installed failed to show any sign of hexavalent chromium. Because of this, the project was stopped until funding becomes available for further site characterization.

A scalable life-cycle cost model (LCCM) was developed using data from the WSMR field test for chromium. This LCCM may be updated to include the cost data from the Hanford deployment should funding become available to complete this project. The purpose of this model is to provide a means to compare estimated costs of using the innovative ISGR technology to the costs of using the baseline excavation and disposal technology. In general, the capital costs and operating and maintenance costs are comparable for both technologies. However, ISGR is generally more cost effective than excavation and disposal due to the significant cost of disposal of the contaminated soils removed. On the other hand, soil excavation and disposal can usually be completed faster than the ISGR can remediate the soil in situ.

# CONTENTS

EXECUTIVE SUMMARY .....	i
1. INTRODUCTION.....	1
2. TECHNOLOGY .....	2
2.1 Chemistry .....	2
2.2 Equipment/Wells.....	2
3. SITES USING IN SITU GASEOUS REDUCTION.....	9
3.1 White Sands Missile Range, New Mexico.....	9
3.2 Hanford Site 183-DR Facility .....	11
4. LIFE-CYCLE COST MODEL .....	12
4.1 Inputs.....	12
4.1.1 In Situ Gaseous Reduction .....	12
4.1.2 Excavation and Disposal.....	13
4.2 Outputs.....	14
4.2.1 In Situ Gaseous Reduction .....	14
4.2.2 Excavation and Disposal.....	15
5. CONCLUSION .....	18
6. REFERENCES.....	22
APPENDIX A: Actual Costs for the ISGR Field Demonstration.....	A-1
APPENDIX B: Sensitivity Analysis Tables.....	B-1

## TABLES

	Page
3-1. Summary of ISGR Technology Demonstration Costs .....	10
3-2. Summary of Characterization Borehole Costs .....	11

## FIGURES

2-1. Gas Treatment System .....	4
2-2. Schematic of Gas Treatment System .....	5
2-3. Well Configuration Showing One Cell.....	6
5-1. Inputs Used to Create Graphs.....	19
5-2. Amount of Hydrogen Sulfide Required vs. Unit Cost to Treat Soil.....	20
5-3. Well ROI vs. Unit Cost to Treat Soil .....	20
5-4. Well Installation Costs vs. Unit Cost to Treat Soil .....	21

## 1. INTRODUCTION

In situ gaseous reduction (ISGR) is being tested to determine the feasibility of using this technology to treat unsaturated soils to immobilize heavy metal and radionuclide contaminants. Most testing has been at the bench scale for various contaminants that have a potential to be reduced to an immobile or less toxic state. Laboratory tests completed by the Pacific Northwest National Laboratory (PNNL) at Hanford have shown 90% or greater immobilization of hexavalent chromium and 50% or greater immobilization of uranium in soil by using this hydrogen sulfide gas treatment (Ref.1). Until recently, the only field testing that had been completed was at the White Sands Missile Range (WSMR) in New Mexico where a corrosion inhibitor containing chromium(VI) spilled and migrated toward the saturated zone. The purpose of this test was to determine how effectively the common contaminant, chromium(VI), could be reduced to its relatively nontoxic trivalent state in the field. Although it is expected that this method for treating soils will work for other contaminants, the contaminant of concern for this report and the life-cycle cost model (LCCM) is chromium.

More recently, the characterization of an area located on the Hanford Site was completed; two boreholes were drilled to provide soil samples for laboratory analysis. The purpose of this was to determine specifically where the hexavalent chromium source contaminating the groundwater is located. Once this was completed, ISGR would be deployed in the field to treat the contaminated soil and eliminate the source of pollution to the underlying groundwater. Analysis of these boreholes did not detect any chromium, and the project was stopped.<sup>1</sup> It is anticipated in the near future additional funding will become available to continue this project to locate and eliminate this source of groundwater contamination.

Excavation, treatment, and disposal of contaminated soil is the conventional method for handling soils contaminated with heavy metals and radionuclides. This baseline method subjects workers to risks associated with the excavation, treatment, transportation, and disposal of the contaminated soils that are removed. In addition, costs for the disposal of this type of waste are usually high. In situ gaseous reduction resulted from tests designed to determine a safer and more cost-effective means for treating unsaturated zones that contain contaminant plumes.

When using ISGR, a diluted mixture of hydrogen sulfide in air is injected into the soil using injection wells. Typically, six extraction wells, configured hexagonally, with an injection well in the center, comprise a cell. The extraction wells draw the hydrogen-sulfide mix through the contaminated zone. Once the gas mixture contacts the mobile hexavalent chromium contained in the unsaturated soil, the contaminant is reduced to its immobile trivalent chemical state. In this reaction, the carcinogenic chromium(VI) is precipitated as chromium(III) hydroxide, which is essentially a stable nontoxic solid (Ref. 2).

To assist in the estimation of the total costs associated with using this technology to remediate a site containing unsaturated soils contaminated with hexavalent chromium, an LCCM was developed using Microsoft Excel™ software. This model allows the user to input site-specific data with a project cost estimation being the output. It is assumed the site has been thoroughly and accurately characterized and the input values necessary have been determined; therefore, these costs are not included in this LCCM. The main objective of this model is to provide a starting point that compares the costs of using this emerging gaseous reduction technology with the baseline excavation and disposal technology.

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<sup>1</sup> Thornton, Edward, PNNL-Hanford, personal communication, July 31, 2000.

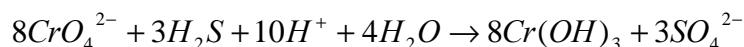
## 2. TECHNOLOGY

To reduce the health and safety risks to workers, researchers have been developing environmental remediation technologies that can be completed without removing the contaminated media. These in situ technologies reduce the workers' exposure to contaminants by treating the contaminant plume in place. The ISGR treats heavy metals and radionuclides in place by injecting hydrogen sulfide around the perimeter of the plume. The sulfide gas moves through the unsaturated soils, reacts with the contaminant, and reduces the contaminant to an immobile compound, and in some cases, to a less toxic form. Excavation, treatment, and disposal is the established baseline for treating contaminated soils.

### 2.1 CHEMISTRY

Various inorganic contaminants can be immobilized in situ as precipitates using different gases; however, this LCCM and report will only consider the reduction of chromium(VI) to its chromium(III) hydroxide precipitate. In its hexavalent state, chromium is considered a toxic, carcinogenic chemical. In the trivalent form, chromium is an essentially nontoxic human micronutrient. Furthermore, chromium(VI) is mobile and easily migrates from the unsaturated soils to the underlying groundwater. Chromium(III) is immobilized because it precipitates as a solid, which reduces the threat of contaminating the groundwater.

Following is the chemical reaction associated with this process (Ref. 2):



Stoichiometrically, 3 moles of hydrogen sulfide are required to reduce 8 moles of hexavalent chromium to its trivalent state. However, in the field, this amount may be different from the theoretical amount. Because this chemical reaction is nonspecific, metals other than the targeted chromium will react with the sulfide gas. In addition, organic materials contained in the soils will compete with the metals in consuming the hydrogen in other chemical reactions. Moisture, temperature, and soil types can also affect this reaction; therefore, the amount of hydrogen sulfide injected into the soils is site-specific. Soils from the site must be characterized to determine whether or not ISGR can be used to effectively treat a site contaminated with chromium. Soil samples need to be gathered and tested to find the total amount of sulfide gas that must be injected to reduce the chromium(VI) to chromium(III).

Once the estimated mass of hydrogen sulfide necessary to reduce a known mass of soil containing the chromium contaminant is determined, other parameters can be estimated. These other parameters are the concentration of the sulfide gas and the flow rate of this gas and air mixture. Another important factor used to determine the amount of gas necessary to treat a given volume of soil is the bulk density. From these values, the time required to treat a given volume of soil containing chromium(VI) can be estimated.

### 2.2 EQUIPMENT/WELLS

The main components of the gas treatment system used to inject the hydrogen sulfide into the subsurface include a blower, vacuum pump, water knockout tank, scrubber, instrument panel, and the associated piping (see Figure 2-1, taken from Ref. 2). Hydrogen sulfide that is contained in a gas cylinder is blended with air before it is injected into the ground (see Figure 2-2, taken from Ref. 2). A

regulator is used to control the flow so the gas can be adjusted and maintained at a concentration between 100 to 500 parts per million (ppm) hydrogen sulfide.

After blending, a blower forces the air/hydrogen-sulfide mixture through the injection wells into the ground. The wellfield network contains as many cells as necessary to cover the area that requires remediation. Each cell consists of six extraction wells that are spaced around a single injection well in a hexagonal wellfield pattern (see Figure 2-3, taken from Ref. 2). Each well is spaced in a manner in which the radius of influence (ROI) of each well overlaps the adjacent wells. These extraction wells are attached to a vacuum extraction pump that pulls the sulfide gas, air, and water vapors out of the ground. This pump needs to be resistant to the hydrogen sulfide and must contain gas-tight seals to keep the gas from escaping into the atmosphere. The number of cells required depends on the size of the plume and the ROI of the gas being injected.

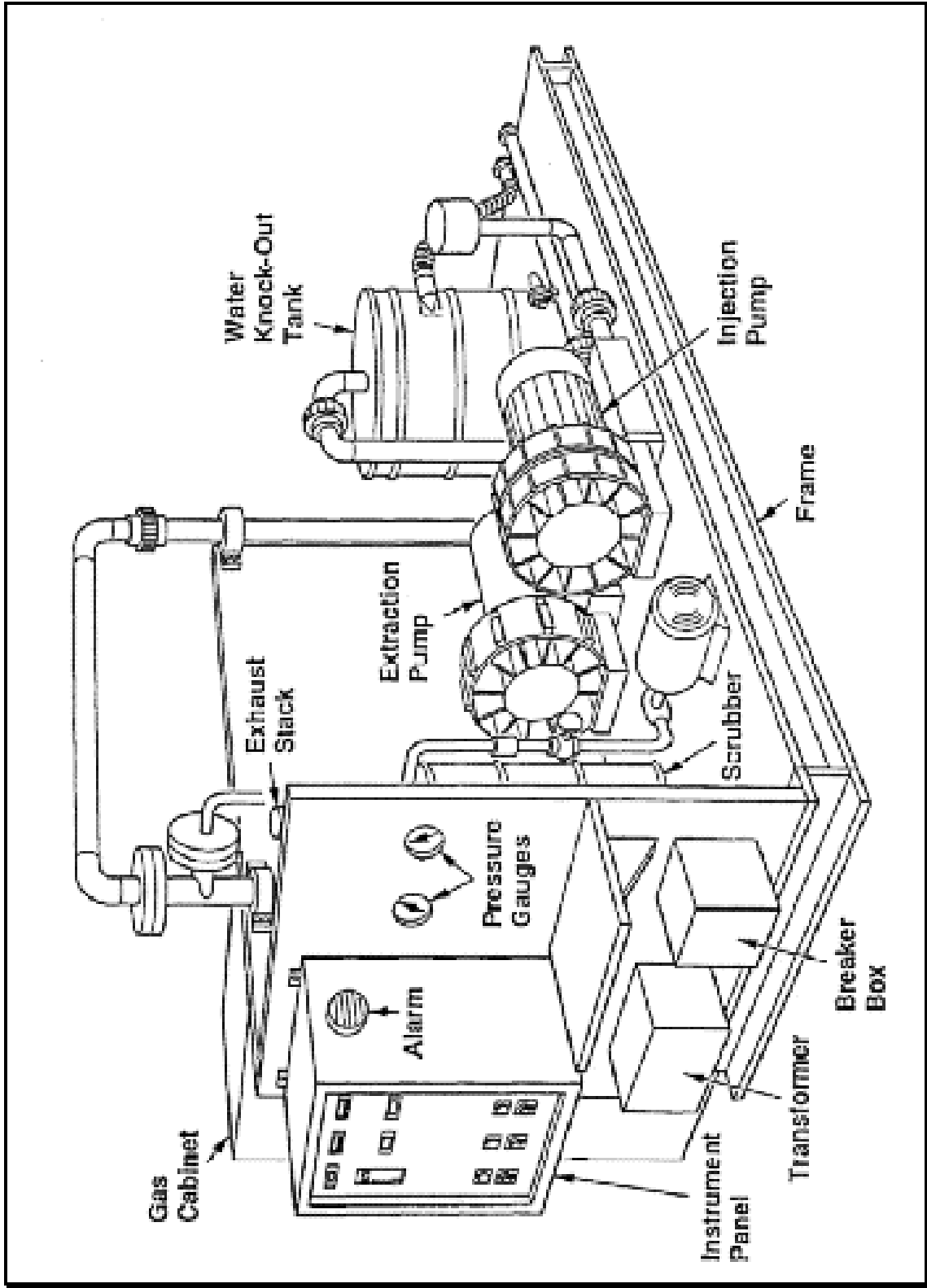


Figure 2-1. Gas treatment system.

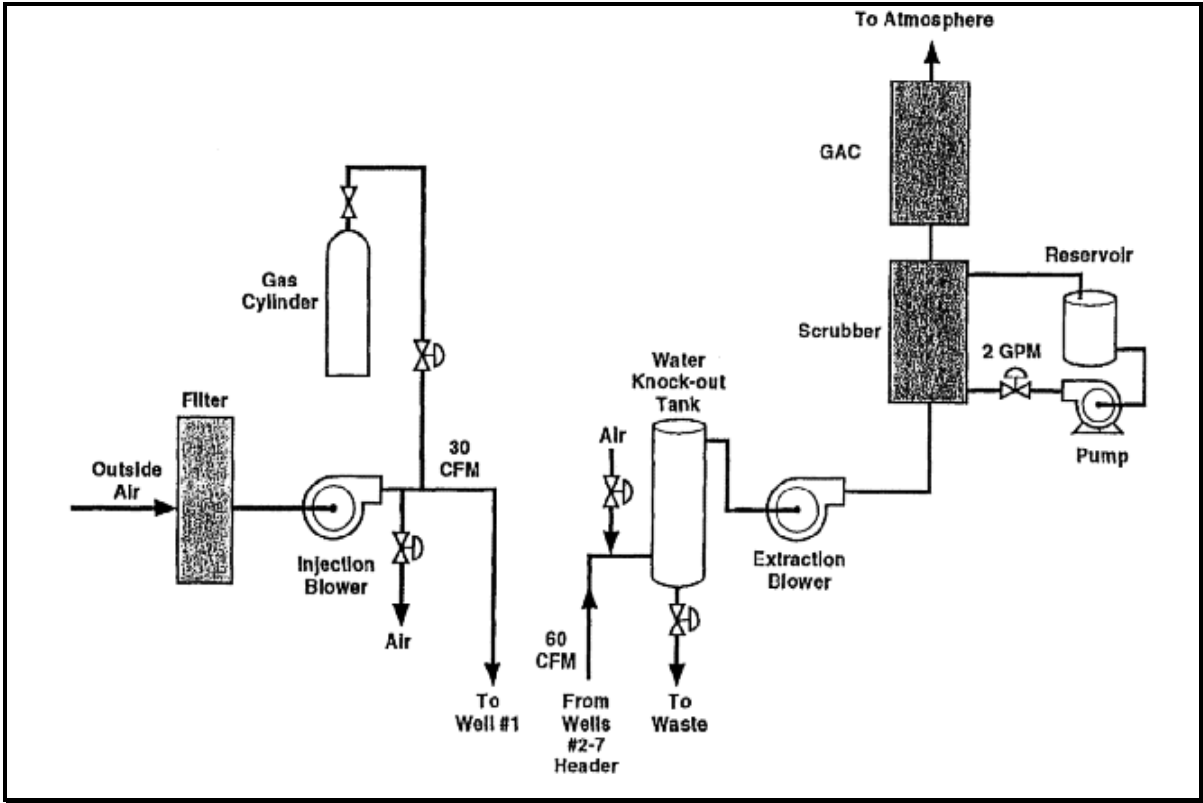


Figure 2-2. Schematic of gas treatment system.

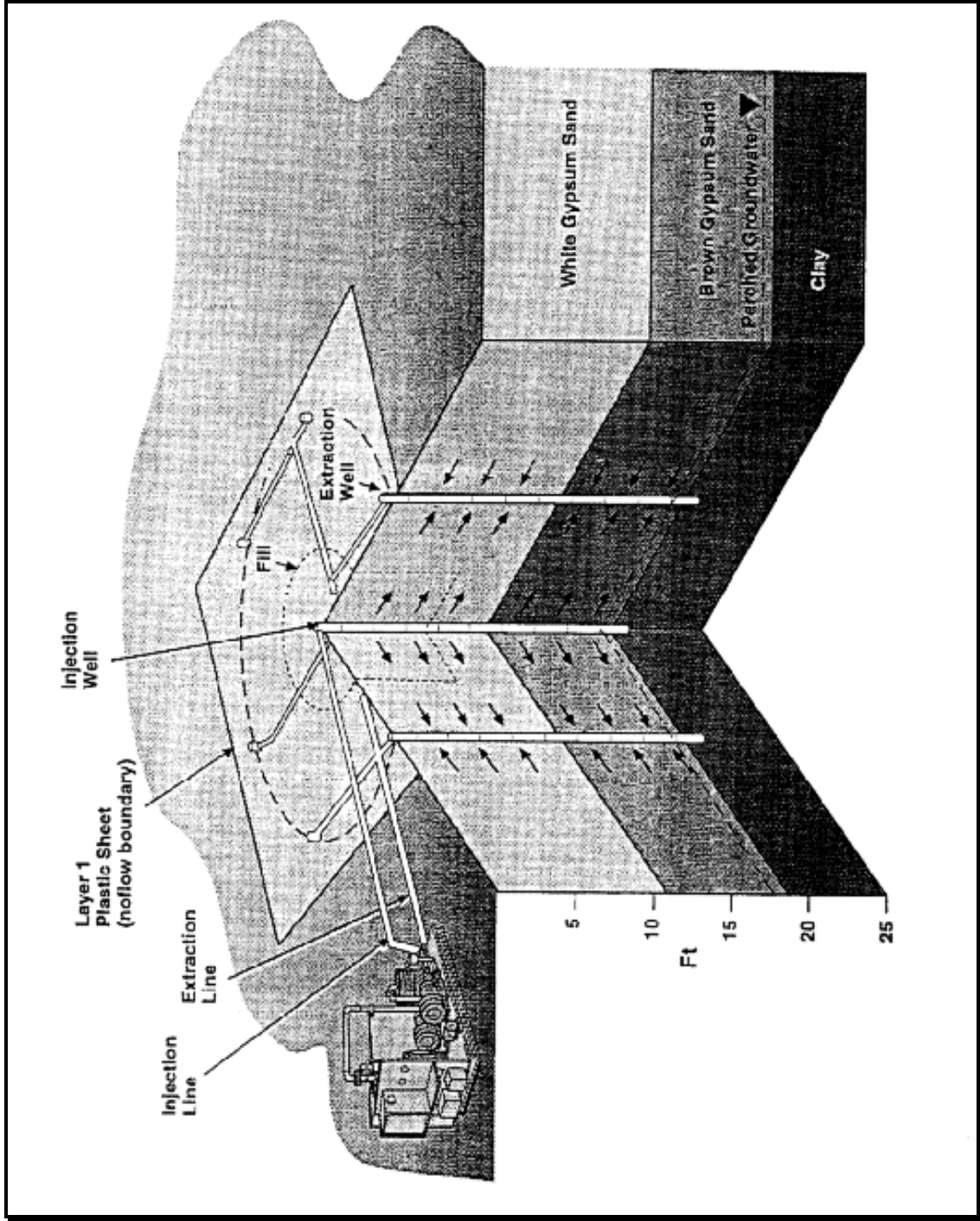


Figure 2-3. Well configuration showing one cell.

Once injected into the soils, the hydrogen sulfide is drawn through the plume toward the extraction wells. This offgas mixture is monitored to determine when the breakthrough of unreacted hydrogen sulfide extracted from the ground has occurred. As long as a reaction is occurring, the sulfide gas reducing agent will not be detected in the offgas. Both extraction and injection wells are made of materials resistant to hydrogen sulfide.

After the offgas is pulled from the subsurface, it passes through the water knockout tank to collect the water vapor and then through the scrubber system. The scrubber system consists of a tank containing a caustic solution that removes acid gases from the offgas. In addition, contaminated sites containing organic compounds may also require a granular activated carbon scrubber to collect dissipated volatile chemicals. After passing through the scrubber system, the offgas is released to the atmosphere.

The depth of the wells depends on how far the contaminant has migrated below surface. Once the plume has been characterized, the total length of each well and the length to which the well is screened can be determined. Generally, the well will be screened over the total vertical length (depth) of the plume so the gas reducing agent can effectively contact, and therefore react with, the chromium contaminant.

Prior to installation of the wells, a tracer gas test is performed to determine the diffusion rates, permeability, and ROI. This preliminary testing provides information used to decide how well the gas will flow through the soil and whether the gas can be recovered without significant discharges to the atmosphere (Ref. 2). Once it is determined ISGR is a feasible technology for a specific site, the hexagonal wellfield can be installed.

After the hexagonal wellfield is installed, a wellfield tracer test using sulfur hexafluoride (SF<sub>6</sub>) diluted in air is injected into the site using the treatment system. The purpose of this tracer is to test for system leaks, determine flow patterns, and verify the gas injection can be controlled. Controlling the injection and recovery of the gas as well as testing for leaks is completed for safety and environmental reasons. Flow patterns are important in determining whether the gas is flowing in a homogeneous manner or whether it is moving through channels in the subsurface. Once the flow has been determined, the operator has some control over the gas flow that is moving in a continuous front toward the extraction wells by adjusting the total injection rate and the flow rate of the individual extraction wells.

Depending on the soil characteristics, the air and hydrogen-sulfide mixture can be injected at various rates. Soils with low permeability reduce the rate at which the gas mixture can be injected. To accelerate remediation time, the injection rate can be increased as bounded by soil conditions. Also, pressures associated with high injection rates can cause problems with the system, e.g., the gas could create channels to the surface instead of flowing as an even front through the soil. Another option to speed up soil treatment is to increase the concentration of the hydrogen sulfide being injected. However, for safety reasons, the concentration of hydrogen sulfide probably should not exceed 300 ppm.<sup>2</sup>

Due to the safety issues related to the use of hydrogen sulfide, real-time emissions monitoring of the gas is completed whenever the ISGR system is in operation. Safety alarms are placed around the perimeter of the gaseous reduction project area. The purpose of these monitors is to alert personnel that hydrogen sulfide is being released somewhere in the system. Although the scrubber system is checked frequently, an in-line monitor in the scrubber stack provides a backup for notifying personnel that the caustic scrubber solution is spent and needs replacing. In addition, personnel entering the site where ISGR is taking place are required to wear personal monitoring devices.

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<sup>2</sup> Thornton, Edward, PNNL – Hanford, personal communication, May 11, 1998.

Influent and effluent gas streams are also monitored for hydrogen-sulfide concentrations by using portable gas monitoring systems. Initially, the sulfide gas will be consumed in the reduction reaction taking place in the subsurface. Once the hexavalent chromium and other compounds, such as iron oxide, have been reduced, unreacted hydrogen sulfide will be detected in the offgas coming from the extraction wells. Influent gas concentration is monitored to ensure the desired concentration of hydrogen sulfide is being injected into the subsurface.

### 3. SITES USING IN SITU GASEOUS REDUCTION

To date, the use of the ISGR technology in the field has been considered at two different sites to treat soil contaminated with hexavalent chromium. In 1998, a field-scale demonstration was successfully completed at a site near Las Cruces, New Mexico. More recently, ISGR was chosen to be deployed at the Hanford Site during fiscal years 1999 through 2001. The following sections provide more detail regarding these sites.

#### 3.1 WHITE SANDS MISSILE RANGE, NEW MEXICO

The first field demonstration for ISGR took place at the High Energy Laser System Test Facility (HELSTF) within the U.S. Department of Defense (DoD) WSMR located in New Mexico. The purpose of this demonstration was to show that hydrogen sulfide injected into the ground reduces the toxic hexavalent chromium to nontoxic trivalent chromium. This contamination is the result of the mishandling of a hexavalent chromium-based corrosion inhibitor, Entec 300 (Ref. 2). It is estimated that approximately 55 gallons of this material were released to the soil in 1982 or 1983.

Once discovered, approximately 17 drums of the contaminated topsoil were removed from the site; clean soil was then used to replace the contaminated soil that was removed, and a cover was built over the site to help prevent further migration of the contaminant. Further site characterization using Geoprobe™ and auger drilling was completed after this site was selected for the ISGR field demonstration. Core samples were taken to determine the extent of contamination, treatability studies were completed to determine the amount of hydrogen sulfide required, and a single well air extraction was completed from which the wellfield was designed.

After installing the wellfield and setting up the gas treatment system, a tracer test using SF<sub>6</sub> was completed. The purpose of this test was to determine the capabilities of the gas treatment system and provide data regarding injection and extraction gas flow rates as well as the ROI at this specific site. This test also proved that gas emissions from the site could be adequately controlled to meet the regulatory requirements.

Soil characteristics at the HELSTF are silty sand comprised mainly of white and brown gypsum to a depth of approximately 18 feet (Ref. 2). Further down is a dense clay layer containing perched groundwater. Although the homogeneity of the gypsum material was favorable to the use of ISGR, the sand had a relatively high moisture content of 20%. This led to low permeability of the sand, which resulted in low flow rates of the hydrogen sulfide being injected. As the soil dries up, the flow rate can be increased without increasing the backpressure on the system. The majority of hexavalent chromium was observed in a layer from 6 to 10 feet below the surface with the highest concentration at 85 milligrams per kilograms (mg/kg) (Ref. 2).

At the HELSTF site, a mixture of air containing approximately 200 ppm hydrogen sulfide was injected at a rate of between 25 cubic feet per minute (cfm) to 50 cfm.<sup>1</sup> In general, the total extraction rate should be 50% higher than the injection rate and the individual extraction wells should be operating at the maximum rate. However, at the HELSTF site, the six extraction wells were operated at various extraction rates ranging from approximately 2.5 cfm to 15 cfm to compensate for changing soil conditions or individual well capabilities until sulfide gas breakthrough was detected in the offgas. The average rate of total extraction was approximately 72 cfm. Once breakthrough occurred, the well containing hydrogen sulfide in the offgas was valved off to direct gas to the other wells. This continued until all wells showed breakthrough of the hydrogen sulfide.

Once the injection of the hydrogen sulfide gas was finished, posttreatment characterization was completed to determine the effectiveness of the ISGR. Soil samples were taken and analyzed for hexavalent chromium to compare to the pretreatment chromium analysis. In the pretreatment characterization, the zone with the highest level of hexavalent chromium was between 4 and 10 feet below surface. The posttreatment characterization showed the majority of this contaminant was reduced to its trivalent form. The average concentration of hexavalent chromium in this zone decreased from approximately 8.1 mg/kg of soil before treatment to 1.14 mg/kg of soil after treatment (Ref. 3).

Pretreatment analysis of soil in the 10- to 16-foot interval showed the average hexavalent chromium concentration was approximately 2 mg/kg of soil. Following treatment, this concentration did not change appreciably. This was attributed to the hydrogen sulfide gas channeling through the more permeable white sand on top and bypassing the less permeable brown sand. From the sampling completed from 17 boreholes at the site, it was concluded that approximately 70% of the mass of hexavalent chromium present had been reduced to its trivalent state (Ref. 3). This demonstration at the WSMR was considered successful and it was felt the remaining hexavalent chromium could be reduced by adding another injection well screened over the 10- to 16-feet below-surface interval.

This field trial at HELSTF contained only one cell in the field network because it was research rather than a full-blown remediation. This LCCM was designed to calculate the total number of cells necessary to remediate an entire site based on the physical characteristic inputs. Although this model does not take this into consideration, it would be possible to install cells as necessary and move the gas treatment system from one area to the next rather than scaling the system to cover the entire contaminated area. However, moving the equipment and extending the remediation time might not result in further cost savings and would need to be determined separately from this model.

Table 3-1, which was obtained from PNNL provides a summary of the actual costs for completing the ISGR field trial at the WSMR in New Mexico. While these costs were higher than expected, field demonstration costs generally are substantially higher than actual remediation costs. The main reason for this is the excessive sampling and oversight required to monitor the effectiveness of the innovative technology. In addition, higher safety, environmental, and reporting requirements need to be met, which further burdens the overall costs associated with a technology being demonstrated in the field.

**Table 3-1. Summary of ISGR technology demonstration costs.**

<b>TASKS</b>	<b>COSTS (\$)</b>
Development of Gas Treatment System	49K
Pretest Characterization and Wellfield Installation	72.5K
Laboratory Treatability Study and Geotechnical Test	9K
Tracer Test	41K
Test Prep., Performance of Injection Test, and Posttest Characterization	545K
Project Reporting and Site Closure	100K
<b>TOTAL COST</b>	<b>817K</b>

Some costs of the WSMR demonstration represent duplication of effort due to the presence of various subcontractors including Sandia National Laboratory (SNL), Mevatec, Westinghouse Hanford Company (WHC), and the WSMR-HELSTF. Since PNNL staff were operating a project located off site from their home base, travel and labor costs were higher than would normally be expected had the project been overseen by personnel at the same location.

While these actual costs should be kept in mind when developing future projects using ISGR, costs for a future site remediation should be considerably lower due to a reduced learning curve. Also since this demonstration treated a small area containing hexavalent chromium, larger contaminated areas would have a lower per unit cost due to economies of scale. Another factor that added to the total costs for this specific project was delays made by the State of New Mexico in requesting further information and public comment. This resulted in more documentation, travel, and labor than usual because of the uncertainty associated with using a technology that had not been tested outside of the laboratory.

For more detailed actual costs, see Appendix A.

### 3.2 HANFORD SITE 183-DR FACILITY

In FY99, a joint effort between PNNL and Bechtel Hanford Inc. was made to deploy ISGR at the former 183-DR facility on the Hanford Site (Ref. 4). This facility was once used as a water treatment plant for the 100-DR reactor. A significant groundwater plume containing hexavalent chromium has been observed in this area. Based on this, it was assumed the source of this contamination was contained at this site.

A preliminary plan was developed to drill boreholes and collect samples for laboratory analysis. In the event chromium was detected, ISGR would be fully deployed, and one of the boreholes installed during the characterization phase would be used as the injection well. The decision to proceed with this project was dependent on locating the source of contamination after drilling no more than two boreholes.

During the preliminary characterization of the site, two boreholes were drilled and samples were taken for laboratory analysis. Each borehole was drilled to a depth of 80 feet at a total cost of approximately \$40,000, or a unit cost of approximately \$500 per foot.<sup>1</sup> However, the project was stopped after the samples taken from the two boreholes installed showed no sign of chromium contamination in the soil. Therefore, because the source of groundwater contamination was not discovered, this project was discontinued until some future date. More detailed costs for installing the two characterization boreholes at the Hanford Site are shown in Table 3-2.

*Table 3-2. Summary of characterization borehole costs.*

Description	Total Cost	Cost Per Well
Drilling Subcontract	\$169,000	\$21,125
Waste Management	\$32,855	\$4,107
Field Support	\$121,200	\$15,150
TOTAL	\$323,055	\$40,382

Had this source been located, ISGR was expected to have been deployed using a cell comprised of six extraction wells installed around the injection well. Based on information obtained from previous site characterizations completed, it is expected that the extent of contamination may be over an area of approximately 90,000 square feet (Ref. 4). Because the ISGR cell used in this case is expected to have an ROI of approximately 50 feet, it has been assumed that a total of 10 cells may be necessary to complete the remediation of this site. It is also assumed the zone of contamination may be as deep as 80 feet below surface, making it impractical and very expensive to excavate. It is anticipated that funding will be provided in FY01 to continue trying to locate the source of contamination and continue with the ISGR project at the Hanford Site.

## 4. LIFE-CYCLE COST MODEL

An LCCM was developed to provide cost estimates for using the ISGR in treating hexavalent chromium-contaminated soil. The ISGR section of this model is based on data obtained from a single field demonstration that was completed at a site located at the HELSTF within the WSMR. This limited amount of data was used to build this scalable cost-estimating tool using Microsoft Excel™ software.

Because of the limited data available, this model has a high level of uncertainty. When compared to the costs estimated by this model, actual costs for contaminated sites with different characteristics and size may vary widely. This LCCM can be updated as more cost data becomes available from other sites, which should reduce the level of uncertainty. It is anticipated that funding will become available in FY01 to continue with the characterization of the 183-DR facility at the Hanford Site. Should this ISGR project be completed in the future, the cost data from it can be added to this LCCM database.

In addition to estimating costs associated with using ISGR, this model also provides cost estimates for the baseline technology, excavation and disposal. The purpose of this is to provide a cost comparison between the innovative technology and the established technology to help in deciding which process should be used to treat contaminated soil.

Costs for excavation and disposal can vary widely from site to site depending on the subsurface characteristics, depth, and safety level. Because of this, the excavation and disposal section of the model is scaled based on several parameters associated with mining. Cost data used to create this excavation section was obtained from cost guides produced by Western Mine Engineering, Inc. Expenses associated with mining but not environmental excavation were removed to reflect costs as accurately as possible.

### 4.1 INPUTS

Values that must be entered into the model include the length, width, and depth of the contaminant plume; the soil bulk density; and the discount rate. These inputs are used in the calculations for both the ISGR and excavation and disposal technologies. These values can be entered using the scroll bars or by manually entering into the adjacent cell shaded in blue.

To manage the complexity of the model, a parameter that may have more than one value (such as the soil bulk density) is entered as an average value. Because of this, the more homogenous the soil geology, the lower the overall error in the total costs estimation. All measurements of length are considered to be in feet and must be input using this unit. Bulk density is in pounds per cubic foot, and the discount rate is entered as a percent. In addition, the cursor can be placed in the spreadsheet cells containing red flags to invoke popup menus that provide further information to clarify input and output values.

#### 4.1.1 In Situ Gaseous Reduction

Inputs for the ISGR section of the model include the mass of hydrogen sulfide required, ROI, per foot cost to drill and install a well, hydrogen-sulfide concentration, injection rate, and the extraction flow rate. These values are determined during lab testing and preliminary site characterization. This model assumes the majority of site characterization has been completed; therefore, these sunk costs are not taken into consideration. However, ISGR requires further characterization that consists of two

preinjection and two postinjection boreholes and soil sample analysis. The total costs for each sampling and analysis is expected to be approximately \$12,500 and is included in the ISGR costs.

The amount of hydrogen sulfide required depends on the soil matrix and the amount of contaminant in the ground. This value is determined in the laboratory by passing hydrogen sulfide through a known amount of soil until breakthrough is reached. The amount of sulfide gas required depends on the contaminant concentration and the reducing capacity of the soil. Soils containing other metals and organic compounds will consume larger amounts of the reducing agent. This value must be entered in pounds so the model will operate properly. The cost of a treatability laboratory study is approximately \$10,000 and takes approximately 1 month to complete.<sup>1</sup>

Due to the wide variation in costs associated with well installation, this value in the model is an input. This is a per foot cost for drilling and installation that includes labor and materials. Although this cost at WSMR was relatively low at approximately \$133 per foot, certain sites such as Hanford can range from \$275 per foot to \$1,590 per foot depending on the geology and contamination.<sup>3</sup>

Hydrogen-sulfide concentration is the amount of hydrogen sulfide in ppm after being diluted with air. This is the concentration at which the sulfide gas is injected into the subsurface. Due to safety concerns, it is recommended the concentration of hydrogen sulfide being injected should not exceed 300 ppm.<sup>1</sup>

Preliminary field testing and engineering must be completed to determine the ROI, the extraction and injection flow rates, and the other soil characteristics. A larger ROI results in a larger area being covered, which potentially reduces the number of wells necessary. In general, the total extraction rate should be 50% or more than the injection rate. The rate at which hydrogen sulfide can be injected into the soil is affected by the soil permeability. The sulfide gas can be injected at greater rates into soils with high permeabilities. When higher injection rates are achievable, the reducing agent can be applied at a faster rate and the time to treat the soil can be reduced. The average ROI must be entered in feet and the flow rates in cubic feet per minute. Also, the injection and extraction rate inputs are averages per well. The total rates are calculated by the model based on the calculated number of wells required. If the total extraction rate is less than the injection rate, an error message reading "Warning! Total extraction rate must be greater than total injection rate." appears. Once the user makes appropriate adjustments to these rates, the error message disappears.

#### **4.1.2 Excavation and Disposal**

Factors that need to be entered in the model for the excavation and disposal section include the production rate, number of shifts worked, and safety level. The production rate needs to be based on the amount of contaminated material excavated in an 8-hour shift due to the way the model was set up. The number of shifts worked per day is used to adjust for an excavation project that operates for more than an 8-hour period. For example, if excavation occurs for 12 hours each workday, 1.5 should be entered for the number of shifts worked per workday. The data used to calculate costs also assumes a standard 5-day workweek.

The safety level can be entered using the dropdown menu or entered manually. This value affects the equipment and labor productivity rate and therefore the overall costs. For example, the higher the safety level, the longer the project will take; consequently, the higher the operating and maintenance

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<sup>3</sup> Thornton, Edward, PNNL – Hanford, personal communication, August 26, 1998.

(O&M) costs. Safety levels are ranked from A to E with A requiring the highest level of safety and E the lowest. For ease in entering the safety level, a key is provided at the bottom of the input sheet.

Although this model will estimate the cost for excavating a site at any depth, excavating to a depth of over 20 feet is considered impractical.<sup>1</sup> Also, the calculated costs associated with excavation assume that all necessary equipment is purchased. To decrease excavation unit cost, smaller sites may want to lease excavating equipment.

## **4.2 OUTPUTS**

Once the necessary inputs are entered, the model calculates the estimated time to remediate, capital costs, annual O&M costs, total costs, and the net present value (NPV) of costs. These estimated values are the result of calculations made by the spreadsheet and are listed in the cost comparison section as outputs. In this section, the remediation time and costs for both excavation and gaseous reduction are given as outputs for comparison purposes. Limited data and varying site conditions make necessary extrapolations difficult for scalable cost-estimating models. Therefore, the input values entered should be as accurate as possible to reduce the overall error.

All cost data used in this model was derived from PNNL sources based on the rates for the HELSTF ISGR project. Because costs rates and soil characteristics vary widely from site to site, actual costs for ISGR projects at other facilities may be different from the actual costs incurred for the HELSTF project.

### **4.2.1 In Situ Gaseous Reduction**

The estimated time to treat is the product of the total amount of hydrogen sulfide required to treat a specific volume of soil over the amount of sulfide gas injected per day. The total amount of gas required is derived from the total volume of soil requiring treatment and the mass of hydrogen sulfide necessary to reduce 1 pound of soil. The amount required to reduce 1 pound of soil is site specific and is determined by preliminary laboratory testing. The hydrogen sulfide injection rate is calculated using the gas concentration and the injection flow rate inputs. Several conversion factors are used to convert this value into total pounds of hydrogen sulfide injected per day. The final output given on the spreadsheet is total time to treat the contaminated site in weeks and years using ISGR.

Total capital and startup costs include the total costs to install and decommission the wells, the gas treatment system, and the required costs to design and start up the system. Cost per well is calculated using the cost per foot for drilling and well installation input and the depth per well input. Total well installation costs are the product of the cost per well multiplied by the total number of wells required. The total number of wells required is based on the total surface area above the plume and the average ROI input for the wellfield. From these values, the total number of wells required to cover the entire plume can be calculated assuming a hexagonal wellfield pattern is used for each cell (see Figure 2-3).

The gas treatment system cost is determined using PNNL cost data and is scaled by applying a commonly used project scaling tool, the engineering six-tenths rule and the total extraction flow rate (Ref. 5). A capacity of 288 cubic feet per minute was used in the denominator of the ratio for scaling the equipment, and the base cost of \$25,000 was used for the gas treatment system operating at this rate. This base cost includes purchasing system components and fabrication. The gas treatment system consists of the injection and extraction pumps, scrubber, water knockout tank, instrument panel,

gauges, and gas cabinet mounted on a skid. The system installation includes monitoring, installation, and the necessary piping.

The equation for the engineering six-tenths rule used to scale the offgas treatment system in this model is as follows:

$$C_{p,v,r} = C_{p,u,r} \left( \frac{v}{u} \right)^{0.6}$$

Where:

$C_{p,v,r}$  is the estimated purchase price of the equipment that has a size or capacity of  $v$  in the year  $r$ .  
 $C_{p,u,r}$  is the purchase price of the same type of equipment in the same year but of capacity or size  $u$ .  
The 0.6 exponent is applied to the capacity ratio to relate the cost of one size to another. The 0.6 is based on an average of exponents derived from a database of completed projects.

Capital costs associated with the project design and engineering are based on the estimated time an engineer would be required. The cost of \$125,000 reflects one full-time engineer with a fully loaded hourly rate of approximately \$60 per hour for 1 full year. Some of this engineer's time is required before treatment begins for further site characterization and for obtaining necessary permits and other documents. Additional time is necessary for overseeing the startup and managing the project until all system problems have been resolved.

Annual O&M for the ISGR technology includes costs for personnel, system maintenance, electricity, chemical, and waste disposal. Personnel costs assume it required one-quarter of one full-time technician to operate the system each year. The technician's work would include taking instrument readings, monitoring the system, and performing basic maintenance. The technician adds a cost of \$26,000 per year based on the quarter-time status and a loaded hourly rate of \$50 per hour.

Costs to maintain the system are calculated using PNNL's estimate of 5% of the total cost of equipment. Electricity costs assume the system is running 24 hours per day, 365 days per year, with 5 scheduled down days for maintenance. Electricity consumption is based on two pumps with a total of 20 horsepower using 14.9 kilowatts of power. The cost of electricity is based on Hanford rates of \$0.12 per kilowatt hour. The total amount of electricity used by the extraction and injection pumps is then scaled using the total number of pumps being used.

Chemical costs include the expense for the hydrogen-sulfide reducing agent and the sodium-hydroxide scrubber solution. This amounts to \$5 for every pound of hydrogen sulfide used to reduce the hexavalent chromium contained in the soil, which is then converted to an annualized basis.

In addition to contaminated soil removed from the subsurface during borehole drilling and testing activities, spent caustic solution is the only waste product generated by this ISGR process. For every pound of hydrogen-sulfide gas used, approximately 3.75 gallons of 0.1 normal sodium hydroxide is required in the scrubber system. The waste disposal cost is the product of the total estimated volume of spent caustic solution and the estimated \$10 per gallon it costs to dispose of it. This total cost is then converted to an annualized basis.

Total costs for ISGR are the estimated capital and startup costs plus the total O&M costs for the projected life of the project. For projects with varying remediation times to be fairly compared, it is necessary to convert these costs to NPV costs. The total NPV costs is the sum of the present value of capital plus the future O&M costs. The discount rate input is used to discount the future operating

costs to present value costs. From the NPV of costs and the total volume of soil being treated, the unit cost per cubic yard of soil is calculated.

#### 4.2.2 Excavation and Disposal

Excavation of contaminated material is similar to mining. Therefore, baseline costs were approximated by using capital and operating costs from hypothetical mining operations. The mining costs were readily available and scalable as well as comparable to excavation and disposal remediation costs. Items associated with mining that are irrelevant to a site remediation using excavation, such as blasting, were excluded from capital and operating costs. The total time to remediate using excavation and disposal is calculated using the total volume of contaminated soil and the production rate per day.

The Western Mine Engineering, Inc., cost estimating book with annual updates was used to model capital and operating costs (Refs. 6 and 7) for the excavation section of the model. The costs were determined for different hypothetical mines operating at different production rates. Four data sets of 250, 500, 1,000, and 2,000 metric ton of contaminated soil removed per day were used for calculating the costs. Associated capital and operating costs significant to the remediation operation were kept in the data analysis (i.e., trucks and excavator), and costs implicitly associated with a mine operation (i.e., blasting truck and blasting powder) were removed.

A stripping ratio of 1:1 was assumed for excavation. In other words, for every cubic yard of contaminated soil excavated, a cubic yard of clean soil or overburden would need to be excavated. This assumption accounts for the additional excavation necessary to remediate larger sites, [i.e., the additional amount of clean material to be excavated to provide the angle of repose necessary to alleviate sloughing of the excavation walls (per Occupational Safety and Health Association standards for soil type)].

For capital costs, it was assumed that equipment purchases would be necessary to remediate up to the next level of data available. For example, if the production rate of contaminated soil removed is 300 metric ton per day, the capital costs of equipment would lie between the data set of 250 and 500 metric ton; therefore, the capital costs for the 300 metric ton would equal the 500-metric-ton costs. The model assumes that it would be necessary to buy additional equipment to complete the job in a reasonable timeframe, and although equipment would usually be leased for smaller excavation projects, this LCCM does not take this into account.

The O&M costs for the excavation and disposal baseline technology were calculated using linear regression. The independent variable is the production rate in metric ton per day excavated and the dependent variable is the O&M costs in dollars per metric ton. The linear regression equation is:

$$COST = -0.00493 \left( \frac{MT}{day} \right) + 11.44$$
$$R^2 = 0.8273$$

To calculate the O&M costs for a year, it was assumed that the amount of time in one work year is 260 days. The data from which the analysis is taken uses the same assumption; however, the total hours worked can be adjusted in the input sheet by changing the number of shifts worked in a day. For most remediation projects involving excavation and disposal, work is performed on a 5-day, 1-shift cycle.

Cost data used in the model for the disposal costs of contaminated material was obtained from costing books (Refs. 8 and 9) and an MSE Technology Applications, Inc., database. Data for waste disposal was separated into five classes according to safety level. The user chooses the appropriate safety level on the data input sheet. The costing book data is a range of values given as dollars per cubic yard. An average value was calculated from the ranges to be used in this analysis. The volume of contaminated soil is calculated based on the physical characteristics of the contaminant plume. Disposal costs are dependent on the safety level; the higher the safety level, the more expensive the disposal costs.

Once the capital and annual operating and disposal costs are calculated, the NPV of costs is calculated using the discount rate input. This NPV calculation is dependent on this discount rate and the time required to complete the project. From the NPV of costs and the total volume of soils excavated, the unit cost per cubic yard of soil is calculated. These values, as well as the values calculated for the ISGR technology, are summarized in the output section of the model for comparison.

## 5. CONCLUSION

Following are some general conclusions that can be drawn regarding the use of ISGR to remediate a site contaminated with hexavalent chromium. When one input variable in the model is changed to observe the effects on the output values, all other variables are assumed to be held constant. In addition, using extreme (unrealistic) values may also yield results that invalidate these observations.

In this section, figures illustrate what effects varying one of the model inputs has on the NPV of the life-cycle cost in the form of per yard unit costs. Figure 5-1 shows the inputs used to create sensitivity analysis tables from which these graphs are based. These sensitivity tables are shown in Appendix B. The following sections identify which input values in the LCCM are varied in the sensitivity analysis and the effect this variation has on the unit cost.

Figure 5-2 illustrates the effect that varying the amount of hydrogen sulfide required to reduce a pound of soil has on the unit cost for each technology. All of the other input variables were held constant. This chart demonstrates that under the given conditions, the ISGR is more cost effective in treating soils requiring approximately 0.001 pounds of hydrogen sulfide or less to reduce the hexavalent chromium in a pound of soil. For soils requiring greater than 0.001 pounds of sulfide gas, excavation and disposal is more cost effective. The reason for this higher cost for the ISGR technology is the larger chemical consumption and an increase in the time required to treat the soil. However, this time, and therefore costs, could be reduced by increasing the flow rates (if possible).

The ROI also affects the costs associated with using ISGR to reduce toxic chromium. A smaller ROI will require a much larger well network to cover a given area contaminated. This increases the capital costs because of the additional injection and extraction wells and pumps required. In addition, operating costs increase due to the greater demand for electricity to run a larger system. Figure 5-3 shows how the ROI affects the unit cost for the ISGR technology. With an average ROI greater than 10 feet, ISGR is significantly less expensive to operate as compared to excavation and disposal under these fixed conditions. With an ROI of less than 10 feet, the fixed unit cost for ISGR approaches that of excavation and disposal.

Well drilling and installation costs have a significant impact on the costs associated with ISGR. Because there is no typical cost for installing a well, the user must first identify this cost for a specific site and then enter it into the input section of the model. These costs depend on the characteristics of the subsurface, the contaminants present, and site-specific cost rates. For this particular case, a site with a total well installation cost of \$1,000 per foot or greater would be more cost-effectively treated using excavation and disposal. Because ISGR is a fairly capital intensive process, the cost of installing wells at this rate would be cost prohibitive. With installation costs less than \$1,000 per foot, ISGR would be a cost-effective way to treat chromium contaminated soil (see Figure 5-4).

While excavation and disposal of contaminated soil is straightforward, there are certain risks associated with this procedure. The potential for workers being exposed to the contaminant increases as do the risks associated with transporting a hazardous waste. Processes such as ISGR that treat the contaminant in place reduce and sometimes eliminate these risks associated with the baseline technology. On the other hand, there are certain risks associated with using an innovative technology, such as ISGR, with limited field testing. Although the gas-injection phase of this field demonstration at the WSMR was safely completed, the effectiveness of the field demonstration has not yet been determined. In addition, it is difficult to determine how well this technology is working until after the gas-injection phase and the postinjection testing is completed. Improved subsurface monitoring equipment would help reduce this uncertainty.

## Cost Comparison of In Situ Gaseous Reduction and the Baseline Excavation

### Inputs

USE SCROLL BARS OR ENTER VALUES INTO HIGHLIGHTED CELLS.

ENTER THE PHYSICAL CHARACTERISTICS OF CONTAMINANT PLUME BELOW.

Length  feet  
 Width  feet  
 Depth  feet  
 Soil Bulk Density  lbs/ft<sup>3</sup>  
 Enter Discount Rate  %

### ISGR Cost Estimating - Includes operating, capital, and startup costs.

Mass of H<sub>2</sub>S Per Pound of Soil  pounds  
 Average Radius of Influence  feet  
 Cost of Well Installation & Drilling  per foot  
 Concentration of H<sub>2</sub>S Injected  parts per million volume (ppmv)  
 Injection Rate Per Well  cubic feet per minute (cfm)  
 Extraction Flow Rate Per Well  cfm per well

### Excavation Cost Estimating - Includes operating, equipment, transportation, and disposal costs.

ENTER ESTIMATED PRODUCTION RATE BELOW. (Production rate must be based on an **8 hour shift per work day**).

Production Rate  yds<sup>3</sup> per 8 hour shift  
 Shifts Worked  per work day

USE DROP DOWN BOX TO SELECT SAFETY LEVEL. SEE THE KEY BELOW FOR ASSISTANCE.

Safety Level (A-E)

- A** Highest level of safety and care required. Example: highly radioactive material
- B** Similar to level A except encap suit not required. Example: low level radioactive waste
- C** Chemical resistant clothing needed. Example: mixed waste
- D** Hard hats, leather boots, safety glasses needed. Example: complex construction
- E** Non-hazardous site has EPA "no hazard" designation. Example: normal construction

### Outputs

Cost Comparison		
Output	Excavation	Gaseous Reduction
Total Time to Treat, weeks	18.8	17
Total Time to Treat, years	0.4	0.3
Total Capital/Startup Costs	\$ 2,045,743	\$ 702,421
Annual O&M/Disposal Costs	\$ 5,614,667	\$ 311,437
Total Costs	\$ 4,070,811	\$ 800,545
Net Present Value of Costs	\$ 4,019,443	\$ 798,163
Unit Costs, \$/yds <sup>3</sup>	\$ 214	\$ 43

**Figure 5-1. Inputs used to create graphs.**

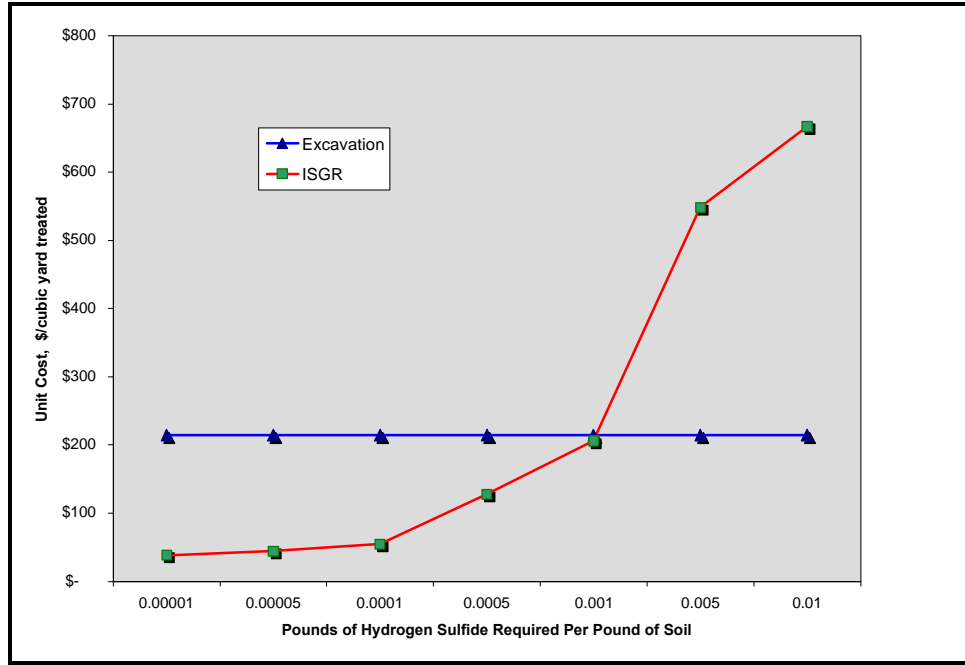


Figure 5-2. Amount of hydrogen sulfide required vs. unit cost to treat soil.

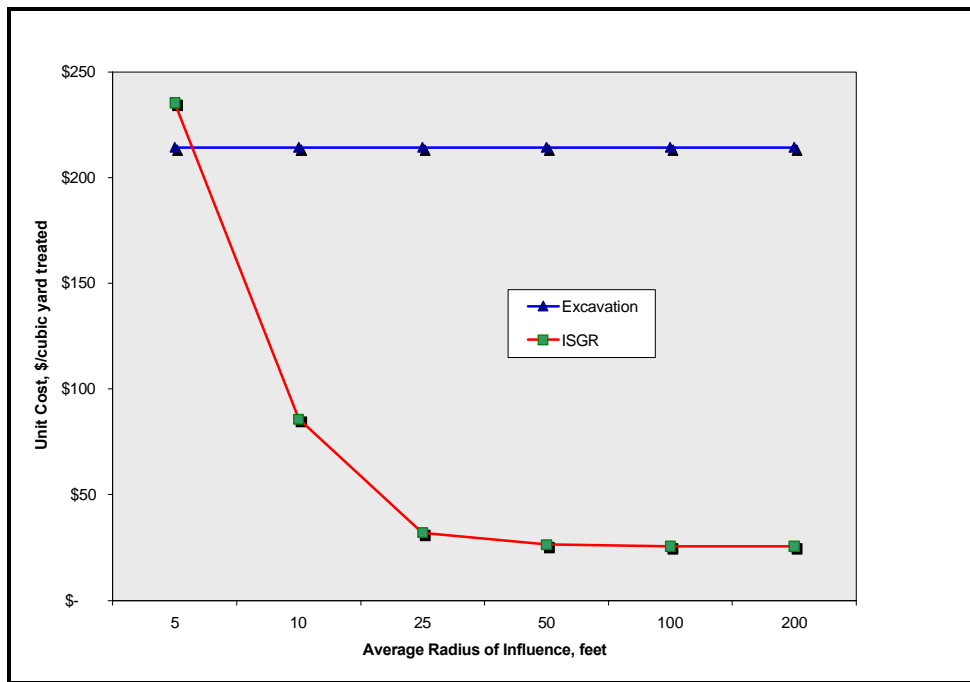
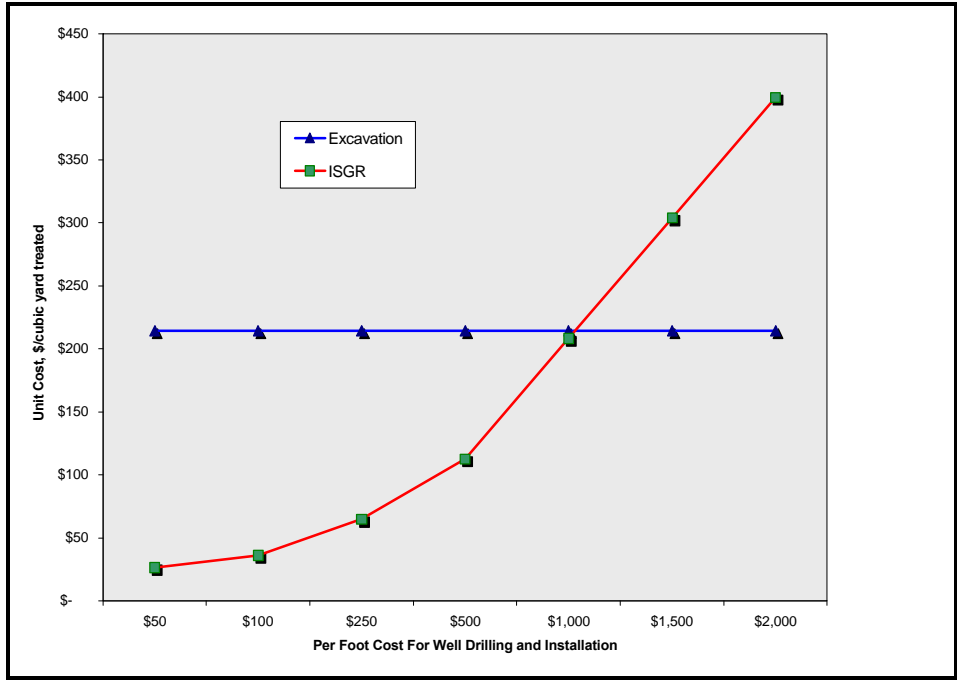


Figure 5-3. Well ROI vs. unit cost to treat soil.



*Figure 5-4. Well installation costs vs. unit cost to treat soil.*

## 6. REFERENCES

1. Thornton, E.C., et al., *Laboratory Evaluation of the Hydrogen Sulfide Gas Treatment Approach for Remediation of Chromate-, Uranium (VI)-, and Nitrate-Contaminated Soils*, Westinghouse Hanford Co., August 1994.
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## **APPENDIX A**

**Actual Costs for Completing the In Situ Gaseous Reduction Field Trial at the White Sands Missile Range**

Table A-1, which was obtained from the Pacific Northwest National Laboratory (PNNL), shows a detailed breakdown of the actual costs for completing the in situ gaseous reduction (ISGR) at the White Sands Missile Range (WSMR) in New Mexico.

**Table A-1. Actual costs for the ISGR field demonstration.**

<b>DEVELOPMENT OF GAS TREATMENT SYSTEM (WHC)</b>	
Design (187hr x \$80/hr)	15K
Fabrication (150 hr x \$60/hr)	9
Material and equipment	19
Blowers and scrubber	5
Water tank	1
<b>SUBTOTAL</b>	<b>49K</b>
<b>PRETEST CHARACTERIZATION &amp; WELDFIELD INSTALLATION</b>	
SNL – three 1-week trips, two technicians (drilling)	13.5K
\$1,000 – travel/trip	
\$3,500 – labor/trip	
Wellfield material (casing, Geoprobe parts, shed, etc)	4
Lab analysis (SNL)	2.5
Lab analysis (WSMR chemist)	2
Mevatec – site support	28
SNL – demo coordinator, two trips	8.4
WHC – PI (two trips), geologist, (one trip)	14.1
<b>SUBTOTAL</b>	<b>72.5K</b>
<b>LABORATORY TREATABILITY STUDY &amp; GEOTECHNICAL TESTS (PNNL)</b>	
Chemist (60 hr x \$80/hr)	4.8K
Technician (60 hr x \$60/hr)	3.6
Material	0.6
<b>SUBTOTAL</b>	<b>9.0K</b>
<b>TRACER TEST</b>	
SNL - 2 weeks field support, one tech	9K
PNNL – 2 weeks, three people	27
Supplies, material, shipping	5
<b>SUBTOTAL</b>	<b>41K</b>
<b>TEST PREPARATION, PERFORMANCE OF INJECTION TEST, POSTTEST CHARACTERIZATION</b>	
<b>SNL</b>	
Engineering analysis	10K
Site utilities	20
Equipment modifications	5
Posttest characterization	
Drilling services	18
Lab analyses (100 samples x \$70/sample)	7

<b>WSMR</b>	
HELSTF support (air modeling, forklift, etc)	10
Chemical lab support (1 week)	5
Communications support (phone lines)	5
WSMR Incidental (generator, fuel, etc)	5
<b>Mevatec</b>	
Waste management	11
Chemical analysis	15
Regulatory/permit activities	7
Site prep/field support	45
Administrative activities	11
<b>FDH</b>	
Gas treatment system and water tank setup	12.2
<b>PNNL</b>	
Labor	232.5
Equipment and material	40.8
Travel	48.1
Program management	16.8
Contract management	14.6
Training	0.4
Hanford services	3.7
Mobile lab shipment	1.7
SUBTOTAL	545 K
<b>Project Reporting &amp; Site Closure*</b>	
Performance assessment & report preparation*	65K
Site closure*	25
Shipment costs*	10
SUBTOTAL (est.)	<u>100K</u>
<b>TOTAL COST</b>	<b>817K</b>

\* Components of the field trial were not completed at the time this report was published and therefore are estimated costs rather than actual costs.

## **APPENDIX B**

### **Sensitivity Analysis Tables**

The following sensitivity analysis tables show how the treatment time and unit costs vary by changes made to a single input in the life-cycle cost model (LCCM). These values are based on the inputs given in Figure 5-1 of the accompanying report, *In Situ Gaseous Reduction Life-Cycle Cost Model*, MSE Report No. ECCP-23, and were used in constructing the graphs contained in that report. This figure demonstrates the large effects the amount of hydrogen sulfide reducing agent, the radius of influence (ROI) of the wells, and the costs associated with installing these wells have on the present value costs for treating a site contaminated with hexavalent chromium.

Shaded areas indicate calculated values.

**Table 1. Varying the size of the plume by length.**

Plume Length, ft	Excavation		IS Gaseous Reduction	
	Time, yrs	Unit Cost, \$/yd3	Time, yrs	Unit Cost, \$/yd3
—————	0.4	\$ 214	0.3	\$ 43
25	0.1	\$ 651	0.3	\$ 99
50	0.1	\$ 378	0.3	\$ 67
100	0.3	\$ 242	0.3	\$ 44
250	0.7	\$ 159	0.4	\$ 33
500	1.4	\$ 130	0.4	\$ 28
1000	2.9	\$ 114	0.4	\$ 26
2000	5.8	\$ 102	0.4	\$ 25
4000	11.5	\$ 90	0.4	\$ 24

**Table 2. Varying the amount of hydrogen sulfide required.**

Lbs of H <sub>2</sub> S per lb of soil	Excavation		IS Gaseous Reduction	
	Time, yrs	Unit Cost, \$/yd3	Time, yrs	Unit Cost, \$/yd3
—————	0.4	\$ 214	0.3	\$ 43
0.00001	0.4	\$ 214	0.1	\$ 39
0.00005	0.4	\$ 214	0.4	\$ 44
0.0001	0.4	\$ 214	0.8	\$ 55
0.0005	0.4	\$ 214	3.9	\$ 128
0.001	0.4	\$ 214	7.8	\$ 206
0.005	0.4	\$ 214	39.2	\$ 548
0.01	0.4	\$ 214	78.4	\$ 667

**Table 3. Varying the average well ROI.**

Average ROI, ft	Excavation		IS Gaseous Reduction	
	Time, yrs	Unit Cost, \$/yd3	Time, yrs	Unit Cost, \$/yd3
—————	0.4	\$ 214	0.3	\$ 43
5	0.4	\$ 214	0.0	\$ 235
10	0.4	\$ 214	0.1	\$ 86
25	0.4	\$ 214	0.6	\$ 32
50	0.4	\$ 214	1.9	\$ 26
100	0.4	\$ 214	3.8	\$ 26
200	0.4	\$ 214	3.8	\$ 26

**Table 4. Varying the per foot cost for drilling and installation of a well.**

Well install & drilling per ft	Excavation		IS Gaseous Reduction	
	Time, yrs	Unit Cost, \$/yd3	Time, yrs	Unit Cost, \$/yd3
	0.4	\$ 214	0.3	\$ 43
\$ 50	0.4	\$ 214	0.3	\$ 27
\$ 100	0.4	\$ 214	0.3	\$ 36
\$ 250	0.4	\$ 214	0.3	\$ 65
\$ 500	0.4	\$ 214	0.3	\$ 113
\$ 1,000	0.4	\$ 214	0.3	\$ 208
\$ 1,500	0.4	\$ 214	0.3	\$ 304
\$ 2,000	0.4	\$ 214	0.3	\$ 400