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SITE Technology Capsule

Unterdruck-Verdampfer- Brunnen Technology (UVB) Vacuum Vaporizing Well

Introduction

In 1980, the U.S. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, committed to protecting human health and the environment from uncontrolled hazardous wastes sites. CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) in 1986 -- amendments that emphasize the achievement of long-term effectiveness and permanence of remedies at Superfund sites. SARA mandates implementing permanent solutions and using alternative treatment technologies or resource recovery technologies, to the maximum extent possible, to clean up hazardous waste sites.

State and federal agencies, as well as private parties, are now exploring a growing number of innovative technologies for treating hazardous wastes. The sites on the National Priorities List total more than 1,200 and comprise a broad spectrum of physical, chemical, and environmental conditions requiring varying types of remediation. The U.S. Environmental Protection Agency (EPA) has focused on policy, technical, and informational issues related to exploring and applying new remediation technologies applicable to Superfund sites. One such initiative is EPA's Superfund Innovative Technology Evaluation (SITE) program, which was established to accelerate development, demonstration, and use of innovative technologies for site cleanups. EPA SITE Technology Capsules summarize the latest information available on selected innovative treatment and site remediation technologies and related issues. These capsules are designed to help EPA remedial project managers, EPA on-scene coordinators, contractors, and other site cleanup managers understand the types of data needed to effectively evaluate a technology's applicability for cleaning up Superfund sites.

This capsule provides information on the Unterdruck-Verdampfer-Brunnen (UVB) in situ groundwater remediation technology, a technology developed to remove volatile organic compounds (VOCs) from groundwater. The UVB system is a patented technology. The developer and patent holder is IEG mbH of Germany, and the United States license holder is IEG™ Technologies Corporation (IEG). The UVB process was evaluated under EPA's SITE program between April 1993 and May 1994 at Site 31, March Air Force Base (AFB) California, where groundwater was contaminated with solvents, including trichloroethylene (TCE). Information in this capsule emphasizes specific site characteristics and results of the SITE field demonstration at March AFB. Results obtained independently by the developer at other sites in the United States and Germany are summarized in the Technology Status section. This capsule presents the following information:

- Abstract
- Technology description
- Technology applicability

SITE
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TECHNOLOGY EVALUATION

- Technology limitations
- Process residuals
- Site requirements
- Performance data
- Technology status
- Sources of further information

Abstract

The UVB technology is an in situ groundwater remediation technology for aquifers contaminated with compounds amenable to air stripping, and is an alternative method to pump-and-treat remediation of groundwater. The UVB technology is designed to remove VOCs from groundwater by transferring the contaminants from the aqueous phase to the gaseous phase and subsequently treating the resulting air stream through carbon adsorption units.

The developer and patent holder is IEG mbH of Germany, the U.S. license holder is IEG® Technologies Corporation. The UVB system consists of a single well with two hydraulically separated screened intervals installed within a single permeable zone. Pumping in the lower section followed by in situ air stripping and reinfiltration in the upper section creates a recirculation pattern of groundwater in the surrounding aquifer. The continuous flushing of the saturated zone with recirculated treated water facilitates the partitioning of adsorbed, absorbed, and free liquid contaminants to the dissolved phase through increased dissolution, diffusion, and desorption. Increased partitioning through these processes is driven by increased groundwater flow rates within the system's radius of circulation cell and increased concentration gradient established by the reinfiltration and recirculation of treated water in the aquifer.

Where applicable, the UVB technology provides an effective long-term solution to aquifer remediation by removing contaminants in the saturated zone without extracting groundwater, lowering the groundwater table, and generating wastewater typical of pump and treat systems. Additionally, once the UVB treatment system is installed and balanced, it requires minimal support from on-site personnel. The UVB technology was evaluated under the SITE program at Site 31, March AFB, where groundwater was contaminated with solvents including TCE.

The demonstration evaluated the reduction of TCE concentrations in the groundwater discharged from the treatment system, the radius of circulation cell of the system, and the reduction of TCE concentrations in the groundwater within the system's radius of circulation cell. The study results showed that the UVB system removed TCE from the groundwater by an average of greater than 94 percent. The mean TCE concentration in water discharged from the system was approximately 3 micrograms per liter (μg/L) with the 95 percent upper confidence limit calculated to be approximately 6 μg/L. The study also indicated that the radius of circulation cell was 40 feet in the downgradient direction and may extend as far as 83 feet based on modeling of the radius of circulation cell in the alluvial aquifer at March AFB by the developer. The radius of circulation cell is largely controlled by the hydrogeologic characteristics of the aquifer and, to a lesser extent, UVB system design. TCE concentrations within the aquifer were reduced laterally by approximately 52 percent in the radius of circulation cell during the 12-month pilot study.

Technology Description

One of the UVB technology designs is an in situ groundwater remediation technology that combines air-lift pumping and air stripping to remove VOCs from groundwater. A properly installed UVB system consists of a single well with two hydraulically separated screened intervals installed within a single permeable zone (Figures 1, 2 and 3). The air-lift pumping occurs in response to negative pressure introduced at the wellhead by a blower. This blower creates a vacuum that draws water into the well through the lower screened portion of the well. Simultaneously, air stripping occurs as ambient air (also flowing in response to the vacuum) is introduced through a sieve plate located within the upper screened section of the well, causing air bubbles to form in the water pulled into the well. The rising air bubbles provide the air-lift pump effect that moves water toward the top of the well and draws water into the lower screened section of the well. This pumping effect is supplemented by a submersible pump that ensures that water flows from bottom to top in the well. As the air bubbles rise through the water column, volatile compounds are transferred from the aqueous to the gaseous phase. The rising air transports volatile compounds to the top of the well casing, where they are removed by the blower. The blower effluent is treated before discharge using a carbon adsorption unit.

The transfer of volatile compounds is further enhanced by a stripping reactor located immediately above the sieve plate. The stripping reactor consists of a fluted and channelized column that facilitates the transfer of volatile compounds to the gas phase by increasing the contact time between the two phases and by minimizing the coalescence of air bubbles. The overall stripping zone of the UVB system extends from the sieve plate to the top

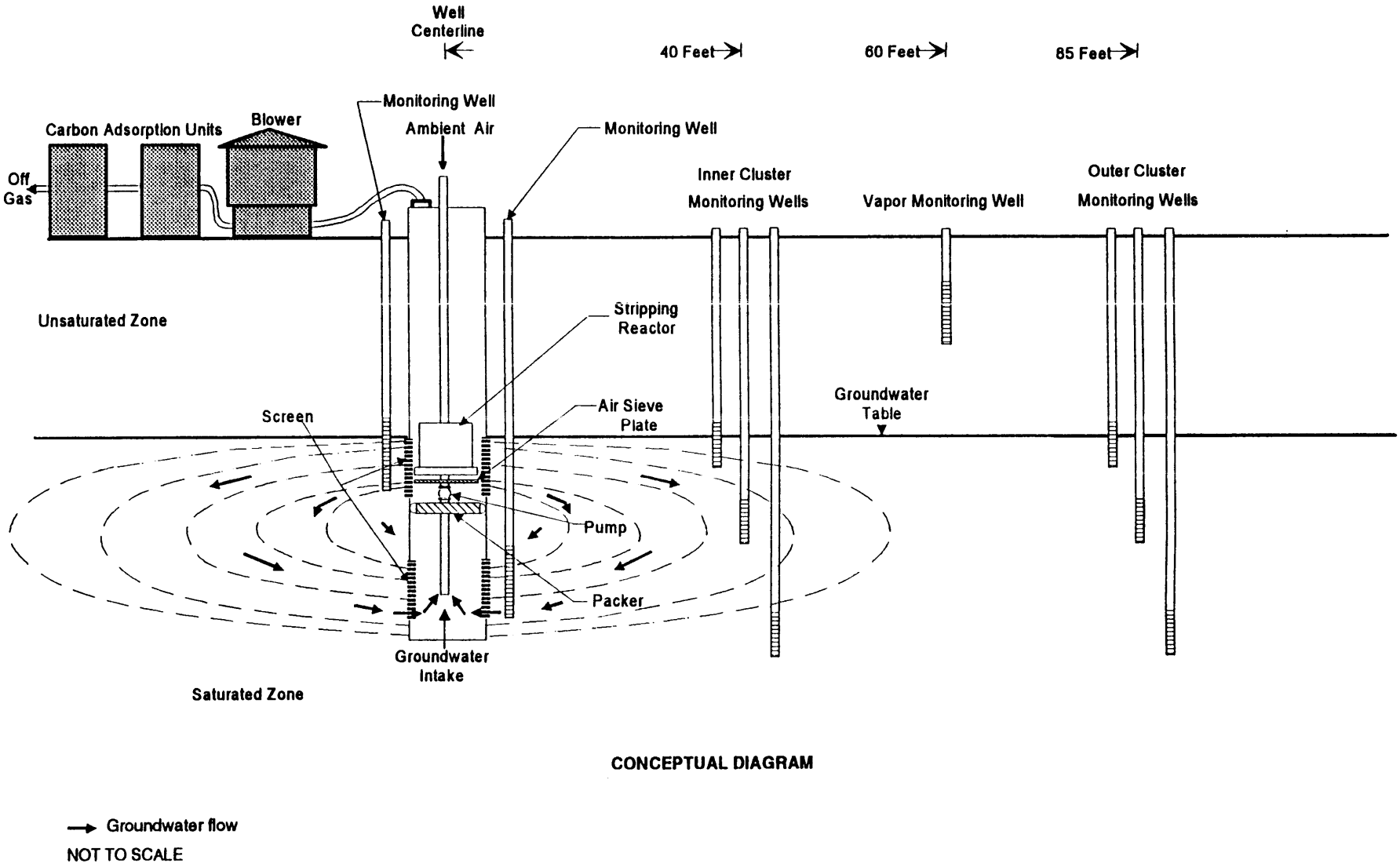


Figure 1: The Unterdruck-Verdampfer-Brunnen Well

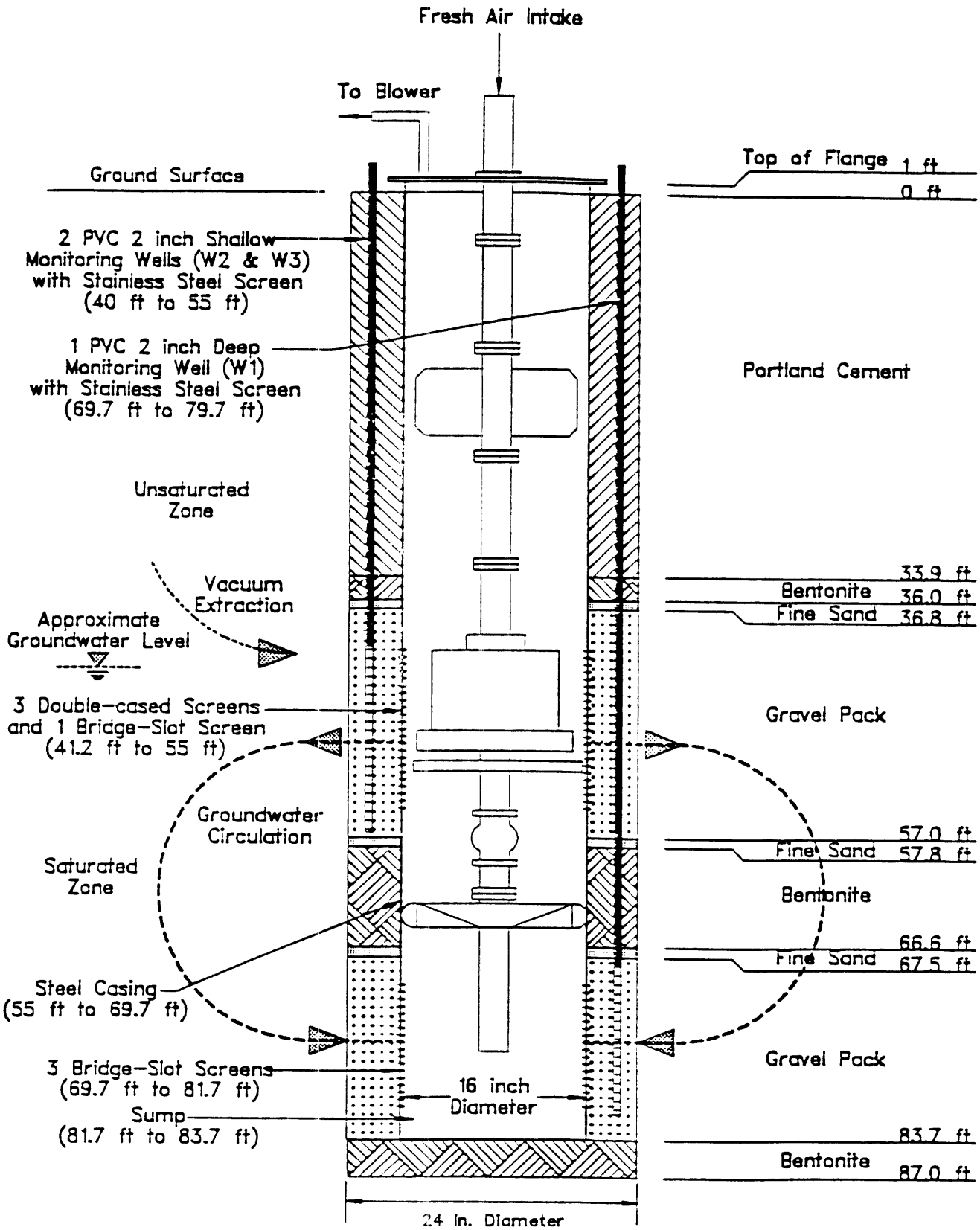
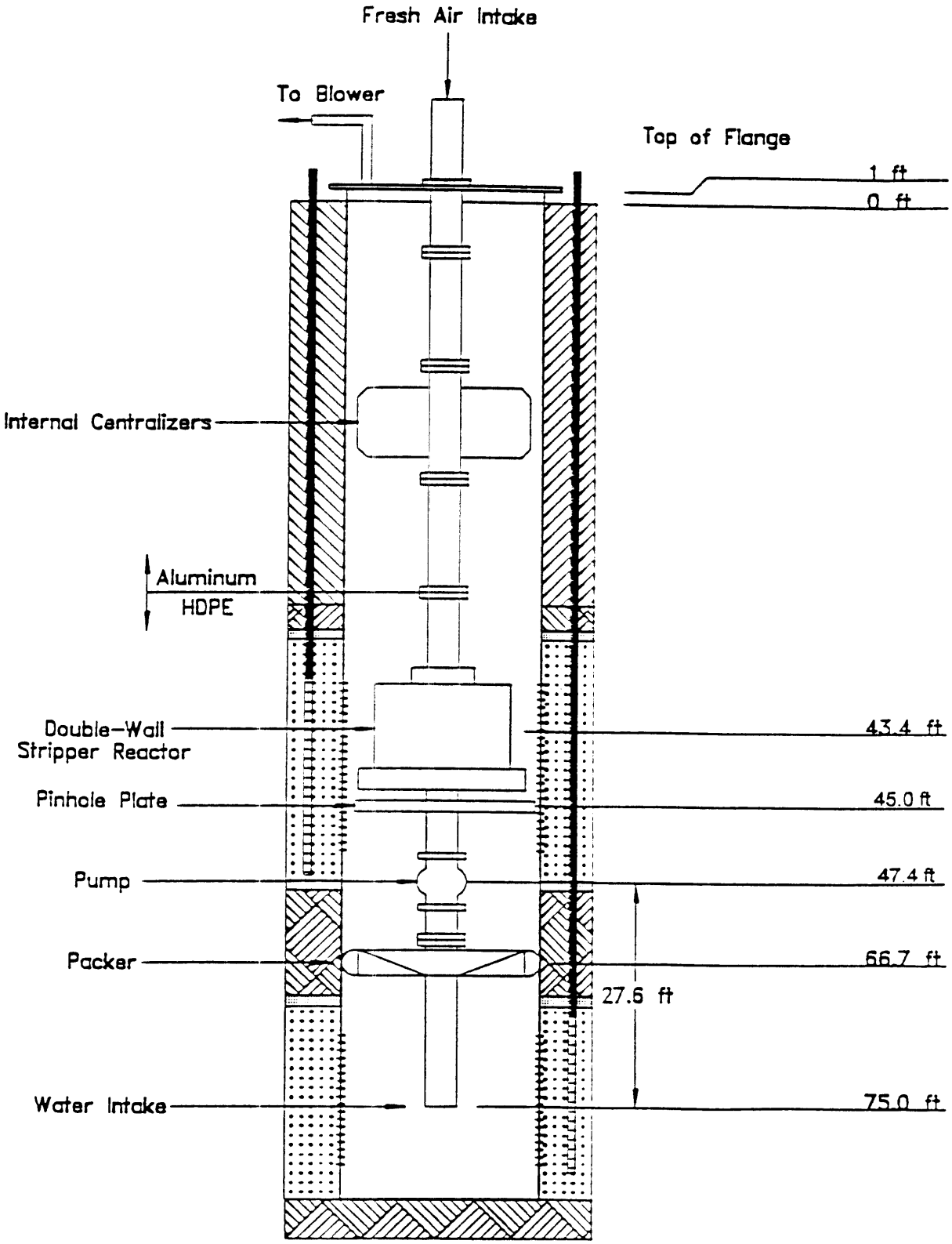


Figure 2: The As-Built Unterdruck-Verdampfer-Brunnen Configuration



HDPE - High Density Polyethylene

NOT TO SCALE

Figure 3: *The As-Built Unterdruck-Verdampfer-Brunnen Internal Components*

of the water column. To maximize volatilization in the stripping zone, the sieve plate and stripping reactor are positioned at a depth that optimizes the reach of the stripping zone and the volume of air flow into the system. The down-well components of the UVB system have been designed with leveling ballast that allows the system to be free floating. This feature allows the system to compensate for fluctuations in groundwater elevation during operation and, thereby, maintain maximum volatilization.

Once the upward stream of water leaves the stripping reactor, the water falls back through the well casing and returns to the aquifer through the upper well screen. This return flow to the aquifer, coupled with inflow at the well bottom, circulates groundwater around the UVB well. The extent of the circulation pattern is known as the radius of circulation cell, which determines the volume of water affected by the UVB system.

The radius of circulation cell and the shape of the circulation pattern are directly related to the properties of the aquifer. The circulation pattern is further modified by natural groundwater flow that skews the pattern in the downgradient direction. Numerical simulations of the UVB operation indicates that the radius of circulation cell is largely controlled by anisotropy (horizontal [Kh] and vertical [Kv] hydraulic conductivity), heterogeneity, aquifer thickness and, to a lesser extent, well design. In general, changes that favor horizontal flow over vertical flow such as a small ratio of screen length to aquifer thickness, anisotropy, horizontal heterogeneities such as low permeability layers, or increased aquifer thickness will increase the radius of circulation cell. As a general rule, the developer estimates the system's radius of circulation cell to be approximately 2.5 times the distance between the upper and lower screen intervals.

Groundwater within the radius of circulation cell includes both treated and untreated water. A portion of the treated water discharged to the upper screen is recaptured within the circulation cell. Treated water not captured by the system leaves the circulation cell in the downgradient direction. The percentage of treated water recycled within the UVB system (IEG estimates that it can be up to 90 percent) is related to the radius of circulation cell and is a function of the ratio of Kh/Kv. The larger the radius of circulation cell and the larger the Kh to Kv ratio values, the smaller the percentage of recycled water for a given aquifer. The recycled treated water dilutes influent contaminant concentrations.

Technology Applicability

The UVB technology's applicability was evaluated based on the nine criteria used for decision making in the Superfund feasibility study process. Results of the evaluation are summarized in Table 1. In general, the UVB technology is applicable for treatment of dissolved phase volatile compounds in groundwater. The developer claims that other UVB system configurations allow for treatment of semi- and non-volatile contaminants and nitrates. In addition, the chemical and physical dynamics established by the recirculation of treated water make this technology suited for remediation of contaminant source areas. The technology employs readily available equipment and materials and the material handling requirements and site support requirements are minimal.

The UVB system demonstrated for the SITE program was designed to remove VOCs from the groundwater, in particular TCE and 1,1-dichloroethene (DCE). The developer claims that the technology can also clean up aquifers contaminated with other organic compounds, including volatile and semivolatile hydrocarbons. According to the developer, the UVB technology in some cases is also capable of simultaneous recovery of soil gas from the vadose zone and treatment of contaminated groundwater from the aquifer as a result of the in situ vacuum. For soil gas recovery, the upper screened portion of the UVB well is completed from below the water table to above the capillary zone. Although the developer claims that the UVB technology reduces VOCs from soil gas in the vadose zone, the technology was evaluated only for its effects in the saturated zone.

Technology Limitations

The UVB technology has limitations in areas with very shallow groundwater (less than 5 ft.). In such areas, it may be difficult to establish a stripping zone long enough to remove contaminants from the aqueous phase. The technology has further limitations in thin aquifers (less than 10 ft.); the saturated zone must be of sufficient thickness to allow proper installation of the system. In addition, the thickness of the saturated zone affects the radius of circulation cell; the smaller the aquifer thicknesses, the smaller the radius of circulation cell.

The majority of water being drawn from the aquifer into the lower screen section is treated water reinfiltrated from the upper section. This recirculation of cleaned water significantly decreases the contaminant levels in the water treated by the system. As the UVB system continues to operate, the circulation cell grows until a steady state is reached. As the circulation cell grows, the amount of recirculated water increases causing a further decrease of contaminant levels in the water treated by the system.

High concentrations of volatile compounds may require more than one pass through the system to achieve remediation goals. This may initially be a problem since a portion of the treated water is not captured by the system and leaves the circulation cell in the downgradient direction.

Table 1: Feasibility Study Evaluation Criteria for the UVB Technology

	CRITERION	UVB TECHNOLOGY PERFORMANCE
1	Overall Protection of Human Health and the Environment	The technology eliminates contaminants in groundwater and prevents further migration of those contaminants with minimal exposure to on-site workers and the community. Air emissions are reduced by using carbon adsorption units.
2	Compliance with Federal ARARs	Compliance with chemical-, location-, and action-specific ARARs must be determined on a site-specific basis. Compliance with chemical-specific ARARs depends on (1) treatment efficiency of the UVB system, (2) influent contaminant concentrations, and (3) the amount of treated groundwater recirculated within the system.
3	Long-Term Effectiveness and Permanence	Contaminants are permanently removed from the groundwater. Treatment residuals (for example, activated carbon) require proper off-site treatment and disposal.
4	Reduction of Toxicity, Mobility, or Volume Through Treatment	Contaminant mobility is initially increased, which facilitates the long-term remediation of the groundwater within the system's radius of influence. The movement of contaminants toward the UVB system within the system's capture zone prevents further migration of those contaminants and ultimately reduces the volume of contaminants in the groundwater.
5	Short-Term Effectiveness	During site preparation and installation of the treatment system, no adverse impacts to the community, workers, or the environment are anticipated. Short-term risks to workers, the community, and the environment are presented by increased mobility of contaminants during the initial start-up phase of the system and from the system's air stream. Adverse impacts from the air stream are mitigated by passing the emissions through carbon adsorption units before discharge to the ambient air. The time requirements for treatment using the UVB system depends on site conditions and may require several years.
6	Implementability	The site must be accessible to large trucks. The entire system requires about 100-700 square feet (average 300). Services and supplies required include a drill rig, off-gas treatment system, laboratory analysis, and electrical utilities.
7	Cost	Capital costs for installation of a single unit are estimated to be $180,000, and annual operation and maintenance costs estimated to be $72,000.
8	Community Acceptance	The small risks presented to the community along with the permanent removal of the contaminants make public acceptance of the technology likely.
9	State Acceptance	State acceptance is anticipated because the UV system uses well-documented and widely accepted processes for the removal of VOCs from groundwater and for treatment of the process air emissions. State regulatory agencies may require permits to operate the treatment system, for air emissions, and to store contaminated soil cuttings and purge water for greater than 90 days.

ARAR - Applicable or relevant and appropriate requirements

However, as the UVB circulation cell is established, the influent concentrations should be diluted to below levels requiring more than one pass, thereby limiting the potential migration of contaminants above target concentrations from the system.

Process Residuals

The materials handling requirements for the UVB system include managing spent granular activated carbon, drilling wastes, purge water, and decontamination wastes generated during installation, operation, and monitoring of the treatment system. Spent carbon generated during treatment of the system air effluent will either be disposed of or regenerated by the carbon vendor. The drilling wastes are produced during installation of the system well. The drilling waste can be managed either in 55-gallon drums or in roll-off type debris bins. Disposal options for this waste depend on local requirements and on the presence or absence of contaminants. The options may range from on-site disposal to disposal in a hazardous waste or commercial waste landfill.

Purge water is generated during development and sampling of the groundwater monitoring wells. Purge water can be managed in 55-gallon drums. Disposal options again depend on local restrictions and on the presence or absence of contaminants. Options range from surface discharge through a National Pollutant Discharge Elimination System (NPDES) outfall, to disposal through a Publicly Owned Treatment Works (POTW), to treatment and disposal at a permitted hazardous waste facility.

Decontamination wastes are generated during installation and sampling activities. Decontamination wastes generated during installation include decontamination water and may include a decontamination pad for the drill rig. The solid decontamination wastes can be managed in roll-off type debris boxes, and the liquid wastes can be managed in 55-gallon drums. Disposal options are similar to those for drilling wastes and purge water.

Site Requirements

A UVB treatment system consists of several major components: an 8, 10, 16, or 24-inch dual screen well, well packer, submersible pump, sieve plate, stripping reactor, blower, and carbon filter units. A drill rig is required to install the system well. Once the well has been completed, the treatment system can be operational within 1 day if all necessary equipment, utilities, and supplies are available.

The site support requirements needed for the UVB system are space to set up the carbon adsorption units and electricity. The system requires standard 120/240 volts (200 amperes). An electrical pole, a 480-volt transformer, and electrical hookup between the supply lines, pole, and the UVB treatment system are necessary to supply power. The space requirements for the above-ground components of the UVB system including the UVB system well, off-gas treatment units, blower, and piping used during the SITE demonstration are approximately 500 square feet. Other requirements for installation and routine monitoring of the system include access roads for equipment transport, security fencing, and decontamination fluids for drilling and sampling.

Performance Data

The SITE demonstration for the UVB technology was designed with three primary and seven secondary objectives to provide potential users of the technology with the necessary information to assess the applicability of the UVB system at other contaminated sites. Demonstration program objectives were achieved by collecting groundwater and soil gas samples, as well as UVB system process air stream samples over a 12-month period. To meet the objectives, data were collected in three phases: baseline sampling, long-term sampling, and dye trace sampling. Baseline and long-term sampling included the collection of groundwater samples from eight monitoring wells, a soil gas sample from the soil vapor monitoring well, and air samples from the three UVB process air streams both before UVB system startup and monthly thereafter. In addition, a dye trace study was conducted to evaluate the system's radius of circulation cell. This study included the introduction of fluorescent dye into the groundwater and the subsequent monitoring of 13 groundwater wells for the presence of dye three times a week over a 4-month period.

The conclusions of the UVB SITE demonstration at March AFB are presented below by project objective.

Primary Objectives:

P1 *Determine the concentration to which the UVB technology reduces TCE and DCE in groundwater discharged from the treatment system.*

The UVB effectively removed target compounds from the groundwater as indicated by the analytical results presented in Table 2. During the demonstration, TCE concentrations in samples from the influent well ranged from 14 μg/L to 220 μg/L with an arithmetic mean of approximately 56 μg/L. The UVB system reduced TCE in the groundwater discharged from the treatment system to below 5 μg/L in nine out of the 10 monthly monitoring

events and on average by greater than 94 percent during the period in which the system operated without apparent maintenance problems. The mean concentration of TCE in the water discharged from the system was approximately 3 μg/L; however, the 95 percent upper confidence limit for TCE in the treated groundwater was calculated to be approximately 6 μg/L.

The UVB system reduced DCE to less than 1 μg/L in groundwater discharged from the treatment system; however, the system's ability to remove DCE cannot be meaningfully estimated due to the low (less than 4 μg/L) influent concentration of DCE.

P2 *Estimate the radius of circulation cell of the groundwater treatment system.*

The radius of circulation cell of the groundwater treatment system was estimated by both direct and indirect methods. The radius of circulation cell was directly measured by conducting a dye trace study. Based on the dye trace study, the radius of circulation cell was measured to be at least 40 feet in the downgradient direction. However, no dye was observed in wells located 40 feet upgradient or cross gradient of the UVB system. The radius of circulation cell was indirectly evaluated by (1) modeling the groundwater flow, and (2) analyzing aquifer pump test data. Groundwater flow modeling results conducted by the developer indicate a radius of circulation cell of 83 feet. Analysis of aquifer pump test data indicates a radius of circulation cell of about 60 feet for a traditioned pumping well near this UVB system. An attempt was made to indirectly evaluate the radius of circulation cell using variations of target compound concentrations and fluctuations of dissolved oxygen in surrounding groundwater monitoring wells. However, these methods did not provide a reliable or conclusive estimate of the radius of circulation cell due to variables independent of the UVB system.

P3 *Determine whether TCE and DCE concentrations have been reduced in groundwater (both vertically and horizontally) within the radius of circulation cell of the UVB system over the course of the pilot study.*

Based on the demonstration results presented in Table 2, TCE concentrations in samples from the shallow and intermediate zone wells were reduced both vertically and laterally except in the intermediate outer cluster well, which showed an increase in concentration. TCE concentrations have been reduced laterally by an average of approximately 52 percent in samples from the shallow and intermediate zones of the aquifer. No reduction of TCE was observed in samples from the deep zone, which could be due to limited duration of monitoring in this zone.

Secondary Objectives:

S1 *Assess homogenization of the groundwater within the zone of influence.*

A convergence and stabilization of TCE concentrations was observed in samples from the shallow and intermediate zones of the aquifer, which suggest homogenization of contaminant concentrations in the groundwater.

S2 *Document selected aquifer geochemical characteristics that may be affected by oxygenation and recirculation of treated groundwater.*

No clear trends in the field parameters, general chemistry, or dissolved metals results were observed that would indicate significant precipitation of dissolved metals, changes in dissolved organic carbon, or the presence of dissolved salts caused by the increase in oxygen in groundwater.

S3 *Determine whether the treatment system induces a vacuum in the vadose zone that suggests vapor transport.*

Although the developer claims that the UVB system has applications to cleanup of both groundwater and soil gas, the system installed at Site 31 was designed to remove halogenated hydrocarbons from the groundwater only. The VOC concentrations and vacuum measurements in the vapor monitoring well indicate that transport of contaminants was not significantly affected by operation of the UVB system as currently designed. Changes in system design and operating parameters may lead to significant transport of contaminants in the vadose zone.

S4 *Estimate the capital and operating costs of constructing a single treatment unit to remediate groundwater contaminated with TCE and DCE.*

Costs are highly site specific. EPA estimates that one-time capital costs for a single treatment unit are $180,000; variable annual operation and maintenance costs for the first year were estimated to be $72,000, and for subsequent years, $42,000. Based on these estimates, the total cost for operating a single UVB system for 1 year was calculated to be $260,000. Since the time required to remediate an aquifer is site-specific, costs have been estimated for operation of a UVB system over a range of time for comparison purposes. Therefore, the cost to operate a single UVB system was calculated to be $340,000 for 3 years, $440,000 for 5 years, and $710,000 for 10 years. Additionally, the costs for treatment per 1,000 gallons of

Table 2: Aquifer Trichloroethene Concentration Summary

Well	Description	Trichloroethene Concentration (µg/L)												
		Baseline	1ST	2ND	3RD	4TH	5TH	6TH	7TH	8TH	9TH	10TH	11TH	12TH
W1	Intermediate System Well	22[a]	57	60	220	35	31	30	22	34	31	14	26	110
W2	Shallow System Well	1[a]	<1	<1	16	2.4	4	<1	<1	38*	2	1	1	69*
Percent Reduction[1]		NC	>98	>98	93	93	87	>97	>95	-12	94	93	95	41
PW1	Shallow Inner Cluster Well	530	500	440	620	608	530	540	600	600	530	300	330	340
PW2	Intermediate Inner Cluster Well	750	1,000	1,900	2,000	1,100	1,200	910	800	620	340	280	240	270
PW3	Deep Inner Cluster Well	100	130	180	310	230	200	250	NA	NA	NA	NA	NA	NA
PW4	Shallow Outer Cluster Well	650	760	760	680	818	980	1,100	1,600	1,400	970	300	340	290
PW5	Intermediate Outer Cluster Well	120	270	310	390	330	350	450	640	360	310	230	210	210
PW6	Deep Outer Cluster Well	110	130	110	130	92	140	150	NA	NA	NA	NA	NA	NA

a Concentration affected by water added during drilling and well installation.

1 Percent reduction = $[[C_{(w-1)} - C_{(w-2)}] / C_{(w-1)}] \times 100$; where $C_{(w-1)}$ = deep well concentration and $C_{(w-2)}$ = shallow well concentration

* Concentration affected by system maintenance problems; therefore, results were not used to evaluate primary objectives.

µg/L Micrograms per liter

< Less than

> Greater than

NC Not calculated

NA Not analyzed

groundwater were estimated to be $260 for 1 year, $110 for 3 years, $88 for 5 years, and $71 for 10 years. The cost of treatment per 1,000 gallons refers to the amount of groundwater pumped through the system. Potential users of the treatment technology should be aware that typically 60 to 90 percent of the water pumped through the system is recirculated water. A more detailed document, the Innovative Technology Evaluation Report (ITER) contains information on the assumption for these cost figures.

S5 *Document pre- and post-treatment off-gas volatile organic contaminant levels.*

The results from air monitoring of the UVB treatment system indicated that low concentrations of TCE were removed from the groundwater. TCE concentrations reduced by the UVB system correlate to trends observed in target compound concentrations in the inner cluster monitoring wells (that is, increasing concentration from the baseline event to the third monthly monitoring event with a subsequent decrease in concentrations).

S6 *Document system operating parameters.*

The temperature of the internal monitoring ports ranged from 18.5 to 44.7 degrees Celsius; the relative humidity ranged from 27 to 100 percent; the vacuum pressure ranged from 13.81 to 15.03 pounds per square inch absolute; the air flow ranged from 100 to 898 standard cubic feet per minute; the air velocity ranged from 1,109 to 9,999 feet per minute; and the discharge through the UVB system was estimated by the developer to be approximately 22 gallons per minute.

S7 *Evaluate the presence of aerobic biological activity in the saturated and vadose zones.*

Carbon dioxide concentrations measured in the vapor monitoring well indicate that carbon dioxide has increased by more than 2 percent since baseline monitoring. Several fluctuations in O2 level were observed; however, there was no evidence of a downward trend of these concentrations. The minor changes in CO2 and O2 measured suggest that bioactivity in the soil and groundwater was not significantly enhanced by operation of the UVB system.

Additionally, CO2 concentrations measured at the UVB system's intake and after the blower reveal minor fluctuations of relative CO2 concentration. These results also suggest that bioactivity due to increased dissolved oxygen levels in the groundwater was not significantly enhanced by operation of the UVB system.

Technology Status

Since its introduction in 1986, the UVB technology has been applied at some 80 sites in Europe. No U.S. installation of a UVB system has required an NPDES permit to date. A UVB system was first installed at a U.S. site in September 1992; currently, there are 22 UVB systems operating in eight states.

A more detailed document, the ITER, contains more information on this documentation, the developer has provided four select case studies that document operation of the UVB system at sites in the U.S. and Germany. Two of the cases are from sites in Germany and involve the remediation of chlorinated hydrocarbons (TCE, 1,1,1-trichloroethane, and dichloromethane) in the groundwater. The two cases from the U.S. document the remediation of groundwater contaminated with benzene, toluene, ethylbenzene, and xylene at an underground storage tank site in Troutman, North Carolina, and Weston's interpretation of the data collected during but independent of this SITE demonstration.

Sources of Further Information

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