

Final Report
Independent Scientific Peer Review

Selected Subsurface Remediation Activities
Savannah River Site

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EXECUTIVE SUMMARY

This report describes the findings and recommendations from a review of selected activities aimed at removing contaminants from the subsurface at the Savannah River Site. The primary focus of the review (90% of the work) is subsurface contamination in the A/M Area. The objective of this part of the review was to critique and develop recommendations related to site characterization activities, clean-up activities, and longer-term goals for addressing the subsurface contamination in this part of the site. A secondary objective (10% of the work) was to develop a list of items that should be considered or done by the site as it prepares to make its transition from Phase I to Phase II at the F&H Area water treatment system.

Excellent work has been accomplished in the cleanup activities at the A/M Area. The Integrated Demonstration Project, for example, enjoys international recognition for contributions related to fundamental and applied research on innovative technologies for characterizing and cleaning soils and groundwater. However, the objective of the review is not to add further praise for what has been done well, but rather to make suggestions regarding what might be done better. These suggestions and recommendations are summarized below.

A. Evaluation of Site Characterization Activities

It has been estimated that roughly 3.5 million pounds of solvents were discharged to the subsurface in the A/M Area. This estimate is based on an assumed evaporation loss within the M-Area Facilities of more than 8 million pounds. Uncertainties in the amount of solvent that was lost to evaporation have not been quantified. These uncertainties have important implications for estimates of the amount of contaminants in the subsurface. If this evaporative loss is smaller than the assumed value, then the amount discharged to the subsurface could be significantly larger than 3.5 million pounds. For example, if the actual amount that “evaporated” is 20% less than the estimated value of 8.7 million pounds, then the amount in the subsurface could be 50% greater than previous estimates.

Relatively little site characterization work has been completed to evaluate the extent and distribution of solvent contamination in the vicinity and beneath the processing facilities 313-M, 320-M, and 321-M. The large majority of the solvents used at the Savannah River Site were used in these facilities. They represent potential sources for significant amounts of additional soil contamination.

Recent efforts at site characterization activities appear focused primarily on collecting data to evaluate the lateral and vertical extent of contamination at known sources. Most of the site characterization data has been collected from the relatively high permeability layers in the vadose zone above the water table. Relatively little characterization work appears to have been completed in the shallow soils or in the M-Area Settling basin.

B. Evaluation of Vadose Zone Remediation Activities

The vapor extraction systems at the A/M Area have been very effective in terms of the amount of contaminant that has been recovered from the subsurface. However, the total amount that has been removed by the vapor extraction system is still a small fraction of the amount that was likely discharged to the subsurface. The total amount removed via vapor extraction (roughly 250,000 pounds) is less than 10% of the estimated amount that was discharged to the subsurface through the A-014 Outfall and the M-Area Basin (roughly 3.5 million pounds).

Statements regarding the amount of time that will be required to clean the soils in the A/M Area are very speculative at this time. Much work must be done to characterize the amount and distribution of soil contamination in the A/M Area. Efforts to characterize the soils beneath the M-Area Facilities are especially needed.

Much of the soil remediation effort has been focused on the deeper soils beneath approximately 40 feet. These soils have higher permeability and are more amenable to characterization and cleanup. It appears that comparatively small effort has been focused on characterizing and remediating the more shallow soils near the ground surface. The technology used to screen for soil contamination (cone-penetrometers or CPT's) does not work well for fine-grained soils. Additional permanent gas probes may be required to better characterize the amount of contamination in these fine-grained soils.

Given the magnitude of uncertainties in the amount of solvents that was disposed into the subsurface and the distribution of this solvent, especially in the vicinity of the processing facilities and in the shallow soils, estimates of time and resources required to address soil contamination are highly speculative. Statements such as "relatively near term (circa 10 years) clean-up of the vadose zone in the A/M Area may be achievable" (Westinghouse Savannah River Company. WSRC-RP-97-0109, March, 1997) could be misleading.

Other approaches should be considered for defining the radius or zone of influence for the vapor extraction wells. The zone of influence is currently defined as the distance from the extraction well where the calculated or predicted pressure decrease equals 4 centimeters of water. An alternative approach for defining zones of influence is based on the area that contributes flow to the extraction well. For example, the zone of influence might be defined as the area or volume of soil that contributes 90% of the flow to the extraction well. This definition focuses on flow rather than pressure drops. The flow is the important parameter for vapor extraction effectiveness. This definition will also explicitly recognize the three dimensional nature of the flow system and the effects of soil layering on this flow.

The approach used to estimate the radius or zone of influence for the vapor extraction wells is overly simplified. The approach that has been used assumes horizontal, one-

dimensional flow and neglects the importance of layering and the 3-dimensional geometry of the actual field system. These one-dimensional methods may be suitable for evaluating short-term field tests, but they are generally not suitable for estimating zones of influence. Three-dimensional flow models can be used to evaluate the flow patterns in the vicinity of the extraction wells. These tools can be used with currently available data to develop more defensible and realistic estimates of zones of influence. They allow the geometric and stratigraphic characteristics to be incorporated into the evaluation. A system as important and expensive as this demands a more refined evaluation.

One of the advantages of soil vapor extraction systems is that the flow rate at individual wells can be adjusted to maximize the concentrations in the air that is extracted. The flow rate at wells with relatively low concentrations can be decreased using valves so that more air is extracted from the higher concentration wells. The concentrations coming from individual wells at the A/M Area are measured annually (Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). If the concentrations were measured more frequently, it may be possible to increase the efficiency of these systems. Costs associated with this additional sampling should be compared with the potential savings that would result from more efficient operations. A cost-benefit evaluation could be conducted to evaluate the expected benefit of increased monitoring.

C. Evaluation of soil cleanup goals

The methods that have been suggested for setting cleanup goals based on groundwater impact are unclear (page 4-24, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998.) It is not clear how the approach based on transport models is or will be related to the approach based on laboratory leaching tests.

The suggested cleanup goal for soils less than 80 feet deep (700 ppbw for PCE) is more than 10 times larger than the cleanup goal for soils greater than 80 feet (56 ppbw for PCE). The basis or rationale for choosing this depth for the cut-off is not presented.

The basis for choosing 40 pounds per week as a cut-off value for active vapor extraction is not obvious. The argument has been presented that this value is larger than the removal rate for a single groundwater extraction well in the A/M Area. The cut-off value should be based on more sound economic evaluations that compare the costs of removing contaminants via the vapor extraction system to the costs for removing contaminants from the groundwater and the costs for removing contaminants in the NAPL phase.

A removal rate of 40 pounds per week corresponds to a vapor concentration of 30 ppmv (30,000 ppbv) for a vapor extraction system that operates at 300 standard cubic feet per minute (p. 4-25, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). Shutting down a system that is removing 30 ppmv (30,000 ppbv) will virtually guarantee that there will be soils in the zone of influence with concentrations above the suggested cleanup levels of 100 ppbw.

Passive vapor extraction (barometric pumping) plays a significant role in the vadose zone monitoring plan. The plan suggests that active systems be switched to passive systems if removal rates are less than 40 pounds per week and if no soil samples have concentrations exceeding 1,000 ppbw. This technology has not been proven to be effective at the Savannah River Site. A passive vapor extraction system has been installed in the A/M Area Miscellaneous Chemical Basin (MCB), but no data have been collected that show what the air flow rates are for these systems or what the zones of influence are (Westinghouse Savannah River, WSRC-TR-99-00058). It is impossible to estimate removal rates and system effectiveness without this information. Estimates of removal rates that have been provide are purely speculative at this point. Much work needs to be done on evaluating this technology if it is to play a significant role in the vadose zone remediation plan at the A/M Area.

Under the proposed flow chart for monitoring the vadose zone, active vapor extraction will be stopped if there are no measured soil concentrations exceeding 1,000 ppbw. This value is also proposed as a cut-off value for soil gas screening in the Processing Facilities area (page 3-18, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). A soil concentration of 1,000 ppbw corresponds to a water concentration of approximately 5,000 ppbw. This is 1,000 times larger than the RCRA Corrective action level for groundwater. The basis for this cutoff value has not been presented.

D. Evaluation of groundwater re-circulation wells

Groundwater pump-and-treat systems similar to what is used in the Central and Northern sectors are much more expensive to operate than the vapor extraction systems that are used to clean soils in the vadose zone. One of the reasons for the higher costs is that water is 1,000 times heavier than air. Much more energy is required to pump the water to the extraction well and still more energy is required to pump the water from the well up to the ground surface and then to the top of the air stripping tower.

The extraction systems in the Central and Northern sectors of the A/M extract groundwater with relatively high concentrations of PCE and TCE. Concentrations in the groundwater in these sectors exceed 1,000 µg/L. Other technologies have been considered for treating the more dilute portions of the groundwater plume in the A/M Area. One approach that is under consideration in the southern sector are re-circulation wells. The general idea behind these wells is to treat the water inside of the well and not at the ground surface. This will reduce energy costs.

A series of groundwater re-circulation wells has been constructed in the southern sector of the A/M Area. The groundwater concentrations in this sector are generally much lower than the concentrations in the central and northern sectors. The primary objective behind the re-circulation wells is to contain migration of the contaminant plume.

It is very difficult to evaluate the radius or zone of influence for the re-circulation wells. Tests have been completed in the A/M Area to evaluate the effectiveness of this technology at this site. These tests have not been able to reliably demonstrate the capture zone or radius of influence for the re-circulation wells.

Much more work needs to be completed to evaluate the zones of influence and the effectiveness of these re-circulation wells. More reliable evaluations of the vertical extent of these zones of influences are particularly important. Reliance on these wells as a key component of the groundwater corrective action is likely pre-mature and unwarranted.

E. The F- and H-area groundwater treatment system

The corrective actions at the F- and H-area are being conducted in a phased approach. Phase I involved constructing the groundwater extraction, treatment, and re-injection systems and operating these systems for three years. Plans for Phase II were due three years after the Phase I operating permit was issued. The intent of this approach was to evaluate the effectiveness of the Phase I system and then decide how to proceed based on the results of the Phase I operations.

The Phase I system is not yet fully operational. The H-Area and F-Area systems were designed to operate at approximately 130 gallons per minute (gpm) and 165 gpm, respectively. If these systems are operated 90% of the time, these pumping rates correspond to roughly 5 million gallons per month in H-area and 6.5 million gallons per month in F-area. The actual operating rates during the previous year are summarized below:

	Volume of water extracted in millions of gallons	
	H-Area	F-Area
Second half of 1998	10.9	13.2
First half of 1999	21.6	12.7
Design volume for 6 months	30	39

Sufficient data have not been collected at this time to reliably evaluate Phase II operating scenarios. It appears, based on the operating data that have been provided and on discussions with site personnel, that many of the difficulties that have limited the operations of these systems are nearly resolved and it is anticipated that the rates in future months will be close to the design levels. Given that the groundwater treatment systems now appear to be operating near their design level, the next steps that are recommended relate to developing plans for Phase II. These include 1) continuing to investigate the feasibility of precision pumping, 2) continuing to evaluate the effects of groundwater injection in H-area on contaminant plumes in the Old Radioactive Waste Burial Ground, 3) continuing to collect additional data to improve characterization of contaminant sources, and 4) performing annual external reviews of the groundwater corrective actions.

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I. INTRODUCTION

This report presents the results of a review of selected activities aimed at removing contaminants from the subsurface at the Savannah River Site. The primary focus of the review is subsurface contamination in the A/M Area. The objective of this part of the review was to critique and develop recommendations related to site characterization activities, clean-up activities, and longer-term goals for addressing the subsurface contamination in this part of the site. A secondary objective was to develop a list of items that should be considered or done by the site as it prepares to make its transition from Phase I to Phase II at the F&H Area water treatment system. The scope and specific objectives for this review were defined in the statement of work for the Independent Scientific Peer Review. This is provided in Appendix A. The statement of work identified a 90% level of effort on the A/M activities and the remaining 10% effort on F&H activities. The main body of this report presents the results of the review activities for the A/M Area. The list of items that should be considered at the F&H Area are included as a separate, stand-alone section attached as Appendix B.

The items covered in the A/M review were more numerous and more extensive than the items discussed in this report. Excellent work has been accomplished in the cleanup activities at the A/M Area. The Integrated Demonstration Project, which began in 1989 in the A/M Area, enjoys international recognition for contributions related to fundamental and applied research on innovative technologies for characterizing and cleaning soils and groundwater. However, the objective of the review is not to add further praise for what has been done well, but rather to make suggestions regarding what might be done better. There are many successes and contributions that are not described in the sections that follow - the reader is referred to the list of items in Appendix C for more positive information on these contributions and successes.

I.A. Format of the Review

The intended audience for this report is the Savannah River Citizen's Advisory Board (CAB) and the public it represents. It is recognized that the expertise and interests of the CAB members are varied. The intent was to provide a sufficient amount of background information so that the conclusions and recommendations can be put in context. Issues or explanations that might provide more detail than some members need or want have been provided as italicized notes within the body of the report. The main goal of the review is identify areas or issues related to the A/M cleanup that the CAB may want to address or follow in the future to help improve the effectiveness and efficiency of cleanup operations.

I.B. General Background on the A/M Area

The A/M Area is roughly 10 square miles and is located in the northwest section of the Savannah River Site. It is situated on a broad ridge that straddles the Upper Three Runs and Tim's Branch drainage basins. The M-Area production facility was designed to process raw materials including uranium and lithium into fuel and target assemblies for SRS production reactors. The A-Area includes administrative and research centers (WSRC-RP-95-1560, 1995).

The primary emphasis of the subsurface remediation activities in the A/M Area is on addressing subsurface contamination by a class of contaminants termed chlorinated hydrocarbons. These chlorinated hydrocarbons were used as solvents and degreasers on the Savannah River Site. They are not unique to the Department of Energy facilities or mission. They are the most common soil and groundwater contaminants other than petroleum products at industrial sites with subsurface contamination. Chlorinated hydrocarbons are often associated with metal manufacturing facilities and also with dry cleaning operations.

The chemical names of the two main solvents used in the A/M Area are tetrachloroethylene and trichloroethylene. Tetrachloroethylene is also called perchloroethylene, or PCE. Trichloroethylene is usually abbreviated as TCE. (A third solvent, trichloroethane or TCA, was also used at the A/M Area but in much smaller amounts.) These compounds are man-made chemicals that do not occur naturally in the environment. They are mainly used as solvents for dry cleaning or to remove grease from metal parts.

Note: PCE and TCE are very similar compounds. Both compounds are colorless liquids at room temperature that evaporate easily into air with an odor similar to ether or chloroform. Because they evaporate so easily, PCE and TCE are classified as "volatile organic compounds" or VOC's. Most people can smell PCE when it is present in the air at a level of 1 part PCE per million parts of air (1 ppm), although some can smell it at even lower levels.

The PCE and TCE compounds have been found in more than one-half of the 1,430 National Priorities List sites identified by the Environmental Protection Agency (EPA). Much of the PCE and TCE that gets into water or soil will eventually evaporate into the air where it is broken down by sunlight into other chemicals or brought back to the soil and water by rain. Microorganisms can also break down some of the PCE and TCE in soil or groundwater. It does not appear to collect in fish or other animals that live in water (ATSDR, 1996). The EPA maximum contaminant level for the amount of PCE or TCE that can be in drinking water is 0.005 milligrams per liter of water (0.005 mg/L). The Occupational Safety and Health Administration (OSHA) has set a limit for air concentrations of 100 ppm (100,000 ppbv) for an 8-hour workday over a 40-hour workweek. (ATSDR, 1996).

Note: Chemical compounds such as PCE and TCE can be classified or grouped based on their molecular structure, their physical properties, and their primary use. In terms of molecular structure, PCE and TCE are chlorinated hydrocarbons. In terms of physical properties, PCE and TCE are termed volatile organic compounds (VOC's) because they readily evaporate. They are also classified as dense, non-aqueous phase liquids (DNAPL's) because they do not readily dissolve in water and because they are more dense than water. Finally, PCE and TCE are classified as solvents because they can be used to readily dissolve grease, oil, and other organic compounds.

TCE and PCE were first detected in groundwater samples in 1981. Concentrations of PCE and TCE in the groundwater beneath the A/M Area exceed the drinking water level of 0.005 mg/L (5 parts per billion) over an area greater than 1200 acres (WSRC-RP-95-1560, 1995). The circumference of this plume is roughly 5 miles. This groundwater contamination is the result of surface spills and discharges at a variety of different locations. These discharges are described in more detail in the chapters that follow. As of 1995, there were seventeen RCRA/CERCLA waste units in the A/M Area organized into nine operable units. These units are various stages in terms of site characterization or remediation (WSRC-RP-95-1560, 1995). The cleanup goals and standards for the groundwater and soil are described in Section IV.

There are two main cleanup activities underway in the A/M Area. One activity is focused on cleaning contaminated soils above the water table. The second activity is focused on cleaning the contaminated groundwater. Because of important issues related to cleanup goals and appropriate technologies, the main focus of the review has been on the activities related to the soil cleanup. Activities related to groundwater cleanup using re-circulation wells are also considered because of concerns regarding the effectiveness of this technology. The technologies that are being used in the cleanup activities at the A&M Area are described on the Savannah River Site webpage at <http://www.srs.gov/general/srenviro/erd/extpage.html>.

The main part of this review is divided into four sections numbered II through V. Section II considers site characterization activities aimed at evaluating the distribution and extent of soil contamination. Section III discusses activities that are underway to remove contamination from these soils and Section IV considers cleanup goals for the soils in the A/M Area. Section V focuses on a particular activity aimed at removing contaminants from the groundwater beneath A/M Area.

I.C. Approach and Material Reviewed

The information and data included in this review were collected through site visits and through reports, documents, and maps. General background information related to the subsurface characterization and clean-up activities at the A/M Area were collected during

two site visits; one in December, 1997 and a second in November, 1998. These site visits were also used to collect information for several other ISPR activities, including those associated with the Integrator Operable Unit Study, the F&H Area, and the Old Burial Ground. Over 75 reports and articles related to the contamination and cleanup activities in the A/M Area were provided as part of this review. These reports and articles are listed in Appendix C. The following subset of these items was selected for a detailed review.

1. Selected portions of Volume III – M-Area Hazardous Waste Management Facility – Postclosure, Rev. No. 3, WSRC-IM-91-53, June, 1994, including the following:
 - a) Materials that are contained in pages E-143 to E-218.
 - i. E.2.2 – Local Surface Hydrology of the General A/M Area
 - ii. E.2.3 – Hydrogeology of the A/M Area
 - iii. E.2.4 – Hydrology of the M-Area HWMF
 - iv. E.2.5 – Effects of M-Area Recovery Wells on Groundwater Flow Patterns at the M-Area HWMF
2. Selected portions of Volume III – M-Area Hazardous Waste Management Facility – Postclosure, Rev. No. 6, WSRC-IM-91-53, February, 1997 including the following:
 - a) Materials contained in ESE-8.1 to ESE-8.2
 - i. Executive Summary of the Corrective Action Plan
 - b) Materials contained in pages E-285 to E-440
 - i. E.8 - Corrective Action Program
3. "Extent of A/M Area Vadose Zone Contamination, Monitoring, and Corrective Action," Westinghouse Savannah River Company. WSRC-RP-97-0109, March, 1997.
4. "A/M Area Vadose Zone Monitoring Plan." Westinghouse Savannah River Company. WSRC-RP-98-00146, March, 1998.
5. "Miscellaneous Chemical Basin Treatability Study: An Analysis of Passive Soil Vapor Extraction Wells (PSVE), FY1998 Update (U)." B. D. Riha, J. Rossabi, and W. K. Hyde, Westinghouse Savannah River Company, WSRC-TR-99-00058, undated.
6. "Development of a Vertical Re-circulation Well System for the A/M Area of the Savannah River Site." By Dennis G. Jackson and Brian B. Looney. Westinghouse Savannah River Company. WSRC-RP-96-477, September, 1996.
7. "Airlift Re-circulation Well Final Report - Southern Sector (U)." By R.M. White.

- Westinghouse Savannah River Company. WSRC-TR-98-00428, Rev. 0, March, 1999.
8. "Performance Test Results – Well SSR 012" prepared by Davis Environmental for the Westinghouse Savannah River Company, Aiken, S.C., September, 1998.
 9. "Assessment of Chlorinated Solvent Contamination in the Crouch Branch Aquifer of the A/M Area," by Dennis G. Jackson, Jr., Brian B. Looney, and Harvey W. Campbell. Westinghouse Savannah River Company. WSRC-RP-97-00247, September, 1997.
 10. "Baseline Mapping Study of the Steed Pond Aquifer and Crouch Branch Confining Unit Beneath A/M Area, Savannah River Site." By Andrew D. Smits, Mary K. Harris, Dennis G. Jackson, Jr., and Kelley L. Hawkins. Westinghouse Savannah River Company. WSRC-TR-98-00357, Rev. 0., September, 1998.

These items were selected either because they provide a broad overview of the cleanup activities or because they focus on specific activities addressed in this review.

I.D. Scope

The total effort allotted to the A/M review was 14 days or 112 hours. The distribution of these efforts is summarized below:

Site visits in December, 1997 and November, 1998	10 hours
Review reports, literature, maps, and data	60 hours
Prepare draft report:	24 hours
Address reviewer comments and prepare final report:	8 hours (estimated)
Prepare presentation for the CAB meeting	2 hours (estimated)
Travel to South Carolina for CAB Presentation	8 hours (estimated)

The effort for developing the list or "road map" for the transition from Phase I to Phase II at F&H Area water treatment system was approximately 2 days, as summarized below.

Site visits in December, 1997 and November, 1998	11 hours
Review reports, literature, maps, and data	4 hours
Prepare list	2 hours

II. CHARACTERIZATION OF CONTAMINATION IN THE A/M VADOSE ZONE

The term "vadose zone" is used to describe the area between the ground surface and the water table. The water table identifies where in the subsurface the soil pores become completely filled with water. Above the water table (in the vadose zone) the pores contain both water and soil air. Below the water table (in the saturated zone) the pores are filled with water. The vadose zone is important with regard to environmental restoration because essentially all subsurface contamination is derived from liquids introduced into the vadose zone.

In terms of contaminated sites and environmental restoration activities, the vadose zone is distinguished from the saturated zone because of the way contaminants move and because of the remediation techniques that are appropriate. The presence of air in the pores within the vadose zone impact fluid movement in several ways. First, the forces of gravity are generally more important in the vadose than the saturated zone. These gravitational forces encourage vertical movement over horizontal movement. This differs from the saturated zone below the water table in which horizontal movement is often as important or even more important than vertical movement. A second effect of air in the vadose zone is that the air makes it very difficult to remove liquids such as water or solvents. The air gets in the way by taking up a part of the pore space. The air also introduces forces that cause the liquid to be attracted to the soil particles. On a more positive note, the presence of the air makes it possible to extract soil air and any contaminants that might be contained within the soil air.

The vadose zone is typically not a direct exposure point for contaminants. Contamination in the vadose zone is a source for air contamination via evaporation at the ground surface. The vadose zone can also serve as a source of groundwater contamination caused by water that infiltrates at the ground surface and moves downward to the water table. Contaminants in the vadose zone will dissolve into the infiltrating water. The role of the vadose zone in contributing to groundwater contamination is generally more critical than the role in contributing to air contamination.

II.A. Description of the Vadose Zone at the A/M Area

The thickness of the vadose zone in the A/M Area is roughly 100 feet (30 m.) It is made up of sediments consisting of sands, sandy clay, clayey sand, and clay. These sediments are laterally discontinuous and were deposited in shallow marine, lagoonal, or fluvial (rivers and streams) depositional environments. A zone of relatively high-permeability sands are located between 40 and 90 feet beneath the ground surface. Fluids such as air and water move more easily and more quickly through these higher-permeability materials. The shallow soils near the ground surface and the deeper soils near the water table are interbedded sands and clays. These materials have relatively low permeability. A series of low-permeability clay stringers is also observed in the middle of the lower sands. The finer-grained materials are important because they tend to hold water and

solvents. It is also more difficult to move air through these layers (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997).

II.B. Distribution of Contamination in the Vadose Zone

II.B.1. Background on DNAPL migration

When DNAPL's such as PCE and TCE are introduced into the subsurface, they move downward because of the forces of gravity. As the DNAPL moves through the soil, small liquid particles are left behind in the pore spaces. These liquid particles have been termed ganglia, globules or "blobs." The fraction of the pore space that is filled with these blobs may be on the order of several percent to several tens of percent, with the remaining fraction being filled with air and water. Capillary forces between the pore fluids and the soil generally cause these blobs to be immobile. (These are the same forces that cause water on your car to "bead" up after it is washed or after a rainstorm. In fact, the water beads behave very similarly to the DNAPL "blobs.") The capillary forces are generally stronger in finer-grained materials such as silts and clays.

The downward movement of the DNAPL's can be interrupted by changes in the soil layering. Lower-permeability layers may cause pools of DNAPL to form at the interface between the lower- and high-permeability layers. These DNAPL pools may spread horizontally until higher permeability zones are encountered in the lower layer. These higher permeability zones may be the result of cracks, fissures, or changes in soil texture. The movement of DNAPL continues vertically until all of the spilled volume has been distributed as small blobs or as pools that develop at layer interfaces. The net result of a DNAPL spill is generally a very complicated and discontinuous distribution of pools and blobs that is very different from the more continuous contaminant plumes that form in groundwater.

The blobs of DNAPL act as ongoing sources of contamination for infiltrating water and for the soil air. The DNAPL will dissolve into the infiltrating water and will then be transported to the groundwater table. It will also evaporate into the soil air where it may diffuse laterally away from the source or vertically to the soil surface or the groundwater table.

PCE and TCE can be degraded or destroyed by naturally-occurring microbes that are found in many soils and aquifer materials. The primary degradation pathway for PCE and TCE involves microbes that prefer to live in environments with very low oxygen concentrations. These "anaerobic" microbes cause the sequential removal of chlorine atoms from the solvent molecules. PCE, with 4 chlorine atoms, is reduced to TCE, which has 3 chlorine atoms. TCE is then reduced to a compound with 2 chlorine atoms (DCE) and DCE is reduced to vinyl chloride, which has only one chlorine atom per molecule. If the last chlorine atom is removed from vinyl chloride, the result is ethene, which is an innocuous and essentially "safe" compound. Unfortunately, the removal of this last

chlorine is very difficult and so vinyl chloride is a relatively persistent compound. It is also more mobile and more toxic than its TCE and PCE “parents”.

II.B.2. Sources of vadose zone contamination in the A/M Area

Although there are multiple locations of soil contamination in the vadose zone at the A/M Area, the ultimate source of much of the subsurface contamination is the processing facilities. The contamination in the subsurface resulted from bringing the solvents to these facilities, using the solvents in the facilities, and then discharging the solvents from the facilities. The primary focus of the ongoing soil remediation activities has been on contamination that resulted when the solvents were discharged from the processing facilities. This discharge occurred through sewer lines that transported the solvents from the processing facilities to either the A-014 outfall or to the M-Area Basin. The A-014 out-fall is located approximately 2000 feet south of the processing facilities and discharges into an unnamed tributary of the Tim's Branch stream. The M-Area Basin is located approximately 2,500 feet southwest of the processing facilities and has an overflow line into Lost Lake. The table below summarizes estimates that have been made regarding where the solvents were used and where they were disposed. All values are millions of pounds of solvent.

Facility	Total Used	Discharge Location		Evaporated or Leaked
		A-014 outfall	M-Area Basin	
313-M	3.2	0.54	0.22	2.4
320-M	3.5	0.98	none	2.5
321-M	5.7	none	1.9	3.8

These estimates are based on a study described in a 1982 report (Christensen and Brendall, 1982). The methods used to develop these estimates are not described and uncertainties in these estimates were not quantified in the reports that were provided for this review. The total estimated amount that was discharged to either the A-014 outfall or the M-Area basin is 3.6 million pounds. Another 8.7 million pounds was lost to evaporation within the processing facilities or to leakage from the processing facilities (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997). The focus of the clean-up activities at the A&M Area is the estimated 3.6 million pounds that have been discharged to the A-014 outfall or the M-Area Basin.

Note: A comparison of the amount of PCE and TCE used at Savannah River Site with the amount used in other industries provides some context to these numbers. Roughly 12 million pounds of solvents were reportedly used at the A/M processing plants during a roughly 30 year period from 1950 to 1980. This is approximately 400,000 lbs. per year. The following table provides estimates of the total amount of PCE and TCE used in the U.S. (from <http://www.speclab.com/>)

	<i>PCE</i>	<i>TCE</i>
1982:	679 million pounds	235 million pounds
1987:	625 million pounds	215 million pounds

Reliable estimates of the amount of PCE and TCE that have been released to the environment nationwide are not available. However, it has been estimated that approximately 80% of the all TCE that was produced in the U.S. in 1986 was used for vapor degreasing of fabricated metal parts (Cohen et al., 1993).

The primary release points for solvents released to the environment in the A/M Area can be grouped into three general locations, as summarized below. These are ordered based on estimated volumes from Christensen and Brendall, 1982.

- i. M-Area Processing Facilities including the 321-M solvent storage tank
(Total estimated release: 8.7 million pounds)

Relatively little characterization work has been completed to evaluate the extent of contamination beneath or near the 313-M, 320-M, and 321-M processing facilities. Access to these facilities was prohibited prior to 1992 and relatively little work has been done to characterize the vadose zone beneath the processing facilities. The large majority of the estimated release of 8.7 million pounds has been attributed to evaporation (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997). Sumps that were located in solvent-use areas may be a significant source for soil contamination directly beneath the facilities. Some work has been completed to characterize the contamination in the vicinity of the 321-M solvent storage tank. This storage tank was removed in September, 1998. Soil contamination was observed during the removal operations (personal communication, Chris Bergren, WSRC).

- ii. M-Area Basin and sewer lines between the processing facilities and the basin
(Total estimated release: 2.1 million pounds)

The M-Area settling basin received solvents from about 1958 to 1979. Between 1958 and 1976, these solvents came only from the 321-M facility. After 1976, solvents from 313-M were also discharged to the M-Area Basin. Of the 2.1 million pounds that were discharged to the M-Area Basin (1.9 million from 321-M and 220,000 from 313-M), it has been estimated that 84% was PCE, 15% was TCE, and 1% was TCA (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997).

Disposal of solvents to the M-Area Basin was stopped in 1979. The basin continued to receive process effluents until 1985. This latter effluent contains metals, acids, caustics. Solvent discharges to sewers stopped in 1979. All liquid discharges to M-Area Settling basin reportedly ended in 1985. The basin was certified as closed under RCRA in 1991 (Westinghouse Savannah River Company, WSRC-RP-95-1560, Rev. 0, December,

1995).

The sewer line connecting the M-Area basin and the processing facilities was constructed of vitreous clay pipe. Cracks and "damage" were observed during an inspection of this sewer line conducted in 1982 inspection. Sumps were located beneath manholes at 350 feet intervals along the sewer lines. The sewer line was removed from the M-area fence to the settling basin in 1989 (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997).

iii. A-014 Outfall and sewer lines between the processing facilities and the outfall
(Total estimated release: 1.5 million pounds)

The A-014 out-fall received solvents from 1952 through 1979. Between 1952 and 1976, these solvents were from both 313-M and 320-M. After 1976, only solvents from 320-M were discharged to the A-014 out-fall. Of the 1.5 million pounds that were discharged to the A-014 out-fall (985,000 pounds from 320-M and 540,000 pounds from 313-M), it has been estimated that 72% was PCE, 27% TCE, and approximately 1% was TCA. The solvents discharged to the A-014 out-fall would likely infiltrate into the ground and or flow via surface water into an unnamed tributary of the Tim's Branch stream (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997).

Soil and soil gas measurements have been made along the sewer line between the A-014 outfall and the processing facilities. These measurements indicate soil concentrations in the range of 100 to 1,000 part per billion and soil gas concentrations in the range of 5 to 500 ppm (5,000 to 500,000 ppb) (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997). These measurements do not identify large sources of soil contamination, relative to the amounts observed near the A-014 outfall or the M-Area Basin.

Other miscellaneous sources with unknown but likely small releases have also been identified. These include solvent storage and degreasing facilities in Building 773-A. Solvent wastes were reportedly released from this building along a "trade waste stream" to A-014 outfall. Small volumes (1 liter intermittently) were also reportedly released to the Metallurgical Laboratory Basin prior to 1985. A degreaser in Building 717-A reportedly discharged approximately 500 lbs. (50 gallons) per year to a sump and then into a storm drain. This degreaser was removed in 1977. Solvents were also stored in building 713-A after the middle part of the 1960's (Westinghouse Savannah River Company, WSRC-RP-97-0109, March, 1997).

II.C. Evaluation of Site Characterization Activities

Relatively little site characterization work has been completed to evaluate the extent and distribution of solvent contamination in the vicinity and beneath the processing facilities

313-M, 320-M, and 321-M. The large majority of the solvents used at the Savannah River site were used in these facilities. They represent potential sources for significant amounts of additional soil contamination. Soil samples should be collected from beneath the processing facilities. Soil vapor concentrations should also be monitored in the vicinity of these buildings.

It should be noted that estimates for the amount of solvents discharged to subsurface are based on an assumed evaporation loss within the M-Area Facilities of more than 8 million pounds. Uncertainties in the amount of solvent that was lost to evaporation have not been quantified. These uncertainties have important implications for estimates of the amount of contaminants in the subsurface. If this evaporative loss is smaller than the assumed value, then the amount discharged to the subsurface could be significantly larger than 3.5 million pounds. For example, if the actual amount that "evaporated" is 20% less than the estimated value of 8.7 million pounds, then the amount in the subsurface could be 50% greater than previous estimates. Similarly, if the evaporative loss is actually 20% larger than the estimated value, then the amount in the subsurface could be 50% less than previous estimates.

Recent effort at site characterization activities appears focused primarily on collecting data to evaluate the lateral and vertical extent of contamination at known sources, as summarized below (from Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998).

1. Data collected to evaluate lateral and vertical extent of contamination at known sources
 - 1997:
 - 3 CPT and 1 core at the A-014 Outfall
 - 2 core at the Solvent Storage Tanks
 - 1 core at the M-Area Basin
 - 1996:
 - 14 CPT soil gas and 6 VOC core at the Solvent Storage Tanks
 - 1994:
 - 13 soil gas monitoring wells at the Process Sewer Line
 - 1993:
 - 8 VOC core and 5 soil gas monitoring wells at the Process Sewer Line
 - 17 VOC core at the Process Sewer Line
 - 1992:
 - 6 VOC core at the Process Sewer Line
2. Data collected to evaluate the effectiveness and completeness of remediation
 - 1997:
 - 3 CPT core and 1 core at the Process Sewer Line
3. Data collected to screen potential and suspect source areas

1997: 13 CPT at M-Area Process Sewer

Most of the site characterization data has been collected from the relatively high permeability layers in the vadose zone using cone penetrometer tests. Cone penetrometer data collected in 1997 along the Process Sewer Line showed no indication of "spot" contamination from sumps beneath manholes. Relatively little characterization work appears to have been recently completed in the M-Area Settling basin. Samples collected in 1981-82 to a depth of 3 meters beneath the bottom indicated extremely high concentrations on the order of 2,000 ppm (2 million ppb) PCE (Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998).

III. REMEDIATION OF CONTAMINATION IN THE A/M VADOSE ZONE

III.A. Description of Vadose Zone Remediation Activities

III.A.1. Background

The solvents that were discharged or spilled into the vadose zone beneath in the A/M Area will be in one of four different phases. A portion of the solvents will be sorbed or attached to the soil particles, a portion will be dissolved in soil water, a portion will be in the vapor phase within the soil air, and a portion may be present as a separate liquid (non-aqueous) phase. Some of these phases can be removed more easily than others. It is very difficult to directly remove soil water or organic liquids from the vadose zone. It is relatively easy to remove soil vapor. In most situations, the only practical ways to remove these types of contaminants from most soils are the following:

- 1) physically dig up the soils,
- 2) cause chemical reactions to occur that make the contaminants less toxic or less mobile,
- 3) cause biological reactions to occur that make the contaminants less toxic or less mobile, or
- 4) cause the contaminants to evaporate.

The first approach, digging up the soils, is only practical for relatively shallow contamination. The excavated soils must generally be treated and replaced. The second approach, chemical reactions, is difficult and is usually tried only when soil concentrations are relatively high. The effectiveness of the third approach, biological reactions, depends upon site-specific conditions and is often relatively slow. The fourth approach, which is often termed soil vapor extraction (SVE), is usually the most effective and is by far the most common method for addressing subsurface contamination by volatile organic compounds such as TCE and PCE.

The idea behind SVE is relatively simple. A portion of the contaminants will always evaporate or partition into the soil vapor. This partitioning may occur from the soil particles, from the soil water, or from organic liquids. The soil vapor can generally be removed relatively easily by applying a vacuum to a vapor extraction well that is screened in the vadose zone. Air will move from the soil surface, through the contaminated soils, and into the vapor extraction well. As the air follows this pathway, it will "pick-up" contamination along the way. The contaminants can then be removed from the extracted air at the ground surface. The effectiveness of the SVE methodology depends in large part on the ability to move significant amounts of air through the subsurface and on the ability to move significant amounts of contaminants from the soil particles, the soil water and the organic liquids into the soil air.

The limitations to SVE generally revolve around difficulties in getting significant

volumes of air to flow into lower-permeability soils and difficulties in getting the contaminants to de-sorb from the soil particles or evaporate from the soil liquids. The rate of de-sorption and evaporation can be increased by heating the soils through steam injection or by imposing electric current through the soils or even through microwaves. The problems associated with inducing air flow through lower-permeability soils are less tractable. Some success has been had in fracturing the lower permeability soils by injecting air and other fluids under very high pressure.

III.A.2. Soil Vapor Extraction at the A/M Area

Soil vapor extraction began in the A/M Area in 1994. The first extraction wells were installed at the solvent storage tanks and near the A-014 out-fall. Additional wells were installed between 1994 and 1995 period at to the A-014 out-fall and at the process sewer line between the Processing Facilities and the M-Area Basin. Horizontal vapor extraction wells that were originally parts of technology demonstration sites along the process sewer line have also been incorporated into vapor extraction operations. Horizontal wells have also been added beneath the M-Area Basin.

There are currently six vapor extraction systems operating in the A/M Area. These are summarized below:

Location	I.D.	Number and types of wells
Process Sewer Line	782-5M	Vertical wells MVE-5 through MVE-8
Process Sewer Line	782-7M	Horizontal well AMH-2
Process Sewer Line	782-8M	Horizontal wells AMH-4 and AMH-5
A-014 Out-fall	782-3M	Vertical wells MVE-4, MVE-9, MVE-10
M-Area Basin	782-4M	Horizontal wells AMH-6 and AMH-7
Solvent Storage Tank	782-6M	Vertical wells MVE-1 through MVE-3

These vapor extraction systems have varying removal rates and efficiencies. The rates that were measured during the 1997 calendar year are summarized below (Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998).

Location	I.D.	1997 Removal Rate (lbs/year)
Process Sewer Line	782-5M	1,750
Process Sewer Line	782-7M	3,090
Process Sewer Line	782-8M	550
A-014 Out-fall	782-3M	61,500
M-Area Basin	782-4M	24,250
Solvent Storage Tank	782-6M	26,550

During the 30 months of operation between the middle of 1995 and the end of 1997, 225,000 pounds of solvents were removed by vapor extraction in the A/M Area. This is 3 to 5 times the amount that was removed by groundwater extraction during this same time period. It is equal to nearly 2/3 of the total amount that has been removed in over 12 years of groundwater extraction.

The total removal rate in 1997 of 118,000 pounds is approximately twice the 1996 rate. The higher removal rate is due in part to a modification in the SCDHEC permit which regulates the allowable emission levels for VOC's from three of the soil vapor extraction units. The allowable emission levels from the vapor extraction units are based on expected exposure levels in the atmosphere. SCDHEC granted a permit modification in September of 1996 that increased the allowable emission rates at the 782-3M, 782-5M, and 782-6M vapor extraction units. The higher emission rates were granted based on air modeling evaluations. These evaluations indicated that VOC concentrations at the plant boundaries were less than one-tenth the allowable air concentrations with the previous rates. Emission rates were increased by a factor of roughly 15 at 782-3M and by a factor of roughly 5 at 782-5M and 782-6M.

Removal rates at several of the vapor extraction systems have apparently decreased in late 1997 and early 1998. This decrease is attributed to two general processes. At 782-5M, the decrease in removal rates is attributed to a reduction in the contaminant concentrations for soils within the zone of influence for the extraction wells. At 782-8M, the decrease in removal rates is attributed inefficient operations that may be due to clogging in extraction wells. This clogging prevents significant air-flow through the subsurface.

III.B. Evaluation of Vadose Zone Remediation Activities

The vapor extraction systems at the A/M Area have been very effective in terms of the amount of contaminant that has been recovered from the subsurface. Although operating costs have not been provided, it is very likely that the costs to remove a pound of contaminants via the vapor extraction system are much less than the costs to remove a pound of contaminants via the groundwater extraction system. However, the total amount that has been removed by the vapor extraction system is still a small fraction of the amount that was likely discharged to the subsurface. The total amount removed via vapor extraction (roughly 350,000 pounds) is approximately 10% of the estimated amount that was discharged to the subsurface through the A-014 Outfall and the M-Area Basin (roughly 3.5 million pounds).

Statements regarding the amount of time that will be required to clean the soils in the A/M Area are very speculative at this time. Much work must be done to characterize the amount and distribution of soil contamination in the A/M Area. Efforts to characterize the soils beneath the M-Area Facilities are especially needed.

Much of the characterization and remediation effort has also been focused on the deeper soils beneath approximately 40 feet. These soils have higher permeability and are more amenable to characterization and cleanup. It appears that comparatively small effort has been focused on characterizing and remediating the more shallow soils near the ground surface. The technology used to screen for soil contamination (cone-penetrometers or CPT's) does not work well for fine-grained soils. Additional permanent gas probes may be required to better characterize the amount of contamination in these fine-grained soils.

Given the magnitude of uncertainties in the amount of solvents that was disposed into the subsurface and the distribution of these solvents, especially in the vicinity of the processing facilities and in the shallow soils, estimates of time and resources required to address soil contamination are highly speculative. Statements such as "relatively near term (circa 10 years) clean-up of the vadose zone in the A/M Area may be achievable" (Westinghouse Savannah River Company. WSRC-RP-97-0109, March, 1997) could be misleading.

Other approaches should be considered for defining the radius or zone of influence for the vapor extraction wells. The zone of influence is currently defined as the distance from the extraction well where the calculated or predicted pressure decrease equals 4 centimeters of water. This magnitude was apparently chosen based in some way on the magnitude of barometric pressure fluctuations at site (Westinghouse Savannah River Company. WSRC-RP-98-00146, March, 1998). An alternative approach for defining zones of influence is based on the area that contributes flow to the extraction well. For example, the zone of influence might be defined as the area or volume of soil that contributes 90% of the flow to the extraction well. This definition focuses on flow rather than pressure drops. The flow is the important parameter for vapor extraction effectiveness. This definition will also explicitly recognize the three dimensional nature of the flow system and the effects of soil layering on this flow.

The approach used to estimate the radius or zone of influence for the vapor extraction wells is overly simplified. The approach that has been used assumes horizontal, one-dimensional flow and neglects the importance of layering and the 3-dimensional geometry of the actual field system. These one-dimensional methods may be suitable for evaluating short-term field tests, but they are generally not suitable for estimating zones of influence. Three-dimensional flow models such as AIR3D can be used to evaluate the flow patterns in the vicinity of the extraction wells. These tools can be used with currently available data to develop more defensible and realistic estimates of zones of influence. They allow the geometric and stratigraphic characteristics to be incorporated into the evaluation. A system as important and expensive as this demands a more refined evaluation.

It has been argued that "Modeling for zone of influence is also contingent upon the completion of grids of geophysical and hydrodynamic properties." (Westinghouse Savannah River Company. WSRC-RP-98-00146, March, 1998). It should be emphasized

that the three dimensional models such as AIR3D can be developed using the same data as was used with the one-dimensional evaluation. They may not give "perfect" results because of data uncertainties, but they will give much more reliable results than the current approach with only a moderate increase in computational effort.

One of the advantages of soil vapor extraction systems is that the flow rate at individual wells can be adjusted to maximize the concentrations in the air that is extracted. The flow rate at wells with relatively low concentrations can be decreased using valves so that more air is extracted from the higher concentration wells. The concentrations coming from individual wells at the A/M Area are measured annually (Westinghouse Savannah River Company. WSRC-RP-98-00146, March, 1998). If the concentrations were measured more frequently, it may be possible to increase the efficiency of these systems. Costs associated with this additional sampling should be compared with the potential savings that would result from more efficient operations.

IV. CLEANUP GOALS FOR THE A/M VADOSE ZONE

IV.A. Description of cleanup goals

The vadose zone remediation activities are being completed in a phased approach. Phase I involved installing the vapor extraction systems (WSRC-IM-91-53, p. E-327). Phase II required four "post-operational" evaluations: 1) Evaluate Phase I performance, 2) Propose remediation goals, 3) Install additional extraction wells, and 4) Install additional vapor extraction units (Westinghouse Savannah River Company. WSRC-RP-97-0109, March, 1997). This section of the review considers item 2, the remediation goals.

The approach that has been proposed for developing goals for the vadose zone remediation activities in the A/M Area is currently based on two general considerations. The first consideration focuses on impacts to groundwater. The general idea is to identify or estimate an acceptable level of contamination that can be left in the soils and still be protective of groundwater. The second consideration focuses on the effectiveness of the remediation technologies. The general idea is to identify the "best" technology to remove contamination from the soil.

IV.A.1. Goals based on impacts to the groundwater

In terms of estimating an acceptable level of contamination that can remain in the soil, the Department of Energy has proposed two methods. The first method is based on laboratory tests that measure how much contamination will be dissolved or leached from soil. The second method is based on computer models that simulate contaminant transport through the vadose zone.

The general idea behind the laboratory test is to measure concentrations of PCE and TCE in leachate derived from soil samples collected at the site (leachate is simply the water that drains from the soil). If the concentrations of PCE and TCE in the leachate are less than some maximum allowable leachate concentration, then the soil is sufficiently clean and, presumably, remediation activities can be stopped.

Note: There are a variety of different methods for conducting these laboratory leaching tests. One of the more common methods was developed by the EPA and is termed the Toxicity Characteristic Leaching Procedure, or TCLP. The TCLP was originally developed to determine if a waste is hazardous before it is placed in a landfill. In very simple terms, a sample of the soil is placed in a jar with some water. After the jar is shaken for a period of time, the water is removed. The concentrations of chemicals in the water are measured to evaluate how "toxic" the soil is. The test procedure specifies what size the soil or waste particles should be, how much water should be added to the soil, how acidic or basic to make this water, and how much and how long to shake up the mixture before analyzing the leachate.

One of the difficulties in determining cleanup levels using the laboratory leaching test is in determining what the maximum allowable leachate concentration should be. This can be accomplished by using mathematical models that simulate contaminant transport through the vadose zone and into the groundwater. These models are used to "back-calculate" an allowable concentration in the vadose zone based on an allowable concentration in the groundwater. For example, if the allowable groundwater concentration is 0.005 mg/l, a model could be used to estimate the maximum soil concentration that will result in a groundwater concentration less than this value. Shallow soils, which are further from the groundwater, would presumably have a larger allowable soil concentration than deeper soils near the groundwater table because of the additional dilution that might occur as the water infiltrates through the vadose zone.

The cleanup goals that have been suggested for the A/M vadose zone are based on the TCLP leach test and are dependent on the soil depth. For soils that are greater than 80 feet deep, the soil will be considered "clean" if the concentration in the leachate is less than 54 $\mu\text{g/L}$ for TCE and 56 $\mu\text{g/L}$ for PCE. For soils that are less than 80 feet deep, the soil will be considered "clean" if the concentration in the leachate is less than 500 $\mu\text{g/L}$ for TCE and 700 $\mu\text{g/L}$ for PCE. The 54 and 56 $\mu\text{g/L}$ concentrations for deep soils are reportedly based on SCDHEC waste-water standards. The 500 and 700 $\mu\text{g/L}$ concentrations for shallow soils are equivalent to the values used by the EPA in identifying a hazardous waste. The justification for choosing these particular levels and for choosing a depth of 80 feet for the cut-off point is not presented.

Note: A second difficulty (or at least point of confusion) encountered in setting clean up goals is that concentrations can be defined and measured in several ways. As discussed earlier, TCE and PCE can be present in the unsaturated soils in one of four different forms or phases. A portion of the contaminants will generally be attached to the soil particles. This is termed to sorbed phase. A portion will also be dissolved in soil water. This is termed the aqueous phase. For contaminants that evaporate easily, a portion will be in the vapor phase within the soil air. Finally, a portion may be present as a separate organic liquid. This is termed the non-aqueous phase. It is generally very difficult to measure the concentration of contaminants in the soil water or in the non-aqueous phase because it is difficult to separate these liquids from the soil. However, the vapor phase can be measured in the field relatively easily. Laboratory measurements (similar to the TCLP test described above) can be used to estimate the total amount of contaminant in the soil, but these tests do not separate how much is sorbed to the soil, dissolved in the soil water, or present as a non-aqueous phase liquid.

Different measures or units are also used to define concentrations in the different phases. For example, the total concentration in a soil sample is usually defined as the mass of contaminant per mass of dry soil. Typical units are micrograms of TCE per kilogram of soil ($\mu\text{g/Kg}$). Concentrations in the soil water are usually defined as the mass of contaminant per volume of water. Typical units are micrograms of TCE per liter of

water (**mg/L**). Concentrations in the vapor phase are often defined as the volume of contaminant per volume of air. Typical units are milliliters of TCE per liter of air (ml/L). The table below gives concentrations that might be expected in the different phases for different total contaminant concentrations. These are based on values presented in Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998.

Soil concentration	Water concentration	Vapor concentration
100 mg/Kg	500 mg/L	50 ml/L

Concentrations are also described in terms of parts of contaminants per billion parts of soil, water or air. The "parts" may be measured in terms of weight or volume. For example, 100 **mg/Kg** in soil is equivalent to 100 parts per billion by weight (ppbw); 500 **mg/L** in soil water is equivalent to 500 parts per billion by weight (ppbw), and 50 ml/L in the soil air is 50 parts per million by volume (ppmv) or 50,000 parts per billion by volume (ppbv).

One way to interpret the table above is that soils with a total TCE concentration of 100 **mg/Kg** is expected to have a water concentration of about 500 **mg/L**. This is only an estimate, however, and the actual value would depend upon specific properties of the soil. A second way to interpret this is that if the vapor concentration in the soil as measured in the field is 50 ml/L, then the water concentration is expected to have a water concentration of about 500 **mg/L**. Again, this is only an estimate, however, and the actual value would depend upon specific properties of the soil.

The cleanup goals that have been suggested for the A/M vadose zone are based at least in part on the TCLP leach test and are dependent on the soil depth (page 4-24, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). For soils that are located at a depth greater than 80 feet, the soil will be considered "clean" if the concentration in the leachate is less than 54 $\mu\text{g/L}$ for TCE and 56 $\mu\text{g/L}$ for PCE. For soils that are less than 80 feet deep, the soil will be considered "clean" if the concentration in the leachate is less than 500 $\mu\text{g/L}$ for TCE and 700 $\mu\text{g/L}$ for PCE. The 54 and 56 $\mu\text{g/L}$ concentrations for deep soils are reportedly based on SCDHEC wastewater standards. The 500 and 700 $\mu\text{g/L}$ concentrations for shallow soils is equivalent to the value used by the EPA in identifying a hazardous waste. The RCRA groundwater corrective action level is 5 $\mu\text{g/L}$ for TCE and 7 $\mu\text{g/L}$ for PCE.

There also seems to be some suggestion that mathematical transport models be used to set a cleanup goal (page 4-24, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). It is not clear how the approach based on transport models is or will be related to the approach based on the TCLP test. This is discussed further in the evaluation Section C below.

IV.A.2. Goals based on technology effectiveness

After a clean up goal has been identified based on groundwater protection considerations, the next step involves identifying the best mix of technologies to achieve that goal. For the vapor extraction systems that are currently operating in the A/M Area, a technology has already been selected and the question of the best mix of technologies reduces to evaluating how best to operate the system. This essentially means identifying when the system should be shutdown.

The decision of when vapor extraction is no longer "effective" is largely one of economics. If a decision has been made to clean the soils to some predetermined level, then presumably one can identify the most cost-effective way to accomplish this goal. The cost effectiveness of vapor extraction depends in part on the rate of mass removal by the system. The rate of contaminant removal by vapor extraction typically decreases with time as the most accessible soils become cleaner. Contaminants that might be trapped in lower-permeability zones must diffuse to the higher-permeability zones where most of the flow of air is concentrated. This diffusion is generally a relatively slow process, and may continue for years or even decades.

The costs associated with operating vapor extraction systems are sensitive to air flow rate. As the rate of mass removal decreases, the costs will stay roughly the same if the air flow is maintained and the cost per pound of contaminant removed goes up. A common approach that has been used to decrease this "cost per pound" is to "pulse" the system. This pulsing is accomplished by shutting the system down for a period to allow the contaminants to diffuse into the higher permeability zones. The systems are then turned on and the contaminants are flushed out of the higher permeability areas. This cycle is repeated until concentrations no longer increase while the system is shutdown. The proposed approach for operating the vapor extraction system in the future, which is described in Section IV.B, includes pulsing.

The risk associated with pulsing is that it takes longer to clean the soil. Although the cost per pound of contaminant removed is decreased by the pulsing, the time required to clean the soils increases because the system is operated less often. The increase in cleanup time means that more contaminants can reach the groundwater due to infiltration through the vadose zone.

A relatively new alternative to pulsing is "passive" vapor extraction. With passive systems, vapor extraction is driven not by mechanical pumps, but by fluctuations in barometric pressures. A passive vapor extraction system, in the most-simple case, involves a well that is screened in the unsaturated zone and open to the atmosphere. Gas will flow out of the subsurface through the open well when the subsurface gas pressure is greater than barometric pressure. If the subsurface gas is contaminated with organic vapors, the contaminated gas that exits the well will dissipate into the atmosphere. Gas will flow into the subsurface through the open well when the barometric pressure is greater than the subsurface gas pressure. The gas that enters the subsurface during these

high-pressure events is typically free of contaminant vapors. The result of passive vapor extraction is a net flow of contaminated gas out of the subsurface.

The effectiveness of passive vapor extraction systems is particularly sensitive to site geology. Sites with thick unsaturated zones or sites with higher permeability layers that are confined by lower permeability layers are most amenable to passive vapor extraction. This includes sites with natural or artificial surface covers. Enhancements have been suggested to improve the efficiency of passive extraction systems. The most common enhancement is to prevent the return flow of atmospheric gas into the subsurface by capping the well during periods of high barometric pressure. This reduces the amount of dilution that occurs in the vadose zone and improves the overall removal efficiency.

IV.B. The proposed flow chart for the vadose zone monitoring program

A decision tree or flow chart has been proposed for shutting down the active vapor extraction systems in the A/M Area. This flow chart is described in Chapter 4 of Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998. The decision can be summarized in the following four steps:

- i) If the removal rate for a vapor extraction system falls below 40 pounds per week, the system will be shut down for at least two to three months.
- ii) If the removal rate falls below 40 pounds per week during the first two weeks after the system is re-started, the system will be shut down for at least four to six months.
- iii) If the removal rate stays above 40 pounds per week for more than two weeks after it is restarted, the system will continue to operate. After the removal rate falls below 40 pounds per week, steps 1) and 2) will be repeated.
- iv) Soil samples will also be collected within the zone of influence during steps 1) and 2). If all samples are less than 1,000 ppbw (1,000 $\mu\text{g}/\text{kg}$ or 1 mg/kg), the vapor extraction unit will be switched from an active system to a passive system (i.e. barometric pumping). If any of the soil concentrations are between 1,000 ppbw and 100,000 ppbw, the active extraction will continue and considerations will be given to adding wells or otherwise modifying the system to improve operations. If any of the soil concentrations exceed 100,000 ppbw, alternate remediation technologies will be considered.

IV.C. Evaluation of cleanup goals

The methods that have been suggested for setting remediation goals based on groundwater impact are unclear (page 4-24, Westinghouse Savannah River Company,

WSRC-RP-98-00146, March, 1998.) It is not clear how the approach based on transport models is or will be related to the approach based on the TCLP test.

The suggested cleanup goal for soils less than 80 feet deep (700 ppbw for PCE) is more than 10 times larger than the cleanup goal for soils greater than 80 feet (56 ppbw for PCE). The basis or rationale for choosing this depth for the cut-off is not presented.

The basis for choosing 40 pounds per week as a cut-off value for active vapor extraction is not obvious. The argument has been presented that this value is larger than the removal rate for a single groundwater extraction well in the A/M Area. The cut-off value should be based on more sound economic evaluations that compare the costs of removing contaminants via the vapor extraction system to the costs for removing contaminants from the groundwater and the costs for removing contaminants in the NAPL phase.

A removal rate of 40 pounds per week corresponds to a vapor concentration of 30 ppmv (30,000 ppbv) for a vapor extraction system that operates at 300 standard cubic feet per minute (p. 4-25, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). Shutting down a system that is removing 30,000 ppbv will virtually guarantee that there will be soils in the zone of influence with concentrations above the suggested cleanup levels of 100 ppbw. A vapor concentration of 30,000 ppbv corresponds to 300 ppbw in the soil water; this is 6 times larger than the reported SCDHEC waste water treatment standard of 50 ppbw. A vapor concentration of 30,000 ppbv corresponds to 60 ppbw in the soil. Because of the effects of mixing and dilution, if the concentration in at vapor extraction well equals 30,000 ppbv, then there are almost certainly locations within the zone of influence where the vapor concentration is significantly greater than this value. Work needs to be done to identify an acceptable level of soil contamination in the vadose zone. Once this has been identified, the cut-off removal rate should be re-evaluated based on the acceptable level of soil contamination and estimates of mixing and dilution in the vapor extraction system.

Passive vapor extraction (barometric pumping) plays a significant role in the vadose zone monitoring plan. The plan suggests that active systems be switched to passive systems if removal rates are less than 40 pounds per week and if no soil samples have concentrations exceeding 1,000 ppbw. This technology has not been proven to be effective at the Savannah River site. A passive vapor extraction system has been installed in the A/M Area Miscellaneous Chemical Basin (MCB), but no data have been collected that show what the air flow rates are for these systems or what the zones of influence are (Westinghouse Savannah River, WSRC-TR-99-00058). It is impossible to estimate removal rates and system effectiveness without this information. Estimates of removal rates that have been provide are purely speculative at this point. Much work needs to be done on evaluating this technology if it is to play a significant role in the vadose zone remediation plan at the A/M Area.

Under the proposed flow chart for monitoring the vadose zone, active vapor extraction will be stopped if there are no measured soil concentrations exceeding 1,000 ppbw. This

value is also proposed as a cut-off value for soil gas screening in the Processing Facilities area (page 3-18, Westinghouse Savannah River Company, WSRC-RP-98-00146, March, 1998). A soil concentration of 1,000 ppbw corresponds to a water concentration of approximately 5,000 ppbw. This is 1,000 times larger than the RCRA Corrective action level for groundwater. The basis for this cutoff value has not been presented.

V. APPLICATION OF GROUNDWATER RE-CIRCULATION WELLS

V.A. Overview of Groundwater Remediation in the A/M Area

In addition to the vadose zone remediation activities described in previous sections, groundwater remediation activities have also been undertaken in the A/M Area. The primary activity related to groundwater cleanup in the A/M Area has been groundwater pump-and-treat. This approach involves pumping contaminated groundwater from the subsurface and transporting it to treatment facilities where the contaminants are removed. The treated water can then be discharged to surface water bodies or it can be re-injected into the subsurface. Approximately 3.5 billion gallons of water have been treated since 1985. Approximately 530,000 pounds of solvents have been removed via this treatment.

The treatment process for groundwater contaminated with VOC's such as TCE and PCE is relatively uncomplicated, at least compared to treatment processes required for waters contaminated with radionuclides, metals, and salts. The process that is used in the A/M Area is air stripping. Contaminated water is pumped to the top of a tower, where it trickles or cascades down as air is blown upward. The contaminants evaporate from the water into the air. The air is then treated or discharged.

There are two main air stripping units in the A/M Area. One of these units, the M-1 air stripper, treats water that is extracted from beneath the "Central Sector" of the A/M Area. This sector includes the M-Area Basin, the solvent storage tanks, the A-014 outfall, and the process sewer lines. The second unit, the A-1 air stripper, treats water that is extracted from the beneath the "Northern Sector." This sector includes the SRL Basins.

The M-1 air stripper began full-scale operation in 1985. It has a capacity of approximately 600 gallons per minute (gpm). The solvent concentrations in the groundwater were on the order of 50,000 µg/L in 1985, 7,000 µg/L in 1993, and 9,500 µg/L in 1995. The system on-line 95% of the time and the stripping efficiency is reported to be 99.95%. (A 99.95% efficiency corresponds to 4.75 µg/L effluent for 9,500 µg/L influent.) The A-1 air stripper began operations in 1992 and was upgraded in 1996. It has a capacity of 250 gpm, greater than 99.9% stripping efficiency, and a 93% on-line utilization rate. The effluent levels are below the "permit level" of 5 µg/L. The off-gas from the stripper is treated using a catalytic oxidation unit (Westinghouse Savannah River. WSRC-RP-95-1560, Rev. 0, December, 1995.

V.B. Groundwater Re-circulation Wells

Groundwater pump-and-treat systems similar to what is used in the Central and Northern sectors are much more expensive to operate than the vapor extraction systems that are used to clean soils in the vadose zone. One of the reasons for the higher costs is that water is 1,000 times heavier than air. Much more energy is required to pump the water to

the extraction well and still more energy is required to pump the water from the well up to the ground surface and then to the top of the air stripping tower.

The extraction systems in the Central and Northern sectors extract groundwater with relatively high concentrations of PCE and TCE. Concentrations in the groundwater in these sectors exceed 1,000 µg/L. Other technologies have been considered for treating the more dilute portions of the groundwater plume in the A/M Area. One approach that is under consideration in the southern sector are re-circulation wells. The general idea behind these wells is to do the air stripping inside of the well, and not in some tower at the ground surface. This will reduce energy costs. The water is re-circulated through the extraction well back and then back into the aquifer. The wells are specially constructed to allow the water to enter the bottom part of the well and then exit the top part of the well. Air is bubbled through the well to strip out the contaminants.

V.C. Evaluation of Re-circulation Wells in the Southern Sector

A series of groundwater re-circulation wells has been constructed in the southern sector of the A/M Area. The groundwater concentrations in this sector are generally much lower than the concentrations in the central and northern sectors. The primary objective behind the re-circulation wells is to contain migration of the contaminant plume. Some testing has been completed on the re-circulation wells but they have not yet been operated on a full-scale.

It is very difficult to evaluate the radius or zone of influence for the re-circulation wells. The drawdowns in water levels are generally much smaller than in a traditional extraction system, and water is being injected at the same time it is being extracted. Tests have been completed in the A/M Area to evaluate the effectiveness of this technology at this site. These tests have not been able to reliably demonstrate the capture zone or radius of influence for the re-circulation wells.

Observation wells in the upper portion of the groundwater plume did not show changes in water levels during the operation of the re-circulation wells. It is not generally possible to estimate the vertical extent of the zone of influence for these re-circulation wells without seeing changes in water levels. (Westinghouse Savannah River Company. WSRC-TR-98-00428, Rev. 0).

A tracer test was also completed to evaluate the zone of influence for these wells (Westinghouse Savannah River Company. WSRC-TR-98-00428, Rev. 0). This test involved injecting bromide into the aquifer in the vicinity of a re-circulation well and monitoring concentrations in observation wells between the point of injection and the re-circulation well. The results from these tests were somewhat inconsistent. The tracer became very dilute, as one would expect if significant mixing were occurring in the aquifer. However, the "breakthrough" curves in some observations wells were very sharp spikes, which is not expected if mixing does occur.

Much more work needs to be completed to evaluate the zones of influence and the effectiveness of these re-circulation wells. More reliable evaluations of the vertical extent of these zones of influences is particularly important. Reliance on these wells as a key component of the groundwater corrective action is likely pre-mature and unwarranted.

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Note: Please see Appendix C for the complete set of reports and articles considered in this review.

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APPENDIX A: STATEMENT OF WORK

INDEPENDENT SCIENTIFIC PEER REVIEW OF SRS
ENVIRONMENTAL DOCUMENTS FOR THE SRS CITIZENS
ADVISORY BOARD

GENERAL DESCRIPTION OF THE SERVICE

The Savannah River Site (SRS) Citizens Advisory Board (CAB) frequently has a need for an independent scientific peer review of SRS environmental documents. These documents include, but are not limited to documents such as: Annual Environmental Report, environmental reporting documents, state or federal environmental permits or permit applications, planning and/or budget documents, pollution prevention documents, waste management documents, remediation or restoration documents, etc.

The members of the CAB have recognized the limitations of their experience and technical expertise and the need for the advice of experienced individuals and qualified, professionally esteemed scientists and engineers. This scope of work establishes a protocol and vehicle to obtain guidance and assistance from individual(s) and recognized expert(s) on the following subjects:

A/M Groundwater Remediation
F and H Area water treatment system

There may be topics added or removed after discussions with the STR, the subcontractor, a WSRC procurement representative, member of the CAB, and others, as appropriate.

The review will focus on reviewing documents, data, monitoring information, performance criteria, modeling information, treatment technologies, and other information necessary to provide an independent scientific review of actions and activities being performed at the Savannah River Site.

Specific work and deliverables with expected due dates are shown below. The deliverable dates may change, if the SRS Environmental Restoration workscope changes.

A/M Groundwater Remediation. Review data from ongoing operations to provide recommendation(s) for the CAB to present to the Department of Energy (DOE), South Carolina Department of Health and Environmental Control. (SCDHEC), and the Environmental Protection agency (EPA). This review would be similar to the work completed in 1995 for F- and H- Area groundwater remediation. It is expected that the work shall be completed by August 15, 1999.

F- and H- Area water treatment system. Develop a list of items (a roadmap) that should be considered or done by the site as it prepares to make its transition from Phase I to Phase II in order to make the transition successful. This item shall be completed by August 15, 1999.

Complete an independent scientific peer review (ISPR) final report to the CAB when the two items above are completed. This report should follow the format and content of the F&H Groundwater Report. The principal parts of the report would be A/M Groundwater (about 90%; a broad ISPR covering all aspects of current operations and remediation efforts) and F&H Area water treatment system (about 10%, specifically the transition from Phase I to Phase II). The focus would be on three tracks (1) what must be done scientifically for the best protection and remediation of groundwater, (2) what must be done to satisfy regulators and/or to obtain regulatory relief; and (3) a best estimate of citizens and the three parties from an overview perspective about what should be done as a roadmap about future scientific reviews regarding future and remaining groundwater issues. The report shall be finished and submitted to the CAB, SRS, EPA and SCDHEC by August 15, 1999. The CAB and other reviewers shall be permitted 15 days to study the report and provide comments to the ISPR so that the final report shall either be changed to reflect the criticisms, or a rationale provided to rebut the criticisms. The final report shall be completed and submitted to the CAB and the Contract Officer by September 30, 1999.

A presentation of the ISPR findings based on the final report shall be made to the CAB at the regularly scheduled CAB meeting in September 1999. This shall be completed by attending the CAB meeting and delivering a presentation in person to the CAB regardless of whether a motion is considered.

APPENDIX B: THE F- AND H- AREA WATER TREATMENT SYSTEM

Items that should be considered by the site as it prepares
to make the transition from Phase I to Phase II

The groundwater corrective actions at the F- and H-area seepage basins were previously evaluated in an Independent Scientific Peer Review that was completed in 1995 at the request of the CAB. The results of this review were presented in October of 1995 in a report entitled "Independent Scientific Peer Review of Ground Water Remediation Technologies, Evaluation of Proposed Groundwater Corrective Actions, F- and H-Area Seepage Basins, Savannah River Site." This report outlined a set of recommendations for proceeding with the groundwater pump and treat systems in the F- and H-areas.

The corrective actions at the F- and H-area are being conducted in a phased approach. Phase I involved constructing the groundwater extraction, treatment, and re-injection systems and operating these systems for three years. Plans for Phase II were due three years after the Phase I operating permit was issued. The intent of this approach was to evaluate the effectiveness of the Phase I system and then decide how to proceed based on the results of these Phase I operations.

The Phase I system is not yet fully operational. The H-Area and F-Area systems were designed to operate at approximately 130 gallons per minute (gpm) and 165 gpm, respectively. If these systems are operated 90% of the time, these pumping rates correspond to roughly 5 million gallons per month in H-area and 6.5 million gallons per month in F-area. The actual operating rates during the previous year are summarized below:

	Volume of water pumped in millions of gallons	
	H-Area	F-Area
Second half of 1998	10.9	13.2
First half of 1999	21.6	12.7
Design volume for 6 months	30	39

The monthly operating time, pumping rates, and extracted volumes for the first half of 1999 are summarized below:

	H-Area			F-Area		
	Volume (Millions)	Rate (gpm)	Time (hr)	Volume (Millions)	Rate (gpm)	Time (hr)
January	259 ^a	68 ^b	1.06 ^c	248 ^a	57 ^b	0.84 ^c
February	421	135	3.40	151	63	0.57
March	732	101	4.46	113	134	0.91
April	489	137	4.01	464	166	4.62
May	304	141	2.58	465	166	4.63
June	720	140	6.07	106	170	1.09

^a Total number of hours the system was operated

^b Average extraction rate in gallons per minute

^c Total amount of groundwater extracted in millions of gallons.

Some of the problems associated with the groundwater extraction, treatment, and re-injection systems had been identified in the 1995 ISPR report. Others were not. In any case, sufficient data have not been collected at this time to reliably evaluate Phase II operating scenarios.

It appears, based on the operating data that have been provided and on discussions with site personnel, that many of the difficulties that have limited the operations of these systems are nearly resolved. (The relatively low extraction volumes in June of 1999 at F-Area are due to a scheduled shut-down for system modifications and maintenance. It is anticipated that the rates in future months will be close to the design levels). Given that the groundwater treatment systems now appear to be operating near their design level, the next steps that are recommended relate to developing plans for Phase II. These are summarized below.

It should be noted that the regulators have shown patience and flexibility during the difficulties associated with Phase I of the corrective action. It is likely that this flexibility will also be needed in subsequent phases.

1. Continue to investigate the feasibility of precision pumping.

The objective of precision pumping is to reduce the amount of water that would be extracted and treated. This would involve two systems of monitoring and control. The first control would be to pump only from wells with high contaminant concentrations. The second control would be to treat only the water that has high concentrations of metals. Extracted water that is contaminated primarily by tritium would be routed around most components in the treatment plant.

Precision pumping might have particular merit as a Phase II technology. The benefits of identifying extracted water with low metals concentrations is that that water can be bypassed around the treatment plant, thereby saving the corresponding operating costs.

2. Continue to evaluate the effects of H-area groundwater injection on the Old Radioactive Waste Burial Ground.

Injection of groundwater upgradient from the H-Area may have a positive effect on controlling groundwater plumes in the Old Radioactive Waste Burial Ground. Computer simulations suggest that the injection system may cause the plume to be less diffuse and

therefore more easily controlled (Westinghouse Savannah River, SRT-EST-98-154, 1998). This should continue to be evaluated and these effects should be included in developing Phase II plans.

3. Continue the experimental program to evaluate the feasibility of lowering metal concentrations in the seep water to acceptable levels via control of aquifer pH.

Injection of water with an elevated pH is a simple technology, and preliminary laboratory results seem to support the hypothesis that elevating the pH in the aquifer would dramatically reduce metal mobility. The results of this experimental program should be available in time to compare in situ pH adjustment with conventional treatment as Phase II alternatives, considering both technical and economic factors.

4. Continue to collect additional data to improve characterization of the contaminant sources.

There are significant uncertainties regarding the amount and distribution of contaminants within the subsurface at the F- and H-area seepage basins. Reduction of these uncertainties may result in improved operations for the Phase I corrective action and in better decisions for subsequent corrective actions. Data collection activities should be aimed at distinguishing zones with high contaminant concentrations from relatively clean zones. The amount and distribution of contaminants and the likelihood of perched water in the vadose zone beneath the seepage ponds should be investigated. This investigation might require drilling through the caps or directional drilling. Data should also be collected to estimate leakage rates through the caps.

5. Perform annual external reviews of the groundwater corrective actions

The operations of the treatment systems should be reviewed on an annual basis to evaluate changes that might be appropriate as technology continues to develop. Changes in influent chemistry might also warrant modifications to the treatment program.

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Test Plan for Methanotrophic Mobile Bioreactor at Savannah River Site: TNX (U). Westinghouse Savannah River Company.

Test Plan for the SOILS Faculty Demonstration – Petroleum Contaminated Soil Bioremediation Facility (U). Savannah River Technology Center, Environmental Sciences for Central Services Works Engineering. Project S-4946. WSRC-TR-94-0179.

Test Plan: The Czechowice Oil Refinery Bioremediation Demonstration of a Process Waste Lagoon. Westinghouse Savannah River Company. WSRC-RP-97-214.

The Methanotrophic Fluidized Bed Bioreactor: From Laboratory to Field Demonstration at the Savannah River Site. For Presentation at the 88th Annual Meeting & Exhibition, San Antonio, TX. Air & Waste Management Association. 95-RA127.02

Three Dimensional Zone of Capture Analysis for the A/M-Area (U). By Dennis G. Jackson, Sebastian E. Aleman. Westinghouse Savannah River Company. WSRC-RP-95-0843

Well Completion Report On Installation of Horizontal Wells For In-Situ Remediation Tests (U). By Dawn S. Kaback, Brian B. Looney, John C. Corey, Leonard M. Wright. Westinghouse Savannah River Company. WSRC-RP-89-784.

Multimedia

Composite of Integrated Demonstration of In Situ Bioremediation. Including Program Numbers 95-021, 94-057, 94-170. (video tape).

VOCs in Non-Arid Soils Integrated Demonstration: An Interactive Technology Summary. Office of Environmental Management Office of Technology Development. (compact disc).

Miscellaneous

A Petroleum Contaminated Soil Bioremediation Facility. By Kenneth H. Lombard, Terry C. Hazen. Prepared for the Nuclear and Hazardous Waste Management International Topical Meeting. August 14-18, 1994.

Bioremediation Treatability and Feasibility Studies at a Polish Petroleum Refinery. By T.C. Hazen, C.B. Fliermans, M.M. Franck, K.H. Lombard. Westinghouse Savannah River Technology Center. pgs. 363-365

Biotechnology in Industrial Waste Treatment and Bioremediation. Edited by Robert F. Hickey, Gretchen Smith. pgs. 80-86.

Catalytic Oxidation of Trichloroethylene and Perchloroethylene Mixtures. By J. Borthen, F. Meyer, K. Lombard, T. Hazen. Prepared for Presentation at AIChE 1993 Summer National Meeting. August 1993.

Chapter 14: Bioremediation. By Terry C. Hazen. CRC Press LLC. 0-8493-8362-5/97. 1997.

In Situ Bioremediation of Chlorinated Solvent With Natural Gas. Savannah River Technology Center.

In Situ Remediation: Scientific Basis for Current and Future Technologies. By T.C. Hazen et al. Prepared for the Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994.

Patent for Bioremediation of Contaminated Groundwater. United States Patent. Hazen et al. Patent Number: 5,384,048. Jan. 24, 1995.

Transmittal of the Federal Facility Agreement Revision.0 Appendix D for Fiscal Year 1998 and Revision.0 Appendix E for Fiscal Year 1998. Department of Energy.

APPENDIX D: RESUME FOR JOEL MASSMANN

Associate Professor of Civil Engineering
University of Washington
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Seattle, Washington 98195-2700
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Academic background

Ph.D.	University of British Columbia	1987
M.S.C.E.	The Ohio State University	1981
B.S.C.E.	The Ohio State University	1980

Professional history

Associate Professor, Department of Civil Engineering, University of Washington, Seattle, WA, 1993-present.
Visiting Lecturer, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 1997-98 (sabbatical leave).
Assistant Professor, Department of Civil Engineering, University of Washington, Seattle, WA, 1992-93.
Assistant Professor, Departments of Geology and Civil Engineering, University of Illinois, Champaign-Urbana, Illinois, 1990-92.
Assistant Professor, Department of Geological Engineering, Michigan Technological University, Houghton, Michigan, 1987-90.
Senior Project Engineer, Hart Crowser, Seattle, Washington, 1985-87.
Research Associate, Department of Civil Engineering, The Ohio State University, Columbus, Ohio, 1981-83.

Refereed Journal Publications

Massmann, J.W. and C.A. Moore, "Effects of Landfill Cover Design on Methane Recovery Systems," ASME Journal of Energy Resources Technology, Vol. 105, No. 4, pp. 528-535, 1983.

Massmann, J.W., Discussion on: "Multidimensional Probabilistic Consolidation." D. Hwang and M.W. Witcak, ASCE Journal of Geotechnical Engineering, Vol. 112, No. 3, pp. 385-388, March, 1986.

- Massmann, J.W. and R.A. Freeze, "Groundwater Contamination from Waste-Management Sites: Interaction between Risk-Based Engineering Design and Regulatory Policy. 1) Methodology," *Water Resources Research*, Vol. 23, No. 2, 351-367, 1987.
- Massmann, J.W. and R.A. Freeze, "Groundwater Contamination from Waste-Management Sites: Interaction between Risk-Based Engineering Design and Regulatory Policy. 2) Results," *Water Resources Research*, Vol. 23, No. 2, 368-380, 1987.
- Massmann, J.W. and R.A. Freeze, "Updating Random Hydraulic Conductivity Fields: A Two-Step Procedure," *Water Resources Research*, Vol. 25, No. 7, 1763-1765, 1989.
- Massmann, J.W., "Applying Groundwater Flow Models in Vapor Extraction System Design," *ASCE Journal of Environmental Engineering*, Vol. 115, No. 1, 129-149, 1989.
- Freeze, R.A., J.W. Massmann, J.L. Smith, T. Sperling, and B. James "Hydrogeological Decision Analysis: A Framework," *Ground Water*, Vol. 28, No. 5, 738-766, 1990.
- Massmann, J.W., R.A. Freeze, J.L. Smith, T. Sperling, and B. James, "Hydrogeological Decision Analysis: Applications in Groundwater Contamination," *Ground Water*, Vol. 29, No. 4, 536-548, 1991.
- Freeze, R.A., B. James, J.W. Massmann, T. Sperling, and L. Smith, "Hydrogeological Decision Analysis: Data Worth and the Development of Site Investigation Strategies," *Ground Water*, Vol. 30, No. 4, 374-388, 1992.
- Sperling, T., R.A. Freeze, J.W. Massmann, L. Smith, and B. James, "Hydrogeological Decision Analysis: Application to Dewatering Design at an Open Pit Mine," *Ground Water*, Vol. 30, No. 3, 376-389, 1992.
- Massmann, J.W., and D. Farrier, "Effects of Atmospheric Pressures on Gas Transport in the Vadose Zone", *Water Resources Research*, Vol. 28, No. 3, 777-792, 1992.
- Massmann, J.W. and M. Madden, "Estimating Air Permeability from Vadose Zone Extraction Tests," *ASCE Journal of Environmental Engineering*, Vol. 120, No. 2, 313-328, 1994.
- Poulsen, T., J.W. Massmann, and Per Moldrup, "Effects of Vapor Extraction on Contaminant Fluxes to Atmosphere and Groundwater," *ASCE Journal of Environmental Engineering*, Vol. 122, No. 8, 1996.

Poulsen, T., Per Moldrup, T. Yamaguchi, J.W. Massmann, and J.A. Hensen, "VOC Sorption in Soil: Soil Type Dependent Model and Implications for Vapor Extraction" ASCE Journal of Environmental Engineering, Vol. 124, No.2, 1998.

Poulsen T.G., Moldrup P, Schjonning P, Massmann J.W., Hansen J.A., "Gas permeability and diffusivity in undisturbed soil: SVE implications, ASCE Journal of Environmental Engineering, Vol. 124, No. 10, pp. 979-986, Oct. 1998.

Ellerd, Michael, J.W. Massmann, D.P. Schwaegler, and V.J. Rohay, "Enhancements for Passive Vapor Extraction: The Hanford Study," Ground Water, Vol. 37, No. 3, May-June, 1999, pp. 427-437.

Accepted and Pending:

Massmann, J.W., L. Johannesen, and S. Shock, "Uncertainties in Remediation Times for Vapor Extraction," Water Resources Research.

Hunt, B. and J.W. Massmann, "Vapor Flow to a Trench in a Leaky Aquifer," ASCE Journal of Environmental Engineering..

Fully-Refereed Conference Proceedings

Massmann, J.W., "Computer Optimization of Landfill Cover Design." Proceedings, Tenth Biennial National Waste Processing Conference, American Society of Mechanical Engineers, New York, May, 1982.

Freeze, R.A. and J.W. Massmann, "A Framework for the Analysis of Groundwater Contamination from Waste Management Sites: 1) The Interaction between Engineering Design and Regulatory Policy," Proceedings, Internat. Sympos. on Management of Hazardous Chemical Waste Sites, IAEG, Winston-Salem, Oct., 1985.

Massmann, J.W. and R.A. Freeze, "A Framework for the Analysis of Groundwater Contamination from Waste Management Sites: 2) Estimating Failure Probabilities," Proceedings, International Symposium on Management of Hazardous Chemical Waste Sites, IAEG, Winston- Salem, October, 1985.

Massmann, J.W. and D.T. Matlock, "Application of Remote Data Acquisition Systems in Assessing Groundwater Flow Directions," Proceedings, Conference on Northwestern Groundwater Issues, NWWA, Portland, Oregon, May, 1987.

Duffield, G., E. Evans, J. Massmann,, R. Freeze, and D. Stephenson, "Demonstration of Risk-Based Decision Analysis in Remedial Alternative Selection at the Savannah River Site," Proc. of the Inter. Conf. on Hydraulic Engin. Software, Valencia,

Spain, 1992.

Books

- Freeze, R.A., J.W. Massmann, R. Zapf-Gilje, L. Cahn, L. Smith, and B. James.
"Advances in the Assessment of Data Worth for Engineering Decision Analysis in Groundwater Contamination Problems," NATO Advanced Research on Analytical and Numerical Groundwater Flow and Quality Modeling, E. Custodio et al. (eds.), Reidel Publ. Co., pp. 665-697, 1988.
- Freeze, R.A., G. de Marsily, J.L. Smith, and J.W. Massmann, "Some Uncertainties about Uncertainty," Geostatistical Sensitivity and Uncertainty Methods for Groundwater Flow and Radionuclide Transport Modeling, Bruce Buxton, Ed., Battelle Press, Columbus, Ohio, pp. 231-260, 1989.
- Smith, J.L., R.A. Freeze and J.W. Massmann, "A Geostatistical Approach to Site Characterization and Risk Assessment Related to Groundwater Contamination at Hazardous Waste Management Sites." A chapter in Risk Assessment and Groundwater Contamination, W.F. McTernan and E. Kaplan, ASCE Monograph Series, New York, pp. 281-311, 1991.
- Massmann, J.W., "Risk Assessment and Groundwater Contamination: Methods and Relationships." A chapter in Risk Assessment and Groundwater Contamination, W.F. McTernan and E. Kaplan, ASCE Monograph Series, New York, pp. 331-368, 1991.
- Massmann, J.W. and Mark Hagley, "A Comparison of Model and Parameter Uncertainties in Groundwater Flow and Solute Transport Predictions," A Chapter in Groundwater Models for Resource Analysis and Management, Aly I. El-Kadi, Editor. CRC Press, Boca Raton, FL, pp. 1-22, 1995.
- Nicot, JP., B. Scanlon and J.W. Massmann, "Soil Aeration," Chapter 8 in The Handbook of Soil Science, Malcom E. Sumner, Editor in Chief, Arthur W. Warrick, Associate Editor, CRC Press LC, Boca Raton, 1999.

Sponsored Research

- 1982-83 Interaction of Toxic Gases with Protective Materials, U.S. Dept. of Defense, Principal Investigator, Geotechnics. (\$50,000)
- 1988-1994 Visual Analyses of Multicomponent Immiscible Flow in Heterogeneous Porous Media, National Science Foundation, Principal Investigator (\$350,000)

- 1989-1990 Research Experiences for Undergraduates Supplement, National Science Foundation, Principal Investigator, Michigan Technological University (\$6,000)
- 1989- 1989 A Stochastic Approach to Hydrogeological Site Characterization at the Oak Ridge Reservation, U.S. Department of Energy, Principal Investigator, Michigan Technological University (\$38,215)
- 1991-1992 Quantitative Methods for the Design of Groundwater Quality Monitoring Networks, U.S. EPA, Co-Principal Investigator, University of Illinois, (\$216,000)
- 1993-1994 An Integrated Approach to Monitoring Network Design and Decision Analysis for Subsurface Contamination Restoration, Battelle Pacific Northwest Laboratory, Co-Principal Investigator (\$36,663)
- 1993-1994 Evaluating Alternatives for Designing and Operating Passive Vapor Extraction Wells, IT Hanford Company, Principal Investigator (\$53,990)
- 1994-1995 Evaluation of Field-Scale Subsurface Remediation Systems, Washington Department of Ecology, Principal Investigator (\$49,600)
- 1994-1995 Renovation of Environmental Engineering and Science Research, National Science Foundation, Co-Principal Investigator (\$1,179,000)
- 1997-1998 “Duwamish Coalition Hydrogeologic Pathways Project,” City of Seattle, Office of Economic Development, Co-Principal Investigator (\$52,000)
- 1995-2000 “Anaerobic and Aerobic Bioremediation of Chlorinated Organic Compounds: Processes and Enhanced In Situ Removal”, NIEHS, Co-Principal Investigator, (Civil Engineering component approximately \$165,000/yr. direct costs.)
- 1995-2000 “Tools for Evaluating the Effects of Subsurface Restoration Technologies on Uncertainty and Risk Reduction”, U.S. DOE Initiative: Consortium to Integrate Risk Evaluation and Stakeholder Participation at DOE Sites,” Co-Principal Investigator (Civil Engineering component approximately \$195,000/yr. direct costs).

Selected project reports (reports to sponsors)

Massmann, J.W., Groundwater Contamination from Waste-Management Sites: Interaction between Risk-Based Engineering Design and Regulatory Policy. Ph.D. Dissertation, Geological Engineering, University of British Columbia, Vancouver,

1987.

Freeze, R.A. and J.W. Massmann, Risk Assessment and Design of Data Collection and Monitoring Networks at Waste-Management Sites. Natural Sciences and Engineering Research Council of Canada, Strategic Grant G 1160, Ottawa, Ontario, 1987.

Massmann, J.W. and J.A. Quinnan, Three Dimensional Simulations of Groundwater Pumping Tests at the West Bear Creek Valley Site, (with J.A. Quinnan). U.S. Dept. of Energy, Project ORNL/Sub/89-SD769/1, 1991.

Fabritz, J., J. Massmann, and D. Booth, Development of a Three Dimensional Numerical Groundwater Flow Model for the Duwamish River Basin, Center for Urban Water Resources Management, Department of Civil and Environmental Engineering, University of Washington, Seattle. August, 1998.

Selected Invited Lectures and Seminars

"Risk Assessment and Groundwater Contamination: Methods and Relationships." Invited Speaker at the Joint CSCE-ASCE International Conference on Environmental Engineering, Vancouver, Canada, July, 1988.

"Application of Decision Analysis in Groundwater Remediation Design." Invited Speaker and Moderator at the 1991 ASCE International Symposium on Groundwater, Nashville, Tennessee, August 2, 1991.

"Geological Uncertainty, Information, and Decisions." Invited Speaker and Panelist at the 1992 Annual Meeting of the American Institute of Professional Geologists, held in Lake Tahoe, Nevada, September 27-30, 1992.

"A Comparison of Model and Parameter Uncertainties in Groundwater Flow and Solute Transport Predictions" presented at the 1994 Pacific Northwest Oceania Conference, Honolulu, Hawaii, March, 1994.

"Seep-less in Seattle: Effects of Salmon on Groundwater Resource Development," be presented to the Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, May, 1998.

"Seep-less in Seattle: Effects of Salmon on Groundwater Resource Development," presented to the Department of Applied Earth Sciences, Stanford University, September 30, 1998.

"Science and Risk in Cleanup Decisions: The Hanford 200 Area," Presented at

Responsive Science: Forging Regulatory Resolution at DOE Sites, CRESO,
Washington, DC, April 12, 1999.

Professional licenses

Professional Engineer #36101, State of Michigan

Professional Society Membership

American Geophysical Union (1987-present)

American Society of Civil Engineers (1981-present)

Professional Society and Other Service

Appointed to U.S. EPA Science Advisory Board, Consultant, 1992-1997.

Appointed to Environmental Restoration Priority System Panel, National Research
Council, Commission on Geosciences, Environment, and Resources, 1992-1994

Appointed to Columbia River Comprehensive Impact Assessment Peer Review
Committee, 1995-1997

Appointed to Washington Dept. of Ecology, Science Advisory Board, Fate and Transport
Subcommittee, 1996-current

Appointed to Hanford Advisory Board, Alternate Member.

Awards and Honors

National Scholarship Award, 1982, American Society of Mechanical Engineers

University Fellowship, 1983-85, University of British Columbia

The Presidential Young Investigator Award, 1988, The National Science Foundation

List of Faculty Ranked Excellent by Students, 1990 and 1991, University of Illinois

The Editors' Citation for Excellence in Refereeing, 1991, American Geophysical Union

The Rudolf Hering Medal, 1990, American Society of Civil Engineers

Select Short Courses, Workshops, and Other Educational Programs

"Probabilistic Analysis and Decision Making in the Applied Earth Sciences." Part of a
three-day course presented by the University of Washington and the Geotechnical
Group of Seattle Section of ASCE, April 2, 4, and 6, 1987.

"Monitoring Networks: Heterogeneity, Uncertainty, and Design." Part of a two-day
course on groundwater monitoring presented by the Association of Environmental
Professionals, August 8 and 9, 1988, Oakland, California.

"Geostatistical Approaches to Subsurface Hydrogeological Characterization." Part of a

- two-day course entitled Subsurface Monitoring presented by the University of Wisconsin in Madison, WI in October, 1989 and Sacramento, CA in December, 1989.
- "Basic Geology and Hydrogeology." A three-day course presented to the Illinois Environmental Protection Agency, Division of Land Pollution Control, January 22-25, 1991.
- "Hydrogeological Decision Analysis." A five-day course presented with R.A. Freeze and L. Smith to the U.S. Department of Energy, Las Vegas, Nevada, September 9-13, 1991.
- "Design of Groundwater Contaminant Capture Systems: Decision Analysis and Optimization," A five day short-course with R.A. Freeze, S.M. Gorelick, and J.L. Smith. Developed for Environmental Educational Enterprises and held in Chicago, IL, July 16-21, 1993; July 11-16, 1994.
- "Subsurface Contamination in the United States: Regulations and Clean-Up Technology," Presented as part of the Training Programme for Polish Experts in Water and the Environment, Tampere University of Technology, Tampere, Finland, November 29-December 3, 1993.
- "Hydrogeological Decision Analysis." A five-day course presented with R.A. Freeze and L. Smith to the Swedish Fuel and Waste Management Co., Stockholm, August 15-19, 1994.
- "Introduction to MODFLOW and MODPATH Groundwater Models: Applications with a Graphical Interface." A short course developed for the Professional Engineering Practice Liaison Program, University of Washington, Presented September, 1994.

Selected Consulting Experience

- Washington Department of Ecology, Midway Landfill, Kent, Washington. Develop a sampling and work plan for completing the remedial investigation and feasibility study for the landfill, including evaluating procedures and methods used to perform the remedial investigation and feasibility study. Project Engineer, 1985-1987.
- Kaiser Aluminum and Chemical Corporation, Oakland, California. Critique the approach proposed by the EPA for setting standards regulating concentrations of hazardous wastes in landfills. Project Manager, 1986.
- Aluminum Company of America, Vancouver, Washington. Design and implement a remedial investigation and feasibility study for groundwater contamination from

- waste piles. Project Engineer, 1986-1987.
- Shell Oil Company, Tacoma Distribution Plant, Tacoma, Washington. Design and install a petroleum recovery system to clean groundwater contaminated with petroleum products. Project Manager, 1986-87.
- Crown Zellerbach Corporation, Lady Island Landfill, Camas, Washington. Evaluation of groundwater flow and leachate impact for a wood-waste disposal facility located on an island in the Columbia River. Project Engineer, 1986-87.
- Rockwell Corporation, Hanford, Washington. Develop an approach for using groundwater flow and mass transport models to assess groundwater contamination from infiltration ponds. Project Engineer, 1987.
- Heller, Ehrman, White & McAuliffe, Seattle, Washington. Provide expertise regarding groundwater and contaminant transport for a CERCLA hazardous waste site, 1988.
- U.P. Engineering, Houghton, Michigan. Evaluation of regional groundwater flow systems for municipal groundwater supply, Baraga County, Michigan, 1988-89.
- Geraghty-Miller, Inc., Reston, Virginia. Application of decision analysis and groundwater modeling techniques in groundwater extraction design for the Savannah River site, Aiken, South Carolina. 1989-1993.
- Hart Crowser, Anchorage, Alaska. Provide technical review and design recommendations for landfill gas control system at the Merrill Field Landfill, 1990-92.
- Argonne National Laboratory, Argonne, Illinois. Review plans developed by the Energy Systems Division for conducting pilot-scale studies related to site remediation and vapor extraction design, 1992-1993.
- Riddell, Williams, Bullitt & Walkinshaw, Seattle, Washington. Provide expertise regarding groundwater and contaminant transport for a CERCLA hazardous waste site. 1993.
- Finnish Ministry of the Environment, Helsinki, Finland. Provide technical review of field characterization activities at a site with soil vapor contamination in Hattulla, Finland. 1993-94.
- Baltimore Gas and Electric, Baltimore, Maryland. Provide technical review of subsurface contaminant transport modeling activities associated with site-remediation at Spring Gardens gasification facility. Evaluation included interactions between groundwater and the Chesapeake Bay. 1993-1995.

Jacques Whitford Environmental, New Brunswick. Provide technical review and advise on gas extraction activities at the Gander, New Foundland site. 1994.

GATX Transportation, Chicago, Illinois. Facilitate implementation of observational approach for conducting remedial actions at Saegertown Industrial Site, Pennsylvania. 1994.

Hart Crowser, Seattle, Washington. Provide technical review and advise on site remediation activities at the Puyallup Municipal Landfill site, Washington. 1994-1995.

Westinghouse Savannah River Company, Savannah River, South Carolina. Provide technical review and recommendations for groundwater remediation activities at the F- and H-area seepage basins on the Department of Energy's Savannah River Site. 1995.

Sperling-Hansen Associates, Vancouver, British Columbia Canada. Provide technical review and advise on approaches for extinguishing subsurface fires at the Campbell Mountain Landfill, in Penticton, British Columbia, 1995-96.

Garvey, Schubert & Barer, Provide expertise regarding groundwater and contaminant transport at a landfill in Kitsap County, Washington, 1995-97.

Westinghouse Savannah River Company, Savannah River, South Carolina. Provide technical review and recommendations for the Management Action Plan for groundwater remediation activities at the Savannah River Site. 1996.

U.S. Department of Justice, Washington D.C. Provide expertise regarding groundwater movement and contaminant transport from the Whidbey Island Naval Air Station, 1996.

Foster-Wheeler Environmental Corporation, Bellevue, WA. Assist in developing risk-based clean-up standards at contaminated sites for the Washington Department of Ecology, 1996-1997.

Boateng and Associates, Mercer Island, WA. Teach environmental scientists to use groundwater and contaminant transport models to design subsurface remediation activities, 1997.

Westinghouse Savannah River Company, Savannah River, South Carolina. Provide technical review and recommendations for the Savannah River Integrator Operable Unit Study, 1997-98.

Portland Water Bureau, Portland, Oregon. Provide technical advice related to assessing

the vulnerability of their South Columbia Wellfield to surface contamination. This is a 100 MGD system that is located beneath an industrialized area. 1998-99.

Muckleshoot Indian Tribe, Auburn, Washington. Provide technical advice and expert testimony related to groundwater resource development and interactions between groundwater and surface water. 1995-present.

Elf Atochem, Tacoma, Washington. Assess the effectiveness of groundwater remediation activities at an industrial site, including the effects of groundwater extraction and barrier wall construction, 1999-present.