Applied Environmental Technology Development at the Savannah River Site: A Retrospective on the Last Half of the 20th Century

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Introduction

Fifty years ago, the Savannah River Site (SRS) was built to produce nuclear materials. These operations impacted air, soil, groundwater, ecology and the local environment. Throughout its history, SRS has addressed these contamination issues directly and has maintained a strong commitment to environmental stewardship. The site boasts many environmental firsts. Notably, SRS was the first major DOE facility to perform a baseline ecological assessment. This pioneering effort, by Ruth Patrick and the Philadelphia Academy of Sciences, was performed during SRS planning and construction in the early 1950's. This unique-early example sets the stage for subsequent efforts. Since that time, the scientists and engineers at SRS have proactively identified environmental problems as they occurred and have skillfully developed elegant and efficient solutions.

On a personal note, I am proud to represent the outstanding environmental scientists of the Savannah River Technology Center (SRTC, formerly the Savannah River Laboratory). Former employees such as Wendall Marine, James Fenimore, Henry Horton, Ed Albenesius, Bill Reinig and Todd Crawford, and current scientists such as Jack Corey, Al Boni and Chas Murphy have served as role models and are my mentors. From these individuals, I learned that developing solutions to environmental problems requires honesty, simplicity, technical creativity and hard work.

The SRTC approach relies an interdisciplinary team of scientists – geologists, engineers, chemists, mathematicians, and others. The solutions developed by the team are based on focused environmental characterization followed by selecting and deploying clean-up technologies that are matched to the problem. Each technological advance is grounded in a clearly stated conceptual model and is developed and refined using the scientific method. Successful technologies always obey natural laws, and often rely on natural processes or capabilities. These are the values that were instilled in me during my career in SRTC, and these are the values that I will try to communicate to you using a few examples below. Many of these technologies, consistent with the recent focus on partnerships with the community, have been transferred to the public for use in solving our nations environmental challenges.

Anatomy of a Contaminated Site

Figure 1 depicts a conceptual diagram of a contaminated site that has impacted its surroundings – in this case, the underlying soil and groundwater. The three ovals – the source zone, the primary contaminant plume, and the dilute fringe – represent different portions of the impacted environment that each has a different character. The source zone contains significant contamination in concentrated and hazardous forms. The source zone can contain materials such as undissolved organic liquids (oils, fuels or solvent), strong acids or bases, high levels of radiation, and/or toxic chemicals or elements. The second oval, the primary contaminant plume, is comprised of contaminated groundwater or vapor than carries pollutants at lower levels, but levels that still represent a potentially significant present or future hazard. The third oval, the dilute fringe, contains contamination at relatively low concentrations, but in large volumes of water.

Efficient and effective environmental clean up requires matching the character of the clean-up and stabilization methods to the character of the target zone of contamination. Thus, aggressive and relatively expensive methods are often appropriate for the source zone, classical pump-and-treat methods are often good for the primary contamination zone, and various methods based on natural processes are often best for the dilute fringe. Figure 1 identifies several example technologies that are appropriate for each of the ovals.

In Figure 2, I have extended this conceptual model by identifying the cost basis for the typical clean up technologies. In the source zone, stabilization and removal methods are normally priced in terms of volume of soil or amount of contaminant in the treatment zone ($ per cubic yard, $ per pound and the like). The reference source zone technologies require aggressive access and subsequent use of targeted energy or chemical reagents. It is clear that in the source zone it is important to characterize the site in such a way that the precise location of the source zone is delineated as carefully as possible. This approach will reduce costs by focusing energy or reagent to areas where they are needed. Equally important, however, is a desire to minimize of any undesired negative impacts (wasting energy, harming microbiological populations, etc.) associated with using aggressive remedies on regions without source level contamination. Similar to a doctor, environmental scientists should “first, do no harm.”

In the primary contaminant plume, treatment technologies are normally priced in terms of the amount of water (or vapor) treated ($ per gallon and the like). Thus, the goal of characterization is to define the flow directions and general plume structure to allow the most contaminant to be treated in the fewest “gallons”. Figure 3 illustrates an important-final extension to our simplified conceptual model. This diagram of the primary contaminant plume at the SRS metals fuel and target fabrication facility (M Area) shows that contamination moves in response to many factors – contaminant release location and type, geology, sources and discharges of water, and many others. The resulting contaminated soil and groundwater zone occupies a complicated three-dimensional shape rather than the simple ovals that we began with. This complexity must be recognized when developing and implementing technologies for both characterization and clean up of the primary contaminant plume.

The dilute fringe contains low concentrations of contamination in large volumes of water. Thus, the best technologies for this zone are those that are priced in terms of time ($ / year and the like). To be successful, these technologies must rely on natural-sustainable-measurable processes. This class of technology has gained recent regulatory support under the terminology “monitored natural attenuation”. For the dilute fringe, technology selection is biased toward understanding the contaminant destruction and stabilization capabilities of native species and natural populations. A second step is identifying engineering interventions, if needed, to maximize the performance and to assure that the attenuation process will operate for extended periods. A critical requirement for these technologies development of logical and cost-effective monitoring strategies.

The three zones depicted in Figure 1 are present at contaminated sites of all sizes. At a "mom-and-pop" gas station, the entire contaminated zone – all three ovals – might occupy a portion of a city block. At a large industrial facility like the M Area at SRS, the contaminated zone can extend over a few square miles. The size of a problem impacts how distinct the actions to address the different zones need to be. Time is also a factor. Concentrations change, as cleanup progresses, so that dilute fringe technologies become appropriate for polishing areas that were formerly at higher concentrations.

Above, I have outlined a conceptual description of a typical class of environmental problem. The description is simple and valuable. It provides clarity in defining what technologies are really needed. It helps us describe our cleanup plans to regulators and interested citizens. It encourages implementation of a suite of technologies – each targeting a problem that it is efficient and effective in addressing.

In the sections below, I highlight how this relatively simple conceptual model of the anatomy of a contaminated site can be the basis for improved environmental technologies. I have summarized examples of improved subsurface access methods, novel characterization techniques, and improved cleanup technologies for each of the ovals.

Source Zone Diagnosis and Treatment

As described above, it is critical to locate the concentrated and hazardous contaminants in the soil and shallow groundwater in the source zone. Data from most sites indicates that source zone contaminants accumulate in thin-highly-concentrated layers – these layers can be only inches thick. Some contaminants concentrate near the point of release (many metals and radionuclides); others can move downward and concentrate at depth as they interact with hydrogeological features such as clay layers or the water table. The resulting challenge for characterization is to develop and use a strategy that defines these discrete intervals for a reasonable cost. Using traditional methods, namely drilling a few holes with limited numbers of expensive samples, has a high potential to miss the thin accumulation zones. While the samples may have a legal pedigree, such an approach does not efficiently support environmental decisionmaking/engineering.

We have proposed a “toolbox” approach that uses technologies ranging from geophysics (looking at the reflection and transmission of energy through the soil) to traditional sampling. The heart of the toolbox for source zones, however, is a group of technologies (sensors and samplers) deployed by direct pushing, or insertion, into the ground (these methods have the generic name cone penetrometer (CPT), and trade names such as GeoProbe and SCAPs). These technologies directly address the problem of the geometry of the expected contaminant distribution. Using inexpensive sensors, CPT provides screening data throughout entire profile. The probability of identifying the thin accumulation zones is maximized.

Early CPT sensors were primarily used for describing geology and were developed for engineering and construction. These basic systems have been supplemented by an array of sensors that provide (as needed) electrical measurements, chemical measurements using spectroscopy or fluorescence (these use fiber optic lines to transfer light), direct viewing of the soil using cameras, and many different samplers to collect water, soil or vapor. Several examples are described on Table 1. In each case, the technology is targeted at delineation of the high concentration source zone so that cleanup can be performed efficiently and safely.

Characterization of a source zone is a necessary step toward the goal of removal and/or destruction. Appropriate classes of technologies to address source zone contamination include enhanced removal, *in situ* (or in place) destruction, stabilization, and barriers. These classes can be used alone or in combination. In collaboration with other DOE labs, federal agencies, universities, and industry, all of these source remediation technology classes have been tested and used (as appropriate) at SRS. With the exception of barriers, all of these technology classes require the “injection and mixing” of energy or treatment chemicals into the source zone. Energy based technologies used at SRS include electrical resistance heating, radio frequency heating, and vitrification. A steam based remediation, known as Dynamic Underground Stripping, in scheduled for full-scale use in 2000. Chemical based systems range from shallow soil mixing units to reagent injection in wells. Figure 4 shows the operation of an example system in which Fenton’s Reagent (hydrogen peroxide and reduced iron) was injected to destroy industrial solvents in a target zone about 150 feet deep.

Primary Contaminant Plume – Stepwise Improvement of the Baseline

This zone is characterized by the presence of contaminants at easily measured and potentially harmful. The contaminants in this zone tend to be somewhat mobile. As a result, baseline methods, like “pump and treat” work reasonably well. Significant quantities of contamination can be removed (either as soil vapor or groundwater) and the contaminants treated at the surface using standard water treatment methods. Advancing the state of the art for this zone requires attention to large-scale plume geometry and incorporation of creative-stepwise improvements in engineering. SRS has made several significant contributions that improve primary contaminant plume technologies. These contributions include improved depth discrete sampling devices (such as the strata-sampler and the cone-sipper), improved data interpretation using 3D imaging techniques, and successful deployment of innovative cleanup systems (recirculation wells and the like). I have summarized two notable contributions below – environmental horizontal wells and *in situ* bioremediation.

SRTC pioneered the use of horizontal wells for environmental cleanup. Environmental horizontal drilling has roots in oil and gas exploration and in shallow pipeline/utility installation. As depicted in Figure 3, the primary contaminant plume has a complicated 3D geometry. The option of matching the geometry of a cleanup system to the geometry of the contaminant distribution using directional drilling, while simple in concept, represents a major advance. Horizontal and directionally drilled wells provide efficient access to contaminants, as well as a range of new and interesting engineering options (intercepting contaminants as they reach facility boundaries, cleanup underneath buildings…). SRTC installed and tested two environmental horizontal wells in 1988 – these wells represent the birth of the industry. Currently, SRS has nine horizontal environmental wells installed at several sites for a variety of uses. SRS research, combined with efforts of others, has resulted in growth of a mature and active horizontal environmental well industry and formation of a national technical and trade association.

SRTC innovations cleanup of the primary plume extend beyond optimizing geometry and improving access to the contamination. SRTC research has documented that natural microorganisms (bacteria, fungi, and the like) that are capable of destroying or stabilizing many pollutants are present in virtually all soil and groundwater systems. SRTC is recognized as a leading institution in developing and implementing methods to utilize this resource – putting these organisms to work for us. We "pay" them by adjusting the natural conditions and providing nutrients that are missing or limiting the rate of decontamination. In the case of gasoline and oil, the beneficial bacteria and other microorganisms consume the pollutants as a primary food source. To do this, they need oxygen, nitrogen and phosphorus. Injecting air (oxygen and nitrogen) provides two of these nutrients. SRTC developed and patented a method of adding phosphorus to air so that all of the important nutrients could be added inexpensively. This technology, PHOSter®, has been widely licensed and is being used throughout the country to clean up sites ranging from "mom and pop" gas stations to large industrial sites.

SRTC has also pioneered technologies to cleanup more challenging contaminants like industrial solvents. While these compounds are not directly used as food, we can add appropriate foods that encourage their destruction. Similar to PHOSter®, we developed a method based on adding air as the carrier. In this case, the air includes trace levels of natural gas and nutrients. The success of this technology has resulted in its licensing and use at a variety of sites across the country. The success of the bioremediation methods developed by SRTC is a testament to the scientific approach and conceptual model – that nature provides the basis for the best environmental solutions.

Dilute Fringe – Green Technologies

In the dilute fringe, even more than in any the other zones, the concept of putting nature to work for environmental cleanup central to success. Creative use of natural forces, natural laws, and site specific conditions is the key to developing cost-effective solutions for low concentrations of contaminant in large volumes of water. Properly configured, tides, weather patterns, gravity, interfacial interactions, natural biological processes, and other basic forces supply energy and mechanisms for contaminant destruction and stabilization. As discussed below, these processes can be inexpensive and effective. Importantly, the goal of dilute fringe technologies should be to reduce contaminant exposure (flux), to protect human and environmental health, and to monitor the performance of the protection in a direct and cost-effective manner. I have highlighted two SRTC developed examples of the "green" technologies that are needed to address the challenging conditions in the dilute fringe – BaroBall™ and Geosiphon™.

The BaroBall™ is a remediation tool that uses variations in barometric pressure to extract contaminants from or inject fresh air into the soil. Without the device, wells screened above the water table inhale and exhale in response to the weather. Soil properties, depth and other factors determine the amount of flow. The BaroBall™ is a simple check valve that uses a ping-pong ball to control flow. Consistent with the need for steady long-term cleanup of dilute fringe levels of contamination, the device provides a reliable performance with minimal use of using energy and minimal maintenance.

A similar creativity in using natural forces is embodied in the Geosiphon™. If left alone, contaminated groundwater moves steadily from its source to a discharge point near a river. Water is moving from higher head, or total pressure, to lower total pressure. The Geosiphon™

recognizes this reality and uses the simple concept of a siphon to exploit the pressure difference to our benefit. The system connects the contaminated groundwater to the river through a large pipe. Importantly, the system contains a treatment bed that purifies and detoxifies the water as it is being siphoned. To operate the system, the large pipe is primed and then the valves are open. Under the influence of gravity, the siphon extracts and treats the water without the need for a pump or pumping power (Figure 5). The low concentrations in the dilute fringe result in a long life for the treatment bed and the overall system is conceptually appropriate for this zone.

As demonstrated by the use of pin-pong balls and siphons, it is clear that environmental technology solutions do not always need to be complicated. Particularly in the dilute fringe, simplicity and creativity are needed. SRTC is studying the potential role of plants and microorganisms near groundwater discharges to determine their potential for contributing to the solution. Dilute fringe technologies must be technically based and must be able to be monitored and documented.

Concluding Remarks

Similar to any large industrial facility, construction and operation of SRS resulted in many significant adverse environmental impacts. Nonetheless, it would have been easy to write this paper as a list of successes and statistics.

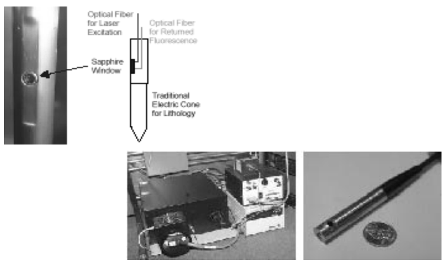
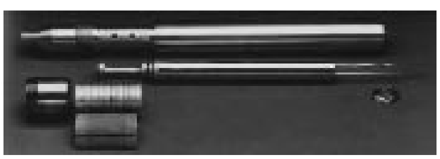
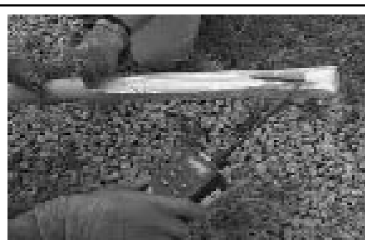
> SRS has treated more than 3 billion gallons of groundwater, removed more that 800 thousand pounds of contamination from soil and groundwater…. SRS has completed or is actively cleaning up more than 300 of its 500 contaminated acres…. SRS has been awarded nineteen environmental technology patents and many national awards for its environmental accomplishments…. SRS is committed to meeting its obligations under a wide array of environmental regulations – NEPA, RCRA, CERCLA, NPDES…. The SRS Environmental Restoration Program has been the most active and successful program in the DOE complex in incorporating new

> technologies into its work to accelerate cleanup and reduce costs…. SRS provides frequent and detailed public information on its environmental impacts…. SRS was a charter federal facility designated as National Environmental Research Park…. SRS is home to the preeminent ecological research center in the world – the University of Georgia Savannah River Ecology Laboratory and a major office of the U. S. Forest Service….

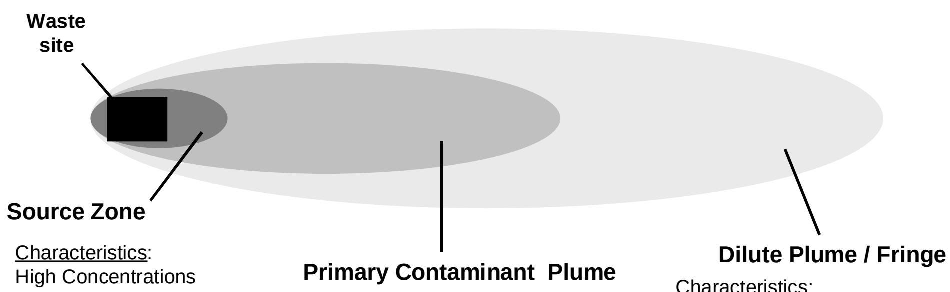
SRS applies creative, interdisciplinary approaches to developing inexpensive and robust technologies. The result has been a steady stream of effective products. SRTC pioneered the use of horizontal wells for cleanup, and has created and licensed important environmental samplers and sensors. Barometric pressure, solar energy and microbiology all have been put to work. Going far beyond hatching new ideas, SRS is also recognized as a leader in developing and demonstrating new technologies. SRS has been instrumental in moving technologies, both those developed on-site and off-site, to field deployment and into widespread use in the private sector.

Lists of progress and accomplishments for each identified "waste site", as well as general chronologies of SRS accomplishments are widely available. I chose, instead, to provide my assessment of how SRS has achieved environmental progress – focusing especially on the technology contributions of the site's scientists and engineers. We are committed to continue the fifty-year environmental technology legacy that has been entrusted to us.

Table 1. Example CPT Characterization Technologies

	The cone penetrometer (CPT) and similar techniques such as the GeoProbe directly push sensors and samplers into the soil and shallow groundwater. This is a photograph of a CPT truck developed by DOD and DOE for testing new environmental characterization methods. The examples discussed below represents a collaboration among scientists from government agencies, industries and universities.
	Fiberoptic probes can be used with a CPT to measure chemicals and subsurface conditions. Spectroscopic measurements such as fluorescence (left picture) and raman (right pictures) can be related to chemical concentrations. Specialized sensors for a variety of uses have been developed, tested and deployed.
	The Geo VIS Probe, a video system developed by DOD to be deployed with the CPT, is used to acquire magnified images of the soil and groundwater at the tip passes. The instrument consists of a CCD color camera, lens/focusing system, and an light-emitting-diode (LED) illumination system
	A variety of samplers can be deployed using a CPT - samplers are available that collect liquids, vapors, or solids. Many systems allow samples to be collected without withdrawing the equipment from the hole. The cone sipper (left picture) is an SRTC developed system used to collect vapor and liquid samples. In some cases, CPT can be used to install monitor in wells and other devices for long term use.
	Specialized measurements can also be made using CPT equipment. One example is the "permeability probe developed by industry (Science and Engineering Associates)
	Creativity is a key to developing tools to find thin layers of contaminant accumulation. This fabric tube, modified by SRTC, can be installed in an open hole (installed by CPT or by drilling). The tube wicks oily contaminants -- these release a dye and the stains on the retrieved fabric tube show the depth of contaminated layers.

Anatomy of a Contaminated Site



Source Zone

Characteristics:
High Concentrations
Significantly perturbed geochemistry

Need:
Aggressive technologies to limit long term damage

Examples:
destruction or stabilization in place; heat/steam; chemical oxidation or reduction; immobilization.

Primary Contaminant Plume

Characteristics:
Moderate to high aqueous/vapor phase concentrations

Need: Baseline methods or moderately aggressive alternatives

Examples: pump (gas or water) and treat; recirculation wells; enhanced bioremediation

Dilute Plume / Fringe

Characteristics:
Low aqueous/vapor phase concentrations;
Large water volume.

Need: innovative technologies - sustainable low energy concepts

Examples: Passive pumping (siphon, barometric, etc.); bioremediation;phytoremediation, geochemical stabilization

Figure 1

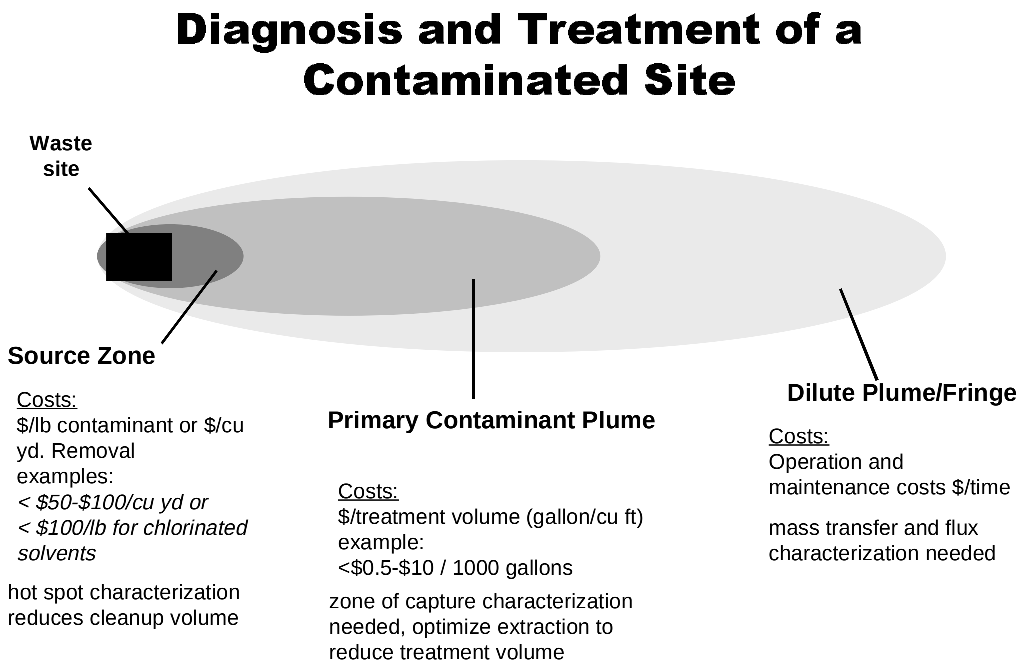

Diagnosis and Treatment of a Contaminated Site
Waste site
Source Zone
Costs:
$/lb contaminant or $/cu yd. Removal examples:
< $50-$100/cu yd or
< $100/lb for chlorinated solvents
hot spot characterization reduces cleanup volume
Primary Contaminant Plume
Costs:
$/treatment volume (gallon/cu ft)
example:
<$0.5-$10 / 1000 gallons
zone of capture characterization needed, optimize extraction to reduce treatment volume
Dilute Plume/Fringe
Costs:
Operation and maintenance costs $/time
mass transfer and flux characterization needed

Figure 2

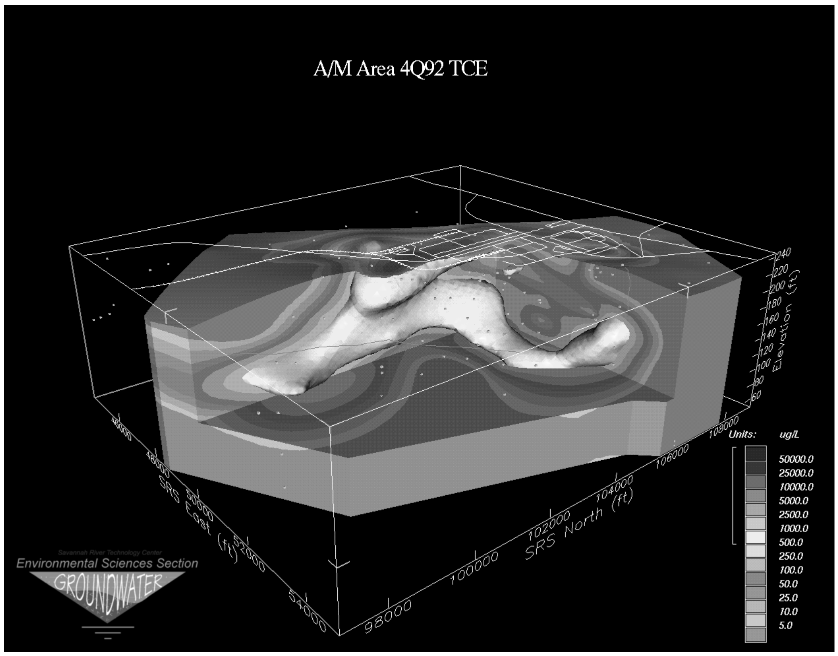


Figure 3. Cut-away diagram showing the 3D structure of a real grooundwater plume

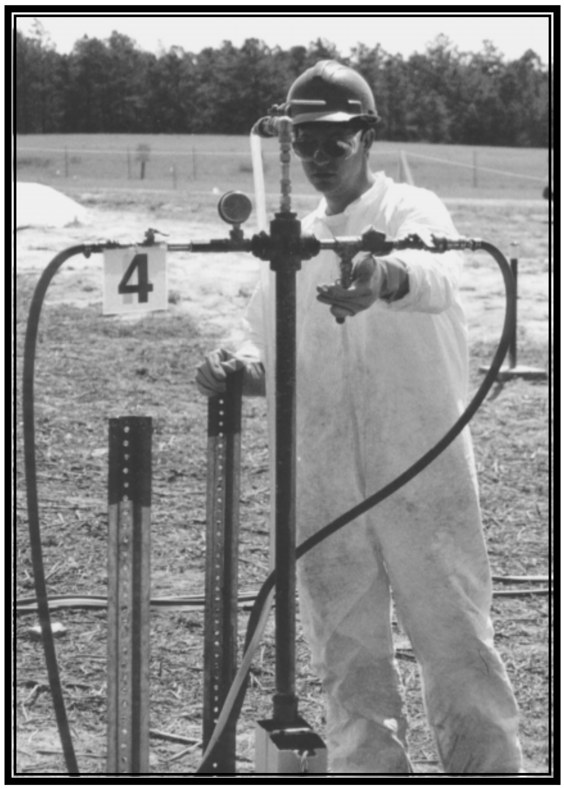


Figure 4. Fenton's Reagent is added to a source zone to destroy NAPL in place. This project was a cooperation between SRTC and industry.

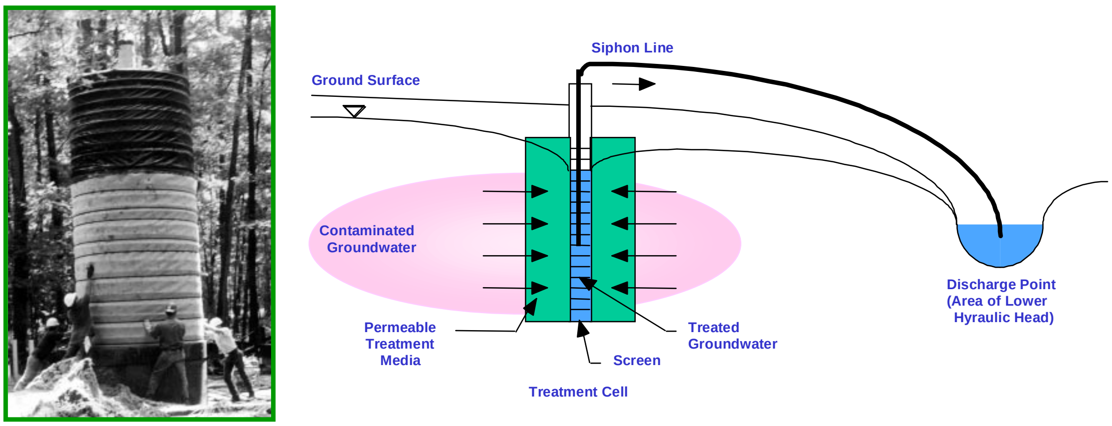


Figure 5. The SRTC GeoSiphon concept (right) and the installation of a GeoSiphon at SRS (left)