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THE ROLE OF INNOVATIVE REMEDIATION
TECHNOLOGIES

J. M. Doesburg

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Environmental Management Operations
Pacific Northwest Laboratory
Richland, Washington 99352

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The Role of Innovative Remediation Technologies

Background

There are currently over 1,200 sites on the U.S. Superfund's National Priorities List (NPL) of hazardous waste sites, and there are over 30,000 sites listed by the Comprehensive Environmental Responsibility, Compensation and Liability Information System (CERCLIS). The General Accounting Office, the U.S. government's auditing arm, has estimated that the CERCLIS could contain an additional 368,000 sites if a more comprehensive inventory were performed. There are even more sites that are candidates for cleanup if the Department of Energy and Department of Defense were to perform comprehensive inventories of candidate sites. This impressive list of potentially contaminated sites can be contrasted with the 63 sites that the U.S. Environmental Protection Agency (EPA) has declared completed to date.

The traditional approach to remediating sites in the U.S. has been to remove the material and place it in a secure landfill, or in the case of groundwater, pump and treat the effluent. These technologies have proven to be very expensive and don't really fix the problem. The waste is just moved from one place to another.

In recent years, however, alternative and innovative technologies have been increasingly used in the U.S. to replace the traditional approaches. This paper will focus on just such innovative remediation technologies in the U.S., looking at the regulatory drivers, the emerging technologies, some of the problems in deploying technologies, and a case study.

Regulatory Background

U.S. regulations designed to protect the environment were first enacted in 1963 with the passage of the Clean Air Act. Over the ensuing decades, other regulations were passed controlling waste-disposal activities, toxic substances, pesticides, and a myriad of other specific concerns. Table 1 lists the more prominent regulations enacted in the U.S. in the past three decades.

Table 1.

- Clean Air Act (1963)
- Federal Water Pollution Control Act (1972)
- Resource Recovery Act (1970)
- Amendments to the Clean Air Act (1970, 1977, 1992??)
- Resource Conservation and Recovery Act (1976)
- Toxic Substances Control Act (1976)
- Occupation Safety and Health Act (1976)
- Clean Water Act: Amendments (1977-1990)
- Comprehensive Environmental Responsibility, Compensation, and Liability Act (1980)
- Hazardous and Solid Waste Amendments (1984)
- National Emission Standards for Hazardous Air Pollutants (1970/1977)
- Superfund Amendments and Reauthorization Act (1986)

Such an impressive list of regulations shows an enduring interest in the environment, yet there has been an apparent lack of progress in remediation. In response, U.S. agencies

have initiated the effort to find better, faster, less expensive ways to remediate contamination from hazardous waste.

The EPA, for example, has established a number of programs in recent years in an attempt to bring new technologies into the field in order to improve our remediation record. Included in these initiatives are the Superfund Innovative Technology Evaluation (SITE) program, The Alternative Treatment Technology Information Center (ATTIC), and the Technology Information Office (TIO).

In addition, the Department of Energy has established the Integrated Site Demonstration program, and the Department of Defense has funded a large number of technology research, development, and deployment centers such as the Air Force Center for Environmental Excellence.

This paper, however, will focus on the U.S. EPA's technologies, primarily because of the scope of their programs and the fact that EPA is involved in most of the cleanup actions in the U.S.

Overview of Existing Remediation Technologies (Alternative Technologies)

Traditional Approach to Remediation

The most common method of disposing of solid waste in the U.S. during the early 1980's was to excavate, transport, and dispose of the material in a landfill. The most common water treatment technology was to pump and treat. These methods have been applied successfully at a number of sites, but their cost, and the fact that the contamination has not been permanently eliminated has made alternative technologies attractive. In the U.S., the liability for contamination stays with the generator, regardless of where it resides, making disposal one of the least attractive options.

Alternative Technologies

Alternatives to the traditional technologies have been promoted aggressively by the EPA. Superfund Amendments and Remediation Act (SARA) (1986) contained provisions to encourage permanent solutions (destruction vs. disposal) to hazardous-waste problems.

Alternative technologies have widespread, full-scale use throughout the U.S. These technologies are classified because classification as "alternatives" is based on the fact that they are alternatives to landfill disposal. The most commonly used alternative technologies are incineration and solidification/stabilization. A recent (September 1991) EPA listing of established alternative remediation technologies included

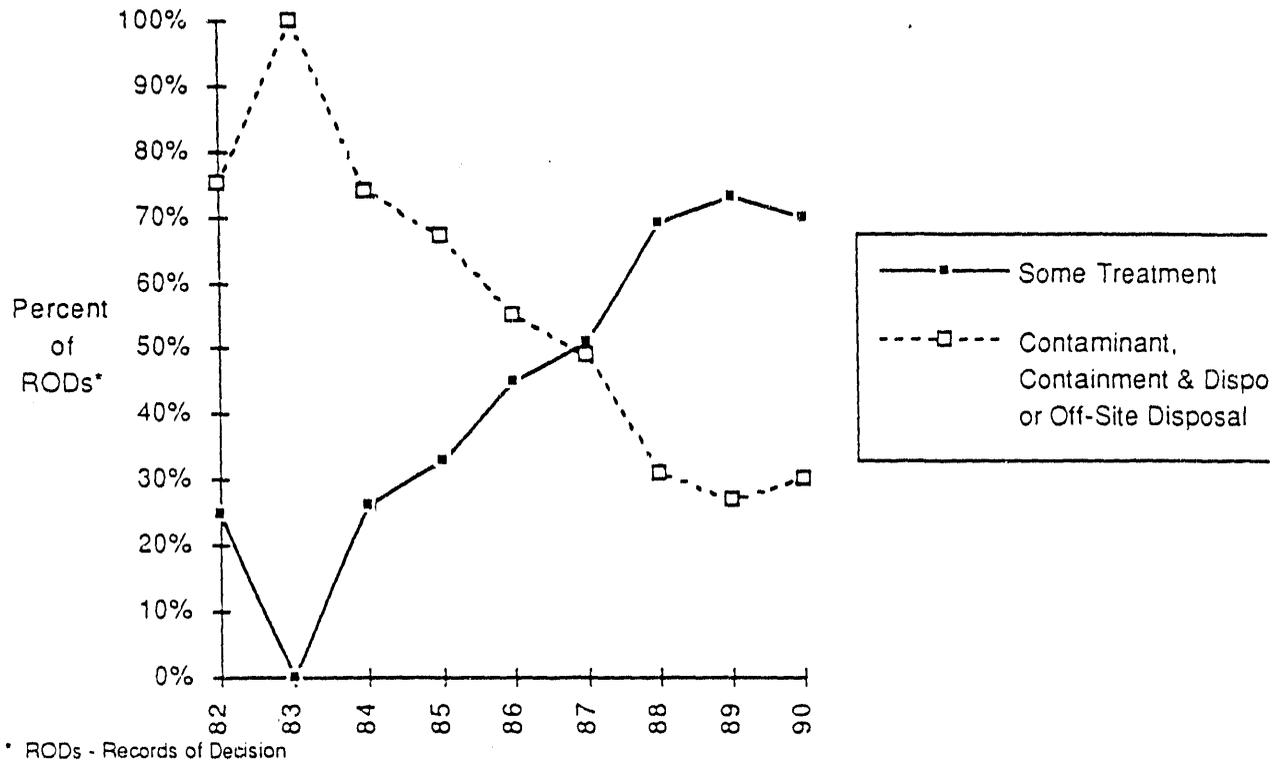
- on site incineration
- off site incineration
- solidification/stabilization
- other (soil aeration, chemical neutralization)

These technologies have been described in some detail in various reports (see list of reference materials).

The number of sites where treatment, rather than disposal, is used has increased dramatically in the U.S. After the passage of SARA in 1986, the number of sites using treatment technologies increased to the point where nearly 70% of the sites currently being remediated are in fact using treatment technologies, as opposed to disposal.

Figure 1 shows this trend in remedial actions.

REMEDIAL ACTIONS: TREATMENT VERSUS DISPOSAL RODs FOR SOURCE CONTROL



TREATMENT VS. DISPOSAL FIGURE FROM TIO REPORT

Innovative Technologies

Innovative technologies are those that are not in common use and where there is a paucity of data on the full-scale applications. These technologies include

- o ex-situ bioremediation
- o in-situ bioremediation
- o chemical treatment
- o dechlorination
- o in-situ flushing
- o in-situ vitrification
- o soil washing
- o solvent extraction
- o thermal desorption, and
- o vacuum extraction

Bioremediation

Ex-situ and in-situ bioremediation rely on microbial organisms to break down and detoxify organic compounds. Ex-situ systems for water are established in a manner very similar to waste-water treatment systems, which enables the engineer to control many of the design parameters. Other types of ex-situ systems include landfarming and composting. In-situ systems are dependent on the natural conditions and the design engineer's options are limited to some extent.

Most organic compounds are, in fact, biodegradable and can serve as a carbon and energy sources for microbial growth, even if they possess toxic properties. Strains of bacteria have even been identified that can resist the effects of many toxic compounds. Of course these specialized bacteria present unique problems. For example, if the concentration of the compound they are designed to destroy is less than the design level, it may be necessary to introduce the specific enzymes needed to degrade the compounds.

Bioremediation progresses by three mechanisms: fermentation, anaerobic respiration, and aerobic respiration. Fermentation is a slower process than respiration and aerobic respiration appears to be used more often than anaerobic.

There are six primary parameters that affect the bioremediation process:

- o oxygen
- o temperature
- o concentration of inhibitory or toxic compounds
- o pH
- o pressure
- o type and concentration of inorganic nutrients

The type of the substrate, the specific microbes, and the overall system design will affect the process as well.

Bioremediation is one of the more popular treatment technologies being tested in the U.S., and there have been many notable successes in the private sector that have not been included in EPA's list of sites. In particular, this technology has shown great promise in the treatment of soils contaminated from leaking underground petrol tanks. There are problems, however, associated with the misapplication of the technology. Soils must have the proper mix of the parameters described above, and that mix is not always intuitively obvious. Many attempts at remediation have been foiled by a lack of oxygen in the system, especially with the in-situ systems. Often these systems take considerable time to reach an acceptable cleanup standard. This may create problems with a regulatory agency and could be a source of concern when dealing with an environmentally sensitive area.

The EPA lists 23 ex-situ and 13 in-situ bioremediation sites in their Semi-Annual Status Report dated September 1991. The contaminants being treated include volatile organic compounds (VOCs, mainly fuels), phenols, creosote, polynuclear aromatic hydrocarbons (PAHs), and dioxins. Included in the appendix is a list of the priority pollutants identified by EPA and a classification of their biodegradability.

Chemical Treatment

Chemical treatment systems also can be either ex-situ or in-situ. The primary processes are precipitation and oxidation/reduction. Precipitation is often used to remove metals

from groundwater with metals being removed as metal hydroxides, carbonates or sulfides. This process is widely used in above-ground systems. In-situ systems can treat contamination by precipitation, oxidation/reduction, and polymerization.

This process has several drawbacks: costs can be high compared to other methods; the in-situ systems may provide spotty treatment in areas where the soils are inhomogeneous; and the waste products from the system may require further treatment.

EPA lists 5 sites where chemical treatment is being applied. Contaminants being treated include carbon disulfide, chromium, arsenic, cyanide, and pesticides.

Dechlorination

This process uses a potassium or sodium-polyethylene glycol solution to breakdown halogenated compounds under increased temperature (100 to 200°C). The reaction is very temperature critical. It must be high enough to achieve dechlorination but low enough to prevent unwanted side reaction. The KPEG solution can be recycled. The process is relatively expensive \$200- per cubic yard and volatile compounds may be released during operation.

The EPA lists 8 sites where dechlorination is being demonstrated. The contaminants being treated include PCBs, DDT, DDD, DDE, dioxins and herbicides.

In-situ Flushing

This system is quite similar to that required in many in-situ bioremediation efforts. In this case, an injection gallery and a withdrawal gallery are established to flush water and additives through the soil. Surfactants, nutrients, pH modifiers, and other additives are injected to wash contamination from the soil. This technique is particularly effective in systems where the substrate is homogeneous and isotropic. Channelization of flow and contaminant retention in the fine material are common problems.

EPA lists 12 sites where in-situ flushing is being demonstrated. Contaminants being treated include VOCs, semi-volatile organic compounds (SVOCs), PCBs, PAHs, and metals.

In-situ Vitrification

This system is a thermal treatment process. Electrodes are placed into the soil; a starter path of graphite and glass frit is laid between the electrodes; and an electrical current is applied. The soil is melted around the electrodes reaching a temperature of over 1600°C. The soil continues to melt until a point of diminishing returns. Soil can be vitrified to a depth of 30 feet.

There are several uncertainties about this process. The process will create large volumes of off gasses that have to be collected and treated before release. In some trial tests, the melt has "burped" some of these gasses, causing the molten soil to splash onto the off-gas collection system and destroy it. The cost for remediation can be quite high-as much as \$1,200 US per ton. Other questions about the behavior of contaminants in the melt have yet to be addressed. Nevertheless, this system is being tested because it holds much promise for sites where other methods would be ineffective.

The EPA lists 8 sites where in-situ vitrification is being demonstrated. Contaminants being treated include VOCs, dioxin, pesticides, mercury, and various other metals.

Soil Washing

Soil washing is a physical separations process that can be used in a number of ways. In some instances, soil washing can be used to totally remediate a site. This is true where the physical properties of the contaminants and soil are sufficiently different that a washing or screening can separate them. More often, however, soil washing can be used to reduce the volume of material that has to be submitted to a secondary process. Studies have shown that much of the contamination in soil will be tightly bound onto the finer fraction. The coarse fraction of soil can be removed by washing prior to a secondary treatment.

Problems associated with soil washing include disposal of the wash water, cost of mobilization of the equipment, complications with treating a finer material in the secondary treatment process, and disposal of the coarser fraction.

The EPA lists 17 sites where soil washing is being demonstrated. Contaminants being treated include VOCs, various metals, SVOCs, pesticides, dioxins, and PAHs.

Solvent Extraction

Solvent-extraction technologies are based on the ability of various solvents to break down the bonds between organic contaminants, solids, and water. The systems use a variety of solvents, such as secondary or tertiary amines or, in one case, liquified propane. The solvents are mixed with the wastes and, after an appropriate period of agitation, the solids separated, the liquids decanted, and the solvents separated from the waste and water. The solvents can be recycled. Some of the problems associated with these technologies are the inability to treat metals, reactivity with the organics, and possible inhibitors, such as detergents, in the waste.

EPA lists 7 sites where solvent extraction is being demonstrated. Contaminants being treated include PCBs, PAHs, VOCs, metals, and SVOCs.

Thermal Desorption

Thermal desorption processes include incineration, pyrolysis, and wet-air oxidation. Contaminants are incinerated, releasing energy with a wide variety of off-gasses. Incineration is usually classified as low-temperature and high-temperature, with off-gas processing systems designed to treat the different products. Pyrolysis breaks down organics in an oxygen-deficient atmosphere, and wet-air oxidation breaks down organics in a high-temperature and high-pressure environment. These technologies all have potentially hazardous waste streams. They are often used in conjunction with other treatment techniques.

EPA lists 17 sites where thermal desorption is being demonstrated. Contaminants being treated include VOCs, PCBs, DDT, DDD, DDE, and SVOCs.

Vacuum Extraction

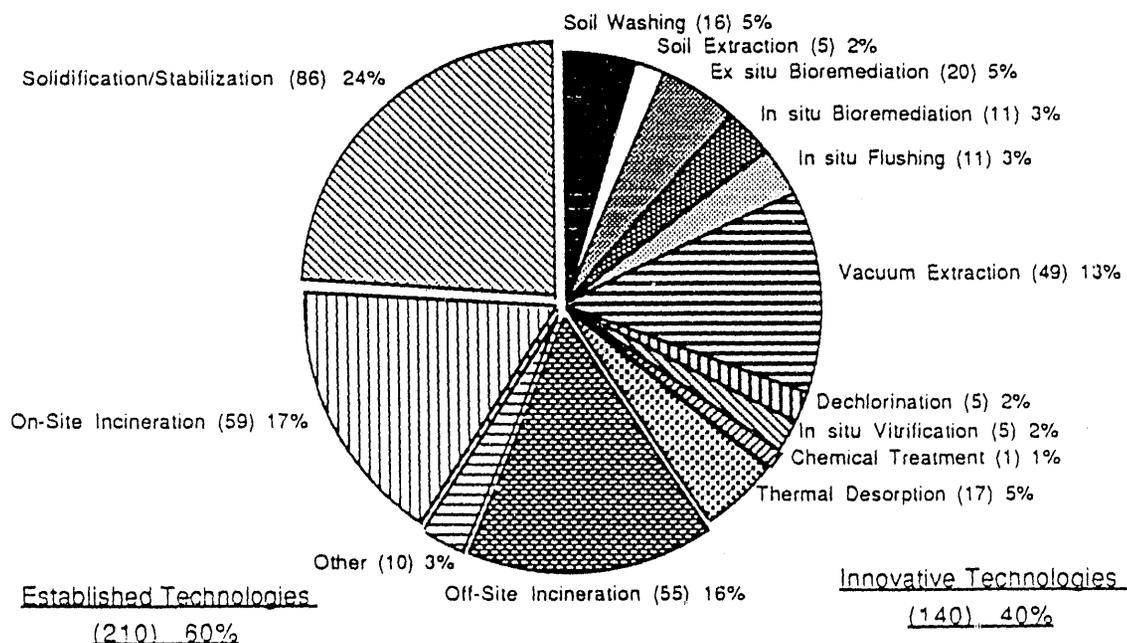
This is a promising technology that is being used throughout the U.S. The basic principle is to apply a vacuum to a well or a series of wells in a zone where the properties of the soil allow relatively free flow of air. The off-gases from the vacuum system are treated to remove liquids and then to treat the gas. These systems can be used in conjunction with bioremediation systems in which air is a necessary additive to stimulate biological activity.

These systems can be used to remove contaminants with high vapor pressures. They have drawbacks in that they are ineffective in removing contamination bound in finer grained materials. EPA lists 51 sites where vacuum extraction is being demonstrated. Contaminants being treated include VOCs and SVOCs.

Figure 2 shows the distribution of established versus innovative technologies currently being used on National Priorities List (NPL) sites.

FIGURE 2

REMEDIAL ACTIONS: SUMMARY OF ALTERNATIVE TREATMENT TECHNOLOGIES THROUGH FY 90



U.S. Research and Development in Remediation Technologies

U.S. research and development is funded through two sources, government and industry. The primary governmental sources of funding include the EPA, the Department of Defense, and the Department of Energy. Virtually every other federal agency has some research or demonstration of remediation technology underway or being planned. These agencies range from the Department of Agriculture (the Agriculture Research Service investigations into herbicides and pesticides) to the Department of Treasury (waste streams associated with the printing of money).

The private sector, primarily large industries, are also funding research into remediation technology. Geosafe, spun off from Battelle Memorial Institute, is a venture attempting to commercialize in-situ vitrification technology. Allied Signal, Bell Laboratories, Ford Motor Company, and IBM are but a few companies that have active research and development programs.

One of the more frustrating problems, however, is the apparent inability to move innovative remediation technologies quickly from the laboratory to the field. This is understandable from the point of view of private industry, which may choose to market their technological advances or at least protect their intellectual property. It is less acceptable when looking at the publicly funded research that stays locked up in the national laboratories or in EPA research facilities. Often the government presents barriers to developing/deploying innovative technologies. For example, under CERCLA, remedial actions must comply with all applicable or relevant and appropriate requirements (ARARS), and at the same time, be cost-effective, provide a permanent solution and use alternative treatment technologies. Decision makers faced with this guidance, tend to avoid the innovative treatment technologies that may pose some risk of failure.

EPA, arguably the lead U.S. agency for waste technology research, has established a variety of offices and programs to help technology transfer. The Superfund Innovative Technology Evaluation (SITE) program promotes the development and use of innovative technologies at Superfund sites. The Department of Energy has initiated the Integrated Demonstration Program, designed to help foster cooperation and information exchange within the DOE. The Federal Technology Transfer Act allows federal laboratories to work with industry to speed the process of getting information out of the lab and into the field. The Department of Defense has established technology centers to coordinate and direct research and remediation activities.

Case Study of an Innovative Remediation Technology at a U.S. Air Force Base

Recent efforts at Eielson Air Force Base (EAFB), located near Fairbanks, Alaska, offer an interesting example of deploying an innovative technology. EAFB is one of the northernmost defense facilities of the U.S. It comprises over 19,000 acres of relatively flat terrain in the Tanana River valley. It is subjected to extreme climatic fluctuations with temperatures dropping below -60°F in the winter and rising above 90°F in the summer. Remedial alternatives that can be economically deployed to this remote site and still withstand the rigors of winter are few.

The air base has been characterized, and over 64 separate sources of contamination have been identified. The majority of the contamination consists of petroleum products from past and existing fueling practices. Much of the contamination is bound in the soil; there are hundreds of thousands of cubic meters of petroleum-contaminated soil.

Previous attempts to remediate the soil were made using a low temperature incineration process. This system proved to be expensive with costs per cubic yard reaching \$130. In addition, the system could only be operated during the summer months. The Air Force asked Environmental Management Operations (EMO) to look into remediation alternatives that would be less expensive and more promising.

EMO and its subcontractor, CH2M HILL, looked at a wide variety of innovative remediation

alternatives that may be suitable for a cold weather environment. The various criteria used to select the technology included

- o effectiveness in remediating petroleum compounds
- o expected cost of remediation
- o ability to deploy technology in a short time, and
- o ability to withstand the local climate.

Composting, a bioremediation process, was selected because it met all of the criteria and it had shown promise in other cold weather applications. It has the advantage of being able to generate and retain heat, thereby increasing temperatures in the system and decreasing the length of operation. In addition, composted soil is generally piled many feet deep, requiring less area in which to operate.

Compost accelerates the natural biodegradation process by engineering some of the factors that control the rate of degradation. The factors that are most likely to limit the rate of biodegradation are

- o oxygen availability
- o nutrient availability
- o moisture, and
- o temperature.

Oxygen can be controlled by pulling air through the pile or by turning the pile over. Nutrients can be controlled by supplementing the compost with fertilizers. Moisture can also be controlled by simply wetting the pile. Temperature can be controlled in part by insulation, heating the intake air, or changing the volume of nutrients in the system.

Rather than construct a full-scale compost pile at Eielson, we elected to construct test cells that would allow a variety of conditions to be examined and still keep costs under control. Soil was collected from one of the contaminated source areas at Eielson. Total petroleum hydrocarbon levels in the cells ranged from 3,000 to 5,000 mg/kg. The soil is a sandy gravel with some cobbles.

Three composting cells were installed at Eielson:

- | | |
|--------|---|
| Cell 1 | Base case cell - nutrient addition and moisture control in an outdoor cell |
| Cell 2 | Organic material amendment |
| Cell 3 | Temperature control - temperature controlled to anticipated summer temperatures |

Cell 1 demonstrated the minimum treatment that would be provided in a composting operation. It also served as a control to compare the heat generated in Cell 2. Cell 2 was amended with sewage sludge in an outdoor cell to evaluate the feasibility of enhancing the biological heat generation thus extending the time of year when composting could be conducted. Cell 3 was operated indoors to determine what cleanup levels were achievable and the period of time necessary to achieve these levels.

Table 2 lists the schedule of operations and activities during the demonstration. Air flow, oxygen content, temperature, soil, and moisture were the primary parameters of interest. Soil was sampled from each cell periodically during the demonstration to determine the extent of bioremediation.

Table 2
Chronology of Operational Activities

Test Cell 1		Test Cell 2		Test Cell 3	
Date	Baseline Sampling	Baseline Sampling	Baseline Sampling	Baseline Sampling	Baseline Sampling
06-Sep-91 07-Sep-91	<ul style="list-style-type: none"> Cell 1 blower placed on a 30-minute on/30-minute off cycle Irrigated Test Cell 	<ul style="list-style-type: none"> Added wood shavings and began alternating flowpaths 	<ul style="list-style-type: none"> Cell 3 blower ran continuously Irrigated Test Cell 		
11-Sep-91	<ul style="list-style-type: none"> O₂ consumption test performed Blower operation changed to 15 minutes on/45 minutes off 	<ul style="list-style-type: none"> O₂ consumption test performed 	<ul style="list-style-type: none"> O₂ consumption test performed Blower operation changed to 15 minutes on/105 minutes off 		
19-Sep-91	<ul style="list-style-type: none"> Performed 2-week sampling Based on O₂ consumption test, blower operation changed to 30 minutes on/30 minutes off 	<ul style="list-style-type: none"> Performed 2 week schedule O₂ consumption test performed Blower operation changed to 20 minutes on/40 minutes off 	<ul style="list-style-type: none"> Performed 2-week sampling O₂ consumption test performed No change in blower operation 		
25-Sep-91	<ul style="list-style-type: none"> O₂ consumption test performed Blower operation changed to 15 minutes on/45 minutes off 	<ul style="list-style-type: none"> O₂ consumption test performed Blower operation changed to 30 minutes on/30 minutes off Discontinued alternating flow path Only pulled air from bottom header 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
04-Oct-91	<ul style="list-style-type: none"> Collected performance monitoring samples 	<ul style="list-style-type: none"> Collected performance monitoring samples 	<ul style="list-style-type: none"> Collected performance monitoring samples 		
15-Oct-91	<ul style="list-style-type: none"> Irrigated Test Cell 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
17-Oct-91	<ul style="list-style-type: none"> O₂ consumption test performed Blower operation changed to 15 minutes on/105 minutes off 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
18-Oct-91	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
23-Oct-91	<ul style="list-style-type: none"> Collected performance monitoring samples 	<ul style="list-style-type: none"> Collected performance monitoring samples 	<ul style="list-style-type: none"> Collected performance monitoring samples 		
30-Oct-91	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed Blower operation changed to 15 minutes on/15 minutes off 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
05-Nov-91	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
14-Nov-91	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation Shut down test cell 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 	<ul style="list-style-type: none"> O₂ consumption test performed No change in blower operation 		
21-Nov-91	<ul style="list-style-type: none"> Conduct final sampling 	<ul style="list-style-type: none"> Shut down test plot 	<ul style="list-style-type: none"> Shut down test plot 		
22-Nov-91	<ul style="list-style-type: none"> Conduct final sampling 	<ul style="list-style-type: none"> Conduct final sampling 	<ul style="list-style-type: none"> Conduct final sampling 		

The results from our test showed that initial TPH concentrations of 1,700 mg/kg were reduced to approximately 130 mg/kg. The rate of degradation was quite rapid during the first month, with a gradual decrease in the ensuing months. The demonstration was run for ten weeks. It is possible (likely) that even further reduction in TPH could have been achieved with a longer period of treatment.

The field-testing of this technique demonstrated that it has a number of benefits over other remediation technologies. Through the controlled aeration of soil in a pile, it was possible to generate and maintain heat in the pile, resulting in significantly elevated temperatures above the ambient. An added benefit was the fact that we were able to consume some of the sewage sludge that was generated at Eielson.

The costs for full-scale composting are projected to vary considerably, from \$42 to \$120 per cubic yard. Much of the cost is dependent on the containment system that would be required for the composting area.

This technology demonstration has been a success at Eielson Air Force Base. Cold-weather composting will be one of the alternatives that will be considered in the Record of Decision at this site.

APPENDIX

Priority Pollutant Biodegradability

- | | |
|---|---|
| Acenaphthene - D, F | Dichlorobromomethane - C, F |
| Acrolein - D, F | Trichlorofluoromethane - C, F |
| Acrylonitrile - D, E | Dichlorodifluoromethane - C, F |
| Benzene - B, E | Chlorodibromomethane - C, F |
| Benzidine - D, F | Hexachlorobutadiene - I |
| Carbon Tetrachloride
(Tetrachloromethane) - A, E | Hexachlorocyclopentadiene - I |
| Chlorobenzene - A, E | Isophorone - I |
| 1,2,3-Trichlorobenzene | Naphthalene - F |
| Hexachlorobenzene - C, G | Nitrobenzene - F |
| 1,1-Dichloroethane - B, F | 2-Nitrophenol - E |
| 1,1,2-Trichloroethane - C, G | 4-Nitrophenol - E |
| 1,1,2,2-Tetrachloroethane - C, F | 2,4-Dinitrophenol - B, E |
| Chloroethane - B, F | 4,6-Dinitro-o-cresol - C, F |
| Bis (chloromethyl) Ether - I | N-Nitrosodimethylamine - F |
| Bis (2-chloroethyl) Ether - I | N-Nitrosodiphenylamine - a, E |
| 2-Chloroethyl Vinyl Ether (mixed) - A, E | N-Nitroso-di-n-propylamine - C, F |
| 2-Chloronaphthalene - C, F | Pentachlorophenol - B, F |
| 2,4,6-Trichlorophenol - F | Phenol - B, E |
| Parachlorometa Cresol - A, E | Bis(2-ethylhexyl)phthalate - B, F |
| Chloroform (Trichloromethane) - B, F | Butyl benzyl phthalate - B, F |
| 2-Chlorophenol - B, E | Di-n-butyl phthalate - F |
| 1,2-Dichlorobenzene - C, E | Di-n-octyl phthalate - B, F |
| 2,3-Dichlorobenzene - C, E | Diethyl phthalate - F |
| 1,4-Dichlorobenzene - C, E | Dimethyl phthalate - F |
| 3,3-Dichlorobenzidine - G | Benzo(a)anthracene (1,2-Benzanthracene) - F |
| 1,1-Dichloroethylene - A, E | Benzo(a)pyrene (3,4-Benzopyrene) - F |
| 1,2-trans-Dichloroethylene - B, E | 3,4-Benzofluoranthene - F |
| 2,4-Dichlorophenol - E | Benzo(k)fluoranthene (11,12-Benzofluoranthene) - I |
| 1,2-Dichloropropane - B, F | Chrysene - C, F |
| 1,3-Dichloropropylene (1,3-dichloropropene) - B, F | Acenaphthalene - B |
| 2,4-Dimethylphenol - E | Anthracene - B, F |
| 2,4-Dinitrotoluene - B, F | Benzo(ghi)perylene (1,12-Benzoperylene) - I |
| 2,6-Dinitrotoluene - B, F | Fluorene - B, F |
| 1,2-Diphenylhydrazine - B, F | Phenanthrene - F |
| Ethylbenzene - E | Dibenzo(a,h)anthracene (1,2,5,6-Dibenzanthracene) - I |
| Fluoranthene - B, F | Indeno(1,2,3-cd)pyrene (2,3-o-Phenylene) - I |
| 4-Chlorophenyl Phenyl Ether - D, G | Pyrene - B, F |
| 4-Bromophenyl Phenyl Ether - D, G | Tetrachloroethylene - B, F |
| Bis (2-Chloroisopropyl) Ether - D, G | Toluene - C, F |
| Bis (2-chloroethoxy) Methane - D, G | Trichloroethylene - B, F |
| Methylene Chloride (Dichloromethane) - I, F | Vinyl Chloride (Chloroethylene) - H |
| Methyl Chloride (Chloromethane) - I, F | Aldrin - I |
| Methyl Bromide (Bromomethane) - I, F | |
| Bromoform (Trihalomethane) - C, F | |

Dieldrin - I
Chlordane (technical mixture &
metabolites) - G
4,4'-DDT - F
4,4'-DDE (p,p'-DDX) - F
4,4'-DDD (p,p'-TDE) - F
a-Endosulfan-Alpha - I
b-Endosulfan-Beta - I
Endosulfan Sulfate - I
Endrin - I
Endrin Aldehyde - I
Heptachlor - I
Heptachlor Epoxide - I
a-BHC-Alpha - I
b-BHC-Beta - I
r-BHC (lindane)-Gamma - I
d-BHC-Delta - I
PCB-1242 (Arochlor 1242) - C, F
PCB-1254 (Arochlor 1254) - D, G
PCB-1221 (Arochlor 1221) - A
PCB-1232 (Arochlor 1232) - A
PCB-1248 (Arochlor 1248) - H
PCB-1260 (Arochlor 1260) - H
PCB-1016 (Arochlor 1016) - C, F
Toxaphene - I
2,3,7,8-Tetrachlorodibenzo-P-dioxin
(TCDD) - G

A - Readily Biodegradable
B - Degradable with acclimated cultures
C - Partially degradable with acclimated cultures
D - Biologically refractory with adapted populations
E - Readily degraded by selectively adapted, enriched cultures
F - Degraded by selectively adapted, enriched cultures
G - Partially degraded by selectively adapted, enriched cultures
H - Biologically refractory in studies conducted to this time
I - Specific data not available

END

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