Solidification Technologies for Restoration of Sites Contaminated with Hazardous Wastes

AEPI

ARMY ENVIRONMENTAL POLICY INSTITUTE

January, 1998

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ABSTRACT

This document collates information on hazardous waste remediation technologies pertaining to Solidification and Stabilization (S/S) used to clean up hazardous waste sites. An explanation of these solidification and stabilization processes provides an insight into the effects that S/S technologies have on hazardous wastes. S/S technologies can (1) improve the handling and physical characteristics of the waste, (2) decrease the surface area of the waste across which transfer or loss of contaminants can occur, and (3) limit the mobility of hazardous constituents of the waste. The goal of this document is to evaluate the S/S technologies using standardized evaluation criteria The standardized criteria allows comparison of different technologies and selection of the technology which provides the best remediation or clean-up per dollar spent There are many possible criteria which can be used to evaluate the compatibility and merits of competing remediation technologies. The criteria used in this document are chemical/physical compatibility between the S/S technology and the waste being treated, contaminant leach rate from the final solidified product, and life cycle cost.

ACKNOWLEDGMENTS

This study was prepared by the Army Environmental Policy Institute under the guidance of the Director Dr. Edward Novak. The project was managed at AEPI by Dr. Francisco Tomei and Dr. Prakash Temkar. The paper was prepared for AEPI by Mr. David Painter and Dr. F. Michael Saunders, School of Civil and Environmental Engineering, Georgia Institute of Technology. Editing and manuscript preparation services were provided by Command Control, Incorporated, contract number DACA01-97-P-0963.

ACRONYMS

DOE	Department of Energy
EPA	Environmental Protection Agency
ESV	*Ex-situ* Vitrification
ISV	*In-situ* Vitrification
KWH	Kilo Watt Hour
ppm	parts per million
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
S/S	Solidification and Stabilization
SEA	Sulfur Enhanced Asphalt
SPC	Sulfur Polymer Cement
TCLP	Toxicity Characteristics Leaching Procedure
VOC	Volatile Organic Compounds

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CHAPTER 1. INTRODUCTION

This document deals with technologies which have solidifying and stabilizing effects on hazardous wastes. To be classified as a solidification or stabilization (S/S) technology, a technology must have a solidifying effect, but stabilization effects are of equal or greater importance in the remediation process.

An explanation of these solidification and stabilization processes provides insight into the effects that S/S technologies have on hazardous wastes. All S/S technologies solidify wastes. A solidified waste is a waste bound into a matrix of high structural integrity. The waste is mechanically encapsulated, without chemical bonding. The waste matrix is formed either by adding a binding agent to the waste or by melting the waste into glass [Bishop, 1991, Colombo *et al.*, 1994]. The matrix structure decreases the waste surface area exposed to leaching. The effect is to reduce waste mobility. Most S/S technologies stabilize wastes. A stabilized waste is a waste whose chemical state has been changed to make it less soluble, mobile, or toxic. [Wolfe, 1995, Colombo *et al.*, 1994]. Further information on solubility stabilization is provided in Appendix A.

S/S technologies: (1) improve the handling and physical characteristics of the waste, (2) decrease the surface area of the waste across which transfer or loss of contaminants can occur, and (3) limit the mobility of hazardous constituents of the waste [Bishop, 1991, Wolfe, 1995].

Advantages of S/S Technologies:

- Many of these technologies can treat complex mixtures of different wastes.
- Most S/S technologies restrict water access to waste contaminants by lowering waste permeability via encapsulation and raising waste density via the waste matrix.
- Most binding agents are relatively inexpensive.
- Many solidified products could potentially be used as a building material.
- Most S/S techniques require low skill levels.

Disadvantages of S/S Technologies:

- Many of these technologies do not decrease contaminant toxicity.
- Many of these technologies increase the volume of waste.
- Many of these technologies use *in situ* mixing of waste and binder. They do not excavate the waste. Control of the mix quality is difficult with these technologies.
- S/S of sensitive areas may inhibit future more comprehensive restoration.

- Volatile air emissions may require costly control.
- Some of these technologies are still at the stage of development where they do not give consistent results.

The goal of this document is to evaluate S/S technologies using standardized evaluation criteria. The standardized criteria allow comparison of different technologies and selection of the technology which provides the best remediation per dollar spent. There are many possible criteria which can be used to evaluate the compatibility and merits of competing remediation technologies The criteria used in this document are chemical/physical compatibility between the S/S technology and the waste being treated, contaminant leach rate from the final solidified product, and life cycle cost.

1.1 Standard Evaluation Criteria

Chemical/Physical Compatibility

One way to look at compatibility is to examine the possible waste types and their treatability via different kinds of S/S technologies The possible waste types are:

Inorganic wastes–These are toxic molecules or elements such as the heavy metal, cadmium. Inorganic wastes can be stabilized by S/S technologies with chelating binders which combine with metals and then are solidified in a waste matrix. Inorganic wastes can also be stabilized by S/S technologies which have inorganophilic binders which sorb them and then are solidified in a waste matrix

Organic wastes–These are toxic organic molecules like benzene. Organic molecules can be stabilized by S/S technologies which apply extreme heat to break the molecule into its less toxic constituent elements which are then are solidified in a waste matrix.. This process is called pyrolysis. Organic molecules can also be stabilized by S/S technologies which have organophilic binders which sorb them and then are solidified in a waste matrix.

Radioactive wastes–These contain radioactive elements such as plutonium Radioactive wastes are usually inorganic and can be dealt with using S/S technologies which handle inorganic wastes. The effect of radiation on the solid matrix must be considered. If the matrix structure is weakened over time by radiation, the S/S technique may not be suitable.

Mixed wastes–These are complex mixtures of organic, inorganic, and/or radioactive wastes Mixed wastes are the most difficult to treat, because the cleanup technique which applies to one component of the waste may not apply to another or may accentuate its toxicity. Multiple remediation techniques applied in sequence must often be applied to handle these kinds of wastes. The effect of each successive technique on all waste components must be considered. The use of multiple techniques adds significant complexity, cost, and risk to the remediation process.

Contaminant Leach Rate

Leaching is the removal of contaminants from the waste matrix by some externally applied leaching fluid. The most commonly encountered leaching fluid is water, but acids also have a leaching effect.

The leach rate is governed by the chemical makeup of the waste matrix and leaching fluid, the physical properties of the waste matrix, and the external environment imposed on the matrix [Wolfe, 1995]. For leaching to occur, the contaminant must dissolve in the pore waters of the solid matrix, then diffuse out. Diffusion can also occur directly from the matrix surface, but the pore water contribution is the most important.

There are many different leach rate tests. Their goal is to simulate the maximum possible leach rate under standard conditions [Bishop, 1991]. No single test provides all of the information required to fully evaluate hazardous waste leach rates. Leach rate tests generally involve pulverizing the waste matrix and placing it in a mildly acidic solution which leaches or extracts some of the hazardous waste which it contains. These tests can involve one or more extractions.

One of the most widely known leach tests is the Toxicity Characteristics Leaching Procedure (TCLP). This test uses acetic acid in a 20:1, liquid: solid ratio, and one 18-hour extraction [Wolfe, 1995]. The TCLP test has flaws. Its end point pH is variable which results in variation in metals released. It does not provide information on release of soluble metal salts and ions. Despite these flaws, it does provide enough information to compare the waste matrix leach rates of different S/S technologies and to make an evaluation of their relative merit TCLP limits for various wastes or contaminants are specified in paragraph 261.24 40, Chapter 1 of the Combined Federal Regulation (7-1-94 Edition) published by the Environmental Protection Agency (EPA). These limits are noted in Table 1 [US EPA, 1994, US EPA, 1993, 542-B-93-005].

Table 1-TCLP Limits	
INORGANIC WASTES	**Allowed concentration-mg/l**
Elemental metal contaminants	
Arsenic	5
Barium	100
Cadmium	1
Chromium	5
Lead	5
Mercury	0.2
Selenium	1
Silver	5
ORGANIC WASTES	
Pesticides	
Chlordane	0.03
Endrin	0.02
Lindane	0.4
Pentachlorophenol	100
Toxaphene	0.5
Volatile Organic Chemicals (VOCs)	
Benzene	0.5
Carbon tetrachloride	0.5
Chlorobenzene	100
Chloroform	6
Cresol	200
Dichlorobenzene	7.5
Dichloroethane	0.5
Dichloroethylene	0.7
Dinitrotoluene	0.13
Heptachlor	0.008
Hexachlorobenzene	0.13
Hexachlorobutadiene	0.5
Hexachloroethane	3
Methoxychlor	10
Methyl ethyl ketone	200
Nitrobenzene	2
Pyridine	5
Tetrachloroethylene	0.7
Trichloroethylene	0.5
Trichlorophenol	2
Vinyl chloride	0.2

Current literature was examined to find TCLP test results for each technology for as many of these substances as possible. Most of the S/S technology waste matrices have been tested for leaching of inorganic wastes like metals. Only a few have been tested for leaching of organic wastes. The available test results are presented with the discussion of each technology.

Life Cycle Cost of a S/S Technology:

The two major elements of life cycle cost are the treatability study and actual remediation [Means, *et al.*, 1995]. Treatability studies for different technologies require similar laboratory and field testing of contaminated soil. These studies are much the same for all technology types and are subsumed in the Startup category of the estimating procedure for actual remediation. .

Varying site conditions make the actual remediation of a specific site using a particular technology unique. This uniqueness makes it difficult to use simplifying assumptions which will apply to multiple sites and technologies. Despite this difficulty, several simplifying assumptions which are listed in Table 2 are used in the estimating procedure for actual remediation. This procedure was derived from an EPA cost analysis in reference [US EPA, 1990, 540-A5-89-005].

The actual remediation cost estimating procedure covers the following categories:

- ***Site preparation***–This category covers design, survey, legal search, and general preparation.
- ***Permitting/regulatory***–This category covers the cost of obtaining permits and of complying with environmental regulations given that the waste is disposed of on site.
- ***Equipment***–Capital and ancillary equipment cost is the total cost of the treatment equipment multiplied by the fraction of the equipment's life span that will be devoted to the project. Auxiliary Equipment cost is the cost of generic support equipment.
- ***Startup***–This category covers moving personnel and equipment to the site, preliminary testing and treatability studies at the site.
- ***Labor***–This category covers all labor costs. Labor cost is based on a nine-man crew working a 40-hour week for 28 days every month, unless otherwise specified. Labor cost is also based on the simplest known technique–excavation, followed by surface mixing with Portland cement binder. An average salary for workers using this simple technique is assumed. More sophisticated techniques which need more expensive workers are adjusted from this base rate.
- ***Supplies and consumables***–This category covers all costs of materials used to treat the waste. It includes reagents, electricity, and water.
- ***Effluent off-site treatment and disposal***–This category covers minor health/safety disposal only. An example is the disposal of contaminated personnel

protective gear. Actual off-site disposal costs for the solidified waste are neglected. Only on-site disposal is considered. If on-site disposal of the final solidified product is not possible, an additional tipping fee on the order of $10–50/ton at a sanitary landfill or $100–300/ton at an Resource Conservation and Recovery Act (RCRA) permitted landfill would be required. The cost of transportation and additional permitting for the transportation of the waste to the landfill would also have to be considered. This cost could be the most expensive part of the remediation procedure. Typically, it is about $.15–60/ton-mile [Means, et al., 1995].

- ***Analytical testing***–This category covers quality assurance and control, toxicity characteristic leaching procedure on stabilized waste unconfined compressive strength and environmental compliance.
- ***Maintenance***–This category covers equipment costs. Maintenance cost is computed by multiplying the total equipment cost by 10% and then by the fractional number of years the project.
- ***Site demobilization***–This category covers final decontamination of the site, site fencing, restoration, and landscaping.
- ***Long-term monitoring***–This category, which covers long-term monitoring and testing, is not addressed in this document. Information on long-term monitoring is scant in the literature. Additional research needs to be conducted before the costs of this category can be estimated with any degree of confidence.
- Radioactive waste remediation cost increases are handled by adding 20% to labor for hazard pay, adding 10% to auxiliary equipment for radiation resistant safety equipment, adding 30% to off-site treatment and disposal for disposing of contaminated safety gear and process equipment, and adding 100% to permitting/regulatory to obtain the necessary permits and to engage in the resulting litigation.

Table 2–Simplifying Assumptions	
Categories	**Assumptions**
Site preparation	Assume $25,000 for all technologies
Permitting/regulatory	Assume $10,000 for all technologies Assume on-site disposal for all technologies
Equipment	Assume equipment life span is 5 years unless otherwise specified Assume auxiliary equipment cost is $10,000 per month
Start-up	Assume $21,000 for all technologies
Labor	Assume that each technique will use a nine-man crew working a 40-hour week for 28 days every month Assume crews using excavation, surface mixing with Portland cement binder Assume that the average salary is $4650/month
Supplies and consumables	Assume electric power cost for vitrification processes is $ 05/Kilo Watt Hour (KWH) Assume vitrification energy requirements are between 800 and 1000 KWH/ton Assume all other supplies consumed total $2870/month
Effluent off-site treatment & disposal	Assume $2150/month
Analytical testing	Quality Assurance/Quality Control (QA/QC)–$600/month, TCLP–$6,000/month, UCS/env –$400/month 3,000/month
Maintenance	No assumptions
Site demobilization	Assume $15,000 for all technologies
Waste mass	Assume one cubic yard of waste weighs one ton Assume the quantity treated is 500 tons Assume the waste is a complex organic/inorganic mixture

A brief summary of costs is presented with the discussion of each technology. More detailed estimates for each technology are provided in Appendix B worksheets.

Technology Classification

S/S technologies are most easily classified by binder type or by melting method. There are many different proprietary binding agents. Currently most commercially available binding agents can be classified as either organic, inorganic, or mixed binders. Inorganic binders include siliceous binders, calcareous binders, phosphoric binders and sulfuric binders. Organic binders include asphalt, sulfur enhanced asphalt (SEA), and organic polymer binders. Mixed binders possess both organic and inorganic constituents. Mixed binders often take advantage of sorption processes. An example of a mixed binder is an organically modified clay binder in which calcium ions have been replaced by ammonium ions [Bates, *et al.*, 1992]. There are also several different ways to melt or vitrify hazardous waste into glass. Currently, the most common methods use either molybdenum/graphite electrodes or a plasma torch.

CHAPTER 2. INORGANIC BINDERS

2.1 Siliceous and Calcareous Binders

Technology Description

There are many different siliceous and calcareous binders. All use similar silicon oxide/calcium oxide chemistry to achieve their binding effect. The most common and the most thoroughly studied of these binders is Portland cement. A description of cement is generally applicable to all siliceous and calcareous binders [Colombo *et al.*, 1994].

While cement has been used for centuries, only recently has an understanding of this complex substance been developed. In its simplest form, cement is the hydration of a solid solution of lime (CaO) from limestone and silicon dioxide (SiO_2) from clay. This solid solution is called clinker. "Clinkering" is the term used for solid solutions in which partial melting of reactants occurs. Contrast this term with "sintering," in which no melting occurs, and "fusion," in which complete melting occurs. The silicon dioxide in clinker contains many impurities which lower its "clinkering" or reactive temperature to 1400–1600°C. Pure silicon dioxide in the form of quartz is prohibitively expensive to use in cement formation. It is also non-reactive until it reaches 2000–3600°C [Mindness and Young, 1981].

Crushed limestone and pulverized clay in a wet slurry are heated in a rotating kiln. As the mixture travels down the long kiln, its temperature rises and a series of important changes occur. First, the mixture loses its free water. Second, at about 1200°C, calcium carbonate loses its CO_2 and the CaAl and CaFe complexes begin to form. Third, at about 1350°C, clinkering begins and the lime, CaO, and silicon dioxide, SiO_2, react to form calcium silicates, Ca_3SiO_7 and Ca_2SiO_4. Finally, rapid cooling occurs. The speed of cooling controls the rate of crystallization of the calcium silicates. The quicker the cooling, the smaller the crystals. Smaller crystals allows faster hydration and faster setting times [Mindness and Young, 1981].

The components of a typical cement clinker are shown in Table 3. The composition and percentage of the components of the overall reagent solution vary for different types of cement [Mindness and Young, 1981].

Table 3–Clinker Components	
Component	**% by weight**
Ca_3SiO_7	50
Ca_2SiO_4	25
$Ca_3OAl_2O_3$	12
$Ca_4OAl_2O_3Fe_2O_3$	8
$CaSO_4 \cdot 2H_2O$ (gypsum)	3.5
Other impurities	1.5
Total	100

The calcium silicates are 75% of the reagent solution by weight. These silicates, Ca_3SiO_7 and Ca_2SiO_4, provide the majority of the compressive strength of hydrolyzed cement. Since their weight percentage is fairly constant among cement types, ultimate compressive strength also does not vary much among cement types. The main difference between types is the time it takes to reach that ultimate strength [Mindness and Young, 1981].

The reaction rates of the reagent components vary widely. Each reagent component is hydrolyzed in parallel to the others, but there are interdependencies between components [Mindness and Young, 1981]. An example of interdependency is the effect of gypsum, $CaSO_4 \cdot 2H_2O$, on $Ca_3OAl_2O_3$, the most reactive component. Gypsum is added to the re-pulverized solution to control the reaction rate of $Ca_3OAl_2O_3$. Gypsum absorbs excess moisture in the air and bound water which would otherwise react with $Ca_3OAl_2O_3$ and begin crystallization.

Table 4–Reaction Rates	
Component	**Reaction Rate**
Ca_3SiO_7	Fast
Ca_2SiO_4	Slow
$Ca_3OAl_2O_3$	Fastest (but retarded by gypsum additive)
$Ca_4OAl_2O_3Fe_2O_3$	Really slow
$CaSO_4 \cdot 2H_2O$ (gypsum)	Retarding agent

Cement types with more Ca_3SiO_7 reach their maximum strength more quickly; types with more Ca_2SiO_4 reach it more slowly. Ca_3SiO_7 provides the early strength of cement. Ca_2SiO_4 reacts too slowly to contribute to the early strength, but it does contribute to the ultimate strength.

Another factor which affects reaction rate is the fineness of the grind. More finely ground cements react more quickly due to the larger reaction surface area in a finely ground cement than a coarsely ground cement. In a sense, the addition of water does more than just bring reactive hydroxide ions in contact with the clinker grains. Addition of water also increases the reaction surface area by about three orders of magnitude by surrounding and separating each clinker grain [Mindness and Young, 1981].

The actual hydration of the reagents is complex and can be modified in many different ways by adding other reactive species to the mix which emphasize different aspects of hydration. Common additives include aluminum, sulfate, iron, and non-cementitious pozzolana. These additives or impurities are important to the chemistry of the overall reaction. They can control the speed of the reaction and affect the strength of the final solid material. The most common additives are iron and aluminum. These do not contribute to the strength of cement and detract from its durability, but they increase the reaction rate Pozzolana are reactive silica. They do not exhibit cementitious reactions by themselves, but participate in cementitious reactions in conjunction with other siliceous materials. Addition of pozzolana to the basic solution gives it a higher percentage of calcium silicates once it hydrolyzes. This confers greater resistance to sulfate attack, increases ultimate strength, but increases the time required to achieve that strength.

The hydration stoichiometric equations are:

$$2Ca_3SiO_7 + 6H_2O = Ca_3Si_2O_7{\cdot}3H_2O + 3CaO{\cdot}H_2O$$
$$\text{and, } 2Ca_2SiO_4 + 4H_2O = Ca_2Si_2O_4{\cdot}3H_2O + CaO{\cdot}H_2O$$

There are five distinct phases of hydration [Mindness and Young, 1981]:

1. ***Initial hydration***–The unreacted clinker grains disperse in water. Clinker begins to dissolve, and calcium and hydroxide ions begin to fill the water in the void space between grain At this point, the reaction rate is controlled by phase formation.

2. ***Dormant period***–The solution quickly achieves saturation. Hydration products grow from the surface of each clinker granule. Initial crystallization begins, but the material is mostly colloidal and is referred to as a gel.

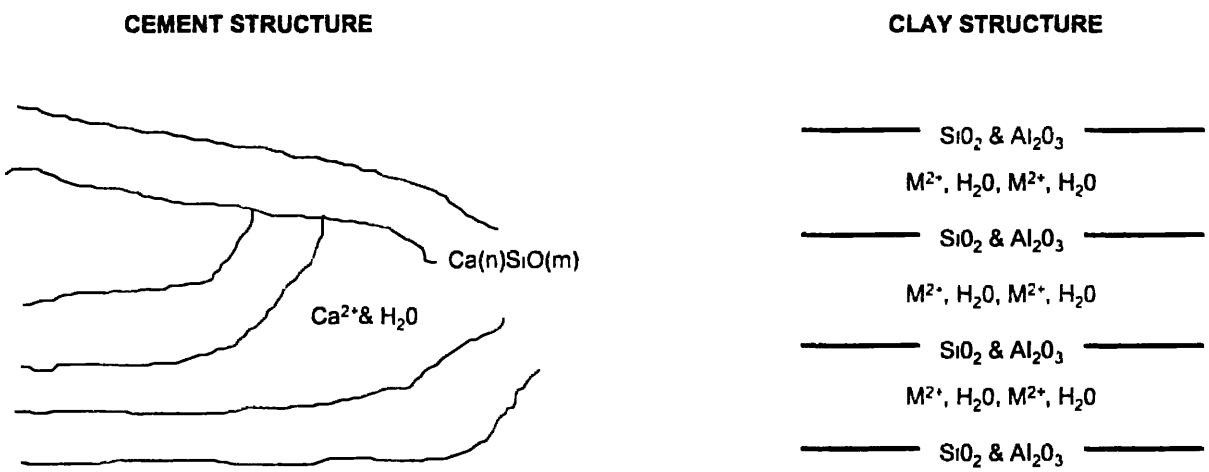
3. ***Acceleration period***–Hydration product gel layer has completely encased each clinker grain. These hydration products are $Ca_3Si_2O_7{\cdot}3H_2O$, $Ca_3OAl_2O_3$, and to a lesser extent $Ca_2Si_2O_4{\cdot}3H_20$. This layer blocks the hydroxide ions which must diffuse through it to the clinker surface to continue the growth of hydration products. Reaction is beginning to be diffusion controlled. Crystallization increases.

4. ***Deceleration period***–The thickening gel expands to fill the voids between clinker granules, and further slows down incoming ions

5. ***Steady state period***–The reaction is completely diffusion controlled. Interlocking polysilicate crystals grow within the gel and provide strength and hardness. These crystals provide a "skeleton". The reaction rate is governed almost completely by diffusion of water and ions to reaction sites. This process can continue for up to 15 years. When it is complete, the cement has attained its ultimate strength.

On a more macroscopic level, the strength of cement begins with the interlocking of the spines of two adjacent Ca_3SiO_7 crystals which grow and intermesh. These crystals are actually quite strong. The relatively low tensile strength of cement is a result of the large-scale flaws of cement than of the weakness of the calcium silicate crystals [Mindness and Young, 1981].

A comparison of the structure of cement and of clay helps in understanding cement properties.



The clay structure consists of sheets of aluminum and silicon oxide. The space between each layer is filled with a mixture of water and magnesium ions which expands and contracts with the amount of water present. Clay is a very flexible and expandable structure [Mindness and Young, 1981].

Cement structure is composed of irregular layers of Ca_nSiO_m with randomly arranged pores filled with water and ions. This structure is relatively rigid and incapable of expansion. The layers are connected to one another at random intervals by covalent bonds but are also held together by van derWaals forces. The total bonding energy is about 70% covalent and 30% van derWaals. Water weakens "cured" cement by pushing its layers apart and decreasing the van derWaals bonding energy [Mindness and Young, 1981].

Applicability of Siliceous and Calcareous Binders

There is a large amount of information on incorporation of wastes into cement. An example of these wastes is the inorganic waste, "fly ash," which is a coal combustion byproduct. Fly ash is often disposed of by incorporation into cement. Usually fly ash comprises 15 to 25 percent by weight of the dry mix, but experiment has shown that as much as 75 percent can be incorporated into the mix. At this high level, concrete strength and durability are reduced by as much as 60 percent, but this outcome may not matter in applications requiring only bulk or mass.

Many other inorganic wastes have been tested for incorporation into cement matrices. Most metals precipitate at medium to high pH in a cement matrix. Cement effectively immobilizes metals as long as pH is kept relatively high. Among these metals are uranium and strontium. Uranium remains in the hexavalent state. Uranium is precipitated by CaOH to form a semi-crystalline phase, $Ca_2UO_4 \cdot (H_2O)$. Strontium and most other metals appear to substitute for calcium, Ca, in the crystal lattice.

Organic chemicals are not well disposed of by this S/S technology. Any material with a high proportion of carbon causes severe strength and durability loss Carbon and carbon containing compounds are more attractive to calcium ions than are silicates and disrupt hydration/gel layer formation by forming compounds such as $CaCO_3$ instead of the gel layer hydration products, $Ca_3Si_2O_7 \cdot 3H_2O$, and $Ca_3OAl_2O_3$.

The performance of cement used for S/S purposes has been studied more than any other S/S technology. Many types of information available for cement binders is not yet available for other binder types. Examples of this kind of information are contained in Appendix C–Cement deterioration mechanisms and in Appendix D–Cement waste retention performance.

Table 5a–TCLP Results									
RCRA/EPA GUIDELINES		**STABILIZATION METHOD:** Binder–inorganic, siliceous/calcareous–drum mixed							
Metal Contaminants in mg/l or Parts per Million (ppm)		**Reference**		**Reference**		**Reference**		**Reference**	
		[Lin *et al*, 1995] pg 15		[Colombo *et al*, 1994] pg 5 28		[Barth, 1990] pg 169		[ARM Inc, 19955] pg 5	
	Allowed concentration	25% PC binder		Profix		Chemfix		Chemfix	
		Raw	Stabilized	Raw	Stabilized	Raw	Stabilized	Raw	Stabilized
Arsenic	5								
Barium	100								
Cadmium	1			34 8	07			28	005
Chromium	5			7 1	05			7	1
Lead	5	40 7	38	4 0	24	655	12 4	38	05
Mercury	0 2								
Selenium	1								
Silver	5								
Organic Chemical Contaminant									
Volatile Organic Chemicals (VOCs)									
Benzene	0 5			30	76				
Chloroform	6			20	2				

Table 6a–Life Cycle Cost Summary	
	METHOD
	Binder-inorganic, siliceous/ calcareous–PC–drum mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$74,400
Startup	$21,000
Labor	$251,000
Supplies and consumables	$118,600
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$1,775
Site demobilization	$15,000
TOTAL	$556,175
Waste mass (in tons)	5000
Cost/ton	$111
Add radioactive component cost increase	*$68,450*
TOTAL	*$624,625*
Cost/ton	*$125*

Advantages of Siliceous and Calcareous binders:

- The cost of siliceous and calcareous binders is relatively low.
- Labor costs are relatively small. The risk involved in working with hazardous waste makes labor costs higher than those incurred in working with ordinary cement, but labor costs should not be excessive. Some special training may be required to ensure that operators do not endanger themselves. Some protective gear will be required, but overall the equipment should be very similar to that used for ordinary cement.

Disadvantages of Siliceous and Calcareous binders:

- Siliceous and calcareous binders are vulnerable to chemical, physical, and biological attack. An example of chemical attack is calcium hydroxide leaching.

An example of physical attack is osmotic pressure. An example of biological attack is microbial sulfur oxidation. All of these cause an increase in permeability to leachant flow.

- Siliceous and calcareous binders increase waste volume. Large quantities of chemicals are added to the waste If careful attention is given to reducing/refining the waste prior to immobilization in cement, this disadvantage can be minimized.
- Siliceous and calcareous binders have doubtful long-term durability. If these binders are used on long-lived waste, a long monitoring period will be required, to include periodic laboratory analysis of collected samples from inspection wells The long-term monitoring will include review of the results by trained and expensive personnel, and may include additional costly remedial action, if the cement matrix fails. All of these factors result in an increase in maintenance costs.
- Siliceous and calcareous binders may not bind a few amphoteric metals like lead effectively. At the high pHs these binders become more soluble and available to leaching [Lin, 1995].

2.2 Phosphoric Binders

Technology Description

These binders are currently under development at Pacific Northwest Laboratory. Phosphoric binders use natural phosphate-bearing minerals of the apatite group, which react with mobile metal contaminants to form immobile, insoluble compounds which stay in a mineral matrix. Relatively little is required to provide effective treatment. There are a variety of methods to introduce apatite into the soil. Apatite can be delivered *in situ* by auger, rototiller, or slurry injection. Unlike most S/S processes, phosphoric binders do not convert the waste into a hardened, monolithic mass. Instead it forms a granular substance with only a small increase in volume over the untreated waste [Colombo *et al.*, 1994]

Applicability of Phosphoric Binders:

Apatite immobilizes hazardous metals. Apatite has been successfully tested for lead, zinc, cadmium, uranium, and strontium immobilization in the laboratory [Wright *et al.*, 1995].

Table 5b–TCLP Results					
RCRA/EPA GUIDELINES		**STABILIZATION METHOD:** Binder–inorganic, phosphoric, apatite–auger mixed			
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**	
		[Wright *et al*, 1995] pp 34,38,39		[Singh *et al*, 1994] pg 8	
	Allowed concentration	25% PC binder		Profix	
		Raw	Stabilized	Raw	Stabilized
Arsenic	5	< 005	0054		
Barium	100	275-	< 005		
Cadmium	1	255	< 005	196	09
Chromium	5			40 4	2
Lead	5	586	< 001	99 7	1
Mercury	0 2	< 005	< 005		
Selenium	1				
Silver	5				

Table 6b–Life Cycle Cost Summary	
	METHOD
	Binder–Phosphoric Apatite–auger mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a .75-month project)	$25,625
Startup	$21,000
Labor	$77,000
Supplies and consumables	$11,200
Effluent off-site treatment & disposal	$3,200
Analytical testing	$7,500
Maintenance	$5,000
Site demobilization	$15,000
TOTAL	$200,525
Waste mass (in tons)	5000
Cost/ton	$40
Add radioactive component cost increase	*$27,860*
TOTAL	*$228,385*
Cost/ton	*$46*

Advantages of Phosphoric binders:

Phosphoric binders can be used in containment as well as full cleanup. These binders can form permeable barriers surrounding a contaminated region.

On a molecular level, apatite rapidly binds metal ions.

Apatite–metal reactions are so fast that the requirement to reduce permeability to minimize leaching of contaminants is avoided. Apatite can be used to remove contaminants out of flowing water.

Apatite is stable indefinitely.

Apatite is insensitive to pH changes over the range of 2 to 12.

Microbial degradation of apatite binding is minimal. The bioavailability of apatite immobilized metals appears to be small.

Volume increase is minimal.

Disadvantages of Phosphoric binders:

- This technique is still under development and has not been tested in a full-scale project. Therefore the cost projections are good guesses at best.
- Some of the available leaching data was not derived from the TCLP test. These data were of limited use in making comparisons to other technologies.

2.3 Sulfuric Binders.

Technology Description

At room temperature elemental sulfur exists as a stable non-polar orthorhombic molecule, Sα, which consists of eight atoms arranged in the form of a crown-shaped ring. Sα is stable and non-polar. Sα is so stable that it does not interact well with metals. When the temperature is raised to 119°C, sulfur begins to melt and a liquid, monoclinic form, Sβ, begins to appear. Sβ has more void space, and is less dense than Sα. When sulfur reaches 159 degrees, it begins to polymerize. Its liquid viscosity increases and its color changes from yellow to dark red. Thermal scission begins to open up the ring structure and linear biradicals ($-S-S^6-S-$) begin to form. These biradicals can combine to form longer chain polymers which react with and immobilize metals [Lin, *et al.*, 1995]. Elemental sulfur by itself can not immobilize some metal compounds sufficiently to satisfy the EPA TCLP test. The polymerization process and the ability to immobilize metals are enhanced considerably by doping with additive species like sodium sulfide, and sodium sulfite. A small amount of sodium sulfite, Na_2SO_3, opens up the Sα ring, allowing formation of an open-chain polymer ($O_3Na_2S-S^x-S-$). This polymeric form is polar and has a much larger surface area so it can bind metals much better. When the temperature is again lowered, sulfur reverts to the stable Sα form, but remains polymerized. Metal which is bound in its high temperature liquid phase remains bound. This solid-liquid-solid progression is known as thermoplasticity [Lin, 1995, Chang, 1995].

Applicability of Sulfuric Binders

Doped elemental sulfur can be used to micro/macroencapsulate waste. It also has the ability to react chemically with most metals to reduce their mobility. It forms stable insoluble compounds with them [Lin, 1995].

Table 5c–TCLP Results							
RCRA/EPA GUIDELINES							
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**		**Reference**	
		[Chang 1995] pp 22-35		[Lin *et al*, 1995] pg 15		[Lin, 1995] pg 79	
	Allowed concentration	7% Na^2SO^3		25%S w/2% Na^2SO^3		15%S w/ 16% Na^2SO^3	
		Raw	Stabilized	Raw	Stabilized	Raw	Stabilized
Arsenic	5	1	18				
Barium	100	4	07				
Cadmium	1	1 4	65				
Chromium	5	ND	051				
Lead	5	353	2 5	40 7	1 2	2000	2 6
Mercury	0 2						
Selenium	1	ND-	07				
Silver	5						

Table 6c–Life Cycle Cost Summary	
	METHOD
	Binder–inorganic, sulfuric modified elemental sulfur–drum mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$74,400
Startup	$21,000
Labor	$251,000
Supplies and consumables	$263,600
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$1,775
Site demobilization	$15,000
TOTAL	$701,175
Waste mass (in tons)	5000
Cost/ton	$140
Add radioactive component cost increase	*$68,450*
TOTAL	*$769,625*
Cost/ton	*$154*

Advantages of Sulfuric binders:

- Sulfur is insoluble in water. This hydrophobicity tends to protect the solidified matrix from leaching.
- Sulfur can be modified with additives like dicyclopentadiene to more effectively treat organic wastes.
- Sulfur has excellent compressive strength and durability characteristics.

Disadvantages of Sulfuric binders:

- Cooling to room temperature causes cracking in sulfur concrete because as the sulfur cools and Sα changes to Sα it also becomes more dense. It shrinks about 6% and cracks.
- It has been shown that elemental sulfur by itself cannot stabilize some metal compounds sufficiently to satisfy the EPA TCLP test. Modification with dopants to improve stabilization adds cost.
- Sulfur is vulnerable to attack by bacteria

2.4 Sulfur Polymer Cement (SPC) Binder

Technology Description

SPC is also known as Modified Sulfur Cement. It was developed by the US Bureau of Mines in the early 1970s as a means of utilizing waste sulfur from flue gas and petroleum distillation processes. SPC contains elemental sulfur plus 5 percent by weight of a modifier which is a 50/50 mixture of the hydrocarbon polymers dicyclopentadiene and cyclopentadiene. These chemicals react with elemental sulfur to form long chain polymers. SPC exhibits thermoplastic behavior. It is heated to slightly above its melting temperature of 119°C and blended with heated aggregate or waste, then cooled to form a monolithic solid [Lin, 1995].

SPC microencapsulates wastes, but SPC alone cannot meet the EPA's TCLP criteria. An additional modifier or dopant like sodium sulfide Na_2S is required. With SPC percentage fixed at 20% and sodium sulfide modifier at .5%, this mixture achieves TCLP goals even with high metal concentrations by forming insoluble compounds. The modifier also reduces thermal expansion and contraction, which results in less shrinkage and cracking upon cooling, therefore in reduced permeability and long-term leaching potential [Lin, 1995].

Applicability of Sulfur Polymer Cement Binder

SPC has been used in the encapsulation of fly ash waste and radioactive wastes. SPC can react chemically with heavy metals to form insoluble compounds and further immobilize them [Kalb, *et al.*, 1991].

Table 5d–TCLP Results							
RCRA/EPA GUIDELINES		**STABILIZATION METHOD** Binder–inorganic, SPC–drum mixed					
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**		**Reference**	
		[Colombo *et al*, 1994] pg 5 15		[Lin, 1995] pg 74		[Kalb *et al*, 1991] pg 9	
	Allowed concentration	(50% SPC w/7% N*2S)		(20% SPC w/1% N*2S)		(49 5% MSC w/7 5% N*2S)	
		Raw	Stabilized	Raw	Stabilized	Raw	Stabilized
Arsenic	5						
Barium	100						
Cadmium	1	85-	2			85	2
Chromium	5						
Lead	5	46	1 5	2000	46	46	1 5
Mercury	0 2						
Selenium	1						
Silver	5						

Table 6d-Life Cycle Cost Summary	
	METHOD
	Binder–inorganic, sulfuric Sulfur Polymer Cement–drum mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$74,400
Startup	$21,000
Labor	$251,000
Supplies and consumables	$433,600
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$1,775
Site demobilization	$15,000
TOTAL	$871,175
Waste mass (in tons)	5000
Cost/ton	$174
Add radioactive component cost increase	*$68,450*
TOTAL	*$939,625*
Cost/ton	*$188*

Advantages of Sulfur Polymer Cement binder.

- It has superior water tightness and freeze-thaw resistance.
- It can be used in acid and salt environments where conventional concrete fails.
- It is stronger than Portland Cement.
- No chemical reactions are required for solidification so no interference with setting.
- Full strength is attained in hours rather than days or years for Portland Cement.
- A variety of common mixing devices like paddle mixers and pug mills can be used to mix it.
- The relatively low temperatures used limit emissions of sulfur dioxide and hydrogen sulfide to allowable values.

Disadvantages of Sulfur Polymer Cement binder:

- It has been shown that SPC alone cannot stabilize some metal compounds sufficiently to satisfy the EPA's TCLP criteria. Modification with dopants to rectify this shortcoming adds cost.
- Sulfur Polymer Cement may be vulnerable to attack by bacteria.

CHAPTER 3. ORGANIC BINDERS

3.1 Asphalt Binder

Technology Description:

Asphalt binder is a thermoplastic material which is used to macroencapsulate waste. Asphalt can be used directly to macroencapsulate large quantities of waste or it can be used in an emulsion. In thermoplastic form, asphalt is melted and mixed with waste in some kind of mechanical mixer, then allowed to cool and harden [Lin, 1995]. In emulsified form, asphalt exists as very fine droplets dispersed in water. An emulsifying agent such as a detergent forms a protective film around the asphalt droplets and carries an electric charge that causes the droplets to repel one another. This charge can be positive or negative, anionic or cationic. The charge on the emulsion determines what waste it can microencapsulate. An emulsifying agent which provides a charge opposite to that on the waste is selected. This process neutralizes the overall charge of the waste/emulsion mixture, which allows the particles to coalesce into a hydrophobic mass, leaving the higher quality water behind. After mixing, the emulsion breaks, the water is released, and the organic phase forms a continuous matrix of hydrophobic asphalt around the waste solids [Colombo *et al.*, 1994].

Applicability of Asphalt Binder

In thermoplastic mode, the effectiveness of encapsulation depends on the chemical compatibility of the waste compounds with the asphalt. In emulsified mode, the effectiveness of encapsulation depends on the electrical compatibility of the waste compounds with the asphalt and/or emulsifying agent [Lin *et al.*, 1995]. Asphalt has been used to encapsulate both inorganic, organic, and low level radioactive wastes. Asphalt is not chemically compatible with some organic wastes like oil and grease [Lin, 1995].

Table 5e–TCLP Results	
RCRA/EPA GUIDELINES	STABILIZATION METHOD: Binder–Inorganic, siliceous/calcareous–drum mixed
Metal Contaminants in mg/l or ppm	
	No information was available in the literature on asphalt leach rate

Table 6e–Life Cycle Cost Summary	
	METHOD
	Binder–Organic Asphalt–drum mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$74,400
Startup	$21,000
Labor	$251,000
Supplies and consumables	$37,350
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$1 775
Site demobilization	$15,000
TOTAL	$474,925
Waste mass (in tons)	5000
Cost/ton	$95
Add radioactive component cost increase	*$68,450*
TOTAL	*$543,375*
Cost/ton	*$109*

Advantages of Asphalt binder

- Asphalt binder is cheaper than other organic thermoplastic materials like polyethylene and polypropylene.
- The mixing, transporting, and placement equipment used for asphalt paving construction could be readily used for waste treatment.
- The hydrophobic nature of the organic phase renders the final solidified product impermeable to water.
- In emulsified form, the process operates at ambient temperature, which reduces volatilization problems and energy costs

Disadvantages of Asphalt binder:

- Chemical incompatibility with certain organic compounds like oil and grease can soften asphalt and decrease its durability.
- The long-term durability/leachability of asphalt is questionable.
- Oxidation during mixing and during useful life limit durability.

3.2 Sulfur Extended Asphalt (SEA) Binder

Technology Description

The Federal Highway Administration initiated research on SEA in the early 1970s. Several SEA pavements have been constructed. Sulfur is first blended with asphalt at about 140°C to produce a sulfur-asphalt mixture. The amount of sulfur varies from 20 to 50 percent. The equipment and processes used from this point on are identical to those used for conventional asphalt [Lin *et al.*, 1995].

Applicability of SEA Binder

Potentially, SEA could be used to encapsulate both organic and inorganic wastes. SEA may be able to chemically stabilize metals contaminants because of the metal complexing ability of sulfur [Lin, 1995].

Table 5f–TCLP Results

RCRA/EPA GUIDELINES		**STABILIZATION METHOD:** Binder–Organic, SEA–drum mixed			
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**	
		[Lin, 1995]		[Lin *et al*, 1995]	
		pg 74		pg 15	
	Allowed concentration	(6 5% SEA w/1% N*2S)		(25% binder)	
		Raw	Stabilized	Raw	Stabilized
Arsenic	5				
Barium	100				
Cadmium	1				
Chromium	5				
Lead	5	2000	2 07	40 7	3 5
Mercury	0 2				
Selenium	1				
Silver	5				

Table 6f–Life Cycle Cost Summary	
	METHOD
	Binder–Organic Sulfur Enhanced Asphalt–drum mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$74,400
Startup	$21,000
Labor	$251,000
Supplies and consumables	$39,850
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$1,775
Site demobilization	$15,000
TOTAL	$477,425
Waste mass (in tons)	5000
Cost/ton	$95
Add radioactive component cost increase	*$68,450*
TOTAL	*$545,875*
Cost/ton	*$109*

Advantages of SEA binder:

- The equipment and process used for producing and using SEA mixtures is identical to that used for conventional asphalt pavements.
- The strength and durability of SEA pavements has been excellent.
- Potentially, SEA could have both the microencapsulation and metal immobilization properties of sulfur as well as the macroencapsulation ability of asphalt.

Disadvantages of SEA binder:

- Care must be taken to keep the temperature of SEA below 150°C during mixing and paving operations. Otherwise, toxic H_2S emissions can occur.
- No studies have yet been done in the use of SEA to treat hazardous waste. No TCLP information is available.

3.3 Organic Polymer Binders

Technology Description

In this process, polymers like urea formaldehyde, polybutadiene, polyurethane, polyethylene, polypropylene, or fiberglass/epoxy are used to immobilize wastes via micro/macro encapsulation. The unpolymerized liquid binder is mixed with the waste; it undergoes polymerization and hardens into a rigid matrix [Lin *et al.*, 1995, Wolfe, 1995].

When the liquid form is applied at elevated temperatures, the organic polymer binder is also known as a "thermoplastic". Thermoplastic polymers consist of branched or linear polymer chains that normally are not cross-linked. Polymers like polyethylene are thermoplastics. Polyethylene has a paracrystalline structure formed through the polymerization of ethylene gas. A polyethylene extrusion process for treatment of radioactive and toxic chemical wastes was developed at Brookhaven National Laboratory. The binder and pre-dried waste are mixed using a carefully selected ratio. The mix is heated and mechanically stirred. The melted mix is forced through an output die into a mold where it cools and solidifies [Colombo *et al.*, 1994].

Applicability of Organic Polymer Binders

Organic polymer binders can be used to encapsulate both inorganic and organic wastes. The technique has been used in S/S of radioactive wastes. The effectiveness of encapsulation depends on the chemical compatibility of the waste compounds with the binder [Lin *et al.*, 1995].

Table 5g–TCLP Results					
RCRA/EPA GUIDELINES		**STABILIZATION METHOD:** Binder–Organic polymer–drum mixed			
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**	
		[Faucette *et al*, 1994] pg 5		[Colombo *et al*, 1994] pg 5 23	
	Allowed concentration	(50% LDPE)		(40% Polyethylene)	
		Raw	Stabilized	Raw	Stabilized
Arsenic	5				
Barium	100				
Cadmium	1	09	ND	< 5	5
Chromium	5	32-	03	4	2
Lead	5	04	ND	9	3 6
Mercury	0 2			5	3
Selenium	1				
Silver	5				

Table 6g–Life Cycle Cost Summary	
	METHOD
	Binder–Organic, polymer Polyethylene–Screw mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$74,400
Startup	$21,000
Labor	$251,000
Supplies and consumables	$2,538,600
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$1,775
Site demobilization	$15,000
TOTAL	$2,976,175
Waste mass (in tons)	5000
Cost/ton	$595
Add radioactive component cost increase	*$68,450*
TOTAL	*$3,044,625*
Cost/ton	*$609*

Advantages of Organic Polymer binders:

- These binders isolate a relatively large volume of waste per amount of binder.
- They exhibit good long-term durability and leach resistance.
- At ambient temperature, the example, polyethylene, is insoluble in virtually all organic solvents and is resistant to many acids and alkaline solutions.

Disadvantages of Organic Polymer binders:

- The cost of these materials is usually high.
- The blending process can be difficult.

3.4 Mixed binding agents

Technology Description

Several of these binders are commercially available. Several mixed binders have been successfully demonstrated in the EPA SITE program. These binders contain both organic and inorganic components. The organic component is usually some kind of sorbent. An example of a mixed binder, is organically modified clay/pozzolanous binder. In this binder, clay is modified by replacing some of its calcium ions with quaternary ammonium ions. These ions enable clay to sorb organic molecules. The ammonium ions increase the interplanar distance between aluminum and silica layers, allowing penetration by large organic molecules [Colombo *et al.*, 1994]. This modified clay is then mixed with a pozzolanous binder. These binders may also contain diluent/surfactants which reduce organic waste concentrations by dispersing them throughout the aqueous phase prior to solidification [Lin, 1995, Colombo *et al.*. 1994].

Applicability of Mixed Binders

Mixed binders are suitable for both organic and inorganic waste. There is a large number of possible mixed binders because there are many organic sorbents and even more combinations of organic sorbents and inorganic binders. Vendors can use more than one sorbent or combination of sorbents with or without diluent/surfactants [Colombo *et al.*, 1994].

Table 5h–TCLP Results			
RCRA/EPA GUIDELINES		**STABILIZATION METHOD:** Bind Binder–Mixed, modified clay/PC–drum mixed	
Metal Contaminants in mg/l or ppm		**Reference**	
		[Colombo *et al*, 1994] pg 4 2	
	Allowed concentration	(STC Corporation process)	
		Raw	Stabilized
Arsenic	5	1 8	86
Barium	100	14	24
Cadmium	1		
Chromium	5		
Lead	5		
Mercury	0 2		
Selenium	1		
Silver	5		
Organic Chemical Contaminant			
Pesticides			
Pentachlorophenol	100	1 5	3 4

Table 6h–Life Cycle Cost Summary	
	METHOD
	Binder–Mixed Modified clay/Portland cement–auger mixed
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a .75-month project)	$25,625
Startup	$21,000
Labor	$77,000
Supplies and consumables	$288,700
Effluent off-site treatment & disposal	$3,200
Analytical testing	$7,500
Maintenance	$5,000
Site demobilization	$15,000
TOTAL	$478,025
Waste mass (in tons)	5000
Cost/ton	$96
Add radioactive component cost increase	*$27,860*
TOTAL	*$505,885*
Cost/ton	*$101*

Advantages of Mixed binders.

- They can be used to remediate complex mixed wastes in a one-step procedure.

Disadvantages of Mixed binders:

- Their long-term leachability is not yet precisely known.
- They are new and still relatively untested.
- Contaminant diffusion from the binder will always be a threat to groundwater.

CHAPTER 4. VITRIFICATION

4.1 Molybdenum/Graphite Electrode Vitrification Method

Technology Description:

Its development began in 1980 for the US Department of Energy (DOE). DOE then licensed the technology to Battelle Memorial Institute's Pacific Northwest Laboratories, who in turn sub-licensed it to the Geosafe Corporation for commercialization. Both *in situ* vitrification (ISV) and *Ex situ* Vitrification (ESV) are commercially available. ISV has been extensively tested under the EPA SITE Program. Numerous ISV field applications have been performed by the DOE and current vendors. ISV has had six full-scale demonstrations conducted on radioactive waste at the Department of Energy's Hanford Nuclear Reservation; and more than ninety successful tests at various scales have been performed on polychlorinated biphenyl wastes, industrial lime sludges, dioxins, metal plating wastes, and other solid combustibles and liquid chemicals [Buelt *et al.*, 1994].

Vitrification uses electrical energy to heat a broad spectrum of wastes and soil which melt and transform into a glass-like material very similar to obsidian. Normally, glasses are not electrically conductive; but, when in the molten state, the alkaline elements within the glass ionize and become mobile, they transmit an electrical charge. Organics are destroyed by pyrolysis while inorganic contaminants are immobilized by incorporation in the melt and resulting synthetic obsidian [Colombo *et al.*, 1994].

ISV requires placement of four molybdenum/graphite (or nickel/chromium) electrodes in a square around the contaminated soil. After driving the moisture off the contaminated soil to ensure the soil is no longer conductive, a mixture of graphite and glass frit is placed on the soil surface to provide an electrically conductive starter path for the electrical current flow. An electric potential is then applied between electrodes, causing a current flow and electrical resistance heating along the starter path. The resistance heating raises the temperature in the adjacent soil to the melting point [Colombo *et al.*, 1994].

Typical soil melt temperatures achieved range between 1600 to 2000°C. The soil melts until the entire area between the electrodes is molten. The soil then forms a molten stream that moves downward and outward, forming an electrically conductive pool. As this process happens, the organic waste constituents are pyrolyzed, with the resulting gases migrating to the soil surface. The inorganic constituents remain in the molten soil and are incorporated into the vitrified mass. Up to 1000 tons of soil can be treated in one individual melt (batch) [Colombo *et al.*, 1994].

An off-gas treatment "hood" is employed over the entire treatment zone to collect the vapors emitted from the treatment area. The emissions are directed to a treatment system consisting of quenching, scrubbing, humidity control, filtration, and carbon adsorption processes. Contaminants collected from these treatment units can then be recycled back to the vitrification process, decreasing the amount of wastes requiring disposal or further treatment [Buelt *et al.*, 1994].

ISV reduces waste volume by removing its void space. The waste volume is reduced generally by 20 to 40 percent, but with incinerator ash the reduction can be as much as 80 percent This reduction leaves the melt area at a lower elevation the surrounding area. Backfilling the area is required to keep an even surface grade [Colombo *et al.*, 1994].

The solidified result of ISV is very similar to obsidian. The product is considered by many sources to be permanently leach-proof. Synthetic obsidian is a ceramic or glass-like material with a high degree of ductility which could be used for industrial applications as aggregate or fill. Use of vitrification end products is not practiced widely because of regulatory limitations These limitations arise mainly from the fact that the long-term environmental compatibility of these materials has not yet been conclusively established. However, some studies indicate that synthetic obsidian permanently immobilizes hazardous inorganics and will retain its physical and chemical integrity for geologic time periods This material has high resistance to leaching and possesses strength properties better than those of concrete. Synthetic obsidian has hydration properties similar to those of real obsidian, which hydrates at rates of less than 1mm/10,000 years [Buelt *et al.*, 1994].

ESV is much the same as ISV There are some important differences The melt material is excavated and conveyed to a refractory-lined crucible where the vitrification occurs. Waste constituents, which can be slurries, wet or dry solids, or combustible materials, are first mixed with glass formers and then conveyed to the molten glass pool. Electrodes are often flat plates at either end of the melting cavity [Colombo *et al.*, 1994].

Applicability of Electrode Vitrification

Electrode vitrification has also been shown to destroy or immobilize complex mixtures of inorganic, organic, and radioactive waste inorganics in contaminated soils and sludges. Electrode vitrification destroys 99 995 percent of organics via pyrolysis due to the high temperature (approx. 3000°F) and strong reducing environment. The process is applicable to contaminated soil; dewatered sludge; organic compounds like VOCs, SVOCs, and fuel hydrocarbons; pesticides; organo-chlorine pesticides; PCBs; and inorganics wastes like sediments, mine tailings, asbestos, heavy metals, and radioactive wastes [Colombo *et al.*, 1994].

There are limits to ISVs applications. ISV cannot be applied to soils that contain free flowing water because water will dissipate heat and the soil will not heat to its melting point. Although ISV can accommodate a significant quantity of rubble, debris, and other inclusions within the treatment zone, this capacity is limited. Each application needs to be addressed in detail to determine whether it may be suitable for ISV processing. ISV requires significant electrical energy, about 1000 KWH/ton of soil The high energy costs associated with this technology has limited its widespread application For vitrification to be applied to sludges, they must contain a sufficient amount of glass-forming material (non-volatile, non-destructible solids) to produce a molten mass that will destroy or remove organic pollutants and immobilize inorganic pollutants. All of these limitations apply to ESV, with the exception of the free flowing water limitation [Colombo *et al*, 1994].

Table 5f--TCLP Results											
RCRA/EPA GUIDELINES		**STABILIZATION METHOD: Electrode Vitrification**									
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**		**Reference**		**Reference**		**Reference**	
		[Colombo *et al*, 1994] pg 5 9		[Applewhite-Ramsey, 1994] pp 3-4		[Circeo, A *et al*, 1994] pg 5		[Detering and Batdorf, 1992] pp 17 - 18		[Timmons *et al*, 1990] pg 81	
	Allowed concentration	(Raw soil-->glass)		(SRS DWPF glass)		(SRS LLMW glass)		(INEL simulated mixed waste)		(GEOSAFE ISV glass)	
		Raw	Stabilized	Raw	Stabilized	Raw	Stabilized	Raw	Stabilized	Raw	Stabilized
Arsenic	5	4400	<5							1345	53
Barium	100	4400	<1	6980	28	224	< 19				
Cadmium	1	4400	<1	18	02						
Chromium	5	4400	2 7	2480	02	765	< 04	50	53		
Lead	5	50-	< 1	3340	14	960	< 13	47 4	46		
Mercury	0 2	46	< 0001					1 5	< 0004		
Selenium	1			102	01						
Silver	5	4400	< 1	72	05			1 6	< 01		
Organic Chemical Contaminant		Destroys from 90% to 99 99999% of all organics									

Table 6i–Life Cycle Cost Summary	
	METHOD
	Heat to melting point Electrode vitrification
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 3-month project)	$155,000
Startup	$210,000
Labor	$502,000
Supplies and consumables	$283,600
Effluent off-site treatment & disposal	$6,500
Analytical testing	$32,900
Maintenance	$62,500
Site demobilization	$150,000
TOTAL	$1,437,500
Waste mass (in tons)	5000
Cost/ton	$288
Add radioactive component cost increase	*$1,652,350*
TOTAL	*$3,089,850*
Cost/ton	*$618*

Advantages of Electrode Vitrification:

- Organic compounds are almost completely destroyed.
- Vitrification binds waste inorganic materials into a chemically durable solid, making it well-suited for wastes containing heavy metals or radioactive constituents.
- The technology can treat complex mixed wastes in a one-step process.
- The *in situ* application capabilities allow treatment without the costs and hazards associated with excavation, handling, pretreatment, and transportation.
- The resulting vitrified product could be used in a variety of applications.
- Synthetic obsidian has high resistance to leaching.
- Synthetic obsidian should retain its physical and chemical integrity indefinitely.

- The process results in a substantial volume decrease of the treated waste.
- Underground storage tank contamination meeting ISV requirements is treatable with this technology.
- Volatile constituents can be recycled into the melt.

Disadvantages of Electrode Vitrification:

- Possible volatilization of lighter radioactive components like cerium requires that these be handled, which increases exposure risks.
- Large-scale electrode vitrification application is limited to Volatile Organic Concentration (VOC) in the treated media in the order of a few percent by weight. This limitation is related to the off-gas treatment systems capability to handle the heat and volume of off-gas.
- Volatile metals may vaporize, complicating the treatment of the off-gases.
- ISV requires some degree of homogeneity of the media.
- ISV is effective only to a maximum depth of approximately 30 feet.
- ISV is limited to operations in areas without free flowing water. Permeabilities greater than 10^{-5} cm/sec will impede the progress of the melt.
- Back fill of area may be required.
- Long-term durability of synthetic obsidian has not been conclusively established.
- Electrode vitrification has a relatively high energy cost–on the order of 1000 KWH/ton.

4.2 Plasma Torch Vitrification Method.

Technology Description

Plasma arc technology was developed over 30 years ago by the National Aeronautics and Space Administration for the United States space program to simulate re-entry temperatures on heat shields. Recently this technology has begun to emerge as a tool in waste solidification processes. A plasma torch is a device which converts electrical energy into thermal energy. Plasma is an ionized gas that is created by a voltage which is established between two points. The plasma acts as a resistive heating element and can produce temperatures ranging from 4000–7000°C. The torch looks like a stainless steel cylinder, several inches in diameter and several feet in length; the dimensions will vary based on the power required. The cylinder contains the electrodes, insulators, gas injectors, and waster dividers [Jacobs, 1994].

About 1% of the plasma gas is consumed during operation. The gas stabilizes the arc and allows the contact location of the arc to be varied [Jacobs, 1994].

The torch is lowered into a borehole or hollow pile, and is turned on at the desired depth. The torch raises the temperature in the adjacent soil to the melting point. Typical soil melt temperatures achieved range between 1600 and 2000°C. As the volume nearest the torch melts, the torch is raised up the hole, leaving behind a column of vitrified material [Jacobs, 1994].

As this process happens, the organic waste constituents are pyrolyzed, with the resulting gases migrating to the surface via the borehole. The inorganic constituents remain in the molten soil and are incorporated into the vitrified mass. A 1 MW torch can process about 5 tons of soil per hour [Circeo, 1995].

An off-gas treatment "hood" is employed over the entire treatment zone to collect the vapors emitted from the treatment area. The emissions are directed to a treatment system consisting of quenching, scrubbing, humidity control, filtration, and carbon adsorption processes. Contaminants collected from these treatment units can then be recycled back to the vitrification process, thus decreasing the amount of wastes requiring disposal or further treatment [Jacobs, 1994].

Vitrification reduces waste volume by removing its void space. It can reduce overall waste volume by 20 to 40 percent. This reduction leaves the melt area at a lower elevation than the surrounding area. Backfilling the area is required to keep an even surface grade.

The solidified product is very similar to obsidian, and is considered by many sources to be permanently leach-proof. Synthetic obsidian is a ceramic or glass-like material with a high degree of ductility which could be used for industrial applications as aggregate or fill. Use of vitrification end products is not practiced widely because of regulatory limitations. These limitations arise mainly from the fact that the long-term environmental compatibility of these materials has not yet been conclusively established. However, some studies indicate that synthetic obsidian permanently immobilizes hazardous inorganics and will retain its physical and chemical integrity for millions of years. This material has high resistance to leaching and possesses strength properties better than those of concrete. Synthetic obsidian has hydration properties similar to those of real obsidian, which hydrates at rates of less than 1mm/10,000 years [Buelt *et al.*, 1994].

Applicability of Plasma Torch Vitrification

Like ISV, plasma vitrification has been shown to destroy or immobilize complex mixtures of inorganic, organic, and radioactive waste inorganics in contaminated soils and sludges. It destroys 99.995 percent of organics via pyrolysis due to the high temperature (approx. 3000°F) and strong reducing environment. The process is applicable to contaminated soil, dewatered sludge; organic compounds like VOCs, SVOCs, and fuel hydrocarbons; pesticides; organo-chlorine pesticides; PCBs; and inorganic wastes like sediments, mine tailings, asbestos, heavy metals, and radioactive wastes [Colombo *et al.*, 1994].

There are limits to plasma applications. Plasma vitrification cannot be applied to soils that contain free flowing water because water will dissipate heat and the soil will not heat to its melting point. A plasma torch requires significant electrical energy, typically about 800 KWH/ton of soil. The high energy cost associated with this technology has limited its widespread application. For vitrification to be applied to sludges, the sludges must contain a sufficient amount of glass-forming material (non-volatile, non-destructible solids) to produce a molten mass that will destroy or remove organic pollutants and immobilize inorganic pollutants [Circeo, 1995].

Table 5j–TCLP Results

RCRA/EPA GUIDELINES		**STABILIZATION METHOD: Plasma Torch Vitrification**									
Metal Contaminants in mg/l or ppm		**Reference**		**Reference**		**Reference**		**Reference**		**Reference**	
		[Colombo *et al*, 1994] pg 5 9		[Applewhite-Ramsey, 1994] pp 3-4		[Circeo, A *et al*, 1994] pg 5		[Detering and Batdorf, 1992] pp 17 - 18		[Timmons *et al*, 1990] pg 81	
	Allowed concentration	(Raw soil-->glass)		(SRS DWPF glass)		(SRS LLMW glass)		(INEL simulated mixed waste)		(GEOSAFE ISV glass)	
		Raw	Stabilized	Raw	Stabilized	Raw	Stabilized	Raw	Stabilized	Raw	Stabilized
Arsenic	5	4400	<5							1345	53
Barium	100	4400	<1	6980	28	224	< 19				
Cadmium	1	4400	<1	18	02						
Chromium	5	4400	2 7	2480	02	765	< 04	50	53		
Lead	5	50-	< 1	3340	14	960	< 13	47 4	46		
Mercury	0 2	46	< 0001					1 5	< 0004		
Selenium	1			102	01						
Silver	5	4400	< 1	72	05			1 6	< 01		
Organic Chemical Contaminant		Destroys from 90% to 99 99999% of all organics									

Table 6j-Life Cycle Cost Summary	
	METHOD
	Heat to melting point Plasma torch vitrification
Site prep	$25,000
Permitting/regulatory	$10,000
Equipment (for a 6-month project)	$340,000
Startup	$105,000
Labor	$1,004,000
Supplies and consumables	$267,200
Effluent off-site treatment & disposal	$13,000
Analytical testing	$65,800
Maintenance	$130,000
Site demobilization	$75,000
TOTAL	$2,035,000
Waste mass (in tons)	5000
Cost/ton	$408
Add radioactive component cost increase	*$1,652,350*
TOTAL	*$3,789,700*
Cost/ton	*$758*

Advantages of Plasma Torch Vitrification:

- Organic compounds are almost completely destroyed.
- Vitrification binds waste inorganic materials into a chemically durable solid, making it well suited for wastes containing heavy metals or radioactive constituents.
- The technology can treat complex mixed wastes in a one-step process.
- The *in situ* application capabilities allow treatment without the costs and hazards associated with excavation, handling, pretreatment, and transportation.
- The resulting vitrified product could be used in a variety of applications.
- Synthetic obsidian has high resistance to leaching.
- Synthetic obsidian should retain its physical and chemical integrity for millions of years.

- The process results in a substantial volume decrease of the treated waste.
- Underground storage tanks are treatable with this technology.
- Volatile constituents can be recycled into the melt.
- Plasma torch vitrification can be used at virtually any depth.

Disadvantages of Plasma Torch Vitrification:

- Possible volatilization of lighter radioactive components like cesium requires that these be handled, which increases exposure risks.
- Volatile metals may vaporize, complicating the treatment of the off-gases.
- Plasma torch vitrification is limited to operations in areas without free flowing water.
- Permeabilities greater than 10^{-5} cm/sec will impede the progress of the melt.
- Backfill of the area may be required.
- Long-term environmental compatibility of synthetic obsidian has not been conclusively established.
- Plasma torches have a relatively high energy cost–on the order of 800 KWH/ton.

The following appendices contain additional information on topics covered briefly in this document. The following tables contain the detailed cost estimates for each technology.

APPENDIX A–METAL SOLUBILITY LIMITING STABILIZATION

Of the chemical state changing stabilizing techniques, solubility-limiting is probably the most important. Water is the most common solubilizing agent, or leachant, that contaminants encounter under field conditions. If contaminants are in a water-insoluble form, their resistance to leaching should be high. An example of solubility-limiting applied to a specific class of contaminants is metal contaminant complexation with hydroxide, OH; sulfide, SO_4; or phosphate, PO_4. These metal complexes are significantly less soluble in water than are uncomplexed metal contaminants. Of course this solubility is dependent on the acidity of the water, but under field conditions water acid levels are usually close to zero, or neutral pH [Lin, 1995, pg 24].

Table 7–Complex Solubility (in mg/l)

RCRA METAL	HYDROXIDE–OH	SULFIDE–SO_4	PHOSPHATE–PO_4
Cadmium	2.1	1.0×10^{-8}	4.0×10^{-2}
Chromium	6.4×10^{-4}	None	None
Lead	1.4	5.8×10^{-9}	9.3×10^{-4}
Mercury	2.4×10^{-1}	5.4×10^{-11}	None
Silver	15.2	5.4×10^{-12}	15.4

These tabulated values are based on real water samples at neutral pH. The solubility of any given metal complex can also be estimated by calculating it using the solubility product, K_{so}

An example of this is the solubility calculation for lead hydroxide. At 25°C, neglecting ionic strength, and at neutral pH solubility is calculated as follows:

Stoichiometric equation

$$Pb(OH)_2 \Leftrightarrow Pb^{2+} + 2OH^-$$

Solubility product expression

$K_{sp} = [Pb^{2+}][OH^-]/[Pb(OH)_2]$ where the activity of the solid phase in the denominator is equal to one.

From a table [Snoeyink and Jenkins, 1980] $pK_{sp} = 14.3$ therefore $K_{sp} = 5.01 \times 10^{-15}$ where pK_{sp} is the negative logarithm of K_{sp}.

From the stoichiometric equation each mole of lead hydroxide which dissolves yields one mole of Pb^{2+} and two moles of OH^- ions.

Letting S = solubility in moles per liter

$[Pb^{2+}] = S$

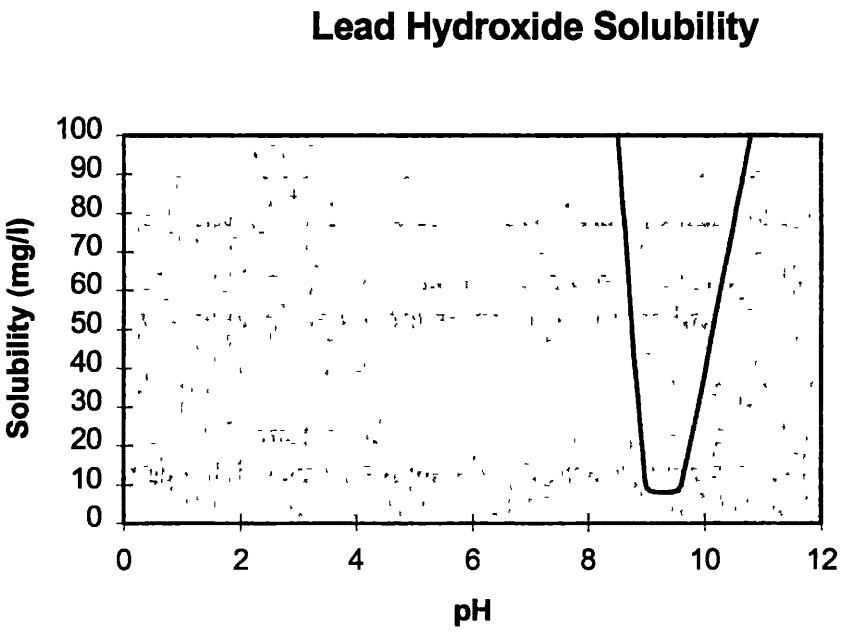
$[OH^-] = 2S$

$K_{sp} = 5.01 \times 10^{-15} = S(2S)^2 = 4S^3$ solving for S

$S = 1.08 \times 10^{-5}$ moles per liter

To convert S from moles per liter to milligrams per liter, multiply S by the molecular weight of lead hydroxide. S = (1.08×10^{5} moles per liter) (241,000 milligrams per mole) = 2.6 mg/l, which is close to, but not the same as, the measured value shown in Table 7 above. The differences between the calculated and measured values can be attributed to the approximations used in the calculation. Approximations are assumptions which are used to make calculation simpler, but which may not be correct. For example, neglecting ionic strength assumes that the only important ionic species in the water are Pb^{2+} and OH^{-}. In a real water sample, this assumption may not be true.

Naturally occurring waters with low pH are becoming more prevalent. An example is the phenomenon of "acid rain." Knowledge about the change in the solubility shown in the table above with pH, or acidity, may be useful. For example, the solubility of lead hydroxide varies according to the following graph [Lin, 1995, pg 25].



The other metal complexing ions have similarly shaped solubility curves. If the leaching fluid that complexed metals are exposed to varies in acidity, there is a possibility that metal contaminants will be released from a waste matrix.

APPENDIX B-DETAILED COST ESTIMATES

Table 8a-Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder-inorganic, siliceous/ calcareous–PC–drum mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 3-month project)		
Cap Equip –specific to process	$5,400	
example Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents - cement + add + proprietary agents	$110,000	[Colombo *et al*, *1994*, pg 3 52]
(sodium silic $165/ton) =$22/ton waste		$22/ton
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip cost over span of proj		
Site demobilization	$15,000	
Final decon , fencing, restoration		

Table 8a–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Long-term monitoring	Not estimated	
TOTAL	$556,175	
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
Cost/ton	$111	
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Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1,950*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$624,625*	
Cost/ton	*$125*	

Table 8b–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–Phosphoric Apatite–auger mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a .75-month project)		
Cap Equip –specific to process	$10,000	
example 4 auger drill mixer		
assume 5 yr life, $801K cost		
Ancillary–specific to process	$625	
example mixing plant		
assume 5 yr life, $50K cost		
Auxiliary–rent or purch of supt equip	$15,000	
Startup		
Moving pers & equip + prelim tests	$21,000	
Labor	$77,000	
Eleven personnel for 75-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents–$85/ton, 2% by wt apatite/soil ratio	$8,500	[Wright, *et al*, *1995*, pg 57]
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$2,700	
Effluent off-site treatment & disposal	$3,200	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$450	
TCLP–$1,500/wk	$4,500	
UCS/env –$100/wk / $750/wk	$2,550	
Maintenance		
10% of annual equip cost over span of proj	$5,000	
Site demobilization		
Final decon , fencing, restoration	$15,000	

Table 8b–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Long-term monitoring	Not estimated	
TOTAL	$200,525	
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Inorganic metal rich waste		
		[Wright, *et al*, *1995*, pg 66]
Cost/ton	$40	$35–$50

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$15,400*	
Add 10% to Aux Equip	*$1,500*	
Add 30% to Off-Site Treat & Disp	*$960*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$228,385*	
Cost/ton	*$46*	

Table 8c–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–inorganic, sulfuric Modified elem sulfur–drum mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 3-month project)		
Cap Equip –specific to process	$5,400	
example. Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		[Lin, 1995, pg 28]
Reagents–15% SPC & 16% Na2SO3	$255,000	$ 17/lb
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip. cost over span of project.		
Site demobilization		
Final decon , fencing, restoration	$15,000	

Table 8c–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Long-term monitoring	Not estimated	
TOTAL	$701,175	
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
Cost/ton	$140	

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1,950*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$769,625*	
Cost/ton	*$154*	

Table 8d–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–Inorganic SPC–drum mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 3-month project)		
Cap Equip –specific to process	$5,400	
example Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim. tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents–SPC $ 17/lb, 25% SPC waste ratio	$425,000	
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip cost over span of project		
Site demobilization		
Final decon , fencing, restoration	$15,000	
Long-term monitoring	Not estimated	

Table 8d–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
TOTAL	$871,175	
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
Cost/ton	$174	

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1,950*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$939,625*	
Cost/ton	*$188*	

Table 8e–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–Organic Asphalt–drum mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 3-month project)		
Cap Equip –specific to process	$5,400	
example Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents–$23/ton, 25% asphalt waste ratio	$28,750	
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip cost over span of project		
Site demobilization		
Final decon , fencing, restoration	$15,000	
Long-term monitoring	Not estimated	
TOTAL	$474,925	

Table 8e–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
		[Colombo *et al*, 1994, pg 2 8]
Cost/ton	$95	$80 - $150

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1,950*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$543,375*	
Cost/ton	*$109*	

Table 8f–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–Organic SEA–drum mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 3-month project)		
Cap Equip –specific to process	$5,400	
example Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents–$25/ton, 25% SEA waste ratio	$31,250	
Assume sulfur adds 10% to asphalt cost		
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip cost over span of project		
Site demobilization		
Final decon , fencing, restoration	$15,000	
Long-term monitoring	Not estimated	
TOTAL	$477,425	

Table 8f–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
Cost/ton	$95	

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1,950*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$545,875*	
Cost/ton	*$109*	

Table 8g–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Organic–binder Polymers–screw mixed Polyethylene	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 3-month project)		
Cap Equip –specific to process	$5,400	
example Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		[Colombo *et al*, 1994, pg 3 20 & 3 26]
Reagents–binder/waste = 2/3, $0 38/lb of LDPE	$2,530,000	$38/lb
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip cost over span of project		
Site demobilization	$15,000	
Final decon , fencing, restoration		

Table 8g–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Long-term monitoring	Not estimated	
TOTAL	$2,976,175	
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
Cost/ton	$595	
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Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1 950*	
Add 100% to Permitting Regulatory	*$10,000*	
TOTAL	*$3,044,625*	
Cost/ton	*$609*	

Table 8h–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–Mixed, modified clay/portland cement, auger mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a .75-month project)		
Cap Equip –specific to process	$10,000	
example 4 auger drill mixer		
assume 5 yr life, $801K cost		
Ancillary–specific to process	$625	
example mixing plant		
assume 5 yr life, $50K cost		
Auxiliary–rent or purch of supt equip	$15,000	
Startup		
Moving pers & equip + prelim tests	$21,000	
Labor	$77,000	
Eleven personnel for 75-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents–cement + add + proprietary reag	$286,000	
Elec power vitrification only	$0	
Utilities–Water, fuel, power	$2,700	
Effluent off-site treatment & disposal	$3,200	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$450	
TCLP–$1,500/wk	$4,500	
UCS/env –$100/wk / $750/wk	$2,550	
Maintenance		
10% of annual equip cost over span of project	$5,000	

Table 8h–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Site demobilization		
Final decon , fencing, restoration	$15,000	
Long-term monitoring	Not estimated	
TOTAL	$478,025	
Waste mass (in tons)	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste		
		[EPA 1990, 540-A5-89-004, pg 26]
Cost/ton	$96	$111 00

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$15,400*	
Add 10% to Aux Equip	*$1,500*	
Add 30% to Off-Site Treat & Disp	*$960*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$505,885*	
Cost/ton	*$101*	

Table 8i–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Binder–Mixed, modified clay/portland cement, auger mixed	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment		
Cap Equip –specific to process	$5,400	
example Mixer		
Ancillary–specific to process	$6,000	
example Tanks, pumps		
Auxiliary–rent or purch of supt equip	$63,000	
example Dump truck rental		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$251,000	
Nine personnel for 3-months, 40 hr/wk, 28 day/month		
Supplies and consumables		
Reagents–cement + add + proprietary reag	$314,000	
Elec power–Vitrification only	$0	
Utilities–Water, fuel, power	$8,600	
Effluent off-site treatment & disposal	$6,500	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$2,400	
TCLP–$1,500/wk	$19,500	
UCS/env –$100/wk / $750/wk	$11,000	
Maintenance	$1,775	
10% of annual equip cost over span of project		
Site demobilization	$15,000	
Final decon , fencing, restoration		
Long-term monitoring	Not estimated	

Table 8i–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
TOTAL	$760,175	
Waste mass (in tons) and type	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste in a volume 3'Dx209'Wx209'L		
		[EPA 1990, 540-A5-89-005, pg 21]
Cost/ton	$152	$152

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$50,200*	
Add 10% to Aux Equip	*$6,300*	
Add 30% to Off-Site Treat & Disp	*$1,950*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$828,625*	
Cost/ton	*$166*	

Table 8j–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
	Heat–Vitrification Plasma torch	cost quote
Site prep	$25,000	
Design, survey, legal search, gen prep		
Permitting/regulatory	$10,000	
Assume waste disposed of on-site		
Equipment (for a 6-month project)		
Cap Equip –specific to process	$80,000	
example 1MW torch melts a 10" dia soil column at 5 tons/hr		
assume 5 yr life, $800K cost		
Ancillary–specific to process	$180,000	
example Off gas system and backup generator		
assume 5 yr life, $1,800K cost		
Auxiliary–rent or purch of supt equip	$60,000	
example Drill rig	$20,000	
$200/hr,1hr/hole, 100 holes		
Startup	$21,000	
Moving pers & equip + prelim tests		
Labor	$1,004,000	
Nine personnel for 6-months, 40 hr/wk, 28 day/month, 5 tons/hr		
Higher skill levels, 2 x normal cost		
Supplies and consumables		
Reagents–cement + add + proprietary reag	$0	
Elec. power–Vitr $ 05/KWH, 1000 KWH/ton	$250,000	
Utilities–Water, fuel, power	$17,200	
Effluent off-site treatment & disposal	$13,000	
Minor health/safety disposal only		
Analytical testing		
QA/QC–$150/wk	$4,800	
TCLP–$1,500/wk	$39,000	
UCS/env –$100/wk / $750/wk	$22,000	
Maintenance	$130,000	
10% of annual equip cost over span of project		

Table 8j–Detailed Cost Estimates		
ESTIMATED FULL-SCALE LIFE CYCLE COST	**METHOD**	**Reference**
Site demobilization	$15,000	
Final decon , fencing, restoration		
Long-term monitoring	Not estimated	
TOTAL	$1,891,000	
Waste mass (in tons) and type	5000	
1 ton = 1 cubic yd		
Mixed organic/inorganic waste in a volume 21'Dx80'Wx80'L		
Cost/ton	$378	

Add radioactive component		
Add 20% to Labor for Hazard Pay	*$200,800*	
Add special Aux Equip	*$1,540,000*	
Add 30% to Off-Site Treat & Disp	*$3,900*	
Add 100% to Permitting/Regulatory	*$10,000*	
TOTAL	*$3,645,700*	
Cost/ton	*$729*	

APPENDIX C–CEMENT DETERIORATION MECHANISMS

Impurities in cement act as ports of entry for aggressive reagents. Impurities are the targets of leaching and limit cement durability. An example of this deterioration is sulfate attack in which water containing sulfate causes cement to deteriorate. Sulfate combines with $Ca_3OAl_2O_3$ to form long, slender crystals called ettringite. These crystals grow rapidly upon being exposed to SO_4 in aqueous solution. They can swell so much that they rupture the cement. One way to reduce this vulnerability is to keep water away from cement. Another way is to manipulate the initial calcium silicate solution so that the calcium in $Ca_3OAl_2O_3$ is diverted to $Ca_4OAl_2O_3Fe_2O_3$, which is much less vulnerable and slower to react than $Ca_3OAl_2O_3$. Another example is MgO, which can form $Mg(OH)_2$ crystals upon exposure to water. Growth of these crystals can also rupture cement [Mindness and Young, 1981].

APPENDIX D–CEMENT WASTE RETENTION PERFORMANCE

Evaluation of degradation is difficult because actual data on the performance of cement matrices under the stress of waste incorporation over long periods is not available. We can make some inferences based on studies of ancient cements, the retention of hazardous materials in natural systems, and laboratory tests which last for relatively long periods. All of these inferences plus knowledge of cement chemical and physical processes can be incorporated into models which are our best chance of predicting the performance of cementitious immobilization. In the model described below, the controlling parameter is diffusion. There are other possible controlling parameters, like advection [Godbee *et al.*, 1993].

A diffusion model:

$$Q = \frac{F \cdot Ao}{tn \cdot S}$$

- Q is waste flux out of the matrix
- tn is some time increment
- S is matrix surface area
- Ao is initial amount of waste

$$F = 1 - 32/(\pi \cdot r^2) \sum_n \sum_m \frac{\exp(-D[\psi m^2 + (2n-1)^2 \cdot \pi^2/4 \cdot l^2] \cdot t)}{(2n-1)^2 \cdot \psi m^2}$$

- F is cumulative fraction leached from the matrix
- R is radius of the container (in this case a 55-gal drum)
- l is half height of the container
- t is time
- ψm is the positive root of a zero order Bessel function

$$D = \frac{Ds}{G(1+K)(1/H)}$$

- D is the effective diffusion coefficient
- Ds is the unconstrained diffusion in water
- H is the relative wetness of the matrix. The quantity of water actually in the matrix/total possible water.

- K measures chemical retardation or matrix bonding without solubility constraint. It is a partition coefficient very similar to the ones we have been studying. It accounts for sorption/desorption and ion exchange. If the waste is solubility constrained, (1+K) is replaced by α^2.
- G measures physical retardation = t^2/γ. where t = tortuosity the average length of the actual particle path divided by the shortest possible path. γ = constrictivity and is proportional to the type of transport.

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