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Superfund | EPA/540/S-94/504 | October 1994

EPA

Engineering Bulletin
In Situ Vitrification Treatment

Purpose

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) mandates the Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants and contaminants as a principal element." The Engineering Bulletins are a series of documents that summarize the latest information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for the latest information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. Addenda will be issued periodically to update the original bulletins.

Abstract

In situ vitrification (ISV) uses electrical power to heat and melt soil, sludge, mine tailings, buried wastes, and sediments contaminated with organic, inorganic, and metal-bearing hazardous wastes. The molten material cools to form a hard, monolithic, chemically inert, stable glass and crystalline product that incorporates and immobilizes the thermally stable inorganic compounds and heavy metals in the hazardous waste. The slag product material is glass-like with very low leaching characteristics.

Organic wastes are initially vaporized or pyrolyzed by the process. These contaminants migrate to the surface where the majority are then burned within a hood covering the treatment area; the remainder are treated in an offgas treatment system.

ISV uses a square array of four electrodes that are inserted into the surface of the ground. Electrical power is applied to the electrodes which, through a starter path of graphite and glass frit, establish an electric current in the soil. The electric current generates heat and melts the starter path and the soil; typical soil melt temperature is 2,900°F to 3,600°F. An electrode feed system (EFS) drives the electrodes in the soil as the molten mass continues to grow downward and outward until the melt zone reaches the desired depth and width. The process is repeated in square arrays until the desired volume of soil has been vitrified. The process can typically treat up to 1,000 tons of material in one melt setting.

ISV technology has been under development and testing since 1980 [1, p. 1]*. ISV was developed originally for possible application to soils contaminated with radioactive materials. In this application, trans-uranium radionuclides are incorporated in the vitrified mass. **At this time there is only one vendor of commercially available in situ vitrification systems. The technology description, status, and performance data are quoted from the published work of this vendor.**

ISV is the proposed remediation technology at eight sites, six of which are EPA Superfund sites [2] [3]. Full-scale units have been constructed. Even so, the technology should be considered emerging in its full-scale application to Superfund sites. EFS mechanisms have recently been developed for pilot- and full-scale systems. This bulletin provides information on the technology applicability, limitations, the types of residuals produced, the latest performance data, site requirements, the status of the technology, and sources for further information.

Site-specific treatability studies are the best means of establishing the applicability and projecting the likely performance of an ISV system. Determination of whether ISV is the best treatment alternative will be based on multiple site-specific factors, cost, and effectiveness. The EPA Contact indicated at the end of this bulletin can assist in the location of other contacts and sources of information necessary for such treatability studies.

Technology Applicability

ISV has been reported to be effective in treating a large variety of organic and inorganic wastes based on the results of engineering- and pilot-scale tests. The technology also has

* [reference number, page number]

proven effectiveness in treating radioactive wastes based on the results of full-scale tests. Radioactive wastes and sludges, contaminated soils and sediments, incinerator ashes, industrial wastes and sludges, medical wastes, mine tailings, and underground storage tank waste can all potentially be vitrified [4, p. 4-1].

Organic contaminants at concentrations of 5 to 10 percent by weight and inorganic contaminants at concentrations of 5 to 15 percent by weight are generally acceptable for ISV treatment [5, p. 13]. The effectiveness of the ISV technology on treating various contaminants in soil, sludge, and sediments is given in Table 1. Examples of constituents within contaminant groups are provided in the "Technology Screening Guide for Treatment of CERCLA Soils and Sludges" [6]. Table 1 is based on current available information or professional judgment where no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment levels achieved will be acceptable at other sites. For the ratings used for this table, demonstrated effectiveness means that at some scale, treatability tests have shown that the technology was effective for that particular contaminant and matrix. The ratings of potential effectiveness or no expected effectiveness are both based upon expert opinion. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular matrix. The technology is expected to work for all contaminant groups listed.

Table 1
Effectiveness of ISV on General Contaminant Groups for Soil, Sludges, and Sediments

	Contaminant Groups	*Effectiveness* Soil	Sludge	Sediments
Organic	Halogenated volatiles	■	▼	▼
	Halogenated semivolatiles	■	▼	▼
	Nonhalogenated volatiles	■	▼	▼
	Nonhalogenated semivolatiles	■	▼	▼
	Polychlorinated biphenyls (PCBs)	■	▼	■
	Pesticides (halogenated)	■	■	▼
	Dioxins/Furans	■	▼	▼
	Organic cyanides	▼	▼	▼
	Organic corrosives	■	▼	▼
Inorganic	Volatile metals	■	■	■
	Nonvolatile metals	■	■	■
	Asbestos	■	▼	▼
	Radioactive materials	■	▼	▼
	Inorganic corrosives	▼	▼	▼
	Inorganic cyanides	▼	▼	▼
Reactive	Oxidizers	▼	▼	▼
	Reducers	▼	▼	▼

■ Demonstrated Effectiveness: Successful treatability test at some scale has been completed
▼ Potential Effectiveness: Expert opinion that technology will work
❏ No Expected Effectiveness: Expert opinion that technology will not work

ISV processing requires that sufficient glass-forming materials (e.g., silicon and aluminum oxides) be present within the waste materials to form and support a high-temperature melt. To form a melt, sufficient (typically 2 to 5 percent) monovalent alkali cations (e.g., sodium and potassium) must be present to provide the degree of electrical conductivity needed for the process to operate efficiently. If the natural material does not meet this requirement, fluxing materials such as sodium carbonate can be added to the base material. Typically, these conditions are met by most soils, sediments, tailings, and process sludges.

Differences in soil characteristics such as permeability and density generally do not affect overall chemical composition of the soil or the ability to use ISV. In many site locations, the soil profile may be stratified and present nonuniform characteristics that can affect the melt rate and dimensions of the vitrified mass. Before applying the ISV technology, soil stratification must be defined so that it may be factored into the remedial design.

Limitations

The ISV process can treat soils saturated with water; however, additional power is used to dry the soil prior to melting and may increase the cost of remediation by 10 percent. ISV is more economical to implement when the soil to be vitrified has a low moisture content. Progression of a melt into saturated soil enclosed in a container can result in a gaseous steam release that can cause the molten glass to spatter.

When treating a contaminated zone in an aquifer, it may be necessary to lower the water table below the zone of contamination in order to vitrify to the desired depth. Alternatively, a hydraulic barrier (e.g., slurry wall) could be placed upstream of the contamination to divert the aquifer flow around the treatment zone. Treatment in a water-saturated zone may result in movement of some of the contaminants from the treatment zone to surrounding areas, thereby reducing the amount of contaminants being destroyed, immobilized, or removed.

The maximum ISV depth obtainable is influenced by several factors, including spacing between electrodes, amount of power available, variations in soil composition and gradation between different strata, depth to groundwater, soil permeability within an aquifer, surface heat loss during ISV, and waste and soil density. To date, treatment depths of only 19 feet have been demonstrated [4, p. 7-6].

The presence of large inclusions in the area to be treated can limit the use of the ISV process. Inclusions are highly concentrated contaminant layers, void volumes, containers, metal scrap, general refuse, demolition debris, rock, or other heterogeneous materials within the treatment volume. Figure

1 gives limits for inclusions within the treatment volume [7, p. 17]. If massive void spaces exist, a large subsidence could result in a very short time period. These problems, as well as those caused by other large inclusions, may be detected by ground penetrometry or other geologic investigations. Some inclusions such as void volumes, containers, and solid combustible refuse can potentially generate gases. However, the oversized hooding is intended to control and mitigate any release. If large volumes of offgases are generated during a short time period, the offgas treatment system may overload. Vitrification of flammable or explosive objects can result in spattering of the molten glass. Underground storage tanks can be treated only if they are filled with soil prior to the vitrification process.

Sampling and analysis of the glass matrix produced by ISV is difficult and must be carefully planned prior to conducting a treatability study or site remediation. Current EPA digestion methods for metal analyses are not designed to dissolve the glass matrix. The metal concentration measured by a standard nitric/hydrochloric acid digestion (SW-846, Method 3050) will likely be highly dependent on the particle size of the material prior to digestion. The digestion specified will not dissolve glass but will leach some metals from the exposed surfaces. Closure of mass balance for the system, therefore, can often be incomplete. However, a recently developed digestion method using hydrofluoric acid with microwave digestion has been known to improve metal analysis for this type of matrix.

Technology Description

Several methods and configurations exist for the application of ISV. At a site that has only a relatively shallow layer of contamination, the contaminated layer may be excavated and transported to a pit where the vitrification will take place. At other sites where the contamination is much deeper, thermal barriers could be placed along the site to be vitrified and prevent the movement of heat and glass into adjacent areas. This will force the heat energy downward and melt depths will be increased.

This bulletin describes the more conventional approach to using ISV; a checkerboard pattern of melts is used to encapsulate the waste and control the potential for lateral migration. The holes in the checkerboard are then vitrified to complete the remediation of the site.

Figure 2 shows a typical ISV equipment layout. ISV uses a square array of electrodes up to 18 feet apart, which is inserted to a depth of 1 to 5 feet and potentially can treat down to a depth of 20 feet to remediate a contaminated area. A full-scale system can remediate at a rate of 3 to 5 tons per hour [4, p. 3-6] until a maximum mass of 800 to 1,000 tons has been treated. Since soil is not electrically conductive once the moisture has been driven off, a conductive mixture of flaked graphite and glass frit is placed between the electrodes to act as a starter path, as shown in Figure 3. Power is supplied to the electrodes, which establishes an electrical current in the starter path. The resultant power heats the starter path and surrounding soil up to 3,600°F, which is well above the melting temperature of typical soils (2,000°F to 2,600°F). The graphite starter path eventually is consumed by oxidation and the current is transferred to the soil which is electrically conductive in the molten state. A typical downward growth rate is 1 to 2 inches per hour. The thermal gradient surrounding the melt is typically 300°F to 480°F per inch. As the vitrified zone grows, it incorporates metals and either vaporizes or pyrolizes organic contaminants. The pyrolyzed products migrate to the surface of the vitrified zone, where they may oxidize in the presence of oxygen. A hood placed over the processing area is used to collect combus-

Figure 1
General Limits for Inclusion Within Volume to Be Treated

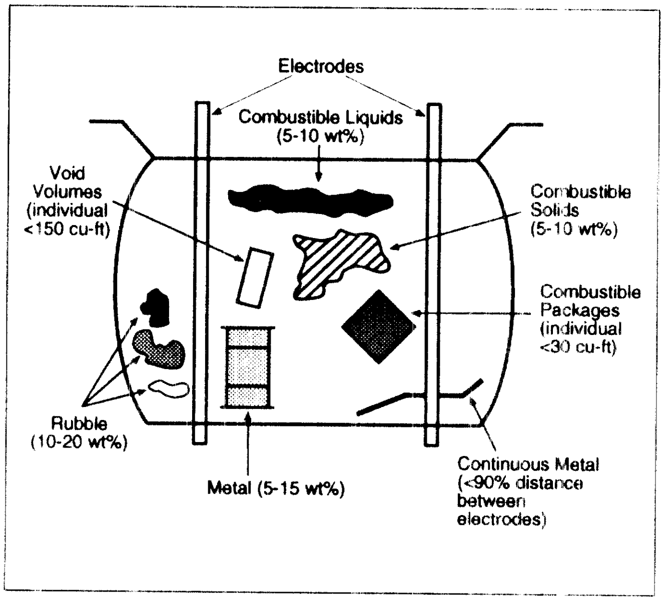


Figure 2
ISV Equipment System

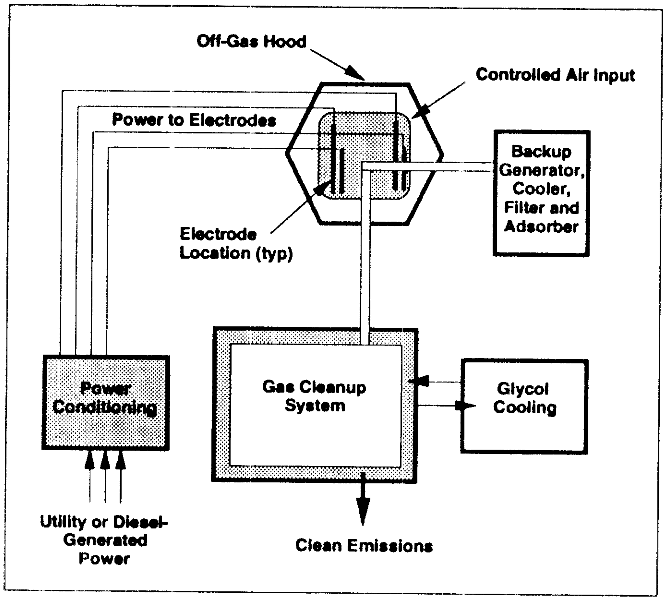
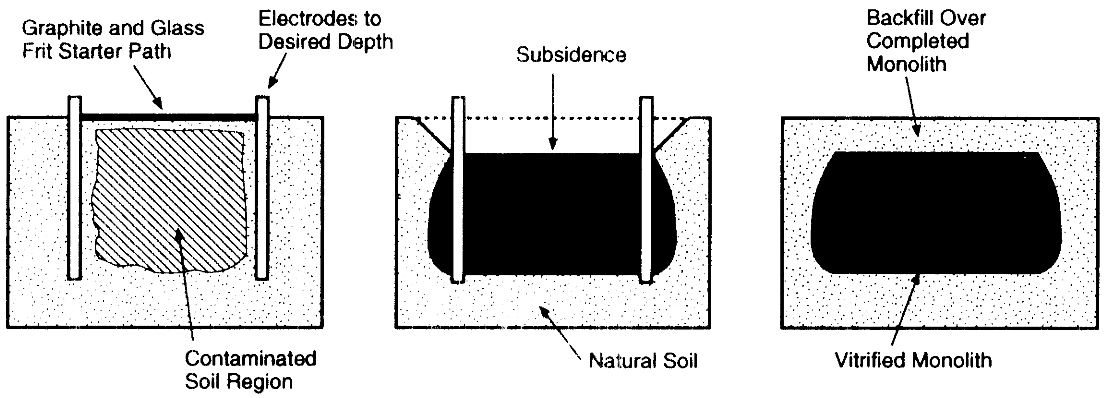


Figure 3
Stages of ISV Processing



tion gases, which are treated in an offgas treatment system.

As the melt grows downward and outward, power is maintained at sufficient levels to overcome the heat losses to the hood and surrounding soil. Generally, the melt grows outward to form a melt width approximately 50 percent wider than the electrode spacing. This growth varies as a function of electrode spacing and melt depth. The molten zone is roughly a square with slightly rounded corners, a shape that reflects the higher power density around the electrodes. As the melt grows in size, the electrical resistance of the melt decreases; thus, the ratio between the voltage and the current must be adjusted periodically to maintain operation at an acceptable power level.

The EFS, now an integral part of all operations, enhances the ability of ISV to treat soils containing high concentrations of metal. In EFS operations, the electrodes are independently fed to the molten soil as the melt proceeds downward instead of being placed in the soil prior to the startup of the test. The system improves processing control at sites with high concentrations of metal. For example, upon encountering a full or partial electrical short, the affected electrodes are simply raised and held above the molten metal pool at the bottom of the melt. During this time, the melt continues to grow downward. The electrodes can then be reinserted into the melt to their original depth and resume electrode feeding operations. These advances have been incorporated into the pilot- and the full-scale ISV systems [8].

The treatment area is covered by a newly designed octagonal-shaped offgas collection hood with a maximum distance of 60 feet between the sides. The hood has three manual viewing ports and provision for video monitoring or recording. The hood is connected to an offgas treatment trailer and a backup offgas treatment system. During the process, the offgases are drawn by a 1,850 standard cubic feet per minute (scfm) blower into the trailer. Flow of air through the hood is controlled to maintain a vacuum of 0.5 to 2.0 inches H_2O on the system. The offgas temperatures are typically 210°F to 750°F when they enter the treatment system. The gases are then treated by quenching, scrubbing, mist-elimination, heating, particulate filtration, and activated carbon adsorption. The backup offgas treatment system is used in the event of a power outage and is powered by a diesel generator. The backup system is designed to treat gases that may evolve from the melt until power is restored to the process and electrodes [9].

Process Residuals

The main process residual produced during operation of the ISV technology is the vitrified soil itself. The vitrified monolith is left in place after treatment due to its nonhazardous nature. The volume of the ISV product formed generally is 20 to 45 percent less than the initial volume treated. Because of the volume reduction during processing, it is covered with clean backfill. It is possible, however, to excavate and remove the vitrified soil in smaller pieces if onsite disposal is not acceptable at a given site.

Typically, the residual product from soil applications has a compressive strength approximately 5 to 20 times greater and a tensile strength approximately 7 to 11 times greater than unreinforced concrete [4, p. 5-3]. It is usually not affected by either wet/dry or freeze/thaw cycling [10, p. 3]. Existing data indicate that the vitrified mass is devoid of residual organics and passes EPA's Toxicity Characteristic Leaching Procedure (TCLP) test criteria for priority pollutant metals. The ISV residual also has been found to have acceptable biotoxicity relative to near-surface life forms [11, p. 79]. The clean backfill can be used to revegetate the site or other end uses.

After processing for a period of time, the scrubber water, filters, and activated carbon may contain sufficient contaminants to warrant treatment or disposal. Typical treatment includes passing the contaminated scrubber water through a filter, settling chamber, and activated carbon, then either reusing the water or discharging it into a sanitary sewer. The activated carbon, filter, and the solids from the settling chamber can then be placed in an ISV setting for vitrification. In this way, the destruction/chemical incorporation of contaminants collected in the offgas treatment system is maximized. Only residuals resulting from the last setting at a site must be treated and disposed of by means other than ISV.

Site Requirements

The components of the ISV system are contained in three transportable trailers: an offgas and process control trailer; a support trailer; and an electrical trailer. The trailers are mounted on wheels sufficient for transportation to and over a compacted ground surface [12, p. 307].

The site must be prepared for the mobilization, operation, maintenance, and demobilization of the equipment. An area must be cleared for heavy equipment access roads, automobile and truck parking lots, ISV equipment, setup areas, electrical generator, equipment sheds, and workers' quarters.

The field-scale ISV equipment system requires three-phase electric power at either 12,500 or 13,800 volts, which is usually taken from a utility distribution system [13, p. 2]. At startup the technology requires high voltage (up to 4,000 volts) to overcome the resistance of the soil, and a current of approximately 400 amps. The soil resistance decreases as the melt progresses, so that by the end of the process, the voltage decreases to approximately 400 volts and the current increases up to approximately 4,000 amps [4, p. 3-6]. Alternatively, the power may be generated onsite by means of a diesel generator. Typical applications require 800 kilowatt hour/ton (kWh/ton) to 1,000 kWh/ton.

Spent activated carbon, scrubber water, or other process waste materials may be hazardous, and the handling of these materials requires that a site safety plan be developed to provide for personnel protection and special handling measures. Storage should be provided to hold these wastes until they have been tested to determine their acceptability for disposal, release, or recycling to subsequent ISV melts. Storage capacity will depend on the waste volume generated.

Site activities such as clearing vegetation, removing overburden, and acquiring backfill material are often necessary. These activities are generally advantageous from a financial point of view. For example, the cost of removal of the top portion of clean soil would generally be much less than the cost for labor and energy to vitrify the same volume of soil [4, p. 9-6].

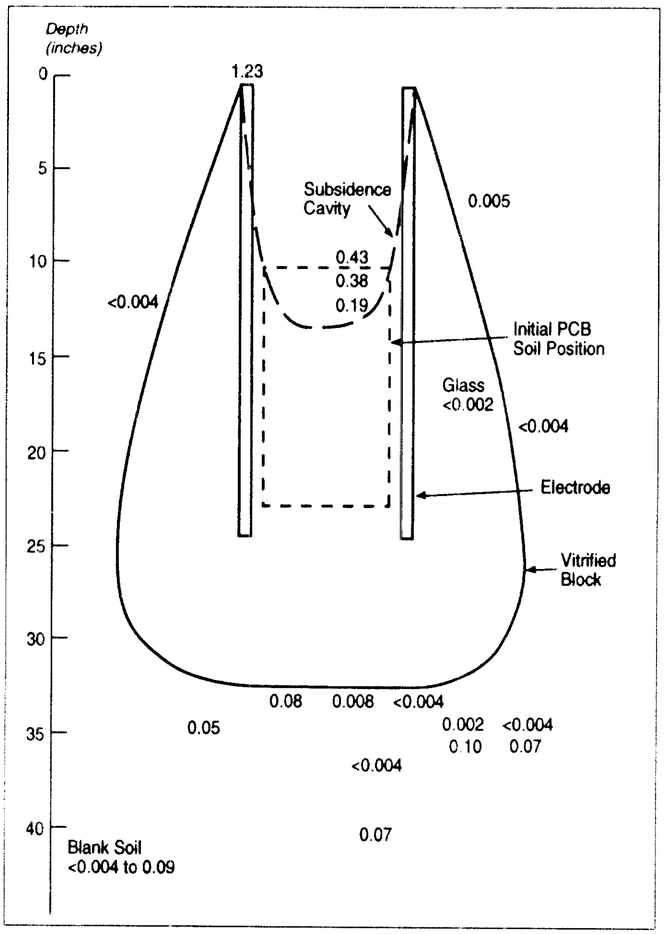
Performance Data

Performance data presented in this bulletin should not be considered directly applicable to other Superfund sites. A number of variables such as the specific mix and distribution of contaminants affect system performance. A thorough characterization of the site and a well-designed and conducted treatability study are highly recommended.

The performance data currently available are from the process developer. ISV has been developed through four scales of equipment: 1) bench (5 to 20 pounds); 2) engineering (50 to 2,000 pounds); 3) pilot (10 to 50 tons); and 4) full (500 to 1,000 tons). The values in parentheses are typical masses of vitrified products resulting from a single setting at the various scales. Several tests have been performed at each scale and on a variety of contaminated media.

An engineering-scale test was performed on loamy-clay soil containing 500 parts per million (ppm) of PCBs. Figure 4 gives the final concentrations of PCBs (in ppm) in and around the vitrified block upon completion of the test [13, p. 4-3]. This figure indicates that migration of PCBs outside the vitrified block is not a significant concern. Data from offgas emissions and soil container smears accounted for 0.05 percent by weight of the initial PCB quantity, which corresponds to a greater than 99.9 percent destruction efficiency (DE) for the ISV process. This DE does not include the removal efficiency of the offgas treatment system. Activated carbon has a 99.9 percent efficiency and can remove any of these offgas emissions effectively. Overall, the destruction removal efficiency (DRE) range for the combined ISV and offgas system is between 6 and 9 nines which is greater than the 6 nines DRE required by 40 CFR 761.70 for PCB incinerators. Analysis of the offgas also indicated the presence of small quantities of polychlorinated

Figure 4
Vitrified Block and Surrounding Soil Sample Positions and PCB Concentrations



dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). However, the levels reported (0.1 µg/L and 0.4 µg/L, respectively) can be removed by the offgas treatment system. An engineering-scale test on PCB-contaminated sediments from New Bedford Harbor [4, p. 4-2] gave a similar DE (99.9999 percent) for the ISV process before additional treatment by the offgas treatment system. During feasibility testing of PCB-contaminated soil from a Spokane, Washington site, a DE greater than 99.993 percent and a DRE greater than 99.99999 percent were obtained [14]. During engineering-scale testing of vitrification of simulated wastes from the Hanford Engineering Development Laboratory, a DRE of greater than 99.99 percent was obtained for a variety of organic contaminants [15].

An engineering-scale test was performed on Idaho National Engineering Laboratory spiked soil at the Pacific Northwest Laboratory. The soil was spiked with eight heavy metals (Ag, As, Ba, Cd, Cr, Hg, Pb, and Se) to 0.02 percent by weight except for lead which was spiked at 0.2 percent by weight [16]. The test results for metals concentrations in the leach extract and maximum concentration limits established by EPA are given in Table 2.

Feasibility testing was conducted using the bench-scale ISV equipment to treat a sample of soil from the old Jacksonville, Arkansas water treatment plant [17]. This soil was contaminated with 2,3,7,8-tetrachlorodibenzo-p-dioxin and placed in a 5-gallon can with a Pyrex-plate lid. Analytical results did not detect any dioxin or furan in the vitrified material or in the offgas. Based on analytical detection limits, the DE was greater than 99.995 percent prior to entry into the offgas treatment system.

Ten thousand kilograms of an industrial sludge heavily laden with zirconia and lime was vitrified successfully by the pilot-scale ISV process. The sludge contained 55 to 70 percent moisture by weight. The volume was observed to be reduced significantly (more than one-third of original volume) after the testing [18, p. 29]. Analysis of the offgas and the scrubber water showed that the melt retained between 98 and 99 percent of the fluorides, chlorides, and sulfates. Analysis indicated that the destruction of organic carbon was good and that ISV was effective in promoting nitrogen oxide (NO_x) destruction. This result minimizes the concern for environmental impact .

Table 2
TCLP Extract Metal Concentrations
Idaho National Engineering Lab Soils

Metal	*Maximum Allowable Leachate Concentration (mg/L)*	*Contaminated Soil Concentration (mg/kg)*	*Vitrified Product Leachate Concentration (mg/L)*
Arsenic	5.0	200	<0.168
Barium	100.0	200	0.229
Cadmium	1.0	200	0.0098
Chromium	5.0	200	0.0178
Lead	5.0	2000	0.636
Mercury	0.2	200	<0.0001
Selenium	1.0	200	0.098
Silver	5.0	200	<0.023

Soil from a fire training pit contaminated with fuel oils and heavy metals was bench-scale tested at the Arnold Engineering Development Center in Tennessee [19]. Results of initial testing and analyses of the soil indicated that an electrically-conducting fluxing agent (such as sodium carbonate) with a lower melting point was required as an addition to the soil for ISV processing to work effectively. The onsite pilot-scale process achieved a high destruction of organics (greater than 98 percent) and high retention of inorganics in the melt. Leach testing using Extraction Procedure Toxicity (EP-Tox) and TCLP tests showed that all metals of concern were below maximum permissible limits. The tests indicate that the fluxing agent should be distributed throughout the entire vitrification depth for optimum operation.

Technology Status

The only vendor supplying commercial systems for in situ vitrification of hazardous wastes is Geosafe Corporation. Geosafe is under a sublicense from the process developer, Battelle Memorial Institute. Four scales of units are in operation ranging from bench-scale to full-scale.

To date, only bench-, engineering-, and pilot-scale test results are available on in situ vitrification of hazardous wastes. Full-scale tests have been completed only on radioactive wastes. Table 3 indicates several sites where ISV has been selected as the remedial action [2].

In April 1991, a fire involving the full-scale collection ISV hooding occurred at the Geosafe Hanford, Washington test site. The vendor was testing a new, lighter hooding material. The hooding caught fire during the test when a spattering of the melt occurred. For a period of time after the incident, Geosafe suspended full-scale field operations. During this time, Geosafe completed analytical, modeling, and engineering-scale testing to allow confident design; defined necessary process revisions; finalized design and fabrication of a new metal offgas collection hood; and performed additional operational acceptance testing to demonstrate the capabilities of the equipment and operational procedures [20]. The new offgas collection hood design is composed entirely of metal rather than high-temperature fabric, which was previously used. The new design is heavier than the fabric hood, but is capable of being transported by the same equipment.

Cost estimates for this technology range from $300 to $650 per ton of contaminated soil treated. The most significant factor influencing cost is the depth of the soil to be treated. High

Table 3
Selected Sites Specifying ISV as the Remedial Action

Site	*Mass/Volume to be Treated*	*Primary Contaminants*	*Status*
Parsons Chemical	Soil: 2,000 cubic yards (yd^3)	Biocides (pesticides), dioxins, metals (mercury)	Site preparation
Ionia City Landfill	Soil with debris: 5,000 yd^3 (15 feet deep)	Volatile organic compounds (methylene chloride, TCA, styrene, toluene), metals (lead)	Treatability testing
Rocky Mountain Arsenal	Soil: 4,600 yd^3 (10 feet deep) Sludge: 5,800 yd^3 (10 feet deep)	Biocides (pesticides), metals (arsenic, mercury)	Remedial design
Wasatch Chemical	Soil: 3,600 yd^3 (5 feet deep) sludge, solids	Semivolatile organic compounds (hexachlorobenzene, pentachlorophenol), biocides (pesticides), dioxins	Remedial design
Transformer Service Facility/ TSCA Demonstration	Soil: 3,500 tons	PCBs	Site preparation
Arnold AFB, Site 10	Soil with debris: 10,000 tons	Mixed organics, heavy metals	Site preparation
Crab Orchard Wildlife Refuge	Soil: 40,000 tons	PCBs and lead	Predesign
Anderson Development	Soil: 4,000 tons	4,4'-methylene bis (2-chloroaniline) (MBOCA)	Predesign

moisture content requires that additional energy be used to dry out the soil before the melting process can begin, thus increasing the cost. Other factors that influence the cost of remediation by ISV are: the amount of site preparation required; the specific properties of the contaminated soil (e.g., dry density); the required depth of processing; and the unit price of electricity.

EPA Contact

Technology-specific questions regarding ISV may be directed to:

Ms. Teri Richardson
U.S. Environmental Protection Agency
Risk Reduction Engineering Laboratory
26 West Martin Luther King Drive
Cincinnati, Ohio 45268
(513) 569-7949

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Mr. Edward Bates	EPA-RREL
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