Site Remediation by In Situ Vitrification

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In situ vitrification (ISV) is a treatment technology that uses electricity to heat contaminated soil sufficiently to produce an inert glass product. Organic contaminants are destroyed by pyrolysis or they are stripped out of the soil with the escaping steam and trapped in the off-gas treatment system. Most inorganic contaminants are incorporated into the vitrified zone. The glass product is similar visually and chemically to naturally occurring obsidian, and like obsidian, the ISV product is also durable. The electrical power is delivered to the soil through special graphite-molybdenum electrodes inserted into the contaminated soil region in a square pattern. The ability of ISV to treat hazardous chemical wastes, radioactive wastes, and mixtures of hazardous and radioactive wastes is a significant advantage of this process over many other treatment technologies.

In situ vitrification (ISV) is a thermal treatment technology that uses electricity to heat contaminated soils in situ to produce an inert glass product. ISV has a number of advantages over current technologies, particularly the ability to treat mixed wastes, including soils with buried trash or drums, dewatered sludge, mine tailings, or sediments. Furthermore, after treatment the by-product will remain inert for many years to come.

ISV allows contaminated materials to be treated in their existing location without any excavation or transportation required. This can result in a large cost savings as compared with almost any other treatment alternative that requires excavation or transportation of hazardous materials. Alternatively, if the contamination is present over a large area and in a thin layer, the contaminated materials may be consolidated on site in trenches for treatment. In this manner, ISV can be used as a treatment process at a site or area that would otherwise require extensive excavation.

In the ISV process, the soil is heated by applying an electrical potential across four electrodes inserted in a square pattern in the contaminated soil and connected to an electrical circuit. Because most soils are initially nonconductive, a starter path of flaked graphite and glass frit (pulverized glass) is placed between the electrodes to initiate the melting process. The entire area is covered by a containment hood to collect all off-gas produced during the vitrification process. Figure 1 shows a typical layout of the starter path and electrode placement in relation to the contaminated soil.

Testing has been performed on four different size systems (1). The distinguishing characteristics of each system are power level, electrode spacing, and mass of vitrified block produced, as presented in Table 1. Presently, engineering scale testing is being performed at the University of Washington using a variety of different soil types and organic chemicals.

DESTRUCTION METHODS

The ISV process destroys organic materials by pyrolysis in a strong reducing environment. As contaminants pyrolyze, some components migrate or bubble to the surface of the melt. At the surface, they combust in the presence of oxygen, and remnants of this combustion are drawn into the off-gas treatment system. Most inorganic materials are incorporated into the melt and spread throughout the molten soil by convective currents caused by heating.

In addition to pyrolysis, several mechanisms including molecular diffusion, carrier gas transport, capillary flow, and flow resistance in the soil column contribute to the destruction of high percentages, commonly 99.995 percent, of organic materials contained in the waste (2).

PRODUCT DURABILITY

The ISV mechanism of melt production and solidification is similar to the natural reactions that create igneous rocks on earth. A typical soil is primarily composed of silica and aluminum oxides that have melting temperatures between 1,100°C to 1,600°C (2,012°F to 2,912°F) (3). When this melt cools, it forms a glass with a random atomic structure and a relatively uniform chemical composition. This uniformity is caused by convection currents caused by the heating of the soil, and the characteristics of the glass are basically the same as obsidian (4). Because the ISV-derived glass has a random atomic structure, its fracture mechanism is conchoidal with no preferential planes of weakness. Tests on ISV-derived glass indicate that its durability is similar to that of granite (3).

The durability of ISV-derived glass can be estimated by examining the durability of obsidian. The weathering process of obsidian involves the hydration with atmospheric water that is chemically absorbed on the surface. The water then diffuses into the obsidian as a function of time and temperature. In the natural environment, obsidian has a hydration rate constant of about 1 to 20 μm^2 per 1,000 years (Larsen and Langford, 1978). Using the conservative end gives an estimate of less than 1-mm hydrated depth for the ISV-derived glass over a 10,000-year time span (5).

ISV-derived glass has been subjected to a variety of leach tests, including the Environmental Protection Agency's (EPA's) extraction procedure toxicity test (EPTOX) and toxic characteristics leach test (TCLP). All of these tests exhibit a uniformly low leach rate for heavy metals of about 5×10^{-4} kg/m^2/day or lower (1).

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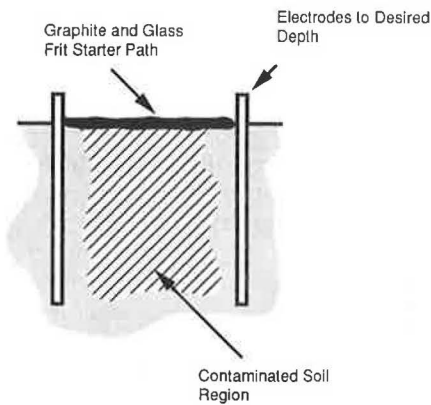
FIGURE 1 Typical ISV layout.

TABLE 1 CHARACTERISTICS OF ISV SYSTEMS

System	Power (kW)	Electrode Spacing (m)	Block Mass (tons)
Bench scale	10	0.11	0.001 to 0.01
Engineering scale	30	0.30	0.05 to 1.0
Pilot scale	500	1.2	10 to 40
Field scale	3,750	5	400 to 800

PROCESS DESCRIPTION

Power System

Three-phase power supplied by the utility grid system or portable generators is delivered to a special adjustable (multitap) transformer that converts it to two single phases and transforms the power supplied to the voltage levels needed throughout the processing. Each electrical phase is connected to a diagonally opposed pair of electrodes in a square pattern; thus a balanced electrical load is created on the secondary side of the transformer. The even distribution of current within the molten soil produces a vitrified product that is almost cubical, a shape that minimizes overlap among adjacent treated volumes. Multiple voltage taps and a balanced load allow for a near-constant power operation; thus run time is shortened and costs minimized.

Adjustable voltage taps are used to maintain a constant input of power to the melt; as more of the soil becomes molten, the conductivity of the soil changes and hence the voltage and current supplied also should be changed to maintain a constant power input. Fourteen adjustment levels permit voltages from a maximum of 4,000 volts to a minimum of 400 volts per phase and currents from a minimum of 400 to a maximum of 4,000 amps per phase. As the melt volume grows downward and outward, power is maintained at a sufficient level to overcome the heat losses from the surface and into the surrounding soil.

In the ISV process, electrical current is delivered to the soil by electrodes. In the large-scale field operation, the electrodes consist of a 50-mm-diameter molybdenum inner electrode core inside a 300-mm-diameter graphite collar (*1*). The graphite collar provides a relatively inexpensive cross section that promotes conduction of current to the melt. It also promotes gas release from the melt by providing a preferential corridor in the vertical direction. The graphite collar is sacrificial in that it is left in the melt when the process is complete. The larger graphite collar also provides a protection layer for the molybdenum inner electrode. This generally means that the more costly inner electrode may be reused, which provides a cost savings.

The electrodes are placed in the soil to the desired treatment depth. The depth of the melt is limited as heat losses from the melt approach the energy level deliverable to the molten soil by the electrodes (*1*). Generally, the melt grows outward to about 50 percent of the spacing of the electrodes. With a typical electrode spacing of 5.5 m, a melt width of 8.5 m would be observed under normal conditions. Full-scale ISV units are designed to operate to depths of 9.1 to 12.2 m. Figure 2 shows how successive melts are accomplished to form a single monolith.

The field-scale ISV system melts soil at a rate of 4 to 6 tons/hr. Accordingly, the rate of melt advance is in the range of 25 to 50 mm/hr. As the thermal gradient advances in the soil, solid and liquid organic materials first vaporize and then pyrolyze (i.e., decompose in the absence of oxygen) into their elemental components. Organic pyrolysis byproducts are typically gaseous; these gases move slowly through the melt toward the upper melt surface. Some of these gases may dissolve
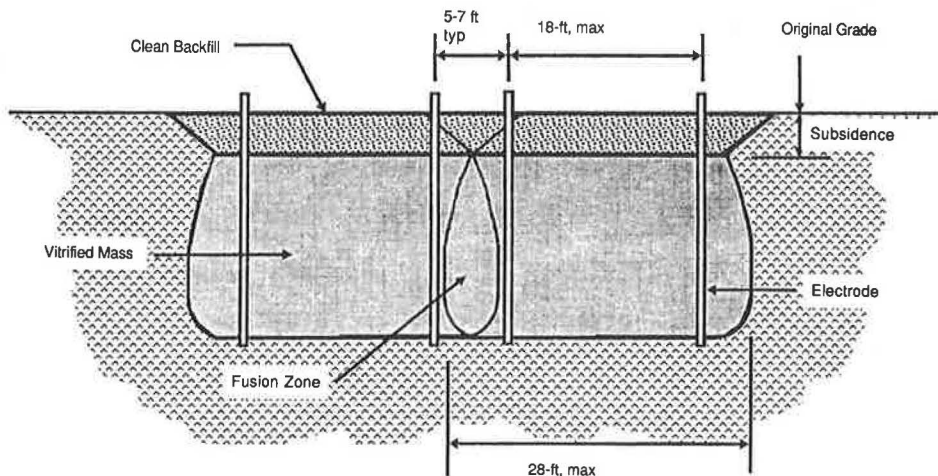

FIGURE 2 Pattern of successive melts.

in the molten mass, but the remainder escape and are collected in the off-gas collection hood for subsequent treatment in the off-gas treatment system.

Individual ISV process settings (with electrode spacings of 5.5 m) may have a mass of 1,000 tons. Adjacent settings fuse together into a single monolith (Figure 2); thus, the residual product presents a minimum of surface area to the surrounding environment. Even when reduced to fine particle sizes, the ISV residual product easily passes EPA's EPTOX and TCLP testing criteria.

Because the soil or other contaminated material is generally nonconductive, a conductive starter path is provided near the surface of the melt zone to provide an initial pathway for the electric current. This starter path consists of a mixture of flaked graphite and glass frit. As the electrical current is applied to the starter path, the glass frit heats up to 2,000°C, which is well above the initial soil mineral melting temperatures of 1,100°C to 1,400°C. Eventually, the starter path is consumed and the energy is transferred into the soil mass. In this way, a molten conductive zone is started in a soil that is initially nonconductive.

The ISV process seeks an equilibrium temperature depending on the fusion temperature of the soil and the particle sizes encountered. In general, the melt can attain temperatures greater than 1,700°C. When a higher fusion temperature layer or a large particle size (greater than 20 mm) layer is encountered, a higher equilibrium temperature is needed to achieve the same downward progression rate for the melt. If necessary, fluxants (e.g., soda ash, lime, and glass frit) injected into the voids of larger grain size materials may be used to enhance the downward melting rate (6).

A layer of ceramic insulation tolerant of high temperature is placed over the surface of the treatment area and surrounding soils. This layer minimizes heat loss from the surface of the melt zone and enables a larger and deeper melt to be accomplished with the same available power input.

A percentage of a soil total volume is made up of voids containing either gas or liquid. During the ISV process, the voids present in the treated soil disappear leaving a glass with nearly zero voids; the only exception is some trapped gas bubbles near the surface. As typical porosites in soil vary from 20 to 40 percent, vitrification produces a reduction in volume that is reflected in a surface subsidence. The surface crater is generally backfilled with clean fill to the original grade. This measure also provides some additional protection for the glass monolith as well as a barrier to possible surface disturbance.

Costs

The cost of ISV operations is highly site specific. The major factors in cost include the following:

- The amount of site preparation and staging work required, if any;
- Specific properties of the waste or soil to be processed;
- Volume of material to be processed;
- Depth of processing;
- Water content;
- Unit cost of electricity; and
- Season of the year and weather

Depth of processing is a significant cost variable that relates directly to the ratio of operating time to down time. Because the ISV process is site specific, the equipment must be moved between treatment sites. It is more economical to treat to a deeper depth and thus allow more treating time relative to down or move time. For shallow contamination (e.g., only a few meters), it is usually more cost-effective to remove and stage the material into a deeper configuration for processing.

Water content is one of the most significant variables affecting vitrification costs, which can vary from $50/ton to $75/ton between dry soil and fully saturated soil.

The cost of electricity is also a major variable affecting total ISV costs. Generally, it is more economical to use utility-provided power if it can be obtained for less than $0.07/kW-hr. Above this range, consideration should be given to using a local diesel generator.

The onsite cost of ISV processing usually is in the range of $250 to $350 per ton of material processed (7).

Off-Gas System

A large collection hood covers the treatment area to trap any gaseous effluents from the process and to direct them to the portable off-gas treatment system. This hood controls the flow of air, provides a chamber for the combustion of pyrolyzed organics, supports the electrodes, and maintains a negative hood pressure of 125 to 250 kPa. Maintaining a negative hood pressure is accomplished by moving the air through the system using a blower attached to the end of the treatment line and sealing the collection hood as well as possible to the ground allowing only one controlled air inlet.

The effluents exhausted from the hood are cooled and treated in the off-gas treatment system. Much of the heat generated during the process is exhausted through the off-gas system. If there is a high concentration of buried solid or liquid organics present in the contaminated soil, the off-gases can be expected to reach a temperature of 750°C. In general, the off-gas system cools, scrubs, sorbs, and filters the organic chemicals exhausted from the hood in three stages (1). First, the gases are scrubbed in two stages, with a quencher and tandem nozzle scrubber. These scrubbers remove particles down through the submicron range. Second, most of the water in the saturated gas stream is removed by a vane separator followed by a condenser and a second vane separator. The gases are then reheated, to ensure that there is an unsaturated gas stream at a temperature well above the dewpoint. In the third treatment phase, the off-gas is filtered with two stages of high-efficiency particulate air filters. Figure 3 is a schematic drawing of the large-scale off-gas treatment system.

FIELD EQUIPMENT REQUIRED

The entire ISV operation, except for the off-gas collection hood and line, is mounted on three standard over-the-road trailers. The off-gas and process control trailer, a support trailer, and an electrical trailer can all be easily hooked together, or unhooked when the system needs to be moved. The off-gas hood and line, which are installed on the site for collection of the gaseous effluents, are dismantled and placed on a flatbed trailer for transport between the sites to be treated. The only other requirement is some method to insert the electrodes into the ground. This can be accomplished by a
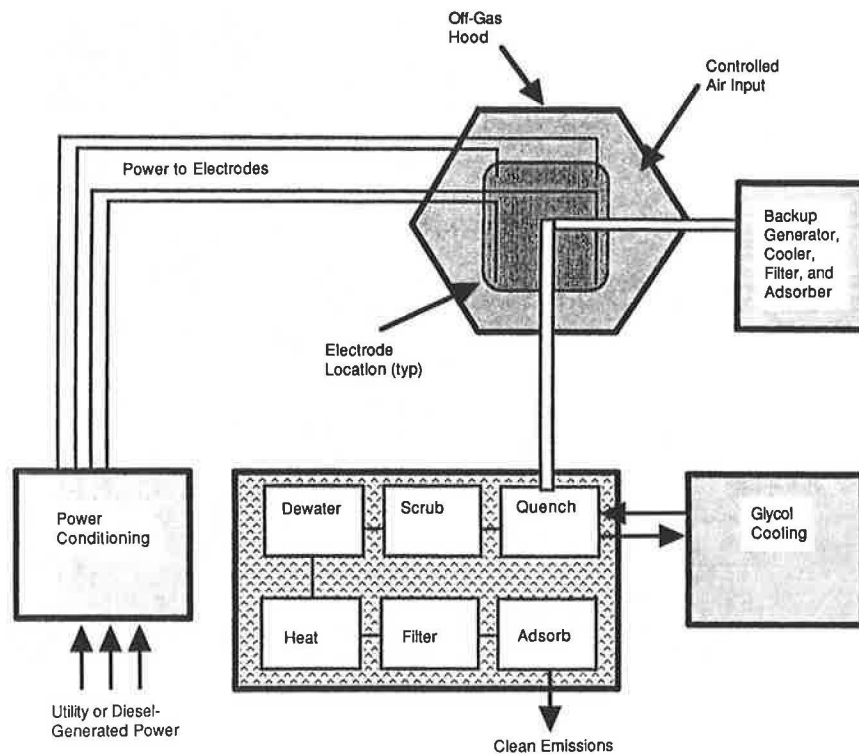
FIGURE 3.   Schematic diagram of large-scale off-gas treatment system.

standard drill rig or other similar method. Typical readiness time is about 1 week after arrival (7).

The large-scale ISV equipment requires three-phase electrical power usually taken from a utility distribution system at typical transmission voltage of 12,500 or 13,800 volts. The equipment draws about 3,750 kW during operation, which corresponds to a specific power consumption averaging for most soils, of 1 kW-hr/kg of soil treated. If no utility distribution system is available at a particular site, power can be generated on site by diesel generators. Figure 4 shows a field-scale operation.

LIMITATIONS

The ISV process was developed and demonstrated through large-scale projects, and wastes treated have included a variety of hazardous chemical, radioactive, and mixed (hazardous chemical and radioactive) wastes. The ability of ISV to process mixtures of these waste types simultaneously is a significant advantage compared with other remediation technologies. With mixtures of waste types, it is usually necessary to use more than one non-ISV technology, in sequential fashion, to accomplish a total remediation.

Although ISV is broadly applicable, there are limits to its uses. Most significant is the rate of groundwater recharge when the treatment zone is below the water table. As ISV heats the soil, the soil reaches the boiling point of the water and cannot go any higher until all of the water is boiled off. This can cause a significant amount of electricity to be expended boiling off water and not increasing the size of the molten zone. Applications involving a hydraulic conductivity exceeding 10^{-4} cm/sec are considered marginal from an energy consumption standpoint; that is, the use of barrier walls,

well points, or some other means to limit recharge would be cost effective compared to removing water by electrical heating (7).

Some soils with an organic chemical concentration of more than 5 to 10 percent by weight will cause an overload in the off-gas system. This system is designed to transfer only a certain amount of heat and organics out of the off-gas. Soils with organic concentrations of these levels will overload the system.

Metal concentrations (e.g., drums and scrap metal) in the range of 5 to 16 percent by weight can be processed without special adaptations. Continuous metal contact (e.g., pipeline or rebar) up to 90 percent of the distance between opposed electrodes also is acceptable. With these capabilities, the process may be used to treat contaminated drums and other metallic components.

ISV can also accommodate a significant amount of rubble, debris, or other inclusions within the treatment zone. Figure 5 shows typical inclusions with their maximum acceptable amounts recommended for ISV.

SUMMARY

ISV is a treatment process that uses electricity to treat a variety of contaminated soils resulting in an inert glass product. This glass product is similar to naturally occurring obsidian in composition and therefore should weather similarly to natural obsidian. The glass product has been found to be stable when tested using the EPA leachability test.

ISV has advantages over most other treatment methods available. They include the ability to treat the waste in place with a minimum of excavation and the ability to treat a variety of wastes including mixed wastes, which is often the case
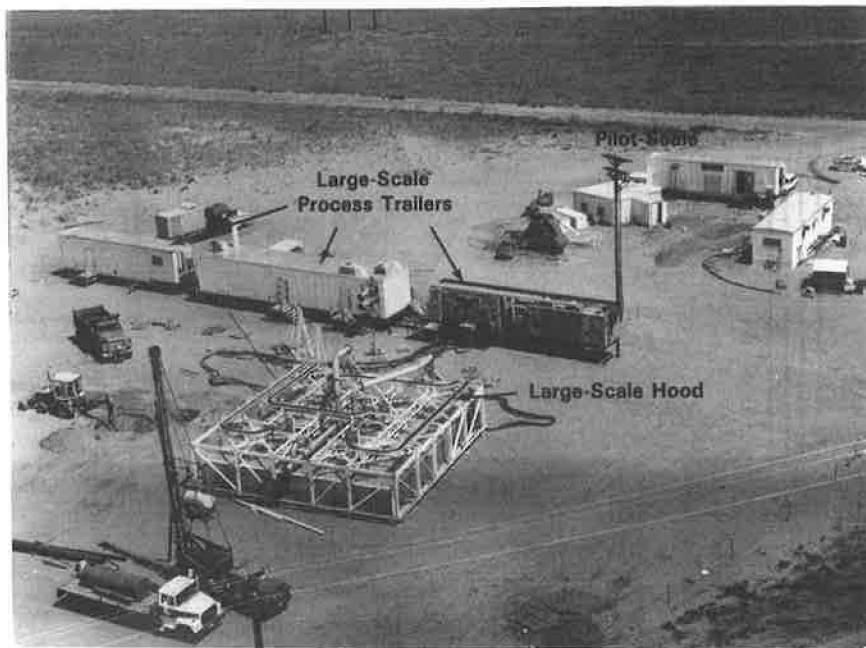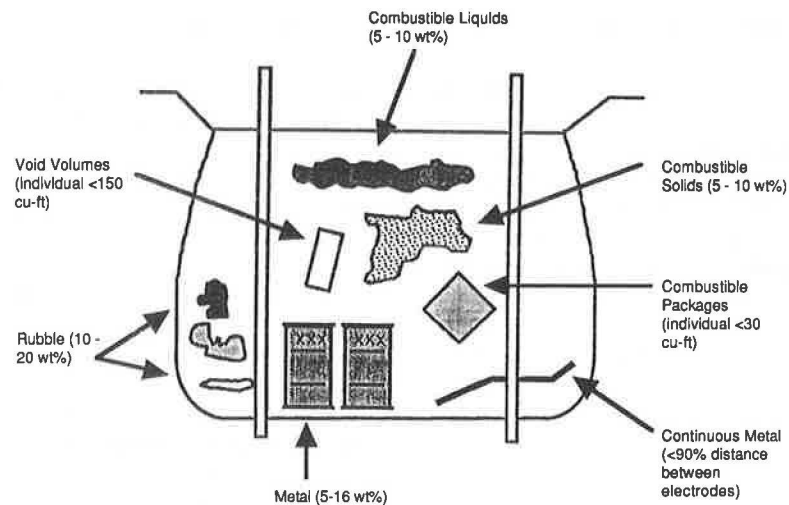
FIGURE 4   Field-scale ISV operations.

FIGURE 5   General limitations for inclusions within volume to be treated.

found on hazardous waste sites. These advantages make ISV a viable alternative for treatment of contaminated soils.

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