VITRIFIED UNDERGROUND BARRIERS

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ABSTRACT

In situ vitrification (ISV), a process for remediation of underground wastes, is now being developed to generate vitrified underground barriers. In this application, clean soil surrounding a waste site will be vitrified in order to isolate the wastes from undesirable contact or transport. Laboratory-scale experiments have demonstrated the following: 1) a subsurface ISV melt can be initiated and maintained, resulting in a horizontal, planar, glass block; 2) the downward growth of a vertical ISV melt can be directed and controlled such that enhanced melt rate and limited outward growth is achieved, resulting in a vertical, planar, glass block; and 3) a vertical ISV melt can be vitrified to a subsurface horizontal ISV block, forming a bond that joins them into one continuous formation.

The results from these experiments demonstrate the feasibility of generating vitrified underground barriers beside, beneath, and/or around a waste site. This paper focuses on the experimental results and includes some discussion of the need for vitrified underground barrier technology and the course of the project.

INTRODUCTION

In situ vitrification (ISV) is a waste remediation technology that has been developed by researchers at the Department of Energy's (DOE's) Pacific Northwest Laboratory (PNL). Over the past ten years, the process has been demonstrated successfully for the treatment of chemically hazardous and/or radioactively contaminated soil, and current work is largely directed at developing the ISV technology for treatment of buried waste and underground storage tanks. Because DOE requires options for long-term isolation and containment of waste sites, ISV is now also being developed to generate underground barriers that will contain the migration and fluid transport of wastes as well as isolate them from contact with animals, plants, and people. A vitrified underground barrier could be created beside and/or beneath a waste site; several such barrier walls and floors could be joined (vitrified together) along with a cap to create a tomb around the contaminated site. Depending on the specific needs of a site, this vitrified underground barrier would act either as a permanent environmental restoration action, as an interim containment and stabilization step until a permanent treatment can be implemented for effective remediation, or as a necessary containment for the application of other thermal, chemical, or biological in situ treatment technologies. Figure 1 depicts various vitrified barrier options for remediation at contaminated waste sites.

In order to generate vitrified underground barriers, it may be necessary to initiate a subsurface melt and to control the melt propagation in a relatively planar, two-dimensional fashion. Laboratory-scale experiments have demonstrated the success of underground start-up of a subsurface, horizontal melt and various techniques for directing and controlling a vertical melt. This paper focuses on the results of these ISV barrier experiments. A brief discussion of the barrier integrity and the future of the project is also included.

BACKGROUND

In situ vitrification is a thermal treatment process developed as a result of PNL's work in glass melter technology for the vitrification of nuclear wastes. The process has been patented domestically and abroad(1). The processing sequence is depicted in Fig. 2. Rather than feeding wastes and glass formers into a melter and containerizing the glass product, ISV is performed by inserting an array of electrodes into the soil to a nominal depth above the waste site. Since the soil is not electrically conductive, a starter path of flaked graphite and glass frit is placed between the electrodes. An electric potential is applied to the electrodes and an electric circuit is established with the starter path acting as a resistive heating element. As the temperature of the starter path increases, the glass frit begins to melt. Heat from the molten starter path is transferred to the surrounding soil causing the soil to melt. Once molten, the soil becomes electrically conductive, and power is gradually increased into the melt. The electrodes are allowed to feed downward as the molten mass grows, vitrifying the soil and contaminants. A hood placed over the area being vitrified contains the release of gases from the melt and directs them to an off-gas treatment system. Power is maintained into the melt until the desired depth is obtained and the soil and its contents are vitrified. Upon cooling, the resultant mass solidifies into a high-integrity block resembling natural obsidian. The tensile and compressive strength of ISV blocks generated from most soils is about ten times that of unreinforced concrete, with a leach resistance approaching that of high-quality laboratory glassware. Studies show that the ISV glass and crystalline monolith will retain its integrity for geologic time periods(2).

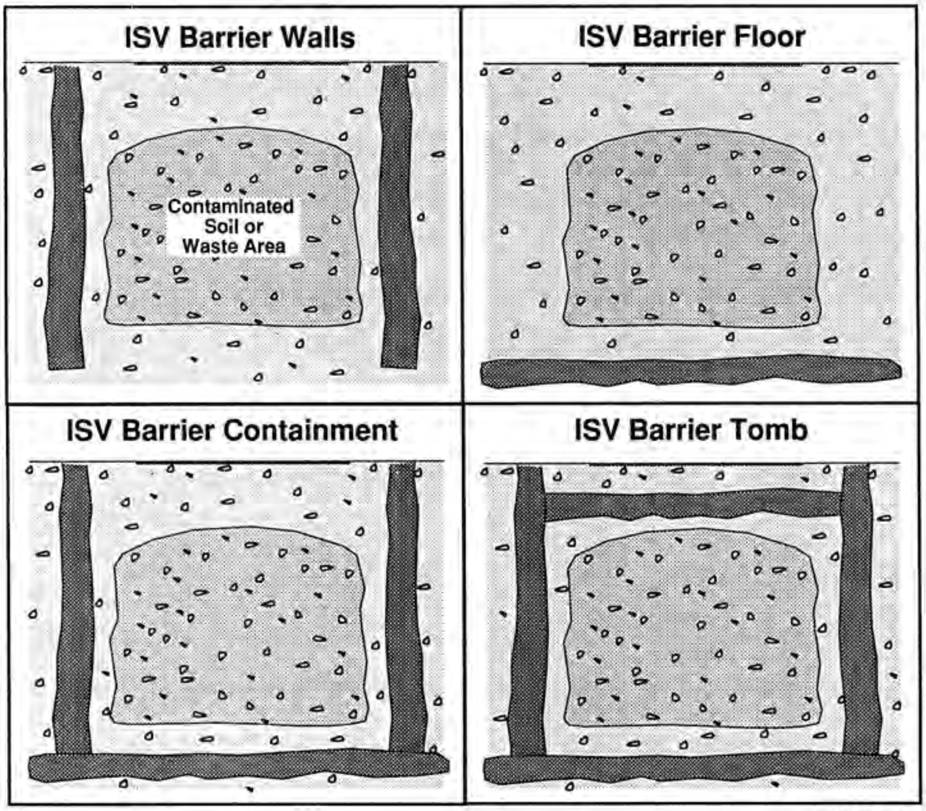

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Fig. 1. Four options for vitrified underground barrier application at contaminated soil/waste sites: vertical barrier walls cut off the flow of groundwater through a contaminated site; a horizontal barrier floor prevents leaching of contaminated site; a horizontal barrier floor prevents leaching of contaminants into lower groundwater levels; a vitrified barrier containment will enclose a contaminated site for treatment by thermal, chemical, or biological in situ treatments; a vitrified barrier tomb will totally encapsulate a contaminated site, preventing spread of the wastes and intrusive contact by plants, animals, or man.

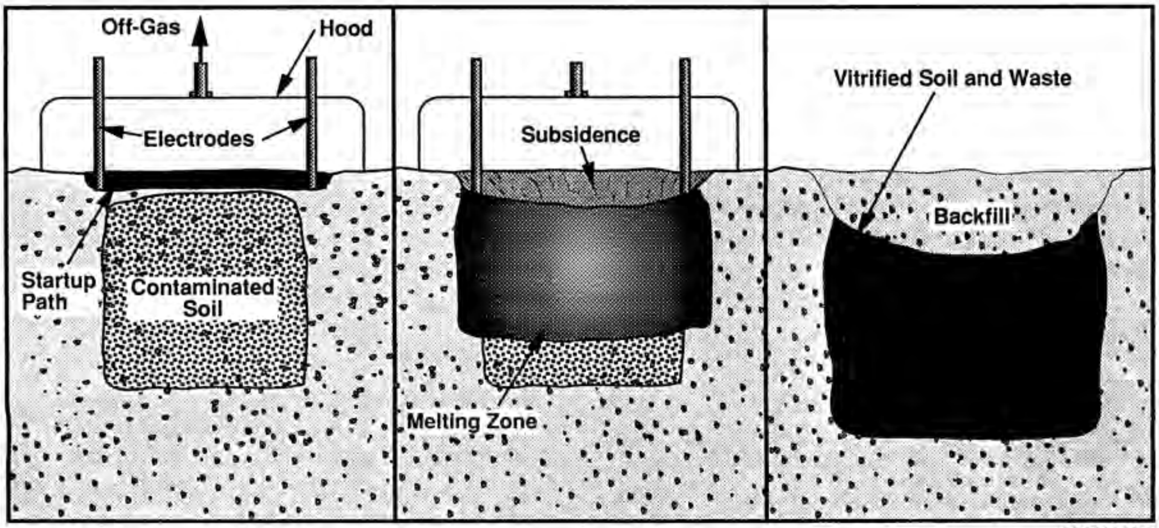

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Fig. 2. ISV operating sequence.

In applying the technology for the generation of vitrified underground barriers, four significant differences from traditional ISV should be noted as follows.

- The soil being vitrified is uncontaminated and lies beyond and/or below the contaminated region. Based on experience with vitrifying uncontaminated soils, treatment of off gases is not expected to be necessary.
- Vertical barriers can be generated from a two-electrode array, thus simplifying the electrical configuration and reducing the amount of energy required to achieve a given depth.
- It is desired to maintain a relatively planar, two-dimensional geometric shape and limit melt growth in the dimension perpendicular to the plane of the two electrodes (vertical barrier) or the plane of the bottom of the electrode array (horizontal barrier).
- Horizontal barriers beneath a waste site will need to be started at a target depth. The challenges to this are twofold: accurate placement of the starter material and controlled start-up methodology. The challenges relating to starter path placement in the field is complex and some methods are mentioned in this paper. Experimental results regarding a controlled start-up methodology are discussed in detail.

EXPERIMENTAL PROCEDURE AND RESULTS

Horizontal Barriers

Vitrifying a horizontal barrier beneath a waste site requires that electric current be delivered through the soil at a target depth to form a planar glass monolith of high integrity. The main issues addressed by the project in general and the laboratory tests specifically are discussed below. The laboratory test set-up for the horizontal barrier experiment is depicted in Fig. 3.

The electrodes must be located to provide the electric current to a horizontal area beneath the waste site with minimal disturbance to the waste itself. This can be accomplished merely by drilling vertical boreholes into which the electrodes can be inserted to the necessary depth. This has been standard ISV procedure for surface-initiated melts before the invention of the electrode feeding mechanism in 1989(3). For the laboratory test, this was done by preparing the test site with an array of four 3.8 cm (1.5 in.) diameter electrodes, vertically arranged with the bottom of the array at a depth of 81 cm below grade. The electrodes were spaced in a square array, 30 cm center-to-center on a side.

A conductive starter path material must be placed between the electrodes. A variety of methods have been proposed, most of which utilize standard geological operations (or variations there of). They include horizontal borehole technology and subsurface hydrofracturing through vertical boreholes. In each case, a conductive starter path material could be injected into the area between the electrodes to initiate the melt. The project has included only a small amount of research on these methods to date, and no attempt was made to duplicate them in the laboratory.

For the laboratory test, the conventional "square and x" starter path was laid between the electrodes after the bottom 20 cm of the electrodes had been buried. Thus, each electrode was connected to the other three by the graphite and glass frit starter path. The site was instrumented with thermocouples to obtain time/temperature data and then buried, leaving the starter path 61 cm below grade. By manually burying the starter path, research focused on underground start-up techniques as described below, rather than starter path placement technology.

Power must be controlled to the melt to effect start-up and must continue until the entire area between the electrodes is vitrified. For the laboratory test, power was applied to the electrodes and gradually increased until either the resistance increased beyond the power capacity of the system (at which time the first test was terminated), or until a total power of about 15 kW was applied to the melt (as during the second test).

Consideration must be given to the fact that vitrification of soil causes a densifying effect due primarily to the loss of interstitial soil moisture, organic content, and void volume. Depending on these conditions and other contents of the soil, the resultant subsidence in ISV melts varies from 20 to 80%. A subsurface melt would release gases, but they would not be expected to disperse through the soil or percolate up to the surface. The first horizontal barrier test included vent pipes around the electrodes to allow for off-gas ventilation. However, this led to premature termination of the test due to premature oxidation of the starter path at the localized areas beneath the vents.

The second test was set up and conducted like the first but without the vent pipes (shown in Fig. 3). The experiment ran for 5 h and produced a block of about 20-cm vertical thickness and approximately 45 cm in diameter. The block appeared to have formed equally above and below the original starter path level. The soil was excavated enough to measure the block, and then the test site was immediately prepared for the vertical barrier test (in which the vertical melt would contact and join the block). It was noted that no apparent subsidence of the soil occurred to account for any densification of the glass. During excavation it was also noted that the soil was quite moist (more so than the pre-test soil moisture) at about 20 to 25 cm above the block; below this level the soil was completely dry down to the block. The soil had been dried out by the vitrification process with some moisture recondensing beyond the 100°C isotherm. There was also no apparent disturbance of the

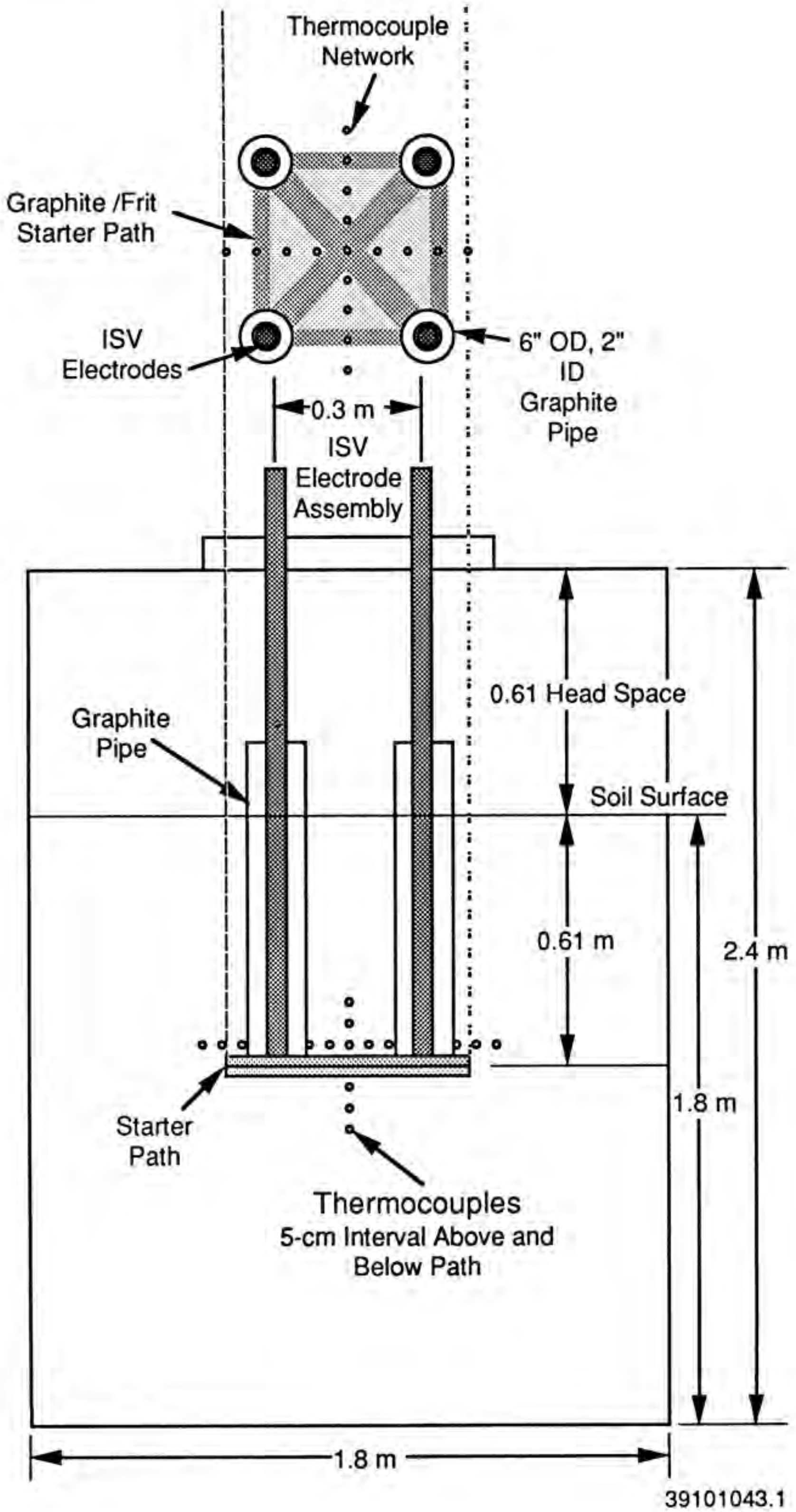

Fig. 3. Diagram showing elevation and plan view cross-sections of the underground start-up test set-up configuration.

soil above the block. The block itself appeared to be a solid formation; no surface cracks were evident. It was concluded that a void space was generated within the vitrified block, with the block neither expanding nor subsiding from the volume of soil vitrified. Figure 4 is a photograph of the top surface of the excavated horizontal block.

Vertical Barriers

Vitrifying a vertical barrier more closely resembles a standard ISV operation. A starter path is laid between the electrodes at the surface of the soil to initiate the melt; as the melt grows, the electrodes are fed downward (usually by gravity) until the desired depth is reached. However, the objective of a vertical barrier is a relatively planar block; therefore, two electrodes are used with single-phase power, and engineering efforts are made to promote downward rather than outward melt growth. Two tests were conducted to evaluate two methods of creating vertical barriers. A second objective was to join the vertical melt to the edge of the underground horizontal block. The first test used fluxed soil, the second used metal ingots in the melt. The plan view of the test configuration is shown in Fig. 5.

In the first test, a vertical trench was constructed between the electrodes, 5 cm wide, and to the depth of the top of the block. The trench was backfilled with a 9:1 soil:flux (in the form of technical-grade sodium silicate crystal) mixture. This was designed to lower the melting point of the material in the trench during vitrification, preferentially directing melt growth downward rather than outward.

The test proceeded normally, gradually increasing power to the melt until 10 kW was obtained. The electrode feed rate progressed steadily with an average rate of 7.4 cm and a peak feed rate during the middle of the run of 10.2 cm/h. After about 6 h, the melt had progressed downward to the top of the horizontal block. The electrodes were held in place but power continued to be maintained in an effort to fuse the two blocks.

Shortly after this, one of the electrodes dropped rapidly about 12 cm and subsequent power readings showed no conductivity between the electrodes. After allowing the block to cool it was discovered that the molten glass had drained from the melt and had evidently filled a void in the horizontal block. Upon excavation, the vertical block (now resembling a hollow glass tank) was found to be firmly bonded to the horizontal block. The vertical block was teardrop shaped, like a traditional ISV melt, showing that the fluxed trench did little to inhibit lateral outward growth. The vertical block measured about 38 cm wide (parallel to the electrode plane), about 30 cm deep (perpendicular to the electrode plane), and about 44.5 cm high from the top of the horizontal block. The size and shape of the horizontal block did not change; however, superficial cracking appeared on the top, likely due to the thermal shock of the rapid inflow of hot glass. The combined weight of the two fused blocks was 91 kg. Based on run times and block dimensions, it is estimated that the vertical melt was about 52 kg before draining, and the horizontal block was about 39 kg.

The horizontal block was cut in half (along a plane parallel to the plane of the vertical electrodes) to reveal two distinct glass zones, one above the other. The top zone was surrounded externally by a distinct layer of glass and sintered soil. This evidence shows that when the horizontal block was generated, it resulted in about 50% subsidence, as expected. The remaining block volume was void space. Once the vertical melt contacted and breached the horizontal block, the glass flowed in substantially filling the void. A photograph of the cross section is shown in Fig. 6.

The second vertical melt was prepared independently (to prevent damage to the results of the first test). The test included the addition of two stainless steel ingots; each were 5 cm in diameter, 7.5 cm in length, and 1.6 kg in mass. The ingots were placed horizontally, end to end, between the electrode array and were covered by 15 cm of soil (see Fig. 5). The ingots were to act as a passive metal electrode, concentrating current at the bottom of the melt (having a greater density than molten glass), thus promoting downward growth. The test progressed rapidly, with the electrodes being fed downward at times as fast as 11 cm, with an average feed rate of about 9.1 cm. Electrical shorting between the electrodes occurred only infrequently, contrary to normal ISV operations with metal at the bottom of the melt. Also, the electrodes were consistently driven downward using the feed system; they were not held above the bottom to prevent shorting as is normal procedure with metal in the melt. Vitrification was terminated after 6 h upon reaching a target depth of 56 cm.

Excavation of this block revealed its shape to have straight sides with no increasing outward growth at the bottom. The block measured about 38 cm wide (parallel to the electrode plane), about 23 cm deep (perpendicular to the electrode plane), and about 57 cm high. The lower 25 cm tapered almost to a point at the bottom of the block. This block was also cut in half between the electrodes on a vertical plane. Surprisingly, the two ingots had not melted but had maintained their orientation, now resting in the glass about 0.5 cm from the bottom of the block. A photograph of the first vertical block (made with fluxed soil) joined to the horizontal block, along with the second vertical block (made with passive metal electrodes) resting beside it for comparison, is shown in Fig. 7. Photographs of the second vertical block and its cross section are shown in Figs. 8 and 9, respectively. A comparison between the results of the two methods of vertical barrier generation is shown in Table I.

Fig. 4. Photograph looking down on the top of the excavated horizontal block. Three electrodes have been cut off at the surface; the lower right one was removed.

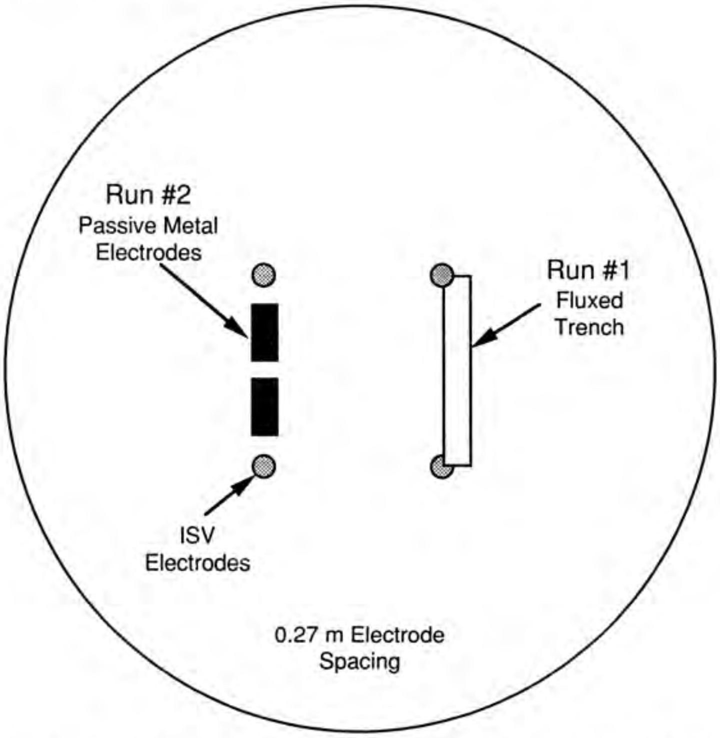

Fig. 5. Diagram showing the plan view of the vertical melt test set-up configuration.

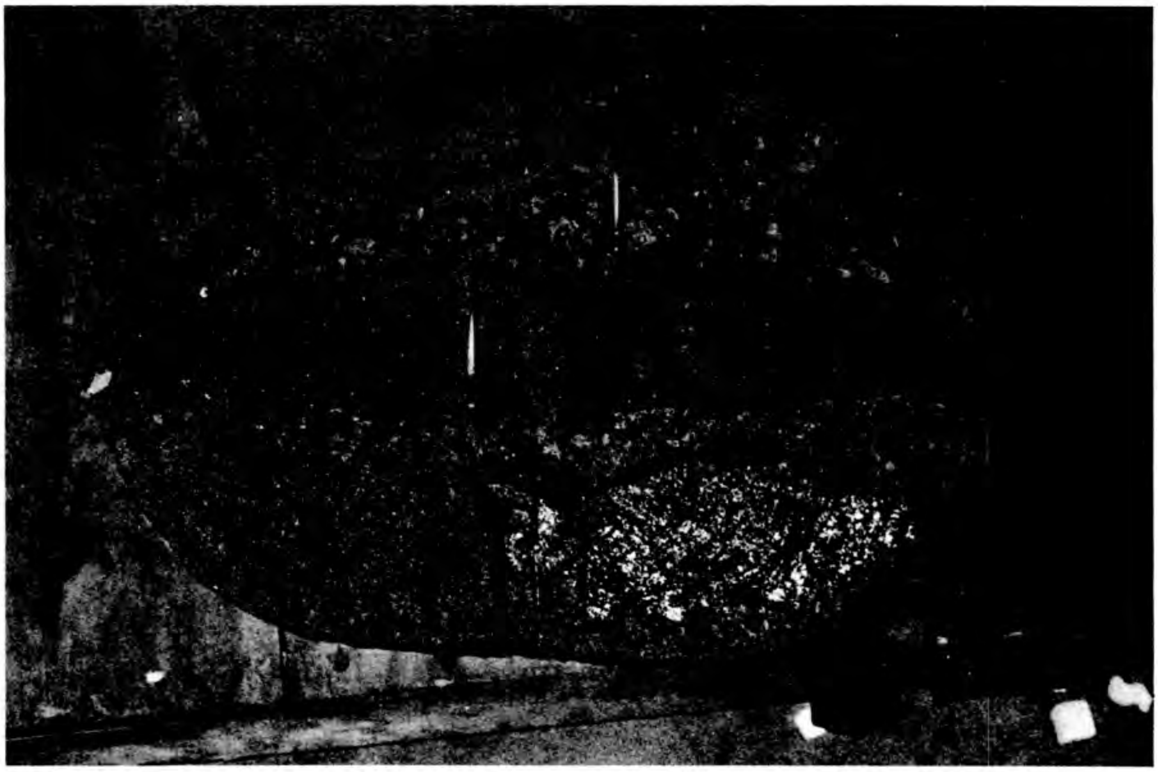

Fig. 6. Photograph of the horizontal block cross section showing the two glass regions formed by underground start-up and subsequent filling of the internal void space with glass from the vertical melt.

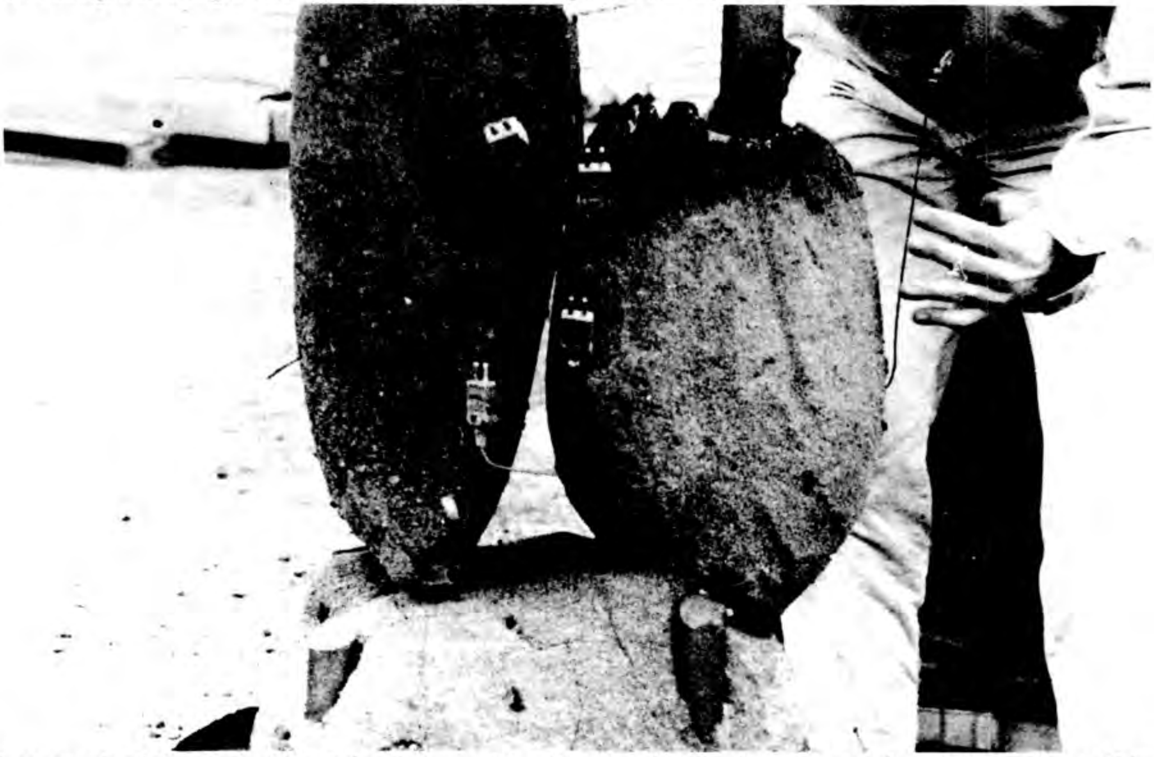

Fig. 7. Photograph of the vertical block (made by melting fluxed soil) joined to the top edge of the horizontal block; the second block (made using passive metal electrodes) is resting upright on the left side of the horizontal block and is shown for comparison.

TABLE I

Comparision Between Vertical Barrier Wall Test Runs 1 and 2

Melt Control Method	Run Time (h)	Final Depth (cm)	Average Electrode Feed Rate (cm/h)	Peak Electrode Feed Rate (cm/h)	Block Mass (kg)
Fluxed Soil	6	44.6	7.4	10.2	52[a]
Passive Metal Electrode	6	54.6	9.1	12.7	57

(a) Estimated from combined mass of 91 kg for the vertical and horizontal melt.

OBSERVATION AND INTERPRETATION

Following completion of the tests, the blocks were allowed to cool to ambient temperature, excavated, removed, examined, and cut in half. The following observations and interpretations were made.

A subsurface ISV melt can be initiated and maintained until the entire area between the electrode array is vitrified, forming a horizontal, planar glass block. Results showed that vitrification should be terminated once feedback data indicate the area is vitrified. Prolonged power application would appear to contribute more to vertical rather than horizontal growth and also to increase the internal void volume.

Fig. 8. Photograph of the second vertical block, made using passive metal electrodes.

The downward growth of a vertical ISV melt can be directed and controlled such that enhanced melt rate and limited outward growth is achieved, resulting in a vertical, planar, glass block. Since the tests were performed using Hanford soil, which has excellent glass-making properties, the addition of a flux did not serve to enhance preferential vertical melting. However, this should not rule out the possible use of a fluxed trench in soil types having poor glass-making properties. The use of metal ingots did serve to enhance preferential vertical melting in the Hanford soil by concentrating power density at the bottom of the melt. Moreover, the metal-to-glass mass ratio was high enough and the downward melt rate fast enough (enhanced by the presence of the metal and force feeding the electrodes) that the ingots never melted. This eliminated the condition of electrical shorting between the electrodes through a metal pool.

A vertical ISV melt can be vitrified to a subsurface horizontal ISV block, forming a bond that joins them into one continuous formation. This bond was a homogeneous glass formation that showed no arrant structural weakness between the two blocks. (Even repeated handling and transportation of this block produced no cracking in the joint.

A subsurface melt generates a void space within the block above the molten soil and surrounded by a glass and sintered soil dome. One method of eliminating the void is by filling with glass from a subsequent melt. (The hollow tank left as a vertical block could merely be filled with soil

Fig. 9. Photograph of the cross section of the second vertical block. The right section shows the metal ingot, still intact, at the bottom of the block. (The ingot from the left side broke out during cutting.).

and re-vitrified to form a solid barrier wall.) It may also be possible to provide surface venting for the gases.

The blocks generated displayed no evidence of severe cracking even at the relatively rapid cool-down rate involved in the laboratory experiments. Only superficial cracking was observed in the dome of the horizontal block. This evidently occurred when the glass from the vertical melt filled the void in the horizontal block. These cracks do not appear to compromise the integrity of the block as they do not penetrate through the interior.

CONCLUSION

Any technology employed to isolate and contain contaminated material in the ground must meet appropriate technical and regulatory requirements, should have a high degree of public acceptance, must prove implementable under a variety of DOE site/waste conditions, and must be cost effective. ISV technology is being developed for the generation of vitrified underground barriers around an underground waste site with these objectives in mind. Laboratory scale testing has proven the ability to generate two types of vitrified underground barriers: vertical, surface-initiated blocks and horizontal, subsurface-initiated blocks. The structures were relatively two dimensional. The tests also showed that the barriers can be joined together. Given the durability and integrity of ISV monoliths, waste sites could be isolated or entombed by vitrified underground barriers effectively functioning for many thousands of years.

Future work on the project will concentrate on analysis and computer modeling of the potential integrity of the vitrified underground barrier and an economic analysis of field-scale testing, demonstration and application. The long-term goal is field demonstration and technology transfer.

ACKNOWLEDGMENTS

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