POTENTIAL FOR USING A SIX-PHASE ALTERNATING CURRENT POWER SUPPLY SYSTEM FOR IN SITU VITRIFICATION

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ABSTRACT

In situ vitrification (ISV) has been identified as a potential treatment technology for stabilizing underground tanks at Hanford and other U.S. Department of Energy (DOE) sites. A key requirement for this application is an electrical system that can supply the power needed to vitrify a tank in a single setting. This paper describes an engineering-scale test conducted at the Pacific Northwest Laboratory (PNL) to assess the efficiency of a six-electrode, six-phase energy supply system in melting soil. The test was conducted with a 30-kW six-phase system. Based on the test results, a six-electrode, six-phase system shows potential for scaleup to larger systems.

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INTRODUCTION

In situ vitrification is a thermal treatment process that converts contaminated soil into a leach-resistant material resembling obsidian. The process was developed by PNL to immobilize contaminated (e.g., radioactive) soil and isolate it from the surrounding environment. It is currently being used to demonstrate soil remediation at DOE-owned facilities at Hanford and other sites, including the Idaho National Engineering Laboratory and the Oak Ridge National Laboratory (ORNL).

In situ vitrification is based on the joule-heating principle used in electric melter technology developed by PNL for the immobilization of nuclear waste. The process is initiated by inserting an array of graphite electrodes into the ground to a nominal depth (0.2 to 1 m). An electric potential applied across the electrodes generates current through an electrically conductive starter path. The resultant power creates temperatures that are high enough (typically about 1700°C) to melt the starter path and the surrounding soil. As the soil melts, it encompasses the contaminated area and incorporates the radionuclides and nonvolatile hazardous elements, such as heavy metals. After the process is complete, the melted soil slowly cools, producing a vitreous mass of relatively high strength and chemical durability.

Work is currently under way to adapt the ISV technology for treatment of previously emptied and other underground tanks at Hanford and other DOE sites. For this application, a key requirement is an electrical system that can supply the power needed to vitrify a tank in a single setting. In November 1990, PNL conducted an engineering-scale test to assess the efficiency of a
six-electrode, six-phase energy supply system in melting soil. Data from this test will be applied in the development of an electrical system for underground tank vitrification. A six-phase system was chosen for the initial evaluation for the following reasons: the circular layout of the electrodes is more compatible with the geometry of the circular tanks; the energy supply system can be scaled up to 30 MW with ease; the electrode voltage is controlled by fixed taps on transformer windings or by changing the taps under load, thus avoiding the power factor and harmonic generation associated with the Scott-Tee method of power supply; the possibility of extending the electrode system to 12 phases is high; and the six-phase system may yield a more rapid heating technique than has been observed with single-phase or T-connected electrical supplies.

TEST DESCRIPTION

Equipment Configuration

The system consisted of an alternating current (ac) power supply and a cylindrical tank (8 ft high by 6 ft in diameter) containing soil and six graphite electrodes arranged hexagonally. The electrodes were placed in insulated brackets so they would drop by gravity as the test progressed. Thermocouples were installed at various locations within the tank to monitor melt rate and melt temperature. The tank was covered and vented to the building vacuum system through a HEPA filter. The soil used in this test was uncontaminated sand from the Hanford Site. Radioactive or hazardous materials were not used in this test. The test plan called for a starter path as shown in Figure 1, with current flow allowed radially between the electrodes. The starter path consisted of a mixture of 65% by volume of graphite and 35% glass powder placed in trenches that were 2-in. deep and 2-in. wide. To provide contact, each electrode was surrounded by a 1-in.-wide, 2-in.-deep band of graphite. The starter path was covered with 6 in. of soil followed by an insulating barrier of 4 in. of fiberglass wool. The delta power supply of 480 volts ac (Figure 2) does not allow neutral current in the source winding, thus yielding complete electrical isolation between the source and the electrodes. Currents can, however, flow in a variety of paths that do not involve neutral conductors, thereby generating a hotter central region due to $I^2R$ losses in the soil. There are 15 options for paths between two electrodes in the six-phase electrode system. This arrangement provides a wider variety of paths for current flow than that provided by the six paths in the T-connected, four-electrode system.

Place Figure 1 here.

Place Figure 2 here.
Power Supply System

The power supply consisted of six four-winding transformers (240, 480/120, 240 Vac) connected two in series per phase to provide 480/480 Vac, three-phase isolated secondary voltage. Each secondary winding was center tapped, with the centertaps made common. These connections yielded six conductors, each having 240 Vac to neutral, each differing in phase by 60 electrical degrees, and labeled (A+, B-) (B+, C-) and (C+, A-) for each of the six phases. These six conductors were connected to the 240-volt terminals of independently adjustable variacs, each rated 16 kVA. (Each variable voltage source consisted of two variacs connected in parallel with a series-equalizing transformer.) The variac neutrals were electrically connected to the secondary centertaps of the transformer to provide a ground for the variac and electrode assembly. The output voltage terminal of each variac was connected to an electrode in the tank.

Figure 2 shows the method used to control electrode voltage (wipers are indicated by arrows). The electrode voltages are adjusted by adjusting the variac wipers independently. This electrical interconnection of transformers and variacs provides a means of supplying electrical energy to each electrode. In contrast, the Scott-Tee connection can permit voltage differences to pairs (A-phase and B-phase) of electrodes only, and the A-phase voltage must be equal to the B-phase voltage to avoid severe power factor penalties.

In addition to avoiding the power factor problem that arises with Scott-Tee transformers, the problems of voltage waveform distortion associated with harmonic generation caused by rectifier or saturable reactor control are avoided when using the variable voltages provided by the variacs. For this test, each variac was initially set to zero.

Test Startup and Operation

To begin the test, the electrodes were inserted to 6 in. below the soil surface. Calibration marks on each electrode showed penetration depth from the soil surface. The test plan called for ramping electrode power over 3 hours from an initial value of 1 kW to 20 kW. However, this plan had to be altered after 2 hours when the starter path developed sporadic open circuits. To keep the test going, we increased selected electrode-to-neutral voltages up to 290 volts to re-establish melt paths after the open circuits appeared. Subsequent short circuits caused excessive currents (94 amps) to flow temporarily until we could adjust the variacs. Occasionally, circuit breaker operations required that the test be halted, but restarting within seconds had little adverse effect. Melted soil paths were established primarily electrode-by-electrode by increasing the voltage of the selected electrode and then controlling the current while attempting another path. After about 30 minutes, all electrode paths through melted soil were established. The problems described above may be eliminated by using a more reliable starter path.
After establishing the melt path, we ramped the electrode power to 20 kW and maintained it in the range of 20 to 25 kW. The starter path was covered with a 6-in. layer of soil and a 4-in. blanket of fiberglass wool. This insulation formed a solid cap on the melt that, although not bonded to the electrodes, held them as the melted soil subsided below the cold cap, forming a void space similar to a volcanic caldera prior to collapse. We had to tap the electrodes with a rubber mallet to free them from the cold cap so they could follow the advancing melt front. As the melt depth increased, the resistance decreased, requiring that we establish a current limit of 40 amperes per phase for the electrode conductors (#10 wire). The resistance continued to decline and, at about 15 hours into the test, the melt was inadequately powered because of the current limit. At about 28 hours, we provided a double circuit supply of #10 wire to the electrodes. This adaptation successfully increased the electrode power. At about 34 hours into the operation, the target depth of 30 in. was achieved and, as shown in Figure 3, the energy supply was shut off.

Place Figure 3 here.

ANALYSIS OF TEST RESULTS

Basis for Using Six-phase Electrode Resistance

The approximation of interelectrode resistance is based on an elementary two-electrode formula found in Stanek (1977). Although this analysis is defective, an analytically sound method yields an equation identical with equation 3.125 from page 257 of Stanek. The analytical method is the solution of problem 1 from page 79 of Panofsky and Phillips (1955). The same solution is more elegantly derived in Kreyszig (1979), page 740 in example 5. The two-electrode formula is derived by Koegler and Kindle (1990).

\[ R_i = \frac{\rho}{2\pi i} \ln \left( \frac{D_i}{d} + \frac{\sqrt{D_i^2 - d^2}}{d} - 1 \right) = \frac{\rho}{\pi i} \ln (2D_i/d), \quad i = 1, 2, 3, \quad (Eq. 1) \]

where

- \( \rho \): melt resistivity (estimated to be 1.2 m\( \Omega \) at 1600°C)
- \( \xi \): melt depth (initially 6 in. and increasing with time to 36 in.)
- \( D_i \): electrode separation (12 in. on the edge of the hexagon for \( i = 1 \))
  \( (2 \times 12 \cos 30^\circ \) on alternate electrodes for \( i = 2 \))
  \( (24 \) in. on diagonal electrodes for \( i = 3 \))
- \( d \): electrode diameter (2 in.)

The interelectrode currents follow paths delineated by \( R_i \), \( i = 1, 2 \) and 3 in Figure 4. The composite resistance between electrodes is evaluated using balanced current approximations to be
\[ R_{a-b} = \frac{1}{(1/R_1 + 1/R_2 + 1/R_3)} \]  

(Eq. 2)

The initial resistance \( R_{a-b} \) was estimated to be 2.395Ω for the 6 in. of melted Hanford soil. Assuming 25 kW of power into the melt, the three paths would require \( 3(V_{a-b})^2/R_{a-b} = 25 \text{ kW} \), which implies \( V_{a-b} = 141.3 \text{ volts} \), or approximately 71 volts electrode to neutral. The current is evaluated using \( 3(I_{a-b})^2R_{a-b} = 25 \text{ kW} \), which implies \( I_{a-b} = 58.99 \text{ amps} \). These calculations were not observable because of the limited current-carrying capacity of the electrode conductors. Consequently, reduced currents and reduced voltages prevailed until the latter part of the test. During the latter part of the test, the 28 kW circuit breaker limited the magnitude of electrode current because it would automatically trip at 28 kW. These data points, together with estimates of the melt size, yield additional approximations of the melt resistivity, an elusive parameter not well documented in the literature. The model for interelectrode resistance assumes an infinite slab approximated by a slice of melt having a finite radius. Subsidence and thermal variation contribute to increase the uncertainty in the estimate of melted soil resistivity.

Place Figure 4 here.

Study of Resistivity

The Stanek formula is an approximation for \( D>>d \) taken from the following more accurate representation shown in Equation 1 above. Here, we have chosen \( p \) as an unknown variable to be evaluated during the analysis. Using Equations 1 and 2 above,

\[ R_1 = 5.175\rho \Omega, \quad R_2 = 6.333\rho \Omega, \quad R_3 = 6.634\rho \Omega, \]

\[ R_{a-b} = 1.993\rho \Omega. \]

These are intermediate results that depend on our observed value of \( p \) to provide data for transformer design in the specification of ISV equipment.

The choice of \( p \) is motivated through the most demanding part of this engineering-scale ISV test. Ohm's Law dictates the following:

\[ I_c = (V_3-V_1)/R_1 + (V_3-V_5)/R_5 + (V_3-V_4)/R_2 + (V_3-V_4)/R_2 + (V_3-V_4)/R_3 \]

\[ = (2V_3-V_4)/R_2 + (2V_3-V_4)/R_2 + (2V_3-V_4)/R_2 + (2V_3-V_4)/R_3 \]  

(Eq. 3)

Equation 3 is derived by inspecting Figure 4, which exhibits the paths for current flow between electrodes. \( I_3 \) is the sum of the currents leaving electrode (0). Values of \( I_0, V_0, V_1, V_2, V_3, V_4 \) and \( V_5 \) were recorded during the test. Data line 7547 was chosen to be used to evaluate the resistivity for the (0) electrode labeled A" in the test.
Data: \( V_a \) (labeled A+) = 70.36°/0° volts, \( V_i \) (labeled A-) = 74.40°/60° volts, 
\( V_b \) (labeled B+) = 75.11°/120° volts, \( V_3 \) (labeled B-) = 71.62°/180° volts, 
\( V_c \) (labeled C+) = 74.77°/240° volts, \( V_5 \) (labeled C-) = 75.22°/300° volts, 
\( 2V_a - V_i - V_5 = 65.91°/0.617° \) volts, \( 2V_a - V_2 - V_4 = 215.7°/-0.078° \) volts, 
\( V_a - V_3 = 141.98 \) volts. Using \( I_a = 57.71 \) amps yields \( \rho = 1.1816 \) + j0.0015 m\( \Omega \).

The other five currents yield similar values. It is interesting to note that this result could be tuned for \( \rho = 1.2 \) by jittering \( \varepsilon \).

For this value of \( \rho \), the viscosity is such that the melted material must be a solid, a contradiction that has been resolved by Koegler in a subsequent study that assumes electrode surface resistances.

Interelectrode resistance is calculated using * with \( \varepsilon \) increasing with melt depth. This relation yields monotone decreasing parabolic behavior of the interelectrode resistance with melt depth. Since uniform energy input per unit of melt is desired, the required current/voltage relation that yields uniform energy per unit volume can be determined. Here we assume the melt is cylindrical and increases in depth linearly with time, which implies that the melt accumulates at a constant rate. The total weight of the vitrified material was 1640 lb. The total energy input was 650 kWh. The ratio gives 0.3936 kWh/lb. We melted a cylindrical volume of soil of diameter 2 ft and depth 40 in. in \( \approx 33 \) hours using the power curve shown in Figure 3. Using 156 lb/ft³, we have \( \approx 10.51 \) ft³ with a cylindrical volume of \( \pi \varepsilon \) where \( \varepsilon = 40 \) in. and \( D \) becomes the equivalent diameter = 2.004 ft, which is well within experimental accuracy. Assuming a volume of \( \pi \) swept out in each increment of time, in 33 hours \( x = 40 \) in. would be melted \( x = 40/12/33 \) ft/hr = 0.0101 ft/hr. Using 650 kWh in 33 hours or 19.697 kWh/h implies \( \approx 20 \) kW. (Initially, \( \varepsilon = 6 \) in. and terminally, \( \varepsilon = 40 \) in. Consequently, \( R_{a+b} = 2.395 \Omega \) initially and 2.395 x 6/40 = 0.3592\( \Omega \) terminally.)

Thermal Characteristics of the Test

The locations of the thermocouples in the tank were shown previously in Figure 1. Table 1 provides temperature data for the test. Thermocouple #1 melted first, followed by thermocouples 9, 10, 3, 4, 11, 5, and 2. In this test, 6 in. of cover soil was placed on top of the starter path. The soil was then covered with an insulating barrier of 4 in. of fiberglass wool. Since the fiberglass wool did not melt during the test, the heat was generally confined to the soil.
Energy Input and Melt Shape

At about 5 hours after startup, we shut off the power and tapped the electrodes to force them to the bottom of the melt. We did not make any additional attempts to position the electrodes until 18 hours into the test. From that time on we tamped the electrodes at 1-hour intervals until the end of the test. At 28 hours, we switched to the double-circuit power supply, which significantly increased the electrode power (see Figure 3).

After the melt block cooled, we obtained measurements at 2-in. intervals along the block. As shown in Figure 5 and listed in Table 2, bulges appear at the subsidence line 24 and 16 in. from the bottom of the block, with a more narrow section 20 in. from the bottom. Although we expected that the electrodes would protrude from the bottom of the melt, they are in the melt, indicating that the assembly and the cold cap held the electrodes, allowing the underlying soil to melt. It appears that the increased electrode energy in the final hours of the test contributed to the increased depth of melt.

Table I. Temperature Data for this Test

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Type</th>
<th>Depth of Thermocouple (in.)</th>
<th>Horizontal Distance from Vertical Centerline (in.)</th>
<th>Time to Obtain 1000°C (hours after start of test)</th>
<th>Temperature Reached</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(a)(c)</td>
<td>K</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>1000°C</td>
</tr>
<tr>
<td>2(b)</td>
<td>K</td>
<td>30</td>
<td>0</td>
<td>29</td>
<td>1000°C</td>
</tr>
<tr>
<td>3(c)</td>
<td>K</td>
<td>18</td>
<td>6</td>
<td>17</td>
<td>1000°C</td>
</tr>
<tr>
<td>4(c)</td>
<td>K</td>
<td>18</td>
<td>9</td>
<td>18</td>
<td>1000°C</td>
</tr>
<tr>
<td>5(c)</td>
<td>K</td>
<td>18</td>
<td>12</td>
<td>20</td>
<td>1000°C</td>
</tr>
<tr>
<td>6(c)(d)(e)</td>
<td>K</td>
<td>18</td>
<td>15</td>
<td>20</td>
<td>880°C</td>
</tr>
<tr>
<td>7(c)(d)</td>
<td>K</td>
<td>18</td>
<td>18</td>
<td>13</td>
<td>480°C</td>
</tr>
<tr>
<td>8(c)(d)</td>
<td>K</td>
<td>18</td>
<td>21</td>
<td>23</td>
<td>240°C</td>
</tr>
<tr>
<td>9(c)</td>
<td>C</td>
<td>12</td>
<td>0</td>
<td>13</td>
<td>1676°C</td>
</tr>
<tr>
<td>10(c)</td>
<td>C</td>
<td>18</td>
<td>0</td>
<td>23</td>
<td>1634°C</td>
</tr>
</tbody>
</table>

1605°C

(a) For this thermocouple, the soil cover and fiberglass wool barrier formed a cold cap over the melt that became an air chamber as the melt subsided.

(b) This thermocouple was located in an aggregate material less capable of holding moisture; thus, data for the 100°C latent heat of vaporization are barely discernible.

(c) These thermocouples showed the plateau for the 100°C latent heat of vaporization.

(d) Thermocouple did not melt.

(e) Subsided to ambient temperature after reaching 880°C.
Table II. Dimensions of Vitrified Block

<table>
<thead>
<tr>
<th>Diameter (in.)</th>
<th>Distance from Bottom of Block (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>33.4</td>
</tr>
<tr>
<td>20</td>
<td>31.8</td>
</tr>
<tr>
<td>16</td>
<td>33.1</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This engineering-scale test ran for 34 hours, producing a 743.9-kg (1640-lb) vitrified block with 650 kWh of energy. This product/power ratio indicates that the six-phase system provides a more efficient method of heating. Additional conclusions follow:

- A six-phase, six-electrode ISV system looks feasible and should be considered for scaleup to larger systems. The melt produced a circular form, with little lateral spreading outside the electrodes.

- The use of multiple starter paths for current in the six-phase system improved the efficiency of the melt.

- The six-phase system avoids the power factor and harmonic generation associated with Scott-Tee transformers.

- The test configuration provided currents and voltages that were used to calculate resistivity (see Appendix A of Richardson 1991). The resulting value is in agreement with values determined in other ISV tests, and corroborates the use of this parameter in scaleup calculations.

In this test, initializing the melt path presented difficulties that could be countered by using a different material (i.e., nichrome wire) to establish the path, or by providing a greater number of starter paths in parallel. Initialization of the test appeared to be limited by the available voltage. Increasing the voltage capability by 20% or more may solve this problem. The final hours of the test were affected by current limitations; however, adequate current-carrying capability was easily supplied without stopping the test.

REFERENCES


FIGURE 1. Electrode and Thermocouple Configuration in the Test Tank
FIGURE 2. Phase Connections for the Electrical Configuration
FIGURE 3. Total Power Input as a Function of Time

FIGURE 5. Vitrified Block Produced by this Test