IN SITU VITRIFICATION: APPLICATION ANALYSIS
FOR STABILIZATION OF TRANSURANIC WASTE

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SUMMARY

Pacific Northwest Laboratory (PNL) is developing the in situ vitrification process for in-ground solidification of radioactive waste. The In Situ Vitrification Program, sponsored by the Department of Energy--Richland Operation Office (DOE-RL), began in fiscal year 1981. The process builds upon the electric melter technology previously developed for high-level waste immobilization. In situ vitrification converts buried wastes and contaminated soil to an extremely durable glass and crystalline waste form by melting the materials, in place, using joule heating. Once the waste materials have been solidified, the high integrity waste form should not cause future ground subsidence. Environmental transport of the waste due to water or wind erosion, and plant or animal intrusion, is minimized.

Environmental studies are currently being conducted to determine whether additional stabilization is required for certain in-ground transuranic waste sites. Since high cost and potential worker exposure are associated with waste exhumation, processing for certification, and placement in a geological repository, in-situ methods may be adequate for permanent stabilization of those waste sites that require additional treatment.

An applications analysis has been performed in support of the National Transuranic Waste Management Program to identify several in situ vitrification process limitations which may exist at transuranic waste sites. Potential limitations due to waste geometry, soil property variations, waste inclusions within the soil, and criticality were evaluated. Certain process attributes which will affect the final selection of an in-situ process were also evaluated, including economics, worker exposure, and product durability.

Based on the process limit analysis, in situ vitrification is well suited for solidification of most in-ground transuranic wastes. The process is best suited for liquid disposal sites, which account for over 80 volume percent of the total transuranic waste inventory (U.S. DOE 1981a and 1982a). Many non-retrievable solid burial sites and selected retrievable sites also appear to

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be within the limits of the process. A site-specific performance analysis, based on safety, health, environmental, and economic assessments, will be required to determine for which sites in situ vitrification is an acceptable disposal technique.

Process economics of in situ vitrification compare favorably with other in-situ solidification processes and are an order of magnitude less than the costs for exhumation and disposal in a repository. Leachability of the vitrified product compares closely with that of pyrex glass and is significantly better than granite, marble, or bottle glass. Total release to the environment from a vitrified waste site is estimated to be less than 10^{-5} parts per year.

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INTRODUCTION

Transuranic (TRU) wastes have been generated in the U.S. since the early 1940's. The current inventory consists of 0.4 to 2.9 million m³ at shallow land burial sites, 2 to 12 million m³ at aqueous disposal sites, and 62,150 m³ which, since 1970, has been placed in 20-year retrievable storage. Environmental studies are currently being conducted to determine whether additional stabilization is required for certain pre-1970 TRU waste sites. Due to the high cost and potential worker exposure associated with retrieval, processing, and disposal in a repository (Murphy and Holter 1980), in-situ processes may be adequate for permanent stabilization of those waste sites that require additional treatment.

Pacific Northwest Laboratory (PNL) is developing the process of in situ vitrification (ISV) for solidification of radioactive waste. The process converts buried waste to an extremely durable glass and crystalline material by melting the waste and surrounding soil in place (Brouns and Timmerman 1982). Once a waste site is solidified, the high integrity waste form should not cause future ground subsidence. Environmental transport of the waste, by wind or water erosion, and plant or animal intrusion, is minimized.

In situ vitrification can be used to complement a deep geological repository in achieving permanent disposal of selected TRU wastes. A site-specific performance analysis will be required to determine whether additional stabilization is required and whether ISV is the proper stabilization method.

Solidification of buried waste and surrounding contaminated soil is achieved by establishing an electric current between electrodes inserted in the soil. Figure 1 illustrates the process operating sequence. For startup, a small amount of a specially prepared graphite and frit mixture is placed between the electrodes on the surface soil. Dissipation of power through the starter material creates temperatures high enough to melt a layer of soil, thereby establishing a molten, conductive path. This molten zone continues to grow and encompasses the waste site as long as sufficient power is supplied to overcome heat losses. A hood over the site is maintained at a slightly negative pressure to contain any gas or particulate which may be released.

FIGURE 1. In Situ Vitrification Operating Sequence.

Two scales of nonradioactive ISV experiments have been utilized for process demonstration and development. An engineering-scale laboratory test unit, which uses two electrodes with a 36 cm spacing, has typically solidified 45 kg of soil per test. A pilot-scale field test system, which uses four electrodes in a 1.2 m square pattern, has successfully solidified up to 10,000 kg of soil, a scale-up of approximately 200.

This report includes documentation of the studies that were conducted at PNL to determine the feasibility of solidifying TRU waste sites using ISV. Potential limitations to the ISV process were identified and evaluated using calculations, mathematical models, available literature, laboratory measurements and ISV experiments.

The process applicability to actual TRU waste was evaluated based on the limits which were identified. In excess of 97 vol% of TRU waste in the United States is believed to be in a form which is processable by ISV, although not all waste will require additional stabilization. Also evaluated were process attributes which will affect the final selection of a stabilization process for TRU waste sites. A preliminary analysis of process economics, operator exposure and product durability is discussed. The 216-Z-12 crib at Hanford was used to illustrate how the ISV process might be applied to an actual TRU reference site.

PROCESS LIMIT ANALYSIS

PROCESS LIMIT ANALYSIS

Several potential limits to the in situ vitrification (ISV) process were identified and evaluated to predict the feasibility of using ISV at different TRU waste sites. The potential limits identified are geometry, soil variations, foreign material soil inclusions, and criticality. The extent of these potential limits has been evaluated based on calculations, modeling studies, laboratory measurements, literature, and actual ISV experiments. In this section, the potential limits are defined, and their methods of evaluation are described.

A reference full-scale ISV system has been defined and is used as the basis for application limit analysis in this report. The reference system, which is based on use of conventional equipment, has four electrodes in a square pattern and is powered by a 3000 kW, 4160 V source (1500 kW per diagonal electrode pair). Selection of the power rating was based on the largest commercially available portable generators. Larger ISV power systems are possible if the waste site to be stabilized is reasonably close to a 4160 V substation (within ~10 km transmission distance).

The reference process off-gas system capacity has been calculated using data from nonradioactive pilot-scale field tests in which soil without waste inclusions was vitrified. The pilot-scale process has 4 electrodes in a 1.2 m square pattern and is powered by a 400 kW, 960 V source.

The required off-gas flow is directly proportional to the hood perimeter distance and is inversely proportional to the amount of soil which is placed around the perimeter to form a seal. The scale-up factor used to predict the reference process off-gas system capacity is 4.33, the voltage ratio of the pilot and full scale power systems (4160/960). Voltage determines the possible electrode separation, and electrode separation determines hood perimeter distance. The pilot-scale ISV off-gas system requires a flow of from 8 to 12 std m³/min to maintain a negative pressure within the containment hood of greater

than 1.3 cm (0.5 in.) water column. Using the scale-up factor, the corresponding off-gas system capacity for a full-scale ISV process would range from 35 to 52 std m³/min. The reference off-gas system capacity is set at 50 std m³/min, which is a conservative value since the integrity of the soil seal around a full-scale radioactive ISV system hood would be greater than that used during pilot-scale tests.

GEOMETRY

Physical geometries of TRU contaminated waste sites range from wide, shallow zones (e.g., ponds) to narrow deep zones (e.g., bore shafts). The zone which an ISV process can vitrify in one operation has certain width and depth limits imposed by the maximum voltage and power level available. A mathematical model was developed to predict the geometric limitations of the reference full-scale ISV system.

Mathematical Model

The mathematical model is based on an isothermal, rectangular block of molten Hanford soil, with constant length and width. As energy is dissipated into the vitrified zone during each of a series of time steps, the model calculates the heat losses through the exposed upper surface and into the surrounding soil. The remaining energy is expended melting soil in the downward direction. The actual vitrification process observed during field tests is similar to this description. Although field tests have demonstrated some outward growth of the vitrified zone during processing, the majority of the vitrification takes place in the downward direction. While heat losses from the top surface are dependent on processing conditions (e.g., the presence of a cold cap), the surface heat losses incorporated into the model are kept near the top of the range measured. This conservatism assures that the geometric limitations determined by the model are feasible.

The mathematical model calculates heat losses into the soil from a constant heat flux value determined from field test data. Using an average

thermal conductivity of $0.20 \text{ W/m}^\circ\text{K}$, the heat flux for various thermal gradients ranged from 2.3 to 3.2 kW/m^2 . The maximum value, 3.2 kW/m^2 , was conservatively selected as the heat flux term for heat losses into the surrounding soil. Based on a measured nominal surface temperature of 570°C , the heat flux through the top surface was calculated mathematically to be 32 kW/m^2 . This value agrees with actual pilot scale test data and was selected as the surface heat flux term for the model.

The results of the mathematical model were compared to the operational characteristics of the first field test. Figures 2 and 3 show the power and electrical resistance curves, respectively, predicted by the model and those measured during the field test. The model very nearly predicts the behavior of the actual case.

FIGURE 2. Predicted and Measured Operating Parameters for Field Test 1

FIGURE 3. Predicted and Measured Electrical Resistance for Field Test 1

Full-Scale Mathematical Predictions

Since the model results agreed well with field test data, the model was then available to predict the geometric limitation of the reference full-scale system. The major control variables were electrode separation and transformer voltage taps.

Since resistance between electrode pairs drops as the vitrified zone grows, the ISV system is based on a power transformer having five voltage taps ranging from 4160 V and 360 A per electrode pair, for startup, down to 400 V and 3750 A per electrode pair. Typical voltage taps one might select for wide and narrow electrode separations are shown in Table 1. In the model, tap changes were made whenever the heat losses were greater than 50% of the net power generated. Run termination was assumed at the end of the fifth tap change, when the net power available for melting had dropped to less than 50% of the total heat losses.

Findings of the modeling studies showed that as electrode separation is decreased, the melt zone depth can be increased. In fact, the reference ISV

TABLE 1. Typical Voltage Taps for 3.5 and 5.5 Meter Electrode Separations^(a)

Tap No.	3.5 m Electrode Separation		5.5 m Electrode Separation	
	Voltage	Maximum Current ^(b) , A	Voltage	Maximum Current ^(b) , A
1	4160	360	4160	360
2	2000	750	2800	540
3	1000	1500	2100	710
4	580	2590	1500	1000
5	400	3750	1000	1500

(a) Electrode separation on a side for a four-electrode square array

(b) Current limit per electrode pair for a 3000 kW power supply

system with electrodes separated 3.5 m on a side can vitrify to a depth of 13.5 m. The calculations are based on Hanford soil with a void fraction of 0.34. However, if collapsible or consumable wastes exist, even greater depths would be obtained. Figure 4 gives a relationship of attainable melt depth as a function of electrode separation for the reference system in Hanford soil. An absolute upper limit of 6.7 m electrode separation is the point where power input equals the top surface heat loss. The practical limit is approximately 5.5 m to achieve a reasonable depth of 3 m. The lower practical limit of 3.5 m separation is determined by the lowest available voltage tap for the power supply.

Figure 5 shows the required startup voltage as a function of electrode separation. The plot was calculated using the one-dimensional model after being calibrated with data from the two-electrode, engineering-scale test unit. The data point for the four-electrode, pilot-scale test unit is the average for the first three tests. The actual startup voltage is lower than predicted, primarily because of the effect of the graphite starter material. Extra graphite can be added to reduce the magnitude of the startup voltage, if necessary.

A Hanford reference crib (216-Z-12) described by Kasper (1981) has been used to demonstrate the range of ISV geometrical configurations. Based on the criterion of solidifying all soil having plutonium concentrations greater than

FIGURE 4. Electrode Separation Versus Total Melt Depth for a Reference Full-Scale ISV System in Hanford Soil

10 nCi/g, the required melt depth for the reference crib is 7.5 m. Figure 6 shows that the plutonium plume beneath the crib bottom extends to an overall width of 11.7 m, according to well log samples, and that the plume is approximately 82 m long (Figure 7). Further testing is required to determine activity near the diversion box and drain entrance. To determine whether the contaminated zone could be easily vitrified without preliminary excavation of the uncontaminated surface layer, the mathematical model was used to determine the optimum electrode separation and voltage taps. These case studies were

FIGURE 5. In Situ Vittrification Scale-Up Correlations for Startup

performed after the mathematical model had been calibrated to existing field test data. Another case, involving excavation of uncontaminated surface soil prior to ISV, was studied for comparison.

An ISV system with an electrode separation of 4.4 m would attain the 7.5 m depth requirement for the reference crib. However, based on the 11.7 m width, a more practical selection would be a larger power system or three sets of side-by-side operations with a system having an electrode separation of 3.5 m. This will allow a 0.5 m overlap between each vitrified block and a 0.5 m buffer zone on either side of the contaminated zone. The edge of the

FIGURE 6. Cross Section View of Reference TRU Crib for In Situ Vitrification (216-Z-12 at Hanford)

FIGURE 7. Elevation View of Reference TRU Crib for In Situ Vitrification (216-Z-12 at Hanford)

vitified zone is not bounded by the electrode location, but extends beyond the electrodes to a width approximately 1.25 times larger than the electrode separation. However, if 4 m of uncontaminated soil is excavated, two sets of side-by-side operations with a 5.3 m electrode separation could be used just as effectively.

The time required to vitrify the 8.0 m depth (which includes a 0.5 m buffer zone) for each ISV operation at a 3.5 m electrode separation, as predicted by the model, is approximately 110 h. The required voltage taps would be 4160 V, 2000 V, 1000 V, and 580 V. A lower (400 V) voltage tap would still be available if extra depth were desired. The overall energy requirements are 0.93 kWh/kg. This approaches the maximum energy consumption efficiency predicted for all cases. Greater depths can be obtained for each electrode separation at the expense of decreased energy efficiency. If 4 m of soil is excavated, the time required for each process at a 5.3 m electrode spacing, would be 72 h to reach a depth of 3.5 m (below excavation). The required voltage taps would be 4160 V, 2600 V, 1800 V, 1300 V and 1000 V. A maximum depth of 5 m could be obtained in 98 h at this wider electrode separation if so desired.

Conclusions

Mathematical predictions have shown that the 3000 kW reference in situ vitrification system can attain depths as great as 13.5 m. The practical operating range for the reference system is an electrode separation of 3.5 to 5.5 m with attainable melt depths of 13.5 and 3.0 m, respectively. These limits could be expanded by using unconventional power supplies larger than 3000 kW or voltage taps lower than 400 V.

SOIL VARIATIONS

In situ vitrification has been successfully demonstrated in tests melting up to 10,000 kg of Hanford soil. Since soil properties vary between waste sites, it is necessary to evaluate potential process limitations due to soil characteristics. The following soil properties are most important to the process:

- fusion temperature
- specific heat
- thermal conductivity
- electrical conductivity
- moisture content.

The fusion temperature, specific heat, and electrical conductivity are dependent on the soil composition. Thermal conductivity is dependent on both composition and soil morphology (e.g., particle size distribution and bulk density). Moisture content depends on climatic and hydrologic conditions at the specific site. These soil properties were obtained from literature surveys and laboratory characterization tests on soil from Barnwell, South Carolina; Hanford, Washington; Idaho National Engineering Laboratories (INEL), Idaho; Los Alamos National Laboratory (LANL), New Mexico; Maxey Flats, Kentucky; Nevada Test Site (NTS), Nevada; Oak Ridge National Laboratory (ORNL), Tennessee; Sheffield, Illinois; and West Valley, New York.

Fusion Temperature

The temperature at which soil begins to fuse and form a glass was measured using soil from NTS, Maxey Flats and West Valley. Approximate fusion temperatures of the other soils were calculated by comparing their $\text{SiO}_2 + \text{Al}_2\text{O}_3$, $\text{K}_2\text{O} + \text{Na}_2\text{O}$, and $\text{CaO} + \text{MgO}$ levels with those of the three previously measured soils. The measured and calculated fusion points are listed in Table 2. Fusion temperatures for all soils tested ranged from 1100 to 1400°C. Glass temperatures observed during pilot-scale tests have exceeded 1700°C, well above the fusion point. Fusion temperatures of the soils tested are too low to impose any process limit.

Specific Heat

Soil specific heat is important in determining the power required to melt the soil. A high specific heat would increase the electrical power costs by increasing the energy needed to heat the soil and by slowing the rate of vitrification. Heat losses become larger as the total time required to reach the desired melt depth increases.

TABLE 2. Approximate Soil Fusion Temperature

<u>Soil Location</u>	<u>Soil Type</u>	<u>Fusion Temperature, °C</u>
Barnwell, SC	Fuquay	1400 ^(b)
Hanford, WA	(a)	1100 ^(b)
INEL, ID	(a)	1100 ^(b)
LANL, NM	Puye/Carjo	1100/1200 ^(b)
Maxey Flats, KY	Tilsit	1300
NTS, NV	Beatty	1100-1200
ORNL, TN	(a)	1100 ^(b)
Sheffield, IL	Fayette	1100 ^(b)
West Valley, NY	Churchville	1100

(a) Soil type not identified

(b) Fusion Temperature estimated from soil composition

The specific heats (C_p) of the soils from the different sites were measured at temperatures of 150 to 550°C using differential scanning calorimetry. Most soils had C_p values in the range of 0.17 to 0.22 cal/g°C. Soil from Maxey Flats was higher at 0.24 to 0.27 cal/g°C. These values are consistent with those found for other ceramic materials (Norton 1968). At higher temperatures (1500°C), the specific heat increases, to 0.25 to 0.28 cal/g°C for most soils. The variation in heat capacities is not considered a process limit.

Thermal Conductivity

Soil thermal conductivity variations can influence the maximum temperature reached by the molten zone and the rate at which heat energy can be transferred to the unmelted soil. A lower thermal conductivity will result in a higher molten zone temperature for a given rate of melt propagation. Thermal conductivity variations within the molten zone will not significantly affect the temperature profile since convective mixing produces a relatively flat temperature profile. Thermal conductivity has its main effect at the boundary layer between the soil fusion zone and soil at ambient temperature.

Thermal conductivity of the soils at ambient temperature is very low, ranging from 0.09 to 0.16 W/m²K. This low conductivity results from the small particle sizes present in the majority of the soils, which increase grain-to-grain contact resistance. Conduction by the gas phase is low because of the extremely small effective pore size in these materials. Because of the small size, convection is eliminated, and conduction within pores is effectively reduced (Parrott and Stuckes 1975). Soils which contained rocks and pebbles, such as those from Hanford and NTS, had higher conductivities. This was expected, as conduction through the solid rocks and pebbles is much higher than through the porous, fine-grained soil.

All soils showed an approximate doubling of conductivity when heated from 200 to 800°C. Figure 8 shows thermal conductivity as a function of temperature for NTS, Maxey Flats and West Valley soils. The rise, below 800°C, is due to an increase in conductivity of the porous phase, plus an increasing contribution of radiant heat transfer as the soil is heated. The large increase in conductivity above 800°C is caused by a larger contribution by radiant heat transfer, and a decrease in grain-to-grain contact resistance due to the onset of soil fusion. The slight variation observed between soil thermal conductivities may result in different ISV operating temperatures; however, no limits would be imposed by the soils evaluated.

Electrical Conductivity

Variations in the electrical conductivities of molten soils will affect the operating voltage of an ISV system. Low-conductance soils may limit the attainable electrode separation if the soil voltage required during startup exceeds the available supply voltage. The reference full-scale ISV system has a maximum supply voltage of 4160 V, which is the limit available from most electrical substations.

Six soils, containing the widest variation in oxides that affect electrical conductivity, were chosen for measurement using the two-probe method. Due to the high melting temperatures of the soils, approximately 10 wt% Na₂O was added to each sample to reduce the melting time and temperature. The measured conductivities, corrected for the Na₂O addition, are shown in Figure 9. The

FIGURE 8. Thermal Conductivities of Selected Soils as a Function of Temperature

soil with the lowest conductivity, West Valley (95–158 cm), contains average amounts of Na_2O and K_2O , which increase electrical conductivity; but it is high in CaO and MgO , which have the greatest effect on decreasing electrical conductivity (Stanek 1977). The soil with highest electrical conductivity, LANL, is high in alkali but low in CaO and MgO . Based on comparison of soil compositions, all other soils in this study are expected to fall within the range shown in Figure 9.

At 1400°C , which is above the fusion point for the soils tested, the electrical conductivities varied only between 3×10^{-2} and $5 \times 10^{-2} (\text{ohm-cm})^{-1}$.

FIGURE 9. Electrical Conductivities of Molten Soil

This slight variation does not impose a limit on the ISV process. Such low variations in soil electrical conductivity can easily be compensated for by modification of the startup technique. The ISV voltage during startup is dependent on the graphite-frit startup mixture, not on soil conductivity. Once the graphite startup material has burned, the voltage reaches its maximum, which is dependent on the cross-sectional area and conductivity of the molten

path. Beyond this point, voltage decreases as the molten zone expands. If the maximum startup voltage exceeds the supply voltage because of a low soil conductivity, the startup voltage can be lowered by increasing the width and depth of the graphite-frit path and by choosing a frit which is highly conductive. These actions will increase the cross-sectional area of the molten path and increase the glass conductivity in that path, thus decreasing the maximum voltage during the startup period.

Moisture Content

Although it has been shown that differences in soil properties throughout the U.S. at various waste sites are small, differences in moisture content between certain sites are large. As an example, soil at Hanford is very dry while ORNL soil is extremely wet. In situ vitrification of moist soil sites may require a significant amount of the additional energy just to evaporate the water. This added heat load decreases the amount of energy available for melting, which lowers the soil melting rate and may decrease the maximum depth attainable by ISV.

Factors which influence the level of moisture in a particular soil are water table depth, climatic events, and soil hydraulic properties. The factor which has the largest effect on ISV is the water table depth. The water table is the upper surface of the water-saturated zone when the aquifer is unconfined. The degree of saturation can range from 10% to 60%, depending on the soil porosity. Additional power is required to vitrify waste disposed of below the water table since water may continue to flow into the area being vitrified. Engineered barriers or water wells could be used to artificially lower the water table and reduce water inflow during an ISV operation.

The climatic events, soil water potential, and soil hydraulic conductivity at saturation are responsible for the soil moisture content above the water table. The volume of precipitation, in part, controls the rate at which water is added to the soil, while soil characteristics determine the conductance of water through the waste site. The volume of bonded water in soil is also somewhat dependent on the rate of drainage.

Water can actually accumulate in a burial trench, even though the trench is located well above the water table. The permeability of the disturbed soil

placed over the waste site is typically much higher than that of the surrounding undisturbed soil. Buried waste, with its irregularities and void space, further increases the waste site permeability. Incoming precipitation can accumulate at the bottom of the trench, becoming ponded above the actual water table, since water drains through the excavated waste area faster than the drainage rate from the waste to the undisturbed soil. Ponded water may exist in TRU waste trench bottoms at sites like ORNL or SRP which receive high annual rainfall. In large waste trenches with relatively impermeable soil surrounding the trench, ponded water will increase the required power input for ISV as it does when waste is buried at depths below the water table.

Of the five major national TRU sites, INEL, ORNL and SRP have relatively high soil moisture levels. Hanford soil is relatively dry because of the deep regional water table and low annual rainfall. Los Alamos also has relatively dry soil because of the deep water table and hilly terrain conducive to surface water runoff.

Limitations to ISV imposed by soil moisture are most probable at ORNL, which has trenches excavated to depths below the water table. Trenches at ORNL are typically 2.1 to 4.3 m deep, and the depth to the water table ranges from ground level to 4.6 m, depending on location and season (Webster 1979). A burial-ground scenario was used to evaluate potential moisture limitations to the ISV process under extreme conditions at ORNL. The burial trench used in the scenario was excavated to a depth of 4.3 m in an area with the water table at ground level and a highly permeable sandy layer below 6.4 m deep (see Figure 10). Water permeability for ORNL soil is recorded as 3.0 cm/d, with a 3.1 cm/d standard deviation (Luxmoore, Spalding and Monroe 1981). Soil in the upper 6.4 m is conservatively assumed to have a porosity of 57% and a permeability of 6.1 cm/d. The sandy area below 6.4 m is assumed to have a high permeability of 500 cm/d.

The mathematical model developed to evaluate geometric limitations was used to determine the maximum depth attainable for ISV in the scenario. Changes were made to the model to account for the increased power needed to evaporate water already present and water which continues to flow into the vitrification area because of the hydraulic head, H_f (Figure 10). The model

FIGURE 10. Burial-Ground Scenario for ISV Moisture Limitations Analysis

simulations are based on saturated ORNL soil (0.93 g/cm^3 dry bulk density), ISV glass density of 2.5 g/cm^3 , and five voltage tap changes on a 4160 V reference power system.

The maximum depth attainable for various electrode spacings and soil moisture conditions is shown in Figure 11. In situ vitrification can effectively solidify soil to the trench bottom with an electrode spacing of 4.3 m or less on a side for the worst-case moisture model. The primary depth limitation is imposed by the aquifer depth. Based on model predictions shown in Figure 11, moisture levels will not limit the ISV process at ORNL, provided that TRU levels of contamination are at least 5 m above any permeable sandy areas.

Waste burial sites at INEL and SRP are above the water table. However, because of rainfall at SRP and snow runoff at INEL, there is a possibility of seasonal ponded water in burial trenches at these two sites. Using the water-saturated soil curve in Figure 11 as a worst-case approximation, the maximum depth attainable per given electrode spacing is decreased by less than 1 m at

FIGURE 11. Maximum ISV Depth for Dry and Saturated ORNL Soils

electrode separations of 3.5 to 4.5 m. However, for a given melt depth, the time required to vitrify a moist site is longer than that required for "dry" soil. Figure 12 shows the effect of ORNL soil moisture on the vitrification rate for different electrode spacings.

It should be noted that Figure 12 only applies to the worst-case moisture scenario (Figure 10). Records of trench water levels at SRP have shown minute volumes of ponded water in the trenches (Horton 1975). While this will affect the maximum vitrification depth attainable for a given electrode spacing, the effect should be almost negligible since the water table is not in the waste site. The same can be said for INEL waste sites.

FIGURE 12. Effect of ORNL Soil Moisture Content on Vittrification Rate

Conclusions

Soil properties from nine different waste sites show little variation. The soil properties important to operation of the ISV process (fusion temperature, specific heat, thermal conductivity and electrical conductivity) are similar to those of Hanford soils. In situ vitrification has been successfully demonstrated in engineering-scale and pilot-scale tests on Hanford soils. Based on the soil samples tested, the process appears feasible at other sites as well.

Fusion temperature of the soils ranged from 1100 to 1400°C, well below the 1700°C (plus) temperatures typically reached in the ISV melt zone. Heat capacities varied less than 23% between the soils, and thermal and electrical conductivities varied by less than 60%. Little if any design changes are

needed to accommodate the property variations expected among soils. Soils with low electrical conductivities may require a power transformer with higher voltage taps.

Water table level can affect the attainable depth of the ISV process. A portion of the available power is required to vaporize moisture in the soil and to continually evaporate moisture which flows into the vitrification hot zone. A mathematical model, based on a 100% moisture content profile at ORNL (water table at ground level), predicts that the melt depth is reduced by less than 1 m for homogeneous soil. Electrical power consumption, however, increases by 32%. Moisture limitations become more prominent as the melt zone approaches a highly permeable region. A permeable sandy zone, located 6.4 m below ground level in ORNL soil, will limit the ISV process to a maximum melt depth of 5.3 m, which is still quite deep.

SOIL INCLUSIONS

Transuranic waste sites typically contain buried inclusions within the soil which may affect the ISV process. Liquid disposal sites often contain wood or concrete cribs, ceramic French drains and tile fields. Solid-waste burial grounds incorporate a large quantity and wider variety of wastes, such as metal drums and process components, combustibles, concrete monoliths, and other wastes. These soil inclusions have been divided into four general categories: metals, cements and ceramics, combustibles, and explosives. Predicted effects and limits of each waste type on the ISV process are discussed in the following sections.

Metals

Metal, which has a much higher electrical conductivity than molten soil, can decrease electrode voltage when present during ISV, and in extreme cases can result in a short circuit. A mathematical model and a series of four engineering-scale ISV tests were used to evaluate the actual effect which metals would have on the process.

The ISV metal inclusion model is based on a two-electrode system. Figure 13 shows the physical model with the metal resting at the bottom of the

FIGURE 13. ISV Metal Inclusion Model

melt in Zone 2. Zone 1 is the high-temperature glass area in which the mean temperature is $\sim 1700^{\circ}\text{C}$, while Zone 2 is the cooler leading edge of the melt zone. As the melt grows and proceeds downward through a metal object, the metal will melt and settle in the cooler Zone 2 area, resolidifying if temperatures are below the metals melting point (1565°C for carbon steel and 1420 to 1500°C for stainless steel).

The metal inclusion model was used to evaluate the effect of varying Zone 1 height, Zone 2 height, metal width and metal volume on the electrode voltage, power and power density. The model was found to correlate quite well with test data when no metal was present.

Figure 14 shows the effect of the metal width as a fraction of the electrode spacing (M/L) on power and voltage for a pilot-scale electrode pair. As the M/L ratio increases, the power and voltage decline gradually until the

FIGURE 14. Effect of Metal Width on Power and Electrode Potential

metal approaches the electrodes and a short circuit occurs. The power distributions as a function of M/L are shown in Figure 15. As the metal path increases between electrodes, hot spots form in the melt between the metal and electrodes in Zone 2. A cold spot is likely to form above the metal in Zone 1 if convective currents are insufficient in the molten glass. The result may be an increased cold cap.

The model also predicts that varying the mass of metal in the soil has essentially no effect on power input and electrode voltage for a given metal width. The power and voltage decrease by less than 0.1% when the metallic mass is increased by a factor of ten for a given M/L ratio, according to the model.

Four engineering-scale laboratory tests, ESLT-10 through ESLT-13, were performed to verify the effects of metal inclusions on the ISV process. Summaries of each test are given in Table 3. The quantity of metal placed in the soil ranged from 2 to 5% of the final vitrified block weight. Each test

FIGURE 15. Effect of Metal Width on Power Distribution

TABLE 3. Summary of Engineering-Scale Laboratory Tests Containing Metal Inclusions

Test Parameter	Test Number			
	ESLT-10	ESLT-11	ESLT-12	ESLT-13
Power Limit (kW)	7	7	10	10
Metal Mass (kg)	1.5	0.9	2.4	1.2
Metal Loading (wt%)	3	2	5	2
Electrode Spacing Fraction Occupied by metal (M/L)	0.35	0.35	0.71	0.35
Combustible Mass (kg)	0	0.2	0	0
Run Time (h)	13	12	11	9
Total Energy (kWh)	78	69	68	83
Average Power (kW)	6	6	6	9
Mass Solidified (kg)	47	46	49	63
Energy/Mass (kWh/kg)	1.6	1.5	1.4	1.3

proceeded to completion with no major difficulties. In ESLT-12, a stainless steel and a carbon steel canister, each containing metal scrap of the same composition, were placed edge to edge occupying 71% of the distance between electrodes. To complete the test, it was necessary to increase the power limit from 7 to 10 kW. This may have been due to the heat-fin effect of the metal which increased heat losses to the soil.

Figure 16 shows the effect of metallic inclusions as predicted by the model compared to actual data from the engineering scale ISV system. The model predicts a larger effect due to the metal inclusion than was actually observed. At a metal-width-to-electrode-spacing ratio (M/L) of 0.7, engineering tests showed a voltage drop of 21%. This effect means that the lowest voltage tap of the power transformer should be designed 21% lower than normal to achieve the same power input level during an ISV operation.

FIGURE 16. Experimental and Predicted Voltage Drop Due to a Metallic Inclusion

Cements and Ceramics

Unlike metals, cement and ceramic waste inclusions do not have high enough electrical conductivities relative to the soil to create a short circuit limitation. Instead, they are usually in the oxide form and are very similar to many of the compounds found naturally in soil. The volume of cement and ceramic waste inclusions is very small compared to combustible and metallic waste. These wastes include large concrete casks used to contain industrial wastes at most TRU sites, cement paste in corrugated metal pipes at LANL, and concrete cribs and vitrified clay French drains at Hanford. Because almost all buried nonmetallic materials are some form of cement product, concrete waste inclusions are analyzed most extensively in this section, although other ceramic materials will also be discussed.

Cement can be defined as an adhesive complex of nonmetallic oxides, with lime (CaO) as the primary constituent. Hardened cement contains up to 33.3 wt% (20 wt% average) water which acts as the adhesive for the complexed oxides (Lea 1971). Concrete contains less water (~5%) because of the high volume of sand and gravel present. During in situ vitrification of soil containing cement or concrete inclusions, a number of events may occur:

1. A decreased electrical and thermal conductivity in the cement may cause the electrical joule heating in the melt to either bypass the inclusion, leaving the concrete unmelted, or melt the concrete and decrease the conductivity of the molten zone enough to limit the power input and interfere with the ISV process.
2. The high percentage of water released from the cement during vitrification may be enough to exceed the off-gas system capacity.
3. The large dimensions of some concrete monoliths and waste packages may be difficult to fully incorporate in one ISV process.

The compounds present in cements are formed by the interaction during burning of lime (CaO), silica (SiO_2), alumina (Al_2O_3) and ferrous oxide (Fe_2O_3) compounds. Although these compounds vary greatly between cement types (see Table 4), when combined they make up over 85% of each cement type. Portland cement is composed of over 90% lime, alumina, and silica. Of the

TABLE 4. Composition of Various Cements

Component	Composition, wt%	
	Portland Cement	Other Cements(a)
CaO	64.1	38 to 65
SiO ₂	22.0	5 to 27
Al ₂ O ₃	5.5	3 to 39
Fe ₂ O ₃	3.0	0 to 13
SO ₃	2.1	0 to 4
FeO	0	0 to 4
S	0	0 to 1

(a) Includes Erz, Ferrari, Kuhl, Portland Blast Furnace, Eisen-Portland, Hochofen, Slag, Supersulphated and High Alumina cements (Lea 1971)

three major oxide constituents in concrete, both CaO and Al₂O₃ lower electrical conductivity upon addition to soil, while silica does not (Stanek 1977). Concrete also has a higher specific heat than soil. As a result, concrete may not heat quickly enough to become completely vitrified during an ISV operation.

To verify the ability of the ISV process to handle cement, two engineering-scale tests were made using relatively large concrete masses in the soil. In the first test, a carbon steel can encapsulated in concrete was vitrified, while in the second test, two monoliths, one of concrete and the other cement paste, were vitrified (see Table 5 for test summaries). After the tests, the vitrified blocks contained no traces of unvitrified concrete. Glass samples of the first concrete ISV test were analyzed and showed extremely uniform calcium distribution throughout the glass melt.

At ambient temperature, hardened Portland cement, with greater-than-20 wt% water, is much more electrically conductive than normal soil. As heat is generated in and around the concrete inclusion, it begins to expand as a result of the thermal expansion coefficient. At temperatures above 100°C, the expansion of the concrete paste and aggregate begins to be opposed by a contraction mechanism as water is driven off. At approximately 300°C, contraction, due to water loss, becomes greater than the thermal expansion, and the

TABLE 5. Summary of Engineering-Scale Laboratory Tests Containing Concrete Inclusions

Test Parameter	Test Number	
	ESLT-14	ESLT-15
Power Limit (kW)	12	17
Cement Mass (kg)	4.9	6.1
Cement Loading (wt%)	8.8	6.5
Metal Mass (kg)	0.16	0.69
Metal Loading (wt%)	0.3	0.7
Electrode Spacing Fraction Occupied by Concrete (M/L)	0.44	0.46
Total Energy (kWh)	63	120
Average Power (kW)	8	13
Mass Solidified (kg)	56	94
Energy/Mass (kWh/kg)	1.1	1.3

material starts shrinking, with ultimately 0.5% or more contraction from the original ambient dimensions (Harada et al. 1972, Zoldners 1971). This continues past 400 to 450°C, where free calcium hydroxide is dehydrated. The partially dehydrated cement starts expanding again at temperatures exceeding 700°C. Because the aggregate is continually expanding while the cement paste is contracting, severe cracking occurs. As a result, the concrete structure is broken up into smaller fragments which are believed to be dispersed throughout the glass by convection currents, facilitating uniform mixing. Although the rate of complete dehydration is slow at 534°C, complete dehydration occurs quickly at temperatures above 1090°C (Petersen 1966).

The electrical resistivity of the melted soil increases as the cement is melted and becomes uniformly dispersed. This was observed during engineering-scale test ESLT-14, in which an 8.8% loading of concrete in the soil raised the molten zone electrical resistivity significantly (see Figure 17). The drop in conductivity caused by CaO in the melt may be significant enough to require changes in system dimensions to achieve maximum melt depths. Because the ISV operating voltage depends on the electrical resistivity of the molten path and the distance between electrodes, an increase in electrical resistivity

FIGURE 17. Effect of Concrete Inclusions on ISV Melt Zone Resistance

caused by concrete can be offset by a corresponding decrease in electrode spacing. A decreased electrode spacing should not be required if the cement inclusion is not at, or near, the surface of the waste site. If the concrete is encountered later in the run, after the melt zone has grown, the voltage has dropped, and one or two voltage tap changes have been made, there should be enough voltage headroom on the power transformer to accommodate the increased resistivity caused by the concrete. The increased resistivity of the molten zone may be accommodated by a step back to one of the previous voltage taps. The power input to the melt zone will not be reduced.

The volume of water vapor given off during concrete dehydration may be greater than the reference ISV off-gas system can handle and still maintain an adequate vacuum on the hood. Figure 18 shows the required off-gas capacity for various concrete and cement loadings. The graphs assume that this specific

FIGURE 18. Off-Gas Requirements for Various Cement and Concrete Loadings

heat and melting rate of the soil, cement, and concrete are the same. At most, even a 100% loading of cement paste in a TRU site increases required off-gas capacities by only 94%. Concrete, which is more common than cement paste, can only increase off-gas requirements by 10%. At most, the off-gas system should be designed to handle 100 std m³/min, two times the reference system capacity, when high loadings of cement are present, and 55 std m³/min when high loadings of concrete are present.

Large concrete structures are common in TRU waste sites (e.g., trench caps, cribs, large industrial waste boxes). Since concrete is more conductive than soil, a passive short may occur in the ISV system if the concrete occupies a large portion of the space between electrodes. It is expected that any passive shorting of the system through the concrete would cause heating of the concrete to dehydration temperatures (300°C), thereby decreasing the conductivity of concrete and allowing ISV to proceed normally for the rest of the melt. Additional ISV tests may be required to confirm this effect.

The effect of ceramic materials on ISV is not expected to cause any significant process limitations. The high melting points and refractory nature of most ceramics will prevent them from completely melting or dissolving. To

determine the degree of encapsulation in the melt, alumina and zirconia bricks were included in one pilot-scale test. Visual inspection of the glass after vitrification revealed a high degree of ceramic encapsulation with minimal surrounding void space.

Combustibles

During ISV of a waste site, any combustible waste within the soil is decomposed or pyrolyzed into combustible gases at the high process temperatures. The gases move upward through the molten zone, expanding as they are heated. Combustion occurs as they are released from the surface, since there is a limited supply of oxygen in the soil, and the molten glass is reducing in nature. There are several undesirable effects of these gas releases:

- The protective cold cap can be broken up as the gases are released, resulting in increased volatilization and heat losses.
- Gases may carry entrained hazardous species with them to the off-gas system.
- Unburned combustible gases which are superheated in the molten zone burn in the hood plenum, creating high temperatures.
- The gas generation rate may exceed the off-gas system capacity, causing pressurization of the containment hood and ejection of soil and molten glass from the vitrification zone.

The magnitude of the undesirable effects is directly proportional to the rate at which pyrolyzed gases are generated and released. Engineering-scale and pilot-scale tests have shown that the gas release is sporadic and may occur in a very short time period. During ESLT-11, 0.2 kg of simulated combustible waste was placed inside a metal canister. Active surface combustion of the pyrolyzed gases occurred over an 18 min period, even though the ISV test had a duration of 12 h. The release period was 2.5% of the total ISV time. Similar observations were made during a pilot-scale field test.

Field test 3 was conducted to evaluate ISV performance with a 208 l (55 gal) metal drum placed between electrodes containing simulated combustible waste and soil. Figure 19 illustrates the simulated waste drum placement, and

FIGURE 19. Field Test 3 Simulated Waste Location

Table 6 gives the waste composition. When the molten soil first contacted the waste drum, rapid venting of pyrolyzed gases and carbonaceous particulate occurred for a period of approximately 30 minutes. The off-gas particle loading was high during this period, reaching 3600 mg/m³. Slower ventings of pyrolysis products occurred at two other times later in the test, lasting for 15 to 30 min each. The ISV process was operated for 38 h; however, most pyrolysis gas venting took place over a period of approximately 1 h (2.6% of the total ISV time).

Figure 20 shows the off-gas system capacity required for stoichiometric combustion of waste loading typical of burial trenches. As the duration of gas release decreases, the off-gas system capacity must increase to handle the gas generation and excess combustion air. If all the pyrolyzed gas is released in less than 10 h, the excess air required to combust the gas accounts for essentially all of the required increase in off-gas system capacity.

Based on engineering and pilot-scale data, a conservative assumption is made that the majority of pyrolyzed gas generated from a full scale ISV process will be released in a 2-h period (approximately 2% of the total ISV time). The

TABLE 6. Waste Drum Combustibles Content during Pilot-Scale Field Test 3

<u>Material</u>	<u>Weight, kg</u>	<u>Weight %</u>
Paper	16.9	44.0
PVC	4.5	11.7
Polyethylene	4.5	11.7
Neoprene	3.2	8.3
Polypropylene	2.3	6.0
Cotton	2.3	6.0
Buna Rubber	1.8	4.7
Hydraulic Oil	1.1	2.9
Ion Exchange Resin	0.91	2.4
Teflon	<u>0.91</u>	<u>2.4</u>
TOTAL	38.4	100

FIGURE 20. Off-Gas System Capacity Required for ISV of Buried Combustible Waste

required off-gas system capacity would be 300 std m³/min (Figure 20) for stoichiometric combustion (no excess air). A more realistic capacity of 500 std m³/min would provide an average of 67% excess air during the combustion period. This is 10 times the capacity of the reference ISV system for contaminated soil. If sufficient soil is mixed with the combustibles, the restrictive heat transfer due to the soil may prevent the rapid decomposition observed in field test 3. For such waste sites, a smaller off-gas system may be adequate. The hood and off-gas line must be designed to operate at high temperatures.

In situ vitrification of one section of a long burial trench or a wide burial pit may create underground burning of combustibles adjacent to the molten zone before wastes can be vitrified. Such burning would be slow because of limited oxygen but could bring hazardous species to the surface at the edge of the molten area. An enlarged off-gas containment hood may be required for such a waste site.

Explosives

Chemicals which have the potential of undergoing partial or full detonation during ISV can result in the same undesirable effects listed in the previous section on combustibles. These effects may be more pronounced because the chemical structures of explosives, which include oxidizers, will provide for very rapid reactions. Explosives may exist as inclusions or homogeneous mixtures within soil, as chemicals within a waste container, or as military ordnance items. The probability of buried military-grade explosives in TRU waste sites is extremely small; however, chemical mixtures such as organics and nitrates are more likely. Conditions required to nitrate organic wastes such as cotton rags by nitric acid are very unlikely at a waste site. To achieve a significant degree of nitration, a hydrophilic agent such as sulfuric acid must be present since the final degree of nitration is strongly dependent on the final water concentration equilibrium (Chedin, Tribot and Feneant 1948; Doree 1933 and Ott et al. 1947). Without such an agent, less than one-third of the hydroxide sites on cotton can become nitrated, even when concentrated 72% nitric acid is present.

The presence of military explosives would be in violation of the Ordnance Safety Manual (AMCR-385-100) which states, "Collected explosives and chemical wastes must not be disposed of by being buried." Any U.S. military organization would have disposed of surplus explosives by burning. Even though it would be very poor practice to bury surplus bulk explosives with radioactive waste, the possibility exists, and the effects upon ISV must be evaluated. An analysis was performed to determine the effect of ISV on explosive inclusions and mixtures within the waste, using military-grade explosives as a worst case.

The hazards associated with the excavation, transportation, and incineration of dry humus soil contaminated with TNT and/or RDX have been assessed by Kirshenbaum (1982). Explosives/soil mixtures were subjected to impact, friction, electrostatic, shock, and flame sensitivity tests. Contaminated soil mixtures from the Alabama Army Ammunition Plant, Umatilla Army Depot, Louisiana Army Ammunition Plant and Savannah Army Depot were also evaluated. Kirshenbaum determined that soil containing up to 25 wt% TNT and/or RDX can be excavated, transported and incinerated safely. Soil containing over 10 wt% of the explosives is thermally reactive, which indicates that such mixtures unconfined could burn when heated to 175 to 200°C. This would indicate that soil containing a homogeneous mixture of greater than 10 wt% but less than 25 wt% explosives will behave similarly to other combustible waste sites and can be safely vitrified.

Explosives typically can achieve a partial or full detonation by three basic mechanisms:

- When held at or above a minimum "critical temperature" for a period of time, explosives can self-heat to a detonation.
- Rapid heating of an encased or confined explosive can result in a detonation.
- Pressurization as caused by an impact or shock wave can cause a detonation.

The minimum critical temperature depends upon the composition, size, and concentration of an explosive. As shown in Figure 21, when the diameter of a specific explosive increases, the critical temperature decreases (Dobratz 1981). Dilution of an explosive with soil will increase the critical temperature or the size required for an explosion at a given temperature.

High explosives, which include ammonium nitrate, ammonium perchlorate, Composition A, Composition B, H-6, HMX, lead azide, lead styphnate, NC, Pentolite, PETN, picric acid, RDX, Tetryl, and TNT, will decompose completely at temperatures below 400°C (Dobratz 1981). All these explosives melt below their decomposition temperatures, typically between 80 and 200°C. During an ISV operation, soil below the advancing molten zone is heated to 100°C, where

FIGURE 21. Critical Temperatures Versus Charge Diameter for Some Pure Explosives (Dobratz 1981)

it remains for approximately 2 h until all moisture has evaporated. Once dry, the soil heats at a rapid rate of approximately $10^{\circ}\text{C}/\text{min}$ until it fuses into the molten zone. At this heating rate, explosive inclusions which were not contained would melt, soak into the surrounding soil, and decompose rather than self-heat to a detonation. Explosives with a critical temperature of 100°C or less could detonate, if unmelted, during the time the soil moisture is evaporating. The probability of a detonation within a disposal site is reduced significantly if the explosive has a critical temperature greater than 100°C . Even a moderately stable explosive such as PETN will not have a critical temperature as low as 100°C unless the charge diameter is 0.6 m or greater

(Figure 21). The probability of such an inclusion is not large. Contained explosives located to the side of the ISV melt zone, however, could soak for a sufficient time above the critical temperature to cause a detonation.

Off gases produced from the decomposition or detonation of explosives such as TNT or HMX do not pose a toxicity hazard as they are mostly N_2 , NO_x , H_2O , CO_2 and CO , which can be easily treated by conventional off-gas equipment. The gas volume generated by these two materials ranges from 0.65 to 0.80 m^3/kg of explosive. An alkaline soil will act to absorb some of the nitric oxides.

Intact ordnance items present a more serious detonation potential. Bombs and shells explode in a few minutes in a fuel fire, usually showing at least partial, if not a full, detonation. Full or partial detonation of a 225 kg bomb in a shallow land burial trench would almost certainly breach the surface. For an ISV soil heating rate of $10^\circ C/min$, a high-integrity ordnance item would explode before the soil around it was fused; therefore, both soil particles and molten glass would be ejected from the trench. Ordnance items that are touching or within a critical separation distance will also undergo sympathetic detonation due to shock pressurization.

All possible explosives have not been evaluated; as such, the safety of processing pure explosives and explosives/soil mixtures in a generic sense by ISV has not been fully resolved. Additional work is recommended to adequately address limitations due to explosive chemical mixtures in the soil. It can be stated, however, that in situ vitrification should not be applied to sites which contain or have the potential of containing intact ordnance items. A historical survey should be made on each site, including a search for written procedures covering disposal practices during the time the sites were in use, to verify that no such ordnance items are present.

Conclusions

Both mathematical modeling and engineering-scale testing predict that metallic inclusions will have minor effects on an ISV process until a short circuit is approached. As the metal path approaches a full short, hot zones form in the molten soil between the metal and electrodes, while less heat is generated in the molten zone above the metal. A metallic inclusion, accounting

for 5% of the final vitrified block weight and occupying 70% of the electrode spacing, reduced the voltage only 21% compared to the case when no metal was present. A full scale ISV system will be flexible enough to process this amount of metal with only minor adjustments to the power system.

Almost all inorganic, nonmetallic inclusions in TRU waste trenches are composed of some form of cement product. In situ vitrification of soil with cement inclusions results in a decrease in electrical conductivity of the melt and an increase in the volume of off gas requiring treatment. The power input to the soil should not be limited by the decreased soil conductivity, provided that the concrete inclusion is not at, or near, the surface. The off-gas system should be designed to handle up to 100 std m³/min, two times the capacity of the reference system.

Any concerns that the low electrical conductivity of dehydrated cement prevents complete melting from occurring have been alleviated. A literature analysis shows concrete undergoing extensive cracking during dehydration at high temperatures. This cracking, accompanied with the strong convection currents in the process, should cause the fractured pieces to separate from the main inclusion, melt, and become dispersed through the molten soil. Two engineering-scale ISV tests have successfully demonstrated the feasibility of vitrifying cement inclusions.

Many other nonmetallic refractory materials do not melt. Nevertheless they are effectively encapsulated by the glass and do not present a problem.

The off-gas system required for ISV of buried combustible wastes must have approximately 10 times the capacity of the reference system used to vitrify a noncombustible waste site. In addition, the hood and off-gas line must be designed to operate at the high temperatures of the combustion gases and molten glass which may be ejected. The height of the hood should also be adequate to minimize the possibility of glass contacting the ceiling.

In situ vitrification of one section of a long burial trench or a wide burial pit may create underground burning of combustibles adjacent to the molten zone before adjacent wastes can be vitrified. Such burning would be slow, due to the limited air supply, but could bring hazardous species to the

surface at the edge of the molten area. An enlarged off-gas containment hood covering several different melts may be required for such a waste site. Additional testing is recommended to verify the ISV off-gas hood requirements.

Kirshenbaum (1982) determined that soil containing up to 25 wt TNT and/or RDX can be incinerated safely as long as the mix is not contained. These and other similar explosives are expected to be processable by ISV when mixed with the soil at less than 25 wt%. Explosives which are contained may partially detonate if they are located to the side of an ISV melt zone and are heated to a temperature at or above their critical temperature. Additional work is needed to determine the extent of this potential limitation. Intact ordnance items can explode upon rapid heating and should not be processed by ISV. Further study is required to better define the types of explosive materials likely to be present at TRU waste sites and the conditions under which those materials can detonate.

CRITICALITY

Since ISV changes the physical and chemical nature of the waste, an evaluation of potential ISV criticality limitations was performed. Transuranic radionuclides which have neutron emission capabilities may reach criticality if they are sufficiently concentrated or if the moderation properties of the waste site become altered.

Transuranic elements common to TRU waste sites which are capable of sustaining a nuclear chain reaction are shown in Table 7 along with their estimated sub-critical mass limits (ANS 1975, ANS 1982, Clayton 1979). Table 8 shows the radionuclide content of buried and stored TRU waste at INEL. These values are approximate values for other TRU waste sites. Since ^{239}Pu accounts for the greatest fraction of fissionable radionuclides at TRU waste sites, and also has one of the smaller subcritical mass limits, the criticality analysis presented in this section is based on the effects of ISV on this isotope.

TABLE 7. Estimated Sub-Critical Mass Limits for Various Transuranic Nuclides

Radionuclides(b)	Sub-Critical Mass Limit,(a) kg (as Metal)	
	Water	Steel
	Reflector	Reflector
^{233}U	7	—
^{237}Np	30	20
^{238}Pu	4	3
^{239}Pu	5	—
^{240}Pu	20	15
^{241}Pu	6	—
^{242}Pu	60	40
^{241}Am	24	16

(a) assumes spherical geometries and optimal moderation (ANS 1975, ANS 1982, Clayton, 1979)

(b) found in significant quantities in TRU waste

TABLE 8. Radionuclide Content of Buried and Retrievable TRU Waste at INEL(a)

Transuranic Radionuclides	Buried Waste		Retrievable Waste	
	g	%	g	%
^{233}U	50	0.01	55,500	20.0
^{238}Pu	31.7	0.01	896	0.32
^{239}Pu	345,000	89.4	192,000	69.1
^{240}Pu	24,300	6.29	14,300	5.14
^{241}Pu	1620	0.42	836	0.30
^{242}Pu	50	0.01	50	0.02
^{241}Am	15,000	3.88	14,300	5.14
^{244}Cm	0	0	13.4	<0.1
Total Weight, g	386,000		278,000	
Total Volume, m^3	62,300		34,000	
TRU Density, g/m^3	6.20		8.18	

(a) Emplaced as of 12-31-77 (U.S. DOE 1979a)

Moderation Effects

An important factor affecting the criticality potential of TRU waste trenches during ISV is the amount and degree of neutron-absorbing and neutron-reflecting material near the fissionable material. It is known that during ISV at least four changes occur that might cause changes in the neutron reflection/absorption properties of the waste site:

- Soil is densified and becomes glass-like.
- Organics and combustibles are pyrolyzed and released from the melt.
- Water is evaporated out of the melt area.
- Metal will melt and settle to the bottom of the melt zone leaving most of the vitrified area free of metal.

Calculations of critical limits have been made for Hanford soil containing plutonium (Ridgway and Carter 1972). These calculations were for soil with 30 and 40 vol% void space containing plutonium and water within the void. The minimum critical mass is that mass of plutonium required to reach a critical configuration under optimized conditions, and is larger than the subcritical mass limit discussed earlier. The minimum critical areal concentration is the minimum plutonium mass per unit area in an infinite slab required to achieve criticality, assuming a homogeneous plutonium distribution within a slab of optimal thickness.

The minimum critical mass for plutonium (97 wt% ^{239}Pu and 3 wt% ^{240}Pu) in soil which is fully saturated with water is given in Table 9 for various degrees of reflection. Water-saturated soil is assumed as a worst case since the minimum critical mass is smallest when fully reflected. All of the minimum critical masses occur in the plutonium concentration range of 10 to 20 kg/m³. As a conservative measure, the minimum critical mass in Hanford soil is taken as 1.7 kg, the value for 40% void space and full water reflection.

The melting process during ISV actually causes the ^{239}Pu minimum critical mass to increase by water removal. Once the moisture has evaporated, the minimum critical mass increases to that of a dry sphere of PuO_2 . The subcritical limit for an oxide sphere is 10.2 kg Pu (11.5 kg as oxide). This value is for water-reflected oxide spheres at optimum conditions.

TABLE 9. Minimum Critical Mass of Plutonium in Water-Saturated Soil

Reflection	Minimum Critical Mass, (a) kg Pu	
	30 Vol% Soil Void	40 Vol% Soil Void
Unreflected	4.1	3.0
2.54 cm Water	3.2	2.3
Full Water Reflected	2.4	1.7

(a) 97 wt% ^{239}Pu and 3 wt% ^{240}Pu (Ridgway and Carter 1972)

The minimum critical areal concentration for plutonium in Hanford soil is about 2.9 kg/m^2 for full water reflection. The concentration at which this occurs is about 8 kg/m^3 for an infinite slab about 36 cm thick. If a waste site has an areal plutonium concentration of less than 1.3 kg/m^2 (45% of the 2.9 kg/m^2 critical areal concentration), with no mechanisms of lateral concentration, or contains a total plutonium mass less than 0.8 kg (45% of the 1.7 kg minimum critical mass), the site should be acceptable for ISV operation.

When fissile and organic materials densify prior to combustible decomposition, their potential for criticality increases. Calculations have shown that plutonium has a smaller minimum critical mass when moderated by materials with higher hydrogen densities than water. In particular, polyethylene as a moderator results in a minimum critical mass of 0.36 kg (Thompson 1977). Both polyethylene and polypropylene are commonly discarded in TRU waste as bags, gloves, bottles, etc. Normal storage of these items results in a low density of moderator in waste containers and packages. However, heating during ISV may cause these materials to melt and collect in a more dense form at the bottom of the waste container. The potential result is a near-optimum distribution of plutonium in the organic moderator before the ISV process can decompose these materials and drive off the hydrogen. This phenomenon, although unlikely, would occur at temperatures under 300°C . The minimum critical areal concentration for plutonium decreases to 2.4 kg/m^2 for a polyethylene reflected

system. The safe ISV operating limit becomes 1.1 kg/m^2 (45% of 2.4 kg/m^2) when large quantities of hydrogenated organics like polyethylene are present in drums or other waste containers.

Plutonium Concentration Mechanisms

Plutonium concentration mechanisms become important if the areal plutonium concentration limits listed in the previous section are exceeded. Several mechanisms have been identified:

- Solubility limits of various TRU radionuclides in ISV glass may be exceeded, allowing some fissionable material to settle out of the molten glass.
- Dense TRU oxide particles may settle to the melt bottom before melting occurs.
- Reducing conditions in the molten zone may cause some fissionable compounds to be reduced to their metallic state and subsequently settle at the melt bottom in a more concentrated form.

Due to its high oxygen affinity, most plutonium in the TRU waste sites exists as an oxide, even though it may enter the waste site as a sulfate, nitrate, hydroxide, halide or carbonate. Because of the high stability of plutonium oxides, any excess sulfate, nitrate, hydroxide, halide, or carbonate should be converted into an oxide form during ISV heating. Plutonium oxide is an extremely stable compound. Plutonium (IV) silicate is also very stable, to the point that if any plutonium oxide reaction occurs during ISV, it will be to incorporate the plutonium into the silicate matrix.

Based on known plutonium solubilities in high-level waste glasses, there should be no solubility limits exceeded during ISV of any TRU waste site. High-level waste glasses, which are very similar to ISV glass, have recorded plutonium solubilities higher than 2% (Scheffler et al. 1977). This solubility limit is over 10 times greater than the highest plutonium concentration at any liquid waste site, with the exception of two or three reverse wells at Hanford.

The thorough convective mixing, characteristic of ISV, is expected to dilute any zones of high plutonium concentration, further reducing the potential for a criticality. This was verified in actual ISV tests where simulated

waste material was spiked with rare earth elements which are expected to behave similarly to plutonium. One of the rare earth elements added to field test 3 was cerium. After melting and sampling of the solidified waste block from test 3, it was found that cerium was uniformly distributed laterally throughout the block at a concentration approximately 14 times less than in the initial waste material (see Figure 22).

Reduction of plutonium from the oxide to the metallic form during ISV is not thermodynamically favorable. An examination of the standard free energy of formation of various oxides as a function of temperature (Figure 23) shows both uranium and plutonium to be highly electropositive metals, with stable oxide forms. This is usually the case with other actinide elements as well. Other major oxides in the soil (including Fe_2O_3 , SiO_2 , and Al_2O_3) are more likely, thermodynamically, to be reduced to their elemental forms than plutonium oxide or uranium oxide.

FIGURE 22. Field Test 3 Ce Concentration Profile Before and After In Situ Vittrification

FIGURE 23. Standard Free Energy of Formation for Various Metal Oxides

Concentration by settling of undissolved plutonium oxide during ISV is considered unlikely for two basic reasons: 1) the ISV melt advances at a very slow rate, less than 12 cm/h, and as such, any plutonium oxide will have a long period to dissolve before significant concentration can occur with plutonium oxide deeper in the waste site; and 2) plutonium oxide is typically a fine powder, which, even if it remained undissolved, would become thoroughly mixed within the glass by convective currents.

Conclusions

In situ vitrification changes the geometry and moderation characteristics of a burial site. When fissionable materials are present in the site, the changes may affect criticality potential (k -effective) without changing fissionable material content. The ISV process could affect a TRU waste site's geometry and moderation characteristics in two ways:

- Fissionable material may concentrate (the solubility limit may be exceeded; oxides may be reduced to the metal).
- The moderating material surrounding fissionable material may change (e.g., water is lost; organics melt and densify).

The limitation analysis was centered around ^{239}Pu , since it is the dominant form of fissionable nuclei at TRU waste sites. An analysis of how ISV might affect the criticality potential of various TRU waste sites indicate the following:

- There is no credible concentration mechanism for ^{239}Pu or any other fissionable nuclei.
- As long as a waste site to be vitrified has a total plutonium mass less than 0.8 kg or an areal concentration less than 1.3 kg/m^2 , it should be safe for ISV stabilization. These limits are set at 45% of the minimum critical values.
- When large quantities of hydrogenated organic materials such as polyethylene are present with plutonium in waste drums or other high integrity containers, the areal concentration limit is reduced slightly to 1.1 kg/m^2 .

Although these values can be used as general estimates regarding criticality, it is recommended that a site-by-site criticality analysis be performed prior to solidification by ISV.

WASTE SITE APPLICATIONS

WASTE SITE APPLICATIONS

Ground disposal of transuranic (TRU) waste materials began in the early 1940's during the Manhattan Project. Transuranic contaminated wastes were originally defined as low-level wastes (LLW), and were not specially segregated prior to burial. Low-level wastes were only segregated according to liquid and solid waste disposals.

Because of increased awareness of potential long-term effects of TRU elements on the environment, the Atomic Energy Commission (AEC) issued a directive in early 1970 requiring all waste containing greater than 10 nCi/g TRU contamination to be placed in 20-year retrievable storage, pending selection and development of a permanent disposal method. The estimated costs for excavation, sampling and stabilization, and storage of in-ground wastes are extremely high (Murphy and Holter 1980). Using ISV as a means of stabilizing these sites could significantly reduce expense by eliminating excavation and minimizing decontamination costs. ISV may also be cost effective for some retrievable waste sites.

A comparison of the DOE inventory of TRU contaminated wastes and soils generated by nonretrievable liquid disposal, nonretrievable solid burial, and retrievable storage is shown in Table 10 (U.S. DOE 1981a and 1982a). The relatively high ratio of nonretrievable to retrievable wastes is due primarily to the 2 to 12 million m³ of contaminated soil in aqueous waste disposal locations primarily at Hanford.

Characterization of nonretrievable waste disposal sites is very difficult since records on early waste disposal are sparse or nonexistent. As a result, the site characterization analysis has been generic regarding waste material types and compositions. This section identifies and describes the various types of waste burials, then categorizes them according to their potential for ISV.

TABLE 10. Inventory of TRU Contaminated Waste Accumulated Through 1980 at DOE Sites^(a)

Waste Category	Volume, m ³	TRU Elements	
		kg	%
Nonretrievable			
Liquid Disposal	2,000,000 – 12,000,000	~200 ^(b)	10.0
Solid Disposal	404,400 ^(c) – 2,868,000 ^(d)	1001	49.9
Retrievable			
Contact-Handled	60,430	797	39.7
Remote-Handled	1,717	9	0.45
TOTALS	2,467,000 – 14,930,000	2007	100

(a) U.S. DOE 1981a and 1982a.

(b) Plutonium content of waste is estimated to be less than 200 kg.

(c) Includes soil which is probably now contaminated to a level >10 nCi/g.

(d) Includes soil which might have to be handled during exhumation of TRU waste.

NONRETRIEVABLE LIQUID DISPOSAL

Ground disposal of liquid wastes began on a limited basis in early 1945. Only small volumes of low-level liquid wastes were disposed of at first. As the selective radionuclide migration in soils became known, the levels and volumes of disposed waste were gradually increased, peaking in the 1950's. Levels were then diminished gradually as liquid ground disposal was minimized. As shown in Table 11, nearly all soils contaminated by TRU liquid waste are located at Hanford (U.S. DOE 1981a and 1982a).

Several types of nonretrievable liquid waste disposals are found at TRU waste sites: cribs and tile fields, absorption beds, French drains, trenches, reverse wells, ponds and ditches, and unplanned releases (spills). These sites are almost exclusively generic to the Hanford reservation, the exceptions being absorption beds (generic to LANL) and unplanned releases. Brief summaries of the various disposal types are presented in this section. It should be noted that all depth ranges listed for each disposal type only refer to the depth at which each site was originally excavated. Soil sampling may have to be performed on each site to determine the actual depth of the TRU waste plume.

TABLE 11. TRU Contaminated Soil from Nonretrievable Liquid Disposal

Site	Volume, m ³	TRU Elements	
		kg	%
Hanford	2,000,000 - 12,000,000	200	99.8
LANL	175 - 7,000	~0.14	~0.07
ORNL	? - 1000	~0.3	~0.15

Since all these sites were used for liquid waste disposal, only a few solid inclusions (e.g., distribution pipes, asphalt liners, and wooden cribs) are found in these sites.

Site Descriptions

Cribs and Tile Fields

Cribs are defined as underground liquid disposal facilities filled with rock, gravel or sand to provide good radionuclide dispersion. They are buried underground at depths of 1.8 to 11.3 m. Liquid waste is dispersed to the soil through the crib bottom, and sometimes through an attached tile field which distributes the waste uniformly over a larger area.

Various designs have been used in the construction of cribs. The earliest cribs were designed as wooden boxes filled with rock and open only at the bottom to allow radionuclide dispersal. They were usually buried at depths greater than 4.0 m to prevent any radiation releases at the ground surface. These cribs ranged in size from 14 to 760 m². Quite often they were either buried in pairs (the second crib being used to handle the overflow from the first), or in conjunction with a tile field. Because of the high void fraction inside the crib and the rotting nature of timber in soil, there have been several ground cave-ins above the cribs; as a result, construction of this type of crib was terminated after 1956. A diagram of a wooden crib and tile field is shown in Figure 24.

Most of the other types of cribs were built by excavating a trench, partially filling it with rock, gravel, or sand, then topping it with an impermeable membrane or asphalt layer, and backfilling. Some cribs, referred to as concrete caverns (e.g., Z-9), had a concrete roof placed over the excavation,

FIGURE 24. Typical Wooden Structured Crib with Tile Field (ready for dirt backfill)

and contained no dispersal material (rock, gravel, sand) to partially fill the crib. Liquid distribution pipes were installed between the impermeable membrane and the trench bottom to provide uniform flow of liquid over the crib bottom. These cribs were generally buried at shallower depths than the wooden cribs and usually ranged in size from 9 to 4100 m². A diagram of a typical excavation crib is shown in Figure 25.

Tile fields can be very large, ranging in size from 100 to 3000 m². The only nonterrestrial solid materials in tile fields are the large networks of clay distribution pipes used to disperse the liquid evenly over the area.

Absorption Beds

Absorption beds at LANL are similar to the cribs, but are not buried as deeply. These beds are about 35 m long, 6 m wide, and only 1.2 m deep. The beds were usually filled with 0.61 m of stone graded from large diameter at the

FIGURE 25. Typical Excavation Crib (Harmon and King 1980)

bottom to small diameter at the top. They were then filled with 0.15 m of gravel and 0.15 m of sand, and topped with 0.30 m of soil. Liquid waste was distributed to the beds by carbon steel piping buried either at or 61 cm above the bottom of the beds. The amounts of transuranic material disposed of in these beds are very small.

French Drains

French drains are also similar to cribs, except that the bed capacity and surface area are much smaller (usually $0.3\text{--}2.5\text{ m}^2$). They consist of vertically buried encasements (usually vitrified clay pipe) partially filled with gravel, the bottoms removed to allow liquid dispersion into the soil. French drains are only used for small-volume waste streams. They are usually buried at depths of 5.2 to 13.4 m. A cross-section of a typical TRU contaminated French drain is shown in Figure 26.

Liquid Disposal Trenches

Trenches are long, relatively narrow, unlined excavations, generally used over short periods for disposal of limited quantities of liquids. The bottom area for each trench is 55 to 273 m^2 . Liquid trenches are either open or

FIGURE 26. Typical TRU Contaminated French Drain Cross Section

covered by a roof during disposal, and are backfilled upon deactivation. Backfilling is sometimes done before the liquid has completely soaked into the soil; thus, the potential for near surface contamination is increased by the splashing of liquid during the backfilling operation. Because of the limited volume of liquid disposed of in each trench, they are also buried at shallower depths than cribs (~2.4 to 4.6 m). The total amount of TRU radionuclide concentration in each trench is much less than that in most cribs.

Reverse (Dry) Wells

Reverse wells are deeply drilled holes (12 to 92 m) encased with metal pipe, with the lower end of the pipe perforated or open to allow liquid seepage into the ground. Reverse wells vary in diameter from 0.15 to 1.20 m and are

buried or covered during use. They were used during the early stages of TRU-waste burial history, but were discontinued because they plugged easily and dispersed the liquid waste too near the water table.

Ponds and Ditches

Ponds are shallow bodies of water used for the disposal of high-volume, low-level liquid effluents. Ditches are long, narrow, unlined excavations used to transport the low-level liquid effluents to the ponds. Liquid discharge to ditches and ponds are limited for the most part to concentrations below 50 pCi/ml. Although the discharge limit to ponds and ditches is very low, the quantity of plutonium can be substantial since the area covered is often quite large. Ponds are typically very shallow and have areas as large as 89,000 m². Ditches are excavated to depths of 0.6 to 3.0 m, are 1.2 to 7.6 m wide, and have a bottom surface area from 557 to 4180 m². When deactivated, ponds and ditches are first dried out; then a layer of soil is placed over the contaminated bottom surfaces.

ISV Applicability

The ISV process can be readily applied to liquid disposal sites because of the low quantity of inclusions and favorable geometries. Table A.1 in the appendix lists the TRU contaminated liquid disposal sites at Hanford (Harmon and King 1980) which account for over 99.9 vol% of all TRU contaminated soil from liquid disposal and approximately 81 vol% of the total U.S. TRU waste inventory.

With very few exceptions, liquid disposal sites should not have criticality limits imposed due to ISV. All liquid disposal sites have an areal plutonium concentration averaging less than the safe limit, 1.3 kg Pu/m², except for two or three reverse wells and possibly sites which have not yet been fully characterized. No credible plutonium concentration mechanism has been identified. Nonradioactive pilot-scale tests indicate that plutonium should actually become more dilute and dispersed during the vitrification process.

Most of the plutonium contamination is located in cribs and tile fields and lies within the top 0.15 m of the soil located below the original excavation. Figure 27 illustrates the relative contamination levels of plutonium, cesium,

FIGURE 27. Sorption Patterns Below a Typical Hanford Crib (Harmon and King 1980)

strontium, ruthenium, tritium, the rare earths and nitrate as a function of depth below a typical crib (Harmon and King 1980). Plutonium concentrations decrease rapidly with depth. At only 5 m below the crib, plutonium concentration is eight orders of magnitude lower than in the crib. Medium-lived fission products like cesium, strontium and ruthenium migrate farther, while tritium and nitrate pass through the soil with essentially no sorption. The vitrification depth typically required to immobilize plutonium contamination greater than 10 nCi/g is the crib depth plus approximately one meter. Vitrification of soil 2 or 3 m below the crib bottom may be required for certain sites where additional stabilization by ISV is deemed necessary. Crib depths average 5.7 m, and the maximum is 11.3 m. The practical operating limit of the

reference full-scale ISV process in Hanford soil is 13.5 m deep; thus, ISV should be able to immobilize TRU contaminated soil in and below any of the Hanford cribs and tile fields.

Crib and tile fields vary in both design and materials of construction. Materials such as rocks, gravel, sand, wood, concrete and steel are found in different systems. A site-by-site analysis must be made prior to ISV to determine the quantity and geometry of the wood, concrete and steel inclusions. The presence of wood, concrete and other gas generators such as nitrates and organics increase the off-gas system requirements. The off-gas system capacity may require enlargement from the reference system capacity of 50 std m³/min up to as high as 100 std m³/min, depending on the actual loading of gas generators. Steel supports and reinforcements in some cribs may present potential for a short circuit between electrodes. Test show that electrodes can be positioned so that metal inclusions occupy over approximately 70% of the space between them without limiting power input or causing shorting. Presence of excessive, incorrectly positioned metal could, however, eliminate some sites as candidates for ISV immobilization.

French drains are circular and are constructed typically of clay tile or vitrified clay pipe with some wood and concrete. Void space present in a French drain will probably result in subsidence of a portion of the molten glass during the early stages of an ISV operation. Depths range from 5.2 to 13.4 m. Each site could be vitrified with just one ISV operation, using a narrow, 3.5 m electrode separation to obtain the required melt depth. The deepest site, 216-A-15, could be completely vitrified to below the 10 nCi/g level by excavating a portion of the uncontaminated surface soil prior to ISV.

Only two of the ten reverse wells at Hanford are within the 13.5 m depth limit of the reference ISV process. Improvements to the operating procedure or system design may, in the future, permit the use of ISV at some of the deeper reverse well sites. Currently, the process could be used to isolate the contamination from the surface by producing a durable vitrified cap above the contaminated zone. Also, noncontaminated surface soil could be excavated to allow ISV to greater depths.

In situ vitrification of liquid disposal trenches and filtration beds would have no imposed limits since the sites are all shallow and have a minimum number of soil inclusions. Hanford ponds and ditches would also have no limits imposed for the ISV process. No ponds or ditches have been classified as transuranic sites, since their contamination levels are extremely low; however, some ponds, which cover several acres, contain a substantial amount of plutonium; and ISV solidification may be considered as a means of immobilization to the extent necessary.

NONRETRIEVABLE SOLID DISPOSAL

Originally, TRU contaminated solid wastes were disposed in much the same way as garbage at a land fill; no set waste packaging or burial methods were followed, and few records were kept. Nonretrievable ground disposal of TRU contaminated solid wastes was initiated in 1944 during the Manhattan Project, and terminated in early 1970 when retrievable TRU waste storage was initiated (Webster 1979, Rogers 1977, Harmon and King 1980).

Nonretrievable solid disposal, unlike liquid disposal, is generic to all major DOE waste sites (see Table 12), although Hanford remains the major location with nearly 60% of the TRU elements. The estimated amount of contaminated soil in nonretrievable solid disposal sites ranges from 26 to 65%

TABLE 12. TRU Contaminated Waste and Soil from Nonretrievable Solid Disposal

<u>Site</u>	<u>Volume, (a) m³</u>	<u>TRU Elements</u>	
		<u>kg</u>	
Hanford	224,200 - 667,000	598	59.7
INEL	113,800 - 213,100	375.5	37.5
LANL	17,400 - 312, 500	12.9	1.3
ORNL	18,000 - 1,606,000	5.2	0.5
SRP	31,000 - 69,000	9.3	0.9
TOTAL	404,400 - 2,868,000	1001	100

(a) Volume range is bounded by: 1) waste and soil which is probably now contaminated to a level >10 nCi/g, 2) waste and soil which might have to be handled during exhumation.

of the total waste volume (U.S. DOE 1981a and 1982a). These percentages tend to vary according to the relative moisture content of the soil and the state of degradation of the original waste packages.

The predominant type of solid waste disposal site is the trench. Trenches can be found at all major DOE sites except LANL, which uses pits and shafts. Pits for large equipment can also be found at INEL. Various types of waste disposal for solid nonretrievable waste are described below.

Site Descriptions

Trenches

Solid waste trenches are very similar in shape and size to liquid waste trenches. Their dimensions range from 2.4 to 7.6 m deep and 1.8 to 18 m wide (Harmon and King 1980, ORNL 1980, U.S. DOE 1979b, U.S. ERDA 1977). They have a prescribed minimum backfill of 0.9 to 1.2 m. However some nonretrievable solid waste trenches (e.g., Hanford) are subdivided into two categories: those trenches containing miscellaneous (routine) wastes and those containing industrial (nonroutine) wastes. Miscellaneous or routine wastes are defined as lab trash, small pieces of equipment, chemicals, animal tissues, sludges, hot cell waste and classified materials. They are buried in packages ranging from small cardboard boxes to small wooden, metal and concrete containers. Industrial or nonroutine wastes include building debris, large failed or obsolete equipment items, and soil or rock removed during site cleanup operations. Nonroutine wastes are usually buried in large wooden, metal or concrete boxes. Miscellaneous wastes are mostly combustible material, while industrial wastes are mostly noncombustible material.

Not only are miscellaneous and industrial wastes physically segregated by trenches from each other, their trench sizes are also different. This is because the large industrial waste boxes need specially designed trenches to accommodate their size. Miscellaneous waste trenches are typically 3.7 m deep, 1.5 m wide at the bottom, 8.8 m wide at the top, and buried with a 0.9 to 1.2 m minimum backfill layer. Industrial waste trenches are typically 4.6 to 7.6 m

deep, 4.9 to 6.1 m wide at the bottom, 14 to 20 m wide at the top, and also covered with a 0.9 to 1.2 m minimum backfill. A typical solid waste trench at Hanford is shown in Figure 28.

Pits

The pits found at LANL and INEL are very similar to the trenches at other sites. They are also the predominant form of nonretrievable solid waste disposal at LANL. Compared to trenches, pits are typically deeper and larger, ranging in depth from 3.9 to 8.8 m and width from 5 to 34 m (Rogers 1977, U.S. ERDA 1977). Miscellaneous and industrial solid wastes were also segregated in pits at LANL, although this was not started until 1971. Pits are usually mounded over with at least 1.8 m of backfill.

Shafts

Shafts are bored or augered holes in the ground that are either unlined, lined with concrete, or lined with asphalt. Shafts range from 0.6 to 2.4 m diameter, and are 3 to 18 m deep. They have been in use at LANL since 1958 for secure disposal of certain miscellaneous waste materials. These include animal tissue, classified material, chemicals, high-level beta-gamma waste,

FIGURE 28. Typical Solid Waste Burial Trench for TRU Waste at Hanford (Harmon and King 1980)

and nonretrievable TRU sludge waste mixed with cement. Shafts are filled to within 1.5 m of the ground surface before being topped with 0.6 m of crushed tuff and sealed with a cement cap 0.9 m thick. They are usually drilled in groups and spaced on 2.3 to 3.7 m centers.

Waste High in Beta-Gamma Activity

Because all solid wastes prior to 1970 were classified as nonretrievable, there are some buried solid wastes high in beta-gamma emitters. Although almost all the solid TRU wastes high in beta-gamma concentration were packaged in special containers (to minimize beta-gamma exposure), most has been buried with the other TRU waste. There are some notable exceptions: at LANL there are concrete lined shafts; and at Hanford, some cases of nonretrievable caissons made of corrugated metal pipe and bored into the bottom of solid waste burial trenches.

ISV Applicability

Certain nonretrievable solid waste disposal sites may require additional stabilization, either by retrieval and processing or by in-situ methods. The need for additional stabilization and the risks associated with the stabilization alternatives will, no doubt, be carefully analyzed prior to selection of a processing scheme which may include ISV.

Most solid waste disposal sites are amenable to immobilization by ISV, provided that the system is designed to accommodate the high loading of soil inclusions. Trenches and pits do not exceed 8.8 m depth, well within the ISV depth range of 13.5 m. Some disposal shafts, however, may not be totally immobilized by the reference ISV system since they extend up to 18 m below grade. Use of a larger power system or future improvements in system design and operating procedure may permit vitrification to this depth. As with reverse wells, however, ISV could produce a durable vitrified cap, immobilizing part of the disposal shaft and providing an impermeable surface barrier above the lower contaminated zone.

Each waste site should be reviewed prior to ISV to determine whether a criticality limit exists. The safe upper limits for ^{239}Pu , the most abundant fissionable element, are delineated as follows:

- Areal concentration should not exceed 1.3 kg/m^2 . If the total mass is less than 0.8 kg, no areal concentration limit is imposed.
- Sites with metal or concrete waste containers should not have an areal concentration of greater than 1.1 kg/m^2 plutonium if hydro-generated organics are present.

Large metal inclusions, or a wide area of smaller metal inclusions in a solid waste burial ground, may cause an electrical short circuit between firing electrodes. This is possible since TRU burial grounds are up to 34 m wide and will require adjacent ISV operations, with electrodes placed directly in the waste, to vitrify. Electrodes placed directly in the waste may be shorted by a large process vessel or an area of 208ℓ (55 gal) metal waste drums, preventing startup. Waste sites which have a reasonable potential for shorting limitations should be identified by reviewing historical burial records or using metal detector or ground resistance systems prior to vitrification. Simulated waste with metal inclusions occupying over 70% of the firing electrode spacing has been vitrified without any difficulty during engineering-scale tests. Narrower trenches could have all electrode placements outside the waste burial zone; thus, waste with metal inclusions could be vitrified much more readily.

A miscellaneous waste trench typically contains up to 21 kg/m^3 combustibles which, upon decomposition by ISV, will produce a large volume of carbonaceous particulate and pyrolyzed gas. Based on data from engineering and pilot-scale tests, a full-scale ISV off-gas system must be sized to handle peak volumes of up to approximately $500 \text{ std m}^3/\text{min}$, ten times the reference system capacity. Most of the added capacity is to provide combustion air for the pyrolyzed gases. Engineering-scale and pilot-scale tests have shown that pyrolysis gas releases sporadically, and as such, an off-gas system should be operated at a lower flow rate with an on-demand capacity of $500 \text{ std m}^3/\text{min}$. The off-gas hood and off-gas line would be designed for high temperatures ($>1200^\circ\text{C}$) created by combustion of preheated pyrolysis gas and ejection of hot glass from the molten zone. The hood would be designed large enough to minimize hot glass contacting the ceiling or walls when gases are released from the

melt zone. An off-gas system designed to handle combustible waste sites is more than adequate to handle the water vapor generated from the thermal decomposition of concrete inclusions.

When gas generators are present, carryover of all elements (both hazardous and nonhazardous) to the off-gas system increases significantly. The protective cold cap is disturbed by gas passing through, and low resistance pathways from the molten zone to the surface are opened up.

Solid-waste burial grounds which contain, or are believed to contain, encased explosives should be treated with caution. A large ordnance item could detonate with enough energy to breach the surface and cause considerable spread of radioactive contamination. Size, type, and depth of burial must be considered. Up to 25% uncontained explosives and oxidizers present in the soil should behave similarly to combustibles and are not predicted to explode during ISV. If there is reason to suspect that contained explosives are present in a trench, a thorough search of historical burial records and procedures in effect at the time the waste was buried should be completed prior to ISV. Additional work is required to determine if only encased ordnance items, and not containerized explosives, will detonate.

No limitations are imposed upon ISV because of soil variations at the nine sites tested. A mathematical model predicts that high soil moisture contents and shallow water tables common to eastern sites will increase the total power required for ISV but will not reduce the attainable depth limit significantly unless a free-flowing aquifer is close to the waste site.

RETRIEVABLE WASTE STORAGE

Retrievable waste storage is divided into remote-handled and contact-handled waste. Contact-handled waste is defined as packaged waste containing less than 200 mR/h activity at the package surface, while remote-handled waste has greater than 200 mR/h activity. Most TRU waste generated today (99%) is stored in the contact-handled, retrievable form.

As shown in Table 13, most of the retrievable waste is stored at INEL. More than 90% of the waste stored at INEL is generated off-site, notably at Rocky Flats.

TABLE 13. Retrievable Waste Storage Inventory(a)

TRU Storage Site	Contact Handled		Remote Handled	
	m ³	%	m ³	%
Hanford	10,537	17.4	1119	65.2
INEL	42,370	70.1	17.8	1.0
LANL	4,352	7.2	13.6	0.8
NTS	235	0.4	0	0
ORNL	381	0.6	567	33.0
SRP	<u>2,555</u>	<u>4.2</u>	<u>0</u>	<u>0</u>
TOTAL	60,430	100	1717	100

(a) U.S. DOE 1981a and 1982a.

Site Descriptions

Contact-Handled Waste

The primary type of storage for contact-handled waste is the TRU pad, generic to all sites except ORNL. TRU pads are asphalt or concrete slabs, at or below ground level, on which metal drums, concrete drums, concrete culverts, or metal boxes are stacked up to 8 tiers high in a close-packed array, and then covered with soil. Usually plywood sheets and either vinyl covers or netting are used to maintain stacking integrity in the TRU site. A diagram of a typical TRU pad is shown in Figure 29.

The width and depth ranges of TRU pads nationwide are large and site dependent. Table 14 gives the TRU pad dimensions for various sites. Pads range from 7.3 to 45.7 m wide. Sites also differ in policies requiring segregation of combustible and noncombustible materials in TRU retrievable storage.

Contact-handled wastes at ORNL are stored in two concrete block buildings, 85% below grade (ORNL 1980). These buildings are 11.8 m wide and 17.5 m long; one building is 4.0 m deep with a metal roof, while the other building is 4.9 m deep with concrete plugs on the roof. Contact-handled waste is usually

FIGURE 29. Typical TRU Pad for Retrievable Transuranic Waste Storage at Hanford (Harmon and King 1980)

TABLE 14. Typical TRU Pad Dimensions

Site	Dimensions(a), m			Number of Tiers	Comments
	Width	Depth	Height		
Hanford(b)	7.3	1.8-3.0	3.0	4-5	See Figure 29
INEL	45.7	Surface	5.2-5.5	5	Filled in 24.4 x 45.7 m sections separated by 0.9 m of soil.
LANL	7.6	7.6	---	up to 8	No asphalt or concrete pad used.
SRP	15.2-18.3	Surface	~3.2	2	Cement casks and metal drums.

(a) Harmon and King 1980, Rogers 1977, U.S. DOE 1979b, and U.S. ERDA 1977.

(b) Waste segregated into combustible and noncombustible (after 1971).

packaged into 114 and 208ℓ (30 and 55 gal) stainless steel drums, although some black-iron drums were used in the early history of retrievability. Although miscellaneous and industrial wastes are usually packaged separately, at ORNL they are stored together. Because of the large amount of void space and ease of retrievability, ORNL's concrete building storage may be economically unsuitable for ISV.

Solidified liquid waste storage at LANL and the V-trench at Hanford are also classified as contact-handled storage sites. Transuranic liquid waste at LANL is often mixed into cement paste and pumped into 6.0 m long by 0.75 m dia corrugated metal pipe (CMP) for retrievable storage. These cemented pipes are placed on end, closely packed, in a trench 7.3 m wide and 5.8 m deep. As of December 1979, 155 pipe lengths had been filled with concrete (Walker et al. 1981). Initially, contact-handled waste at Hanford was stored in a concrete-lined V-trench with a depth of 3.7 m, a width of 7.3 m, and a height of 4.9 m (Figure 30). This trench had carbon steel drums stored diagonally against one of the 45° cut trench sides (lined with concrete). After all the drums had

FIGURE 30. Concrete Lined V-Trench Used for Early Retrievable Transuranic Waste Storage at Hanford (Harmon and King 1980)

been placed in the trench, they were covered with a metal liner and topped with 1.2 m of soil. The concrete-lined V-trench was replaced by the TRU pad after only a portion of the contact-handled TRU waste trench was filled.

Remote-Handled Waste

Remote-handled sites can be segregated into above-ground and below-ground storage. Most remote-handled waste (62%) is stored above ground in tunnels and caverns. Due to the ease of retrievability, the large void area, and a lack of sufficient soil, ISV of the above-ground sites currently appears impractical. Thus, this section will emphasize the description of below-ground remote handled storage sites.

Below-ground remote handled storage includes concrete and metal caissons at Hanford, steel cylinders at INEL, steel-lined concrete casks at LANL, and both stainless-steel-lined concrete wells and buried concrete casks at ORNL. By far the most abundant forms of below-grade remote handled storage are the 190 buried concrete casks at ORNL, and the 159 below-grade caissons at Hanford.

Buried concrete casks at ORNL are 1.3 to 1.4 m in diameter and 2.1 to 2.4 m high. Their wall thicknesses are either 11.4, 15.2 or 30.5 cm. Through 1979, concrete casks at ORNL were placed in unlined earthen trenches and back-filled with native soil. This practice ended in 1979, when the concept of storing the casks in cave-like structures was introduced.

The retrievable solid-waste burial caissons are used at Hanford to store 3.8, 7.6 and 18.9ℓ (1, 2, and 5 gal) paint cans of retrievable hot cell waste. A caisson consists of a 0.10 m thick concrete chamber, usually 3.0 m high and less than 3.0 m wide, into which these cans were transported by a bent 0.9 m diameter metal distribution pipe capped off with either concrete or steel lids. The burial depth of these concrete chambers ranges from 7.3 to 17.7 m. Figure 31 shows an elevation view of a typical caisson for remote-handled waste.

All remote-handled waste generated at LANL (13.6 m^3 as of December 1980) is stored in three trenches 4.0 m wide and 2.4 m deep. Inside each of these trenches are stored two rows of ~0.76 m diameter, ~1.8 m high concrete casks at 1.2 m spacings. Each cask holds two 115ℓ (30 gal) metal drums of waste

FIGURE 31. Typical Caisson for Remote-Handled Waste

contaminated with heat source plutonium. The trench is covered to 1.0 m above the top of the cask with tuff. After each cask is filled, the concrete lids are sealed with asphalt material.

All remote-handled waste at INEL (17.8 m^3 as of 12/80) is stored in steel-lined holes with closed bottoms and openable lids. Remote-handled waste is canned in 115ℓ (30 gal) drums and placed in the liners. The facility has been designed for 27 rows on 3.7 m centers with approximately 40 holes per row on 1.8 m centers.

Very high radiation level, beta-gamma TRU waste at ORNL is generated in relatively low volumes and packaged on a case-by-case basis. This waste consists mostly of fuel elements and similar material cut up for examination as part of ORNL's nuclear fuel program. This waste is stored in stainless-steel-lined wells of 3.0 to 4.3 m depth, 0.20 or 0.76 m diameters, and ~1.5 m centers.

ISV Applicability

In situ vitrification may be desirable at certain retrievable waste sites to enhance the retrievability of the waste. Risks associated with retrieval for final disposal at a deep geological repository could be reduced by converting the waste to a vitrified form which could be handled and transported more safely. Also, the ISV process could be used to provide "greater confinement" of the waste than that provided by retrievable storage alone. This would complement a repository in achieving permanent safe disposal of selected TRU wastes which are not easily retrievable.

Engineering features incorporated to provide 20-year retrievability of TRU waste increase the difficulty for processing by ISV. TRU pads and the single V-trench, which constitute most contact-handled wastes, may be unsuited for processing by ISV. Further study is required to identify how this waste can be readily vitrified. The waste is typically stored in 208L (55 gal) metal drums which are tiered and in a close pack. Several difficulties are encountered when applying ISV to this waste. Minimum site width is 7.3 m, exceeding the 5.5 m maximum practical electrode separation for the reference process; thus, a short circuit could occur during ISV. If desired, wider electrode spacing can be achieved by using a larger power system. Wider electrode separations may also be possible since retrievable waste typically has a high void fraction. Additional tests are required to determine the maximum separation under these conditions. Most drums do not have the soil backfill between them which is necessary to produce a continuous molten zone between electrodes. Molten glass formed in the startup zone may drain into the void areas, breaking the conductive startup path. If soil is added to the cover layer or between the drums, ISV of TRU pads may be possible.

A site-by-site criticality analysis should be performed to determine whether any limits are applicable. The areal plutonium concentration should not exceed 1.3 kg/m^2 (1.1 kg/m^2 if hydrogenated organics are present).

The contact-handled liquid waste pit at LANL is 7.3 m wide. The waste is mixed with cement to form a paste and is then stored in corrugated metal pipe (CMP) placed vertically in a close-packed array. The ISV process is not well

suited for this site, since the metal pipe provides a conductive path for the full width of the pit, which exceeds the 5.5 m practical limit for reference-system electrode separation. Underground building storage sites for contact-handled waste at ORNL are not suited for ISV because of the lack of soil, high void fraction, and ease of retrievability.

Several remote-handled waste types are more suitable for immobilization by the ISV process. Buried concrete casks at ORNL and steel-lined concrete casks at LANL could be processed by ISV fairly easily. The casks are buried in single rows and are less than 2.5 m deep. The off-gas system can be sized to handle combustibles which are present in the miscellaneous waste, and shielding may be added depending on the beta-gamma levels of radioactivity present.

Caissons at Hanford which are within the ISV depth range appear to be good candidates for immobilization. A single ISV operation could vitrify an entire caisson, provided the off-gas system is sized to handle the combustible wastes present. Steel cylinders at INEL and steel-lined wells at ORNL can be vitrified to 13.5 m with an enlarged off-gas system for combustibles.

CONCLUSIONS

Table 15 gives a summary of ISV applicability to TRU waste types. In situ vitrification of nonretrievable liquid disposal sites is straightforward with no major limits imposed. The process can also be applied to most nonretrievable solid disposal sites, as long as the off-gas system is properly sized for the type of waste and the electrodes are positioned to prohibit a short circuit when metal is present. The liquid and solid disposal sites constitute over 97 vol% of all TRU-contaminated waste. Transuranic pads, the V-trench, and corrugated metal pipe retrievable storage sites appear to be difficult to immobilize by ISV. Large expanses of adjacent metal drums may create a short circuit between electrodes. Many sites do not have soil in or around the waste drums. Other forms of retrievable waste which are more likely candidates for ISV include concrete casks, caissons, steel cylinders and steel-lined wells.

TABLE 15. Summary of ISV Applicability to TRU Waste

Waste	Ease of Solidification by ISV	Special Considerations
<u>Nonretrievable Liquid Disposal</u>		
Cribs and tile fields	Straightforward	Off-gas system would be sized to handle gas generation from wooden cribs. Metal inclusions should not exceed ~70% of the electrode spacing.
Absorption beds	Straightforward	none
Trench drains	Straightforward	Excavation of surface layer may be required to completely vitrify deepest site.
Liquid disposal trenches	Straightforward	none
Reverse wells	Straightforward for shallow wells	Deeper wells are beyond the predicted 13.5 m melting limit of the reference ISV system. Also, two or three reverse wells have high areal plutonium concentration, requiring further criticality analysis.
Ponds and ditches	Straightforward	none
<u>Nonretrievable Solid Disposal</u>		
Trenches	Possible with certain constraints	Off-gas system would be sized to handle gas generators from combustibles and concrete. No military ordnance items or other containerized explosives should be present. Metal inclusions should not exceed ~70% of the electrode spacing.

TABLE 15. (contd)

Waste	Ease of Solidification by ISV	Special Considerations
Pits	Possible with certain constraints	(same as trenches)
Shafts	Possible with certain constraints	(same as trenches) Deeper shafts are beyond the predicted 13.5 m melting limit of ISV.
<u>Retrievable Waste Storage</u>		
TRU pad	Difficult	Metal waste drums may provide an electrical shorting path between electrodes. soil may not be present between many drums. Off-gas system would be sized to handle gas generated from combustibles.
V-trench	Difficult	(same as TRU pad)
Corrugated metal pipe	Difficult	Corrugated metal pipe provides a shorting path between electrodes. Off-gas system would be sized to handle water vapor released from the cement.
Concrete casks	Possible with certain constraints	Off-gas system would be sized to handle gas generated from combustibles waste and cement.
Caisson	Possible with certain constraints	(same as Concrete casks)
Steel cylinders	Possible with certain constraints	(same as Concrete casks)
Steel-lined wells	Possible with certain constraints	(same as Concrete casks)

PROCESS CONSIDERATIONS

PROCESS CONSIDERATIONS

The final selection of a stabilization process for TRU waste sites will not only will be made on a basis of process limitations, it must also include consideration of other process attributes. In this section, preliminary analysis of three process considerations is discussed:

- Economics
- Operator exposure
- Product durability.

The presentation of these factors should allow for relative comparison to other alternative TRU waste management strategies (Walker et al. 1981, U.S. DOE 1982b). Analysis is first made for generic cases, but specific reference is made to the Hanford Z-12 crib when possible.

ECONOMIC ANALYSIS

The cost of ISV for a specific site is primarily affected by the geometry of the site and the power input. As previously discussed under "Geometry" in the Process Limit Analysis section, various electrode separations and electrode voltage taps are available for a specific geometry. The amount of overlap between each vitrified block and the amount of buffer zone on either side of the contaminated zone also affects total cost. Operating costs are mainly limited to electrode, manpower, and electrical power costs.

Two electrode materials have been successfully demonstrated for ISV use. The approximate cost of a molybdenum electrode, 7.6 cm dia and 6 m long, is \$25,000. Graphite electrodes are 25 times less costly than molybdenum electrodes. Electrode reuse would be required for molybdenum electrodes to be cost effective; but in the case of graphite, re-use, although feasible, is not required. Electrode costs may be amortized over multiple trenches if electrode reusability is demonstrated to be successful over several unit operations. Manpower costs for setup and removal of each vitrification process unit will be relatively fixed and independent of electrode separation. Thus, larger electrode spacings may be less costly, but the effect of electrode separation on depth and power requirements must also be considered. The other factor

related to manpower costs is the time required for vitrification. Increasing the power input to the system will reduce operating time and, thus, manpower costs. Electrical power costs vary with geographic region. An electrical energy cost of \$0.025 per kWh has been selected as a conservative number for Hanford. The national weighted average power cost for industrial service in 1981 was \$0.06 kWh (U.S. DOE 1981b). At around \$0.09 kWh, use of portable diesel generators becomes cost effective.

A cost of \$420/m³ of waste was estimated for ISV application to radioactive wastes already buried in trenches (Brouns and Timmerman 1982). For the purpose of the estimations, a generic trench containing 3000 m³ of waste was assumed to be completely vitrified, along with a buffer zone, which resulted in total vitrification volume of 4500 m³ (5 x 6 x 150 m long). Costs were based on a 10-yr equipment life and electrical energy costs of \$0.025 per kWh. At \$0.09 per kWh, the cost would be \$550/m³. Table 16 summarizes the cost of the ISV process per cubic meter of waste. Labor is the most significant cost; however, as previously mentioned, this could be reduced by increasing the power input to the system, thus reducing the operating time. For this estimate, an average power consumption of 2000 kW was selected.

A comparison of costs for ISV and several other in-situ stabilization methods for the generic 5 x 6 x 150 m trench is shown in Table 17. In situ vitrification is comparable to the cost of chemical grouting methods, and is a factor of 2 to 5 times more costly than cement grouting methods. Costs for excavation, encapsulation, and deep geological disposal are estimated to range from \$1800/m³ (Walker et al. 1981) to \$5500/m³ (Murphy and Holter 1980).

TABLE 16. Estimated Unit Cost for In Situ Vitrification
(1981 dollars)

<u>Cost Category</u>	<u>\$/m³ Waste</u>
Equipment	38
Labor	275
Materials	40
Power and fuel	<u>67</u>
TOTAL	420

TABLE 17. Cost for In-Situ Stabilization Alternatives
(1981 dollars)

Process	Total Cost for 5 x 6 x 150 m Trench, (a) \$ Millions	Unit Cost, \$/m ³ of waste
In Situ Vittrification	1.3	420
Cement	0.24	80
High Silicate Cement	0.7	230
Urea-Formaldehyde	1.4	480
Acrylamide	1.7	560

(a) Aroa et al. 1980, Brouns and Timmerman 1982.

Thus, costs for ISV and other in-situ stabilization methods are an order of magnitude below the cost of exhumation, processing, transportation and deep geological disposal. Grouting methods of stabilization result in encapsulated waste formations that are expected to be reasonably durable for between 25 and 100 years (Murphy and Holter 1980, Aroa et al. 1980). On the other hand, ISV produces a glass and crystalline waste form which is expected to remain relatively inert for thousands of years.

Estimated costs to stabilize the reference Z-12 crib were based upon four options:

1. 3.5 m electrode spacing (unexcavated) with a melt depth of 8 m
2. 3.5 m electrode spacing (unexcavated) with a melt depth of 12.5 m
3. 5.3 m electrode spacing (excavated 4 m) with melt depth of 3.5 m
4. 5.3 m electrode spacing (excavated 4 m) with melt depth of 5 m.

Details of the cost calculations are given in Appendix B and are summarized along with the data base in Table 18. The cost without excavation ranges from \$370 to \$400/m³; however, a reduction in cost is realized if 4 m of soil is excavated. Resulting costs are \$260 to \$300/m³. This is much less than the \$420/m³ of waste given for the generic 5 x 6 x 150 m trench. The difference illustrates the need to calculate costs for specific sites since electrode

TABLE 18. Cost to Stabilize Z-12 Crib by In Situ Vittrification

	Option			
	1	2	3	4
Excavation depth, m	0	0	4	4
Electrode spacing, m	3.5	3.5	5.3	5.3
Melt depth, m	8	12.5	3.5	5.0
Vitrified soil volume, m ³	8400	13,200	3700	5300
Number of ISV operations	66	66	28	28
Time per operation, h	110	180	72	98
Total time for Z-12, d	435	627	140	170
Total cost, \$1000	3306	4862	1115	1354
Cost per m ³ of vitrified soil, \$	394	368	301	255

spacing, and melt depth vary between sites and greatly influence labor costs. The option of excavating uncontaminated surface soil prior to ISV is very cost effective.

OPERATOR EXPOSURE

As in other in-situ stabilization processes, operator exposure is greatly reduced when compared to alternative processes which require considerable handling due to exhumation, processing, transport, and disposal. The ISV process is very simple; operator exposure would be obtained only during the brief periods of electrode placement, off-gas and electrode support frame placement, electrode and frame removal, and (if required) during backfill operations. The operator within the off-gas treatment system facility would also receive limited exposure.

To obtain a general knowledge of the dose rates, ISOSHLD calculations (Engel, Greenborg and Hendrickson 1966; Simmons et al. 1967) were performed for hypothetical radionuclide concentrations in a vitrified block, and in a water-filled effluent tank in the off-gas treatment system. The radionuclides used in the calculations were plutonium of three different ages, ¹³⁷Cs/^{137m}Ba,

^{60}Co , $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$. The quantities of these radionuclides were chosen to allow simple scaling, up or down, depending on actual predicted radionuclide concentrations.

The vitrified block was assumed to be a cube 1.83 m on each side, containing 100 g of plutonium. The computer model assumed a slab source 1.83 m x 1.83 m x 10 cm, with the dose points situated on a line perpendicular to a 1.83 m x 1.83 m face. The 10 cm slab thickness was chosen because it corresponds to about 16 mean free paths of the low-energy photons from plutonium; photons emitted from regions deeper than 10 cm would make a negligible contribution to the dose. Fission product content was assumed to be very low in the contaminated soil (as in the case for Z-12, Table 22) and was not considered in the vitrified block exposure calculations. Since volatile fission products may be concentrated in the effluent tank, they were considered in the off-gas system exposure calculations.

The off-gas effluent tank was assumed to be a cylinder 96.5 cm in diameter and 76.2 cm high, with a steel wall 3.2 mm thick. The tank was assumed to be full of water. Dose rates were calculated for four positions:

- Dose point 1: 7.6 cm from the tank wall, corresponding to a person leaning against the off-gas treatment facility
- Dose point 2: 46 cm from the tank wall, corresponding to a person walking near the treatment facility system
- Dose point 3: 5.1 cm from the tank wall, inside the facility, where a person may be performing maintenance
- Dose point 4: 9.1 m from the back edge of the facility, positioned where process monitoring and control data acquisition equipment may exist.

Dose points 1 and 2 were assumed to have one extra shield besides the tank wall between the contaminated water and the dose point. This shield corresponds to the facility wall, and it was modeled as a steel sheet of thickness 3.0 mm. Dose points three and four were assumed to have one extra shield besides the tank wall, a 6.4 mm-thick sheet of safety glass.

The calculated dose rates due to radionuclides in the vitrified block and in the effluent tank are presented in Tables 19 and 20. The radionuclide concentrations for these configurations were not chosen to reflect the concentrations that have been predicted to occur, but were chosen to give values that can easily be scaled up or down depending on postulated concentrations. Thus, the dose rates presented in Tables 18 and 19 are not necessarily the dose rates that would be expected to occur during the ISV operations. Dose rates due to radionuclide concentrations that are predicted to be either in a vitrified block or effluent tank can be determined by multiplying the appropriate calculated dose rate by the ratio of the predicted concentration to the concentration used in these calculations.

A second ISOSHL D computer code calculation was conducted to determine the dose rate from the Hanford Z-12 trench selected as a reference in this report. The following calculations were performed:

- undisturbed trench, with 0.30 m of uncontaminated soil on top
- undisturbed trench, with no soil on top
- vitrified block, with all plutonium and americium on one face
- vitrified block, with all isotopes evenly distributed throughout the block.

The radionuclides were assumed to be uniformly distributed throughout the Z-12 crib. Since the plutonium inventory was stated in terms of grams of plutonium, it was necessary to assume an isotopic composition. The composition assumed for this study corresponds to that typical of defense wastes, and is presented in Table 21. The ^{241}Am content was calculated assuming a build-in

TABLE 19. Calculated Dose Rates Due to a Vitrified Block

Distance from Face of Block (cm)	Dose Rate (R/hr) due to 100 g of each contaminant		
	Pu-10 Years	Pu-20 Years	Pu-30 Years
1	3.38×10^{-5}	5.21×10^{-5}	6.32×10^{-5}
30	3.16×10^{-5}	4.89×10^{-5}	5.94×10^{-5}
100	1.46×10^{-5}	2.28×10^{-5}	2.77×10^{-5}

TABLE 20. Calculated Dose Rates Due to Effluent Tank

Dose Point	Dose Rates due to Radionuclides, R/h						
	1.0 Ci $^{137}\text{Cs}/^{137\text{m}}\text{Ba}$	1.0 Ci ^{60}Co	1.0 Ci $^{90}\text{Sr}/^{90}\text{Y}$	1.0 Ci $^{106}\text{Ru}/^{106}\text{Rh}$	100g Pu-- 10 Year	100g Pu-- 20 Year	100g Pu-- 30 Year
1	0.39	1.92	2.93×10^{-3}	6.98×10^{-2}	2.26×10^{-5}	2.38×10^{-5}	2.44×10^{-5}
2	0.12	0.595	9.77×10^{-4}	2.24×10^{-2}	8.56×10^{-6}	9.02×10^{-6}	9.27×10^{-6}
3	0.14	0.603	1.17×10^{-3}	2.54×10^{-2}	2.49×10^{-5}	3.35×10^{-5}	3.87×10^{-5}
4	1.41×10^{-3}	6.17×10^{-3}	1.12×10^{-5}	2.49×10^{-4}	2.33×10^{-7}	3.16×10^{-7}	3.66×10^{-7}

TABLE 21. Typical Defense Waste Plutonium
Isotopic Compositions

<u>Isotope</u>	<u>Weight%</u>
^{238}Pu	0.007
^{239}Pu	93.288
^{240}Pu	6.398
^{241}Pu	0.169
^{242}Pu	0.138
^{241}Am	(decayed from ^{241}Pu)

that began during the trench's period of service and continued to March, 1982. The build-in time period for Z-12 was taken as 16 years.

Table 22 lists the quantity of each radionuclide used in the calculations (Maxfield 1979). The "Full Crib Inventory" is the total amount of radionuclides contained in the whole crib and the "Radionuclide Concentrations" are listed in Ci/cm^3 . These values are assumed to be constant throughout the entire crib. The crib was assumed to consist of soil at a density of 1 g/cm^3 . This density is probably low by about 50%, introducing another factor of conservatism. The slab shield above the crib for the covered-crib calculations was assumed to also consist of soil at 1 g/cm^3 .

For a worst-case calculation, all TRU isotopes were assumed to migrate to one face of the vitrified block ($1.52 \times 1.52 \times 1.83 \text{ m}$ for this case). No shielding was assumed to be between the contaminated face and the dose points. The non-TRU radionuclides were assumed to be uniformly distributed throughout the block. A test calculation showed that the non-TRU isotopes contributed well under 0.1% to the dose, so they were ignored in this set of calculations. The quantity of TRU radionuclides distributed in the block was found by multiplying the radionuclide concentration from Table 22 by the volume of the block.

For a more realistic calculation of the dose rate from a vitrified block, a set of calculations was performed with all of the radionuclides uniformly distributed throughout a block. The source region for this set of calculations was modeled as a rectangular solid 1.52 m by 3.00 m by 10 cm deep. The 10 cm depth was chosen to avoid excessive computer computational time: the dose rate

TABLE 22. Radionuclide Inventory and Concentration in Z-12 Crib(a)

Radionuclide	Full Crib Inventory, Ci	Radionuclide Concentration, Ci/cm ³
⁶⁰ Co	0.011	3.24×10^{-12}
⁹⁰ Sr	0.063	1.85×10^{-11}
⁹⁰ Y	0.063	1.85×10^{-11}
¹⁰⁶ Ru	3.25×10^{-4}	9.56×10^{-14}
¹⁰⁶ Rh	3.25×10^{-4}	9.56×10^{-14}
¹³⁷ Cs	0.063	1.85×10^{-11}
²³⁸ Pu	29.9	8.80×10^{-9}
²³⁹ Pu	1440	4.24×10^{-7}
²⁴⁰ Pu	353	1.04×10^{-7}
²⁴¹ Pu	4284	1.26×10^{-6}
²⁴² Pu	0.14	4.12×10^{-11}
²⁴¹ Am	69.9	2.06×10^{-8}
²³³ U	2.22×10^{-5}	6.53×10^{-15}
²³⁴ U	2.28×10^{-5}	6.71×10^{-15}
²³⁵ U	6.90×10^{-7}	2.03×10^{-16}
²³⁸ U	1.66×10^{-5}	4.89×10^{-15}
²³⁴ Th	1.66×10^{-5}	4.89×10^{-15}
^{234m} Pa	1.66×10^{-5}	4.89×10^{-15}
²³¹ Th	6.90×10^{-7}	2.03×10^{-15}

(a) Data from Maxfield 1979 decay corrected to 2/30/82

is primarily due to low-energy X-rays emitted by plutonium isotopes, and 10 cm corresponds to about 16 mean free paths of these X-rays. Thus any radiation emitted from points deeper than 10 cm would contribute almost nothing to the dose rate. The quantity of radionuclides for this set of calculations was found by multiplying the radionuclide concentrations from Table 22 by the volume of the source region, 1.52 m x 1.83 m x 10 cm. Dose rate calculations for the uncovered and covered (0.30 m) Z-12 crib are presented in Table 23. The dose points are considered to be above the center of the crib, which is the position receiving the highest dose rate.

TABLE 23. Calculated Dose Rates from Z-12 Crib

<u>Condition</u>	<u>Calculated Dose Rate, mR/h</u>
Surface of uncovered crib	0.605
Surface of covered crib	1.12×10^{-3}
1 m above uncovered crib	0.407
1 m above covered crib	1.12×10^{-3}

The dose rate due to a vitrified block was calculated for seven points distributed along a line through the center of a 1.52 m x 1.83 m face. For TRU isotopes concentrated at this face, the dose rates were calculated at all seven points. For the TRU isotopes distributed evenly through the block, only four of these points were used. These four points were sufficient for making a good comparison. The results of these calculations are presented in Table 24.

The calculated dose rates due to the uncovered crib are less than 1 mR/h. This dose rate should allow workers to work at that point with few restrictions, since a worker spending 40 h/wk for 50 weeks in a 1 mrem/h field would incur a dose of 2 rem, well below the annual limit of 5 rem. (Adequate monitoring would, of course, be necessary to ensure that dose rates were indeed sufficiently low.) The addition of a 0.30 m cover of soil over the crib increases the margin of safety, with all doses well under 1 mrem/h.

A vitrified block of Z-12 soil would give high dose rates if all of the TRU isotopes were deposited on one face of the block, with no shielding on top of it. A worker could be near this source for no more than a few minutes at a time to avoid overexposure. Since the radionuclides would likely be uniformly distributed throughout the block, however, the dose rates would be much more reasonable—no more than 1 mR/h, which illustrates the importance of shielding. In reality, radionuclides would not be totally distributed on the outside surface of a block, but in a worst case would probably be distributed in an outer layer of the block. This type of distribution would provide a great deal of additional shielding, since most radionuclides would have at least a thin film of shield above them.

TABLE 24. Dose Rates Due to a Vitrified Block of Z-12 Soil

Distance From Face, cm	Dose Rates, mR/h (Isotope Distribution)	
	Face	Block
1	1850	—
10	846	1.18
25	478	—
50	242	0.34
100	83.9	0.12
150	36.0	—
200	17.6	0.027

PRODUCT DURABILITY

Leach resistance studies have been performed on both nonradioactive and radioactive vitrified soil samples. Two types of leach studies have been performed in ISV field tests (Brouns and Timmerman 1982): 24 h soxhlet in 99°C deionized water and 28 d MCC-1 (Material Characterization Center 1981) tests in 90°C solutions of deionized water, silicate water, and brine. Figure 32 shows the resulting total weight loss per day during soxhlet leaching. For comparison, published data on typical commercial glasses and some common minerals which have existed in nature for millions of years have been included (Platt 1973, McElroy 1975). Leaching results show that the vitrified soil has a bulk leach rate significantly better than granite, marble, or bottle glass and comparable to Pyrex.®

Results from leach resistance tests using a 28 d MCC-1 test in 90°C solutions are presented in Table 25, along with other waste glasses for comparison. The MCC-1 results show an improvement over proposed defense and commercial waste glasses. In another MCC-1 28 day test in 90°C deionized water, it was shown that normalized elemental losses of cesium and strontium from the vitrified Hanford soil were comparable to these from PNL 76-68 (in fact, cesium release was less by a factor of 5 for the vitrified soil).

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FIGURE 32. Comparative Leach Resistance of Selected Materials

Leach tests were also conducted on vitrified Z-12 soil samples using the MCC-1 test method. A soil sample (200 g) was obtained from well drilling No. 182 of the Hanford Z-12 crib (Kasper 1981). The soil was vitrified in a crucible placed within a resistance-heated laboratory furnace. The furnace was programmed to dry the soil before heating to the vitrification temperature of 1600°C. After 2 h at 1600°C, the melt was furnace-cooled to 800°C, held there for 2 h, and then furnace-cooled at 100°C/h.

The vitrified melt was radioactively nonsmearable and free of major cracks, allowing easy cutting of the samples for the MCC-1 leach test, 28-day matrix, in deionized water at 90°C. Both unvitified and vitrified Z-12 soil were sampled for chemical analysis. The nonradioactive chemicals were analyzed by ion-coupled plasma spectroscopy (ICP), and the americium and plutonium by total alpha counting followed by plutonium stripping and alpha recounting.

TABLE 25. Leach Resistance of Vitrified Hanford Soil

Waste Form	Normalized Elemental Loss, g/m ² (a)				
	Si	Na	Ca	Al	Fe
<u>Deionized Water</u>					
In Situ	2	2	2	1	1
Commercial ^(b) (PNL 76-68)	36	54	0.3	--	<0.01
Defense ^(b) (SRL-131)	46	107	<0.1	6	<0.01
<u>Silicate Water</u>					
In Situ	3	<0.03	3	4	2
Commercial ^(b) (PNL 76-68)	36	60	<0.3	---	<0.01
<u>Salt Brine</u>					
In Situ	<0.01	--	4	<0.05	<0.01
Commercial ^(b) (PNL 76-68)	8	--	33	--	<0.01

(a) MCC-1: 90°C, SA/V = 10 m⁻¹, 28 d

(b) Strachen, Turcotte and Barnes 1980

The MCC-I leach test results are listed in Table 26 along with the results for three other TRU waste forms (Ross et al. 1982). This comparison with other TRU waste forms and the 76-68 MCC control sample allows a relative evaluation of the benefits from ISV melting Z-12 crib soil. The overall leach rate of the Z-12 soil glass is better than the reference 76-68 glass and other TRU waste forms. However, there is a markedly higher release of plutonium from the Z-12 soil glass, compared to the borosilicate and aluminosilicate glasses. Plutonium in aqueous solution is pH dependent (Rai and Ryan 1981), but the data masks the pH effect on the analytical solution because of the inclusion of plutonium plateout on the container wall. This is a procedural requirement of the MCC-1 test, which does not separate leach solution content from the container plateout content. The pH data shows no trend towards total plutonium release. Similarity in plutonium release from the Z-12 crib soil glass and basalt glass ceramic indicates that the plutonium, in both waste forms, may be in a form (e.g., associated with crystalline phases) that is more readily

TABLE 26. MCC-1 Leach Test Results for TRU Waste Forms

Waste Form	Leach Time, d	Elemental Release, (a) g/m ²							pH
		Al	Ca	Fe	Na	Si	Pu	Am	
Z-12 ISV glass	3	6.11 E-2	2.00 E-1	2.64 E-2	--	1.64 E-1	2.97 E-2	1.41 E-2	7.1
	7	7.14 E-2	5.57 E-1	5.40 E-2	2.89 E-1	5.16 E-1	3.43 E-2	4.63 E-2	6.9
	14	7.34 E-1	1.51 E0	4.32 E-2	7.07 E-1	1.44 E0	4.80 E-2	1.81 E-2	7.9
	28	1.05 E0	2.10 E0	1.63 E-1	1.03 E0	2.03 E0	6.68 E-2	3.58 E-2	8.2
Borosilicate Glass ^(b)	3	4.26 E-1	1.33 E0	2.46 E0	2.27 E0	2.33 E0	6.45 E-3	--	5.46
	7	3.72 E-1	2.69 E0	3.91 E-1	2.91 E0	3.32 E0	7.88 E-3	--	7.05
	14	8.71 E-1	3.62 E0	9.43 E-1	4.62 E0	4.27 E0	6.45 E-3	--	6.46
	28	3.22 E0	4.49 E0	5.8 E-2	1.52 E-1	1.21 E-1	2.9 E-3	--	9.46
Aluminosilicate Glass ^(b)	3	6.93 E-1	3.53 E0	1.54 E0	4.40 E0	2.25 E0	1.44 E-3	--	4.67
	7	8.07 E-1	3.73 E0	2.21 E0	5.23 E0	3.51 E0	2.88 E-3	--	5.19
	14	7.84 E-1	4.04 E0	1.97 E0	6.17 E0	4.51 E0	1.44 E-3	--	6.57
	28	3.03 E0	5.05 E0	1.92 E0	9.0 E0	6.62 E0	4.8 E-3	1.11 E-2	9.06
Basalt Glass Ceramic ^(b)	3	9.98 E-1	1.01 E0	5.86 E-1	2.10 E0	8.27 E-1	4.02 E-2	--	3.95
	7	1.10 E0	1.25 E0	1.18 E-1	1.71 E0	1.29 E0	4.69 E-2	--	3.93
	14	1.55 E0	1.67 E0	1.02 E0	3.05 E0	1.88 E0	1.67 E-1	--	4.29
	28	1.6 E-1	8.6 E0	--	1.7 E0	1.0 E0	3.2 E-2	5.6 E-2	5.60
76-68 Glass (control)	28	1.70 E-1	1.05 E0	6.59 E-1	2.60 E-1	1.81 E-1	--	--	9.58

(a) Leached in deionized water at 90°C

(b) Ross et al. 1982

leached. The 1600°C melt temperature is less than the 1700°C (plus) temperatures obtained during ISV. Thus some unmelted or crystalline material might be present in the crucible melt. Leach resistance studies on nonradioactive vitrified soil containing large fractions of crystalline products have indicated that devitrification or crystalline phases are not detrimental to leach resistance. In fact, some improvement has been observed for samples containing crystalline phases. Thus, the mechanism of plutonium leachability in vitrified soils needs further study. Even considering the plutonium anomaly, leach testing has shown the ISV process to generate a highly durable waste form. This is especially true since the surface area of the ISV waste form is much lower than that of the unvitified soil.

CONCLUSIONS

In addition to process limitations, other process attributes must be considered in the evaluation of the application of ISV to the stabilization of TRU waste. Preliminary analyses of process considerations such as economics, operator exposure, and product durability have been very favorable. In situ vitrification process costs are comparable to other in-situ stabilization methods. When compared to excavation, processing, and disposal processes, all in-situ stabilization processes are less costly by at least an order of magnitude. Estimated costs for vitrification of the Z-12 crib at Hanford range from \$3.3 to \$4.9 million. Costs can be further reduced to between \$1.1 and \$1.4 million by excavating 4 m of uncontaminated soil and vitrifying to a smaller depth.

Operator exposure inside the off-gas system facility is within suggested guidelines. Dose rates due to an uncovered crib were calculated to be less than 1 mR/h, which should allow workers access with only a few restrictions. The addition of 0.3 m of cover would greatly reduce exposure to ≤ 1 mrem/h. In the unlikely event that all of the radionuclides were concentrated within one face of the vitrified block, workers could only be present for a few minutes. With the expected uniform distribution, dose rates would be no more than 1 mR/h.

The leach resistance of vitrified Hanford soil is comparable to that of Pyrex glass and other nuclear waste forms. When the observed low leach rates are combined with the expected large particle size (low surface area), total dissolution from the vitrified waste if it were immersed in ground water is estimated to be less than 10^{-5} parts per year.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

In situ vitrification is an attractive process, well suited for solidification of most in-ground TRU wastes. The process converts contaminated soil and buried waste into an extremely durable glass and crystalline material. An applications analysis has been performed to identify any process limitations which may be imposed by TRU wastes. Economics, operator exposure and product durability have been included in the analysis.

Several conclusions have been made regarding the applicability of ISV for solidification of TRU wastes:

- Over 97 vol% of all in-ground TRU waste is disposed of in a form which appears to be processable by ISV.
- Liquid disposal sites, which account for approximately 81 vol% of the waste inventory, are best suited for solidification by ISV. With the exception of several deep reverse wells at Hanford, no major process limits have been identified.
- Most nonretrievable solid burial grounds can be processed by ISV. The off-gas system would be sized for the type of waste and the electrodes would be positioned to prohibit a short circuit when metal is present.
- Certain remote-handled retrievable stored wastes, such as caissons and concrete casks, appear to be processable by ISV. Contact-handled waste, such as that stored on TRU pads, poses special problems.
- Estimated costs for vitrification of the Z-12 crib at Hanford range from \$3.3 to \$4.9 million. If 4 m of noncontaminated soil is excavated prior to ISV, cost can be further reduced to between \$1.1 and \$1.4 million.
- Leachability of vitrified soil from Hanford compares closely to that of pyrex glass and is significantly better than granite, marble, or bottle glass. Total release from the waste form is estimated to be less than 10^{-5} parts per year.

- The predicted geometric limits of a reference full-scale 3000 kW, 4160 V ISV system in Hanford soil are 6.9 m width and up to 13.5 m depth. The electrode separation must be decreased to 3.5 m to obtain the maximum melt depth. These geometric limits can be increased by using a power supply larger than the reference 3000 kW system. The reference size is based on the largest readily available portable generating unit.
- Soil moisture increases the time and power required to vitrify a waste site; however, the effect on the maximum attainable geometric limits of ISV are small. Based on data from a mathematical model, fully saturated ORNL soil can be vitrified to a depth of 5.3 m if the water table is at ground level and an aquifer is located at 6.4 m depth.
- Soil from nine different U.S. locations were tested and found to be similar in the properties which could affect the ISV process. Properties of the soils are within the limits of the ISV process.
- Dose rates during ISV are calculated to be 1 mR/h directly above an uncovered crib. This should allow worker access with few restrictions.
- No credible concentration mechanism for ^{239}Pu or other TRU fissionable isotopes has been identified. The ISV melt zone has strong convective currents which promote dilution and thorough mixing of waste species.
- Calculations show that TRU waste sites with areal plutonium concentrations less than 1.3 kg/m^2 can be vitrified safely without a criticality. Sites which contain hydrogenated organics in waste containers are limited to an areal plutonium concentration less than 1.1 kg/m^2 .
- Metallic inclusions do not significantly affect ISV unless a full electrical short circuit is approached. An engineering-scale ISV test successfully demonstrated that metal occupying over 70% of the electrode spacing, and accounting for 5% of the final block weight, can be vitrified.

- Cement and concrete inclusions within a waste site fracture as they are heated during ISV. Strong convective currents within the melt promote distribution and dissolution of the fragmented pieces. Two engineering-scale tests have verified that there is complete dissolution of the cement within the glass waste form.
- Calcium within cement increases the electrical resistivity of vitrified soil during ISV; however, the ISV power input will not become limited unless the cement is at, or near, the soil surface.
- Water vapor is released during ISV of cement and concrete inclusions. The off-gas system capacity would be enlarged up to 10% for large concrete inclusions and up to 100% for large cement inclusions to accommodate the added water vapor volume.
- High-melting ceramic materials do not dissolve during ISV; rather, they are encapsulated within the vitrified zone.
- Buried combustible waste is pyrolyzed by the high ISV temperature and limited oxygen supply in the soil. Upon release from the molten soil, pyrolysis products ignite and burn sporadically in the containment hood.
- The off-gas system required for ISV of a buried combustible-waste trench should have an "on-demand" capacity of approximately ten times that of the reference off-gas system used for ISV of contaminated soil.
- Intact military ordnance items will explode upon heating. If ordnance items or other contained explosives are suspected within a waste site, careful study of possible type, depth, size, and other factors is required.
- A preliminary evaluation indicates that up to 25 wt% of uncontained explosives in soil can be safely processed by ISV. Explosives melt and become dispersed within the soil before the temperature is reached at which a self-propagating explosion can occur.

Several recommendations have been made as to the future direction of the ISV TRU application analysis program:

- Use a systems analysis approach to identify which TRU sites would benefit from ISV solidification.
- Perform an ISV process safety analysis.
- Continue the pilot-scale ISV test program to verify predictions as to:
 - off-gas system design for a combustible waste site
 - underground burning of combustibles adjacent to an ISV operation
 - effects of soil moisture.
 - effects of large cement and concrete monoliths
 - width and depth limitations.
- Perform additional work to determine the extent of explosives limitations at TRU waste sites. Types of possible explosives should be identified and the effects of size, distribution and burial depth should be evaluated.
- Investigate methods to solidify large arrays of buried metal inclusions such as a field of 208& (55 gal) waste drums.

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APPENDIX A

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APPENDIX A

TRU CONTAMINATED LIQUID DISPOSAL SITES AT HANFORD

TABLE A.1. TRU Contaminated Liquid Disposal Sites^(a) at Hanford

Site No.	Dimensions, m (Length x Width x Depth)	Contamination(b)				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
<u>Cribs and Tile Fields</u>						
216-A-2	6.1 x 6.1 x 8.5	130	3.5	7.7	0.21	Rock-filled
216-A-4	6.1 x 6.1 x 7.6	140	3.8	33	0.89	Rock-filled
216-A-5	10.7 x 10.7 x 9.8	65	0.57	180	1.6	Rock-filled
216-A-10	84 x 13.7 x 4.6	340	0.30	3500	3.0	Rock-filled
216-A-21	18.3 x 4.9 x 5.8	150	1.7	258	2.9	Gravel-filled
216-A-22	1.8 dia. x 4.9	NA ^(c)	NA	<1	<0.4	Rock-filled
216-A-27	61 x 3.0 x NA	97	0.52	260	1.4	Sand-filled
216-A-30	427 x 3.0 x 3.7	<71	<0.06	710	0.54	Crushed-stone-filled
216-A-31	21.3 x 3.0 x NA	9	0.13	580	8.7	Gravel-filled
216-A--36A	30.5 x 3.4 x 7.6	80	0.78	7000	68	Gravel-filled
216-A-36B	153 x 3.4 x NA	<180	<0.35	5700	11	Crushed-stone-filled
216-A-41	3.0 x 3.0 x 1.8	NA	NA	<1	<0.1	Gravel-filled
216-B-7A	4.3 x 4.3 x 4.3	4300	117	6800	186	Wooden structures
216-B-7B	4.3 x 4.3 x 4.3					

(a) Defined as sites containing >0.04 g Pu/m². 1) Estimated from plant discharge data, 2) based on the definition of TRU as >10 nCi/g and 3) assumes that most of the Pu is located in the top 0.15 m of soil.

(b) Inventory as of December 31, 1973 (Harmon 1980).

(c) NA - not available.

TABLE A.1. (contd)

Site No.	Dimensions, m (Length x Width x Depth)	Contamination				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
216-B-8	3.7 x 3.7 x 4.3 (92 x 1.2 x 4.3 tile field)	30	2.2	73	5.4	Wooden structure
216-B-9	4.3 x 4.3 x 4.0 (55 x 1.2 x 5.2 tile field)	170	2.1	31	0.39	Wooden structure
216-B-10-A	4.3 x 4.3 x 6.1	9.8	0.54	6.8	0.37	Wooden structure
216-B-12	49 x 15.2 x 9.1	370	0.50	2400	3.3	Wooden structure
216-B-14	12.2 x 12.2 x 4.0	25	0.17	870	5.9	Steel, concrete and wood
216-B-16	12.2 x 12.2 x 4.0	10	0.07	1800	12	Steel, concrete and wood
216-B-17	12.2 x 12.2 x 4.0	10	0.07	490	3.3	Steel, concrete and wood
216-B-18	12.2 x 12.2 x 4.0	10	0.07	580	3.9	Steel, concrete and wood
216-B-19	12.2 x 12.2 x 4.0	10	0.07	620	4.2	Steel, concrete and wood
216-B-44	9.1 x 9.1 x 4.3	15	0.18	4500	54	Concrete slab cover Supported by concrete pipe
216-B-45	9.1 x 9.1 x 4.3	10	0.12	5500	66	Concrete slab cover supported by concrete pipe
216-B-46	9.1 x 9.1 x 4.3	20	0.24	2200	26	Concrete slab cover supported by concrete pipe

TABLE A.1. (contd)

Site No.	Dimensions, m (Length x Width x Depth)	Contamination				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
216-B-47	9.1 x 9.1 x 4.3	5.0	0.06	980	12	Concrete slab cover supported by concrete pipe
216-B-48	9.1 x 9.1 x 4.3	5.0	0.06	2300	27	Concrete slab cover supported by concrete pipe
216-B-49	9.1 x 9.1 x 4.3	15	0.18	4000	48	Concrete slab cover supported by concrete pipe
216-B-52	177 x 3.0 x 2.4(+)	19	0.04	470	0.87	Wood cover
216-C-1	7.0 x 2.4 x 4.0	8	0.62	270	16	Concrete
216-C-4	6.1 x 3.0 x 4.9	1	0.05	36	1.9	Gravel-filled
216-C-5	6.1 x 3.0 x 4.9	1	0.05	13	0.69	Gravel-filled
216-S-1 and 2	28 x 12.2 x 11.3	1200	3.6	7500	22	Wooden structure
216-S-3	6.1 x 6.1 x 1.8	0.5	0.05	63	6.8	
216-S-5	64 x 64 x 4.6	580	0.14	240	0.06	Gravel-filled
216-S-6	64 x 64 x 4.6	470	0.11	970	0.23	Gravel-filled
216-S-7	30.5 x 15.2 x 7.3	440	0.95	6500	14	
216-S-9	92 x 9.1 x 9.1	65	0.08	1300	1.6	Gravel-filled
216-S-13	12.2 x 12.2 x 10.1	8	0.05	12	0.08	Wooden structure

TABLE A.1. (contd)

Site No.	Dimensions, m (Length x Width x Depth)	Contamination				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
216-S-20	27.4 x 12.2 x 8.8	170	0.51	250	0.76	Wooden structure
216-T-5	15.2 x 3.0 x 7.6	180	3.9	90	1.9	
216-T-6	27.4 x 4.3 x 7.9	390	3.3	690	5.9	
216-T-7	3.7 x 3.7 x 7.9 (2434 m ² tile field)	130	0.05	134	0.05	Wooden structure
216-T-8	3.7 x 3.7 x 7.6	5	0.04	2.3	0.02	Wooden structure
216-T-12	4.6 x 3.0 x 2.4	1	0.07	19	1.3	
261-T-18	3.0 x 3.0 x 3.0	1800	190	78	8.3	Concrete
216-T-26	9.1 x 9.1 x 4.6	59	0.70	1090	13	Concrete
216-T-27	9.1 x 9.1 x 4.6	13	0.16	400	4.7	Concrete
216-T-28	9.1 x 9.1 x 4.6	70	0.84	1400	17	Concrete
216-T-32	20.7 x 4.3 x 7.9	3200	36	61	0.7	Wooden structure
216-T-33	9.1 x 1.5 x 3.4	5.0	0.36	2.0	0.14	Gravel-filled
216-T-34	61 x 9.1 x 4.9	110	0.19	1300	2.3	Gravel-filled
216-T-35	137 x 3.0 x 4.6	66	0.13	83	0.21	Rock-filled
216-U-1	4.3 x 4.3 x 7.3	43	1.2	19	0.52	Wooden structures
216-U-2	4.3 x 4.3 x 7.3					
216-U-8	50 x 15.2 x 9.4	370	0.50	2.7	0.01	Wooden structure
216-Z-1	4.3 x 4.3 x 5.2	7000	385	0.24	0.01	Wooden structure
216-Z-2	4.3 x 4.3 x 5.2					

TABLE A.1. (contd)

Site No.	Dimensions, m (Length x Width x Depth)	Contamination				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
216-Z-1A through -1AC	(Boundaries Undefined)	58,000	24	2.3	<0.01	Tile field
216-Z-3	21.3 x 1.5 x 7.6	5700	175 (ave)	0.32	0.01	Rock-filled
216-Z-4	3.0 x 3.0 x 4.6	2.0	0.22	0.2	0.02	Hole
216-Z-5	24.4 x 4.3 x 7.3	340	3.3	150	1.5	Wooden structure
216-Z-6 and 6A	15.2 x 1.8 x 0.6	5.0	0.18	0.2	0.01	Wooden structure
216-Z-7	42.7 x 1.5 x 11.0	2000	15.4	1200	9.3	Two wooden
structures						
216-Z-9	37 x 27.4 x 6.1	38,000 ^(d)	229 ^(d)	0.3	<0.01	Cavern, concrete
roof						
216-Z-12	91 x 6.1 x 6.1	25,000	42	0.6	0.001	Gravel-filled
216-Z-16	55 x 3.0 x 4.6	<700	<0.43	<0.2	<0.001	Rock-filled
216-Z-18(5)	63 x 3.0 x 6.1 (each crib)	22,900	23	NA	<0.04	Fine-rock-filled cribs
French Drains						
216-A-11	0.8 dia. x 9.1	NA	NA	<50	<100	
216-A-12	0.8 dia. x 9.1	NA	NA	<50	<100	
216-A-13	0.6 dia. x 5.5	NA	NA	<1	<3	
216-A-14	0.8 dia. x 8.8	NA	NA	<<1	<<2	
216-A-15	0.6 dia. x 13.4	NA	NA	<50	<133	

(d) Prior to excavation.

TABLE A.1. (contd)

Site No.	Dimensions, m (Length x Width x Depth)	Contamination				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
216-A-16	1.2 dia. x 5.2	NA	NA	<10	<8	
216-A-17	1.2 dia. x 5.2	NA	NA	<1	<0.8	
216-A-23A	1.1 dia. x NA	NA	NA	<50	<4.4	
216-A-23B	1.1 dia. x NA	NA	NA	<5	<6	
216-A-26A	0.9 dia. x NA	NA	NA	<1	<1.4	
216-A-26B	1.2 dia. x NA	NA	NA	<1	<0.8	
216-A-33	1.8 dia. x NA	NA	NA	<1	<0.4	
216-A-35	1.8 dia. x NA	NA	NA	<1	<0.4	
216-B-13	1.2 dia. x 5.5	NA	NA	<1	<0.8	Limestone-filled, Wood cover
216-B-51	1.5 dia. x NA	NA	NA	<10	5.6	Wood cover
216-T-29 ^(e)	30.5 x 14.6 x 1.1	NA	NA	<8	<8	
216-U-7	0.8 dia. x NA	NA	NA	<1	<2	
216-Z-8	0.9 dia. x 5.2	484	735	NA	NA	Concrete
<u>Trenches</u>						
216-B-42	77 x 3.0 x 3.0	10	0.04	1500	6.4	
216-B-53-A	18.3 x 3.0 x 2.4(+)	100	1.8	0.91	0.02	
216-B-53-B	45.7 x 3.0 x 2.4(+)	5.0	0.04	26	0.19	

(e) Previously classified as a sand filter sewer. Does not conform to typical dimensions of a French drain.

TABLE A.1. (contd)

Site No.	Dimensions, m (Length x Width x Depth)	Contamination				Comments
		Pu		Beta		
		g	g/m ²	Ci	Ci/m ²	
216-B-58	61 x 3.0 x 2.4(+)	6.7	0.04	31	0.16	Plywood cover
216-Z-17	91 x 3.0 x 4.6	50	0.18	0.02	<0.01	
<u>Reverse Wells</u>						
216-B-4	0.2 dia. x 33.5	NA	NA	<<1	<<1	Vertical culverts
216-B-5	0.2 dia. x 92	4300	100,000	160	3900	
216-B-6	0.2 dia. x 22.9	NA	NA	<10	NA	
216-B-11-A and B	1.2 dia. x 12.2	4	3.4	66	56	
216-C-2	0.3 dia. x 12.2	NA	NA	<1	<13	
216-T-2	0.2 dia. x 29.9	NA	NA	NA	NA	
216-T-3	0.2 dia. x 63	3300	(high)	117	(high)	
216-U-4B	0.9 dia. x 22.9	0.05A	0.08	0.57	0.87	
216-Z-10	0.2 dia. x 46	50	5000	NA	NA	

Ponds and Ditches

No ponds or ditches have been classified as Transuranic or Transuranic-Fission Products disposal sites.

APPENDIX B

APPENDIX B

ESTIMATED COST TO STABILIZE Z-12 CRIB AT HANFORD BY IN SITU VITRIFICATION

Costs were estimated for four basic cases (see Table B.1): two with no excavation, the other two with excavation of 4 m of noncontaminated soil (4500 m^3). Electric power costs were calculated for 2.5¢/kWh , and labor costs were estimated at $\$35,000$ per man year plus 110% overhead costs. Equipment costs were estimated to be $\$3.11$ million in 1981 dollars (Table B.2) with an upper uncertainty range of 50%. Costs were based on actual bid information for a pilot-scale ISV unit and were scaled up for full-scale reference system using procedures described by Peters and Timmerhaus (1968). Assuming an average 10-year operating life for the equipment and a cost of money of 10%, the annual fixed charge for equipment is approximately $\$506,000/\text{yr}$. Graphite electrodes without reuse were used at a cost of $\$170/\text{m}$. Excavation costs were obtained from Means (1981). Clamshell excavation of 0.38 m^3 capacity and rate $15 \text{ m}^3/\text{hr}$ was selected which resulted in $\$5.23/\text{m}^3$. A 0.57 m^3 capacity clamshell at $23 \text{ m}^3/\text{hr}$ would cost $\$3.32/\text{m}^3$. Other alternatives, such as a drag line, could reduce excavation costs further to $\$2$ to $\$3/\text{m}^3$.

A summary of the cost calculations is presented in Table B.3.

TABLE B.1. Options for ISV of Z-12 Crib

Item	Option			
	1	2	3	4
Excavation depth, m	0	0	4	4
Electrode spacing, m	3.5	3.5	5.3	5.3
Melt depth, m	8	12.5	3.5	5.0
Vitrified soil volume, m ³	8,400	13,200	3,700	5,300
Solidified weight, T metric	13,900	21,700	6,100	8,700
Number of ISV operations	66	66	28	28
Time per operation, h	110	180	72	98
Time to move and set hood for next operation, h	48	48	48	48
Total time for Z-12, d	435	627	140	170

TABLE B.2. Cost Estimate for ISV Equipment

Equipment	Cost, \$1000 (1981 Dollars)
Substation unit	260
Power line installation inch towers, insulators, etc	600
Hook-up and electrode frames	80
Equipment to move electrode frames, 10 ton crane	60
Equipment to drill holes for new electrodes	50
Off-gas treatment system	1800
Radar equipment to survey the burial trenches	100
Radiation and off-gas monitors and alarms	50
Melting verification instrumentation	50
Backfilling tractor-dozers	60
	<u>3110</u>

TABLE B.3. Labor and Cost Estimate for ISV of Z-12 Crib

	Option			
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
<u>Direct Labor, man years</u>				
Controls and Instrumentation	14.3	20.6	4.6	5.6
Hole drilling, moving cables, backfill	3.6	5.2	1.2	1.4
Radiation Monitoring	4.8	6.9	1.5	1.9
Supervision	<u>3.6</u>	<u>5.2</u>	<u>1.2</u>	<u>1.4</u>
Total Labor	26.3	37.9	8.5	10.3
<u>Costs, \$1000</u>				
Labor				
Direct	921	1327	298	361
Overhead (110%)	1013	1459	327	397
Total Labor Cost	1933	2786	625	757
Excavation Cost	0	0	24	24
Electrodes	359	561	101	95
Electric Power	348	543	153	218
Diesel Fuel	63	103	18	24
Equipment	<u>603</u>	<u>869</u>	<u>194</u>	<u>236</u>
Total Cost	3306	4862	1115	1354

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