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**ENVIRONMENTAL
RESTORATION
PROGRAM**

**In Situ Vitrification Demonstration
at Pit 1, Oak Ridge National Laboratory**

Volume 1. Results of Treatability Study

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LTR/ERPS-97-129

December 12, 1997

R. M. Skinner, Melton Valley Team Leader
Department of Energy, Oak Ridge Operations
55 Jefferson Ave.
Oak Ridge, Tennessee 27831-8540

Dear Mr. Skinner:

Contract DE-AC05-84OR21400, Transmittal of *In Situ Vittrification Demonstration at Pit 1, Oak Ridge National Laboratory: Volume 1. Results of Treatability Study and Volume 2. Site Characterization Report of the Pit 1 Area* (ORNL/ER-425/V1&V2)

Enclosed are 10 copies of the subject report for your information. These two volumes summarize the technical accomplishments, through September 1997, and status of the treatability study carried out on seepage Pit 1 to establish the field-scale technical performance of in situ vitrification (ISV).

On April 21, 1996, a melt expulsion occurred during ISV operations. As a result of this expulsion, the ISV demonstration was reviewed in detail and a decision was made not to continue with ISV activities at Pit 1, even though the isolation of contaminants was successful up to the time of the melt expulsion. The decision to terminate Pit 1 activities was based on the fact that with the high watertable and underlying bedrock conditions at the Pit 1 site, there was no way of assuring that a melt expulsion would not occur during the rest of the planned ISV treatability activities.

These volumes were developed to provide the data, information, lessons learned, and details necessary to continue evaluation of ISV as an alternative technology for remedial action at appropriate locations.

If you have any questions or need additional information, please call Dr. Jerry Kuhaida at 576-5506.

Sincerely,

W. D. Brickeen
ORNL EMEF Senior Project Manager

cc: L. B. Raulston
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**In Situ Vitrification Demonstration
at Pit 1, Oak Ridge National Laboratory**

Volume 1. Results of Treatability Study

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PREFACE

In Situ Vitrification Demonstration at Pit 1, Oak Ridge National Laboratory Volume 1. Results of Treatability Study and Volume 2. Site Characterization Report of the Pit 1 Area (ORNL/ER-425/V1&V2) summarize the technical accomplishments, through September 1997, and status of the treatability study carried out on seepage Pit 1 to establish the field-scale technical performance of in situ vitrification (ISV).

On April 21, 1996, a melt expulsion occurred during ISV operations. As a result of this expulsion, the ISV demonstration was reviewed in detail and a decision was made not to continue with ISV activities at Pit 1, even though the isolation of contaminants was successful up to the time of the melt expulsion. The decision to terminate Pit 1 activities was based on the fact that with the high watertable and underlying bedrock conditions at the Pit 1 site, there was no way of assuring that a melt expulsion would not occur during the rest of the planned ISV treatability activities.

These volumes were developed to provide the data, information, lessons learned, and details necessary to continue evaluation of ISV as an alternative technology for remedial action at appropriate locations. This work was performed under Work Breakdown Structure 1.12.06.10.01.11 (Cost Center Activity Data Sheet 3330, "Waste Area Grouping 7 In Situ Vitrification").

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ABBREVIATIONS

CAM	continuous air monitor
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DOE	Department of Energy
EFS	electrode feed system
EPA	Environmental Protection Agency
FY	fiscal year
G-M	Geiger-Mueller
Geosafe	Geosafe Corp.
HEPA	high-efficiency particulate air
HVAC	heating, ventilation, and air-conditioning
ICPAES	inductively coupled plasma atomic emission spectroscopy
ISV	in situ vitrification
LMES	Lockheed Martin Energy System
MAS	materials addition system
MEI	maximally exposed individual
MM5	modified method 5
MMES	Martin Marietta Energy Systems
NEPA	National Environmental Policy Act
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NPDES	National Pollutant Discharge Elimination System
NRWTP	Nonradiological Wastewater Treatment Plant
OAT	operational acceptance test
OREPA	Oak Ridge Environmental Peace Alliance
ORNL	Oak Ridge National Laboratory
ORSSAB	Oak Ridge Site-Specific Advisory Board
PCBs	polychlorinated biphenyls
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
RAM	Radiation Air Monitor
ROD	Record of Decision
TCLP	toxicity characteristic leach procedure
TIE	Technology Information Exchange
TSCA	Toxic Substances Control Act
WAG	waste area grouping
WC	water column

EXECUTIVE SUMMARY

A treatability study was initiated in October 1993 to apply in situ vitrification (ISV) to at least two segments of Oak Ridge National Laboratory (ORNL) seepage Pit 1 by the end of fiscal year (FY) 1995. This treatability study was later extended to include all of Pit 1 and was performed to support a possible Interim Record of Decision or removal action for closure of one or more of the seepage pits and trenches beginning as early as FY 1997. This treatability study was carried out to establish the field-scale technical performance of ISV for (1) attaining the required depth, nominally 15 ft, to incorporate source contamination within and beneath the pits; (2) demonstrating field capability for the overlap of melt settings which will be necessary to achieve fused, melted segments of the source contamination; (3) demonstrating off-gas handling technology for accommodating and minimizing the volatilization of ^{137}Cs ; (4) demonstrating adequate site characterization techniques to predict ISV melting kinetics, processing temperatures, and product durability; and (5) promoting public acceptance of ISV technology by demonstrating its safety, implementability, site impacts, and air emissions and by coordinating the treatability study within the regulatory closure process. In April 1996 an expulsion of an estimated 10% of the 196 Mg (216 tons) melt body occurred resulting in significant damage to ISV equipment and, ultimately, led to an indefinite suspension of further ISV operations at Pit 1. This report summarizes the technical accomplishments and status of the project in fulfilling these objectives through September 1997.

The existing Department of Energy (DOE)-owned large-scale ISV equipment was shipped from Pacific Northwest National Laboratory, which was also the major collaborator on this project, to Oak Ridge in April 1995 to the Pit 1 site. The site was extensively prepared for this equipment with major tree clearing, leveling, and graveling to the east and north of Pit 1. The pit surface was sculpted down approximately 4 ft into the clean fill leaving an approximately 80 x 140 ft level earthen pad for off-gas hood maneuvering. A new off-gas hood was procured with a number of needed capabilities for future ISV operations in ORNL Waste Area Grouping (WAG) 7 including automobility, improved off-gas collection aerodynamics, materials addition capability during ISV operations, electrode section hoisting and handling capability, and initial off-gas filtration capability. To recoup lost project time caused by significant delays in procuring the hood, the initial assembly of the entire hood was carried out on site between June and September 1995. During acceptance testing of the assembled hood, a major structural failure occurred which required approximately six months to design and fabricate additional parts and to make repairs.

The major change in off-gas handling technique for the Pit 1 ISV operations centered on the use of a roughing filter, which employed high-temperature Nextel® ceramic filter fabric in a baghouse located in the center of the new hood; this baghouse had a blowback feature to periodically shake accumulated particulates from the filter bags and return them to the melt surface directly beneath. The previous pilot-scale ISV demonstration in 1991 had established the effectiveness of off-gas high-efficiency particulate air (HEPA) filtration in removing radioactive contaminants prior to off-gas treatment. HEPA prefilters were placed in the off-gas line between the hood's roughing filter and the off-gas treatment trailer to remove radioactive contaminants in the event that the experimental roughing filter did not perform as well as anticipated.

The major finding of site characterization tasks (described in Volume 2) was that the maximally-contaminated strata, which contained ^{137}Cs at a maximum activity of 135,000 Bq/g and was the target for ISV treatment, actually resided between 24 and 26 ft below the original asphalt

cap over Pit 1 rather than at the 15 ft depth presumed prior to site characterization. Apparently, clean soil was imported not only to fill Pit 1, but also to cover residual peripheral surface contamination during its 1981 capping operation. However, the proven ISV depth capability is presently only 20 ft. By a combination of site grading to remove an average of 4 ft of overlying clean fill and ISV startup within a 6-ft deep excavated trench, the target depth for Pit 1 ISV was kept within this current capability. Pit 1 also exhibited perched groundwater at a seasonally varying depth of 7 to 10 ft below the surface. During ISV operations, the elevation of perched water around the melt body averaged about 10 ft above the bottom of the melt body and a resulting calculated 80-90,000 gallons of water were distilled from Pit 1 over the 20 days of ISV operations. The four graphite electrodes were employed as dipsticks to measure melt body depth which averaged approximately 15 ft at the time of the melt expulsion; although this depth attainment met the study's technical objective, ISV operations were planned to continue to fully penetrate the maximally-contaminated soil layer in Pit 1 during this first of three planned overlapping melt settings.

The first twelve days of ISV operations were considered an operational acceptance test (OAT) phase after which the performance of new ISV equipment and operational procedures would be evaluated while the melt body was still within the relatively clean soil fill of Pit 1. Before reinitiating full electrical power to the melt body approximately three days after the OAT pause when the average electrode penetration depth was 12 ft, major systems were judged to be performing adequately to continue further melting into the maximally-contaminated depths of the pit. Although the melt surface video monitoring system, the subsurface temperature monitoring system, and the subsurface vent pipe system were apparently not functioning after the OAT, both the melt power processing and off-gas handling systems were performing excellently and the melt operations were continued. A sample of the melt body after the OAT was obtained by pushing a steel rod into the molten mass from an off-gas hood port beneath the work platform and collecting the cooled adhering glass; using the measured concentration of rare earth tracers, which were placed in the melt zone prior to operations, the mass of the melt body was calculated to be 139 Mg at the end of the OAT.

After an additional 3 days of full-power operations, the melt expulsion occurred on April 21, 1996, at 6:12 p.m. Details of the melt expulsion event and discussion of its causes and prevention have been published elsewhere (ESERP 1996a,b,c) and are not repeated in this report. The melt expulsion incident demonstrated the need for extensive modifications to ISV equipment and procedures both to minimize the probability of additional melt expulsions and to endure their effects without interrupting ISV operations. A number of strategies to reduce the probability of melt expulsions were formulated for additional melts at Pit 1; however, the projected additional costs and undemonstrated nature of many of the proposed remedies led to the indefinite suspension of the project except for completion of this final report. Details of these and other cost increases and schedule delays over the entire life of the project are described extensively.

Samples of the final ISV product were obtained using expelled materials from various locations within and around the off-gas hood. Previous investigations had established that ISV melt bodies are well-mixed and chemically homogeneous; thus, the overall sampling strategy was greatly simplified requiring only a few replicates to produce a representative average composition. After delivering a total of 529,000 kWh of electrical energy to the Pit 1 melt body, a final mass of 196 Mg (216 ton) of product was formed as determined from the final concentration of holmium and lutetium tracers. The final product exhibited an elemental composition reflecting the inclusion of minor amounts of amended materials including a starting low-melting feldspar sand and 3,600 lb

of limestone gravel added after the OAT. The final composition was 20.3% Al_2O_3 , 2.9% CaO , 6.1% FeO , 3.4% K_2O , 1.7% MgO , 0.1% MnO , 1.0% Na_2O , 62.6% SiO_2 , and 0.8% TiO_2 . The ISV operating temperature for this composition was estimated at around $1,600^\circ\text{C}$. The final melt body was found to contain a total inventory of 2.92, 0.129, 0.000713, and 0.000856 Ci of ^{137}Cs , ^{90}Sr , ^{238}U , and $^{239/240}\text{Pu}$, respectively. The final melt body incorporated only 7.5% of the estimated 38.8 Ci of ^{137}Cs in the maximally-contaminated source soil in Pit 1 due to the limited penetration of the melt body into this layer at the time of the expulsion. Post-melt probing, established the maximum melt body average radius at 10 ft which, if projected on plan view, would lead to an estimate of 16% of the total Pit 1 target area incorporated into the melt.

Pulverized and intact samples of this final ISV product were subjected to three laboratory leach tests to determine their quality as waste forms and to compare them to the performance of a sample of the maximally-contaminated Pit 1 soil. These leach tests included the Toxicity Characteristic Leach Procedure (TCLP), the Product Consistency Test (PCT), and a recently-developed sequential leaching procedure using dilute calcium chloride followed by hydrochloric acid to simulate cation exchange and acidification mechanisms for soil mobilization. Major fractions (i.e., 12–98%) of the ^{90}Sr , ^{238}U , and $^{239/240}\text{Pu}$ activities in untreated soil were removed by sequential leaching and other leach tests indicative of their potential environmental mobility; this state of potential mobility of these radionuclides in soil is the overwhelming reason for considering remedial actions like ISV. Pulverized ISV product, equivalent in surface area to the starting soil, exhibited dramatic improvement in leachability with no radionuclide showing more than 1% extraction. When intact pieces of ISV product, just small enough to fit into the leaching test containers, were employed radionuclides averaged less than 0.1% extractability. Similar results were found in the TCLP and PCT extraction tests for all radionuclides. The TCLP extractant is a sodium acetate buffer and probably removes mostly cation exchangeable species from soil and ISV product while the PCT is basically a hot-water extraction and, thus, reflects water soluble species in the materials. The extractability of ^{137}Cs was extremely low in all materials including the starting soil; the highly particle-reactive nature of ^{137}Cs in soil obviates remediation if institutional controls on the site are maintained long enough for the radioactive decay of the source to occur. However, it is a ubiquitous co-contaminant with the more hazardous and environmentally mobile ^{90}Sr . The ISV product was also found to exhibit concentrations of inorganic hazardous elements below target concentration in the TCLP; however, no hazardous element concentrations were found in pit soil. The values of elemental normalized releases from the ISV product in the PCT showed it to be of high durability, comparable to other nuclear waste glasses and to the excellent ISV products resulting from previous ORNL ISV demonstrations.

Analyses of both the roughing filter and HEPA filters after ISV operations showed that in combination they removed all detectable radioactive contaminants from the off-gas. The large volume (25,000 gal) of condensed water collected in the ISV off-gas scrub solution was not found to contain radioactivity. More importantly, the melt body was found to retain at least 99.9982% of all four radionuclide contaminants in Pit 1 with the off-gas filters removing what little did evolve from the melt body. This finding was a major advance, by about an order-of-magnitude, over melt retentions measured following previous pilot-scale ISV demonstrations in Oak Ridge. Future ISV operations in WAG 7 pits and trenches, where a single melt setting could process up to 10,000 Ci of mixed fission products, can be performed with no more than a total of 0.18 Ci within the off-gas system and all of that in the filter systems away from operators and without risks for environmental releases. Future ISV operations can focus off-gas treatment techniques on filtration and return of

resulting particulates to the melt body, akin to the operation of the baghouse roughing filter in the Pit 1 project. Both lead and zinc, although present at only normal background concentrations in Pit 1 soils, were found to be significantly volatile in the ISV process and a major portion of their inventory was contained in the filter particulates.

During the melt expulsion, a calculated volume of 230,000 standard L of off-gas was released in an uncontrolled mode as the pressurized hood was lifted from the ground surface. Off-gas sampling during this event revealed that the activity of ^{137}Cs in the off-gas was 0.93 dpm/L resulting in a total release of 9.6×10^{-8} Ci. Using worst-case meteorological assumptions of wind speed, direction, and dispersion, such a release could have delivered a hypothetical and insignificant dose of 0.015 μrem to the nearest resident over 2 km away. Were an ISV melt body, containing over 10,000 Ci of ^{137}Cs , to experience a similar melt expulsion, a correspondingly larger hypothetical dose of 55 μrem could be delivered to an individual at the same location. This is well below the DOE administrative limit of 10 mrem/yr for the general public. Although no preventable uncontrolled release is justified, this calculation puts into perspective the magnitude of the risks posed by ISV even under such a worst-case accident scenario.

Among the treatability study's original objectives, the demonstration of ISV product quality, depth capability, and off-gas handling capability, even considering the unplanned melt expulsion, have been well established by the results reported here. The objective to demonstrate site characterization techniques to establish ISV targets and to plan ISV operations is addressed in the site characterization report (see Volume 2). The objective to demonstrate melt setting overlap capability was not attained because the project was suspended after the melt expulsion and neither the second nor third melt settings were attempted. However, since the conception of this project in 1993, Geosafe Corp. has clearly established this capability for ISV by producing 37 overlapping large-scale melt bodies at the Wasatch Chemical site in Salt Lake City in 1995 and other large, overlapping melts in Michigan and Washington. The remaining objective, to establish public confidence in ISV technology, has clearly not been fulfilled due to the melt expulsion incident and its perceived results and implications. The implementation and selection of ISV technology for remediation of the WAG 7 seepage pits and trenches or other waste management units in Oak Ridge will require a considerable effort to involve the public in the decision process and, thereby, increase their appreciation of its benefits. The main findings of this Pit 1 treatability study are the excellence of the ISV waste form, compared to any other technology, and the inherent conservatism of the process with respect to off-gas release of radioactivity during normal and accident situations. Much remains to be understood as to the proper economic comparison of ISV with other technical options for Oak Ridge contaminated soils, particularly the inherently large costs associated with any technology requiring long-term monitoring. The ability to prevent, control, and endure melt expulsions during ISV operations needs to be factored into the expected operating cost, as well as programmatic and public expectations. Increased and continued experience with ISV operations in very humid regions with saturated soil near the ground surface, like Oak Ridge, will, by necessity, result in empirical procedures, practices, and strategies which will minimize the probability of future melt expulsions. These risks are small and manageable compared to the enormous benefits of essentially permanent and complete waste isolation of radioactive contaminants from virtually all future environmental transport.

1. PROJECT DESCRIPTION

1.1 IN SITU VITRIFICATION TECHNOLOGY

As an aid to interpreting the various phases of the in situ vitrification (ISV) operations at the Oak Ridge National Laboratory (ORNL) Pit 1, a brief summary is included here to describe the general concept of ISV operations, the equipment available for ISV technology at the start of the Pit 1 ISV treatability study, and a summary of previous ISV experience at ORNL for radioactive applications. In addition, since the initiation of this project in 1994, Geosafe, Inc. (Geosafe) has performed several remedial actions using ISV at commercial sites. Geosafe's experience has enlarged considerably the understanding of site parameters and technology applications beyond the state of ISV technology described in the project work plan (Spalding 1994a).

1.1.1 Conceptual Process Description and Present Limitations

In situ vitrification is a promising technology that could be applied to the pits and trenches on the Oak Ridge Reservation as well as other contaminated sites. ISV, developed and patented for the U.S. Department of Energy (DOE) by Battelle Pacific Northwest National Laboratory (PNNL), involves placing electrodes in an array above a contaminated volume of soil, applying power to the electrodes, and melting the entire mass of soil into a chemically homogeneous and durable glassy-to-microcrystalline waste form (U.S. EPA 1992). Figure 1.1 depicts the ISV processing sequence as applied to a liquid waste disposal seepage trench. An array of vertical electrodes is inserted into the soil to a nominal depth (about 2 ft) above the waste site, and, since dry soil is not electrically conductive, a conductive material (typically glass frit and graphite flake) is placed in paths between the electrodes to act as a resistive heating element. The soil-melting process is initiated when an electric potential applied to the electrodes establishes a current in the path, in turn heating the path and the surrounding soil to temperatures above the melting point of soil. Once molten, the soil becomes electrically conductive. Power to the melt is controlled as the process continues and the molten soil mass grows downward and outward (typically maintaining temperatures between 1400°C and 2000°C). Power to the melt is maintained until the desired depth is obtained and the soil and its contents are melted. Since the conductivity between electrodes increases as the melt volume increases, the ISV power supply is equipped with a series of voltage taps to maintain a constant power level to the melt.

The melt dissolves and/or incorporates radionuclides and nonvolatile hazardous elements, such as heavy metals, and destroys organic components by pyrolysis. Semivolatile metals (e.g., Co, Cs, Cu, and Pb) are largely retained in the melt, but the small quantity of material that does escape from the melt is captured and treated. Volatile metals (e.g., As, Cd, Hg, and Zn), which emanate from the melt, are captured by the process off-gas system. A hood placed over the area being vitrified confines the gases released from the melt and directs them to an off-gas treatment system that uses a combination of wet-scrubbing and dry-filtering.

Upon cooling, the molten soil solidifies into a vitrified mass resembling natural obsidian in appearance and, most importantly, in durability, with a leach resistance approaching that of high-quality laboratory glassware (Buelt et al. 1987; Callow et al. 1991). In the 1991 ORNL pilot-scale test (Spalding et al. 1992), significant crystallization of the melt material occurred during

Fig. 1.1. Schematic illustration of the in situ vitrification process applied to an ORNL seepage trench.

cooling. However, this crystallization did not result in any decrease in leach resistance of the ISV product. Due to ISV experience by Geosafe at commercial sites since 1993, ISV proven depth capability has increased to 21 ft and single-melt bodies up to 1200 tons have been produced. Typical processing rates of 3-6 tons/hr have been achieved with a power usage factor of 700-1000 kWh/ton of soil processed.

1.1.2 Equipment Description (Off-Gas Handling, Control, and Hoods)

The large-scale process equipment for ISV is shown in Fig. 1.2. The process immobilizes contaminated soil and isolates it from the surrounding environment. Controlled electrical power is distributed into the ground through an array of graphite electrodes for melting while special equipment contains and treats the gaseous effluent. The process equipment required to perform these functions can be described most easily by dividing it into its major components:

- electrical power supplies
- off-gas hood
- off-gas treatment system
- glycol cooling system
- process control station
- off-gas support equipment.

Except for the off-gas hood, all the components are contained in three transportable trailers diagrammed in Fig. 1.3. They consist of an off-gas treatment trailer, a process control trailer, and a support trailer. All three trailers are mounted on wheels sufficient to accommodate a move to any site over a compacted ground surface. The off-gas hood and off-gas line, which are installed on the site for collection of gaseous effluent along with other ancillary components, are dismantled and placed on flatbed trailers for transport. The effluent gases exhausted from the hood are cooled and

treated in the off-gas treatment system. The entire process is monitored and controlled from the process control station. A fourth trailer is required to support the backup diesel generator.

Fig. 1.2. Typical arrangement of pre-1994 large-scale in situ vitrification trailers and off-gas hood at Richland, Washington.

1.1.2.1 Trailer descriptions

The off-gas trailer is enclosed and contains an internal containment module. The containment module houses and isolates the off-gas treatment equipment. The containment module is a large glovebox constructed primarily of stainless steel. It isolates operators from processing equipment and protects them from being contaminated during an abnormal condition such as a leak in pressurized piping. The containment module is vented by two independent blowers with HEPA filters at the air entrance and exit. A slightly negative pressure (1 cm [0.4 in.] of water) is maintained within the containment module relative to the atmosphere. The off-gas treatment trailer measures 3.6 m (12 ft) wide x 18.3 m (60 ft) long and weighs 55,000 kg (121,000 lb). The maximum height of the off-gas trailer including the undercarriage is 4.32 m (14.2 ft). Because it is 50% over the legal public highway weight, as well as oversized, this trailer was specially fitted with extra axles for transport over public highways.

The process control trailer is a covered fifth-wheel van with dimensions measuring 2.4 x 13.7 x 4.08 m (8 x 45 x 13.4 ft). All process monitoring operations are performed from the process control station located in this trailer. In addition, the trailer houses miscellaneous and ancillary support equipment for the ISV system. A soundproof wall exists between the support equipment and the process control equipment. Like the off-gas trailer, the process control trailer is constructed of aluminum and painted steel walls that are insulated with a noncombustible material.

The electrical trailer houses the electrical power supply and glycol cooling system. A standard fifth-wheel flat-bed trailer, it measures 2.6 x 14.6 x 1.40 m (8.5 x 48 x 4.6 ft). Overall height with equipment mounted on the trailer is 4.1 m (13.6 ft). The trailer's total load capacity is 41,000 kg (90,000 lb).

Fig. 1.3. Functional equipment in process trailers of large-scale in situ vitrification unit.

Communication stations are established in each of the three trailers for operational control and safety. For example, an operator making an adjustment to a valve in the off-gas trailer can be in constant contact with the operator monitoring the process from the control trailer. Indoor and/or exterior lighting are provided on all three trailers. Outdoor electrical services are provided for air sampling and other support equipment. Low-voltage power for all lighting and communication services is provided by a circuit that is independent from the high-voltage soil melting power supply.

The areas occupied by operating personnel in the off-gas and control trailers are ventilated by their own heating, ventilation, and air-conditioning (HVAC) system and ductwork designed to maintain comfortable working conditions. The ventilation in the aisle of the off-gas trailer is separate from the containment module ventilation from which exhaust is HEPA filtered to protect the environs. The access aisles in the off-gas trailer can be monitored for alpha- or beta-bearing contaminants by continuous air monitors (CAMs). Various radiation area monitors (RAMs) are also included. In addition, the process effluent stack, which also exhausts the containment module ventilation, is monitored continuously by a beta CAM unit. The control station and ancillary equipment area are serviced by one HVAC system in the control trailer. The system's inlet is HEPA filtered. In addition to a comfortable working environment, the control trailer's HVAC system must provide clean, controlled conditions for the process control equipment in the control station. The electrical trailer is an open flatbed and is not equipped with an HVAC system. However, the transformer is a dry type and is cooled with forced air when operating and includes heaters to minimize condensation.

1.1.2.2 Process equipment

The six major components of the large-scale ISV process, electrical power supply, off-gas hood, off-gas treatment system, glycol cooling system, process control station, and off-gas support equipment, are integrated to provide a flexible system capable of treating various contaminated soils and buried wastes. A description of individual features and capabilities of the major components follows.

1.1.2.3 Electrical power supply

The electrical power supply provides and regulates power for soil melting. It is composed of a 3,750-kVA power supply and a 15-kV circuit protection switchgear. Power is supplied through an array of electrodes into the ground from the 3,750-kVA Scott-Tee power supply, which has 16 different voltage taps. A Scott-Tee transformer converts three-phase (3-wire) power to a balanced two-phase (4-wire) system. Voltages on the load side are provided from 4160 V to 440 V at an amperage from 450 A to 4000 A per phase. The voltage taps must be changed manually after interrupting power. Saturable reactors on each phase in series with the load control power to the melt between voltage taps for maximum efficiency, safety, and control. The operator will change taps only after shutting down power. The power supply measures 4.33 x 2.4 x 2.4 m (14.2 x 8 x 8 ft) and weighs approximately 27,000 kg (59,525 lb).

Power to the 3,750-kVA power supply is provided at 13.8 kV and can be interrupted by the 15-kV circuit protection switchgear located adjacent to the power supply. Power can be shut down at the switchgear or remotely from the control panel. The switchgear measures 0.91 x 2.4 m (3 x 7.9 ft) long and can be serviced through removable side panels. Power interruption to the 3,750 kVA power supply will not interfere with the power to the off-gas equipment.

Power to the off-gas process equipment is provided by the 750 kVA transformer, located next to the 3,750 kVA transformer on the support trailer, and is distributed by the motor control center located in the control trailer. The 750 kVA transformer provides 480 V power to the motor control center from a 13.8 kV supply. If line power is interrupted to the site, a transfer switch in the motor control center will automatically activate a standby 600 kW (800 hp), 750 kVA diesel generator equipped with its own battery powered cranking system. This system will provide emergency power to all off-gas system and ancillary components to maintain off-gas collection, treatment, and process control. The backup generator does not supply power for melting soil.

High-Efficiency Particulate Air Prefilter. Between the off-gas hood and the off-gas treatment trailer, is an off-gas HEPA prefilter system (Fig. 1.4). This system consists of two high-temperature HEPA filter units and a by-pass line; the concept was tested in the 1991 radioactive pilot-scale test at ORNL (Spalding et al. 1992). The system contains valves which allow off-gas to be routed through either or both housings or for both housings to be by-passed. Valves are manually actuated, using a remote controller on a pendant, and the housings are bolted into the off-gas line using standard flanges. The unit is supported on a structure which provides a working platform for changing filters. Differential pressure drop is measured across the housings to monitor solids loading on the filter units. The housing is also monitored for beta-gamma activity, using a RAM, in close proximity to the face of the filter elements. This off-gas HEPA prefilter design was found to be extremely effective in removing ^{137}Cs activity from ISV off-gas during the 1991 pilot-scale test at ORNL (Spalding et al. 1992). It has been scaled up for implementation on full-scale Pit 1 ISV operations.

Off-Gas Treatment System. The off-gas treatment system (Fig. 1.5) cools, scrubs, and filters the gaseous effluent exhausted from the hood. Its primary components include: a gas cooler, two wet scrubber systems (tandem nozzle scrubbers and quenchers), two heat exchangers, two process scrub tanks, two scrub solution pumps, a condenser, three mist eliminators (vane separators), a heater, a dual stage HEPA filter assembly, and a blower system. Table 1 gives the system's mass and energy balance, which is based on maximum expected conditions at an ambient temperature of 38°C (100°F).

Because of the additional heat load if high concentrations of buried solid and liquid organic combustibles are processed, off-gases entering the off-gas trailer can be expected to reach a maximum temperature of 750°C (1,382°F). To keep the size of the heat exchange equipment manageable for a transportable facility, a gas cooler is provided to remove a major portion of the heat load from the off-gases before quenching. The gas cooler is a finned air-to-glycol heat exchanger (Glycol System A) which cools the gases to 300°C (572°F) at 104 standard m³/min (3,670 ft³/min). The gas cooler is bypassed by operating three 40-cm (16-in.) pneumatic-actuated butterfly valves when the temperature is below 300°C (572°F). Although the off-gas system is designed to handle 750°C (1,382°F), the nominal off-gas temperature expected during radioactive operations at Pit 1 is estimated to be less than 250°C (482°F). This low off-gas temperature is due to the lack of combustible waste constituents in ORNL Pit 1. Thus, the off-gas cooling system was not used during Pit 1 ISV operations.

Fig. 1.4. Conceptual design of the in situ vitrification HEPA prefilter system.

From the gas cooler, the off-gas is directed into one of two parallel wet scrubber systems. Each system has a capacity of about 60 standard m^3/min (2,120 ft^3/min); normally only one system is used at a time. Two scrubbing systems provide an operating flow ranging between 30 and 104 standard m^3/min (1,060 and 3,670 ft^3/min). Because scrubbing efficiency falls drastically with flow rate, two parallel systems are required for this range of flows. At flows less than 60 standard m^3/min (2,120 ft^3/min), only one system will operate. The dual scrub system also provides redundancy in the event of single component (e.g., pump) failure. Each scrubber system is composed of a quench tower, a tandem nozzle scrubber, and a vane separator. The quencher reduces the gas temperature from 300 to 66°C (572 to 151°F) and provides some scrubbing action to remove 90% of the particulates and semivolatile radionuclides. The tandem nozzle scrubber's primary functions are to remove an additional 90% of particles 0.5 μm diameter and larger, condense remaining semivolatile components, and provide additional cooling of the off-gas. The vane separator that follows each tandem nozzle scrubber removes all droplets 12 μm and larger. Under the conditions given in the mass and energy balance (Table 1), the exit temperature from the scrubber system is 60°C (140°F). The scrubber system is normally run as warm as possible to minimize water condensation in the treatment system.

Fig. 1.5. Flow diagram for the large-scale in situ vitrification off-gas treatment system.

The scrub solution injected into the quenchers and tandem nozzle scrubbers is cooled through two single-pass heat exchangers before being returned to the process scrub tanks. Each heat exchanger measures 2.5 m (8.2 ft) long and 20 cm (8 in.) in diameter. Each can remove 120 kW (6,830 Btu/min) from the scrub solution, which flows at 178 L/min (47 gal/min) from 62°C (144°F) as it exits the scrubber system to 52°C (126°F). Each heat exchanger transfers the heat to a glycol solution (Glycol System B) flowing at 760 L/min (201 gal/min).

Two independent scrub pumps recirculate the scrub solution from the process tanks to the wet scrubbers. Each pump's suction is located about 25 cm (10 in.) from the bottom of the lowest portion of its respective tank. Each pump can deliver 510 L/min (135 gal/min), with a maximum deliverable pressure of 690 kPa gauge (100 psig). In addition, the scrub pumps can flush out the remainder of the gas cooler and off-gas piping that are not wetted by the wet scrubbers.

Following the scrubber systems, the off-gas is recombined and cooled further from 60 to 52°C (140 to 126°F) in a single-pass condenser. The condenser and mist eliminator provide additional decontamination of the off-gas (90 to 99% removal) by condensation and removal of water droplets. The condenser, which measures 3.26 m (10.7 ft) long x 61 cm (24 in.) in diameter, transfers 320 kW (18,200 Btu/min) from the off-gas into glycol flowing at 1,500 L/min (396 gal/min). The mist eliminator, a vane separator measuring 1.2 m (3.9 ft) long from flange to flange, removes droplets 12 µm and larger. Both the condenser and mist eliminator are rated at 104 standard m³/min (3,670 ft³/min) at the outlet.

Table 1.1. Energy and mass balance of the large-scale in situ vitrification off-gas treatment system

Equipment	Flow	Inlet Temperature (°C [°F])	Energy Transfer (kW [Btu/min])
Gas cooler	104 ^(a) (3,670)	750 (1,382)	-1,100 (-62,600)
	340 ^(b) (90)	92 (198)	1,100 (62,600)
Quencher (each)	52 ^(a) (1,840)	300 (572)	-271 (-15,400)
	57 ^(c) (15)	52 (126)	271 (15,400)
Tandem nozzle scrubber (each)	59 ^(a) (2,080)	66 (151)	-68 (-3,870)
	121 ^(c) (32)	52 (126)	68 (3,870)
Vane separator (each)	57 ^(a) (2,010)	60 (140)	0
	121 ^(c) (32)	60 (140)	
Heat exchanger (each)	178 ^(c) (47)	60 (140)	-120 (-6,830)
	760 ^(b) (201)	48 (118)	120 (6,830)
Process scrub tank (each)	178 ^(c) (47)	52 (126)	0
Condenser	114 ^(a) (4,020)	60 (140)	-260 (-14,800)
	1,500 ^(b) (396)	46 (115)	260 (14,800)
Mist eliminator	104 ^(a) (3,670)	52 (126)	
	7.9 ^(c) (2.1)	52 (126)	56 (3,190)
Heater	104 ^(a) (3,670)	52 (126)	
HEPA filter	104 ^(a) (3,670)	77 (171)	
Blower system	104 ^(a) (3,670)	77 (171)	
Glycol system A	340 ^(b) (90)	133 (271)	-1,100 (-62,600)
Glycol cooling system B	1,500 ^(b) (396)	52 (126)	-500 (-28,500)

(a) gas (standard m³/min [ft³/min]).

(b) glycol (L/m [gal/min]).

(c) scrub (L/m [gal/min]).

After reaching the condenser/mist eliminator, the gases flow to the heater and HEPA filters. To prevent moisture condensation in the HEPA filters, the off-gas is reheated above the dew point. The heater, which measures 2.6 m (8.5 ft) long x 0.70 m (2.3 ft) in diameter, is capable of raising the off-gas temperature by a maximum of 50°C (120°F) at 104 standard m³/min (3,670 ft³/min). Final decontamination of off-gas particulates is achieved in the two-stage HEPA filter assemblies. The first stage is composed of two parallel housings, each holding four 61 x 61 x 30-cm (24 x 24 x 12-in.) deep filters. If the differential pressure across the housing becomes too high, the off-gas will be automatically diverted to the parallel housing. Each filter is rated at 28 standard m³/min (990 ft³/min) at 2.08 cm (0.82 in.) water for a total rating of 113 standard m³/min (3,990 ft³/min) per filter housing.

The gaseous effluent are drawn through the off-gas system components by an induced draft system. The driving force is provided by a 149 kW (200-hp) primary blower capable of achieving 104 standard m³/min (3,670 ft³/min) at 90°C (194°F) and -229 cm (-90 in.) of water. A back-up blower rated at 0.25 the capacity is also provided in the event of failure of the primary blower. The secondary or back-up blower is not intended to pull excess inlet air into the hood, but rather to maintain a negative pressure on the off-gas hood to prevent direct release of effluent until the process can be safely shut down. The back-up blower is automatically activated by the process control system when the hood vacuum is reduced below a preset limit. After the blower system, the off-gases are exhausted to the stack, which is monitored continuously for radionuclides (beta CAM), NO_x, SO₂, CO, CO₂, and O₂. The stack is removable and extends high enough (3 m [9.8 ft] above the off-gas trailer) to prevent interference with the off-gas and control trailer's HVAC systems.

The process off-gas path, flow, vacuum, and pressure drop are controlled by 12 butterfly valves, which are described below:

- one 30-cm (12-in.) control valve on the air inlet to the off-gas hood. The degree of opening is controlled by the hood vacuum control circuit.
- three 40-cm (16-in.) valves that control the direction of the off-gas through the gas cooler or its bypass. These valves can be manually operated or actuated automatically via the process control system when the off-gas temperature exceeds 300°C (572°F). Should the pressure drop across the gas cooler exceed a certain limit, the valves will direct the off-gas flow through the bypass.
- two 30-cm (12-in.) control valves to the quencher inlets. They control the direction of the off-gas through one or both scrubber systems and can be opened or closed manually or opened automatically when hood vacuum or oxygen concentration is reduced.
- four 40-cm (16-in.) valves surrounding the first stage HEPA filter compartments. These are manually or automatically operated and allow the flow to be directed through the parallel primary filter systems if pressure drop across one housing becomes excessive.
- one 40-cm (16-in.) flow control valve located between the second stage HEPA filter and the blower assembly. Flow is controlled via the differential pressure controller across the two scrubber systems.
- one 15-cm (6-in.) control valve located on the inlet bypass to the blower. It maintains a constant blower inlet vacuum via a pressure controller, regardless of other control parameters.
- one 15-cm (6-in.) valve that directs flow to the back-up blower during primary blower failure.

All valves are specified with fail-safe positions. All off-gas valves between the hood and blower are fail-to-open. The air inlet valve is fail-to-30% open, and the inlet bypass control valve is fail-to-close. In addition, the flow control valve is provided with a feature that does not allow it to be fully closed. The five gate valves on the HEPA prefilter assembly all fail in their current position, i.e., they are dual action cylinders requiring energizing to open and energizing to close.

Glycol Cooling System. Glycol cooling solution is pumped between the support trailer and off-gas trailer to remove the heat from the gaseous effluent. The glycol is recirculated between trailers through flexible jumpers by two pumps in two independent loops. The glycol recirculating through the heat exchangers and condensers is kept separate from the glycol loop for the gas cooler. Both loops, however, are assembled in one glycol cooling assembly that is located on the support trailer. The assembly consists of two fan-cooled radiator systems, each dedicated to and separated from its respective glycol loop (A or B). The entire assembly, which fits on the front 6 m of the support trailer, will remove 1,600 kW (91,100 Btu/min) at an ambient temperature of 38°C (100°F). Because the off-gas cooler has not been used for Pit 1 applications, the glycol system only cools the off-gas indirectly. Its primary function is to cool the condensate from the quencher, scrubbers, and vane separators (mist eliminators).

Process Control Station. The process control station consists of a distributed microprocessor monitoring and control system and a control console for the power supply. It monitors and controls important process parameters. In addition, it automatically activates back-up equipment or reroutes off-gas flow in the event that certain equipment fails.

The distributed microprocessor control system consists of three process control units (PCUs) and two operator interface units. The PCUs are connected to critical and informational sensors located throughout the process equipment. These sensors include readings from pressure elements, thermocouples, gas monitors, and flowmeters. In addition to monitoring key parameters, the control system controls the pressure drop across the scrubber systems by a pneumatic flow control valve at the blower inlet. It also controls the blower inlet vacuum with a separate pneumatic valve that governs the magnitude of recycle through the main blower. The control system could automatically activate the standby scrubber system if hood vacuum or oxygen concentration were to be reduced. This action subsequently increases the flow capacity of the process to 104 standard m³/min (3,670 ft³/min). The control system also provides automatic batch logic sequencing of specific operations in the event of equipment failure. For example, the control system will automatically restart the off-gas system in a preprogrammed sequence in the event of power failure; and it will automatically activate the parallel HEPA filter assembly if pressure drop across one housing exceeds predetermined levels. Also, it will automatically shut down power to the melt and start the back-up or secondary blower upon primary blower failure.

Although the control system is connected to sensors and to an automatic shutdown circuit on the 3,750 kVA power supply system, it does not directly control the power supply. A separate control console fulfills that function. The power supply controller provides the necessary saturation current to the saturable reactors that govern the power to the electrodes. This control module maximizes the efficiency of the electrode power system and provides a quick reduction in power in the event of off-standard conditions.

Ancillary Support Equipment. Various support and back-up equipment are necessary to ensure the safe operation of the off-gas system. They provide electrical, water, and air services to the off-gas equipment. The support equipment includes the following:

- motor control center
- 112 kVA transformer
- air compressor
- process water supply pump and agitator.

The motor control center, located in the control trailer, provides power to the off-gas treatment system components as well as the power supply control module and process water supply pump and agitator. The 112 kVA transformer, which provides 120 V service from 480 V, is also located in the control trailer.

The control trailer also houses the scrub solution supply tank and the air compressor. The scrub solution supply tank provides makeup water storage for additional scrub solution as required by the process. It is equipped with an agitator for mixing chemicals such as NaOH and a pump for transfer to the off-gas trailer process tanks. At the direction of the operator, fresh scrub solution can be pumped from the supply tank to the scrub tanks through flexible jumpers located between trailers. However, the system is designed with a check valve so that any slightly radioactive scrub solution cannot be pumped back to the control trailer. The air compressor provides instrument air at 520 to 690 kPa gauge (75 to 100 psig) for the pneumatic actuators on the butterfly valves. The air flows through flexible jumpers between the control trailer and off-gas trailer or hood to the butterfly valves.

1.1.3 Review of Previous ISV Projects at ORNL

Since the invention of ISV by Battelle PNNL in 1980 and prior to the initiation of this project, 24 intermediate-scale (pilot-scale) melts, up to 50 tons, and 6 large-scale melts, up to 900 tons, had been completed by Battelle PNNL. In addition, numerous bench-scale (to 10 kg) and engineering-scale (to 1 ton) melts have also been completed. These ISV tests established most of the technical approaches employed in the present treatability study at ORNL seepage Pit 1.

ORNL had completed two field demonstrations of ISV for application to radioactively contaminated soil sites like those in Waste Area Grouping (WAG) 7. In 1987, a nonradioactive pilot-scale field demonstration was completed using chemical amendments for tracing the radioisotopes that would be encountered in actual application to pits and trenches (Spalding and Jacobs 1989a). That demonstration made a 20-ton glass block in a simulated seepage pit configuration at a site on a hilltop only 300 ft to the southeast of the present Pit 1 demonstration area. That demonstration showed encouraging retention of cesium (99.87%) and strontium (>99.9999%) within the ISV melt, good melt mixing, excellent quality of the product formed from indigenous soil and limestone materials, and ISV compatibility with the geologic features within the residual soils in WAG 7. This demonstration was located in an area above the groundwater table rather than in a saturated zone. The demonstration raised concern about the present ISV capability to handle even a potentially small amount of volatilization of ^{137}Cs to process off-gas, which might occur in an actual ISV application on a significant inventory of radioactive soil.

In 1991, a radioactive demonstration was completed (Spalding et al. 1992), also at the pilot-scale, using a sample of sludge from one of the seepage pits that contained a limited but measured amount of radioactivity (10 mCi of ^{137}Cs) and that was incorporated into 13 tons of final product. This demonstration established an off-gas processing technique to handle ^{137}Cs volatilization using a high-temperature, HEPA prefilter placed in the off-gas collection system prior to the off-gas scrubbing and quenching system. This prefilter removed all detectable ^{137}Cs from the off-gas and

thus demonstrated a method for avoiding radiation exposure to ISV operators from what otherwise would be a buildup of ^{137}Cs in the off-gas handling equipment. However, this demonstration experienced a volatilization of 2.4% of the ^{137}Cs inventory to process off-gas, unlike the 1987 demonstration where only 0.12% of the cesium amendment was volatilized. The prefilter was also found to contain other radioisotopes at or below detection limits: $\leq 0.0001\%$ of the ^{90}Sr , $\leq 0.007\%$ of the ^{241}Am , $\leq 0.006\%$ of the $^{239,240}\text{Pu}$, and 0.17% of ^{60}Co in the melt inventory. A more accurate estimate of transuranic isotope capture on the prefilter was obtained from the analyses of Ce, La, and Nd tracers also used in the test; only 0.0005% of the added amounts of these tracers were found on the prefilter.

The increased volatilization of ^{137}Cs in the 1991 demonstration was determined to be caused by chloride-enhanced volatilization of ^{137}Cs ; the source of chloride was a polyvinyl chloride (PVC) pipe used for access to emplace the radioactive sludge and left in the trench immediately prior to ISV. Subsequent laboratory investigations have shown that low chloride amendments ($<2\%$ by weight) to crucible melts, whether added as sodium chloride, PVC, or hydrochloric acid, result in markedly enhanced volatilization of ^{137}Cs during heating (Spalding 1994b). Laboratory crucible melts have identified many elements and chemical species that can be present in ISV melts without affecting volatilization of ^{137}Cs ; these species include fluorides, phosphates, nitrates, sulfates, carbonates, polystyrene, graphite, molybdenum, stainless steel (both 316 and 304), iron, strontium, sodium, lithium, potassium, and cesium. Nonetheless, the 1991 demonstration established (1) the feasibility of ISV using a new electrode feed technique, which eliminated the need to place electrodes into contaminated material prior to ISV; (2) the applicability to sites where dolomite, instead of limestone, was used as a trench backfill; (3) the applicability of several geophysical techniques for nondestructive monitoring of melt progress; and (4) the effectiveness of HEPA filtration for complete removal of any volatilized ^{137}Cs .

Since the start of this Pit 1 ISV treatability study in 1993, Geosafe has been applying ISV to commercial hazardous waste sites. A total of 54 large-scale melts have been completed processing over 20,000 tons of contaminated soil at four sites in the United States. Two of these sites, Parsons Chemical in Grand Ledge, Michigan, and Wasatch Chemical (Wasatch) in Salt Lake City, Utah, contained soils with moisture contents near field-capacity. Contaminants treated include polychlorinated biphenyls (PCBs), dioxins, volatile and semivolatile organic contaminants, heavy metals, as well as diverse waste and debris. Geosafe has obtained a national Toxic Substances Control Act operating permit for PCBs to 17,860 ppm. Geosafe has also contracted to remediate mixed-transuranic buried waste in Australia.

One of the Pit 1 ISV treatability study objectives, to demonstrate control of melt bodies to demonstrate adequate overlap of multiple settings, has been well established by Geosafe. There were 33 overlapping melts at the Wasatch site and 9 overlapping melts, each at the Parsons and Spokane sites. Thus, this was no longer necessary for demonstration during the Pit 1 treatability study.

1.2 PIT 1 SITE DESCRIPTION

1.2.1 Historical and Records Summary of Pit 1

The operational records of disposals at ORNL Pit 1 are quite limited, amounting to a total of a few paragraphs in about six monthly reports. These records are briefly summarized here so the reader can have a general appraisal of the nature and magnitude of the contamination present.

Detailed evaluation of the records, particularly in comparison to the inventories found during site characterization, are discussed more fully in the Pit 1 site characterization report (Volume 2 to this document).

Pit 1 (Fig. 1.6) was constructed in August 1951 by digging a 30 by 115 ft trench into weathered shale residuum to a maximum nominal depth of 15 ft. During the following 3 months, Pit 1 is estimated to have received about 389 Ci of mixed fission products, 200 kg of depleted uranium (0.0678 Ci if ^{238}U), and 266 mg of plutonium (0.017 Ci if ^{239}Pu), as sludge suspended in highly alkaline liquid waste (approximately 123,000 gal). The exact mixture of fission product isotopes was not reported in the disposal records for Pit 1. Disposal records did estimate that total beta emitters disposed in Pit 1 were 60% ^{137}Cs and 40% ^{106}Ru . If it is assumed that the Pit 1 fission product waste is similar to the sludge from ORNL pit 2, which was analyzed and used in the 1991 radioactive ISV test (Spalding et al. 1992), then 80.2% of the present activity would be composed of ^{137}Cs and 19.8% would be composed of ^{90}Sr while ^{106}Ru , with its 367 day half-life, would have decayed completely in the 42 years since Pit 1 use. If it is assumed that the recorded beta activity of " ^{137}Cs " was actually a mixture of ^{137}Cs and ^{90}Sr , as found for the pit 2 sludge, and correcting for decay to 1993, then the estimates of ^{137}Cs and ^{90}Sr presently in Pit 1 would be 71.0 and 17.5 Ci, respectively. However, these must be viewed as working estimates based on the number of assumptions and the disposal record quality. Thus, a significant part of the present treatability study centered on a better characterization of the present Pit 1 radioisotopic inventory.

Pit 1 was a proof-of-principle operation, and, although it leaked into a nearby drainage, a larger pit 2 was constructed in 1952, becoming the operational disposal unit for liquid radioactive waste at ORNL. Although not used for routine liquid waste disposal after 1951, Pit 1 received discharges via a buried pipeline from drains in the nearby decontamination building (7819) between 1962 and 1970. These discharges of acids, soaps, and chelating agents were not measured, but this contact-handled equipment decontamination facility probably did not add significantly to the inventory of radioactivity in Pit 1. During this and previous operations, Pit 1 was spanned by a wooden roof with asphalt-coated corrugated metal sheeting to divert precipitation. In 1981, the pit was filled with soil and capped with asphaltic concrete. Since that time the pavement has been resealed occasionally with various asphaltic coatings and the site surrounded by a 4-ft-high barbed-wire fence with appropriate hazard warning signs.

1.2.2 Site Characterization Summary

Prior to the capping and filling of Pit 1 in 1981, the site contained several runoff swales or ditches (Fig. 1.6) which intersected the southeastern corner of the pit. Although these runoff channels were not present when this ISV project was initiated in 1993, subsurface relict structures may still exist in that region and may still function to recharge perched groundwater in the pit. In 1993, the topography at the site was as indicated in Fig. 1.7. This change from pre-1951 shows the general filling and leveling of the site and the apparent large import of clean soil to avoid sculpting any of the downslope soil contaminated by overflow from Pit 1. This is the topography on which the site characterization effort (see Volume 2) was carried out to determine the depth and lateral targets for ISV as well as constraints on site preparations for equipment setup and movement.

Fig. 1.6. Plan view of ORNL seepage Pit 1 overlaid on the original topography (pre-1951) of the site showing runoff channels to the southeast. DOE Grid North is top of page and true north is approximately $38^{\circ}46'$ clockwise from DOE Grid North.

Fig. 1.7. Topography of Pit 1 site in 1993 prior to site preparation or in situ vitrification operations but depicting potential ISV melt settings and characterization penetrations. DOE Grid North is top of page and true north is approximately 38°48' clockwise from DOE Grid North.

1.2.2.1 Pit 1 ISV depth and lateral targets

The lateral and depth targets for ISV were based on the depth and areal extent of radioactive contamination. Much peripheral contamination of downslope surface soil (buried under clean fill in 1981) was identified in this characterization. However, there appeared to be a significant break in the level of contamination between peripheral areas and a uniformly radioactive layer deep within the pit. The separation between lower peripheral and higher residual source contamination is discussed in detail in the characterization report (see Volume 2). The level of radioactive contamination within and around Pit 1 was quite high so that extensive soil sampling was not required to identify the contaminant distribution. In situ logging with a Geiger-Mueller counter within pipes and drill rods driven into the pit and surrounding soil provided excellent three-dimensional contaminant distribution. The plan view of the ISV source term contamination is depicted in Fig. 1.8. This target area was found to be 1,992 ft² which, if vitrified to the total depth of contamination, i.e., 26 ft, would require processing of 51,792 ft³ of soil. Not surprisingly, the dimensions of this target area were consistent with the stated dimensions of Pit 1. In addition, the source contaminant area was coincident with the deeper penetration refusals indicative of fill material within a generally denser unweathered material.

Fig. 1.8. Plan view of ORNL Pit 1 source contamination as a target for in situ vitrification.

However, very little of the complete 26-ft deep soil layer was actually contaminated with radionuclides. The bottom few feet, near the contact of the original excavation, contained virtually all of the source contamination (Fig. 1.9). However, the source contamination was not a uniform depth layer but curved up the walls of the original excavation probably due to the ambient level of contaminated water within the pit during its operational lifetime. The north-south cross-section of Pit 1, depicted in Fig. 1.9, was the long axis of Pit 1 measuring approximately 92 ft.

Pit 1 was found to be quite narrow (Fig. 1.6) with an average width of approximately 23 ft on the east-west transect (Fig. 1.10). This maximum width was determined to be quite compatible with ISV melt zone capabilities where, under unconfined conditions, melt body diameters are generally found to be about twice the electrode separation. The ORNL off-gas hood was designed with

electrode spacing variability between 10 and 17 ft. Thus, the entire width of Pit 1 source contamination was determined to be susceptible to vitrification within a typical single setting of the large-scale ISV equipment. This compatibility of Pit 1 width and ISV melt setting capability was also an important factor in both upgrading the original project objective of overlapping pilot-scale melt bodies and, later, in upgrading the project objectives of two overlapping large-scale melts within Pit 1 to attempting to vitrify all of Pit 1 in three overlapping large-scale ISV settings.

Figure 1.9. North-south cross-sectional profile of ORNL Pit 1 excavation (penetration refusal) depths and radioactive contamination at and slightly above the contact of fill and undisturbed formation.

1.2.2.2 Other operational criteria resulting from Pit 1 site configuration

In addition to setting the targets for ISV depth and lateral extents, site characterization revealed several limitations to the design of ISV operations. The need for a large all-weather leveled area for equipment setup necessitated much of the vegetation clearing and importing of gravel fill (see subsequent discussion). The presence of significant surface soil contamination to the south, west, and north of Pit 1 precluded unrestricted use of these areas for staging and support areas. More importantly, the presence of buried contaminated layers on the north and particularly the west sides of Pit 1 (which presumably resulted from overflow of contaminated water downslope from Pit 1) limited the amount of pit surface contouring, which could be performed without generating significant volumes of contaminated soil. The depth of the maximally contaminated strata in Pit 1 was found to be between 25 and 27 ft below the original asphalt cap on the site.

To make the maximally contaminated strata fall within the 1993 ISV depth capability (20 ft), it would have been desirable to simply sculpt away approximately 8 ft from the surface of Pit 1 including its asphalt cap. However, significant buried contaminated soil was found to be present within 6 ft of the surface at one location. This peripheral contaminated soil depth on the west side left little room for error in planning site sculpting. A decision was made to sculpt only 4 ft of soil from the Pit 1 surface at this point (a maximum depth of 5 ft was attained in the northeast corner) in an attempt to avoid intercepting this shallow contamination. However, it was also determined that within the original excavation, clean soil was present to considerable depth (about 20 ft) as long as the walls of the pit were avoided. Thus, additional ISV starting depth was designed by use of a startup excavation to an additional 6-7 ft near the center of the pit. Thus, the start of ISV operations would be only 16-17 ft above the target depth, i.e., 26 ft - 4 ft sculpted from the site - 6 ft of startup trench excavation, and, thus, well within its established depth capability.

Fig. 1.10. East-west cross-section at the center of ORNL Pit 1 depicting the depth internal of the maximally contaminated soil layer.

However, starting ISV melting at a total of 10-11 ft below the original pit surface would mean starting at an elevation likely to be within the perched water table in Pit 1. The water table elevation within Pit 1 was found to vary over the year between 6 and 10 ft below the pit surface. Thus, ISV startup elevation would be within the water table. A small sump was designed to be placed within the startup trench to suppress the water recharge to the startup trench during ISV electrode setup and initial operations. After the ISV melt body had progressed down several feet and destroyed the sump pump, additional water removal would be maintained by evaporation of water near the boiling water isotherm around the growing melt body.

Thus, site characterization revealed peripheral soil contamination and perched groundwater elevations within Pit 1, which posed significant constraints on the design of ISV operations at Pit 1.

The other pits and trenches in WAG 7, unlike Pit 1, are positioned on the tops of hillocks and do not appear to have significant upslope groundwater recharge areas. All of the pits and trenches do appear to have perched water within them; but, addressing a small quantity of perched water is a significantly less difficult problem than a pit like Pit 1 with significant peripheral recharge and likely-buried hydrologically active features.

1.2.3 Site Preparation and Equipment Positioning

In general, site preparation involved grading, excavating, and filling operations to provide space and stable ground surfaces on which to position and operate the ISV equipment (Fig. 1.11). All of these tasks were performed by MK-Ferguson personnel and most were completed before the ISV equipment arrived from Richland, Washington, at the Pit 1 site in April 1995. However, the excavation of the ISV startup trench was delayed, of necessity, until all ISV equipment, including the new off-gas hood, had been assembled and later repaired on site in March 1996. Site electrical service was upgraded from 2.4 to 13.8 kV to a point near WAG 7, Pit 3, where a new set of step-down transformers were installed to return the feeder line to 2.4 kV.

1.2.3.1 Grading pit surface

The asphalt cap over Pit 1 (100 x 30 ft) was removed; it consisted of a nominal 4-in. thick asphalt overlying a 6-in. crushed rock base over clean fill soil which was imported to fill Pit 1 when it was covered in 1981. The asphalt cap and cover soil were pushed and hauled downslope to the west and used to extend a level area from the pit approximately 10 ft to the west. The soil underlying and surrounding the asphalt cap had been sampled extensively and no radioactive contamination had been observed within the depth interval of removal. Additional sampling of perched groundwater in the pit failed to detect any hazardous organic or inorganic contaminants at more than background concentrations. Grading work was performed by personnel of MK-Ferguson using an existing small bulldozer with minor hand shovel work around the protruding characterization pipes. A silt fence was placed around all downslope areas and runoff drainages were protected from silting with anchored hay bales.

Approximately fifty pipes were protruding from the ground after this cap grading; these pipes had been placed into the pit to carry out in situ radiation monitoring to determine the depth intervals of radioactive contamination. Pipe sections were to be removed by hoisting until a coupling joint was exposed; pipes were installed by coupling 5-ft sections and driving into the soil using a vibratory electric hammer. After decoupling the elevated pipe section, the residual pipe train was driven just below the ground surface using the excavation shovel. An existing electrical power pole was also removed after line power was turned off and electrical wires removed by ORNL Electrical Services Department. The pole was cut down and the stump removed by pushing with the bulldozer. The pole and residuals were buried in the fill area to the north of the present site. Following completion of grading, the level area was draped with plastic sheets to prevent surface erosion or recharge of precipitation to the pit.

1.2.3.2 Site clearing

Small trees (maximum 6-inch diameter) were removed from an approximately 20,000 ft² area immediately north and northeast of the pre-1993 cleared area. Trees were pushed down with a bulldozer into the depression in the area to the northwest of the site. Crushed rock was used to build up the elevation in this new cleared area. The additional level area was required for placement of temporary waste storage tanks and tanker trailer parking during liquid waste pickup. Additional access area was also provided by this clearing and was necessary for the three large ISV processing trailers to be towed onto the site. Significant surface soil contamination exists just to the north and to the northwest of the proposed cleared area due to waste transfer line leaks in the past (Williams et al. 1987). Because no removal of materials (trees or soil) from the site occurred as part of the site clearing and because fill rock was imported to raise the grade in this area, no contamination or exposure of personnel or equipment was experienced.

1.2.3.3 Site surface graveling

After completing the asphalt cap removal and grading, the site access improvements, and site clearing and grading to the north described above, a geofabric subsurface liner was spread over all the level area and a 6-in. thick gravel layer constructed for all-weather vehicle access and movement. Permanent monitoring wells were protected from damage by covering with steel plate during construction activities. Two portable skid-mounted buildings (8 x 20 ft) were moved with a forklift for gravel placement underneath and then returned to near their current positions. Gravel (limestone) was hauled to the site from a commercial supplier using dump trucks and spread using bulldozer or grader. An 18 x 56 ft bermed area was constructed in the tree-cleared area north of the present site as secondary containment for four 3000-gallon capacity tanks for excess ISV scrub solution waste. The berm was one foot high and was overlain by a 60-mil impermeable geomembrane. The actual as-built configuration of the cleared and filled areas was slightly different than indicated in the grading plan drawing (Fig. 1.11). The notch in the gravel fill area to the northwest of the site, immediately west of the tank farm storage area, was extended considerably to the northeast to provide a much enlarged and level work area. The graded pit surface area was also enlarged approximately 15 ft further north than indicated on the plan and was also extended approximately 15 ft further west with additional gravel fill. This enlarged pit surface was required to maneuver the new off-gas hood which, in final design, became much wider (60 ft) than originally planned (50 ft).

1.2.3.4 First startup trench excavation

In order for the ISV melt to reach down to the elevation of maximum contamination within Pit 1, the ISV melt was required to be started considerably below the final Pit 1 grade. A startup trench was dug between 6 and 7 ft deep at the approximate center of Pit 1. This roughly circular trench had tapered walls with a maximum 32 ft diameter at the surface, narrowing to a maximum of 20 ft diameter at its bottom. All excavation was performed with a power shovel. No personnel were permitted enter the excavation once its depth exceeded 4 ft until approval by safety personnel. Excavation did not encounter any contaminated soil; however, one buried cedar tree (approximately 10 ft long) was encountered and found to be slightly contaminated and was added to the contaminated tree storage pile to the northwest of the site. Excavated soil was stored on the northwest corner of the level area for use later to refill the ISV subsidence crater after completion of the first melt. Stored soil was covered with plastic sheet to prevent erosion during storage. A radiation protection technician was present continuously on site and monitored excavated soil to determine if any unplanned contamination had been encountered.

Immediately after completing the startup trench excavation, the off-gas collection hood was driven over the startup trench. This off-gas collection hood (whose assembly was completed prior to starting trench excavation and whose characteristics and operation are described subsequently) has a wheel span of approximately 60 ft and was driven via a radio controller from a position several feet away. Its position over the startup trench was adjusted to its final configuration for ISV operations. However, at this point, several weeks of equipment and site setup work were required before the start of ISV melting operations. In the interim, the off-gas hood functioned to prevent accumulation of precipitation in the startup trench and as a barrier to access to the open trench perimeter.

1.3 PIT 1 IN SITU VITRIFICATION OPERATIONS DESCRIPTION

The ISV operations at ORNL Pit 1 employed significant modifications to existing equipment and fabrication of new equipment in order to meet the objectives of the treatability study. In addition, many of the normal operating procedures were modified to meet the constraints of the required melting configuration within Pit 1. Because of the unique nature of the contaminants and their configuration in Pit 1, the design of monitoring and measurement systems was significantly different from previous ISV operations.

1.3.1 Description of New Equipment

The major piece of new equipment for ISV at Pit 1 was the off-gas hood (Fig. 1.12). This new hood was designed and fabricated for application of ISV to all of the remaining pits and trenches in WAG 7. Once the decision was made to increase the scope of the treatability study from the initial objective of producing two overlapping pilot-scale melts within Pit 1 to producing two large-scale melts, a decision was made to replace the existing damaged large-scale hood located in Richland, Washington, and build another with characteristics which would make ISV operations at ORNL more efficient. Unlike any existing ISV off-gas hood, this hood has electric-powered automobility with four-wheel independent steering; this attribute would overcome the previous necessity to lift the hood from melt setting to melt setting using an expensive but intermittently needed heavy crane (hood weight was 115,000 pounds). Thus, the hood could be driven from setting to setting within a site and, given wide enough access, driven from site to site such as between pits within WAG 7. The entire off-gas hood consisted of a hood shell, with bolt-together stainless-steel panels, and is suspended over the melt body area from the superstructure.

The hood shell is assembled from a set of 304L stainless steel 18 ga. sheet-metal panels. There are a total of 202 separate panels comprising 26 different panel shapes. Once assembled, the hood shell covers an area of approximately 50 x 50 ft (6 ft high) with a total flat area of 3,450 ft² and a total plenum volume of 13,840 ft³. This hood shell provides confinement of gases emanating from the ISV melt body by maintaining a slight negative pressure within. The hood shell provides level contact with the ground surface; a seal was provided by lowering the bottom edge into a nominal 4-in. deep x 6-in. wide trench and manually packing soil around the inside and outside walls. Leakage of air through the panel joints is limited by high-temperature fiberglass gaskets. The hood shell has a variety of sealed penetration ports facilitating such operations as electrode insertion, visual and remote (video) observation, instrumentation and sampling, air inlet and off-gas removal, and solid material addition. The hood shell is suspended from the superstructure using shackles and chain. The hood shell can be decontaminated by removing selected panels. Personnel can also access the interior, during setup or demobilization, by removal of one or more side panels.

The superstructure is a steel framework which provides support for all the hood components and is constructed of steel structural members. It was designed for ease of assembly/disassembly for transport from site to site and is comprised of a variety of interchangeable or modular components mostly made from tubular steel. The members are joined using flanged plates with bolt fasteners or clevis ends with pin fasteners. Tensioning members, made of steel cable and turnbuckles, are used to truss the structure and reduce deflection, minimize sway, and optimize stresses.

Another costly and tedious task addressed by the new hood is the replacement and addition of graphite electrode sections as the melt progresses downward. Previously, this was performed with a separate crane (not always available on demand from plant services) to lift the 500-pound 12-in. diameter graphite rods to screw into the top of the subsided previous electrode column. The new

Fig. 1.12. The new large-scale off-gas hood designed and fabricated for application of ISV to WAG 7 seepage pits and trenches.

hood has an electrode feed system (EFS) which supports and positions the electrodes in a vertical orientation and allows controlled feeding of the electrodes into the melt body. The EFS consists of a series of four electric hoists riding in an overhead I-beam trolley system, which allows operators to retrieve additional electrode sections from a staging area at the side of the hood, transport the sections to the penetration point in the hood shell, and assemble the new section onto the electrode column. The hoist is electrically isolated from the energized electrodes by an insulating lifting link above the lifting hook. A clamping device, placed on the electrode, acts as a stop when the electrode has descended to the bottom of its travel interval and supports the electrode column while the hoist is detached and additional electrode sections are being added. The clamp also acts as a holding wrench when assembling or removing electrode sections. The clamping device and its support ("cradle") on the work platform also provide electrical isolation from the superstructure. Each hoist is operated (raise or lower motion) either locally by an individual pendant or remotely (off the work platform) from a single hand-held console with separate switches for each hoist. Trolleys and bridge sections of the overhead crane rail system are operated (lateral motion) by a chain-fall attached to a drive wheel. Details of the operation of this system as well as all other hood components, are contained in the ISV Hood Procedure (ISV-TS-P95, Rev. 1.0, October 1996, in project records).

Power is delivered to the melt through a set of 16 parallel 1000-MCM portable power cables attached to the four graphite electrodes with four cables per electrode. The cables are terminated at one end in four junction boxes, mounted at the base of the superstructure (Fig. 1.12) and at the other end at a copper contactor which grips the electrode. Similar electrical cables run from these junction boxes to the ISV power supply transformer and must be removed from the junction boxes for hood movement. The cables run up the superstructure to above the rail system in cable trays, are properly oriented to eliminate undesirable induction effects, and are suspended from the top of the

superstructure to termination at the electrodes. The cables drape in a manner that allows the electrode and fixed contactor to travel the length of one electrode section (6 ft).

The work platform is suspended from the upper frame of the superstructure using steel beams and provides a surface for ISV operators on the hood system. The surface of the work platform is smooth steel grating. Stairs are provided at both ends of the hood and catwalks are provided from the stairways to the work platform for access and use during electrode additions. The central region of the hood shell is suspended from the work platform and the centrally-located roughing filter housing is mounted to the center of the work platform. Where the electrodes penetrate through the work platform, a cradle is positioned which holds the electrode support clamp and can be rotated to allow for variable electrode spacing. Electrical insulation is provided in the penetration to avoid the energized electrodes from contacting the work platform.

The hood provides a valve-controlled supply of inlet air to the hood shell plenum, off-gas filtration, and an emergency or backup off-gas removal system. A manifold pipeline evenly distributes air to four ports located near the corners of the top of the hood shell (Fig. 1.12). A control valve (which fails in its current position should power be interrupted) at the head of the manifold regulates air into the hood plenum for cooling and control of the negative pressure in the plenum.

Off-gas is withdrawn from the hood plenum directly through a roughing filter which provides the first stage of particulate removal. The roughing filter is a high-temperature, renewable baghouse type filter, 6 ft wide x 12 ft long x 6 ft high made from 316 stainless steel sheet metal. It is supported by the work platform and is fixed at its base to the hood shell panels. The filter bank (Fig. 1.13) is composed of 128 bags (4 ft long x 0.5 ft diameter) made from high-temperature woven ceramic fabric (Nextel®, 3M Inc.) and is designed to remove at least 99% of particulate greater than 0.5 micrometer in size. The bags are placed over stainless steel wire cages which are inserted into a tube sheet manifold from the top of filter housing which has a manually removable cover. An electronically-controlled air blow-back device regularly cleans loaded filters and is normally controlled by a signal measuring pressure drop across the filter unit; alternately, it can be manually controlled or automatically controlled by a timer.

A backup blower, mounted on the work platform, provides emergency off-gas removal in the event of loss of negative pressure in the hood plenum or failure of the off-gas treatment system. It is routed through a bank of four standard-size, high-temperature HEPA filters (same as the prefilter) installed between the hood plenum and the blower to provide filtration of off-gas prior to atmospheric release.

The hood also contains a vacuum relief seal pot which consists of a 12-in.-diameter sheet metal pipe immersed in a drum of water. The end of the pipe is inserted into a fixed depth of water which then sets the maximum vacuum the hood could experience before the seal pot allows air to enter the hood. This relief seal pot is strictly designed to protect the hood shell from experiencing a vacuum beyond design limitations.

The off-gas hood also contains a solids materials addition system (MAS) which allows for delivery and dispersion of solid materials to the melt surface either before, during, or after the melting, without the necessity of moving the hood or removing hood panels. Materials that can be added include clean soil, to cover surface contamination inside the hood before moving after a melt, insulation material such as Firelite® aggregates, to conserve heat in a melt body or to filter off-gas, and melt modifiers such as limestone, to lower ISV operating temperatures or viscosities. The MAS is supported by the superstructure and penetrates the hood shell centrally near one end of the

roughing filter housing (Fig. 1.13). A rotary spreader at the discharge provides for distribution of solids over the melt surface. A 2-yd³-capacity hopper is located on the hood perimeter superstructure (Fig. 1.12) for material storage and provides feed material to a rotary screw-conveyor. The hopper has a remotely operated lid to aid in sealing the hood vacuum. Controls for the hopper vibrator, door, feed conveyor, and rotary spreader are located in a control panel box mounted to the hood perimeter superstructure.

Fig. 1.13. View of a few roughing filter bags from beneath the hood shell showing where ISV off-gas exits the hood. The material addition spreader is visible in the background.

Travel and steering for the hood are provided by four running gear wheel assemblies mounted on turntable bearings at the corners of the lower framework of the superstructure. The travel system is operated by a radio frequency, hand-held, remote controller. There are four speed settings programmed into the travel system corresponding to 0.5, 1, 2, and 5 ft/min. There are three steering modes: crab steer, sideways steer, and center spin steer. Hydraulic cylinders mounted on each wheel assembly provide for leveling the superstructure or raising the hood shell off the ground during transport; each wheel assembly can be independently raised or lowered. Landing gear are mounted at the corners of the superstructure to provide foundation support to the superstructure during ISV operations because the wheel assemblies were not designed to take an additional full 5-in.WC vacuum load from the hood on the superstructure.

1.3.2 Equipment Configuration

The planned layout of the Pit 1 site showing equipment and work areas is depicted in Fig. 1.14. An aerial photograph showing the major equipment configuration can be seen in the actual site photograph (Fig. 1.15) taken on April 22, 1996, the day after the melt expulsion incident.

Fig. 1.14. Configuration and identity of major equipment at the ORNL Pit 1 site and location of hazardous zones. DOE Grid North is top of page and true north is approximately 38°48' clockwise from DOE Grid North.

Fig. 1.15. Areal photograph of ORNL Pit 1 site on April 22, 1996, the day after the melt expulsion event, depicting the location of major ISV equipment. Top of photograph is west.

Although the configuration of major equipment at the ISV site was an optimization of space, project objectives, operational simplicity, and costs, similar factors played a significant role in the configuration design for the melt body and its associated monitoring and measurement objectives. As discussed previously, the depth objective was made feasible by starting the ISV melt body within an approximately 6-ft deep startup trench. This placed the maximally contaminated layer within Pit 1 within a maximum of 16 ft beneath the melt body starting elevation. The major technique for monitoring the melt depth was designed to be the measured electrode penetration; each electrode functioned as a dipstick because it was allowed to sink into the melt body resting on unmelted soil at the bottom of the melt body. Lateral progress of the melt would be measured through an array of thermocouples at various distances and depths relative to the melt body. In addition, because of the necessity of melting into the watertable in Pit 1, supplementary vent pipes were identified as a prudent technique to vent generated steam around the planned melt body. Before discussing the design configuration of the thermocouples and vent tubes, the planned configuration of the first melt body was considered (Fig. 1.16).

Fig. 1.16. Planned configuration of the first melt body prior to start of ISV operations showing melt widths, subsidence cavity, and startup trench excavation.

The dimensions of the planned first melt body set significant constraints on the placement of the vent pipes and thermocouples within and around it. Because the melt body width (26-27 ft) was desired to span the entire Pit 1 east-west width (23 ft), the melt body would engulf a significant amount of the dense undisturbed soil/rock formation. As discussed in the characterization report (see Volume 2), this dense undisturbed soil/rock formation could not be penetrated by driven drill rod or pipe; thus, placement of vent pipes or thermocouples would not be possible from the east or west sides of Pit 1. The initial melt was positioned in the center of Pit 1, leaving significant portions of

the north and south lateral edges of the melt body comprised of less dense soil fill within Pit 1. Thus, driven penetration holes for vents and thermocouples were feasible from the north and south along arc segments out towards the east and west pit walls.

Thermocouples were placed in angled holes which entered into the projected melt zones at various depths and distances from the melt centerline (Fig. 1.17).

The actual depth positions (relative to grade) of these thermocouples along N-S, NW-SE, and NE-SW transects are depicted in Figs. 1.18, 1.19, and 1.20.

The ORNL Hologator® angle drill was used to produce the access holes for the thermocouples; either an AWJ or Geoprobe® drill rod was pneumatically hammered or hydraulically pressed into the pit at the desired angle to the desired depth for each thermocouple. After knocking off the expendable drive points on the rod, the thermocouple and sheathed wire leads were inserted into the hollow stem and the drill rod withdrawn using the hydraulic arm of the drill head mast. Although most of the thermocouples were not emplaced into contaminated sections of Pit 1, radioactive contamination monitoring was continuous during withdrawal of the drill stem from each hole. The depths and lateral extent of radioactive contamination within Pit 1 were well documented from the extensive in situ radiation assays performed in pipes in and around Pit 1 (see Volume 2). All thermocouples were emplaced prior to startup trench excavation and subsequent hood covering. Bundles of thermocouple wires exiting to the west and south of the pit, which project away from where excavation equipment would be positioned, were selected for this installation. Shallow (6-8 in.) trench runs were hand excavated to bury all wires prior to hood assembly and startup trench excavation. Most thermocouples were type K which would be destroyed if contacted by molten soil. Their use was designed to indicate when the melt reaches their depth or lateral position and, thus, they provide much information on melt depth and shape until destroyed by the melt. They also would provide cooling kinetics information on heated but unmelted perimeter zones. Additional type C thermocouples, sheathed in alumina tubes, were positioned into several projected melt zones and were designed to survive contact with the melt. They would provide information on actual melt temperatures during ISV operations and melt cooling kinetics after power was terminated. The use of Type C thermocouples for this purpose was very successfully demonstrated in the 1991 ORNL pilot-scale test (Spalding et al. 1992).

Vent holes were positioned under and around projected ISV melt zones prior to ISV operations (Fig. 1.21). Vent holes were inserted with slotted well screen over the entire length of the hole. Holes were made using the Hologator angle drill with AWJ drill casing with expendable drive points. Drill rod, with attached expendable drive points, was driven pneumatically or pushed hydraulically. Continuously slotted galvanized well screen was then inserted or pushed into the AWJ casing; screen sections (1.25-in. inside diameter) were coupled using standard pipe couplings as the well stem was assembled during insertion. The AWJ casing was withdrawn leaving the well screen in the ground. All well screen stems projected to the surface inside the planned hood containment area. At least four vent holes were installed into each of three depth layers angling under the projected melt zone at various stages of melt progress. The lowest layer of vent screens was positioned at contact with the pit bottom (penetration refusal) and was not expected to survive the final melt depth. Melting into vent pipe screen would destroy vent hole connection with the surface as the steel screen melts and voids fill with molten soil. A group of several vent holes was positioned vertically just beyond the projected melt zone diameter and was expected to maintain connection to the ground surface throughout the melting operations. The cross-sectional projections of all the vent pipes on either the southeast-northwest or southwest-northeast transects are depicted in Figs. 1.22 and 1.23.

Fig. 1.17. Plan view of thermocouple installation around the planned center of the first melt at Pit 1 showing both the radial position of the sensor end and the exit hole for sensor wires. North is 0 degrees.

Thermocouple Positions N-S Section

Fig. 1.18. Depth and lateral placement of thermocouples relative to the center line of the first ISV melt body on a north-south transect.

Thermocouple Positions NW-SE Section

Fig. 1.19. Depth and lateral positions of thermocouples relative to the center of the first Pit 1 melt body along a northwest-southeast transect.

Thermocouple Positions SW-NE Section

Fig. 1.20. Depth and lateral positions of thermocouples relative to the center of the first Pit 1 melt body along a southwest-northeast transect.

Fig. 1.21. Plan view of off-gas vent pipes relative to the planned center of the first Pit 1 melt body showing bottom and exit points of each vent. North is 0 degrees.

Fig. 1.22. Vent pipe orientations relative to the center of the first Pit 1 melt body projected along a southeast-northwest transect.

Fig. 1.23. Positions of vent pipes relative to the center of the first Pit 1 melt body projected along a southwest-northeast transect.

Several tracers were placed into the test zone to aid in the evaluation of ISV performance. First, two rare earth oxides were placed in the two separate penetration holes within the initial projected melt volume. These tracers, present in the Pit 1 soil at only trace levels, would be conserved (not volatilized) in the ISV melt and, thus, their final concentration in the melt product was used to compute the melt mass. These tracers (1,361 and 3,743 g of Lu and Ho as their oxides) were contained in polyethylene bottles and inserted into holes opened into the projected pit melt zone. Holes were constructed with AWJ drill casing hydraulically pushed or pneumatically driven with the Hologator drill rig. However, the tracer container holes were vertical, projecting only about 5 ft below the projected starting melt surface; tracers were emplaced prior to startup trench excavation to avoid more difficult operations from the off-gas hood work platform. The sealed tracer containers were dropped into the open holes to the desired depth. A 1 kg cesium chloride tracer was also positioned into the melt zone to be attained during the operational acceptance test (OAT) in the first melt. This semivolatile cesium chloride would function for testing the removal efficiencies of the off-gas roughing filter and HEPA prefilter when these were sampled and analyzed along with ISV product samples following completion of the OAT.

1.3.3 In Situ Vitrification Operations Procedures

An OAT was performed on the first melt setting of Pit 1. It encompassed melting Pit 1 earthen materials down to a depth about 5 ft above the known maximal contamination elevation within Pit 1. Thus, the OAT processed relatively uncontaminated materials. The OAT was terminated by reducing melt power and monitoring the product temperature while allowing three days for evaluation, modification, and repair to equipment or procedures.

The OAT had several purposes. First, it functioned for equipment performance checks including the new off-gas hood and the large-scale ISV equipment, the data acquisition system (DAS), and all

installed sensors. Second, it provided training for the operations crew, some of whom had no previous experience with ISV, in all facets of ISV operation before radioactive contamination was encountered. Third, it provided performance information including melt operating temperatures, downward and lateral melt growth rates, vent effectiveness, perched water impacts, scrub solution waste generation rates, and off-gas characteristics which would facilitate planning operational procedures for the contaminated sections of Pit 1. Fourth, it provided information on possible additional sensor placement needs for the subsequent melting into Pit 1 contamination. Fifth, the OAT termination provided time to sample off-gas system components for any volatilized stable cesium which was buried in the projected melted volume of the OAT and verify the removal efficiencies of the off-gas filtration components. After completing the evaluations of the OAT, power would be increased to the melt body to complete the depth and lateral goals into the contaminated strata of Pit 1. Details of the operation of the large-scale ISV off-gas and power equipment are contained in the equipment safe operating procedure (Safe Operating Procedure for ISV Large-Scale System. Procedure No. 58, Rev. 9., Battelle PNNL. June 1995, in project records).

Details of the ISV operations and application to Pit 1 are contained in the project test plan (Test Plan for ORNL Full-Scale ISV Demonstration. Battelle PNNL. July 1995, in project records). This test plan and operating procedure contain detailed instruction for performing each system operation and sign-off records for the completion of each setup and task completion. These details will not be repeated here. The following is a summary of only the major operational tasks and the rationale for performing them in the specified manner.

The project test plan included a checklist of items to be completed, signed, and approved by the ORNL and Battelle PNNL project managers prior to the start of the OAT. The test plan includes many items which had to be completed before supplying electrical power to initiate the melt. Major items on this checklist included: a check of the performance of the video monitoring and recording system; a check of performance of all sensors in the process equipment and around the projected melt zone; a check of both DASs for recording and displaying sensor data; a walkthrough to verify visually operation of off-gas handling equipment and sensors relative to their DAS-indicated parameters; a walkthrough to verify the operations of the perimeter air samplers; a tour and briefing for all fire department, emergency response, and laboratory shift supervisor personnel; a check for the operation of all communications equipment including telephone, cellular phones, and two-way radios; completion of required notification of intent to startup including ORNL shift supervisor and the ORNL readiness review board chairperson; and a verification that all components of the run plan have been signed off by required individuals.

1.3.3.1 DAS assembly

The DAS for the in ground sensors (thermocouples) and off-gas radiation monitors was assembled by ORNL project personnel. In-ground thermocouples were wired through high-voltage isolators in a electrical box mounted to the back of the DAS/Break Room storage shed, in case of contact with the high voltage in the melt. The DAS consisted of National Instrument data acquisition equipment linked to a Macintosh IIfx computer operating LabView software as a display and data management and recording system.

1.3.3.2 Sensor performance checks

Prior to start of ISV operations, all sensors (thermocouples, radiation sensors, pressure and flow transducers) required calibration and/or performance checks. Radiation detectors were performance checked by placing radioactive sources next to detector and noting the instrument response.

Thermocouples were checked for their performance before placement in the buried access holes using ambient and ice-water temperature checks. Details of sensor calibrations and performance checks are contained in the project quality assurance plan. Sensor performance was checked by Battelle PNNL and ORNL project personnel. Deficiencies and changes in performance were noted in the project field log book (e.g., when thermocouples burn out or exhibit erratic performance). Monitoring was either terminated or continued with performance deficiencies recorded for interpretation of data at a later date.

1.3.3.3 Melting operations and monitoring

Power Characteristics Monitoring and Adjustments. The potential for feedback harmonics from ISV operations into the ORNL feeder electrical delivery line necessitated the monitoring of power characteristics in that delivery line. A Dranetz Power Platform monitor was used to monitor the supply side voltage and amperage characteristics. The signal probes were connected by MMES electrical engineers to the input connections inside the power trailer and were monitored regularly before and during ISV operations although no electrical anomalies were encountered. In addition, the primary and secondary power characteristics (but not harmonics) were monitored for current, voltage, and power for both phases by the large-scale system process control DAS. Tap changes were required from time to time on the 3,750 kVA transformer to maintain optimal power to the melt. These were performed with interruption of power to the electrodes by ISV operating personnel. ISV operations personnel included employees of ORNL, Battelle PNNL, and Geosafe for the duration of the field operations. Power was interrupted to the melt occasionally to add electrode sections as the melt progressed, to repair damaged electrodes, or to perform work on the hood or prefilter work platforms. Access to the hood system work platform was not permitted when the secondary side of the 3,750 kVA transformer was energized. Work within the off-gas hood safety zone was performed with the 3,750 kVA transformer energized provided the worker was wearing certified and inspected high-voltage electricians gloves and insulating rubber boots in addition to the required personal protective equipment (PPE).

Test Monitoring. Although the DAS in the process control trailer for the ISV equipment had many sensors which alarm at the monitoring console, numerous performance checks and verifications were performed regularly throughout ISV operations. Many sensor alarms functioned to alert operators to take action in response to alarms (such as scrub tank high level alarms which then required solution transfer to waste holding tanks). Other sensor alarms required that the operator investigate the cause of the sensor alarm, i.e., was the operating equipment in out of normal range or had the sensor itself failed. The complete list of alarm conditions and operator's response are detailed in the standard operating procedures for the large-scale ISV equipment. ISV operations personnel corrected equipment deficiencies as required. These operations required use of hand tools; electrical power and other hazardous energy sources to affected equipment were de-energized following lockout/tagout protocols before initiating work on the defective component.

The DAS was monitored to determine off-gas and melt temperatures and, by inference, the depth and lateral extent of the melt. Depth monitoring was determined when the scrub solutions were sampled and when electrode additions were made. Finally, monitoring determined when the target depth for the OAT had been reached and, thus, when the OAT was to be terminated. In addition, the melt surface condition and electrode condition were to be monitored using the video images from the two cameras mounted on the off-gas hood.

As an independent check on the depth of the melt, the extent of electrode penetration was monitored by routine observation during ISV operations. Graduations corresponding to melt depth

were painted onto each of the four electrode and their position relative to the fixed reference of the electrode column cradle were observed from the control trailer or area around the hood. By reference to their starting penetration depth, the depth of the OAT melt was monitored using the electrodes as dipsticks.

Electrode Section Additions. As the melt progressed downward, the graphite electrodes fed through their guides and rested on the bottom of the molten body; periodically, the electrode column needed to be extended by adding additional 6-ft lengths to maintain the melt progress. A total of three electrode section additions (18 ft) were made to each electrode column during the course of Pit 1 melting operations. To add electrode sections, power to the electrodes was de-energized. ISV operations personnel used the electrode feed system (EFS) hoist to raise new graphite sections and screw them onto the protruding electrode stem. The electrode gripper held the residual electrode stem in place while the new added section as rotated into the threaded connection while attached to the hoist. After completion of electrode assembly, the crew left the work platform and removed locks and tags from the electrode power switch and the melt was resumed.

Melt Additions (Limestone). To reduce melt operating temperatures, electrode oxidative corrosion, and melt interface viscosity, additions of limestone were initially planned to keep the ISV melt approximately 10% in CaCO_3 content. Based on the projected melt volume and melt density, approximately 3,600 pounds (1.5 yd^3) of crushed limestone was planned for addition to the growing ISV melt body for each foot of downward melt progress. The limestone gravel would be added using the solids MAS attached to the off-gas hood (described in section 1.3.1). Limestone gravel (washed 1-2-in. diameter) was delivered to the site and stored just inside the Melton Valley access gate. ISV operations personnel could load gravel onto a feed conveyor with shovels which delivered the required volumes to the hood's MAS hopper and then to the top of the melt. However, no regular limestone additions were made during the OAT or later ISV operations because the melt was progressing quite rapidly and facilely; apparently the large addition of feldspar starting sand, with its high content of sodium and potassium, was sufficient to maintain a reasonably low-temperature melt process without the need for additional limestone. At the end of OAT, 2 yd^3 of limestone was added to the melt as the initial test of the performance of the MAS after its exposure to ambient ISV thermal stresses and operations.

Thermal Barrier Additions. After termination of electrical power to the melt after the OAT, an insulating barrier was to be added to the melt surface. The purpose of the barrier was 1) to preserve heat in the melt body for restart of ISV operations for contaminated regions of Pit 1 after several days and 2) to provide an in situ filtration layer to aid in removal of any volatilized ^{137}Cs during the subsequent ISV operations into the contaminated region of Pit 1. The insulating material was a high-temperature aluminosilicate aggregate (Firelite® insulating aggregates described in the site characterization report). Approximately, 4000 lb of this aggregate was added after the OAT. A minimum of approximately 500 ft^3 of insulating material was desired to maintain a nominal 1-ft deep layer on the melt surface at the termination of the OAT. In addition, ISV operators added about 200 lb of Firelite® aggregate around the base of one electrode, which appeared to exhibit excessive oxidation (diameter reduction). The aggregate was poured through an open electrode port.

Post-OAT Sampling, Analyses, and Evaluation. Following termination of the OAT, many systems and equipment components had to be evaluated to assure their anticipated performance during subsequent planned ISV operations into the contaminated regions of Pit 1. A more complete report of the OAT evaluation is contained in the technical evaluation of the melt expulsion event (ESERP 1996a).

Sample Product with Dipstick. A sampling of the OAT ISV product was attempted shortly after termination of power to the melt. This product sample provided information on chemical composition, tracer concentrations, and level of radioactive contamination. Sampling was completed by manually inserting a carbon steel "dipstick" (Geoprobe rod) from the off-gas hood work platform at one electrode port cover. Geoprobe rod was selected because the 0.5-in. diameter internal bore allowed placement of a type C thermocouple into the melt body to verify operating temperature. The rod was withdrawn after apparent equilibration of the thermocouple and the adhering glass was allowed to cool for a few minutes while resting the rod on the melt surface or nearby unmelted perimeter. The dipstick was then removed and top uncoated section of rod removed. Product glass was removed by fracturing the glass with a hammer to yield the few hundred grams necessary for analyses.

Power Initiated to Melt 1. Following all the required notifications to initiate melt 1 and associated approvals, full-power was re-initiated to melt per the SOP for the large-scale ISV equipment. Electrical power characteristics to the contaminated melt operations phase were monitored identically to that during the OAT as were all other systems and operations.

1.3.3.4 Off-gas processing operations and monitoring

Scrub Solution Transfer. The two off-gas scrub solution tanks were filled to their minimum operable volume prior to start of ISV operations. However, due to the very moist soil and perched water in Pit 1, scrub-solution volume grew to full levels every few hours during operations as the water evaporated from the melt was condensed in the process trailer. Periodically, the scrubber tanks were returned to their minimum operable volume by transferring excess solution to the four 3,000 gal capacity waste storage tanks to the north of the site. This was accomplished by routing the scrubber solution circulation pump through a bypass line to one of the waste holding tanks. Operators recorded tank volume in the transfer log immediately before start of transfer and immediately after completion of transfer; transfer volumes were also recorded from a water meter flow totalizer in the hose transfer line between the off-gas trailer and the tank farm. Scrub solution pH was monitored automatically during operations and recorded by the DAS; increments of caustic soda solution were added to keep the solution pH between 8.0 and 9.0.

Scrub Solution Sampling. The tank scrubber solutions were sampled at predetermined intervals during operations to provide samples for low-level radioactive and chemical analyses. Scrub solution sampling was to be initiated after each foot of ISV melt body production or immediately prior to each liquid transfer to the waste storage tanks (a frequent event). Sampling was accomplished by valving partial recirculation flow into a 250-mL plastic bottle prelabeled with a sample number. The prelabeled sample bottles were placed into and removed from the treatment system's containment through a glovebox port using bag-in/bag-out procedures. The date, time, tank, and sampler's name were recorded in the sampling log book next to the sample number.

Scrub Solution Waste Transfer. Scrub solution was transferred as required from the four waste storage tanks to the tanker trailer for transfer to the ORNL liquid waste disposal system; five 5,000 gal tanker trailer loads of wastewater were generated prior to the melt expulsion incident. Although this waste solution was planned to be both nonhazardous and nonradioactive, except for possible low levels of tritium less than the drinking water standard, it was hauled to the ORNL liquid waste disposal system to discharge to surface water through the Nonradiological Wastewater Treatment Plant (NRWTP), regulated by an existing ORNL National Pollutant Elimination System (NPDES) permit. A sample of each full tanker was taken and analyzed overnight for gross radioactivity and hazardous elements prior to each pickup. Transfer of liquid waste from the storage

tanks to the waste transfer tanker trailer was accomplished using electric-powered centrifugal pumps. The intake of the pump was connected to the floor valve of a 3000-gal tank via quick-connect fittings and the outflow hose routed to the top hatch of the tanker trailer. The pump was positioned within the bermed area so that any leakage or spill was contained.

1.3.3.5 Off-gas emissions and ambient air monitoring

Modified Method 5 (MM5) Off-Gas Sampling. The off-gas samplers for MM5 have been described elsewhere (Off-Gas Sampler Procedure. ISV-TS-PM5. June 30, 1995, in project records). It was not the intent of the project to use the MM5 samplers to continuously sample off-gas during ISV operations; they were originally planned to be operated periodically for approximately one hour intervals once a shift (8 hr). However, the frequency of MM5 sampling was reduced to once a day when it became apparent how much effort was being expended for relatively little information; the HEPA filters on the off-gas line provided the same type of sample (particulates) integrated over their interval of use. MM5 samplers were set up at two positions in the off-gas processing equipment: between the roughing filter and the HEPA prefilter and between the HEPA prefilter and the off-gas trailer line. This was designed to provide information on the off-gas particulate (and its associated radioactivity) and removal efficiency of the HEPA filters. Direct off-gas from the ISV process was also sampled occasionally by opening the roughing filter bypass valve and collecting the MM5 sample at the sampling port before the HEPA prefilters. ISV operations personnel placed new glass-fiber filters on the filter holder and fresh ice in the sampler condenser bath as described by the sampler operations procedure. Sample filters were removed after operating for the predetermined interval, usually one hour, and placed in Petri dishes inside seal-lock plastic bags which were labeled with date, time, sample location, and sampler's name.

Off-Gas Radiation Monitoring. The samplers and monitors for the off-gas were periodically visited by ISV operations personnel to verify their proper functioning and to perform sensor performance checks. The off-gas stack and perimeter radiation monitors had their filters changed periodically when flow was diminished. Time series of process off-gas samples were collected on particulate paper tape samples, drawing samples continuously from a line sampling the roughing filter face and another sampling the off-gas line immediately prior to the HEPA prefilter. These Graseby-Andersen paper tape samplers pulled an off-gas sample through a 1-in.-diameter spot on a paper tape at a fixed flow rate (typically 2 L/min) for a fixed interval (typically 20 or 60 min); the paper tape was then automatically advanced to a new spot and the residual paper tape was spooled automatically on the sampler. Each paper tape sampler was fitted with a Geiger-Mueller (G-M) counter with the probe positioned just above the previous sample spot; the real-time output from the G-M meter was collected by the DAS although this represented condition of the off-gas at present-minus-20 min rather than current condition.

The off-gas exiting the process trailer was sampled from the exit stack on the roof using a fixed flow-rate sample, designed for isokinetic sampling from the fixed off-gas discharge rate, using an Eberline AMS-4 radiation monitor. Filters for the AMS-4 detection chamber were changed when indicated by the monitor. Signals from the AMS-4 monitor were also collected by the DAS. Operations personnel performance checked each of these samplers and monitors at least twice each 8-hr period and adjusted accordingly. Operations of the samplers is detailed in three project procedures: Operating Procedures for Graseby Andersen Particulate Air Samplers with Bicon Frisk-Tech G-M Count-Rate Meter (Primary Mode of Operation). ISV-TS-P09. March 27, 1996; Operating Procedures for Graseby Andersen Particulate Air Samplers with Bicon Frisk-Tech GM Count-Rate Meter (Alternate or Back-up Modes of Operation). ISV-TS-P10. March 27, 1996; and

Operating Procedures for Eberline AMS-4 Beta Particulate Air Monitors. ISV-TS-P07. March 27, 1996.

Off-Gas Filter Monitoring. Both the roughing filter and HEPA prefilter were monitored automatically for pressure differential across the filter as an indicator of particulate loading and potential clogging. When the pressure differential became too large (generally above 7-8 in. WC), the filter was bypassed or valved off-line for replacement. Proximate radiation and thermocouple monitors on each filter determined the thermal and radiation hazards to be confronted during changeout (no unusual radiation hazards were experienced during ISV operations). Both filter systems have control valves which allowed access to the filter unit without interrupting operations. The HEPA prefilter also had an alternate parallel filter unit which could be valved in line while replacing the other filter unit during operations. The roughing filter had an automatic blow-back capability to remove accumulated particulates on the filter bags. This automatic feature was designed to maintain roughing-filter performance. When blow-back operations failed to maintain the baghouse at an acceptable pressure differential, the unit was bypassed for further operations or adjustments to the blow-back system. The roughing filter bags were not replaceable during operations.

Ambient Air Monitoring. A third Graseby-Anderson paper tape sampler with G-M meter was operated as a down-wind ambient air sampler. This was usually placed on the perimeter of the exclusion zone either to the southeast or northeast depending on average daily wind directions. Ambient air inside the off-gas processing trailer was also sampled and monitored continuously using a second Eberline AMS-4 sampler set up inside the off-gas trailer. After several days of more-or-less continuous problems with the off-gas AMS-4 stack sampler/monitor, due to condensation of water in the detector chamber, this AMS-4 monitor was switched to ambient air monitoring from its fixed position just to the north of the off-gas process trailer. Output from all three of these ambient air samplers/monitors was collected by the DAS.

Change of flow from one HEPA prefilter to the other was accomplished by opening and closing valves. Replacing the loaded HEPA was preformed by ORNL millwrights and iron workers. This operation was performed five times prior to completion of the OAT and twice after the start of contaminated melting operations. After valving both sides of the HEPA housing closed and allowing it to cool to near ambient temperature, the housing cover was removed and the two HEPA filters pulled into containment bags. New HEPA filters and gaskets were then slid into position, the holding clamps adjusted to fit, and the housing cover returned and clamped. The loaded used filters were removed and saved for future analyses and sampling. Changeout of HEPA filters in the off-gas processing trailer followed a nearly identical procedure although potential for hazardous or radioactive contamination was greatly lowered because these filters were at the end of the off-gas processing system immediately before discharge to the atmosphere. Valves on both sides of the HEPA filter housing had to be locked out and tagged out by all personnel prior to opening the housing access. The HEPA filters in the off-gas trailer were changed only once, after the termination of the OAT.

Sample/Change Roughing Filter Bags. The condition and need for possible replacement of the roughing filter bag elements was evaluated after termination of the off-gas collection system following the OAT. Three filter bags were removed as samples to determine the nature and amounts of particulates. Work was performed from the off-gas hood platform by ISV operations personnel. Clamps retaining bags to the wire-mesh cages were removed. Bags attached to their wire mesh cages were placed in plastic bags for storage until analysis. New bags and cages were installed to replace the sampled bags and cages.

Hood and Off-Gas Line Smear Sampling. After the OAT, sections of the off-gas line and hood panels were sampled using project procedures (Cline 1995). Smear samples were collected from surfaces which were accessible from inside the roughing filter housing and prefilter housing. Smear sampling was designed to determine both particulate loading of internal surfaces and deposition of cesium tracer and any contamination.

1.3.3.6 Groundwater monitoring

Pit 1 Perched Water Elevation Monitoring. As perched water in Pit 1 evaporated during ISV operations, the level of standing water in the pit fell steadily. Periodically, the water table elevation was measured using electric water level tape (see project procedure ISV-TS-P01) using the driven well screen samplers already in Pit 1 (wells 105 and 106). In addition, temperature of the pit-1 perched water was indirectly monitored at various points with the thermocouples placed in and around the test area for melt depth monitoring. Wells 718 and 719, downgradient and upgradient, were used to monitor the surrounding water table.

1.4 PIT 1 TREATABILITY STUDY PROJECT CHANGES

1.4.1 Major Changes in Technical Scope After Initiation

1.4.1.1 Addition of cesium soil decontamination evaluation subtask

Previous ISV demonstrations at ORNL had indicated that ^{137}Cs could be readily volatilized from soil during thermal treatments, like ISV, when sufficient chlorine-containing species were present or were added (Spalding 1994b). For certain applications of ISV, volatilization of radioisotopes from soil may be preferable to retention in the melted product. Investigations were initiated in the laboratory to determine the potential of thermal soil decontamination for other radioisotopes including ^{99}Tc , ^{90}Sr , ^{60}Co , U, and Pu. This task was added in FY 1994 to assess a potential new technology for soil decontamination or cleaning by thermal processes. In addition, the interaction of physical and chemical factors influencing the volatilization of radioisotopes during ISV was investigated.

This task was completed in November 1994 with delivery of a project report (Shor and Dial 1994). This report described the work on the technical feasibility of volatilizing other radionuclides from soil as a decontamination technique. Previous work, resulting from the 1991 pilot-scale ISV demonstration, had discovered a potentially useful technique to decontaminate soil of ^{137}Cs by heating after amendment with a small amount of salt (Spalding 1994b). The feasibility of thermally-induced volatilization of both ^{99}Tc and ^{60}Co from soil were identified as possible soil decontamination techniques. However, neither ^{90}Sr nor uranium exhibited appreciable volatile behavior during thermal treatments.

1.4.1.2 Change from two pilot-scale to two large-scale melts

As originally formulated in the project work plan (Spalding 1994a), the treatability study was to perform two overlapping melts in Pit 1 at pilot-scale (10-ft diameter x 11-ft deep) to address the objectives of the study. This was based on the assumption that the radioactive contamination was present 15 ft below the present site surfaces. Characterization activities subsequently established that the depth was actually 25-26 ft, well below the depth capability of the pilot-scale (11 ft) and even the large-scale (19 ft) ISV equipment. The project was then rescoped for the large-scale equipment

to attain this depth using an existing pilot-scale hood (with additional surface sculpting and startup excavation to get within the 19-ft depth limitation) which added approximately \$650K to transportation, preparation, and operational costs. It also added approximated \$150K necessary for the electrical line upgrade to provide adequate power to the site. Upgrade of the electrical power line from 2.4 kV to 13.8 kV was completed in April 1995 allowing adequate power for large-scale operations at Pit 1 and for future applications in WAG 7.

At that point, it was decided to vitrify as much of the pit as the large-scale equipment would allow because the costs of site preparation, equipment mobilization, and setup were fixed regardless of melt size. Obviously, a larger melt size would cost more for operations; but the increase in operational costs would be small in comparison to the fixed cost of site preparation, line upgrade, and equipment setup. In addition, it was determined that large-scale melts would address all operational issues without the requirement to extrapolate them to real-size applications in the pits and trenches. The decision to pursue large-scale, full-width melts at Pit 1 made the limitations of existing ISV off-gas hoods apparent. The pilot-scale hood could only span approximately 16 ft of ground surface making it inadequate to vitrify the entire width (23 ft) of Pit 1 source contamination; generally, a hood needs to span approximately twice the width of an ISV melt body to assure that subsidence does not compromise its seal to the ground surface. Refurbishment of an existing but damaged large-scale ISV hood in Richland was estimated to require approximately \$400K which would allow its use for the Pit 1 ISV melts. Geosafe had recently procured a new ISV off-gas hood for approximately \$500K and it was decided that a similar hood could be procured for a similar cost even with some additional features appropriate for Pit 1 needs.

1.4.1.3 Change to fabricate new off-gas hood

Battelle PNNL initially began design work on the new off-gas hood but soon realized that the project could be performed better with a combined design and fabricate subcontract to meet their rigid design functional criteria. Battelle PNNL prepared functional design criteria for a new hood and its capabilities and prepared a request for proposals for design and fabrication of a new fully-featured hood. While all of the advanced functional features were viewed as necessary for application of ISV to the remaining WAG 7 seepage pits and trenches, they were only considered as desirable, not critical, for the completion of the treatability study at Pit 1. These advanced features included a solids handling and addition system for adding insulating materials and melt modifiers during operations and also soil backfill after completing an ISV melt; a self-travel system which would eliminate the need for a 100-ton crane on site for hood movement between melt settings; an integrated trolley and hoist system for electrode assembly, placement, and feeding which would also eliminate the need for on-site rigging support during operations; and a system allowing variable electrode spacing (from 10 to 17 ft) for ISV capability to address different application geometries from small auger holes to large holding basins.

Proposals were received from six vendors for design and fabrication of an ISV off-gas collection hood, but the low bid was approximately one million dollars over the project's budget of \$500K for this subtask. The cause of this discrepancy appeared to be a poor preliminary estimate, made 18 months previously, based on a design for a basic hood which had been recently procured by Geosafe. Several options were investigated to keep the project within its present budget and still achieve all its technical objectives. First, the design of the planned hood was reduced in capabilities to the minimum required for Pit 1 ISV operations only; however, this option reduced proposed bids only to approximately one million dollars. Second, refurbishment of an existing but damaged large-scale ISV hood was estimated to require approximately \$400K to allow its use for the Pit 1 ISV melts. However, both of these options would result in an off-gas hood without the useful features

for performing ISV at the other six WAG 7 seepage pits and trenches. It was then considered that procuring either of these less costly options for an off-gas hood to use during the Pit 1 melts, even though either option would allow the present study to be completed, would ultimately prove to be money wasted in the long term, particularly for the projected ISV applications to the other six ORNL seepage pits and trenches. All of the features of the planned off-gas hood would be necessary for these further ISV applications in Oak Ridge. Thus, any interim hood would probably not be very useful for continued ISV applications in WAG 7; whatever money was spent on an interim hood would essentially be a one-time expense, and future ISV applications would ultimately require procurement of a similar new hood in the near future. Even if the other potential interim hoods could be modified for future operations, they would require significantly more operating costs for assembly/disassembly and transport between melts and sites compared to the proposed new design. The new hood would make ISV much more versatile in the types of waste geometries for remediation, greatly reduce ISV operating costs, reduce secondary wastes and contamination problems via its advanced off-gas flow and filtration systems, and reduce repair and maintenance costs through interchangeable hood panels and structural members. With such justification, the additional one million dollars in required funding was identified and procurement of the new fully-featured hood authorized.

1.4.1.4 Change to treat all source contamination in Pit 1

A third melt was designed in January 1995 to complete all source-term contamination treatment by ISV within Pit 1. The previous plan to produce two large-scale overlapping melts in Pit 1 was estimated to leave 30–50% of Pit 1 untreated. With all equipment, experienced personnel, contracts, and project knowledge and momentum in place, leaving this residual portion of Pit 1 untreated seemed very cost ineffective. In addition, it became apparent that treatment of all source contamination within Pit 1 would make possible a full-site post-treatment evaluation that would otherwise not have been possible. The third melt was planned to be of similar size and scope to the previously planned two overlapping large-scale melts and was to be completed within a month of completion of the first two melts. Contracts with both PNNL and Geosafe were adjusted to reflect the adjustments in staff commitments. Battelle PNNL committed to provide the support necessary for completing the third melt. The estimated total cost for the third melt was \$500K which included all participating parties: Battelle PNNL, Geosafe, and Lockheed Martin Energy Systems (LMES). This additional funding was reallocated in April 1995.

1.4.2 Project Schedule Changes

1.4.2.1 New off-gas collection hood changes

The subcontract for design and fabrication of the new off-gas hood was awarded on December 12, 1994. Originally, the off-gas hood was scheduled for delivery to Oak Ridge on June 12, 1995. However, several fabrication delays were experienced and the contractor ultimately agreed to an August 30, 1995, delivery date with many components to be initially assembled on site to save the project from even further delays. The method for partial schedule recovery involved incremental shipment of the off-gas hood from the subcontractor to Oak Ridge. The target for the start of ISV melt operations was delayed until September 30, 1995.

Another major delay in the project occurred on September 23, 1995, when a major structural failure in the new off-gas hood was experienced during functional testing at ORNL. The root cause of this structural failure, as revealed by subsequent structural modeling, appeared to be an inadequate design resulting from the use of an inappropriate structural model by the design and fabrication

subcontractor. Structural steel tube in the superstructure was modeled as line beams rather than three-dimensional tubes. The line-beam model did not indicate any excess stress within superstructure beams, whereas the three-dimensional model indicated excess stress at exactly the points of failure on the bottom surface of the steel tubes. The hood superstructure is shown in Fig. 1.24 with the point of failure indicated; two of four corners cracked during the incident. One of the actual failure cracks can be seen in Fig. 1.25.

More importantly, this structural failure and its associated delays for repair design, planning, and implementation (as well as other numerous required ORNL tasks for field fitting and unrelated hood repairs not completed by the fabricator and other unrelated costs for setup and maintenance of the large-scale ISV equipment) increased estimated costs by \$1,382,000 to complete this project. Much of this cost was associated with maintenance of key project personnel during the period of intense uncertainty while the amount and nature of required modifications were assessed. All project personnel, required for the first Pit 1 ISV melt, were on site at the time of the failure and preparing various equipment for that operation to begin the subsequent week.

Fig. 1.24. Superstructure of the new ISV off-gas hood showing two points of structural failure on September 23, 1995.

1.4.2.2 Melt expulsion event changes

The melt expulsion event raised important concerns about the entire design and approach to the ISV of ORNL Pit 1 including changes in personnel operating procedures, changes in equipment

Fig. 1.25. View of one structural failure crack on the underside of the main superstructure frame of the new ISV off-gas hood.

configuration and design, and changes in site configuration to minimize the probability of future melt expulsions. Practically all of these changes are discussed thoroughly in the evaluation of the melt expulsion event (ESERP 1996b). Details of these changes and their rationale will not be repeated here. Only a summary description is contained below. Because the ISV melting operations at Pit 1 have not yet been restarted, most of these changes have not been implemented but exist only as conceptual designs.

Although no personnel were in any of the heat-affected areas at the time of the melt-expulsion incident, many regular tasks did require personnel to enter potentially dangerous areas on and around the off-gas hood. Procedures will be modified to minimize the need for personnel entry into dangerous areas or provide adequate protection during necessary tasks. Many data collection and process control tasks can be done remotely through small modifications to equipment. Other monitoring tasks can be automated to eliminate the need for personnel access. One task, the addition of electrode sections, will still require personnel access to the hood work platform with the present off-gas hood design. Personnel protective clothing for thermal stress may be required for this task.

The off-gas hood itself, in addition to repairs, needs to be modified to handle future melt expulsion events in a controlled manner. Venting techniques, possibly including hood lifting, can be designed to relieve pressure surges and deliver the off-gas to areas that will be restricted from personnel access. The minimal airborne contamination experienced allows for unfiltered releases during possible future incidents. Some areas of the hood would be insulated where equipment might still receive thermal stress. The fabric elements of the off-gas roughing filter, which in the present configuration are directly exposed to any expelled molten material, can be analyzed for protective techniques to prevent damage by splashes of molten glass.

Several possible techniques have been identified to minimize the probability of future melt expulsions. First, groundwater within Pit 1 must be drawn down well below the target depth for ISV treatment. Before the melt expulsion incident, the bottom of the Pit 1 molten body was approximately 10 ft below the regularly monitored elevation of standing water in the pit within 30 lateral ft of the melt body center. Although the movement of this water may have contributed to the melt expulsion, its presence indicates that all surrounding soil porosity was filled with water, thus, little unsaturated pore space was available for potential transmission of steam away from the melt body. Therefore, removing standing water around an ISV melt body would divert this potential hydrostatic constraint on steam movement from the heated zone. The dense unweathered formation, into which Pit 1 was excavated, also presents a significant potential constraint on steam movement around the melt body. Techniques to open or fracture this dense confining material should also be investigated to prevent steam pressure from building beneath the melt body.

Second, flow-monitored and curved vent pipes will be considered for installation at several layers beneath the growing melt body to provide facile pathways to release steam into the off-gas hood without relying on the obviously unpredictable soil porosity. The use of straight vent pipes in the previous ISV test design resulted in significant submelt strata being inherently inaccessible to venting; lack of a credible vent pipe operational verification technique was also apparent in the present incident. Venting could also be enhanced by soil drying and dynamic disruption of the dense strata.

Third, pressures beneath the melt body need to be measured to ascertain when steam pressure approaches the lithostatic pressure of the melt body so that power to the melt might be attenuated to reduce the rate of steam generation. Submelt pressure measurement can be attempted using buried screened-end tubing connected to pressure transducers above ground. Submelt pressure measurement represents the only plausible method to predict potential melt expulsion in sufficient time to take action to prevent it.

Fourth, quality video monitoring of the melt surface activity needs to be attained in future ISV operations at Pit 1. Previous melt expulsion incidents were apparently sometimes preceded by smaller bubbling activity or unusual melt surface movements. Some melt bubbling is normal during all ISV processing. Geosafe has recently been experimenting with rectangular and planar melt shapes, which enhance transport of vapors to the off-gas hood. The Pit 1 ISV operations lost its video monitoring capability due to fouling of windows, which resulted in extremely poor to entirely indistinct video images.

1.4.3 Project Cost Changes and Effects

As discussed above, all of the major changes to the treatability study had significant cost increases associated with each change. These are summarized in a project time line chart in Fig. 1.26. The rationale for each change has been discussed above while the costs and schedule impact for each change are contained in Fig. 1.26. The original project scope began in October 1993 encompassing two pilot-scale melts into ORNL Pit 1 to be completed in 3.0 years for \$3.4 million. The key to the numbered changes presented in Fig. 1.26 is as follows:

1. Added cesium soil decontamination subtask in February 1994 for \$500K but no change in original schedule.
2. Rescale ISV scope in March 1994 for two full-width overlapping melts using large-scale equipment for a cost increase of \$650K and a schedule increase of 3 months.

Fig. 1.26. History of major budget and schedule changes in the ORNL ISV treatability project between 1993 and 1998.

3. Upgrade site electrical service in April 1994 from 2.4 to 13.8 kilovolt required for large-scale equipment for \$150K but no change in schedule.
4. Add site grading extension in May 1994 for 65-ft hood span and for liquid waste tank farm for \$150K but no increase in schedule.
5. Add an LMES WAG/Project Manager in June 1994 for \$177K but no increase in schedule.
6. Decision in July 1994 to change new hood design from Battelle PNNL to RFP for design and build contract for a cost increase of \$500K and a schedule increase of 3 months.
7. Low bid for hood design and fabricate in October 1994 was approximately \$1 million over estimate but no increase in schedule.
8. Add scope in February 1995 for a third large-scale melt to incorporate all source term contamination at ORNL Pit 1 for \$500K increase in cost and 2 month increase in schedule.
9. Delay in hood fabrication in May 1995 by subcontractor and associated decision to perform first assembly at ORNL to avoid further potential delays to the project and increased cost by \$800K and further increase in schedule by 3 months.
10. First hood assembly in July 1995 at ORNL by Plant and Equipment crafts increased costs by \$1.3 million but no increase in schedule.

11. Hood structural failure in September 1995 triggered redesign, review, fix, inspections, extra readiness review at a total cost of \$717K and an increase in schedule of 6 months.
12. Melt expulsion event during first melt in April 1996 required incident investigation(s), hood repairs, redesigns, project plan redesign, investigations of preventive measures at a cost of \$1.5 million and a schedule increase of 7 months.
13. Budget cut of \$1.5 million from DOE/Environmental Restoration Waste Management Oak Ridge Operations in December 1996 suspended project.
14. New funding needed in March 1997 to complete watertable drawdown, subsurface barrier breakup, safety improvements, two additional melts, product core sampling, analyses, testing, and final treatability study report requires a minimum of \$2.6 million and an additional 4 months to complete from the time funding is secured.

2. TREATABILITY STUDY OBJECTIVES

Before advocating ISV for the stabilization and closure of the ORNL seepage pits and trenches, several technical issues required resolution. These issues dictated the objectives of this treatability study and were formulated in order of priority. Although the objectives are obviously interrelated and inseparable, they were addressed in this order where possible, in case resources, time, or safety considerations impinged on the project's capability to completely address all objectives. Completion of all objectives would resolve all field-scale issues related to implementation of ISV for the ORNL seepage pits and trenches.

2.1 MELT DEPTH DEMONSTRATION

In 1993, it had not been established that ISV could attain the depth of 15 ft, which was thought to be required to reach the bottom of seepage trenches and beneath to stabilize undisturbed soil contaminated by transported radionuclides in the WAG 7 geologic setting. Although a maximum depth of ISV of 18 ft had been demonstrated at other sites, this maximum depth did not factor in the geologic, hydrologic, and geometric conditions of the ORNL seepage pits and trenches. For example, during the pilot-scale demonstration in 1987, it was found that the melt body tended to grow horizontally, following a path of least resistance into the less densely packed materials used to backfill the trench. Although the melting of this scale-model seepage trench reached its target depth of 9 ft, the ability to attain a 15 ft melt depth at ORNL remained to be demonstrated. The preference for melting into low density backfill needed to be overcome so that downward melting into contaminated, higher-density, and undisturbed soil could be assured. The required melting into and beneath the watertable within and around Pit 1 had a significant potential to inhibit normal depth capability. The depth objective of this treatability study was the actual bottom of Pit 1, including significant contaminated soil beneath the pit-soil formation contact. The depth goal of 15 ft below starting ground surface was to be maintained, even when the pit proved to be much deeper, unless geologic or hydrologic conditions prohibited or lateral ISV melt body growth exceeded off-gas hood dimensions. Methods were devised to ensure that the maximally contaminated layer within Pit 1 was within 15 ft of the ISV starting surface; these methods included sculpting up to 4 ft of uncontaminated soil from the starting Pit 1 surface and excavating a 6-ft deep startup trench for the initial Pit 1 ISV melt.

2.2 MELT OVERLAP DEMONSTRATION

Due to their size and aerial extent, all of the seepage pits and trenches in WAG 7 will require multiple melt settings to complete vitrification of their source material and contaminated soil. The ability to overlap melts sufficiently to ensure complete treatment between settings needed to be established within the particular geologic and geometric characteristics of the contaminated pits and trenches. In addition, the ability to move a contaminated off-gas hood and establish a second array of electrodes to produce an overlapping and fused melt in a contaminated environment also needed to be demonstrated. As discussed previously, since the initiation of this project in 1993, Geosafe has repeatedly demonstrated ISV capability to overlap melt bodies many times, although not to the depths needed for WAG 7 pits and trenches. Thus, the technical feasibility for melt overlap no longer required demonstration in 1996 when the field melting operations at Pit 1 were finally initiated. However, the driver for multiple melt overlaps at pit 1 switched in 1994 from a need for technical demonstration to a need for demonstrating complete treatment when the scope of the treatability

study was enlarged to include all source contamination within the pit. Geosafe's demonstration of melt-body overlap was accomplished by a combination of post-melt probing and operational temperature monitoring in the field, neither of which quantified the degree of melt body overlap, i.e., the amount of one melt incorporated into an adjoining melt. This treatability study would have provided unique quantitative evidence for the degree of melt overlap and mutual incorporation. Unique rare earth element tracers were to be used in each setting to measure the mass of each melt body produced. But, the incorporation of the tracer from one melt setting into an adjoining melt body would allow direct measurement of melt body overlap and mutual incorporation.

2.3 OFF-GAS HANDLING DEMONSTRATION

A more practical design at the operational field scale for the off-gas HEPA prefilter technique needed to be developed and demonstrated during this treatability study. One conceptual design for such a filtering technique would have placed HEPA prefilters within the off-gas containment hood at a position where they could be dropped into the melt near the end of the run after ^{137}Cs volatilization rates had subsided. The 1991 demonstration clearly established that ^{137}Cs volatilization occurred predominantly when the melt initially contacted the depth where the contaminated sludge had been positioned. Thus, near the end of ISV melting, rates of volatilization would be minimal and the prefilter, containing the ^{137}Cs volatilized earlier in the run, could be incorporated back into the melt. Alternatively, a rolling prefilter, where the active surface was slowly and continually renewed, could be employed with the spent filter fabric directed into the melt. However, pre-1993 off-gas containment hoods would have required significant modification to accomplish either of these capabilities. Based on the 1991 demonstration's findings that 2.4% of the ^{137}Cs inventory volatilized under unique and disadvantageous conditions, it would be expected in a worst-case scenario that a maximum of 0.2 Ci of ^{137}Cs might be trapped on a prefilter from one melt setting at ORNL pit 1, assuming an inventory of about 10 Ci (decay corrected to present) of ^{137}Cs per setting, i.e., about one quarter of the pit. An alternate design for a renewable primary or roughing filter was ultimately selected which employed a high-temperature fabric (Nextel®) filter baghouse, built into the new off-gas hood at the central off-gas intake location, which could be shaken clean during operation. The HEPA prefilters, between the off-gas hood and the process off-gas scrubbing trailer, were also selected because of their success in the 1991 demonstration. It was thought that should the new roughing filter prove adequate for off-gas handling and decontamination during this treatability study, then the HEPA prefilters would be unnecessary during routine ISV operations and could be by-passed. However, the conceptual approach, effectiveness, safety, and reliability of both filter types needed to be demonstrated at the field scale for removal of ^{137}Cs and for trapping of other radionuclides from Pit 1 which might become entrained in the off-gas.

2.4 PRODUCT QUALITY DEMONSTRATION

Product quality and its field performance needed to be demonstrated to ensure that the benefits of ISV were established adequately to support its implementation for closure of the ORNL seepage pits and trenches. A large amount of information about the leach resistance of various vitrified materials existed in 1993 at the initiation of this study (Buel et al. 1987). Although data gathered from laboratory tests support many models of field waste form performance, many scale-related factors remained unaddressed. For example, if transient perched water were to contact a monolithic ISV product in the field, prediction of site performance is presently difficult given uncertainties of surface area and melt edge effects. Thus, as part of the treatability study, in addition to laboratory measurements of ISV product quality as obtained in the 1991 demonstration (Spalding et al. 1992),

the field-produced waste form was to be monitored in situ after ISV to determine its leaching characteristics and performance in the field. Comparisons to untreated regions of pit 1 or other seepage pits would be established to aid in site performance assessment. However, given the condition of Pit 1 after the expulsion event during the first melt and apparent failure to melt completely through the maximally contaminated layer in Pit 1, this field approach could not be pursued. However, as an alternative, samples of the ISV product from the initial melt into Pit 1, were collected and subjected to standardized laboratory leaching tests for comparison with other ISV products and vitreous waste forms.

2.5 PUBLIC AND TECHNICAL COMMUNITY ACCEPTANCE

Public and technical community understanding and acceptance was to be established through both public distribution of test information and regulatory agency review and involvement in test planning and analysis. The ISV technology and this project were featured in four DOE-sponsored public meetings during the project. It was recognized that a well-documented and fully-demonstrated treatability study would accelerate and facilitate implementation of a Record of Decision for WAG 7. In addition to the seepage pits and trenches, WAG 7 contains other waste management units that may not be amenable to ISV, including an inactive decontamination building, contaminated streambeds and peripheral soil, and near-surface contaminated grout sheets from the initial ORNL hydrofracture test site. However, ISV was considered only for the major radioactive contamination sources—the seepage pits and trenches—in WAG 7. Performance information on the ISV process would thus support decisions for the remedial investigation and feasibility study for WAG 7.

3. RESULTS OF TREATABILITY STUDY DEMONSTRATION

This treatability study was successful in meeting most of its objectives including melt depth capability demonstration, off-gas handling demonstration, and product quality characteristics as determined by laboratory leach testing. As discussed in the description of the test objectives, the demonstration of melt body overlap was not attained because only a single melt was performed prior to the melt expulsion. In addition, expectations for public and regulatory agency acceptance criteria fell considerably short of the work plan objectives, in particular, in the area of safe operations assurance.

3.1. MELT DEPTH DEMONSTRATION

Melt depth was demonstrated based on three criteria: the penetration of the graphite electrodes, post-test probing of melt body width, and post-test chemical analyses of ISV product for the spiked rare earth tracers to determine the mass of product formed.

3.1.1. Electrode Penetration Data

During the course of ISV operations at Pit 1, the cumulative penetration of each of the four graphite electrodes was monitored by observing how deep each settled into the melt body. The average electrode penetration from the start of ISV operations is depicted in Fig. 3.1. Several conclusions can be deduced from these time series data. First, the target penetration depth objective (15 ft) was attained within the accuracy of the measurements. The melt body had entered into, but had not completely engulfed, the maximally contaminated strata within Pit 1. The melt was terminated by the expulsion incident and considerably more melting was thought to be needed during this initial melt to fully engulf the contaminated strata. Second, the rate of electrode penetration and, hence, the rate of downward melt progression was relatively constant during ISV operations. The slope of the penetration data (Fig. 3.1) was constant except for the 3-day interval, during which the results of the OAT were being evaluated when minimal power was maintained into the melt and further electrode penetration was held up. There was no indication that the penetration rate was slowing down as the melt body approached the bottom of Pit 1 – the contact between loose soil fill and undisturbed formation. Third, the melt body depth progressed steadily in spite of the melt body bottom elevation being well beneath the surrounding water table elevation throughout ISV operations.

The two monitoring wells for perched water table elevation measurement were located within Pit 1 approximately 30 ft to the north and south of the melt center. The melt body reached a maximum depth of 9 ft below the water table and appeared to maintain this degree of submersion from the eighth day up until the melt expulsion on the nineteenth day of melting operations. The three increases in the water table around the melt shown in Fig. 3.1 were due to rainfall events during ISV operations. Obviously, the melt body was functioning as a drawdown well, pumping water by evaporation from the central position within Pit 1 and the cone of water table depression began to influence the surrounding water table by the eighth day of operations.

The final depth penetration of the electrodes, and the inferred melt body, are depicted in the north-south and east-west cross-sections through Pit 1 (Figs. 3.2 and 3.3). The depth penetrations of the electrodes clearly show that the strata of maximally contaminated soil at the boundary of the backfill-undisturbed formation were in contact with the melt body at the time of the melt expulsion.

Indeed, the level of contamination of the melt body with ^{137}Cs was clear evidence of significant contact with the maximally contaminated strata within Pit 1. The magnitude of the melt body width, also projected in Fig. 3.3, is based on the combination of melt body mass considerations and width measurements.

Fig. 3.1. Average depth of graphite electrode penetration beyond starting elevation and surrounding perched water table elevation during ISV operations at ORNL Pit 1.

3.1.2. Melt Body Width Measurements

The width of the melt body was measured by probing for the hard edge of cooled melt body with Geoprobe® drill rod two weeks after the melt expulsion incident. Two criteria were used to identify when the edge of the melt was encountered. First, refusal of further drill rod penetration was interpreted as contact with the usual hard rind of fused but unmelted soil around the melt body; by the time of probing with drill rod, the melt body had cooled significantly below molten temperatures.

Second, the temperature of the refusal point had to be significantly above 100°C indicative of heated dry soil. Temperature was measured by sliding a type K thermocouple into the drill rod to the point of refusal and recording temperatures at 1-ft intervals during withdrawal. Generally, only a few minutes at each withdrawal point was sufficient to attain an equilibrium stable temperature reading. Probing could only be completed along the north-south axis of Pit 1 where loose backfill was encountered; probing from the east or west sides was not possible due to the dense undisturbed formation near the contact with the melt body (Fig. 3.3). The angles of drill rod penetration were selected to probe refusal points at different depths around the melt body using several penetration points (Fig. 3.4). Penetration angles were measured using a digital level flush with the projecting stem of the drill rod train. The cross-sectional view of these probe lines is depicted in Fig. 3.5.

Fig. MELTRD13FD

Fig. 3.2. Projected cross-section of ORNL Pit 1 after the first ISV melt.

Fig. 3.3. East-west projection of the ORNL ISV melt body within Pit 1.

As can be deduced from Fig. 3.5, the melt body was found to be approximately 20.7 ft at its widest point. Both these points were approximately 13 ft below the starting ground surface and exhibited probe end temperatures of 304 and 150°C showing excellent evidence as points on the melt body boundary. Notably, the melt body was found to be about twice as wide to the south, as to the north, of the starting center of the electrodes. Deeper probes failed to encounter melt body boundaries as no temperatures were above 100°C, although several points along the probe line were clearly elevated above background (10-15°C) indicating some proximity to heated soil. These deeper probes lines apparently glazed the borders of the heat-affected area around the melt body; they function to establish proximate depths and widths where melting had not yet occurred.

3.1.3. Final Melt Body Sampling Needs

In addition to the need for melt depth measurement from the penetration of the graphite electrodes, confirmation of the depth and width of the melt body was planned via coring of the final cooled melt body. In addition to direct melt depth measurements, core sampling through the melt body would have provided information on the unmelted material in contact with the melt body at the time of the melt expulsion. The density and thickness of any residual loose soil fill and distance to the undisturbed formation would provide some helpful information on the formation of the melt expulsion bubble(s). It also would have provided information on the required remaining depth for

completing the treatment of source term contamination within Pit 1 and under the initial melt body. Core sampling would also have provided information on the width and shape or curvature of the melt body beyond the electrode array. However, all of this information on the initial melt body can be gathered at any future time at Pit 1.

Fig. 3.4. Plan view of melt width probe lines after first ISV melt showing off-gas hood and Pit 1 outlines.

As discussed in Sect. 3.3.1, the mass of the melt was found to be 196 Mg, i.e., 216 tons, using the measured final concentrations of rare earth tracers in the ISV product. Using the previously discussed depth and width estimates for the melt body, the consistency of all information about the melt body volume and mass can be assessed. ISV melting was started at 12.00 ft below a fixed reference elevation, i.e., the top of the hood's working platform. The actual recorded measurements

averaged 12'4" to the top of starter path tubes but must be reduced by 4" for the additional starter feldspar sand added later to cover these starter tubes. The final melt surface was measured at 17.74 ft below the reference elevation. These final melt surface measurements were obtained on May 15, 1996, using a tape measure at two points near each of the four electrodes. The melt bottom was 14.71 ft, the average electrode depth below the starting melt surface elevation. An approximate melt body cone section was, thus, 8.97 ft thick (i.e., 12.00 ft + 14.71 ft - 17.74 ft = 8.97 ft). The melt density is assumed to be 2.83 Mg/m³ (177 lb/ft³) using a melt thickness of 8.97 ft, and a cone section geometry can be used to calculate the melt volume. The assumed melt density of 2.83 g/cm³ comes from the final report of the 1991 ISV radioactive pilot-scale test (Spalding et al. 1992). A minimum bottom radius equal to 1 ft outside the equivalent electrode radius, i.e., 8.07 ft, can be assumed. This minimum equivalent electrode diameter was 10 ft x $\sqrt{2}$. A minimum top radius equal to the startup trench radius, i.e., 10.00 ft, can also be assumed. It was further assumed that relative variation in the bottom and top melt radii would increase linearly from these assumed minimum radii. The calculated melt masses, as functions of top and bottom radii, are presented in Table 3.1.

Fig. 3. 5. Cross-sectional view of drill rod refusal points and equilibrium temperatures around first ISV melt body at ORNL Pit 1 (angles in degrees, lengths in feet, and temperatures in degrees Celsius).

Given the depth and width of the melt body, it can be seen from Table 3.1 that a melt body of 20 ft diameter (10 ft radius) is consistent with the melt mass of 196 Mg. Larger average radii of the first melt body would produce considerably more melt mass than was actually achieved at Pit 1. Thus, various indirect ISV melt mass indicators, like total power placed into the melt divided by an historical average weight of product produced per unit of energy consumed (i.e., 0.8 kWh/kg produced), can be very misleading; the 500,000 kWh consumed in the first melt would lead to an estimate of 625 Mg of ISV product formed. Obviously, a great deal of the consumed power must have been used to evaporate water and to maintain heat losses into Pit 1 or to the off-gas hood.

Table 3.1. Mass of ISV melt bodies for various sized cone sections with increasing radii

Top Radius (ft)	Bottom Radius (ft)	Melt Volume (ft ³)	Melt Volume (m ³)	Melt Mass (Mg)	Melt Mass (tons)
10	8.07	2330	66	186	205
11	9.07	2860	81	229	252
12	10.07	3460	98	277	305
13	11.07	4110	116	329	362
14	12.07	4810	136	385	425
15	13.07	5580	158	446	492
16	14.07	6400	181	512	564

3.2 MELT SETTING OVERLAP DEMONSTRATION

As discussed in the test objectives (Sect. 2.0), the demonstration of melt setting overlap was not possible due to the melt expulsion event. Also, since the initiation of the project, Geosafe has demonstrated melt overlap of large-scale melt bodies on numerous occasions, although not to the depths required for Pit 1. Thus, the generic need to demonstrate this capability is no longer as necessary as it was at the project's initiation. However, many secondary needs would have been fulfilled by overlapping several melts at ORNL Pit 1 including an assessment of revolatilization of ¹³⁷Cs by an adjoining melt and direct measurement of melt boundary overlap through mutual incorporation of rare earth tracers unique to each melt setting. However, eventually, if ISV is pursued as the remediation alternative at ORNL Pit 1 or if melt-setting interruptions are experienced at other WAG 7 seepage pits and trenches during ISV, recovery from cooled small melts may be necessary. Thus, a plan for re-initiation of ISV operations at ORNL Pit 1 may address to both future possibilities. This planning activity was performed as part of the restart activities after the melt expulsion event. It is documented here to guide future ISV remediation projects which may be confronted with similar technical challenges.

3.2.1. Planned Technical Approach for Multiple In Situ Vittrification Settings at Pit 1

The proposed location for the second melt at Pit 1 should be to the south of the first melt (Fig. 3.6). The main reason for choosing south, instead of north, of the first melt body would be to locate the next melting operation as far as possible from the ISV process trailers until the conditions conducive to melt expulsions, such as melt pressures, and operational controls are better understood. This location minimizes the potential for equipment damage during another melt expulsion event simply by maximizing its distance from the melt. The reasons for locating the melt center where indicated on the south side of Pit 1 (ORNL Grid 26860E, 18802N) are several. To attempt to melt all the source contamination between the south end of the pit and the residual melt 1 ISV body, this central location would seem necessary. This target spans a distance of almost 35 ft of untreated contamination within Pit 1 and, thus, given the experience with the first melt in Pit 1, may be slightly too large for ISV capability using a conventional approach.

However, two significant changes from melt 1 operations are anticipated. First, the electrodes should be configured at their maximum separation, i.e., 14 ft, which will enlarge the next melt

significantly. The electrodes could also be spaced in a rectangular pattern with 10-ft in the east-west direction and 14-ft in the north-south direction to induce the desired elongated melt as depicted in Fig. 3.6. Second, perched water in Pit 1 should be drawn down prior to the initiation of the melt. The groundwater may otherwise have functioned during melt 1 to restrict lateral and overall growth of the melt body; the constant flow of groundwater towards the melt body during the first melt would have tended to cool the perimeter leading to preferred downward growth as well as dissipation of much of the applied electrical power to remove water rather than melt soil. Nevertheless, positioning the second melt center 26 ft from the first melt's center should assure melting of the south end source contamination (Fig. 3.7).

Fig. 3.6. Planned location of a second melt at ORNL Pit 1 (DOE Grid North is top of page).

Fig. 3.7. Proposed location of the second melt at ORNL Pit 1.

If this design fails to overlap the first melt body, the center section of Pit 1 could be remelted, after a third melt to the north of the first melt, to produce the required melt body overlap. Notably, even a melt body of a width similar to that of melt 1 should completely incorporate all source term contamination on an east-west transect through the melt center (Fig. 3.8). Again, the apparent overlap of the melt body with the eastern wall of Pit 1, which does seem to narrow somewhat in the southern end of Pit 1, may result from the drawing artifact which employs a linear connection between the limited number of actual probe locations. The melt body would actually be expected to dissolve more slowly into the dense undisturbed soil on the east and west pit walls compared to growth into the less dense soil backfill along the north-south transect. Thus, the restraints of the undisturbed formation on the east and west will function to elongate the next melt body regardless of electrode spacing. The degree of incorporation of the Lu and Ho rare earth tracers in the first melt will provide a direct measure of the overlap or incorporation of the first melt into the second.

Fig. 3.8. Projected east-west transect through melt 2 body at ORNL Pit 1.

3.2.2. Review of Recent Geosafe Projects with Melt Overlaps

In 1995, Geosafe completed the treatment of 6,000 tons of soil and debris at the Wasatch Chemical site in a commercial/industrial area near the center of Salt Lake City, Utah. One-half of the material was present in a 125-ft square concrete evaporation pond. The other half was excavated from around the site and staged on top of the in situ pond materials. Additional clean soil was bermed around the pond area to serve as a clean working surface for the off-gas hood. Groundwater existed below the concrete pond. Thirty-seven overlapping melts were performed to a total treatment depth of 7 to 8-ft. The width of individual melts was limited to less than 30 ft because of the shallow processing depth. Geosafe performed 36 melts in a 6 x 6 array, plus one additional melt of staged liquid dioxin removal waste in the middle of the array. This arrangement enabled complete treatment of the evaporation pond and the formation of a single large continuous monolith.

Although Geosafe had a problem with one melt expulsion at their Wasatch site, the remaining 35 melts were carried out without incident. Melting operations were slowed when the concrete floor was approached. This dense subsurface barrier is similar to the problem posed by the undisturbed formation beneath ORNL Pit 1 although the Pit 1 boundary is much deeper. The target contamination in Pit 1 is also located within and/or near the contact with the undisturbed formation whereas the Wasatch contaminants were more equally distributed throughout the depth of soil in the pond. The criteria for melt overlap at the Wasatch site was evaluated through probing from the soil surface. An analogous approach for Pit 1 would be limited by the surrounding boundaries of formation which limit probe penetration particularly around additional melts where probing approaches will be much more limited than after the first melt.

3.3. OFF-GAS HANDLING DEMONSTRATION

One of the key capabilities to be demonstrated in this treatability study is the handling of off-gas which may contain volatilized contaminants from the melt body. As discussed in the objectives (Sect. 2.0), most of this concern centers on ^{137}Cs which is both a major constituent of the radioactive contamination in the ORNL seepage pits and trenches and a potentially volatile species during ISV as experienced in the pilot-scale radioactive demonstration in 1991 (Spalding et al. 1992) and during heating of soil under certain conditions (Spalding 1994b). However, in addition to direct volatilization from an ISV melt body, other radioactive and hazardous elemental contaminants may volatilize or become entrained with particulate releases from the melt body.

To plan the application of ISV to other WAG 7 seepage pits and trenches, which contain much greater inventories of radioactive contamination than Pit 1, the mass balance and distribution of radionuclides and hazardous chemical elements in the overall ISV process had to be determined during the Pit 1 field-scale operations. To complete this assessment, normalized distributions were constructed for each element and radionuclide among the ISV melt body and off-gas system components including the roughing filter, HEPA prefilters, off-gas scrubber solution, and final atmospheric releases. In addition, kinetics of contaminant release from the ISV melt body were also assessed by obtaining discrete samples over specific time intervals. Further, uncontrolled releases during the melt expulsion event were also determined. The uncontrolled, maximum credible release of ^{137}Cs during the melt expulsion was determined to be 0.096 μCi with a hypothetical maximum off-site dose of 0.015 μrem . These release and dose calculations are presented in the technical evaluation summary of the melt expulsion (ESERP 1996b) and will not be repeated here.

The technical approach for measuring the distribution of each element and radionuclide in the ISV process system was to measure the amounts or activities in off-gas system components and in the final ISV melt body. From off-gas filters and scrub solution, samples were obtained and activity or concentration determined on a volume (solution) or area (filter) basis. Concentration or activity, when multiplied by the total filter area or total solution volume, yields the total calculated inventory. For the ISV melt body, samples were analyzed for elemental concentrations or activities on a weight basis and the total inventory in the melt body obtained by multiplying by the total mass of the melt body. Measurement of the total mass of the melt body is the most technically challenging step needed to determine the total inventory of each element or radionuclide. This was achieved by measuring the final concentrations of rare earth tracers in the ISV product which had been spiked with a known amount of tracer by placement of the tracer chemical into the melt zone prior to ISV.

3.3.1. Melt Size and Treated Contaminant Inventories

As discussed above, measurement of the final or interim melt mass by tracer dilution is critical to establishing elemental and radionuclide processing inventories. Five potential rare earth tracers were selected for spiking into the three planned melt bodies at ORNL Pit 1, including Ho and Lu used in the first melt. An ideal rare earth tracer would have no background concentration in Pit 1 soil or any materials which might be added to or incorporated into the melt body during operations. The tracers were selected for their low background concentrations in these materials and for their ease and sensitivity for analyses by neutron activation; neutron activation was performed via ORNL, Chemical and Analytical Sciences Division, Standard Analytical Method AC-MM-222003, Issued April 15, 1993, Multi-Element Comparative Neutron Activation Analysis. Two tracers were employed, rather than one, so that two independent measurements of melt mass could be obtained. The calculation of melt mass is quite straightforward using the measured concentrations in the ISV product and the known amounts placed in Pit 1 (Table 3.2).

Only two samples of the final ISV product were analyzed for tracer composition; both were expelled glass material obtained from outside the off-gas hood in the week following the melt expulsion. These are designated the glass flow to the east-southeast (ESE) and south (S). Previous sampling efforts on ORNL ISV pilot-scale melts had established that ISV melt bodies are well mixed and that post-test samples exhibited uniform concentrations of elements and contaminants from all regions of the melt body. Only two significant adjustments to the measured Lu and Ho tracer concentrations in the final ISV product samples were required to calculate the melt mass. First, the background concentration in the Pit 1 soil amounted to approximately 5% of the final measured concentration in the ISV product; thus, a corrected or net concentration of both Lu and Ho was used to divide into the spiked (added) amounts (Table 3.2). Second, both rare earth tracers were found to contain measurable amounts of each others' element; thus, 1360.96 g of lutetium tracer actually contained 31.12 g of holmium and the spiked amounts were adjusted upward accordingly (Table 3.2). None of the other materials, known to be incorporated into the ISV melt body, including the starter feldspar sand, limestone gravel, or insulating Firelite® aggregates, exhibited enough background concentration of either Lu or Ho to affect these mass calculations; in the case of the insulating aggregates, although the concentration of Lu was found to be 0.25 mg/kg, only an estimated 4,000 lb was added, which made only an insignificant effect on the Lu inventory. Both tracers yielded the same estimate for melt mass (196 Mg) in the final ISV product lending a high degree of confidence in the mass measurement. Analytical uncertainties place this estimate in a 95%-confidence interval of 183-207 Mg.

Table 3.2. Rare Earth Tracer Composition Used To Calculate ISV Melt Mass

Sample/Material	Lu (mg/kg)	Ho (mg/kg)
ISV Product (ESE Flow)	7.34	20.10
ISV Product (S Flow)	7.46	20.54
ISV Product (OAT)	11.10	26.04
Starting Soil	0.402	1.04
Feldspar Starter Sand	0.015	<0.05
Limestone Gravel	0.068	0.058
Firelite® Aggregate	0.250	<0.05
Tracer Added:	(g)	(g)
Primary	1360.96	3711.98
Secondary	0.08	31.12
Total	1361.04	3743.10
	(Mg)	(Mg)
ISV Melt Mass at End	196	196
ISV Melt Mass at OAT	127	150

The sample of ISV product, obtained immediately after the OAT phase of melting operations, yielded a smaller melt mass measurement (average of 139 Mg for both tracers) at that point in run time, i.e., after approximately 12 days of melting operations. This melt mass is consistent electrode depth and thermal monitoring performed during ISV operations up to this time. This time dependence of the tracer concentration illustrates how tracer dilution could be used to measure melt mass at various run times if small (<100 g) samples of the melt body can be obtained safely. The OAT sample was obtained by pushing a Geoprobe® drill rod into the melt body by hand from the working platform on the hood. The viscous glass readily sticks to the steel rod upon withdrawal. Given the hazards of the melt expulsion experienced later, this sampling method would need to be automated rather than hand-operated as was carried out to obtain the present sample.

In addition to the analyses of Lu and Ho, a total of twelve rare earth elements were analyzed by neutron activation in the samples of ISV product after the OAT and the melt expulsion. Although the ten additional rare earth element concentrations are not directly useful in calculating melt mass, they do represent typical background concentration of these elements in ISV melt bodies derived from Oak Ridge soils and will be useful in planning future melt body mass measurements by rare earth tracer spiking (Table 3.3). These analytical results can also be compared to the background concentrations found in Pit 1 soils and supplementary materials used during ISV (see site characterization report in Volume 2). The concentrations in Table 3.3 had associated uncertainties of about 5% in their reported values. It can also be observed how the planned spiking of additional melts at Pit 1 with Tb, Sm, and Yb would have resulted in convenient concentrations for calculating their final masses.

Table 3.3. Average concentrations of rare earth elements in ORNL Pit 1 ISV products

Rare Earth Element	Final ISV Product Concentration (ppm)	OAT ISV Product Concentration (ppm)
La	48.8	47.7
Ce	100.0	95.7
Nd	36.1	34.6
Sm	6.25	5.65
Eu	1.36	1.29
Gd	5.84	5.96
Tb	0.74	0.70
Dy	4.48	4.45
Ho	20.3	26.1
Tm	0.39	0.40
Yb	2.99	2.95
Lu	7.44	11.2

Given the measurement of total ISV melt mass, contaminant inventories can then be calculated from measured ISV product concentrations or activities. Concentration and activities were measured on three samples of the final ISV product (the ESE Flow and S Flow, described in the rare-earth tracer discussion above, and a sample of splattered ISV glass dangling from roughing filter bag elements when these were sampled in the week after the expulsion incident). Samples were ground to a powder in an agate ball mill, sieved to <100 mesh, and prepared for analyses by fusion with lithium metaborate and dissolution in nitric acid (ASTM 1986) as described in project procedures (see Volume 2). In addition, a sample of the ISV product from the OAT interval was also analyzed. Elements were analyzed by ICPAES and radionuclides by the same procedures detailed in the site characterization tasks (see Volume 2). The concentrations of elements and activities of radionuclides of the average of three final and one OAT samples are presented in Table 3.4 along with the computed inventory based on a total melt mass of 196 Mg.

The elements are presented as oxide percentages under assumed reducing conditions, i.e., Fe and Mn oxides were calculated as FeO and MnO rather than Fe₂O₃ and MnO₂. This assumption is validated by the gain in sample weight when these specimens were ignited at 1000°C; the loss-on-ignition values in Table 3.4 are reported as negative numbers, indicating that the samples actually gained in weight, i.e., had a negative weight loss, as the ferrous and manganous species were oxidized to the heavier ferric and manganic oxides. The use of graphite electrodes in ISV operations appears to impose reducing conditions on the melt body with the graphite's elemental carbon acting as the reducing agent. Electrolytic reduction of these or other elements by the applied electrical potential is not feasible because ISV technology employs alternating current rather than direct current electric power.

Among the elemental oxide compositions, several expected transitions from the OAT to the final ISV product can be observed. First, the CaO content increased slightly but significantly from the OAT to final product due to the incorporation of 3,600 lb of limestone gravel after the OAT. This would be the equivalent of 935 kg of CaO which be expected to raise the CaO content by 0.47%

Table 3.4. Average elemental oxide and radionuclide composition and inventory of Pit 1 ISV melt body at the end of the operational acceptance test (OAT) and final phases

Elemental Oxide	Final ISV Product (%)	OAT ISV Product (%)	Total Element In 196 Mg Melt (kg)
AgO	<0.049	<0.049	<6.9
Al ₂ O ₃	20.33	19.98	21090
As ₂ O ₃	<0.50	<0.50	<750
BaO	0.054	0.054	95.8
BeO	<0.0063	<0.0063	<4.5
CaO	2.92	2.59	4095
CdO	<0.0261	<0.0260	<45
CoO	<0.048	<0.048	<75
Cr ₂ O ₃	<0.111	<0.110	<150
CuO	<0.038	<0.038	<60
FeO	6.12	6.07	9330
K ₂ O	3.36	3.09	5470
MgO	1.72	1.50	2030
MnO	0.060	0.050	92
MoO ₂	<0.114	<0.113	<150
Na ₂ O	0.96	1.12	1390
NiO	<0.097	<0.096	<150
P ₂ O ₃	<3.50	<3.46	<2990
PbO	<0.411	<0.407	<750
Sb ₂ O ₃	<0.456	<0.452	<750
SeO ₂	<0.536	<0.531	<750
SiO ₂	62.56	62.11	57300
SnO	<0.038	<0.022	<58.1
SrO	0.0170	0.0179	28.17
TiO ₂	0.786	0.755	923
V ₂ O ₃	<0.068	<0.068	<75
ZnO	0.0140	0.019	37.6
ZrO ₂	<0.052	<0.051	<75
Loss-On-Ignition	-0.56	-0.59	
Sum of Oxides	98.46	96.87	
Radionuclide	(dpm/g)	(dpm/g)	(Ci)
¹³⁷ Cs	33064	2839	2.92
⁹⁰ Sr	1463	309	0.1292
²³⁸ U	8.07	2.15	0.000713
^{239/240} Pu	9.70	0.083	0.000856

which is very close to the 0.33% difference found in Table 3.4. Similarly the Na_2O content of the melt body was reduced from 1.12% at the OAT to 0.96% in the final composition. This was produced by the continued melting of low Na soil into the OAT melt, which had initially received a significant pulse of Na_2O from the starter feldspar sand (Na_2O content of 8.04%). Other bulk elemental oxide contents were not much changed by the continued melting beyond the OAT, when the melt mass increased from 139 Mg to the final mass of 196 Mg (Table 3.2).

The major contrast between the present Pit 1 ISV melt composition and that of the previous radioactive pilot-scale demonstration (Spalding et al. 1992) was the much lower content of CaO in the Pit 1 melt. The 1991 ISV melt composition was approximately 17 and 6% CaO and MgO whereas the Pit 1 melt was only 3 and 2%, respectively, due to the significant addition of limestone to the 1991 melt configuration. Thus, the 1991 melt had a significantly lower measured ISV operating temperature (1500°C) than the estimated 1600°C operating temperature of the Pit 1 melt (ESERP 1996a).

The major change in melt composition between the OAT and the final melt body can be seen in the radioisotopic composition (Table 3.4). The ^{137}Cs , ^{90}Sr , and $^{239/240}\text{Pu}$ concentrations all increased significantly as the OAT melt body enlarged downward and engulfed a significant amount of the maximally-contaminated strata or layer at the bottom of Pit 1. The more particle reactive (strongly adsorbed) ^{137}Cs and $^{239/240}\text{Pu}$ increased their activities in the melt by factors of 12 and 117, respectively, while both ^{238}U and ^{90}Sr activities increased by a factor of approximately 4. The smaller difference in ^{238}U activities could be expected due to the significant average background activity (2.26 dpm/g) of ^{238}U even in pristine Oak Ridge soils (see site characterization descriptions, Volume 2). For a different reason, ^{90}Sr also exhibited a smaller difference between OAT and final compositional activity; ^{90}Sr is more mobile in soil and, thus, more dispersed in the fill material within pit, whereas the strongly adsorbing ^{137}Cs and $^{239/240}\text{Pu}$ would be confined to a narrower depth interval nearer to their original contact with the pit bottom. Thus, relatively more of the final ^{90}Sr contamination would be expected in the OAT melt body.

The total inventory of ^{137}Cs in the final ISV melt body was estimated to be 2.92 Ci which translates to the incorporation of 7.5% of the 38.8 Ci calculated in the Pit 1 inventory (see Volume 2). On plan view of the Pit 1, the final melt body, with its 314 ft^2 area (radius = 10 ft), amounted to about 16% of the 1992 ft^2 target area. This apparent discrepancy with the percentage of ^{137}Cs incorporated in the melt body is due to melt body position at the time of the melt expulsion; at that time, the ISV melt body was in the process of engulfing the maximally-contaminated layer in Pit 1, and further melting would have been necessary to fully widen the melt body near the pit bottom. Nevertheless, a significant inventory of ^{137}Cs was incorporated into the ISV product resulting in sufficient quantities and activities for characterization and leach testing. Large pieces of the ISV product, when surveyed on the ground surface around the hood following the melt expulsion, exhibited maximum dose readings of 8 mrem/h at contact, regardless of thickness, indicative of a uniformly contaminated material. None of the expelled product exhibited any detectable transferrable contamination, which observation is consistent with leaching characteristics of the final product (Sect. 3.4).

The maximum dose reading of 8 mrem/hr for the expelled ISV product was due almost exclusively to its activity of ^{137}Cs (33,000 dpm/g) because the activities of other radionuclides were so much less. This dose reading can be normalized to the activity of ^{137}Cs in order to calculate surface dose rates of ISV products which could be produced in future ISV applications to other WAG 7 pits and trenches. Expressing the dose rate in this manner yields a normalized value of 537 mrem/hr/ μCi of ^{137}Cs /g of solids (or 2.42×10^{-4} mrem/hr/dpm/g). Thus, an ISV melt body of

500 Mg, which contained 10,000 Ci of ^{137}Cs , would be expected to exhibit a dose rate at contact of 10.7 rem/hr! Thus, a melt expulsion event, of similar size to that experienced at Pit 1 but with a much larger inventory of radioactivity being processed, would present dose rates which would prohibit direct handling of the cooled ISV product during cleanup activities.

3.3.2. Roughing (Baghouse) Filter Performance

In the project work plan (Spalding 1994a), the conceptual design of the off-gas preliminary filtration system was not developed; the work plan wording called for a nonspecific renewable filter, with possible return of spent filter material directly into the melt body, to be placed before the HEPA prefilters to minimize the level of contamination of off-gas system components.

The HEPA prefilters were well defined in both design and performance based on their use in the 1991 radioactive pilot-scale demonstration (Spalding et al. 1992); the HEPA filter capacity was simply doubled, from a single to a twin standard filter housing, to accommodate the greater off-gas flow of the large-scale system for the Pit 1 project. For the preliminary or roughing filter, a newer gas-filtering technology was employed. Nextel® (3M, Inc.) high-temperature filter fabric had been commercially developed in the early 1990s as an alternative to HEPA filter technology at temperatures too high for standard or even high-temperature HEPA materials. In addition, use of such materials avoids the need to cool moist hot off-gas and remove resulting moisture particles which otherwise would clog conventional HEPA filters while providing particle removal efficiencies near those of HEPA filters. These attributes of Nextel® filter fabric made it a highly promising candidate for filtration of ISV off-gas which is moist and hot and requires sub- μm particle filtration to remove reactive contaminants like ^{137}Cs . The required surface area to allow off-gas flow at the large-scale off-gas unit's maximum capacity led to the design of a 128-unit baghouse described in Sect. 1.3.1. The potential need to clean accumulated particles or solids from the fabric surface, to maintain sufficient flow through (or avoid excessive pressure drop across) the filter unit, necessitated the blow-back self-cleaning design described previously.

To evaluate this roughing filter performance for the removal of ^{137}Cs and other contaminants during ISV operations, three independent techniques were envisioned. First, at the completion of ISV melting operations, several filter bags would be sampled and analyzed for all contaminants. Notably, ^{137}Cs was the only contaminant which could be assayed nondestructively using known areas of sampled material; all other radionuclides and hazardous elements required destructive dissolution of the sampled fabric and its adhering particulates and contaminants. Because the fabric and adsorbed particulate material cannot be quantitatively separated, known sample areas of fabric and adhering particulate required grinding, homogenization, and dissolution identical to that required for the ISV product; indeed, much of the adsorbed particulate may be composed of entrained solids from the ISV melt body, although these are likely to have been diluted by other solids (e.g., clean soil) carried into the off-gas system. Thus, the same sample preparation, dissolution, and analytical methods were applied to these filter samples as were applied to the ISV product and starting soil samples. The second technique to assay roughing filter performance was to sample bags after the OAT and determine the amount of stable cesium chloride deposited during the OAT; a known weighed quantity of CsCl was buried within the melt zone of the OAT prior to start of ISV operations. However, it was recognized that both the assay of filter inventory of ^{137}Cs after final melt operations and of Cs after the OAT would fail to measure the amount of ^{137}Cs or Cs removed and returned to the melt by the blow-back system. Thus, any apparent removal efficiency for Cs would be, of necessity, too low because only the inventory remaining on the filter at the end of the period would be determined. A third technique to overcome this limitation in measurement of roughing filter performance was employed by isokinetic modified method 5 (MM5) sampling of off-gas from

the pipe immediately before the HEPA prefilter; on several occasions after the OAT when processing significant activities of ^{137}Cs in the melt, the off-gas was sampled with and without the roughing filter bypass valve opened. Thus, the difference in off-gas ^{137}Cs activity, as measured on the MM5 filters, between filtered and unfiltered off-gas, would provide a direct measure of the filter removal efficiency during that interval of ISV operations. Although a number of these MM5 samples were collected and archived, none have been assayed for ^{137}Cs due to limitations in funds for post-test evaluation. Similarly, no analyses of the elemental Cs on the sampled bags after the OAT have been completed although these samples have been archived. However, the elemental and radioisotopic analyses of the samples of the final filter fabric have been completed.

3.3.2.1. Radionuclides on the roughing filter

Although ^{137}Cs could be assayed nondestructively on samples of fabric from selected bag elements, analyses of other radionuclides and elements required destructive sampling and analyses as discussed above. Three of the 128 Nextel® bags were removed from the roughing filter baghouse and placed into plastic bags for survey and storage on site; the three locations were randomly selected from the 16 x 8 grid of 128 bag elements. From the mid-section of each sampled bag, an approximate 10 x 10 cm square subsample was removed by cutting with scissors and placed in a plastic bag for transport to the laboratory. For nondestructive assay of ^{137}Cs , smaller 2 x 2 cm squares were removed, weighed, placed in scintillation vials, and subjected to gamma spectroscopy by project methods (see Volume 2). Remaining material was ground, sieved, and dissolved as described above; all three bag samples were blended for a single composite sample for the destructive analyses although duplicates of the composite were prepared. The loading of particulates or solids on the samples was determined by the difference in weight per unit area between the used fabric samples and the average of pristine, unused fabric samples. Radionuclide and chemical analyses were carried out on the composite sample and on a sample of unused fabric material and, thus, were determined on a per unit weight of material basis. The amount of each radionuclide or element was then calculated on a per unit area basis using a background or clean-fabric corrected concentration multiplied by the net solids deposition per unit area, in turn multiplied by the total area (747,000 cm²) of 128 bags.

The average activities of radionuclides on the roughing filter fabric, unused fabric, and deposited solids are listed in Table 3.5. In addition, the computed inventories of each radionuclide and element are also listed and that inventory expressed as a fraction of the inventory of radionuclide or element in the final melt body. Only a small fraction of the total melt radionuclide inventory was deposited on the roughing filter at the end of the first melt. Except for ^{238}U , which exhibited an activity (126% greater) in the deposited solids similar to its activity in the melt product (Table 3.4), the other three radionuclides, which do not have significant background activities in uncontaminated soil, exhibited activities in the deposited solids considerably less than the activity in the final ISV product (Table 3.4); the activity of ^{137}Cs , ^{90}Sr , and $^{239/240}\text{Pu}$ were 44, 80, and 33% that of their respective activity in the ISV product. Overall, such activity similarities between the filter particulate and ISV product supports the conclusion that most of the particulate originated from particulate releases from the melt body, diluted somewhat by other uncontaminated solids, i.e., surface soil, entrained into the off-gas stream. Also, very little, if any, volatilization of ^{137}Cs seems to have occurred during the Pit 1 melt in dramatic contrast to the behavior of ^{137}Cs during the pilot-scale radioactive demonstration in 1991 (Spalding et al., 1992). In that test, ^{137}Cs activity on HEPA filter-deposited solids was enriched by a factor of over 115 times its activity in the final ISV product whereas in the Pit 1 ISV melt ^{137}Cs activity in the solids was only 44% that of the product. In the Pit 1 melt, the ratios of ^{137}Cs activity to the other radionuclides were similar to those in the

Table 3.5. Radionuclide and elemental composition and inventories of the ISV roughing filter after completion of the first melt at ORNL Pit 1

Elemental Oxide	Final Roughing Filter (%)	Unused Fabric Filter (%)	Net Filter Deposited Solids (%)	Total Element Inventory (kg)	Fraction of Melt Inventory
AgO	<0.047	<0.051	<0.020	<0.0012	<0.000012
Al ₂ O ₃	55.53	58.72	33.32	1.94	0.000023
BaO	<0.0082	<0.0089	<0.0035	<0.00020	<0.000002
BeO	<0.0061	<0.0066	<0.0026	<0.00015	<0.000012
CaO	0.129	0.025	0.0852	0.050	0.0000087
CdO	<0.0252	<0.0273	<0.0107	<0.00062	<0.000012
CoO	<0.0468	<0.0506	<0.0199	<0.00116	<0.000012
Cr ₂ O ₃	<0.108	<0.117	<0.0457	<0.00266	<0.000012
CuO	<0.0369	<0.0399	<0.0157	<0.00091	<0.000012
FeO	0.428	0.0878	2.79	0.163	0.000013
K ₂ O	<1.06	<1.15	<0.45	<0.026	<0.000004
MgO	0.244	0.264	0.104	0.00604	0.000002
MnO	0.0128	0.0126	0.0138	0.00080	0.000007
MoO ₂	<0.110	<0.120	<0.047	<0.00273	<0.000012
Na ₂ O	0.76	0.21	4.56	0.266	0.000142
NiO	<0.0937	<0.101	<0.0398	<0.00232	<0.000012
PbO	0.691	<0.429	2.51	0.147	0.000182
Sb ₂ O ₃	<0.441	<0.477	<0.187	<0.0109	<0.000012
SeO ₂	<0.517	<0.560	<0.220	<0.0128	<0.000012
SiO ₂	23.66	24.98	14.51	0.845	0.000007
SrO	0.00191	<0.0038	0.00346	<0.00020	<0.0000061
TiO ₂	<0.037	<0.040	<0.0156	<0.00091	<0.000006
V ₂ O ₃	<0.066	<0.071	<0.0279	<0.00163	<0.000012
ZnO	4.53	0.028	35.84	2.09	0.043
Loss-On- Ignition	0.30	0.19			
Sum	86.16	84.16			
Nuclide	(dpm/g)	(dpm/g)	(dpm/g)	(μCi)	(fraction)
¹³⁷ Cs	1828	nd	14540	38.2	0.0000131
⁹⁰ Sr	147	8.3	1166	3.06	0.0000236
²³⁸ U	1.28	nd	10.2	0.0268	0.0000207
^{239/240} Pu	0.41	0.12	3.26	0.0086	0.0000099

ISV product whereas the 1991 demonstration resulted in marked increase in ¹³⁷Cs activity ratio to other radionuclides. The behavior of ¹³⁷Cs in the 1991 demonstration was determined to result from chloride-induced volatilization originating from a PVC pipe within the 1991 test configuration. By avoiding such incidental inclusions of chloride in the Pit 1 ISV melt, the volatilization of ¹³⁷Cs was virtually eliminated as a significant pathway for transport from the melt. The CsCl placed in Pit 1

was placed well above the maximally contaminated layer and was completely incorporated in the melt body before it engulfed significant ^{137}Cs . Because chloride only exerts its effect on ^{137}Cs volatility in unmelted soil, it would not be expected to affect volatility from Pit 1. Essentially all of the radionuclides behaved the same manner and their presence in the filter particulate resulted from entrainment of solids in the off-gas stream.

3.3.2.2. Ambient hazardous elements

Although neither the starting untreated soil nor the final ISV product exhibited significant concentrations of hazardous elements (Sect. 3.3.1.) or hazardous element concentrations in standardized leach tests above regulatory toxicity classification targets (Sect. 3.4.3.), the roughing filter (and by calculation, its filtered solids) was analyzed for constituent and trace elements (Table 3.5). Knowledge of the behavior of all these elements would be extremely useful in planning ISV remediation in areas containing other contaminants due to the similarity of elements and radionuclides (e.g., ^{60}Co and elemental Co). Additionally, the behavior of background concentrations of hazardous elements, i.e., As, Ba, Cd, Cr, Pb, Hg, Se, and Ag, in Pit 1 soil will be directly applicable to the behavior of these same elements during ISV if present at higher concentrations sufficient to classify other soils or wastes as hazardous.

On the roughing filter, only three elements (Na, Pb, and Zn) exhibited significant enrichment in the deposited solids. Sodium was only slightly enriched and its behavior has no implication for hazardous elements or radionuclides unless it were amended to a melt body as a chloride which could result in significant volatilization of ^{137}Cs . However, both lead (Pb) and zinc (Zn) were dramatically enriched in the deposited solids on the roughing filter, comprising 2.5 and 36% of the elemental oxide composition of these solids, respectively! Although only a small fraction of the melt inventory of these elements (0.018 and 4.3%) escaped the melt body, they accumulated on the roughing filter solids. Both of these elements behaved similarly in the 1991 radioactive demonstration where about 15 and 10% of their inventory volatilized from the ISV melt (Spalding et al., 1992); in the 1991 test, Sb and As, which were added as tracers, were also observed to have significant volatilities with 10 and 13% of their inventories appearing in the filter solids. Other elements in Table 3.5 were not detectable below the analytical detection limit; these elements are reported as "<" values and were carried through all calculations to yield maximum values for both the inventory mass and fraction of the melt on the filter. Thus, filtered solids from ISV melts will likely contain significant fractions of all four of these elements, in addition to Hg and Cd, which, if present at more than background concentrations in the treated volume, could result in filters which could be classified as hazardous or mixed waste. The toxicity characteristic leach procedure test has not been performed on the roughing filter fabric waste to determine whether it was a mixed waste. Because of its radionuclide content, it is, at least, a radioactive waste.

3.3.2.3. Pressure differential and filter particulate loading

As discussed in the ISV equipment description (Sect. 1.3.1), the roughing filter used on the new ISV off-gas hood was a baghouse designed to shake particulate off the bags and drop it back to the melt surface. The bags were shaken by a pulse of air blown into the bag assembly from a pulse pipe, one of which was positioned over each row of bags. The pulse of air was controlled for pressure differential (ΔP), duration, and/or time interval. Since the Pit 1 project was a prototypical application of this baghouse design, it was expected that some adjustments during operations would be required. Experimental adjustments were made frequently to the roughing filter pulse controls. During the many days of the OAT, an operational practice became established that related melt power to roughing filter control; during periods of high power (>1800 kW), it appeared that

particulate generation increased such that the ΔP across the roughing filter approached the design limit of 10 in. water column (WC). When this occurred, it appeared that the air pulse system was unable to sufficiently clean the bags requiring that the roughing filter be bypassed for a short period (usually 15 to 30 min) to allow the bags to be sufficiently cleaned. It became operational practice to try to keep the power levels between 1500 and about 1800 kW, depending on the ΔP of the filter housing. The fairly frequent adjustments to the roughing filter air pulse controls and its compressed air supply pressure contributed to increased personnel stay times in the exclusion zone.

Over the course of operations, an issue related to the off-gas flow rate was identified. It appeared that the flow rate being drawn from the hood was about twice that for which the prefilter and roughing filter systems were designed. That is, the off-gas system was designed to pull a maximum of about 104 standard m^3/min of air. However, according to design data and information available at the time the filter systems were designed, the off-gas system was designed to operate normally at between 40 and 60 standard m^3/min . Therefore, the filter systems were designed for a maximum flow of about 60 m^3/min . It should be made clear that exceeding the design flow rate does not compromise any safety aspects of the equipment, it merely reduced its filtration performance efficiency. This lack of performance efficiency contributed to some of the increased stay times in the exclusion zone as operators tried to optimize the operation of the roughing filter under the demanding flow conditions. This contributed to an increased usage of HEPA filters in the prefilter system because the ΔP increased more rapidly than otherwise would have been experienced. The actual flow rates, as well as potential modifications to the filtering hardware, should be assessed before future use of this ISV equipment. It may be more cost efficient to decrease the off-gas flow rather than redesign the filter systems to accommodate the increased flow rates.

Because the roughing filter operated almost continuously near its maximum ΔP , the particulate loading at the termination of the ISV melt and at the termination of the OAT was measured to determine this loading maximum. After the melt expulsion event, the roughing filter was found to have a net solids loading of 6.10 mg/cm^2 yielding a loading of 4.56 kg of solids over its 747,000 cm^2 total filter area. After the OAT, the average net solids of the three fabric samples was 6.75 mg/cm^2 for a total loading of 5.04 kg of solids. Thus, at the off-gas flow rate of 104 standard m^3/min , the maximum roughing filter loading was about 5 kg. If the roughing filter had been operated at its design flow rate, then considerably greater particulate loading could be expected although the relationship between flow rate and maximum loading is not necessarily linear.

3.3.3. HEPA Prefilter Performance

One of the successes of the 1991 radioactive pilot-scale demonstration was the complete removal of ^{137}Cs from the ISV off-gas preventing the contamination of the off-gas scrubbing system (Spalding et al. 1992). The prevention of the unnecessary spread of contamination, although a major cost savings and technical accomplishment in its own right, was not the major purpose for its implementation during the test. When ISV is performed on some of the major sources of radioactive contamination in WAG 7 (e.g., seepage pit 7), a single melt setting may process up to 10,000 Ci of ^{137}Cs and ^{90}Sr . Even small volatilized fractions (e.g., 1-10 Ci of ^{137}Cs) of such large inventories can lead to contamination of equipment which would impose dose limitations on ISV operators and result in significant risks for waste (off-gas scrub solution) spillage and air emissions. Thus, the 1991 demonstration established an excellent technology (HEPA filtration) to avoid significant equipment contamination and unnecessary doses to workers in most anticipated applications of ISV at ORNL. Such HEPA filtration was, thus, included in the off-gas treatment system for the Pit 1 project. It was hoped that the Nextel® filter fabric baghouse technology would be so successful that it could replace the HEPA filter system, or, at least relegate it to a contingency or backup system in

future ISV remediation. Avoiding the use of HEPA filtration by substitution of a renewable and reusable baghouse system would lower costs and waste generation, and reduce contamination levels and dose rates by returning most contaminated particulates to the melt body. The HEPA prefilters were also integral to the evaluation of the roughing filter in the Pit 1 project. The inventory deposited on the HEPA prefilters would be a direct measure of the contamination and solids which were not removed by the roughing filter. Thus, an overall removal efficiency of the roughing filter could be calculated from the ratio of its contaminant inventory to the total inventory in all off-gas components (roughing filter, prefilters, and scrub solution).

3.3.3.1. Radionuclides

The twin-filter capacity HEPA filter housings required filter changes whenever the pressure differential (ΔP) across it exceeded 8 in. WC. Changing HEPA filters was facilitated by employing two housings on the prefilter system; when one set of HEPA filters became loaded beyond its maximum ΔP , off-gas flow was routed to the alternate housing and the HEPA filters scheduled for change out from the previous housing at a convenient daytime hour when extra ISV project personnel were available. A total of seven sets of HEPA filters were employed during the entire Pit 1 ISV operations, five sets during the OAT and two sets after the OAT before the melt expulsion. Spent filters were surveyed by a radiation control technician and placed in double plastic bags until their sampling could be completed. The five sets from the OAT were sampled in a single afternoon campaign during the three-day interval before reestablishing full power to the melt body; the two remaining sets were sampled several days after the melt expulsion event. The seventh set in the west housing was in use at the time of the expulsion while the sixth set had been valved out from the off-gas flow, but not yet replaced, about 38 hours prior to the melt expulsion.

HEPA filters were sampled by cutting out sections of the filter material and its aluminum spacer material after removing the stainless steel containing screen welded to the filter frame. This operation was conducted in full level C PPE and full-face respirators on a plastic sheet within a temporary radiological zone area at the field site. Radiation readings of filter material, when removed from the housings after recent contact with ISV off-gas, exhibited high α -radiation readings ascribed to high radon content; within 24-hours of removal, α -radiation readings were no longer detectable with only low β/γ readings due to the presence of ^{137}Cs . Very approximate 20 x 20 cm sections were removed from 3-4 adjoining fanfolds in the central region of each filter. Only one of each pair of HEPA filters from the first five sets (OAT) was sampled while both filters (the top and bottom) were sampled from the two sets (seventh and sixth) used during and immediately prior to the melt expulsion. In addition, one of the single set of four HEPA filters in the backup blower housing on the off-gas hood was sampled after the melt expulsion; the backup blower operated briefly after the melt expulsion but was also subject to off-gas discharge during the pressurization of the melt expulsion. Undisturbed subsamples from the center of each sampled filter were prepared in the laboratory, after removal of the corrugated aluminum spacer, by cutting 2 x 2 cm squares, weighing, oven drying, and weighing again. Particulate loading was determined by difference in weights of similarly prepared pristine, unused HEPA filter material. Nondestructive assay of ^{137}Cs was carried out on duplicates of each sampled filter. As with the roughing filter material, all other analyses were destructive and were carried out on pulverized composited materials; only the composite samples from the sixth (east) and seventh (west) HEPA filter sets were destructively analyzed for radionuclides and elemental composition. Amounts and inventories of radionuclides and constituent and hazardous elements were determined as described for the roughing filter (Sect. 3.3.2).

The activity of radionuclides found on the west (in use during the melt expulsion event) and east (in use up to 38 hours before the melt expulsion event) HEPA filters are presented in Tables 3.6 and 3.7. These two HEPA filter samples were the only ones analyzed for all radionuclides other than ^{137}Cs . The analyses of the east HEPA filters were presumed to be representative of the five previous sets of HEPA filters; amounts of other radionuclides on the five previous sets of HEPA filters were calculated by proportioning their activities to the actual measured ^{137}Cs activity which was determined nondestructively on all HEPA filter samples. Activities of other radionuclides on the four HEPA filters from the backup blower housing on the off-gas hood were calculated by proportioning to the activities on the west HEPA filters; the backup blower would have received most or all of its contaminant load during the melt expulsion event and, thus, the west HEPA filters were presumed to be more representative of contaminants on the backup blower HEPA filters than would analyses of the east HEPA filters.

The activities of all radionuclides on the east and west HEPA filters represent extremely small fractions of the total activities in the melt body accounting for only 0.00034 and 0.00012% of the total ^{137}Cs and similarly trivial percentages of the other radionuclides. Although about three times as much activity of ^{137}Cs was found on the HEPA filters which experienced the melt expulsion (Table 3.6) than those in use prior to the melt expulsion (Table 3.7), the difference cannot necessarily be ascribed to the melt expulsion. At the time of the melt expulsion, the melt body was in the process of engulfing the maximally-contaminated depth layer in Pit 1; the processing inventory of ^{137}Cs was thus rapidly increasing within the melt body. This condition is supported by the approximate ten-fold increase in ^{137}Cs activity in the ISV product between the end of the OAT and its final composition (Sect. 3.3.1.). Thus, the comparatively larger activity of ^{137}Cs on the last set of HEPA filters may simply be representative of more contaminated off-gas during the latter stages of melting.

The overall behavior of ^{137}Cs throughout the seven sets of HEPA prefilter changes is depicted in Fig. 3.9. Although the melt body was gaining depth steadily, i.e., the cumulative electrode penetration was nearly linear over the 18 days of ISV operations, a sharp increase in the rate of release of ^{137}Cs and solids from the melt was observed in the last set of filters. The near identical behavior of solids and ^{137}Cs provides an important indication of the mechanism of ^{137}Cs transport from the melt body; ^{137}Cs was transported as a particle-reactive contaminant rather than a volatilized species as discussed previously (Sect. 3.3.2). Thus, the ^{137}Cs activity increased in the last set of filters because an increased load of particulate was released from the melt body; presumably most of this occurred during the melt expulsion. It should be noted that the west HEPA filters were badly deformed when sampled after the melt expulsion indicative of a high velocity pulse of off-gas moving down the off-gas pipe. This high-velocity pulse could well have facilitated the entrainment and transport of more than normal amounts of suspended particulate.

The total cumulative inventory of ^{137}Cs on the seven sets of HEPA filters amounted to 19.2 μCi and can be used to establish the removal efficiency of the roughing filter. The total activity of ^{137}Cs on the roughing filter was 38.2 μCi . Expressing the roughing filter activity as a percentage of the combined total results in an apparent removal efficiency of 67% for the roughing filter. This is considerably lower than the expected 99% removal efficiency based on the particulate removal specification of the Nextel® fabric filter. However, two inherently unquantifiable conditions contribute to this low calculated value. First, the roughing filter returned particulate to the melt using its blowback capability throughout ISV operations; this would make the inventory on its filter fabric far lower than the total activity it removed from the off-gas. Second, the roughing filter itself was frequently bypassed whenever its ΔP exceeded the selected threshold (usually 10 in. WC) and off-gas would flow directly to the HEPA prefilter system. This would tend to increase the apparent

Table 3.6. Radionuclide and elemental composition and inventories of the ISV HEPA prefilter (west) in use during the melt expulsion event at ORNL Pit 1

Elemental Oxide	Final West HEPA Filter (%)	Unused HEPA Filter (%)	HEPA Filter Deposited Solids (%)	Total Element Inventory (kg)	Fraction of Melt Inventory
AgO	<0.052	<0.051	<0.020	<0.0051	<0.000054
Al ₂ O ₃	15.26	5.50	20.09	1.97	0.000049
BaO	2.17	3.95	1.28	0.126	0.00118
BeO	<0.0067	<0.0065	<0.0068	<0.00067	<0.000054
CaO	2.32	1.76	2.59	0.254	0.000044
CdO	<0.029	<0.027	<0.030	<0.0030	<0.000058
CoO	<0.0513	<0.0500	<0.052	<0.0051	<0.000054
Cr ₂ O ₃	<0.118	<0.115	<0.120	<0.0117	<0.000054
CuO	<0.0405	<0.0394	<0.041	<0.0040	<0.000054
FeO	0.457	0.0803	0.642	0.0629	0.000005
K ₂ O	1.56	2.70	1.00	0.098	0.000015
MgO	0.375	0.300	0.412	0.0404	0.000012
MnO	0.0243	0.0124	0.0301	0.00295	0.000025
MoO ₂	<0.121	<0.118	<0.123	<0.0120	<0.000054
Na ₂ O	4.19	9.43	1.61	0.158	0.000084
NiO	<0.103	<0.100	<0.104	<0.0102	<0.000054
PbO	8.70	<0.424	12.79	1.253	0.00155
Sb ₂ O ₃	<0.484	<0.471	<0.490	<0.048	<0.000054
SeO ₂	<0.568	<0.553	<0.575	<0.056	<0.000054
SiO ₂	31.81	55.94	19.90	1.95	0.000016
SrO	0.0548	0.0708	0.0458	0.00459	0.000138
TiO ₂	0.070	0.100	0.055	0.0054	0.0000035
V ₂ O ₃	<0.072	<0.070	<0.073	<0.00715	<0.000054
ZnO	13.08	3.23	17.93	1.76	0.0362
Loss-On- Ignition	7.74	4.27			
Sum	88.62	88.01			
Nuclide	(dpm/g)	(dpm/g)	(dpm/g)	(μCi)	(fraction)
¹³⁷ Cs	1520	nd	2270	10.0	0.00000343
⁹⁰ Sr	385	34.4	575	2.53	0.0000197
²³⁸ U	1.66	0.43	2.48	0.0109	0.0000153
^{239/240} Pu	3.03	nd	4.52	0.0200	0.0000233

Table 3.7. Radionuclide and elemental composition and inventories of the HEPA prefilter (east) in use before the ISV melt expulsion at ORNL Pit 1

Elemental Oxide	Final East HEPA Filter (%)	Unused HEPA Filter (%)	HEPA Filter Deposited Solids (%)	Total Element Inventory (kg)	Fraction of Melt Inventory
AgO	<0.050	<0.051	<0.048	<0.00094	<0.0000098
Al ₂ O ₃	11.08	5.50	20.30	0.40	0.000010
BaO	2.31	3.95	-0.39	-0.0078	-0.000073
BeO	<0.0076	<0.0065	<0.0094	<0.00019	<0.000015
CaO	2.68	1.76	4.21	0.083	0.000015
CdO	<0.026	<0.027	<0.025	<0.0005	<0.0000098
CoO	<0.0489	<0.0500	<0.047	<0.00093	<0.0000098
Cr ₂ O ₃	<0.112	<0.115	<0.108	<0.00213	<0.0000098
CuO	<0.0385	<0.0394	<0.037	<0.00073	<0.0000098
FeO	0.737	0.0803	1.824	0.0360	0.000003
K ₂ O	1.84	2.70	0.432	0.0085	0.000013
MgO	0.598	0.300	1.090	0.0215	0.0000064
MnO	0.0145	0.0124	0.0179	0.000352	0.0000030
MoO ₂	<0.115	<0.118	<0.111	<0.00219	<0.0000098
Na ₂ O	5.11	9.43	-2.04	-0.040	-0.000021
NiO	<0.098	<0.100	<0.094	<0.00186	<0.0000098
PbO	2.520	<0.424	5.99	0.118	0.000147
Sb ₂ O ₃	<0.460	<0.471	<0.443	<0.0087	<0.0000098
SeO ₂	<0.540	<0.553	<0.520	<0.0102	<0.0000098
SiO ₂	37.18	55.94	6.152	0.121	0.0000010
SrO	0.0588	0.0708	0.0389	0.000766	0.000023
TiO ₂	0.204	0.100	0.376	0.0074	0.0000048
V ₂ O ₃	<0.069	<0.070	<0.066	<0.00130	<0.0000098
ZnO	13.86	3.23	31.43	0.620	0.0131
Loss-On- Ignition	10.07	4.27			
Sum	90.09	88.01			
Nuclide	(dpm/g)	(dpm/g)	(dpm/g)	(μCi)	(fraction)
¹³⁷ Cs	1533	nd	4069	3.61	0.00000124
⁹⁰ Sr	85.4	34.4	227	0.201	0.00000156
²³⁸ U	1.22	0.43	3.25	0.00288	0.00000404
^{239/240} Pu	0.39	nd	1.03	0.00092	0.00000108

"passed" activity inventory and, thus, lower the apparent removal efficiency. Given the evaluation technique, there is no method to correct for either of these conditions both of which would result in lower calculated removal efficiencies for ^{137}Cs , other contaminants, and particulate. Nonetheless, knowing that the apparent removal efficiency of the roughing filter is greater than or equal to 67%, leads to the conclusion that its use in future ISV operations will provide significant protection from equipment contamination (at least 67% less) and would reduce dose rates to personnel in proximity to down-flow off-gas handling equipment including the prefilter system and off-gas scrubber system.

Fig. 3.9. The accumulation of solids and ^{137}Cs activity on HEPA prefilters and melt body depth (electrode penetration) during ISV operations at ORNL Pit 1.

3.3.3.2 Hazardous elements

Like the roughing filter, the HEPA prefilters removed significant amounts of solids and associated elements (Tables 3.6 and 3.7). Also like the roughing filter, the west HEPA filter solids exhibited a significant content of PbO and ZnO , amounting to 13 and 18% (Table 3.6) of the total solids! Less this condition be thought to result from some release during the melt expulsion, it should be noted that the set of HEPA filters in use before the expulsion also contained solids which were composed of 6 and 31% PbO and ZnO , respectively. The solids on the HEPA filters were, thus, very similar in composition to the solids on the roughing filter (Table 3.5). The filtered solids on both the roughing and HEPA filters were highly enriched in Pb and Zn relative to either the starting soil or ISV final product composition. Notably, the zinc solids on only these two sets of HEPA filters amounted to over 5% of the inventory. This observation is consistent with the true volatilization of these elements from the ISV melt body. Although these elements are volatilized from ISV melts, they are efficiently captured by the various filters and off-gas scrub system so that they are not released to the atmosphere by the overall ISV process. The filter solids also seem slightly enriched in both

K and Na whose partial volatility from ISV melt bodies would be expected and has been observed previously (Spalding et al. 1992). There was an apparent "negative" deposition of BaO on the east HEPA filters (Table 3.7). Although this result had also been observed for the HEPA prefilters in the 1991 demonstration, it likely results from a computational artifact; the unused HEPA filter had a nearly 4% content of BaO and dilution by removed solids containing little or no BaO from the off-gas resulted in a situation where a small difference is calculated between two large numbers, i.e., the starting and final Ba concentrations.

3.3.3.3. Total particulate and filter loading

As can be seen in Fig. 3.9, HEPA filters required changing every few days whenever their ΔP exceeded about 8 in. WC. This condition was typically produced when 750-800 g of solids were loaded onto the filters, amounting to about 5 mg/cm² of filter area. The total particulate removed by the HEPA filters amounted to 21.9 kg. This latter total can be compared to the solids removed by the roughing filter (5.04 kg) and results in an apparent particulate removal efficiency of only 19% for the roughing filter. This should be interpreted as a minimal value for the roughing filter due to the conditions, discussed in Sect. 3.3.3.1, which would result in a low computed value. Totalling all solids captured in the ISV off-gas (roughing, prefilter, and backup hood blower) results in an estimate of 28.9 kg of solids from the 196 Mg melt mass in Pit 1; these total evolved solids amount to 0.0147% of the melt body or, alternately expressed, 99.985% of the treated mass remained in the final ISV product. In the 1991 radioactive pilot-scale demonstration, 2.41 kg of solids were evolved from a 12 Mg melt body resulting in 99.980% solids retention or 0.0200% evolution. Thus, considering only gross particulate behavior, the previous pilot-scale and the present large-scale ISV operations appear quite similar in the needs for particulate handling and removal. Returning the majority of these solids to the melt through the use of an adequately designed roughing filter will do much to minimize the mass and volume of secondary filter waste from ISV operations.

3.3.4. Off-Gas Scrub System Performance

Operationally, only two problems were experienced with the off-gas scrub system. First, the addition of caustic solution became complicated when the supply of liquid sodium hydroxide was depleted after only a few days. It was intended to be able to add the concentrated liquid caustic solution to the scrub tanks via the caustic tank addition procedure and not have to handle the mixing of solid caustic pellets. Once the liquid caustic supply was depleted, the standard procedure was employed of mixing solid caustic pellets to form the caustic solution to be added to the scrub tanks. This generated significant heat in the mixing tank leading to plugging and damage to transfer lines which was labor intensive and time consuming to repair. It is recommended that sufficient supply of liquid caustic be obtained for future operations. Caustic solution is required to maintain the scrub solution in a pH-balanced condition; without it, the scrub solution becomes very acidic because of the nature of the off-gases generated by the ISV process. Processing highly acidic scrub solution contributes to deterioration of scrub system components and generates a hazardous waste (pH < 2.0). The use of solid caustic material did create an additional safety hazard for ISV operators which had to be managed, but which can easily be avoided in the future.

Second, on April 8, a problem with the #1 scrub pump motor was encountered. The problem manifested itself by elevated motor current and loss of pump pressure. The problem was temporarily and immediately remedied by switching the process over to scrub system #2, per operational procedure. Over the course of the next several days, the motor (suspected of having a bad bearing) was removed and a spare was installed in its place. After several days, the #1 scrub system was brought back on line.

3.3.4.1. Water condensation and removal from Pit 1

Although approximately 25,000 gallons of water was condensed in the off-gas scrub system during ISV operations at Pit 1, a significant additional amount was merely transferred out the process stack. The scrub system operates between 48 and 60°C with a typical temperature of 52°C at the mist eliminator and is subsequently heated prior to the final bank of HEPA filters before release to the atmosphere. This critical heating step is necessary to raise the temperature of the off-gas above 52°C and, thus, well above its dew point so that water does not condense on and clog the HEPA filters. Thus, the ISV off-gas is near saturated relative humidity at this temperature and would contain 0.00570 lb of water ft³ of gas. The mass of water exhausted out the stack was determined to be 14,300 gal, which when added to that condensed, yielded 40,600 gal processed by the off-gas system. Correcting for inflow of ambient humidity, an estimated 37,700 gal were removed from Pit 1. The water evaporated, which was discharged up the off-gas processing trailer stack, contains virtually no dissolved or suspended materials because these are concentrated in the scrub solution condensate and recirculated. Ideally, it would be desirable to evaporate as much water as possible to the atmosphere and generate only a minimal volume of scrub solution waste. However, the capability of the post-scrubber system heater to evaporate is not sufficient to keep pace with the rate of generation of water from the melt body. In more arid climates, where soils have both a much lower moisture content and an absence of standing water, the ISV off-gas process system can keep pace with rates of generation from the melt. Scrub solution, under these conditions, may need to be replaced periodically due the accumulation of dissolved and suspended solids which interfere with its pumpability and flow in the scrubbers. Hazardous contaminants will also be concentrated in the scrub solution waste under such operating conditions and, in the case of Pit 1 soil, could result in much elevated Hg, Pb, and Zn concentrations (see below).

3.3.4.2. Waste volumes and characteristics

As described in Sect. 1.3.3.2, the scrub solution regularly filled its holding tank within the process trailer requiring regular transfers to one of the four 3000-gallon waste holding tanks. Waste was transferred from these tanks to a 5000-gal capacity tanker trailer. Prior to pickup of a full tanker, a sample was submitted for ICPAES analyses of hazardous and other elements and chemical species to determine if it met the waste acceptance guidelines of the ORNL liquid waste system. The first tanker exceeded the waste acceptance criteria for Cd with a measured concentration of 0.025 mg/L exceeding slightly the acceptance guideline of 0.01 mg/L; the waste was accepted as it was well below guideline concentrations in all 17 other chemical species (Ag, As, B, Ba, Be, Cr, Cu, Fe, Hg, Ni, Pb, Sb, Se, Zn, nitrate, sulfate, and pH). The next four tanker trailer loads and all residual tanks volumes exceeded the Hg concentration guideline of 0.004 mg/L with concentrations ranging from 0.62 to 0.0041 mg/L; however, all of these waste shipments were also accepted as they were well below all 17 other guideline criteria. Only two shipments exceeded the TCLP criteria of 0.2 mg/L Hg and none exceeded the Cd concentration of 1 mg/L. On average, the ISV scrub solution waste would not be classified as hazardous. In general, unless significant amounts of volatile contaminants are included in future ISV target areas, process scrub solution waste should continue to be acceptable to the ORNL liquid waste disposal system.

The total determined quantities of chemical constituents in the waste scrub solution and the subtotals in the five tanker trailer shipments and three residual holding tanks are listed in Table 3.8. As expected the dominant cation was Na as this is the constituent cation of the caustic used to keep the scrub solution near neutral pH. The dominant measured anions were sulfate and chloride as the alkaline scrub solution removes SO_x, NO_x, HCl, and CO₂ from the acidic off-gas; the other dominant counter anion expected would be bicarbonate, HCO₃⁻. However, alkalinity was not measured because

Table 3.8. Inventory of chemical species in ISV off-gas scrubber waste solution in five 5000-gallon tanker trailers and three 3000-gal farm tanks after ISV operations at ORNL Pit 1

Chemical Species	Tanker-1 (kg)	Tanker-2 (kg)	Tanker-3 (kg)	Tanker-4 (kg)	Tanker-5 (kg)	Farm-1 (kg)	Farm-2 (kg)	Farm-3 (kg)	Total (kg)	Maximum (kg)
Silver (Ag)	0.0001	0	0	0	0	0	0	0	0.0001	<0.0009
Arsenic (As)	0.0064	0	0.0023	0.0013	0.0074	0	0	0	0.0174	<0.0266
Boron (B)	0.3785	0.1183	0.0587	0.0549	0.053	0.0204	0.0806	0.1453	0.910	<0.910
Barium (Ba)	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0009	<0.0009
Beryllium (Be)	0	0	0	0	0	0	0	0	0	
Calcium (Ca)	0.0492	0.0231	0.0136	0.0136	0.0227	0.0126	0.0762	0.1139	0.325	<0.325
Cadmium (Cd)	0.0005	0	0	0	0	0	0	0.0007	0.0012	<0.0019
Chromium (Cr)	0.0016	0.0005	0.0006	0.0008	0.0028	0.0004	0.0015	0.0037	0.0119	<0.0119
Copper (Cu)	0.0006	0	0.0001	0.0002	0.0005	0	0	0.0002	0.0016	<0.0023
Iron (Fe)	0.01	0.002	0.0025	0.0028	0.0068	0.0023	0.002	0.0291	0.0575	<0.0575
Mercury (Hg)	0.0001	0.0007	0.0023	0.0023	0.0108	0.0015	0	0.007	0.0247	<0.0247
Potassium (K)	0.3028	0	0	0	0	0	0	0	0.303	<0.666
Magnesium (Mg)	0.0174	0.0129	0.0068	0.0042	0.0068	0.0024	0	0.0366	0.0871	<0.0876
Manganese (Mn)	0.0018	0.0005	0.0003	0.0005	0.001	0.0007	0.001	0.0049	0.0107	<0.0107
Molybdenum (Mo)	0.0053	0.0029	0.0006	0.0008	0.0028	0	0	0	0.0124	<0.0151
Sodium (Na)	14.1938	20.2119	14.5723	13.4368	24.6025	8.9137	15.3065	7.8122	119.0	<119.0
Nickel (Ni)	0.0007	0.0014	0.0011	0.0017	0.0044	0.0011	0.0036	0.0164	0.0304	<0.0304
Lead (Pb)	0.1609	0.0038	0.0036	0.0051	0.0146	0	0.0036	0.0177	0.209	<0.210
Antimony (Sb)	0.0015	0	0	0	0	0	0	0	0.0015	<0.0104
Selenium (Se)	0.001	0.0039	0.0038	0.0028	0.0028	0	0	0	0.0143	<0.0176
Silicon (Si)	0.5867	0.155	0.0814	0.0719	0.0814	0.0315	0.0659	0.1342	1.208	<1.208
Vanadium (V)	0.0001	0	0	0	0.0001	0	0	0	0.0002	<0.0003
Zinc (Zn)	0.0946	0.0191	0.0125	0.0108	0.0208	0.0099	0.0803	0.3463	0.594	<0.594
Chloride (Cl)	1.4572	2.3846	1.7411	1.3815	1.6086	0.897	1.022	1.1923	11.68	<11.68
Nitrate (NO ₃)	0.01	0	0	0	0	0	0.05	0	0.06	<0.1414
Sulfate (SO ₄)	8.2135	8.3459	8.7055	7.7593	9.3679	7.1991	6.8925	5.0303	61.51	<61.51
pH	7	7	8	9	9	9	12	9		
Gamma / Beta	nd	nd	nd	nd	nd	nd	nd	nd		

nd = not detected

the nature of alkalinity in the ISV scrub solution was well characterized in the 1991 and other ISV demonstrations (Spalding et al., 1992; Buelt et al., 1987). Two sums of each chemical species are listed in Table 3.8: the first is based on actual determinations where values reported as less than (" $<$ ") were computed as zero; the second total was a maximum based on actual values with all the less than reported values calculated at their stated detection limits. These inventories in kg are labeled with the "<" prefix to indicate that they are maxima. Only three hazardous elements were found to have significant inventories: Hg, Pb, and Zn with 25, 209, and 594 g totals, respectively.

No radioactivity was detected in any of the scrub solution samples or in samples from the tanker trailer loads. However, the analytical detection limit of 0.1 dpm/mL for the assay of ^{137}Cs means that up to 4.26 μCi of ^{137}Cs could have been contained in the 25,000 gal of scrub solution waste and would fail to be detected. Although the average activity of ^{137}Cs in this large volume of scrub solution would be well below any criteria which would classify it as radioactive, this condition makes the use of scrub solution analyses for ^{137}Cs to compute HEPA filter removal efficiency impractical or, at best, misleading. Thus, the cumulative total of ^{137}Cs on all seven sets of HEPA filters (19.21 μCi) represents 82% of the maximum inventory (19.21 + <4.26 μCi) in the HEPA prefilter/scrub system. Thus, it can be fairly stated that the HEPA prefilter system exhibited a removal efficiency of >82% for ^{137}Cs in the Pit 1 melt. A smaller scale HEPA prefilter system removed >99% of the ^{137}Cs in the ISV off-gas during the 1991 radioactive demonstration (Spalding et al. 1992) and that efficiency was probably representative of the actual performance of the HEPA prefilter in the present ISV operation at Pit 1.

3.3.4.3. Total particulate

Suspended solids in the ISV scrub solution have not yet been determined although samples of the various tanker trailers and farm tanks have been archived. However, visual observations of the scrub solution waste revealed little turbidity or apparent suspended solids in the samples. As in the 1991 pilot-scale demonstration, use of the HEPA prefilter appears to have virtually eliminated suspended solids in the scrub solution waste (Spalding et al. 1992). As discussed below, suspended solids in the ISV scrub solution may have been as high as 30 mg/L (based on total SiO_2 analyses) which would not correspond to much turbidity. In the 1987 pilot-scale ISV demonstration at a site approximately 500 ft to the southeast of Pit 1, where no off-gas filtration was employed prior to the scrub system, suspended solids in the scrub solution ran as high as 50,000 mg/L (Spalding and Jacobs 1989). Thus, the qualitative evidence from the Pit 1 ISV operations support the conclusion that the combination of the roughing filter and the HEPA prefilter system was extremely effective in removing particulate from the off-gas and should be continued in future ISV applications.

3.3.4.4. Final HEPA filter performance

The inventories of elements in the scrub solution waste (Table 3.8) cannot simply be totaled to yield a sum of solids to use in calculating the particulate removal efficiency of the HEPA prefilter; much of the present total solids resulted from addition of caustic soda and the resulting adsorbed (scrubbed) acidic gases in reaction to its alkalinity. However, the total silicon is indicative of suspended solids in the scrub solution and represents a total equivalent of 2.586 kg of SiO_2 ; this represents a total removal efficiency of about 89% based on the total inventory of 21.0 kg of solids on the seven sets of HEPA filters. Additional evidence for the off-gas removal efficiency of the HEPA filters can be gained from the behavior of volatile elements. Although Hg was not measured on the filtered solids, totals for all off-gas filter solids for Pb and Zn were 2,790 and 8,453 g, respectively. Thus, these additional inventories in the scrub solution waste (Table 3.8) added less than 10% to the final inventory for these elements removed from the melt body. The prevalence of

Pb and Zn on the filter solids and their enrichment over the average concentration in the ISV product pointed to the true volatile transport of both Pb and Zn; but notably, 93% of both the Pb and Zn in the ISV off-gas was found on the filtered solids and, thus, were effectively removed by the HEPA filtration system. Thus, HEPA filtration, prior to off-gas scrubbing, will be a very effective technique to remove contaminants from off-gas and should be maintained in future ISV operations.

3.3.4.5. Options for future in situ vitrification operations

As discussed in Sect. 3.3.4.1, a large amount of water is processed through the ISV scrub system. Any ISV operations in humid regions, even if groundwater were below the melt body depth or were suppressed to that level by pumping operations, will generate large amounts of water to the off-gas. Something more than half the total amount of water was condensed and collected and, ultimately, disposed as a waste in the Pit 1 project. The results of the roughing filter and HEPA prefilter system performance in this treatability study discussed above demonstrated that particulates and contaminants were largely removed by these systems and only a small fraction of the hazardous contaminant inventory and none of the radioactive inventory survived to the off-gas scrub system in the process trailer. The obvious conclusion, based on these results, is that the scrub system may not be needed for ISV operations in WAG 7. Although the scrub system could be maintained in a backup or contingency state during ISV operations, bypassing its use has the potential to save enormous costs for ISV applications. Much operator time was devoted to monitoring, adjustment, and repair of the system and to waste solution transfer operations, analytical measurements, and waste disposal; all of these operations and costs could be eliminated by bypassing the scrub system. The scrub system does remove acidic gases (SO_x , NO_x , HCl , and CO_2) from the ISV off-gas but this is done only incidentally to particulate removal; when the large-scale ISV off-gas processing system was built, the scrubber system was designed as the sole process to remove radioactive contaminants from the off-gas prior to a final HEPA filtration before release to the atmosphere. With the success of the roughing filter and HEPA prefilter systems, the environmental compliance need to partially remove acidic gases from the ISV off-gas should be assessed. If it is determined that release of acidic gases is not a constraint for the ISV technology, then bypassing the scrub system may represent a major cost savings for ISV technology. Multiple filtration subsystem operation will then focus on heating techniques to prevent moisture in the off-gas from condensing and all water derived from the melting operations could be released to the atmosphere. In addition to reducing waste and disposal costs, such a technical approach could free ISV operators from the approximately 50% of their time devoted to scrub system operations. However, acidic off gas may be harmful to the present blower, and thus for the present system, bypassing the off-gas scrubber may not be prudent.

3.3.5. Overall Off-Gas Handling System Performance

The previous three sections discussed the specific performance of the three major off-gas handling systems: the roughing filter on the off-gas hood, the HEPA prefilters, and the off-gas scrubbing system in the ISV process trailer. The fractional distribution of contaminants, both radioactive and hazardous, among and between coupled and serial component systems has been stressed in these discussions. In general, both the roughing filter and HEPA filters were found to exhibit excellent removal efficiencies for various elements and radionuclides from the off-gas. However, the overall off-gas system performance can best be put into perspective and, thus, used for planning future ISV operations at ORNL, by comparing the normalized distribution of each contaminant, element, species, or radionuclide, particularly between the melt body and the total off-gas system. Such comparisons facilitate planning of ISV operations and modifications to equipment and run procedures to safely process other WAG 7 waste management units and contaminated soils in general.

3.3.5.1. Mass balance and melt retention of radionuclides

A preliminary normalized distribution of ^{137}Cs between the melt body and the various off-gas system components was presented in the technical evaluation summary of the melt expulsion (ESERP 1996b). Based on the more elaborate and extensive analyses of filter and ISV product samples, this normalized distribution has been slightly modified with only minor adjustments among the various off-gas system components (Fig. 3.10). The overall result found that 99.9982% of the ^{137}Cs activity contacted by the ISV melt body remained in the final ISV product. Of the 0.0018%, which was released to the off-gas, 99.8% was captured by the various filter systems. The maximum air release, presented in Fig. 3.10, occurred during the melt expulsion event on April 21, 1996, and was calculated from off-gas sampling data (ESERP 1996b). The overall retention of ^{137}Cs in the Pit 1 ISV product was significantly greater than either the 99.88% retention in the 1987 pilot-scale demonstration or the 97.6% retention in the 1991 radioactive pilot-scale demonstration. These two order-of-magnitude improvements in ^{137}Cs retention in this large-scale ISV melt makes application of ISV for other WAG 7 seepage pits and trenches very attractive. In planning a large-scale ISV melt into a contaminated volume containing 10,000 Ci of ^{137}Cs , it can be expected, based on the present project's findings, to handle only 0.18 Ci in the off-gas system; presumably, most (at least 75%) of that can be returned to the melt body by a well-designed roughing filter. Based on the best results from the 1987 pilot-scale demonstration (Spalding and Jacobs 1989a), it had been expected that ISV of 10,000 Ci of ^{137}Cs in a single melt setting would require the off-gas system to handle 12 Ci, which condition would impose dose rates up to 4.6 R/h in the ISV process trailer (Spalding et al. 1992); this estimate has been based on a dose modeling coefficient of 0.39 R/h/Ci of ^{137}Cs for the radiation field around the scrub solution tank wall (Oma et al. 1982). Not only do the present improved melt retention findings reduce this potential dose by two orders of magnitude, but the success of the roughing and HEPA filtration systems now places this greatly reduced radioactive contamination source away from the ISV process trailer and within the off-gas hood (i.e., the roughing filter area). Thus, results from this Pit 1 ISV project, particularly with ^{137}Cs , greatly reduce the risks for contamination and exposure of ISV operators and the risks for environmental releases based on processing significant inventories of contamination within the ISV process trailer.

The distributions of the other three radionuclides (^{90}Sr , ^{238}U , and $^{239/240}\text{Pu}$) in Pit 1 between the melt body and the off-gas are depicted in Fig. 3.11. The subsequent distributions of each radionuclide among the off-gas component systems, as in Fig. 3.10, were very similar to that found for ^{137}Cs and need not be presented in this overall summary. All four radionuclides in Pit 1 were particulate-reactive in the ISV off-gas and behaved similarly within the filtration systems. What was surprising in the comparative behavior of the four radionuclides was, not so much that ^{137}Cs behaved similarly to ^{90}Sr , ^{238}U , and $^{239/240}\text{Pu}$ in the off-gas system, but more that ^{137}Cs actually exhibited the greatest retention in the melt body of all four radionuclides. The fractions released to the ISV off-gas were in the order $^{238}\text{U} > ^{90}\text{Sr} > ^{239/240}\text{Pu} > ^{137}\text{Cs}$, with releases of 0.0060, 0.0048, 0.0038, and 0.0018%, respectively. This is particularly reassuring for planning future ISV operations in that no preferential volatilization or release of ^{137}Cs should be expected, provided that significant inclusions of chloride-containing materials are avoided as was experienced in the 1991 pilot-scale demonstration (Spalding et al. 1992).

3.3.5.2. Mass balance and melt retention of hazardous elements

Although ORNL Pit 1 was found not to contain hazardous concentrations of organic species or inorganic elements (see Volume 2), the background concentrations of hazardous and constituent elements in Pit 1 soil were sufficient to determine their behavior during ISV. Much like the retention behavior of radionuclides, discussed in the previous section, a mass balance and distribution of each

element was constructed (Fig. 3.12). For many elements, both maximum inventories in the melt body and maximum inventories in the off-gas system components were calculated from the less-than (" $<$ ") values reported in the various analyses. Thus, many of the computed off-gas fractions in Fig. 3.12 contain the symbol, $<$, to indicate that they are maximum fractions based on the analytical detection limits. Nevertheless, these " $<$ " off-gas fractions are quite useful in that they set limits for planning ISV operations in soils which may contain elevated concentrations of hazardous elements. Most of the elements behaved similarly to the radionuclides, discussed previously, in that their total release from the melt is $<0.01\%$; many behave similarly to the total solids, of which many are constituents and of which slightly greater than 0.01% were released to the ISV off-gas. The two elements with significant release to ISV off-gas were lead (Pb) and zinc (Zn). The lead release fraction is labeled as greater than (" $>$ ") because its concentration in the ISV product was below detection limits although much Pb was found in the various off-gas system filter solids well above (about two orders of magnitude above) the analytical detection levels; thus, the lead content of the melt could be quite a bit less than that computed from the detection limit, in which case, the fraction of Pb inventory released could be much greater (perhaps $>10\%$) than the 0.4% indicated in Fig. 3.12. The Pb probably behaves similarly to the Zn where over 10% of the inventory was released from the melted soil to the ISV off-gas. In the case of Zn, both the concentrations in the off-gas components and in the ISV product were well above detection limits and, thus, the overall calculated release is well defined. The behavior of all the measured radionuclides is also depicted in Fig. 3.12 so that a direct comparison can be made with the elemental behaviors. In general, the radionuclides were equally or better retained in the ISV melt than most elements.

Fig. 3.10. Distribution of ^{137}Cs in the ISV off-gas system components and the final melt body following ISV operations at ORNL Pit 1.

Radionuclide Distribution Following In Situ Vitrification at ORNL Pit 1

Fig. 3.11. Distribution of radionuclides between off-gas and melt body following in situ vitrification of 196 Mg of contaminated soil in ORNL Pit 1.

Percentage of Element To Off-Gas During In Situ Vitrification

Fig. 3.12. Percentage of element of radionuclide inventories released from the ISV melt body to off-gas following ORNL Pit 1 ISV operations.

The possible volatile behavior of elements and/or radionuclides can best be assessed by computing the ratio of element concentration or radionuclide activity in the off-gas solids to the concentration in the ISV product. If a given element ratio is less than unity, it can be interpreted that solids, other than particulate from the ISV molten body, or solids from the ISV molten body although earlier in operations when the melt body contained less radioactivity or contaminants, have diluted the solids originating from the ISV molten body. If the ratio is near unity, then it can be interpreted that the off-gas system solids are largely of origin from the molten ISV body as they have the same composition. If the ratio is much greater than unity, then the particular contaminant is enriched in the off-gas solids relative to the ISV molten body and mechanisms for this enrichment (like volatilization from a molten body and condensation on the cooler filtered solids) need to be invoked to explain the behavior. Such volatile behavior of Pb and Zn is clearly evidenced in the ratios of >11 and >1000 , respectively, depicted in Fig. 3.13. Other elements (notably Hg was not analyzed) did not exhibit much volatile behavior as their concentration ratios were near or below 1. All of the radionuclides exhibited concentration ratios significantly below 1. These observations are reassuring for planning future ISV operations in that volatilization of radionuclides and hazardous contaminants at background levels should not be expected.

Concentration Ratio of Off-Gas Solids To In Situ Vitrification Product

Fig. 3.13. Concentration or activity ratio of elements and radionuclides in ISV off-gas solids to ISV product after ISV operations at ORNL Pit 1.

3.3.6. Off-Gas Characteristics During the Melt Expulsion

Although the analyses of the various off-gas filtration systems provide accurate and useful information about the total amounts of contaminants released from the melt body, they provided only crude time resolution of these emissions. At best, the regular changes of HEPA filters provided an integrated sample over several days, i.e., from the previous filter change. The filter analyses were of little use in answering questions about shorter time periods, i.e., during the few minutes of the melt expulsion event. To address questions about what releases may have occurred during the melt expulsion, particularly during the few seconds when the off-gas hood was lifted from the ground and off-gas was released without filtration, analyses from the off-gas samplers and monitors must be investigated. To determine how much activity may have been released during the uncontrolled melt expulsion, two quantities needed to be determined: the activity per unit volume of off-gas during the event and the total volume or maximum possible volume of off-gas released. The activity in the off-gas at the time of the uncontrolled release can be obtained from the off-gas monitoring and sampling equipment. The estimated volume of gas released must be calculated from various process parameter limitations.

3.3.6.1. Off-gas radioactivity monitoring

Samples of the various filters and tapes from off-gas samplers were assayed for ^{137}Cs activity for the intervals immediately before, during, and after the off-gas release melt expulsion incident. Of particular interest was the Graseby-Andersen paper tape off-gas sampler on the hood which pulled off-gas from the intake of the roughing filter; this sampler would yield the best representative sample of the off-gas released during the uncontained interval of hood pressurization. Although this particular sampler had been malfunctioning frequently prior to the melt expulsion incident, due to off-gas moisture condensing on the paper tape, causing it to fall apart regularly, the sampler was functioning correctly and its performance verified during a regular field check by an ISV operator about 80 minutes prior to the melt expulsion incident. It is not known exactly how long the sampler was withdrawing an off-gas sample when the electrical power was shut off to the off-gas hood at around 6:30PM, within 20 min of the start of the melt expulsion incident (6:12PM). An average total of 37 dpm of ^{137}Cs was detected on the segments of the paper tape in operation before and during the time of the melt expulsion incident (Fig. 3.14). This value is based on the average for all samples in the five intervals before and during the expulsion, except those with no detectable (0) activity, for both off-gas samplers: the hood sampler and the roughing filter sampler which accessed off-gas from the off-gas pipe after the roughing filter. Both samplers' analyses were used because there was no significant difference between the samplers and no significant difference among the five sampling intervals. Because the average 95% confidence interval of all these samples was over $\pm 100\%$, not much discussion of any differences between samplers or times should be made. When dealing with such highly variable quantities, inclusion of as many determinations as possible makes for the best overall estimate; this was the rationale for using the average value over several time intervals rather than relying on a single analyses with a very wide counting error. Previously, in the technical evaluation of the melt expulsion (ESERP 1996b), a preliminary estimate of 49 dpm of ^{137}Cs had been employed. The present analyses have been completed using a lower background analyzer, longer counting intervals, and a more efficient NaI detector; although these final analyses have not changed the activity estimate very much, they have narrowed the confidence interval considerably providing improved confidence in the analyses. Previous estimates of releases and doses, based on this determination, may now be adjusted downward.

Assuming the off-gas sample was collected over the entire 20 min selected sampling interval, the off-gas activity concentration of ^{137}Cs was 0.925 dpm/L of off-gas (the sampler collected 2L/min

for 20 min). Any pressure surge into the sampling line during the melt expulsion incident would result in a lower calculated activity in the off-gas and, hence, the reported activity is conservative, i.e., tending towards a probable higher number. This activity can be used in combination with an estimate of off-gas volume released during the period when the hood was off the ground surface and pressurized.

Fig. 3.14. Activity of ^{137}Cs in off-gas from the ISV melt body at five sampling intervals before and during the melt expulsion event from the hood plenum (hood sampler) and from the off-gas pipe after the roughing filter (roughing filter sampler) on April 21, 1996.

Assuming the off-gas sample was collected over the entire 20 min selected sampling interval, the off-gas activity concentration of ^{137}Cs was 0.925 dpm/L of off-gas (the sampler collected 2L/min for 20 min). Any pressure surge into the sampling line during the melt expulsion incident would result in a lower calculated activity in the off-gas and, hence, the reported activity is conservative, i.e., tending towards a probable higher number. This activity can be used in combination with an estimate of off-gas volume released during the period when the hood was off the ground surface and pressurized.

3.3.6.2. Ambient air monitoring

Immediately before and during the pressurization and melt expulsion incident, three ambient air samplers/monitors were functioning. A Graseby-Andersen paper tape sampler was located approximately 30 ft to the southeast of the hood during the melt expulsion incident. This sampler

was powered from an electrical outlet at the portable storage building; the two portable storage/office buildings drew their electrical power directly from the supply line to the east and, thus, were not interrupted during the emergency power shutdown shortly after the melt expulsion incident. Activities on these samples could not be distinguished from background before, during, or after the melt expulsion incident. The other two ambient air samplers were AMS-4's which contained air filters which were replaced manually at intervals of approximately one day. One sampler was positioned inside the off-gas processing trailer to monitor the operators' breathing air; hence, it was shielded from any contact with outside air during the melt expulsion incident. No activity was detected on this monitor. The other AMS-4 had been used as an off-gas stack monitor for most of the melting operations but had been converted to an ambient air monitor after the OAT because of continuing moisture condensation problems when sampling the off-gas stack. It was located on the north side of the off-gas processing trailer approximately 70 ft north of the northeast corner of the off-gas hood but shielded from the hood by the process trailer. It appears unlikely that this sampler was in the influence of any of the off-gas release which was centered more to the west. Regardless, no detectable activity of ^{137}Cs was observed on the last filter sample collected from this monitor.

In general, winds at the time of the melt expulsion incident were from the southwest although velocities were low and variable. It was observed that the smoke cloud from the subsequent hood perimeter fires rose quite high before being directed slowly to the northeast of the site. Thus, none of the ambient air monitors or samplers were in a position for optimal interception of any escaping off-gas plume. Thus, it is not surprising that no detectable activity was found on any of these ambient air filter samples.

3.3.6.3. Estimate of uncontrolled off-gas release

To estimate the volume of off-gas released during the period of unconfined and pressurized hood conditions, the universal gas law ($P \cdot V = n \cdot R \cdot T$) was used along with the off-gas hood's confined volume, estimated temperatures, and confining pressures under pre-event, maximal event, and post-event conditions. From the activity of ^{137}Cs collected on the Graseby-Anderson paper tape sample of the hood off-gas for the volume sampled during the event, an activity per unit volume in the off-gas was calculated as discussed above; using this measured activity and the estimated total volume of off-gas released, the total release of ^{137}Cs activity was then calculated. This method provides a rough estimate, tending to be conservative, in the sense of estimating a maximum credible volume of off-gas released.

Volume of uncontrolled off-gas release

The amount of off-gas in moles (n), contained in the off-gas hood volume (V) at a given pressure (P) and temperature (T) can be calculated using the universal gas law with the constant (R) in appropriate units:

$$n_1 = (P_1 \times V_1) / (R \times T_1)$$

where:

$$P_1 = -0.5 \text{ in. H}_2\text{O or } 406.3 \text{ in. H}_2\text{O absolute (1 atm = 406.8 in. H}_2\text{O)},$$

$$R = 82.054 \text{ (cm}^3 \times \text{atm) / (mole} \times \text{deg-K) or } 1.1788 \text{ cu.ft. - in. H}_2\text{O/mole - deg-K (in units useful to these calculation),}$$

$T_1 = 250^\circ\text{C} = 523^\circ\text{K}$, the average normal ISV operating temperature,

V_1 = combined volume of hood, startup trench,, and subsidence crater:

hood = $50 \times 50 \times 6 \text{ ft} = 15,000 \text{ ft}^3$,

startup trench = volume of cylinder with average radius of 11.75 ft and 7 ft depth or $3,036 \text{ ft}^3$,

subsidence trench = cylinder of 10 ft radius and 7 ft depth = $2,199 \text{ ft}^3$.

= total volume of $20,235 \text{ ft}^3$.

thus, $n_1 = 13,335$ moles of gas contained in the hood prior to the event.

Maximal event conditions:

$$n_2 = (P_2 \times V_2) / (R \times T_2)$$

where:

$P_2 = P_1 + 10 \text{ in. H}_2\text{O}$ (this high number was taken from the PNNL underground storage tank (UST) test of 1991). Actually the 15,000 lb hood (just the stainless steel panels) plus adhering soil, requires only 1.1 to 1.5 in. H_2O to lift its own weight plus some additional force for its upward acceleration.

$$P_2 = 416.3 \text{ in. H}_2\text{O},$$

$$T_2 = 1500^\circ\text{C} = 1773^\circ\text{K}$$

$$V_2 = V_1 + 0.5 \text{ in. of additional lift volume (i.e., } 50 \times 50 \times 0.5 \text{ ft)}$$

$$V_2 = 21485 \text{ ft}^3,$$

thus, $n_2 = 4,279$ moles of gas.

Post-event conditions:

$$n_3 = (P_3 \times V_3) / (R \times T_3)$$

where:

$$P_3 = 1 \text{ atm.} = 406.8 \text{ in. H}_2\text{O}$$

$$V_3 = V_1 = 20,235 \text{ ft}^3,$$

$$T_3 = T_2 \text{ or } 1773^\circ\text{K}$$

thus, $n_3 = 3,939$ moles of gas when the hood settled down after release.

The amount of gas expelled would be $(n_1 - n_2) + (n_2 - n_3)$ or, more simply, $n_1 - n_3 = 9,396$ moles of gas. At standard pressure (406.8 in. H_2O) and temperature (298°K), this volume would be 230,000 L or $8,120 \text{ ft}^3$. This total has not been corrected for any off-gas withdrawal by the ISV off-gas system during the few seconds of the event's duration. If all of this pressurization and release

occurred in a few seconds (e.g., 5 sec), then the off-gas system, with its flow capacity of 3,670 scf/min, would only have reduced the release volume by 306 scf, a reduction of only 4%.

Radioactivity in uncontrolled release

The calculated concentration of ^{137}Cs activity, as discussed above, in the off-gas was 0.925 dpm/L. This was the average activity measured for the last five samples on the Graseby-Andersen tape samplers of off-gas within the hood and the sampler within the off-gas line; the concentration was calculated from the sampler settings of a 20-min sampling interval and a flow rate of 2 L/min. This would yield an uncontrolled release of $0.925 \times 230,000 = 212,752$ dpm or $9.58\text{E-}08$ Ci of ^{137}Cs .

3.3.6.4 Dose impacts of uncontrolled release

The release of $9.58\text{E-}08$ Ci of ^{137}Cs was employed to calculate a hypothetical dose to the nearest resident to the Oak Ridge reservation, approximately 2290 m to the southwest across the Clinch River. The dose calculations to this maximally exposed individual (MEI) of the general public were performed by ORNL environmental compliance office personnel using regulatory-approved dose models (CAP-88) and assumptions of worst-case meteorological conditions, i.e., steady slow winds with little atmospheric dispersion directly to the MEI. This dose calculation methodology is similar to that performed for an uncontrolled release during an ISV accident as reported in the project's site-specific health and safety plan (Spalding and Naney 1995). The other three radionuclides in Pit 1 were not included in the release estimate because all of them, if present, would have activities orders-of-magnitude less than that of ^{137}Cs . The resulting hypothetical dose was 0.015 μrem for this maximum possible release of ^{137}Cs . Previously, a dose of 0.02 μrem had been reported (ESERP 1996b) based on the higher release estimate of $1.3\text{E-}07$ Ci of ^{137}Cs at that time. In either case, the hypothetical dose is trivial compared to the DOE limit of 10 mrem/yr to the general public.

3.3.6.5 Use of expulsion data for future in situ vitrification impacts assessments

Two major potential uses of the data on the uncontrolled release of ^{137}Cs during the melt expulsion event at Pit 1 are possible. First, a more realistic release during an ISV accident can now be supported by the data on off-gas emissions. Previously, accident scenarios had to rely on a fractional release of (or, alternately, melt retentions for) ^{137}Cs which were considerably less realistic. Both the 1987 and 1991 pilot-scale ISV demonstrations found ^{137}Cs melt retentions orders-of-magnitude less than the 99.9982% found in this Pit 1 project. Thus, the accidental release scenarios, used prior to the Pit 1 project, found considerably higher potential doses to both on-site workers and the off-site general public than can now be supported by the Pit 1 data.

Second, the off-site dose modeling for Pit 1 can be extrapolated for other seepage pits and trenches at least approximately. All of the WAG 7 seepage pits and trenches are equal to or less than the distance to the nearest off-site residence (2290 m) used for the Pit 1 dose calculation. Because all dose model parameters and assumptions are linear with respect to the released activity, a constant of $1.5\text{E+}05$ $\mu\text{rem/Ci}$ of ^{137}Cs can be employed for scaling up to other potential ISV melt accidental uncontrolled releases. For example, an ISV melt processing 10,000 Ci of ^{137}Cs would be expected to release 360 μCi of ^{137}Cs during a melt expulsion which would translate to a hypothetical dose of 55.4 μrem to the MEI of the general public. Thus, estimates of the impact of uncontrolled releases from future ISV operations in WAG 7 are quite low and well below the 10 mrem/yr DOE standard, although the latter is a maximum total for all sources of emissions from the DOE Oak Ridge Reservation.

3.4. IN SITU VITRIFICATION PRODUCT QUALITY

As discussed in the study objectives (Sect. 2.0), the overwhelming reason to consider ISV as a remediation technology for the WAG 7 pits and trenches is its potential to convert in situ leachable porous contaminated soil into monolithic nonleachable glass. In particular, the radioactive contaminant, ^{90}Sr , which is both environmentally mobile in soils and groundwater and also the radionuclide which dominates off-site doses from White Oak Creek watershed, can be converted to a comparatively immobile form by ISV. The major method to establish the degree of improvement brought about by ISV is to compare the leaching behavior of ^{90}Sr in the starting untreated soil in Pit 1 with that of the final ISV product. The three leach tests employed were the Toxicity Characteristic Leaching Procedure (TCLP), used to determine if wastes release significant concentrations of hazardous substances; the Product Consistency Test (PCT), a hot-water extraction test for glass solubility; and the recently developed sequential leaching with dilute calcium chloride and hydrochloric acid to determine cation exchangeable and weatherable fractions of radioisotopes. The site characterization report (Volume 2) contains detailed descriptions of the behavior of both ^{90}Sr and ^{137}Cs in soil leaching tests including the TCLP, the PCT, and a sequential dilute CaCl_2 and HCl soil extraction. In this section, these leaching tests are performed on the actual field-produced ISV waste form for a direct quantitative comparison to the untreated soil. In addition, the behavior of the other radionuclides in Pit 1 (U and Pu) are also evaluated for leaching behavior and for soil from the maximally contaminated strata within Pit 1. The leaching behavior of hazardous elements and some glass structural constituent elements in the ISV waste form are also evaluated using the TCLP and PCT.

3.4.1. Product Sampling and Preparation - Planned, Actual, and Rationale

As discussed in the work plan for this treatability study (Spalding 1994a), samples of ISV product for laboratory leaching tests were to be obtained by core sampling from several positions within each melt body. Although it was recognized that the strong convective motion of an active ISV melt body leads to homogenization of the final product, each of the three planned melts could have had quite different elemental compositions depending on the nature and quantities of melt additives (feldspar, limestone, and insulating aggregates) whose manipulation and variation was planned for the various melts. In addition, the degree of melt overlap actually attained could result in significantly different compositions among the three melt bodies. Coring would also provide valuable material in the thermal transition zone around the melt body which would help to verify contaminant incorporation and/or the possibility of thermally-induced contaminant migration from the melt. Such transition material could also likely provide evidence for conditions at the time of the melt expulsion such as the porosity and density of melt boundary material which may have restricted flow of off-gas around the melt body. Such ancillary sampling needs can be addressed at almost any time in the future by core sampling the first melt body in Pit 1 when the need arises.

However, given the melt expulsion and the decision not to pursue further ISV melts in Pit 1 for the present, most of the technical need for geometrically-weighted sampling became moot. In addition, because only a small portion of the Pit 1 source contamination (roughly 7.5%) was actually incorporated into the limited-sized first melt body, in situ monitoring of groundwater within and around the melt body also became meaningless as contaminants from the untreated zones within the pit would still dominate groundwater quality. Thus, the only remaining avenue for establishing ISV product quality was to employ three independent samples of the final product in laboratory leaching tests. The same samples used for product elemental composition were employed for leach testing. Although all three ISV product samples were ground to <100 mesh to employ a uniform reproducible particle size (and surface area) material, subsamples of one of the ISV product samples (ESE Flow)

were prepared in the largest size diameter (about 0.5 cm) capable of fitting into the extraction container for all three leach tests. Although <0.5 cm is still considerably smaller (and greater surface area per unit weight) than the monolithic field waste form (which probably approaches 0.5 m effective diameter even with severe field fracturing), it provides a material with approximately 1000-fold less surface area per unit weight than the <100 mesh pulverized material used for the standardized leach tests. In addition, a standard <100 mesh pulverized soil, from the maximally contaminated zone in Pit 1, was carried through each type of leach test for two reasons. First, the concomitant soil sample provided both a temporal and within-reagent batch comparison for all the ISV product leach results even though several other soil samples were examined for their leaching behavior during the site characterization tasks (see Volume 2). Second, the behavior of other contaminants, notably U and Pu, was examined for the first time in some of these tests and a direct comparison with the untreated soil was needed.

3.4.2. Sequential Leaching Test Performance—ISV Product Versus Untreated Soil

The previously developed sequential leaching procedure (Spalding et al. 1992) was employed on the pulverized ISV product samples and on a pulverized sample from the maximally contaminated zone in Pit 1 (core 118). Leaching tests were replicated by employing three independent samples of each of five solid materials (three pulverized ISV products, one whole or intact (0.5 cm diameter) ISV product, and one pulverized untreated soil). The sequential leaching procedure was designed to quantify the release of radionuclides from soil by the two dominant mechanisms of chemical retention. First, the dilute (0.1N) CaCl_2 releases any cation exchangeable radionuclide species on the soil using the dominant soil exchangeable cation, Ca^{+2} ; the amount of calcium added to the soil, in the five sequential batches, totals to 2 milliequivalents per g of soil, which far exceeds a typical soil cation exchange capacity of about 0.2 milliequivalents per g. Thus, the CaCl_2 extraction is sufficient to replace about ten times the ambient exchangeable cation capacity in a soil sample. Second, the dilute (0.1N) HCl extractant removes the dilute acid soluble phases in the soil simulating the longer-term weathering process of soil acidification. The amount of acid, added in an additional five sequential extracts to the sample previously extracted with the CaCl_2 , also totals to 2 milliequivalents per g of soil. This acidification dose was found adequate to remove up to 10% CaCO_3 , which soil phase is known to sequester ^{90}Sr as a coprecipitate in a non-cation exchangeable form (Spalding 1985). Thus, the combined CaCl_2 and HCl sequential leaching removes available ^{90}Sr from soil and separately measures both the cation exchangeable and carbonate-sequestered forms.

3.4.2.1 Pulverized ISV product

The leaching behavior of ^{90}Sr from the three samples of pulverized ISV product and from the starting contaminated soil is depicted in Fig. 3.15. For the untreated soil, approximately 60% of its contaminating ^{90}Sr was removed by the overall sequential leaching; most of this was removed by the exchangeable cation preliminary extractant. This is not very surprising in that ^{90}Sr exists primarily as an exchangeable cation in soil. The nature of the residual nonexchangeable nonextractable ^{90}Sr phase is also of interest to establish mechanisms for immobilization of ^{90}Sr in soil. By melting soil and pulverizing it back to a particle size similar to the pulverized starting soil, ISV converted the fraction of extractable ^{90}Sr to something considerably less than 1% (Fig. 3.15). The observation that the sequential leaching function levels out or plateaus in the later stages of leaching provides evidence that leaching has removed all or most of a given phase in the ISV product or soil; further sequential leaching would not seem very productive in providing stronger evidence for an immobilized phase in the material. Once a soil has been melted, ^{90}Sr becomes a glass structural element, just like Ca, and the small fraction which can be extracted probably resides on the glass powder surface where it can be either exchanged by Ca or dissolved in the dilute acid. In untreated

soil, ^{90}Sr resides on the cation exchange surface complex and may be adsorbed to surface minerals which are accessible to the extractants. Thus, the several order-of-magnitude improvement in the leaching behavior of ^{90}Sr on vitrification of soil appears to result from incorporation of the ^{90}Sr completely into the solid phase of the glass. Similar behavior would be anticipated for other radioactive contaminants by this same mechanism.

Fig. 3.15. Behavior of ^{90}Sr in sequential leaching with dilute CaCl_2 and HCl from ISV products and untreated soil.

It should be pointed out that the units for ^{90}Sr leaching in Fig. 3.15 are in fractional rather than activity units. Although the average activity of ^{90}Sr in the ISV products was 1460 dpm/g, the total activity in an ISV product is irrelevant to the leaching behavior. The activity of ^{90}Sr in an ISV product could be increased over a million-fold and that activity would exert no influence on the elemental and chemical composition of the ISV product; this phenomenon is due to the very high specific activity of ^{90}Sr which results in its trivial influence on the mass of element present. Thus, the leaching behavior in Fig. 3.15 would be expected and be applicable to ^{90}Sr at any activity level in ISV products made from much higher radioactive inventories in other WAG 7 seepage pits and trenches. Thus, use of fractional leaching behavior is directly applicable to evaluating potential release from ISV products at any total activity. Indeed, the cation exchange and acidification mechanisms could probably be modeled directly from the data in Fig. 3.15, groundwater quality, transport velocities, and in situ waste form surface area.

3.4.2.2. Pulverized versus minimally-disturbed in situ vitrification product

The behavior of 0.5 cm diameter particles of ISV product (intact chunks or solid) was compared to the <100 mesh pulverized ISV product in Fig. 3.15. Not pulverizing the ISV waste form produced an approximately order-of-magnitude decrease in the fraction of ^{90}Sr which could be extracted. Actually, the activity of ^{90}Sr in the extracts of the ISV solid were very close to the detection limit of the analytical method. Thus, modified tests to extract even larger chunks were deemed impractical to demonstrate even further reductions in the leaching of ^{90}Sr with decreased surface area per unit weight. As discussed previously, at the scale of the field waste form monolith, the surface area per unit weight of ISV product can increase by many orders of magnitude and the leaching behavior for constituent contaminants like ^{90}Sr improved accordingly. Thus, in addition to changing the nature of the ^{90}Sr species in soil, ISV attains much improvement in waste form performance simply due to the dramatic decrease in contaminated material surface area. As part of this surface area reduction process, the porosity of soil is decreased from a typical value of 50% to essentially 0% in the vitrified form.

The behavior of ^{137}Cs in the sequential leaching tests is in marked contrast to that of ^{90}Sr (Fig. 3.16). The vertical scale in Fig. 3.16 is identical to that used for ^{90}Sr in Fig. 3.15 so that the contrasting leaching behavior of the two dominant radionuclides in Pit 1 and WAG 7 can be easily compared by visual inspection. Unlike ^{90}Sr , all of the samples, including the starting untreated soil, exhibited less than 1% extractability of ^{137}Cs . The strong specific irreversible adsorption of ^{137}Cs to soil clays, particularly illites like those in Oak Ridge soils, makes ^{137}Cs virtually immobile in groundwater (Howorth and Sandalls 1987). Of course, if ^{137}Cs were the sole radioactive contaminant in the WAG 7 pits and trenches, there would be no need for any remediation. It is the ^{90}Sr contamination which drives the need for remediation of WAG 7 pits and trenches. However, the abundant contamination of these waste management units with both ^{90}Sr and ^{137}Cs requires that ^{137}Cs be considered in the overall ISV process and in the performance of the ISV waste form. As can be seen in Fig. 3.16, ^{137}Cs leaching behavior from the pulverized ISV products was virtually indistinguishable from its leaching behavior in the starting soil. At the very least, it can be concluded that there is no deterioration in the leaching properties of ^{137}Cs when it is converted into a glass waste form. Indeed, the leaching behavior of ISV solids or chunks exhibited about an order-of-magnitude improvement in the retention of ^{137}Cs compared to the pulverized samples; assay of ^{137}Cs in extracts of these ISV chunks was very close to the analytical limit of detection. The decrease in extractant accessible surface area is likely responsible for this improvement, and the large-scale in situ ISV product would be expected to perform proportionally better as its surface area per unit weight decreased.

In addition to the importance of the leaching behavior of ^{137}Cs and ^{90}Sr from ISV products and starting soil, other contaminant radionuclides can also be important. In Pit 1, the only other significant radionuclides found were ^{238}U (depleted uranium) and $^{239/240}\text{Pu}$. There was not sufficient activity of these isotopes in the limited volumes of sequential extracts to obtain a complete sequential leaching profile as was obtained for ^{90}Sr and ^{137}Cs . After completing the nondestructive assay of both ^{137}Cs and ^{90}Sr on the ten sequential product extracts from each of the five solid samples (three pulverized ISV products, one solid ISV product, and one pulverized starting soil), the ten (five CaCl_2 and five HCl) 20-mL extracts were combined into one 200-mL sample for analysis of U and Pu isotopes via radiochemical fractionation and subsequent α -particle spectroscopy. The procedures for uranium and plutonium analyses had been revised and improved since completion of the radiochemical analyses reported in the site characterization tasks (see Volume 2); Lockheed Martin Energy Systems, Analytical Services Organization, Technical Procedure ASO-MM-2 22012, Rev. 1,

Issued June 4, 1997, was employed for the present analyses. This variation in analytical procedure also argued for a repetition of the U and Pu analyses of the starting soil, at least for the sample selected for leach testing. Thus, in addition to U and Pu isotopic analyses of the various leaching extracts, the sample of the starting soil in addition to the ISV products were assayed for total activity of these isotopes via the revised method. The American Society for Testing Materials (ASTM) D-4503-86 method, lithium metaborate fusion and dissolution into nitric acid, was applied to these samples and the resulting analyses used for total U and Pu isotopic activities. Both lithium metaborate-nitric acid and various extract matrices were spiked with known amounts of National Institute of Standards and Technology (NIST, formerly National Bureau of Standards) traceable standard isotopic solutions of uranium or plutonium. All blind (to the analyst) spikes assayed were within 90-110% of their expected values lending a high degree of confidence in the reported results. Although isotopes of both U and Pu, other than the reported ^{238}U and $^{239/240}\text{Pu}$, were detected, only these two isotopes are discussed because of their dominance of the radioisotopic composition of the α -emitting species. Leaching results are reported as fractions of the total activity, calculated from the measured composition and the weighed quantity of solids employed in a particular leach test.

Leaching of ^{137}Cs From ISV Product and Starting Soil

Fig. 3.16. Behavior of ^{137}Cs in sequential leaching with dilute CaCl_2 and HCl from ISV products and untreated soil.

The behavior of ^{238}U and $^{239/240}\text{Pu}$ in the sequential leach test of untreated soil is depicted in the top right-hand segment of Fig. 3.17. Not unlike ^{90}Sr , major fractions of both ^{238}U and $^{239/240}\text{Pu}$ in untreated soil were extracted by the sequential leach: 98% of the ^{238}U and 24% of the $^{239/240}\text{Pu}$. Because of the necessity to combine all ten extracts for these analyses, these results do not directly support conclusions as to the form of these isotopes in the Pit 1 contaminated soil. However, it seems likely that the majority of both isotopes were removed by the dilute acid (final pH about 1.5) rather than the dilute CaCl_2 (average pH 5.8) because, in general, U and Pu are more soluble under acidic rather than neutral conditions. Both U and Pu tend to be adsorbed, particularly to hydrous iron and manganese oxides, as contaminants in soils rather than retained by cation exchange mechanisms. Regardless, the extractability of both ^{238}U and $^{239/240}\text{Pu}$ in the leaching sequence points out the potential for environmental mobility, particularly in the long term because of their very long half-lives. The transuranic isotopes in WAG 7 pits and trenches dominate the long term risks and potential doses from this area. After several hundred years, all of the fission products, mostly ^{90}Sr and ^{137}Cs , will have decayed to trivial activities, but ^{238}U and $^{239/240}\text{Pu}$ and other transuranic isotopes will still be present at virtually undiminished activities.

Conversion of the untreated soil to a pulverized ISV product dramatically reduced the extractability of ^{238}U and $^{239/240}\text{Pu}$ to levels below 1% of their total activities (central right-hand segment of Fig. 3.17). As was observed with ^{90}Sr and ^{137}Cs , both ^{238}U and $^{239/240}\text{Pu}$ are converted to uniformly distributed constituents of the glass matrix in the ISV product rather than surface adsorbed species susceptible and accessible to extractants. As a point of observation, all four radionuclides exhibited similar degrees of extractability from the pulverized ISV product, probably indicative of their uniform distribution throughout the glass matrix. When intact chunks (0.5 cm diameter) of ISV product were assayed in the sequential leach procedure, the fraction of ^{238}U and $^{239/240}\text{Pu}$ removed dropped an additional order-of-magnitude to less than 0.1% (lower right-hand segment of Fig. 3.17). This decrease in extractability is ascribed to a proportional decrease in surface area per unit weight with the increasing particle size. Again, in a field-scale waste form, leachability and extractability should be reduced even more dramatically.

3.4.3. Toxicity Characteristic Leaching Procedure—ISV Product Versus Untreated Soil

The same five samples of solid materials (three pulverized ISV products, one whole (0.5 cm diameter) ISV product, and one pulverized untreated soil) were subjected to the TCLP (ASTM D5233-92) test with minor modification. Due to the limited amounts of solid materials available for testing, the entire test was scaled back from the 100-g sample size to a 7-g sample size employing 140 mL of extraction fluid 1 (pH = 4.88). This yielded a sufficient volume of extract for assay of all four radioisotopes and analyses by ICPAES of elements. None of the organic species, listed in the TCLP, were analyzed because the ISV product, because of its high temperature formation, does not contain any organic species. Likewise, Hg, if it were present in a material being vitrified, would volatilize and not be present in the residual glass; hence, Hg was also not analyzed in the extracts of the ISV products. Several reagent blanks of the TCLP extract were spiked with known amounts (NTIS traceable) of elemental species; the blind spikes yielded analytical results within 90% of their expected values for all elements providing confidence in the overall analytical results.

3.4.3.1. Actual required test elements

The results of the eight hazardous elemental analyses in the TCLP are depicted in Fig. 3.18. The logarithmic vertical scale in Fig. 3.18 was employed so that the range of TCLP target concentrations for the eight test elements could be depicted in a visually distinguishable single graph. All of the ISV pulverized products yielded extract concentrations well below the TCLP target

Fig. 3.17. Leaching behavior of ^{90}Sr , ^{137}Cs , ^{238}U , and $^{239/240}\text{Pu}$ from ISV products and untreated soil in the Product Consistency Test (PCT), Toxicity Characteristic Leach Procedure (TCLP), and the CaCl_2/HCl sequential leaching procedure.

Fig. 3.18. Comparison of TCLP hazardous element test result and target concentrations for ISV products and untreated soil from Pit 1.

concentrations; many reported concentrations were below the analytical detection limits and are reported with a "<" symbol in Fig. 3.18. It should quickly be pointed out that the untreated soil sample from Pit 1 also exhibited test concentrations, all of which were below the target levels. Thus, from the perspective of hazardous elements, Pit 1 soil could not be classified as containing hazardous substances. But, equally important, its conversion to a vitreous waste form by ISV, did not change this nonhazardous characteristic as measured by the TCLP.

3.4.3.2. Radionuclides

Although the TCLP was developed as a test of hazardous substance leaching from solid waste if codisposed with municipal garbage, it has acquired common regulatory interpretation as a general test of whether a waste is hazardous or not. The slightly acidic sodium acetate/acetic acid extractant was envisioned to simulate organic acids from municipal garbage which could result in solubilization of hazardous species from other materials which these organic leachates might contact. Because of the common use of the TCLP as a hazardous substance classification tool, it was desired to determine the behavior of the Pit 1 radionuclides in the TCLP. Although radionuclide leaching behavior has little precedent for investigation by TCLP extraction, use of this common and familiar test was anticipated to provide some assurance in the interpretation of modified leaching behavior resulting from ISV treatment. Such radionuclide leaching results would also support the more detailed, but less frequently performed, sequential leaching procedure discussed above.

The results of the TCLP on the extraction of ^{90}Sr , ^{137}Cs , ^{238}U , and $^{239/240}\text{Pu}$ are depicted in Fig. 3.17. Significant fractions of both ^{90}Sr and ^{238}U (43 and 36%, respectively) were removed in the single TCLP extract of the starting untreated soil. However, neither ^{137}Cs nor $^{239/240}\text{Pu}$ exhibited significant removal by the TCLP extractant. All isotopes, except $^{239/240}\text{Pu}$ which had an extremely

low extract concentration to begin with, were markedly reduced in TCLP extractability in the pulverized ISV products and further reduced in the intact ISV product. The TCLP extractant is approximately 0.1N in sodium acetate and its use to extract soil would, thus, be expected to remove most of the exchangeable cation species. The 43% removal of ^{90}Sr from the Pit 1 soil is, thus, not surprising as this is approximately the same fraction of ^{90}Sr removed by the dilute CaCl_2 in the sequential leaching procedure discussed previously (Fig. 3.15). The behavior of ^{238}U is also not surprising because U tends to form strong carbonate and organic acid complexes and reagents like sodium citrate have been found to be efficient extractants for U-contaminated soils (Francis 1993). In conclusion, vitrification of radionuclide-contaminated soil significantly reduces the extractability of isotopes using the TCLP leach test. The sequential leaching test is more powerful than the TCL or PCT because greater fractions of all radionuclides were removed.

3.4.3.3. Comparison with previous in situ vitrification pilot-scale products

The TCLP has not been applied to evaluate ORNL ISV products from previous pilot-scale tests. However, the radioactive sludge sample, used in the 1991 pilot-scale test, was tested for TCLP hazardous elements and all eight elements were well below their target concentrations (Spalding et al. 1992). Thus, in that demonstration, the TCLP was not performed on the ISV product because it was assumed that a soil which did not exceed any of the TCLP element thresholds could not produce a waste form when vitrified which could exceed the TCLP limits. That conclusion is validated by the results of the present Pit 1 ISV product TCLP tests.

The sequential leaching procedure was first developed and applied to the ISV products from the 1991 radioactive ISV field demonstration (Spalding et al. 1992) as a tool to establish the improved leaching performance. Before and after ISV leaching results for both ^{90}Sr and ^{137}Cs for the 1991 ISV product were very similar to those presented above for the Pit 1 ISV product. The 1991 ISV product contained almost 30% limestone addition to the melt body in an attempt to simulate the ISV products from ORNL seepage trenches like WAG 7 trenches 5, 6, or 7, where limestone gravel fill was used. Pits 1-4 were operated as open trenches and, thus, did not contain limestone gravel fill; their ISV elemental compositions will be much lower in Ca and Mg due to the absence of limestone. In spite of the compositional differences in alkaline earth elements (Ca and Mg) in 1991 and present ISV products, leaching behavior of ^{90}Sr was essentially identical. It might have been expected that the 1991 ISV product, with its higher CaO/MgO content, would leach more ^{90}Sr than the 1996 Pit 1 ISV product; however, both ISV product compositions exhibited very low ^{90}Sr leachabilities indicating that ISV waste forms, from either the limestone-containing trenches or the limestone-absent pits, should be of identical and excellent environmental performance.

3.4.4. Product Consistency Test—ISV Product Versus Untreated Soil

The Product Consistency Test (PCT) was developed by Janzten and Bibler (1989) to evaluate the chemical durability of homogeneous and devitrified glasses by measuring the concentrations of the chemical species released from a crushed glass to a test solution. The specific test selected for ISV product evaluation was a crushed glass durability test for seven days using distilled water at 90°C in Teflon vessels. This test method has been used previously to evaluate the 1991 radioactive pilot-scale ISV demonstration product (Spalding et al. 1992) and ISV products made at the Richland site (Luey et al. 1992; Buelt et al. 1987) using the Material Characterization Center (MCC) -TP-19, Rev. 0 (Battelle Pacific Northwest Laboratory. 1986), a precursor to the PCT and almost identical hot-water extraction test. The PCT test data performed on the Pit 1 ISV product relates the resulting chemical durability of the Pit 1 ISV product to a large set of information on nuclear and other waste

glass characteristics. Additional PCT information was gathered on the starting, untreated Pit 1 soil and simulated ISV product and is reported in the site characterization task (see Volume 2).

3.4.4.1. Release of glass product-forming elements

The average chemical composition of the PCT 7-day extracts are listed in Table 3.9. The soil surface adsorbed elements (e.g., Ca and Mg) were significantly reduced in solubility from untreated soil to vitrified product. These elemental leaching changes probably reflect the improvement of most soil contaminants which are largely adsorbed on the soil surface, notably like ^{90}Sr . Mineral constituent elements (e.g., Al, Fe, Mn, and K) were largely unaffected to slightly increased in solubility by conversion from soil to ISV product; the soil's crystalline aluminosilicate minerals contain most of these elements and the change from crystalline to amorphous glass (ISV product) would be expected to increase their solubility. However, their increase in solubility is mostly due the change of ISV product from monolith to a <100 mesh powder by grinding.

To eliminate the effect of surface area of the test material on the interpretation of PCT results, the PCT results are normalized to sample surface area (i.e., mean mesh size) and to the material elemental composition. To obtain normalized values, the product of the blank-corrected concentration of an element found in the leachate and the volume of the leachate is divided by the product of the mass fraction of the element in the sample and the surface area per unit mass of the crushed sample particles used in the test.

The formula for normalizing is

$$NL_i = \frac{(C_{ij} - B_i) \times V_j}{f_i \times SA_j \times m_j} = \frac{(C_{ij} - B_i)}{f_i \times m_j \times (SA_j / V_j)}$$

where:

- NL_i = release of element i from specimen j in terms of the surface area,
- C_{ij} = concentration of element i observed in leachate from specimen j,
- B_i = concentration of element i observed in leachate from blank,
- V_j = initial volume of leachate in test vessel containing specimen j,
- f_i = average mass fraction of element i in the specimen = (mass fraction oxide in material) $\times$ (atomic weight metal in oxide) / (atomic weight of oxide),
- m_j = original mass of specimen j,
- SA_j = surface area per unit mass of specimen j.

Calculating the surface area per unit mass involves assuming a spherical particle of mean diameter between the sizes of the screen mesh openings. The openings of the sieves were 100 mesh = 0.150 mm and 200 mesh = 0.075 mm. Therefore, the mean diameter of particles passing a 100-mesh screen and retained on a 200-mesh screen is ~0.110 mm. A density of 2.7 g/cm³ for the ISV material was used in the calculation.

$$\text{Surface area (sphere)} = 4\pi r^2$$

$$\text{Volume (sphere)} = 4/3(\pi r^3)$$

So,

$$SA = \frac{4\pi r^2}{4/3\pi r^3 \times 2.7\text{g/cm}^3} = 0.02\text{m}^2/\text{g}$$

These normalized values for the key constituent matrix elements are presented in Fig. 3.19. All of the constituent element normalized values, except aluminum and silicon, were decreased by vitrifying Pit 1 soil (contrast Pit 1 soil with 1996 ISV product). Again, the calcium in Pit 1 soil, most of which is present as an exchangeable soil cation, was decreased about two orders-of-magnitude in inherent solubility by vitrification in which it is converted to a glass structural element. The 1996 ISV product was slightly more soluble than the 1991 radioactive pilot-scale demonstration ISV product, perhaps due to the crystalline nature of the 1991 product in contrast to the vitreous nature of the 1996 ISV product. In comparing the untreated Pit 1 soil to the ISV powder, the normalized release values eliminate the effect of surface area. But, the performance of the ISV waste form, particularly in the field, is greatly enhanced over the starting soil due, in great measure, to the decrease in the waste form surface area; evaluation of ISV waste form should encompass this additional important attribute rather than focus solely on the normalized values per se. In conclusion, the 1996 Pit 1 ISV product was chemically quite durable compared to the starting soil and was typical of many excellent vitreous waste compositions.

3.4.4.2. Release of Radionuclides

Due to the limited amount of ISV product available for analyses in the PCT, only the extractability of ^{90}Sr and ^{137}Cs were determined; these were performed nondestructively on the extracts prior to submission for elemental concentrations via ICPAES. Even though the PCT is merely a hot-water extraction test, over 12% of the ^{90}Sr was removed from untreated soil, similar to the behavior of soil calcium discussed above. In the final ISV product, whether pulverized or intact, the extractability of ^{90}Sr was decreased to only 0.02% of the total. The extractability of ^{137}Cs was also decreased significantly; however, only 0.1% of the ^{137}Cs was extractable from the starting soil. Based on the similar behavior of U and Pu to ^{137}Cs and ^{90}Sr in the TCLP and the sequential leaching procedure, it would be fair to conclude that both U and Pu isotopes would be decreased in PCT extractability similarly. Thus, in addition to the decrease in cation exchangeable and dilute acid soluble radionuclide contaminant phases in soil, ISV also, not surprisingly, greatly reduced the intrinsic water solubility of these radionuclides.

The equation for computing the normalized release values, given in the previous section, contains a combination of terms which is equivalent to the fraction of an element or radionuclide released during the PCT:

$$\text{Fraction Released} = \frac{(C_{ij} - B_i) \times V_j}{f_i \times m_j}$$

Thus, normalized release values for radionuclides, mathematically equivalent to those for the elements, can be computed as follows:

$$NL_j = \frac{\text{Fraction Released}}{SA_j}$$

Table 3.9. Element concentrations in PCT extracts of ISV Products and Starting Soil

Element	Average PCT Analytical Result (mg/L)		
	Pit 1 Soil	ISV Powder	ISV Solid
Aluminum	0.24	4.6	2.9
Antimony	<0.10	<0.10	<0.10
Arsenic	<0.10	<0.10	<0.10
Barium	0.022	0.0044	0.0046
Beryllium	<0.00060	<0.00060	<0.00060
Cadmium	<0.0060	<0.0060	<0.0060
Calcium	67	3.9	2.7
Chromium	<0.020	<0.020	<0.020
Cobalt	<0.010	<0.010	<0.010
Copper	0.017	0.012	<0.0080
Iron	0.022	0.111	0.031
Lead	<0.10	<0.10	<0.10
Lithium	0.0095	0.093	<0.0080
Magnesium	3.8	0.660	0.650
Manganese	0.029	0.0036	0.0051
Molybdenum	<0.020	<0.020	<0.020
Nickel	<0.020	<0.020	<0.020
Phosphorus	<0.40	0.51	0.43
Potassium	8.6	6.0	4.3
Selenium	<0.10	<0.10	<0.10
Silicon	7.4	25.4	12.6
Silver	<0.012	<0.012	<0.012
Sodium	8.0	5.6	2.3
Titanium	<0.0060	0.011	<0.0060
Vanadium	<0.010	0.019	<0.010
Zinc	0.080	0.082	0.061

using the measured release fractions and the same SA_v value ($0.02 \text{ m}^2/\text{g}$) employed to compute the elemental normalized release values. The radionuclide normalized releases can then be directly compared with the behavior of other specific elements in the glass. The behavior of both ^{90}Sr and ^{137}Cs is compared to that of elemental Sr, Ca, and K in the pulverized ISV product and starting soil (Fig. 3.20). In the starting soil, ^{90}Sr was about an order-of-magnitude more soluble than elemental Sr; elemental Sr would be expected to be rather uniformly distributed as a trace constituent element in many soil minerals whereas ^{90}Sr would be largely present as an exchangeable cation on the surface of soil particles. In the soil, ^{137}Cs was much less extractable than soil K demonstrating its strong specific adsorption to soil clay minerals discussed in the site characterization report (Volume 2). After conversion to ISV product, ^{90}Sr extractability was greatly reduced even more markedly than

elemental Sr and Ca although these were also significantly reduced in extractability. Both ^{137}Cs and K exhibited only minor reductions in extractability compared to soil. The overall conclusion is supported that contaminants like ^{90}Sr , and presumably U and Pu, manifest these much reduced extractabilities from ISV products because they become uniformly distributed within the resulting glass matrix compared to their starting condition as surface adsorbed contaminants.

Fig. 3.19. Comparison of normalized elemental releases during the product consistency test of ISV products, Pit 1 untreated soil, and other wastes glasses.

3.4.4.3. Release of trace elements

Relatively few trace elements in the Pit 1 soil were found above detection limits in the PCT extracts (Table 3.9). Comparing pulverized ISV product to soil, elements like Ba and Cu were significantly decreased in extractable concentrations whereas Zn was relatively unaffected. A significant increase in the extractability of Fe was noted. This increase probably resulted from the conversion during ISV of the soil's ferric iron species to the reduced ferrous species in the ISV product; the Fe^{+2} is inherently more soluble than Fe^{+3} in the starting soil. More supportive evidence for this change in oxidation state of iron was noted in the increase in weight of the ISV product on ignition and the associated change in color from green to red; FeO increases about 11% in weight as it is oxidized to Fe_2O_3 during ignition.

Fig. 3.20. Normalized releases of ⁹⁰Sr and ¹³⁷Cs from ISV product and soil in the PCT compared with similarly behaving elements.

3.4.4.4. Comparison of pulverized and minimally-disturbed isv product

The effect of pulverizing ISV product on the increase in extractability of most elements can be best observed in the PCT extract concentrations (Table 3.9). Readily soluble elements (Ca, K, and Na) all increase in extractability from intact to pulverized ISV product. Similar increases in extractability from pulverized ISV product were observed for major constituent elements (Al, Si, and Fe). The normalized releases of the intact ISV product were not computed due to the very irregular shape of the 2-3 particles employed. However, because this is the same material as the ISV powder, it would be expected to show identical values when normalized for the decrease in surface area per unit weight of their larger diameter (0.5 cm) particles.

The normalized release values obtained from the PCT can be quite useful in estimating potential releases to groundwater of elements and particularly radionuclides from the more monolithic field ISV product. The sample for the PCT is pulverized into a narrow particle size distribution (100-200 mesh) with its mean particle diameter of 0.011 cm. As discussed previously, spherical particles or powders of such size have a surface area of 200 cm²/g of material. For comparison, a cooled ISV melt body can be viewed as a single spherical particle with a typical diameter of 500 cm, at a density of 2.7 g/cm³, and, thus, a mass of 177 Mg. Such a large "particle" or spherical melt body would have a surface area of only 0.0044 cm²/g, a considerable reduction compared to the typical PCT test powder. Using a representative value of normalized release (i.e., 0.01 g/m²) for an element or radionuclide (Figs. 3.19 and 3.20), the released fraction can be

calculated for different surface areas using the equations in Sect. 3.4.4.2. The behavior of surface area and the solubilized or released fraction of a radionuclide or element from various particle diameters is depicted in Fig. 3.21. The conditions of the PCT are annotated on Fig. 3.21 at a typical measured radionuclide fractional release of about 0.004; the fractional releases of ^{90}Sr and ^{137}Cs are similar enough to be considered as a single value for this assessment. The particle size and surface area of the above-described ISV monolith are also annotated in Fig. 3.21; for this ISV body, the fractional release of radionuclides is reduced to well below 10^{-6} of its total inventory or by more than four orders-of-magnitude to that observed in the PCT! Also depicted in Fig. 3.21, is a typical soil material with its greater surface area (1,000 to 10,000 cm^2/g) and smaller mean particle size (<0.001 cm); for such a soil powder, release fractions between 1 and 10% would be expected, even if the soil material were chemically identical to pulverized ISV product. Thus, the benefit of an ISV monolith, compared to soil, exceeds a five order-of-magnitude reduction in radionuclide release fraction! This reduction in surface area is the major mechanism for the improvement in waste form performance mediated by vitrification of contaminated soil.

Fig. 3.21. Fractional release of radionuclides from soil, pulverized ISV product, and a field ISV monolith calculated from PCT normalized release values.

A common concern with such an assessment of the field performance of ISV waste forms is that final cooled ISV melt bodies are not spherical and, thus, do not exhibit the minimal surface area per unit weight of such geometries. Geometrical representation of ISV melt bodies as other forms (e.g., cone sections, cylinders, or pear-shaped bodies) does not change the estimated surface area per unit mass by more than a few percent and, thus, would not be expected to significantly affect contaminant fractional release estimates. More significant is the potential of fracturing of the melt body during cooling or subsequent weathering to increase the surface area exposed to groundwater and, thus, increase the fractional release of radionuclides or other contaminants of concern. The normalized release values can be used to assess the influence of fracturing on contaminant releases

if a method can be accepted to calculate the increase in surface area of the melt body per fracture. Considering the same 500 cm diameter melt body, described above, the most conservative yet mathematically tractable method to fracture it would be to bisect the sphere with a planar fracture; this planar fracture is the most conservative in that it yields the largest increase in surface area per fracture. This planar fracturing model can be repeated for any number of fractures along a common strike resulting in a prediction of geometrical surface area/unit mass as a function of number of bisecting fractures (Fig. 3.22). It can be seen from Fig. 3.22 that to change a monolithic ISV waste body (i.e., no fractures) to one with a surface area equivalent to a pulverized PCT ISV powder (i.e., 200 cm²/g), would require over 100,000 fractures through the monolith. A more useful parameter than total number of fractures would be the fracture density (i.e., number per unit length) in the ISV waste body. Fracture density is also presented in Fig. 3.22 by computing the number of planar fractures divided by the body diameter; this would be the "observed" fracture density in a hypothetical core through the waste body at any angle other than the common strike of the assumed bisecting planes. Over 200 fractures/cm of core would be required for the melt body to attain a surface area/mass equivalent to the PCT powder, i.e. 200 cm²/g. This relationship between fracture density and total waste form surface area can also be used to assess the importance of the observed fracture density in cores from ISV bodies. Although the Pit 1 melt body has not been cored, previous core sampling of the ISV products in the 1987 and 1991 pilot-scale melts frequently yielded monolithic core segments up to 50 cm in length. Thus, those melt bodies probably exhibited a maximum fracture density of only single digit values per meter. The overall effect on melt body surface area and, thus, the potential increase in fractional contaminant release would be rather insignificant. If the Pit 1 ISV melt body is sampled by coring at some future time, the observed incidence of fractures should be quantified but interpreted carefully. The expulsion of an estimated 20% of the molten body and associated rapid cooling, as groundwater returned, may have introduced unusually large stresses in the rapidly cooled glass; this may manifest itself in a comparatively high fracture density, compared to more normal ISV bodies, which cool significantly slower and, thus, avoid much rapid-cooling stress.

Fig. 3.22. Effect of fracturing of a hypothetical spherical ISV waste body on surface area per unit mass and resulting fracture density.

3.4.4.5. Comparison with other waste glasses and waste forms

Also in Fig. 3.19, the normalized elemental releases for two other vitrified waste forms are presented: the ISV product from the Hanford 116-B crib demonstration (Luey et al 1992) and a high-level waste glass from West Valley Nuclear Services (WVNS). Additional high-level waste glass PCT values are available (Buel et al. 1987; and K. A. Olsen, unpublished data, personal communication to G. K. Jacobs) and show similar normalized values. ISV products are generally much more durable than high-level waste glasses because ISV inherently avoids the inherent waste-loading effects associated with high-level waste. Basically, low-level radioactive ISV products from ORNL WAG 7 seepage pits and trenches have virtually no waste loading effects because they are prepared from contaminated soils where the radioactive contaminants make no contribution to the vitreous mass composition. In addition, nuclear waste glasses tend to have significant amounts of sodium, due to inherent waste loading and to amendments, in order to process them at a lower temperatures than ISV products; the concentration of sodium in glass is, in general, inversely proportional to the glass's durability as measured by aqueous extraction.

3.5. PUBLIC ACCEPTANCE

As described in the project work plan (Spalding 1994a), one of the major objectives of this treatability study was to obtain general public acceptance in the safety, benefits, and overall technical approach of ISV for remediation of the WAG 7 seepage pits and trenches and other Oak Ridge waste management units. The solicitation of public acceptance may be more difficult in the future because of the melt expulsion event. However, both the insignificant environmental impact of the melt expulsion and the excellence of the ISV waste form, should be compelling arguments for future or continued ISV operations in Oak Ridge.

Prior to initiating field activities at ORNL seepage Pit 1, a four-page flier was prepared describing the site needs, ISV technology and its capabilities, and the goals for the treatability study; the flier was oriented for a nontechnical audience. In addition to the project flier, a DOE Fact Sheet on the project was prepared. In addition to making these flyers and the fact sheets available at various technical meetings, they were made available during public meetings conducted by DOE's Environmental Restoration and Waste Management Division when remedial actions were proposed or discussed for public comment. Poster display material supplemented these fliers and gratis samples of the nonhazardous, nonradioactive ISV product from the 1987 test at ORNL were made available to those interested. The fliers and fact sheets were also made available, along with sample materials, at the Information Resource Center in Oak Ridge. Previously published materials and ISV reports were made available to individuals upon request, and their availability and points of contact were advertised in the flier and fact sheet; numerous group briefings and site tours were made to interested organizations or groups upon request. For group briefings and educational presentations, a beaker-scale ISV demonstration, using 110-V single-phase power, was developed to aid public appreciation of the inherent simplicity of the ISV process and the modest levels of electricity required to melt soil by ISV; the common public impression that regional "brownouts" and, thus, high costs would result if ISV were performed at actual scale can be overcome with these demonstration minimelts. As in previous demonstrations, provisions were made for visitors and press coverage during actual ISV field operations. An updated flier was prepared for these site tours describing the site, ISV technology, and the goals of the study. A detailed press and public visitation day was planned during operations of the second of the three planned melts at Pit 1. In addition, various releases of progress information and interim reports were made, with copies distributed to both the DOE technical community and information newsletters. For example, the Pit 1 project was

featured along with other Oak Ridge environmental restoration projects in the special Oak Ridge issue of the Technical Information Exchange (TIE) newsletter (Volume 43, Fall/Winter 1995).

3.5.1. Regulatory Agency Issues and Concerns

The major input of both the U.S. Environmental Protection Agency, Region IV, and the State of Tennessee Department of Environment and Conservation were made in comments to the draft project work plan. Although the final work plan (Spalding 1994a) incorporated significant responses to many minor comments, which will not be reiterated here, a review of the major comments would be useful to future ISV planning. First, it was pointed out that, although the test was being conducted as an on-site Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) action and did not require formal National Emission Standard for Hazardous Air Pollutant (NESHAP) approval (40 CFR 61, Part H), the treatability study must comply with the substantive requirements of NESHAP. The ORNL Office of Environmental Compliance reviewed the project and carried out the required sampling and monitoring of ISV air emissions following the melt expulsion to comply with the overall site NESHAP standard, i.e., 10 mrem/yr, and monitoring requirements. Secondly, it was stressed that the data generated from this study support the evaluation of short term effectiveness of the technology including potential impacts to workers, the community, and the environment. This final treatability study report, hopefully, fulfills most of this recommendation. Thirdly, it was recommended the DOE consider treating the entire trench during the ISV study in that it would be cost effective to treat the entire trench while the equipment and personnel were available. Additional funds were identified for the treatment of the entire trench. Unfortunately, following the melt expulsion, the scope of the project became too large for available budgets and would have required costly and substantive changes in procedures, equipment, and technical approach. Thus, plans for additional melts at Pit 1 were suspended.

After the melt expulsion, several questions were posed to DOE by the regulatory agencies through the regulatory working group. A briefing to the regulators was requested for a meeting on June 3, 1996, to address 1) information obtained in both the site radiological assessment and the assessment of potential equipment damage, 2) potential and/or probable causes of the unexpected expulsion of steam and/or molten glass, and 3) impacts to the ISV project including both schedule effects and funding issues. The information, available at the time, was presented. Final discussion of all these points is contained in the present report.

3.5.2. Department of Energy Issues - Cost, Safety, Effectiveness, and Public Relations

In addition to the normal programmatic management and oversight by DOE, the ISV project had a well defined readiness review process with a DOE Readiness Review Board whose approval was required prior to initiation of ISV melting operations at Pit 1 (ORNL/ER-294, May 1995). Readiness review board members (a total of eight individuals had major involvement) provided substantive and useful comments on many aspects of the project. The LMES readiness review team chairman, L. S. Hawk, maintained a detailed living document of each readiness review checklist item, as well as new questions or issues raised and the project member's response to close out each issue or question. This huge volume of documentation will not be reiterated, or even summarized, here. Future ISV technology planners can access all of it in the project files available from the Environmental Restoration Document Management Center. When restart of ISV operations at ORNL Pit 1 was envisioned in later 1996 or early 1997, the DOE readiness review board produced a list of core requirements for assessment prior to approval of restart ISV operations; these are described in Sect. 3.5.6.

3.5.3. Questions Raised by the Oak Ridge Environmental Peace Alliance

After the melt expulsion of April 21, 1996, several questions, issues, and proposed actions were directed in letters to DOE by Oak Ridge Environmental Peace Alliance (OREPA) members. Although these specific questions and concerns are not necessarily representative of majority public concerns, they are pertinent questions which were addressed by the project technical team. OREPA members were given a tour of the Pit 1 site by DOE on September 13, 1996, and project personnel answered oral questions; technical reports of the melt expulsion incident were then delivered to OREPA to address many of the technical issues. The following is a summary of written concerns raised by OREPA and the project's replies. This will be of benefit to planning future ISV projects in Oak Ridge or elsewhere and is presented here for that reason. The questions and replies, unedited except for minor typos, were as follows:

1. How big is the new demonstration area? What levels of radioactivity are in this area?

There is really no new demonstration area. We will be performing two additional "settings" of ISV melts which we plan to overlap with the first residual melt block of April 1996 at ORNL Pit 1. Each of these new "settings" is planned to be about 700 tons with the final dimensions of a cylinder 30 ft in diameter and approximately 10 ft deep. Each of these overlapping "settings" should contain about 18 curies of radioactivity, 98% of which will be cesium-137 and 2% strontium-90 with trace activities of uranium-238 and plutonium-239 and 240. ORNL Pit 1 was an open trench approximately 90 feet long, 22 ft wide, and 25 ft deep as characterized in 1994.

2. What's being done to prevent a "burp" this time? How will they avoid hitting groundwater?

To prevent a burp in our subsequent ISV melts, we are incorporating several techniques into our operational procedures. We plan to monitor the performance of each of these techniques during the next melt to determine its effectiveness and need for implementation in subsequent operations. We cannot guarantee with absolute assurance that another "burp" will not occur in any subsequent melts. This is our most important lesson learned from the recent incident. Thus, in addition to incorporating what we believe to be burp preventing techniques, we are modifying our equipment and procedures to endure a similar "burp" without damage to equipment or injury to personnel and minimal interruption to ISV operations.

Techniques to decrease the probability of a recurrence of a "burp" are several. First, we are pumping down the water table in the area so that the elevation of groundwater will be several feet below the target depth for ISV. Both the water table drawdown operations and associated water table elevation monitoring will be continued during ISV operations. Second, we plan to install vents from the zone beneath the growing melt body to the interior of the off-gas collection hood and, thus, prevent the buildup of submelt pressure to the point of initiating a burp. Both flow and temperature within several of these vent pipes will be monitored continuously to verify their performance and utility. Third, we plan to regulate electrical power to the melt in response to submelt gas pressure, off-gas hood pressure (vacuum) changes, electrical power fluctuations, and melt body surface bubbling activity. All of these melt characteristics have been implicated or suggested as "indicators" of subsequent burping activity. (See Sect. 3.6.3 for further details.)

3. What will happen to treated soils after the demonstration? Is this an interim or final stage?

After this demonstration, the resulting melted soil volume will be left in place. The potential contamination of recharging groundwater will be monitored to determine "in situ" waste form performance. This monitoring data will determine the environmental acceptability of leaving the ISV product as is. It should be noted that ISV of contaminated soil does not necessarily require that the waste form remain where it was made. Subsequent removal and redispersion, although it is hoped to be unnecessary, is quite technically feasible. Indeed, exhumation of ISV product would be inherently much safer than exhumation of untreated soil.

4. If this demonstration is successful will other areas be treated without going through a National Environmental Policy Act (NEPA) process?

If this demonstration is successful, ISV remediation of other contaminated areas will be advocated following the CERCLA process. The U.S. DOE has a secretarial policy (June 1994) which relies on the CERCLA process to address NEPA values. Public involvement procedures, as stipulated in that secretarial policy, will be followed. The present ISV treatability study has been undertaken to obtain the technical information on which to evaluate the potential environmental impacts of future ISV remedial actions or records of decisions.

5. In the previous demonstration would the hood lifting up negate the effectiveness of the negative pressure, off-gas and filters? Would the emissions have by-passed the system?

Yes, the hood lifting off the ground surface does negate the effectiveness of the negative pressure confinement of the ISV off-gas. It is the positive pressure of the rapidly heated off-gas within which causes the hood to lift from the ground. During the interval of hood lifting or whenever positive pressure exists within the hood, uncontrolled emissions do occur from the ISV off-gas. However, when the hood returns to the ground surface within seconds, negative pressure confinement of the off-gas is reestablished. The environmental impact of such a situation is driven by the concentration of contaminant in the off-gas and the total volume of off-gas which escapes during the interval of hood lifting. However, the inherently low volatility of radionuclides in the ISV process typically results in extremely low activities in the off-gas and, consequently, in the extremely low uncontrolled discharge (as was measured during the April 1996 ISV burp) and environmental impacts off or on site.

6. What is the mobile vitrification unit and how is it used? What are the plans for its use? Has this transportable technology been done at Oak Ridge before?

The mobile vitrification unit is a technology and project completely independent of the ISV project. ISV project personnel are not adequately aware of that project's plans or history to respond adequately to the question about its past or future use in Oak Ridge. The question will be addressed in later action.

7. At what point do the engineers admit that the high moisture content of the soil and the high water table make in-situ vitrification a questionable, if not incompatible technology at Oak Ridge?

If the measures, which are planned for implementation during the resumed ISV operations at ORNL Pit 1, fail to prevent another burp incident, then the project personnel will admit that ISV on high moisture soils within a watertable cannot be performed, nor should be advocated, without rigorous and rather thorough drying of the soil prior to ISV. Performing ISV on a dry

soil presents little challenge and very little risk of burping during melting. The purpose of assuming the risk of addressing the moisture challenge of saturated soil conditions like those frequent in Oak Ridge is to establish whether or not ISV can be performed safely without the additional costs and effort of completely drying the soil. The watertable suppression, which is planned for the resumed operations at ORNL Pit 1, should remove potentially mobile gravitational water in the soil leaving only unsaturated bound soil water with which ISV technology has frequently and successfully dealt in recent commercial applications.

8. Does underground flight of contaminants occur? How is testing accomplished beneath the vitrified soil to ensure that migration of contaminants has not occurred?

We assume underground flight to mean the migration or movement of contaminants away from the growing melt body, i.e., the extreme heat of the molten body drives contaminants away from their starting configuration or distribution. Although this concept has been hypothesized for some time relative to vitrification, in situ or otherwise, there is no evidence that the phenomena occurs to any measurable extent. Previous ISV studies in Oak Ridge have indicated quantitative capture of radioactive contaminants in the ISV product or its off-gas. Sampling of soils beneath ISV product, after core drilling to obtain access, has not detected radionuclides in thermally unaltered soil beyond background activities. The most volatile of chemical species during ISV, i.e., water, is collected by the off-gas cooling system and excess is not driven into the surrounding soil.

9. How can DOE use a categorical exclusion from 1990 to do a new area?

The use of ISV at a "new" area is not considered a new activity or process. It is a repetition of a test activity, albeit at larger scale than the 1991 pilot-scale ISV test and addressing a real "unmanipulated field" contamination scenario, but for the same purpose, i.e., the collection of key information. The activity at ORNL is not considered a remedial action but a field-scale treatability study as defined under CERCLA guidelines. ORNL Pit 1 has quite a limited inventory of radionuclides (about 39 curies) compared to the other six seepage pits and trenches which were used between 1952 and 1966 to dispose of over a million curies of mixed fission products in liquid waste. Pit 1 was actually the field-scale test of the concept of liquid radioactive waste disposal in shallow pits and, perhaps appropriately, is being used as the test site for a promising remediation technology for the much larger remediation challenge of the ORNL seepage pits and trenches.

10. What radioactive or hazardous contaminants abide in the water vapor?

Water vapor, which is the major constituent of ISV off-gas, can contain a few radioactive or hazardous constituents in low concentrations. The one of most concern in ISV application to the seepage pits and trenches is cesium-137, although it is only slightly volatile (99.998% of it remains within the ISV melt body). However, due to the relatively large inventory of cesium-137 in these pits and trenches, the processing of off-gas has been designed prudently. Off-gas is subjected to filtration and scrubbing prior to release to the atmosphere and, thus, no detectable activity was released by the controlled and monitored emissions from the equipment. Some hazardous elements, such as lead, mercury, cadmium, and zinc, are somewhat volatile during soil melting and readily measurable fractions end up in the off-gas scrubbing waste solution or on the off-gas filters. Although these elements are present in Pit 1 soil only at their natural soil background concentration, ISV resulted in detectable concentrations in the off-gas scrub waste. However, the off-gas scrub solution was found not to be hazardous using the

Environmental Protection Agency's (EPA's) toxicity characteristic leaching procedure. Nor was any radioactivity in the waste solutions.

Subsequent to the site tour, additional written questions were received from OREPA to which project personnel provided additional replies as follows:

1. Technical report, p. 4 [note: page numbers refer to an earlier draft of ORNL/ER-374/R1 (ESERP 1996b) and may not correspond exactly with the final revised version]: how soon was the power to the off-gas system turned off after the expulsion? P. 4 says the shift engineer hit the emergency electrode power switch ten minutes before the expulsion. Was the off-gas system turned off then, too?

P. 4 of the report does not say the shift engineer hit the emergency electrode power switch ten minutes before the expulsion. It says, "The shift engineer also reported some qualitative fluctuations in the visual displays of the process amperage and voltage about 10 min before the melt expulsion incident." The next sentence reports that the shift engineer hit the emergency electrode power switch when he felt a slight tremor which was a few seconds into the event. The emergency electrode power switch only controls power to the electrodes; all other systems, including the off-gas collection and processing system kept functioning until they were turned off some time later. The melt expulsion event occurred at 6:12pm and all power to the ISV equipment, including the off-gas system, was turned off at about 6:30pm in anticipation of fire fighting actions which were slightly later determined to be unnecessary. Thus, the off-gas system remained on at least 18 minutes after the event.

2. Technical report, pp. 9-10 The Graseby-Andersen paper tape sampler would yield the best representative sample of the off-gas released. This sampler had been malfunctioning frequently" prior to the melt expulsion. Condensation caused the paper tape top "fall apart regularly." The sampler was last checked 80 minutes before the expulsion.

The ISV off-gas sampler on the hood and the one on the off-gas line sampling just prior to the HEPA prefilters, were working fine at, before, and after the incident. Yes, these tape samplers had been giving a lot of trouble, off and on, over the previous 20 days for just the reasons cited. Their performance was checked and repaired, if necessary, four times per 8-hr shift which is documented in the project data collection sheets. We were fortunate to have the sampler functioning at the time of the event. The functioning had been checked at 5:06, as noted on the data log; the sampler was set to advance one unit of length or one spot every 20 min. We actually observed five sample spots, the tape is discolored by the particulates removed by the filter, when we retrieved the tape the day after the event. These spots would thus have been initiated at 5:06pm, 5:26pm, 5:46pm, 6:06pm, and 6:26pm with the second to last spot covering the event period and the last spot verifying that the sampler was still functional after the event although the power was shut off at about 6:30pm, as discussed above, yielding only a partial sample for the last spot. The critical sample, which covered the interval of the hood lift, was only slightly elevated in radioactivity relative to the samples immediately preceding the event. Obviously, we did not go into all this detail in the report because that level of detail about each reported analyses would make the report unnecessarily very long. We are quite confident that we have a good representative sample of the off-gas which escaped during the hood lifting event.

3. Report that hair dryer (p.35) was positioned to blow across sampling tape to dry it. Would this compromise the sample collection?

We do not believe the hair dryer compromised the sample(s). The hair dryer was actually aimed mostly at the metallic housing which clamped around the tape where the current sample is being taken. By heating the metal housing, we were oftentimes able to prevent moisture in the off-gas from condensing on the tape and housing. When a sample is changed by the sampler, the housing opens slightly (like lifting a paper weight slightly) and the paper tape is advanced by pulling onto a reel like a tape recorder. The particulate seems pretty well adhered to or penetrating into the tape as we cannot remove it by scraping in the laboratory. We actually cut the tape into segments and counted the segments in low-background conditions in the laboratory in order to achieve a given uncertainty in the count rate. The assay is entirely nondestructive and the samples are still available for additional or repeated radioactive counting.

4. Report that there was question whether the sampler could adequately sample the volume of air. Was this even more of a problem when the volume increased dramatically (the event)?

The discussion on p.11, relative to the representativeness of the critical sample taken during the interval of the event, was intended to point to the conservativeness of assuming that this sample is representative of the off-gas which escaped. The sampler pulls gas through the tape at a rate fixed by a vacuum pump at the end of its processing train. If the intake pressure were to increase significantly (as during the pressurization event), then the actual volume of gas pulled through would be increased. By assuming that the activity on the tape sample was drawn at the low fixed rate, the resulting calculated activity per unit volume of gas would be too high if flow were actually increased by a pressure pulse. Thus, we conclude that the reported activity per unit volume of gas may be either correct or too high but definitely not too low! the reported releases may be lower than we reported due to this uncertainty in activity concentration in the off-gas. That is what is meant by conservative.

5. Report that the "last spot" on the paper sampler (p.13,2.2.5.4) reading was used to estimate releases - does this mean the paper tape was destroyed at some point in the event by the heat/force/whatever?

No, the tape was not destroyed; nor did it appear damaged in any way. They are still available for inspection or further analyses. As discussed in the reply to item 2 (above), the sampler was turned off at 6:30 when all electrical power was switched off. We refer to the last sample meaning the last complete sample (20 min interval). The paper tape sampler advanced one position about 6:26 +/- 1 min and the power was terminated to the sampler at 6:30 +/- 2 min. Thus, the last partial spot could have collected off-gas for as long as 7 min or as short as 1 min; this partial sample was not used in any analyses. Only the last full spot for a full 20 min sample, taken over the interval including the event, was used.

6. The release estimates calculate what it would take to lift the 15,000 pound hood twelve inches for 10 seconds (as per eyewitness report) in order to estimate how much gas was released. This would be the lowest possible number for release. The highest bound would be the amount of pressure required to lift the hood and the transportation frame, since the frame constrained the hood from rising further than twelve inches.

Actually, the calculation of the volume of off-gas released (pp. 12-13) was not made under the assumption of the equivalent confining pressure of the hood alone (i.e., about 1.15 in. of water column for 15,000 lb hood) but at equivalent confining pressure (10 in. water column) for the whole 130,000 lb hood and superstructure. Although the pressure estimate was made for another reason (p. 12, 2.2.5.2, 3rd line down), an assumed pressure of 10 in. of water column was actually used in the calculation. This was done because it was the highest observed ISV off-gas pressurization observed in previous operations as referenced in the report. Thus, the estimate of the volume of off-gas released appears to be conservative, i.e., it is based on a greater than probable confining pressure. The method of the calculation of the released volume is a bit complicated, but we believe it to be conservative. We have tried to formulate the worst-possible case for the size of the uncontrolled release.

7. Does the report presume that all angel hair and "glob," some of which were apparently found 300 feet from the hood (exec sum, vxii, paragraph 5), were collected? Where does this certainty come from?

The report does not presume that all the angel hair was cleaned up. The report states only, "Subsequent cleanup efforts revealed a total of only a few pounds of these contaminated fibers at the site." From the areas clear of plants, i.e., the extensive gravel-covered site area, probably "all" of the fibers were cleaned up. Extensive vacuuming and radioactive surveying of these graveled areas was carried out by personnel over the three-weeks following the event. Undoubtedly there may be small fibers remaining in the area, particularly off the graveled areas. However, the area, except in the immediate vicinity of the still contaminated hood, has been delisted as a contamination area.

Other issues

8. ES&H report says future plans must consider the possibility of an MEE similar to or greater than the April 21 event (p.15, 3.1). The technical report says the April 21 event becomes the DBE. How is DOE reconciling these two opinions? How large of an MEE is possible? How large is the proposed DBE for restart?

The technical report (p. xviii, paragraph 5, sentence 4) only states that "the design basis for all future ISV operations must be a melt expulsion event similar to that experienced on April 21, 1996." By "similar" we do not mean size but only in character, i.e., that an expulsion of molten product of some, as yet, undetermined amount can occur during ISV operations. The project team is pursuing the definition of a maximum credible event to be the design basis for hood repair, modifications, and personnel operating procedures; this work is still in progress and will be available when it is completed. However, it is quite clear that a design basis event will be considerably larger than the April event. Hopefully, this will lead to a redesign which will prevent glass particle release, hood damage, and personnel injury under all future ISV operations.

9. ES&H report, p.13, first paragraph, discusses a series of items which were neglected. What steps have been taken to assure these "lessons learned" are not repeated in the future?

Practically all of the referenced discussion concerns documentation and review of change control for ISV equipment and procedures. Although all of the implemented changes in the ISV operations at Pit 1 were documented, the changes were not approved by anyone independent of the project team. Nothing was particularly wrong or in violation of DOE conduct of

operations with this method of operation. Now, that a melt expulsion event becomes the design basis for all future ISV operations, any change to equipment or procedure which could even remotely affect personnel safety will be subject to review of the independent personnel who approve, for example, the Health and Safety Plan. The identification of equipment and procedures, which will require review prior to change control, will be spelled out in the revised test plan and approved by the readiness review team and board prior to restart of ISV operations.

10. The vent pipes, considered essential for off-gas venting, did not extend to the depth of the melt. It would appear that this is a contributor to the event. (ES&H report, p.10,2.7.1). How do project personnel justify this lapse?

The vent pipes were not considered "essential" for off-gas venting. Both the pipes and the entire concept of venting were under test during the first melt at Pit 1. Vent pipes have never been used in an ISV test previously, at any scale. They were neither defined as safety systems nor even safety class items. At this point, due to the inability to move the damaged hood which is necessary to gain access to the residual vent pipes, it is not clear whether the vent pipes functioned at all during ISV operations, much less whether the melt expulsion was affected by their absence from the region at the bottom of the melt. The concept of providing conduit to the hood or short circuit for any steam generated beneath the melt body seems worthy of pursuit. Several modeling and design calculations are underway to more thoroughly evaluate their potential effectiveness in preventing ISV melt expulsions.

11. Does Pit 1 contain only radioactive wastes, or does it also contain hazardous wastes from the decontamination drainage? Would this not be mixed waste? Can DOE provide a statement with documentation about the precise nature of these wastes?

More details of the nature of the wastes in ORNL Pit 1 will be made available when a Pit 1 site characterization is issued in the next few months. No hazardous waste constituents or characteristics have been observed in the many samples of soil and water taken from Pit 1 to date. This may be a characteristic unique to Pit 1, with its limited use history; other seepage pits and trenches will likely contain mixed waste contaminants. ISV technology is certainly appropriate for remediating hazardous contaminants as well as radioactive ones. All organics are combusted, incidental to the vitrification process. Most hazardous elements are incorporated into the glass similar to the radionuclides under study at Pit 1.

3.5.4. Technical Community History and Feedback

As discussed throughout this report, previous ISV technology tests and demonstrations have been widely published in the open scientific literature and in numerous DOE-contractor technical reports. Given the concerns raised by the melt expulsion event of April 21, 1996, it is obviously apparent that the prediction of melt expulsions is not possible at this time. A group of technical experts in ISV and related technical areas was assembled in Oak Ridge on October 15-17, 1996, to identify strategies to overcome this continuing problem for ISV technology when applied to high-moisture soils and/or subsurface barriers.

3.5.4.1. History of scientific publications and presentations

A current and relatively complete list of available ISV publication is contained in an appendix to the In Situ Vitrification Workshop of October 15-17, 1996, described in the subsequent section. The evolution of the ORNL Pit 1 treatability study project is summarized in Sect. 1.1.3, where the publications of the various ORNL pilot-scale tests are referenced. Between the workshop appendix and the references in this report (Sect. 4.0), most pertinent published reports are mentioned. The scientific community responses to various technical reports has almost always centered on specific concerns such as how ^{137}Cs volatility is measured or controlled or what leaching test data means or is appropriate. Safety concerns relative to melt expulsions have been addressed occasionally (Battelle Pacific Northwest National Laboratory, 1996).

3.5.4.2. Summary of the Department of Energy October 1996 workshop on in situ vitrification needs

A workshop on the needs for ISV technology implementation with DOE was held in Oak Ridge on October 15-17, 1996, and was sponsored by the DOE Office of Science and Technology, Characterization, Monitoring, and Sensor Technology Cross-Cutting Program and the Subsurface Contaminants Focus Area. Approximately 35 technical experts from across DOE sites and academic institutions were assembled to identify technical strategies to avoid ISV melt expulsions either through better site selection and screening or through process monitoring. Although no obvious direct solutions to the problem of ISV melt expulsions was identified or agreed upon by the group of experts, a number of recommendations were made. First, it was recommended that DOE should continue to pursue applications of ISV for contaminated soil remediation. Second, site characterization and site-specific planning, including projections of ISV performance (modeling) should be a part of every application; the degree of planning and prediction will vary according to site and contaminant conditions. Third, engineering measures to modify a site in preparation for ISV (e.g., dewatering or mechanical disruption) should be considered where analysis of characterization data indicate the possibility of a melt expulsion event. Fourth, monitoring tools for use during ISV need to be developed, adapted, and improved. Fifth, engineering measures to control the impacts of melt expulsion events were not considered in this workshop but merit further evaluation. Although these recommendations all sound rather general, there is some substantive discussion of mechanisms in the text of the workshop report. In addition, there is an initial attempt to list and prioritize possible research topics to address ISV needs.

3.5.5 Feedback From General Public

3.5.5.1. Public meeting history

DOE presented a description of the project status at three public meetings prior to the initiation of ISV operations and at two public meetings after the melt expulsion as part of planning for restart of ISV operations. No formal substantive questions or comments were received. However, during the subsequent or antecedent poster presentations by project personnel during these public meetings, numerous inquiries for information, samples, and publications were received.

3.5.5.2. Educational interactions

As the result of public meetings and flier circulations, numerous requests for information were received. It is difficult to estimate the number of high school and college term papers produced on ISV technology as a result of these requests. Although these requests placed a significant demand

on ISV project personnel, most were addressed. A technology like ISV is likely to attract similar attention in any future implementation and adequate allowance should be made for these demands on project personnel.

3.5.5.3. Comments by the Oak Ridge Site-Specific Advisory Board

The Oak Ridge Site-Specific Advisory Board (ORSSAB) was not constituted until 1995 by which time the ISV project was already anticipating the start of operations at Pit 1. Thus, the project never came to the attention of the ORSSAB or was placed on their agenda. However, any future ISV projects will certainly have to be considered by the ORSSAB as part of their planning process. Geosafe has initiated interactions with the ORSSAB and is planning to present its commercial experience and other information of interest to the ORSSAB Technology and Deployment Committee at a public meeting in 1998.

3.5.6. Unresolved, Lingering, and Potential Public and DOE Concerns

The DOE readiness review board, prior to the decision not to pursue restart of ISV treatment of ORNL Pit 1, provided detailed core requirements for lines of inquiry for field readiness review. Although many of these are most relevant to persons familiar with the technical details of the project, they also reflect a general concern for safety, project success, and environmental protection, which is indicative of general public concern. Thus, at least the major concerns will be discussed here. First, concerning systems to prevent a melt expulsion event (MEE), there was a question if an adequate understanding exists to ensure that project personnel understand the physical phenomena which resulted in the MEE. A maximum credible event for the MEE should be formulated to show such understanding and to provide design basis for future equipment, procedures, and safety systems. Presupposing some necessary changes in ISV operations, it will be required to demonstrate that groundwater has been effectively lowered below the planned bottom of the melt. Similarly, there is a stated need for a submelt-body pressure monitoring system with established design, implementation, and performance testing. If subsurface venting is employed to prevent an MEE, the system should be adequate to prevent a MEE. The video monitoring of the melt surface should be adequate in design for continuous viewing of the melt surface. A system for adequate power voltage and current monitoring should be designed so that anomalies, presumed to precede MEEs, can be recognized. Key safety systems need also to be clearly identified.

Second, systems to mitigate the impacts of an MEE need to be in place. It is generally recognized that elimination of all risk of an MEE is impossible and that both equipment and procedures must be adequate to endure MEE. Off-gas deflection barriers, to protect personnel and equipment, should be adequately designed and emplaced. Hood venting must be designed into the overall system of mitigating impacts of a MEE. Personnel protective equipment must be adequate for any required tasks during ISV operations.

Third, management systems must be in place to address a MEE. Worker safety practices to minimize the risks of a MEE must be in place and understood. Emergency response plans must be clearly established and understood. Adequate alarm systems must be in place for critical safety systems and for personnel notification. All equipment must have as-built drawings for its configuration control.

Fourth, procedures must be revised to reflect all changes in operations. Procedures should define when, why, and how the DOE Program Manager and DOE Site Manager are notified of changes that impact safety and health.

Fifth, workers must be adequately trained and retrained to revised procedures. Workers must understand their responsibilities as defined in the procedures.

3.6 LESSONS LEARNED BASED ON MELT EXPULSION EVENT

Several critical lessons were learned relative to ISV operations in Oak Ridge and, in general, in areas with high soil moisture contents and/or groundwater elevations near the planned ISV melt body depth. Three reports on the melt expulsion incident of April 21, 1996, were produced which describe details of probable causes and remedies for future ISV operations at ORNL Pit 1 (ESERP 1996a, 1996b, 1996c). The interested reader is referred to these reports for specific details which will not be presented here except for a summary of strategies to address many issues which were listed but unresolved in these post-event reports. In addition, the interested reader is referred to the unusual occurrence report (ORO-LMES-X10ENVRES-1996-0006) for details of the incident and post-incident plans for ISV restart.

In order to understand the following discussion of lessons learned for ISV operations, a brief summary of the melt expulsion incident is necessary. On April 21, 1996, at 18:12, approximately 20 tons of molten glass was expelled from a 216-ton body of molten (approximately 1,600°C) radioactive contaminated soil (containing 2.9 Ci of ^{137}Cs) at a field site at ORNL. The melt expulsion was caused by pressurized steam venting rapidly through, rather than by the desired path around, the molten body. During the previous 17 days, an old seepage pit was undergoing ISV to convert it from porous, leachable soil into a monolithic, impermeable vitreous waste form. Approximately 2 MW of electrical power was being delivered to the molten body which was contained in the ground. The area was covered with a stainless-steel hood maintained under slight negative pressure to collect, filter, scrub, and monitor off-gas. Off-gas into the hood was rapidly heated by the expelled molten material from a typical operating temperature of 250°C to over 1000°C with an associated surge of low pressure differential sufficient to lift the 15,000-lb hood approximately 12 in. off the ground on one side. A small pool of molten glass was able to flow up to 3 ft outside the hood while it was raised off the ground. The escaping hot off-gas and/or molten glass ignited several small fires in combustible components near or attached to the external hood frame (e.g. wire insulation, plastic hose, fiberglass trays, etc.). Fire department personnel responded to the emergency notification within minutes but were not needed because the small fires self-extinguished within an hour. Four project personnel were performing tasks at the site at the time of the melt expulsion; none were injured or contaminated during the melt expulsion incident. Air samples taken from the hood perimeter near the small fires did not detect any airborne radioactive contamination.

Subsequent analyses of ambient air collected by the project's three air samplers did not reveal any airborne contamination. However, analysis of off-gas sampled directly from the ISV hood, coupled with an estimate of the volume of off-gas released from the pressurized hood, revealed that a maximum of 0.10 μCi of ^{137}Cs could have been released. This activity of ^{137}Cs could have delivered a hypothetical and unmeasurable dose of 0.015 μrem to the nearest private residence outside the Oak Ridge reservation under worst-case meteorological conditions. Subsequent analyses of off-gas processing filters revealed that they contained 99.7% of all off-gas radioactivity. Moreover, the residual molten material was found to contain 99.9982% of the ^{137}Cs being processed at the time of the melt expulsion. Small fragments of expelled glass were found within 300 ft of the off-gas hood; they apparently formed when the high-velocity off-gas was escaping under the hood and across the surface of molten glass. Many light pieces of this fiberglass were apparent as well as a few globular clusters very close to the hood. Subsequent cleanup efforts revealed a total of only a few pounds of these contaminated glass fibers at the site. All expelled glass particles were found to have a uniform

specific activity of ^{137}Cs ($1.5\text{E-}08\text{ Ci/g}$) indicative of their origin from the well-mixed molten body. The glass, indicative of the excellent quality of the vitreous waste form, contained no smearable or transferrable activity. Thus, the overall environmental impact of the incident relative to spread of contamination, either airborne or solid fragments, was insignificant. Of course, the magnitude and distribution of radioactive contamination during the melt expulsion incident was poorly defined at the time and caused concern for potential impacts to personnel and the environment until initial sample analyses were completed.

The fire damage and general thermal stress to the project's equipment was completely limited to the off-gas hood; all other off-gas processing and control equipment, data acquisition systems, and electrical transformation equipment were undamaged. Approximately \$450,000 in direct damage to hood components was estimated including the central baghouse filter unit, the material addition system, and various electrical lines and control and monitoring devices on the hood.

Although no personnel were in any of the heat-affected areas at the time of the melt expulsion incident, many regular tasks did require personnel to enter potentially dangerous areas on and around the off-gas hood. Procedures can be modified to minimize the need for personnel entry into dangerous areas or to provide adequate protection during necessary tasks. Many data collection and process control tasks can be done remotely through small modifications to equipment. Other monitoring tasks can be automated to eliminate the need for personnel access but may require more significant modifications. One task, the addition of electrode sections, still requires personnel to access the hood work platform. Personnel protective clothing for thermal stress and protective thermal barriers would be required for this task. Personnel protective clothing should be selected to minimize operator stress and maximize flexibility.

The off-gas hood itself, in addition to repairs, can be modified to handle future melt expulsion events in a controlled manner. The minimal airborne contamination experienced allows for unfiltered releases during possible future incidents. Some areas of the hood can be insulated where equipment might still receive thermal stress. The fabric elements of the off-gas roughing filter, which in the present configuration are directly exposed above the melt body, can be protected by a guard to prevent damage by splashes of molten glass.

3.6.1. Melt Expulsion Event Contributing Factors

The root cause of the melt expulsion incident was an inadequate design for project operations. The melt expulsion incident was clearly not considered very probable and, thus, its potential effects were not addressed adequately in either the equipment design or the project procedures. Although similar melt expulsions events had been experienced in three of the previous 70 large-scale ISV melts by PNNL and Geosafe, previous incident investigations have implicated man-made subterranean structures, such as tanks, concrete barriers, or drums, which were thought to constrict the normal flow and dissipation of off-gas around the growing molten body (PNNL 1992; Roberts et al. 1992; Geosafe Corp. 1993). The present Pit 1 melt expulsion may also have resulted from the dense layer of unweathered rock at the bottom of the Pit 1 excavation.

Off-gas from ISV melts is composed mostly of steam as soil moisture is distilled in proximity to the molten body. Pit 1 site characterization investigations eliminated the possibility of man-made structures like concrete floors/walls as well as buried objects like tanks or drums. However, Pit 1 was constructed in 1951 by excavation to a strata of dense, unweathered rock, which could have functioned to constrain off-gas (steam) movement around the melt body within the soil-filled pit during ISV. Although several corrective actions can be implemented to minimize the possibility of

melt expulsion events in future ISV operations at ORNL Pit 1, the design basis for all future ISV operations must be a melt expulsion event similar in nature to that experienced on April 21, 1996. Operating procedures must address this design basis to protect both personnel and equipment while also attempting to minimize the probability of its recurrence. Unless water can be lowered below ISV target depths and dense confining formations adequately disrupted, then ISV may not be the technology of choice.

As pointed out in the occurrence report of this incident, the root cause of this melt expulsion was an inadequate design for ISV of soil within or proximate to groundwater and/or subsurface barriers to off-gas movement. Thus, the direct cause was an inadequate procedure to perform ISV under these conditions with a contributing cause being inadequate training of project personnel to address these possible events in preparing equipment designs and project operating procedures. As a first step in addressing an adequate design for ISV continued operations on Pit 1, considerable effort was expended on establishing the definition of a maximum credible melt expulsion event to provide a basis for equipment design and preparation of safe operating procedures.

3.6.2. Maximum Credible Melt Expulsion Event

Future ISV operations need to consider a maximum credible melt expulsion in project design. One of the salient problems raised by the melt expulsion event of April 21, 1996, during ISV operations at ORNL Pit 1 was that the present off-gas collection hood was not designed to function during any significant pressurization or heating resulting from an expulsion of molten ISV product. The lifting of the hood from the ground surface and concomitant release of apparently high-velocity, high-temperature jets of off-gas/steam along the ground surface caused significant thermal damage to many hood perimeter components either directly or indirectly through secondary fires in surrounding combustible materials. More importantly, the unplanned and uncontrolled release of hot gases occurred in areas where personnel had been performing regular tasks during ISV operations and, thus, raised serious concerns for the safety of personnel during operations with the present hood design.

As part of the evaluation of this melt expulsion event, many changes in ISV operational design, personnel task procedures, and equipment should be considered. Due to the present inability to predict either the environmental or operational conditions leading to a melt expulsion or its timing, it has become necessary to design ISV operations, equipment, and procedures as though a melt expulsion may occur during melting operations. Obviously, the probability of a melt expulsion event and its size increase significantly with increasing melt size and/or depth in a given operation.

Given that a melt expulsion should be the basis for redesigning or retrofitting the ISV hood and attached equipment, the definition of a conservative maximum credible event (MCE) becomes necessary. The MCE will provide the maximum criteria for functional design. These criteria would include temperature, pressure, volume of off-gas/steam generated, and gas-generation rate; it could also include kinetic impacts of molten glass projectiles to various hood components which are positioned along potential trajectories from the molten ISV body. Designs can then address methods to overcome or, at least, endure these pressure, thermal, mechanical, and flow stresses without damage to equipment, interruption of operations, unacceptable environmental releases, or personnel injury. Due to the present limited understanding of the exact mechanism of water contacting the molten ISV mass and its resulting melt expulsion, approaches to defining an MCE are not straightforward or obvious. The various approaches to the definition of an MCE are discussed subsequently. Investigations of previous large-scale ISV melt expulsions have also been inconclusive (Geosafe Corp. 1993; Roberts et al. 1992; PNNL 1992) although all previous melt-expulsion

investigations have implicated man-made off-gas barriers (e.g., tanks, drums, or relict concrete floors) as major contributing factors to these events. In the case of ORNL Pit 1, no man-made structures have been identified or implicated although soil and/or geologic discontinuities coupled with saturated hydrologic conditions may have functioned in a similar fashion. Although the floor of the pit was known to be quite dense (see characterization report, Volume 2) because it refused penetration of A0 rod (1.75 in. diameter), it was frequently penetrated by driven 0.5 in. diameter rods. Because of this frequent penetration, it was presumed to lack the integrity of a concrete floor.

The unplanned lifting of the hood from the ground surface during the April 1996 melt expulsion was an obviously undesirable event. Initial discussion among project and independent investigation team members centered on methods to prevent the hood from lifting during a melt expulsion event. Prevention of hood lifting would meet several design objectives for ISV operations. First, personnel would be protected from hot off-gas flow and direct contact with high temperature gas. Personnel could more readily be protected from the much slower radiant and conductive heat transfer from a hot hood surface than from the rapid convective heat flow in off-gas or steam jets. Similarly, a designed prevention of hood lifting could function to define safe areas on the hood's work platform or around the hood's perimeter. If venting to prevent hood lifting were planned through engineered structures, then specific danger areas around these structures could be defined.

Second, prevention of hood lifting could function to protect equipment, particularly around the hood perimeter from exposure to hot off-gas escaping at vulnerable points. If planned venting points or areas were defined by venting structures, then secondary fires in perimeter combustible materials, i.e., wire insulation, rubber hoses, or fiberglass conduit, could also be prevented.

Third, prevention of hood lifting would also prevent the expulsion of molten ISV product, particularly the fine, fibrous glass or "angel hair" observed around the hood perimeter following the April melt expulsion. Obviously, if the hood is prevented from lifting from the ground surface, then no surface runoff of molten ISV product would occur like the "lava" flows observed to the southeast of the hood after the April melt expulsion. Likewise, the secondary fires caused by contact of combustibles with this molten product would also be avoided. The formation of the fine fibrous glass particles was caused by a high-velocity flow of off-gas over a molten surface in the small gap between the lifting/falling hood and the molten surface which had flowed underneath it; several frozen glass strings were observed around the hood base after the event indicating their origin and method of formation. Less frequent globular particles, up to several hundred grams, were also observed expelled from the hood at much shorter distances from the hood base. Thus, if the hood were prevented from lifting or if molten ISV product were prevented from flowing under a lifted hood, expelled glass would not have escaped the hood. None of the expelled glass particles, fibrous or globular, appeared to be primary expelled particles, i.e., particles whose trajectories could have originated in the melt body; all appeared to be secondary particles formed from the molten surface runoff by the action of high-velocity gas at the hood base.

Although all three of the above objectives would be achieved by prevention of hood lifting, they could all be achieved by alternate designs or approaches. For example, personnel could be protected from direct contact with high-velocity off-gas by a perimeter gas-deflecting barrier; this could be as simple as a circumvallation with concrete "Jersey" bouncers. Most combustible or thermally vulnerable equipment on the hood perimeter could be either moved or protected with insulation or secondary metal sheet. Glass expulsion and flow from under the hood could be prevented by a berm inside the hood which would prevent any molten ISV product from contacting the hood walls even if these lifted from the ground surface. Indeed, many of these alternate approaches to meeting the same objectives inherent in preventing the hood from lifting, may be

implemented by the project regardless, as secondary engineered barriers for personnel protection, equipment protection, and product containment.

Design strategies to prevent hood lifting

Before discussing the definition of the MCE for design of the hood and ISV operations, a brief discussion of several design approaches would seem worthwhile if only to focus on the necessity for an agreed definition of the MCE. The first approach, of course, would be to implement techniques which would prevent melt expulsions or hood pressurization from occurring. Improved subsurface venting and water table drawdown are two approaches to providing relief to any subsurface barrier constraints on off-gas movement away from the growing melt body. However, such techniques are only conceptual at this point and cannot be relied on until proven in field practice. Alternately, potential indicator parameters, i.e., measurable parameters which probably precede a melt expulsion, could be monitored carefully, and operational parameters, such as total electrical power to the melt body, reduced in time to prevent an expulsion. Parameters such as amperage fluctuations, subsurface pressure, hood pressure, melt surface motions or bubbling, and sonic anomalies, have been suggested as potential precursors or indicators of melt expulsions; however, none have been documented conclusively in the ORNL or previous melt expulsions. Thus, neither preventative techniques nor process monitoring techniques have been established with a confidence sufficient to prevent or avoid melt expulsions during ISV.

Alternately, lifting could be prevented by adding weight to the hood sufficient to withstand the maximum pressure exerted by the MCE until dissipated by the normal maximum flow of the ISV off-gas collection system. However, the hood was designed to withstand only 5 in. W.C. vacuum and was not designed as a pressure vessel. In general, this approach is quite difficult because the present 2,500 ft² hood will require approximately 13,000 lb of increased weight per in. W.C. increase in its pressure containment. Although this weight could be placed on the hem of the hood and, thus, not become a burden to the already limited superstructure, the amount of weight required and its movement between melt settings poses some large engineering challenges.

An alternate variation of adding weight to the hood hem would be to bury or anchor the hood to the ground surface. Of course, this strategy still requires the hood to act as a pressure vessel with all of those inherent design needs. In addition, it will rely on the geotechnical properties of the particular soil formation being used for ISV. Anchors or burying the hood footing may provide sufficient strength in a high-clay, high-strength soil but be virtually useless in a noncohesive soil. In general, it would be better to design engineering features into the equipment than to shift the burden to site characterization for a minimal soil strength.

Another variation of the increased hood weight approach would be to change the hood suspension design in the superstructure from hanging chains to rigid beams. In addition, to imposing a very stringent level ground surface contour for a rigidly fixed hood, this strategy would, in essence, only increase the hood restraining pressure by the weight of the superstructure; the 2,500 ft² hood would increase in effective weight from 15,000 to 130,000 lb, which would increase its static lifting pressure from 1.15 to 10.0 in. W.C. pressure. If such pressure could be exceeded during a MCE, then both the hood and superstructure would lift during a melt expulsion of sufficient size. Of course, whether the hood panels could withstand 10 in. W.C. pressure is presently unknown but could be determined by structural analyses. In addition, many other hood features, such as work platform stability, would be sacrificed by a rigid attachment of the hood to the superstructure. Thus, structural unification of the hood and superstructure would not seem to provide a simple solution to preventing of hood lifting.

An alternate design strategy to prevent hood lifting would be to construct vents on the present hood which would actuate at a pressure less than the hood lifting pressure. Such vents could not only prevent the hood from lifting but could also direct vented hot gas away from areas reserved for personnel tasks and vulnerable equipment. Critical to the design of such vents would be to have sufficient flow capacity to accommodate the generation rate of steam/off-gas from a MCE without exceeding the trigger lifting pressure of the hood. Thus, the definition of the MCE is paramount in setting the functional criteria for any venting design.

Another design strategy for managing hood lifting would be to abandon the concept of preventing hood lifting and address directly the design objectives which would have been fulfilled by preventing hood lifting; these include personnel protection, equipment protection, and ISV product containment. Such an approach would shift from alternate to necessary if engineered vents should prove unfeasible for the present hood. This approach is really just another venting design without a specified venting area and without precise knowledge of venting direction. However, if all the objectives, which could be attained by preventing the hood from lifting, could be achieved by alternate approaches, then hood lifting as a venting technique should be considered as a valid design strategy. Alternately, a preferred venting area could be encouraged by anchoring one side of the hood.

ISV Hood Venting Design Criteria

Of necessity, hood venting design will be performed whether for new, additional engineered structures or, by default, for hood lifting during a MCE. It is useful at this point, prior to discussing the MCE itself, to specify those design criteria or limitations already applicable to the present ISV hood. Specific vent designs must accommodate the MCE pressure without lifting from the ground surface. Alternately, total hood lifting area must be calculated in order to design adequate deflection barriers for the resulting gas jet velocities originating from the lifted hood. Many of the venting design criteria are highly interactive with other criteria (e.g., vents must not exceed the structural strength of the existing superstructure). Thus, other criteria will likely be formalized during the design process as dependent variables are understood. These minimal present design criteria are as follows:

1. Vent area - The design vent area must be sufficient to prevent the hood from lifting during maximum credible melt expulsion event. Alternately, the area exposed during an allowed hood lift must be sufficient to prevent the superstructure from lifting during a MCE.

2. Present Hood Lifting Trigger Pressure - The present 2,500 ft² hood, weighing approximately 15,000 lb, can be lifted by a minimum positive pressure of only 0.042 psi or 1.15 in. H₂O. This pressure for initiation of lifting may be considerably lower if partial or one-sided lifting is considered. When the combined weight of the hood and superstructure (approximately 130,000 lb) is considered, a second step lift initiation pressure of 0.36 psi or 10.0 in. H₂O would result in lifting of the hood superstructure. The hood can only lift at most 12 in. around its perimeter before it physically contacts the superstructure frame and is subsequently restrained from further lifting by the superstructure's weight.

3. Maximum Venting Area During Hood Lift - An average 6"-lift over the entire 200 ft perimeter is considered a maximum lift height due to the center vertical movement restraint at the connection to the superstructure at the roughing filter and due to an asymmetrical nature of probable lift. Thus, 100 ft² is considered to be the present maximum venting area during a hood lift. If the hood and its

superstructure both lift, the venting area becomes equal to the entire hood area (approximately 3,700 ft²).

4. Superstructure Strength - Any weight added by venting structures must be within design strength limitations of superstructure and other structural members. Due to a structural failure in the initial superstructure, the superstructure was modified to improve its strength. However, the present strength is limited and any further addition of weight will need to be considered by further structural analyses.

5. Interference With Other Hood Systems - Any venting modifications must not interfere with other critical functions of ISV hood. These systems include the travel system, electrode addition and visual monitoring systems, personnel access to the work platform, roughing filter system, and electrical power delivery system.

Descriptions of Scenarios for In Situ Vitrification Hood Pressurization and Heating

Several scenarios for the size and mechanism of a melt expulsion event have been proposed by various investigators. Many of these involve some simulation of the perceived characteristics of the April 21, 1996, melt expulsion event at ORNL. Simulation of the events of April 21 may not represent the maximum credible event (MCE) for an ISV melt expulsion. Because the mass of the ORNL Pit 1 melt was only 216 tons at the time of its melt expulsion, it cannot represent an MCE because ISV melts sizes have ranged >1000 tons. It is also uncertain that the April 21 melt expulsion even represented a MCE for its 200-ton size. Thus, a MCE for a 1000-ton ISV melt cannot simply be scaled-up from the assumed characteristics of the April 21 melt expulsion event. The ISV hood needs to be designed for, or, in this case, retrofitted for some MCE in terms of its robustness to damage from thermal stress and its potential to vent pressurized off-gas to prevent loss of off-gas containment during the MCE. Because of the poor understanding of the exact mechanism of water or steam intrusion into the melt body during the melt expulsion event, a design basis for a MCE must be formulated on a very conservative, yet not impossible, basis. The specific scenarios considered for a MCE are summarized as follows (other potential scenarios may also exist):

The 25-gallon vaporization - In this scenario, 25 gallons of water is heated by the melt to steam at an assumed 1800°C and 0.5 psi and is released to the hood over 5 seconds. Although the assumed temperature of the steam is quite conservative, i.e., it approaches the maximum credible melt temperature, both the volume of water contacted by the melt and the time interval over which the subsequent steam is generated, are arbitrary. The 25 gallons originated from an assumption of the melt contacting a 55-gal drum, which is approximately half filled with water or full with water-saturated sludge. The generation interval of 5 sec originated from the assumed lifting interval of the ISV hood during the melt expulsion event of April 1996. Obviously, the volume increase does not include any heating of ambient off-gas contained in the hood by expelled molten glass. Mixture of the 110,000 ft³ of steam generated from the 25 gal of water with ambient off-gas in the hood could only result in a net cooling of the mixture and, thus, an effective decrease in net volume expansion.

Bubble velocity scenario - In this scenario, 13.2 gallons (50 kg) of water is engulfed within the bottom of the melt body, i.e., intrudes into the melt body, at 2000°K generating steam bubble(s) and/or froth which rise by buoyancy with a bubble period of 1 sec. This model is more sophisticated in allowing for the physical process of bubble buoyancy, limited contact between the intruding water sphere and the melt body, and kinetic heating of the steam bubble. It also allows final bubble pressure to be calculated. However, the rationale for the mass of water contacted by the melt is arbitrary relying on a similar contact with a fixed volume of water. The maximum steam bubble

produced has a volume of 15,745 ft³ at a pressure of 0.33 psi and a calculated temperature of 1727°C over an interval of 1 sec.

Kinetic hood plenum heating - In this scenario, the 15,000 ft³ of off-gas in the ISV hood is heated to 1500°C at 500°Rankine/sec using a differential equation solver allowing the hood to lift and relieve pressure with and without various assumed venting areas on the hood. The model is the most sophisticated in allowing hood pressure to be relieved by the exposed lifted area. Its heating rate, however, was selected to simulate the descriptions of the April 1996 melt expulsion event in that the resulting magnitude of the hood lift was similar to that observed in the ORNL event. It also assumes that the mechanism of pressurization of the hood results solely from heating of the ambient air due to the expulsion of the molten glass; there is no steam generated. The model generates a low peak pressure of 0.15 psi (4.2 in. WC) after 3 sec from a thermal expansion of 35,850 ft³ within the hood at a temperature of 1500°C.

Maximum bubble from an 800-Mg melt - In this scenario, a bubble of steam is formed at the bottom of the melt body displacing the entire melt body upwards until merging with the hood plenum off-gas. The pressure of the bubble is set equal to the melt body's lithostatic pressure, its temperature to that of the melt (1800°C), and its volume to that of a melt body of 800Mg, the largest ISV melt envisioned in ORNL WAG 7. The kinetics of bubble generation are assumed to be twice the free-fall time (0.9 sec) of the displaced melt body to a height of one diameter. Although the melt body is expelled into the hood, it is not assumed to heat the ambient off-gas in the hood but is assumed to fall quantitatively back into the melt subsidence trench. This results in the generation of 10,346 ft³ of steam at 1800°C generated over a 1.8 sec interval. Although the process can be repeated many times in this scenario, as in other scenarios, the maximum generation rate for subsequent repetitions could not be larger than the first as the returning melt body would be both slightly cooler and slightly smaller as some glass would be permanently expelled.

Maximum bubble from a 200-Mg melt - This scenario is identical to the maximum bubble from an 800-Mg melt body (above) except that the size of the melt is smaller, i.e., approximately the size of the ORNL Pit 1 melt body. This results in the generation of only 2,535 ft³ of steam at 1800°C generated over a 1.49 sec interval. Obviously, this scenario cannot function as an MCE due the limited melt size assumed. It was only performed to calculate a maximum steam generation rate for simulating the April ORNL melt expulsion event.

Static hood plenum heating - In this scenario, only the static volume of off-gas within the ISV hood plus its underlying starter pit (21,485 ft³) is allowed to heat over a 5-second interval to 1500°C. This is similar to the kinetic hood plenum heating scenario above, except that the pressure is not allowed to dissipate. This is due to the hood lifting and the plenum volume being larger due to including the volume of the starter/subsidence trench in the total plenum volume. Like the kinetic heating model, it assumes no steam generation and an arbitrary generation interval over 5 sec. Thus, this scenario generates considerably more thermal expansion volume (68,597 ft³) than the kinetic scenario (35,850 ft³).

Combined static plenum heating and maximum bubble generation - In this scenario, the effects of maximum bubble steam generation and complete thermal heating of the plenum off-gas are combined into a total volume expansion rate. Although the total expansion volume (78,943 ft³) is the sum of the steam and ambient off-gas thermal expansion volumes, the generations occur over slightly different time intervals and at slightly different temperatures. The critical parameter, the overall gas volume generation rate, can be calculated from the sum of the independent generation rates. The generation rate for all these scenarios is given in Table 3.10. The combined static plenum

heating and maximum steam bubble scenario produced the largest generation rate: 236,600 standard (atmospheric pressure and 293°K) ft³ per min. Thus, this scenario will be employed as the MCE for an ISV melt expulsion event as it is the most conservative of the scenarios evaluated to date.

Vent Area Required to Prevent Hood Lifting

One of the significant questions, raised during discussions of the MCE as a design basis for the ISV hood and the project test plan, was what area of vents would be required to prevent the hood from lifting from the ground during the MCE. This analysis assumes quasisteady-state conditions for flow development in vents and, thus, is likely to be quite conservative. With such a calculated area, it would be possible to determine 1) if venting is possible and 2) the number, cost, and vent design required to prevent hood lifting. Because resistance to gas flow is highly dependent on the specific geometry of vents or openings, it is not possible to compute a generic required total venting area. It is necessary to assume a specific vent design to determine the maximum flows at the required hood pressures to prevent lifting. Regardless, a very fair "generic" vent design can be used for this calculation.

A "generic" vent is proposed with 3.14 ft² total area which is made from a 24-in. diameter pipe of 4-ft length with frictionless and massless louvers, i.e., an open pipe with flow permitted in only one direction. Such a pipe is about as large in diameter as would fit into most hood panels. Such large diameter pipe has the advantage of an inherently low resistance to gas flow compared to an equivalent number of smaller diameter pipes or vents with the same total area; under a given set of fixed conditions, flow is proportional to the square of the pipe diameter. The proposed "generic" length is the minimum necessary to route off-gas outside the superstructure; regardless, a range of pipe length between 1 and 10 ft has, by comparison to other geometric parameters, little effect on maximum flow rate.

The governing equation for calculation of pressure differential (ΔP) across a pipe is:

$$\Delta P = \frac{q^2 \times K_t \times T_i \times S_g \times P_i}{459,684 \times Y^2 \times d^4}$$

where:

ΔP = differential pressure across pipe (psi)

q = volumetric flow rate (scfm) adjusted to standard pressure and temperature

K_t = total resistance factor = $K_i + K_p + K_o$

where K_i = inlet resistance factor = 1.0

K_p = resistance factor of pipe = $(f \times L)/D$

where f = friction factor which for 24" pipe = 0.012

L = pipe length (ft)

D = pipe diameter (ft)

K_o = outlet resistance factor = 1.0

T_i = temperature of inlet gas (degrees Rankine)

S_g = specific gravity of gas = M_{gas} / M_{air}

Y = expansion factor dependent on K and $\Delta P/P_i$

d = diameter of the pipe (in.)

P_i = pressure of the gas at the inlet (psi)

for the ISV off-gas, a temperature, $T_i = 3192^\circ\text{Rankine}$ (1500°C) was used and the off-gas, assumed to be largely steam, was assigned a $S_g = 0.62$ (18/29). The "generic" 24-in. diameter pipe has the following values for the parameters in the above equation:

$$d = 24 \text{ in}$$

$$D = 2 \text{ ft}$$

$$K_p = 0.024 \text{ (therefore, } K_t = 2.024)$$

$$Y = 0.70 \text{ for } \Delta P/P_i = 0.5 \text{ and } K_t = 2.0$$

$$P_i = 14.558 \text{ psi (or 0.0249 psi below atmospheric due to hood vacuum)}$$

$$\Delta P = P_i / 2 = 7.279 \text{ psi}$$

The above equation can be solved for q , the volumetric flow rate, of one vent given a constraint that $\Delta P/P_i < \text{or} = 0.5$ to allow sufficient flow such that ΔP does not approach P_i , a condition, which would lead to hood lifting as the resistance pressure differential approaches the inlet or hood pressure. Actually, any fixed ratio of $\Delta P/P_i$ could be selected but it will have marginal effect on the calculated value of q compared to other parameters in the equation.

The calculated value of $q = 43,193 \text{ scfm}$ for this "generic" vent under the assumptions and parameters described above. The maximum credible event (MCE) for an off-gas hood pressurization has a combined steam generation and thermal expansion rate of 236,620 scfm (Table 3.10). To handle this flow without lifting the hood (i.e., $\Delta P/P_i > 0.5$), a total of 5.5 (i.e., $236,620/43,193$) of these "generic" vents would be required. This sums to a total of 17.2 ft² of venting area or only 0.47% of the total of approximately 3,700 ft² of total hood surface area. Thus, it appears that the hood can readily be vented to prevent it from lifting during a MCE. It needs to be emphasized that these "generic" vents are hypothetical open pipes. If they were fitted with real louvers, valves, flappers, or blow-off panels, the value of K_t in the above equation would rise markedly, probably an order-of-magnitude as is typical of valves. If the reasonable number (Table 1) of these open "generic" pipes are sufficient to vent the hood, however, realistic structures to handle flow may require significantly more area for adequate venting capability. If K_t were to increase by an order-of-magnitude, the required venting area would still be less than the 202 ft² of reasonably accessible hood panels (discussed subsequently) available for installation of mechanical vents and attached conduit. Any vents must also bear the stresses of normal negative hood pressure.

In Situ Vitrification Hood Mechanical Vent Design Limitations

For the efficient use of available vent areas on the hood, the "generic" pipe vents will probably not be the actual configuration used to construct vents. More likely, rectangular columns will be fabricated between existing hood panels and potential exhaust zones which are clear of vulnerable components or structural members of the superstructure. These rectangular chimneys or ducts can efficiently use most of the area of an individual hood panel. Exhaust structures could either conduct off-gas vertically above the superstructure (chimneys) or horizontally at selected locations beyond the outside perimeter of the superstructure beam or attached vulnerable components (ducts). However, due to the areal extent of the work platform surface and the great number of structures (beams, cables, wires, and trusses), only a limited number of panels have clear paths for exhaust. Thus, the hood, by this definition, has a limited fraction of its surface area actually available for venting. These include:

Horizontal Vents - Horizontal vents would be limited to 8 20"x50" panels for a total of 55.5 ft² of vent area. Most of the vertical panel members are obstructed from outward construction by the combination of beam trusses and tensioning cables on the main superstructure beam. This design has

Table 3.10. Volumes, temperatures, and durations of various credible ISV melt expulsion events

Scenario	Water Vaporized (gal)	Steam/Gas Volume (ft ³)	Gas Temp. (°C)	Gas Pres. (psi)	Gas Vol at Std T/P (ft ³)	Gen Time (sec)	Gen Rate Equivalent (scfm)	Gen Rate at T&P (cfm)
25-gal vaporization	25	110872	1800	0.5	16050	5	192600	1330464
bubble velocity model	13.2	15745	1727	0.33	2335	1	140100	944700
kinetic air heating	0	35850	1500	0.15	5919	3	118380	717000
max bubble - 800Mg	17.3	10346	1800	16.39	3063	1.8	102100	344867
max bubble - 200Mg	3.5	2535	1500	10.88	721	1.49	29034	102081
static air heating	0	68597	1500	0	11210	5	134520	823164
combined heat+max bubble	17.3	78943	mix	16.39	14273	mix	236620	1168031

Scenario:	Vent Area Required For No Lift (ft ²)	Number of Std Vents (number)	Max Vent Veloc. for 202 ft ² (mph)	Hood Lift Max Veloc. for 100 ft ² (mph)	Max Veloc. Vent+Lift for 302 ft ² (mph)
25-gal vaporization	14.0	4.5	75	151	50
bubble velocity model	10.2	3.2	53	107	35
kinetic air heating	8.6	2.7	40	81	27
max bubble - 800Mg	7.4	2.4	19	39	13
max bubble - 200Mg	2.1	0.7	6	12	4
static air heating	9.8	3.1	46	94	31
combined heat+max bubble	17.2	5.5	66	133	44

the advantage of limiting dangerous hot off-gas contact areas to a few designated regions on the ground surface surrounding the hood. However, this design has the disadvantage of long ducts, dead volume, weight, activation time and pressure, and proscribed access to ground areas.

Vertical Vents - Vertical vents are limited to 12 26"x68" panels for a total of 147 ft² of vent area. This design has the advantage that it vents away from personnel at all times and would have no proscribed access areas on ground. It has the same disadvantages as the horizontal vents but will also obscure observation of hood-working platform.

Combined Horizontal and Vertical Vents - Combining horizontal and vertical vents raises the total venting area to 202.6 ft².

Blowout Panels - The concept of blowout panels is limited to vertical panels and, in reality, only those on the ground surface. These are also limited by many hood structural components (e.g., hood beam trusses, beam tensioning cables, and travel system). They also have the potential to limit hood structural support in vertical panels and appear not to improve the potential for thermal damage to peripheral equipment over hood lifting.

3.6.3. Approaches to Reduce Probability of Melt Expulsion

Several techniques have been identified to minimize the probability of future melt expulsions. First, groundwater within Pit 1 can be drawn down well below the target depth for ISV treatment. Prior to the present melt expulsion incident, the bottom of the Pit 1 molten body was approximately 10 ft below the regularly-monitored elevation of standing water in the pit within 20 ft of the melt body. Although the movement of such standing water may have contributed to the melt expulsion, its presence indicates that an analysis of soil porosity was filled with water and, thus, little unsaturated pore space was available for potential transmission of steam away from the melt body. Thus, the removal of standing water around an ISV melt body removes this potential hydrostatic constraint on steam movement away from the heated zone.

Second, as an alternative to watertable drawdown, or, in addition to it, soil drying could also be attempted prior to ISV; dry soil has virtually no probability for a melt expulsion.

Third, the permeability of the dense barrier of undisturbed rock around Pit 1 could be increased or broken up in situ through a number of geotechnical techniques.

Fourth, flow-monitored and curved vent pipes could be installed at several layers beneath the growing melt body to provide facile pathways to release steam into the off-gas hood without relying upon the obviously unpredictable soil porosity. The use of straight vent pipes in the present ISV-test design inherently resulted in significant submelt strata being inaccessible to venting; lack of a credible vent pipe operational verification technique was also apparent.

Fifth, pressures beneath the melt body could be measured to ascertain when steam pressure approaches the lithostatic pressure of the melt body and, thus, power to the melt must be attenuated to reduce the rate of steam generation. Submelt pressure measurement could be attempted using buried screened-end tubing connected to pressure transducers above ground. Submelt pressure measurement represents the only plausible parameter to predict potential melt expulsion in sufficient time to take action to prevent it.

Sixth, quality video monitoring of the melt surface activity must be attained in future ISV operations at Pit 1. Previous melt expulsion incidents were sometimes preceded by smaller bubbling activity or unusual melt surface movements. The Pit 1 ISV operations lost its video monitoring capability due to window fouling resulting in extremely poor to entirely indistinct video images. Reducing the probability of a MEE may also be addressed through melt body shape manipulation using rectangular electrode arrays or planar melt bodies. Strategic thermocouple placement coupled with strategic knowledge can provide a means to monitor steam transport away from the melt body.

3.6.3.1 Suppressing perched and regional groundwater table

Pit 1 is located on a hill slope on the east and south sides. Thus, the water table elevation within the pit is maintained by shallow subsurface flow and surface runoff from these upslope areas (Fig. 3.23). Several approaches to drawing down the water table elevation within Pit 1 prior to and during ISV can be envisioned. First, drawdown wells could be placed directly into and through Pit 1. The advantage of this approach is that water within the pit will probably be drawn down quickly due to the relatively high hydraulic conductivity of the soil backfill (see Volume 2, the site characterization report). The major disadvantage of this approach is that the pumped water will be relatively contaminated with radioactivity which is comparatively high in groundwater within the pit (see site characterization report). This can produce a large volume (30,000 to 50,000 gallons) of contaminated wastewater to be disposed. The ^{137}Cs contamination may be substantially reduced by incorporating a zeolite or other ion exchange material in the bottom of the wells; these could be left in place to be processed by the ISV melt. Alternately, a suite or line of drawdown wells could be positioned near but outside the pit. If watertable suppression can be achieved by pumping these wells, recharge to the pit can be eliminated; in addition, perched water from the pit can also be drawn down through the soil formation which would adsorb most of the radioactivity. If this perimeter drawdown well approach is not adequate (due to limited regions of groundwater suppression around each well then a more costly approach of installing a interceptor trench on the south and east sides of Pit 1 could be attempted. Groundwater would have to be actively pumped from such a trench as there is no potential drain outlet at an elevation below the bottom of Pit 1.

In September of 1996, a suite of drawdown wells was installed at Pit 1 (Fig. 3.24) to test the feasibility of a line of groundwater suppression wells in protecting Pit 1. Six boreholes were augured on the upslope perimeter of Pit 1 to a minimum of 40 ft and one met refusal (Fig. 3.24). Criteria for their location were to place them as close as possible to, but not within, Pit 1 and out of the way of hood movement. They were also positioned in the Pit 1 topographic setting to intercept recharge from upslope areas. By placing them close to but not within Pit 1, it was desired that they yield minimally contaminated water during their pumping using the intervening soil's adsorptive capacity to remove radioactivity during the water flow through the soil formation to the drawdown point. All boreholes were augured to 40 ft, well below the desired ISV target elevation of 22 ft, so that strong hydraulic gradients to the wells can be maintained during pumping. However, most well boreholes remained opened to a nominal 30+ ft (Table 3.11) due to the inability of the auger to remove all drill cuttings from the borehole. All boreholes were 4.5-in diameter and all casing was 2.5-in diameter with flush-wall PVC screens and risers. Cleaning out several boreholes after temporarily removing the well casings, using a rotating water jet with repeated auguring, was attempted to open several boreholes to 40 ft to enable steep hydraulic gradients to be maintained in the drawdown wells. Submersible pumps were procured and tested to function in the well casings.

Fig. 3.23. East-west cross-sectional view of ORNL Pit 1 under high water table conditions with five-fold vertical exaggeration.

As can be seen from the depths to first encounter of hard/gray (unweathered) rock in each borehole (Table 3.11), it would be difficult to excavate a drainage trench in this area to the required 30 ft depth using conventional power-shovel or "ditch witch" techniques; rock blasting or rock mine drilling machinery would be required. It can also be seen that the depth to competent rock was considerably greater in the four boreholes (4-7) to the northeast of the pit than in the three boreholes (1-3) on the southeast and south of the pit. It is apparent that the surface of competent rock (penetration refusal or unrippable by a backhoe) dips significantly to the northeast to accommodate the additional data of competent rock on the Pit 1 bottom. Unfortunately, boreholes to the north or west of Pit 1 were not augured because of the known shallow contamination in these directions (see site characterization report). This shallow buried contamination in this area apparently resulted from Pit 1 overflow onto the original land surface before the pit was filled and the area covered with 5-10 ft of clean soil in 1981.

This well system failed to effect the necessary drawdown in Pit 1, forcing the necessity to consider additional wells directly into the pit north of the first melt body and dewatering the pit by direct pumping. It was desired to avoid this necessity because of the large volume of highly contaminated wastewater which will result. However, direct pumping remains a straight-forward feasible, albeit undesirable, alternative for dewatering Pit 1 prior to and during ISV.

Fig. 3.24. Location of groundwater drawdown wells around ORNL Pit 1.

The array of drawdown wells is designed to lower the water table in the vicinity of and within Pit 1 to below the target depth for ISV. The major advantage of drawdown will be that it will convert the soil porosity around the melt body from one completely filled with water to one where only about 65% of the porosity remains filled with water; this opening of soil porosity surrounding the melt body should be of enormous benefit in facilitating the transport of steam around, rather than through, the melt body. It should also remove the potential for rapid gravitational groundwater movement, i.e., saturated flow, near or within the melting zone. This technique will probably work; however, it may not continue to work adequately at all times, i.e., be able to keep up with large recharge during and immediately after an interval of heavy rain during melting operations. Thus, there will remain a risk for a significant water intrusion to the melt during a vulnerable point in melting (hence a risk of a melt expulsion). Alternately, the drawdown system may miss pockets of perched water at or near the pit bottom resulting in unaffected conditions conducive to another melt expulsion. It would be invaluable to know the kinetics of both drawdown and storm recharge through a few events before it is necessary to depend on the system's performance. There will always be a risk of a worst-case rainfall event during future ISV operations.

Table 3.11. Present well construction characteristics of drawdown wells located around ORNL Pit 1 (all units in ft)

Drawdown Well Construction Summary						
Well	Auguring Dates	Depth to Initial Hard Layer	Depth to Initial Water	Depth to Initial Gray Rock	Total Borehole Depth	
1	7/15/96	7	30	9	40	
2	7/16/96	6	18	6	40	
3	7/16-17/96	6	ND	9	40	
4	7/17/96	9	19	20	40	
5	7/18/96	ND	7	17	17	
6	7/18-19/96	18	17	ND	40	
7	7/19/96	9	ND	18	40	

Well	Initial Casing Length	Initial Screened Interval	Reinserted Casing Length	Reinserted Screened Length	Approximate:	
					ORNL Grid East	ORNL Grid North
1	35	20	30	20	26874	18760
2	30	20	20	15	26900	18768
3	37.5	20	32.5	20	26892	18807
4	35	20	30	20	26867	18898
5	None	None	None	None	26877	18865
6	30	20	27.5	20	26874	18877
7	37.5	20	30	20	26870	18890

ND = not determined

3.6.3.2. Drying soil in situ prior to ISV

The risk of a melt expulsion could be almost completely eliminated by drying soil prior to ISV. Obviously, such preparation methods may be time-consuming yet cost-effective to implement, but such an approach does seem technically feasible due to the emergence of in situ heating technology in 1995. Terratherm Environmental Services Inc. (Terratherm), Woodlands, Texas, now markets an in situ heating technology which places arrays of vertical resistors into the soil or horizontal resistors on the soil surface. The primary application of this technology is to treat and remove PCBs from soil but the technique actually heats the soil to several hundred degrees Celsius to desorb PCB and, in the process, completely dries the treated volume. The process off-gas is collected, monitored and filtered very similarly to the ISV off-gas so that the off-gas handling hardware and techniques are quite similar. The major drawback for this technology as a soil-drying technique is that it will be quite slow. The energy placed to a given resistance heated in situ must be transported through the soil mass which, due to its low thermal conductivity, is time consuming to heat up. Even an array

of vertical resistors spaced on 5-ft centers would take several weeks to complete matrix heating above the boiling point of water.

An alternative to such immersion heating of soil in situ, is the PNNL-developed technology termed "Six-Phase Soil Heating" (SPSH). Electrical power is placed into the moist soil using the natural resistance to generate heat between an array of seven electrodes. SPSH has the direct application to soils contaminated with volatile or semivolatile organic hazardous substances but removes a great deal of soil moisture in the process of heating soil to near the water boiling point. However, it cannot completely dry the soil as this condition terminates the process as electrical conductivity falls on soil drying. Indeed, a small fraction (<10%) of the water removed must be reintroduced to soil near the electrodes to maintain adequate soil moisture for the process to continue. However, a significant amount of soil moisture may be removable by SPSH. It has the additional advantage over the Terratherm process in that heat is generated throughout a large soil volume between the six electrodes rather than from an array of resistance heaters.

These soil drying techniques have the potential to remove significant to complete soil moisture immediately prior to ISV. Both have electrical power delivery systems similar in size to that of ISV and both have off-gas handling techniques similar to ISV. Such techniques, if coupled to ISV in close time proximity, could use their residual soil heating as an efficient pretreatment for ISV. However, both may add to the time and perhaps the cost of vitrification. Additional evaluation will be required to quantify the potential effectiveness of either of these technologies and their potential combination with ISV.

3.6.3.3. Increasing soil permeability prior to in situ vitrification

In addition to and in combination with high soil moisture and perched groundwater, the contact between the relatively loose soil fill and the dense unweathered rock in which Pit 1 was excavated has been identified as a key characteristic leading to the melt expulsion. This dense material may have functioned as a subsurface barrier to the planned transport of steam around the growing melt body. One approach to avoiding this barrier effect would be to disrupt it prior to ISV. Such geotechnical techniques as dynamic disruption can be envisioned using pile-driven H-beams which would fracture underlying rock as they are driven through it. Limited modeling using TOUGH 2 (a two-phase groundwater thermodynamic transport code) was conducted with application to the existing soil conditions at Pit 1 and to the unweathered rock after a permeability increase of two orders-of-magnitude was imposed. Results showed significantly less pressure buildup beneath the ISV melt for the disturbed soil conditions versus those currently existing. Whether such necessary changes in soil permeability can be achieved is unknown. At least one company providing such soil fracturing capability and experience has been identified. Techniques to measure changes in soil permeability in situ, before and after dynamic disruption, would need to be developed. In addition, modeling of soil and water heating and gas-phase pressure would need to be validated so that safe operating characteristics of soil formations for ISV can be assured. Dynamic disruption of such dense strata may also distribute the maximally contaminated layer within Pit 1 to wider and deeper targets for ISV; this effect, too, would need to be understood well before proceeding with ISV. Nonetheless, deep dynamic disruption has the potential to overcome a potential major barrier to safe ISV operations where subsurface gas-confining features must be modified prior to ISV.

3.6.3.4. Venting regions beneath in situ vitrification melt bodies

There were a number of attributes of the planned Pit 1 ISV melts which were thought to minimize the potential for large melt expulsions or, at least, to mitigate their impact. First was the

planned use of vent pipes to connect the volume of soil beneath the ISV melt with the soil surface within the off-gas hood. Continuously-screen well points were driven at various angles into the soil volume beneath the melt zone (Fig. 3.25). As the melt grew downward, these vent screens would intercept the surrounding dry zone at various elevations; they would, thus, offer short circuits for generated steam and hot gases and, thus, were thought to prevent the buildup of pressure due to constrictions in the natural dry-soil porosity. Contact of the melt body with the steel screen would melt and shut off an individual screen obviating further functioning of that screen. But, additional screens at different distances and angles would continue to function beneath the now deeper and larger melt. The region of influence around the placed screens is not known. The second attribute mitigating a melt impact was the use of the excavated startup trench, which added significantly to the hood buffer volume and well as adding an earthen container of several feet deep.

Fig. 3.25. Conceptual design for placing straight angled vent pipes into the wet soil zone around and beneath ORNL Pit 1 ISV melt bodies.

Unfortunately, visual observations during ISV operations were inadequate to determine if these angled vents actually conducted any off-gas or steam during ISV. The vent socks attached to the many vent pipes could not be seen in their inflated state by the nonfunctioning video cameras. Post-event inspection, for those vent pipes which could be found (no socks were found) under the expelled glass coating on the ground surface inside the hood, did not reveal any compelling evidence that they had been functioning or not functioning during operations. Regardless, inspection of Fig. 3.25 indicates that no vent pipes would be expected to have survived to the time of the melt expulsion as the melt body was near the floor of Pit 1 and all angled sub-melt body vent pipes would have been contacted and destroyed at this time.

In an attempt to provide functional vents beneath the growing ISV melt body, a technique for driving curved vents into the next melt region was conceived (Fig. 3.26). These pipes, with their designed open-screen intervals on the bottom ends, are planned to facilitate steam movement into

the off-gas hood rather than depending solely on the natural porosity of the soil formation. By the use of curved pipe, it should be possible to vent regions of the subsurface which were "unventable" using the previous melt's design of straight-angled pipes driven to various depths.

Fig. 3.26. Planned curvature radii for driving vent pipes beneath an ISV melt body.

However, because the examination of the previous vent pipes proved inconclusive, the big risk during another ISV melt will be whether the new vents are of sufficient size, spacing, and orientation to have the desired pressure relief effect. The soil formation itself may prove more of a limit to permeation of steam than any arrangement or design of screened vent intervals. In addition, because vent pipes cannot be driven through the dense Pit 1 bottom strata, it cannot be assured that this interval, at the critical melt contacts is vented. It would be desirable to melt into this bottom strata to assure that all the source contamination in Pit 1 is treated. Thus, there will remain a narrow but critical depth interval which cannot be vented and, thus, remains vulnerable to a melt expulsion event. An additional difficulty with the use of curved vent pipes is a technique to accurately locate the end of pipe position.

3.6.3.5. Monitoring gas pressure in regions beneath in situ vitrification melt bodies

It was planned to implant open stainless steel screens (3/8" OD x 21" long or longer using extensions) into the soil beneath the next ISV melt. The current catalog of Geoprobe Inc. tools illustrates how these screens are placed into the subsurface. The major difference between the

manufacturer's and the proposed project method was that curved rod would be used to drive into the ground near the planned bottom of the melt. This placement technique would be similar to that envisioned for the vent pipes (Fig. 3.26). Shallower arrays of pressure-monitoring screens could be attained by driving straight Geoprobe rod sections at an angle. Geoprobe rod, bent to a 23-ft radius in the ORNL machine shops using a pipe bending machine was test driven and withdrawn at Pit 1; use of this curved rod allowed positioning the area access screen near horizontal under the melt and still contain the surface opening (origin of penetration) within the hood (Fig. 3.26). In the test driving of the curved Geoprobe, it was determined that the manual effort to jack out the rod is probably more expensive than purchasing additional rod to leave in the ground once driven to the desired position. The test did confirm that the Geoprobe rod maintained its radius of curvature after driving and withdrawal which allows some confidence that any pressure tubing access point would be positioned at the desired point underneath the melt body.

The screens would be connected to stainless steel tubing which, in turn, would be connected to pressure transducers above ground outside the hood. All tubes could be routed through bulkhead fittings at a designated hood panel and additional tubing extended to an array of pressure transducers at a location in a safe area (behind a barrier, etc.). Three-way valves could be fitted on each tubing line connected to a vacuum or pressurized air source which would allow each line to be blown clear should it become filled with water. A short length of nonmetallic tubing could also be inserted in the line outside the hood to electrically isolate the transducer and/or tubing fittings from operator contact. Pressure transducers themselves, their electric signal transmission, and data acquisition methods need to be investigated for proper system design; it appears that the present data acquisition system would probably be adequate for the maximum of 20 new sensors. Use of the previous PNNL pressure transducer array could also be planned.

In addition to curved pressure-sensing screen implants at or near the bottom of the projected melt depth, other implants at shallower depths could be placed through straight Geoprobe rods. Implant pressure-sensing screens could also be placed inside the bottom of vent pipes; a pressure differential between the bottom of a vent pipe and its top or the hood plenum may be a facile method of monitoring or verifying the functioning (flow) of the vent pipes. Just about every other gas flow monitoring technique would require putting some electronic sensor in the hostile environment of the vent pipe itself.

3.6.3.6. Holding in situ vitrification electrodes off melt body bottom

One strategy to minimize the amount of steam pressure building up under an ISV melt body as it contacts a dense subsurface barrier is to hold the electrodes up when electrode penetration approaches a known depth of a subsurface barrier. Geosafe used such a technique at the Wasatch site when ISV melt bodies approached the concrete floor of a residual evaporation/disposal pond. At Pit 1, electrodes could be held when approaching the depth of contact with the undisturbed rock. However, this technique will only slow down the melting depth velocity, but slowing down through the dense stratum may be sufficient to avoid conditions for a melt expulsion. At ORNL Pit 1, maximal contamination appears to rest on the contact with the undisturbed formation and, thus, it must be vitrified for several feet to assure treatment of all source contamination. Whether the undisturbed rock can be vitrified safely at any velocity is unknown. Nevertheless, holding electrodes from further penetration and slowing melt progress through a dense subsurface stratum has empirical evidence as to its merits in avoiding a melt expulsion.

3.6.3.7. Regulate power to in situ vitrification melt

There is only anecdotal testimony that previous melt expulsion events were preceded by electrical power fluctuations. It does seem plausible that if the path between electrodes is interrupted by significant gas bubbles, resistance would go up and, at the constant applied voltage, the current should fall and rise again as the electrical path is interrupted by a rising bubble in the melt body. However, it is not clear exactly how ISV operators will conclude this is happening. Operators would need to be watching monitor screens at the right time. An alarm condition among the ten or sensors which seem chronically and intermittently to alarm would need to be noticed. A large fluctuation must be seen in time to take action. A bubble fluctuation must be distinguished from a broken electrode condition. Thus, it is difficult to design such a monitoring or warning system and to know the exact antecedent characteristics of a melt expulsion.

3.6.3.8. Avoid melt body cold cap formation

Cold-cap formation can result in increased effective confining pressure for the ISV melt body on its submelt zone. As a cold cap collapses or is reincorporated into the melt body, the confining pressure is then afforded only by the hydrostatic (perhaps more correctly, lithostatic) head of the melt body, and pressurized steam could vent rapidly through the melt body. By preventing or eliminating cold-cap formation, fluctuations in effective confining pressure could be avoided and, possibly, rapid changes in steam venting through the melt body. What role a cold cap or its collapse may have played in the April melt expulsion is not known; the three days of low power to the melt body during the period of evaluation of the OAT phase of melting would be a condition conducive to formation of an extensive cold cap. Subsequent reestablishment of higher power to the melt after this three-day holding period would certainly have increased the steam generation rate.

Techniques to avoid cold caps from developing include maintenance of sufficient electrical power to the melt to prevent the cooling conditions necessary for cold-cap formation or frequent and regular electrode up-and-down movement to keep cap openings functional. Alternately, addition of melt temperature modifying materials (e.g., soda ash) to the cap surface would greatly lower cap-melting temperature and result in reincorporation of the cap material back into the melt. Another melt-lowering additive, limestone, was added to the Pit 1 melt at the end of the OAT. The degree to which it was incorporated into the melt is unknown except that limestone gravel was not visible on the present melt surface or expelled glass. However, the mixing during the melt-expulsion event is likely to have precluded the possibility of making this determination by examining the present melt surfaces or materials.

However, due to the unknown role of cold caps in contributing to submelt pressurization, such techniques cannot be advocated as a established technique for relief of submelt pressurization, although the concept seems desirable. Cold caps can, however, substantially reduced radiant heating to the off-gas plenum and result in much lower hood and off-gas temperature.

3.6.3.9. Manipulate in situ vitrification melt body configuration

An alternative to keeping the cold cap from forming and redissolving would be to approach the problem from the opposite direction by actively maintaining a large cold cap which would, in turn, maintain a significant confining strength, thereby preventing a melt expulsion. Such a situation could be envisioned by starting the melts at Pit 1 under several feet of confining soil overburden. This could readily be achieved by filling in the ISV startup trench with compacted soil after placing the starter path and/or starter sand. If a startup trench identical to that used in the initial Pit 1 melt setting

were employed, then such a subsurface startup would have an additional soil overburden of 7 ft to contain the melt body. This overburden would amount to an additional 4-5 psi of static pressure and a nominal unconfined compressive strength of 50 psi. It is difficult to determine if such additional effective confining pressure would be sufficient to prevent a melt expulsion or if it would only be sufficient to increase the failure pressure and, thus, increase the size of the expulsion event when it finally occurred.

In general, the risk of a melt expulsion is directly related to the size or mass of the ISV melt body and, indirectly, to the time required to melt a given volume of contaminated soil. Thus, alternatives to the standard ISV approach, of starting at the soil surface with electrodes spaced as far apart as necessary for the final desired width of the melt body, should be considered. The conventional ISV approach, particularly at Pit 1 where contamination is clustered in a layer near the original excavation depth, a large volume of uncontaminated fill soil has to be melted through just to approach the target contamination at depth. To some extent, the initiation of ISV at Pit 1 in a 7-ft deep starter trench, encompasses this approach by avoiding that much more unnecessary melting of clean soil; the primary reason for initiation of Pit 1 melting in a starter trench was to assure that the required melting depth was well within current ISV-depth capability, i.e., 21 ft. A deeper startup trench was considered but deemed problematic because of both the elevation of perched groundwater within the pit and the upward curvature of the source contamination layer along the sidewalls of the original excavation which was considered part of the source target. However, Geosafe has tested alternatives, involving electrode rectangular spacing and manipulation during melting which allows the melt body diameter to be widened as the melt progresses downward. This approach would avoid the unnecessary melting of the significant volume of uncontaminated soil with Pit 1. In addition, the approach would produce an inherently smaller mass and volume of melt while incorporating the same target contamination. Rectangular melts provide a shorter horizontal distance for vapors generated beneath the melt to escape upward around the melt body. It would be inherently less risky for melt expulsions because of the smaller melt body size. However, this approach, although it should be incorporated in future ISV operations if only from the economic view of lower cost resulting from lower operating time, would not in itself assure the elimination of a melt expulsion possibility and should be employed in combination with other techniques to reduce risks of melt expulsions.

3.6.3.10. Improve melt body visual monitoring system

There is additional anecdotal testimony that previous ISV burps were preceded by smaller bubbles or surface activity. It does appear plausible that excess steam generation under the melt would manifest itself through smaller bubbles first. Operators must see these bubbles in time to take action. Operators must be watching the video screens at the right time with all the other things they have to do.

The video viewing system, used during the initial melt at Pit 1, was grossly deficient in meeting its stated objectives. Obviously, the air-jet window cleaning technique did not function as the windows were rapidly coated with off-gas particulates and the video images were not discernable. The manual window cleaning operations used during Pit 1 ISV operations cannot be allowed during future operations. In addition to replacement of existing video cameras with ones of proper viewing angle and focus and an automatic iris to accommodate the variation in melt light emission, a remotely-controlled window cleaning system must be developed. Electric wiper window systems or rotating window systems are available for many kinds of chemically and thermally harsh environments and should be employed for future ISV monitoring. Testing of the selected window cleaning technique needs to be completed under similar environmental conditions to those

experienced or anticipated on the ISV hood. Monitoring of the melt body surface for motion, turbulence, bubbling, and brightness provide ISV operators with valuable information on melt behavior. Had a video monitoring system been operable during the April 1996 melt expulsion incident, extremely valuable information about the size, location, and kinetics of the expulsion event may have been obtained on the video recordings even if those recordings ended after the melt expulsion. Positioning of a video camera directly over the melt should be reconsidered because this puts the camera in a very vulnerable position for thermal stress. The importance of video imaging for ISV operations is such that redundant, probably for a total of three, cameras should be considered to assure continuity of visual monitoring.

3.6.3.11. General site characteristics conducive to melt expulsions

The ISV workshop, sponsored by DOE in Oak Ridge on October 15-17, 1996, reached several conclusions regarding site characteristics compatible with safe ISV operations (In Situ Vitrification Workshop Final Report, unnumbered, Office of Science and Technology, U.S. DOE, 1996). The two most important site attributes that are essential to melt expulsion event development and which, therefore, must be identified during site characterization are: 1) possible sources of gas or vapor generation, typically water, and 2) a confining structure or medium, either sealed containers or soil zones of low hydraulic conductivity. Although neither of these factors alone is believed to cause a melt expulsion event, the most prudent approach is to avoid or control both. Numerous additional factors such as porosity and permeability of the site, composition of the soils and wastes to be treated, etc. are important to planning, design, and operation of ISV. The presence of groundwater is readily characterized. Other possible sources of gas such as bound water, carbonate minerals, or volatile waste constituents can also be identified with only slightly greater difficulty.

In general, the workshop recommended that engineering methods to modify a site in preparation for ISV (e.g., dewatering or mechanical disruption) should be considered where analysis of characterization data indicate the possibility of a melt expulsion. For application of ISV to other pits and trenches in ORNL WAG 7, where perched but not necessarily recharge area groundwater elevations may be elevated higher than the required ISV target depth, dewatering and soil drying should be considered. Careful characterization of transitions in bulk density and/or lithologic characteristics will need to be pursued to determine if engineering methods for mechanical disruption of potential subsurface barriers is required.

3.6.4. Approaches To Minimize Impacts of Melt Expulsions on In Situ Vitrification Operations

Even with implementation of all the techniques and strategies to prevent ISV melt expulsions (Sect. 3.6.3), the degree of understanding of melt expulsion mechanisms is not sufficient to assure that they will not occur again. This condition of inadequate understanding is likely to continue for several years until enough experience with ISV in regions of saturated soil moisture is gained. Thus, more attention must be given to the management of a recurrence of the melt expulsion incident. First and foremost, operations personnel must be protected from injury during performance of necessary tasks in any hazardous zone around or on the off-gas hood. Second, protection of ISV equipment on or around the hood should be made sufficient to withstand a similar episode without the degree of damage incurred in the Pit 1 melt expulsion and to maintain the functional status of the ISV equipment.

3.6.4.1. Internal berm to eliminate glass flow and particle releases

A great deal of damage after the Pit 1 melt expulsion could have been prevented by the use of a small soil berm inside the hood to contain molten material flow and prevent its contacting hood walls and flowing out underneath as the hood lifted. Such containment could prevent much of the thermal damage of hood panels and the secondary fires outside the hood which were caused by direct contact between molten glass and combustible materials. In addition, both the formation and dispersion of the fibrous contaminated glass particles could also have been prevented; these hair-like fibers were formed when high velocity off-gas was blowing over the pool of molten material just beneath the raised hood panel foot. A convincing picture (Fig. 5 in ESERP 1996b) of such fibers, frozen in the process of formation, was captured after the melt expulsion incident near the edge of the off-gas hood. Even a low earthen berm, constructed by plowing up the uncontaminated surface soil, just inside the perimeter of the hood, would block surface flow of molten material; in addition to preventing the formation of the contaminated fibrous glass, and would also prevent the escape of molten glass from the hood perimeter with all of its consequent damage and effects.

3.6.4.2. Thermal protection of in situ vitrification hood equipment

Although much of hood damage sustained during the Pit 1 melt expulsion resulted from escape of molten glass at the hood perimeter and associated secondary fires, all components on and in close proximity to the hood would still endure a considerable thermal stress during a melt expulsion if the hood is again heated to a cherry-red glowing temperature, even if molten glass escape was eliminated by the use of the earthen berm described above. Several modest equipment changes could be performed which could result in a fully functional hood after a melt expulsion.

Roughing filter splash guard. The roughing filter needs to be protected in future melt operations because, whether or not the hood leaves the ground in future melt expulsions, the roughing filter will likely sustain similar damage from direct splashes of molten glass. Practically all the 128 filter elements were splashed with molten glass, which adhered well to the ceramic fabric. More importantly, when sampling the fabric, it was found to be extremely brittle and friable. Initially, the fabric is quite flexible and durable and, even when sampled after the OAT, it was still quite strong and not noticeably brittle or friable. Nextel® fabric has a specified temperature resistance of 1204°C for short duration and 760°C for continuous use. It is not known whether the brittleness of the ceramic fabric after the event was the result of its proximity to and contact by molten glass or a result of the general thermal surge within the hood. Regardless, the roughing filter bags should be protected from melt splashes in the future. If a redesigned hood could vent off-gas well, i.e., sustain no mechanical damage, and also endure the thermal shock without damage to wires, air, and hydraulic lines, then a probable down time of several weeks simply to replace damaged roughing filter bags, which would be covered with radioactive glass, would be very short-sighted. In addition, the cost of replacing all the bags and fingers and refabricating the badly warped filter housing was over \$100,000. It is not known whether such a thermal shock, but without the splashing with molten glass, would maintain a functional filter. However, it would be unlikely that damage to metallic components would occur and the remainder of an interrupted melt could still be performed with the roughing filter by-passed. Conceptual designs for a metallic splash guard for the roughing filter have been proposed and fabrication of the splash guard seems fairly easy and inexpensive.

Remove vulnerable hood controls from potential impact zone. Most of the hood subsystem controls were mounted on the main beam outside perimeter and included the circuit breaker boxes for all systems, the hood automotive control system, the material addition system controls, the off-gas sampler, the roughing filter blow-back controls, light switches, video camera controls, and the

air-compressor controls. Practically all of these systems received some damage due to the thermal impacts of the melt expulsion. In addition, the melt perimeter monitoring wells were located approximately 10 ft to the north and south of the hood as were the staging areas for graphite electrode section loading onto their hoists. All of these controls and monitors could be either moved outside the possible thermally affected area or protected with insulation. Details of the possible means to control thermal damage to these systems are described in the summary of the melt expulsion (ESERP 1996a 1996b) and need not be repeated here. In addition, movement of these controls and monitoring instruments outside the possible hazardous zone will preclude the need for operations personnel to enter hazardous areas for their operation.

Remove combustibles from potential impact zone. It would be quite expensive to relocate all of the hood's vulnerable equipment outside the danger zone. However, most of the damage to the equipment on the hood's superstructure base was caused by secondary fires. Thus, removal of all possible combustible material from the danger zone would greatly reduce most of these secondary fires. Items such as wooden cribbing and fiberglass grate walkways would be quite simple to remove. Items like the hood's tires would be more difficult but possible to remove prior to ISV operations.

Other thermal damage was caused by proximity to expelled molten glass. Items such as electrical conduit, hydraulic lines, electrical junction and circuit breaker boxes and instrument housings can be protected by being wrapped in high temperature insulation, particularly on their bottom and inside surface where most of the paint scorching has been observed. Electrical cords and sensor signal wires on the hood work platform can also be insulated to protect them against the relatively short duration thermal insult of such a melt expulsion. Tires, if not removed, can be protected by rigid thermal insulation boards. Additional insulation of the superstructure's main beam and components can be placed around areas near any venting structures on the hood.

Hood Spray System. A hood-cooling external water spray system, similar to that designed by Geosafe for their ISV off-gas hood, could provide excellent additional equipment protection. The Geosafe spray system does not function to cool hood panels but only to propel mist into the air surrounding the hood, thus, cooling and preventing combustibles from igniting. Such a system would need to deliver a significant volume of water and be manually activated by operations personnel in response to predetermined criteria.

3.6.4.3. Off-gas deflection barrier

One of the fortuitous results of off-gas jetting from under the hood on the north side during the Pit 1 melt expulsion was the presence of a steep slope between the hood and the off-gas control trailer where the pit surface had been graded down approximately 4 ft. This steep slope functioned to divert the hot off-gas jet up into the atmosphere rather than into the side of the trailer. The singed, unaffected grass boundary on the top of this embankment left a direct record of this deflection of hot gas. This fortuitous result pointed to the effectiveness of deflecting expelled off-gas from horizontal flow where the potential for personnel injury is greatest. Thus, a perimeter deflecting structure can be used as a secondary confining barrier for uncontrolled off-gas release and function to protect equipment and personnel from injury. The barrier itself could be made of concrete, steel, or earthen materials. Its function as a safety system will necessitate a detailed engineering evaluation of its effectiveness. A deflection barrier would seem a prudent feature for future ISV operations in addition to any pressure relief designs in case the venting design should prove inadequate for some large-magnitude or other unanticipated event. Such a barrier could be as simple as an interlocking line of concrete "Jersey Bouncers" which are commonly used for traffic separation and deflection on high-speed highways. By moving this deflection barrier as close to the hood as possible,

deflection of off-gas from a maximum 12-in. hood rise could be achieved even by a standard 3-ft concrete barrier. Design considerations need to address the aerodynamics of such a barrier at different and maximum off-gas jet velocities on the area outside the barrier. Presumably, an inexpensive and well designed and tested barrier could be implemented in routine ISV operations.

3.6.4.4. Automation of electrode additions

The present off-gas hood design could not be modified to allow automation of the electrode section additions. This major task required operating personnel to transit the danger zone both around the hood and on the hood work platform to add electrode sections. The present design of the electrode hoist system has only enough room for an extension of one 6-ft long graphite section above the hood penetration point. Thus, after a melt has proceeded downward the length of one electrode section or when an electrode column breaks, operating personnel would still need to perform this task manually on the hood work platform. The hoist is disconnected from the electrode column in the melt and used to lift, position, and attach another section onto the existing electrode column. Although various improvements to this process, to decrease the time required to complete it or the number of personnel needed have been discussed in the summary of the melt expulsion (ESERP 1996b), this task cannot be eliminated by any simple engineering solution. A considerable effort was expended on a value engineering study in July 1996 to elicit engineering design concepts to address this critical element (see project record files for draft report issued August 18, 1996). With the indefinite delay or termination of the Pit 1 project, restart of ISV operations should consider such a redesign effort on any new hood. Hopefully, this one remaining hazardous task can be eliminated through automation of the electrode addition process.

3.6.4.5. Modeling and testing of melt expulsion safe conditions

One of the recommendations of the October 1996 ISV workshop report was that projections of ISV performance (modeling) should be part of every application. In particular the Pit 1 melt expulsion can be attributed to the build-up of steam pressure beneath the melt body. To evaluate various techniques to overcome this problem (such as water table suppression or dynamic disruption of dense subsurface strata) coupled thermal-hydraulic modeling offers the greatest potential to understand and assess the contribution of various site characteristics and process parameters to the melt expulsion. Spatial and temporal modeling of steam pressure beneath ISV melt bodies has been attempted previously (Roberts et al. 1992). Even some preliminary modeling of the Pit 1 configuration and site characteristics has been initiated (P. S. Lowery, project records). However, modeling, in itself, will not be sufficient to provide assurance of adequate understanding and control of the ISV process. A physical testing method will need to be developed to validate model results for key site parameters like permeability, porosity, and fluid movement in response to thermal inputs and gradients. Modeling can provide guidance in testing and in the sensitivity to process parameters of testing devices and monitoring techniques. Thus, modeling and testing of soil pressurization need to be pursued simultaneously to develop adequate understanding of the ISV melt expulsion process so that conditions conducive to its occurrence can be avoided.

3.6.4.6. Automation of personnel tasks in the potential impact zone

During Pit 1 ISV operations, several routine tasks were performed by the operators within what, in hindsight, would be classified as a hazardous zone. These tasks included measurement of groundwater levels, roughing filter blow-back adjustments, off-gas sampler and monitor checks, adjustments, and repairs, air-compressor resets and adjustments, turning outside lighting on and off, video camera adjustments, repair, and window cleaning, radiation surveys, watering of soil around

hood base to improve hood-to-ground seal, solids addition through the material addition system, and addition of electrode sections. All of these tasks, except electrode addition, have relatively straightforward conceptual techniques to either automate, eliminate, or remove them to areas outside the potential impact zone; several approaches are discussed in the technical evaluation summary (ESERP 1996a and 1996b) and will not be reiterated here. During ISV operations, even when power is interrupted to the melt body, the potential for a melt expulsion will continue to exist and these tasks should not be performed manually by operations personnel in future ISV operations. Thus, ISV operational procedures in the future will need to devise methods to automate, eliminate, or remove such tasks from the potential impact zone of a melt expulsion.

3.6.5 In Situ Vitrification Equipment Modifications for Improved Routine Operations

In addition to the changes to ISV equipment and procedures mandated by the risks of another melt expulsion, the results of the Pit 1 ISV operational performance suggest several possible changes in equipment or operations which could reduce cost, improve performance, and reduce risks.

3.6.5.1. Off-gas handling alternatives for radionuclides

The off-gas filtration results, discussed in Sect. 3.3, established the effectiveness of both the roughing filtration system, using Nextel® high-temperature ceramic filter fabric, and high-temperature HEPA prefiltration to remove all radionuclides entrained in the ISV off-gas. Thus, the need for off-gas scrubbing in the ISV process trailer can be questioned, as this process merely removed residual acidic gasses which otherwise could have been released to the air, because particulates and their associated radioactive contaminants in the off-gas had already been removed. Thus, the amount of time and effort expended in maintaining the operation of the off-gas scrubbing system may not be necessary for future ISV operations. All moisture, generated from the ISV melt, could be discharged to air rather than condensed as a large volume of secondary waste. The future ISV off-gas system design needs to focus on filtration techniques, perhaps with a variety of contingency treatment options and backup systems. Maintaining the effectiveness of either filtration system will depend on preventing moisture from condensing out of the off-gas and clogging filter materials. Thus, supplemental off-gas heating may be necessary at various points in any reconfigured off-gas handling system. Future filtration systems should be positioned as near the point of collection within the hood as possible to keep radioactive contamination and associated doses away from ISV operators. Methods to return filtered particulate to the melt body, like the roughing filter blowback system, should be pursued in future designs as well as techniques to return spent or contaminated filters themselves to the melt or to subsequent melt bodies. Such off-gas handling techniques could greatly reduce quantities of secondary filter wastes.

3.6.5.2. Upgrade process control, monitoring, and data logging system

Pit 1 ISV operations revealed many significant limitations with the two Bailey process controllers currently employed in the large-scale ISV equipment. Although these controllers were state-of-the-art industrial process controllers when the large-scale equipment was constructed in 1984, they have limited data display, reaction time, and data storage and logging capabilities by present-day standards. For example, it required several days to download process data to useful standard floppy disks after the melt expulsion event. The limited storage capability necessitated that key process data be collected as 4-min average values; this condition eliminated the possibility of recording the needed time resolution of key parameters (e.g., electrical current and voltage fluctuations prior and during the melt expulsion) which may have aided in the understanding of this event. Current industrial process controllers have much improved data storage, logging, and control

functions and could greatly improve both process control and data logging of the many sensors necessary for ISV control and monitoring.

3.6.5.3. Three-phase versus present two-phase power transformation

The present use of two-phase electrical power to an array of four electrodes for ISV requires the transformation of standard three-phase line-supplied power to two-phase secondary power. The transformation is rather rare in industrial processes and the 3750-kVA transformer is a custom manufactured unit and, thus, has many singularities. Transformation of three-phase primary to three-phase secondary power has been evaluated as one of several potential process improvements for ISV operations (Luey et al. 1992) ; PNNL has procured a new 1.25 MW three-phase transformer for the pilot-scale ISV equipment although this unit has yet to be tested in ISV operations. For future ISV operations, the use of three-phase power transformation should be carefully evaluated. Three-phase (electrode) delivery would inherently have a smaller melt diameter than a four-phase electrode configuration.

3.6.5.4. Off-gas hood design changes

As discussed in Sect. 3.6.4.4, the present off-gas hood is not amenable to modification to automate the electrode addition process so that ISV operators can remain outside the potential impact zone of a melt expulsion. The design of any future ISV off-gas hood needs to address either the automation of this process during ISV operations or, alternately, a method to assemble and maintain an electrode column of sufficient length prior to the start of ISV operations. The latter electrode column probably needs to be at least six sections long (36 ft total length) with a total weight of 3,048 lb when using 12-in. diameter graphite. Stabilization of such a column length, along with electrical isolation and maintenance of electrical contact, will pose some challenge to the designer. On the other hand, automation of the electrode process with its manipulation for lifting, positioning, and rotating graphite sections and the loosening and tightening of nut-and-bolt fixtures and electrical contacts will also pose some design challenges.

3.6.5.5. Off-gas piping and routing

During the Pit 1 ISV equipment setup, the amount of time and labor spent on off-gas pipe fabrication and assembly was very large. The need for elevation of the off-gas line and the use of bolted flange connection techniques could be redesigned for much more flexibility in its configuration. This could save setup time and costs, as well as time and costs for hood mobilization between melt settings. The function of the off-gas line is to connect the off-gas hood to the process trailer where the scrubbing operations are performed. If the need for off-gas scrubbing can be eliminated, as discussed in Sect. 3.6.5.1, and filtration systems can be moved onto the hood, a fixed pipe off-gas line may no longer be necessary. Perhaps, only a flexible line to supply hood vacuum may be all that is needed. Any of a variety of design concepts may result in ISV equipment of greatly improved simplicity. Alternately, if the present off-gas piping approach should remain, more flexible joints and routing options can be designed with a view to reducing assembly, disassembly and fabrication costs.

3.6.6. In Situ Vitrification Operating Procedural Changes for Improved Productivity

Short of the major modifications to ISV equipment, discussed in Sect. 3.6.5, several changes in operational procedures, using existing or similar equipment, may be possible for improved efficiency in ISV operations.

3.6.6.1. Discharge rather than condense all water

One of the conclusions from the evaluation of the off-gas scrubbing system, when used with the roughing filter and HEPA prefilter systems during Pit 1 ISV operations, was that it had no function in the removal of radioactive contaminants which had already been effectively removed from the off-gas by the filter systems. Because the scrubbing operations of this system need to operate well below the boiling point of water, a great deal of moisture is condensed by the system and results in a large volume of liquid waste. By-passing the wet scrubber system may be quite feasible for future ISV operations using the same or similar equipment. However, protection of the off-gas blower from acidic off-gas corrosion must also be considered. The scrubber system could remain as a backup off-gas processing system should one or more of the filtration systems fail during operation. In addition to the reduction in secondary waste volume, by-passing the scrubber should eliminate a significant amount of operator time required to monitor, sample, and maintain this system.

3.6.6.2. Automate all off-gas monitoring and sampling

A significant amount of ISV operator time was devoted to checking, adjusting, and repairing monitors and samplers of the ISV off-gas. The Pit 1 ISV operations were part of a treatability study to determine best practices and technical approaches for future routine ISV operations. Thus, many of the off-gas sampling approaches were, at best, experimental and, therefore, required a lot of operator time to adjust. The major finding of the Pit 1 off-gas monitoring was that the radionuclide contaminants were all very particle reactive and, thus, were facilely removed by various filters in the off-gas line. Monitoring of off-gas also employed filtration both as a sampling technique and as a technique to concentrate radioactivity for presentation to various radioactive detectors. However, frequent filtration problems were encountered due to condensation of moisture on sampler filters and resulting disintegration of the paper filters. Automation of off-gas sampling must focus on keeping the off-gas well above its dew point (heated) until the filter has been passed. Although such automated sampling and monitoring techniques may require significant investment for their proper design, the savings in operator time can recoup that investment very quickly from time savings in routine operations.

3.6.7. Public Information and Involvement

The implementation and selection of ISV technology for remediation of the WAG 7 seepage pits and trenches or other waste management units in Oak Ridge will require a considerable effort to involve the public in the decision process and, thereby, increase their appreciation of its benefits. Unfortunately, the melt expulsion at Pit 1 has probably left an impression in many minds that ISV technology is both unsafe and environmentally risky. The Site-Specific Advisory Board will need to be fully informed as an initial part of this effort. The main findings of the Pit 1 treatability study are the excellence of the waste form, compared to any other technology, and the inherent conservancy of the process with respect to off-gas release of radioactivity during normal and accident situations. Much work remains to be done on economic comparison of ISV with other technical options for Oak Ridge contaminated soils, particularly the inherent large costs of any technology which requires long-term monitoring. The ability to prevent, control, or endure melt expulsions during ISV operations needs to be factored into the operating cost as well as programmatic and public expectations. Increased and continued experience with ISV operations in very humid regions with saturated soil near the ground surface, like Oak Ridge, will, by necessity, result in empirical procedures and strategies which minimize the probability of future melt expulsions. Alternately, ISV applications to WAG 7 pits and trenches could address the technical

challenges of high water tables and dense subsurface barriers by selecting future sites to avoid, at least initially, such conditions and increase the degree of difficulty as further experience is gained. These risks are small and manageable compared to the enormous benefits of essentially permanent and complete waste isolation of radioactive contaminants from virtually all future environmental transport.

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