



**ENVIRONMENTAL
RESTORATION
PROGRAM**

**Technical Evaluation
of the In Situ Vitrification Melt Expulsion
at the Oak Ridge National Laboratory
on April 21, 1996,
Oak Ridge, Tennessee**

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Energy Systems Environmental Restoration Program

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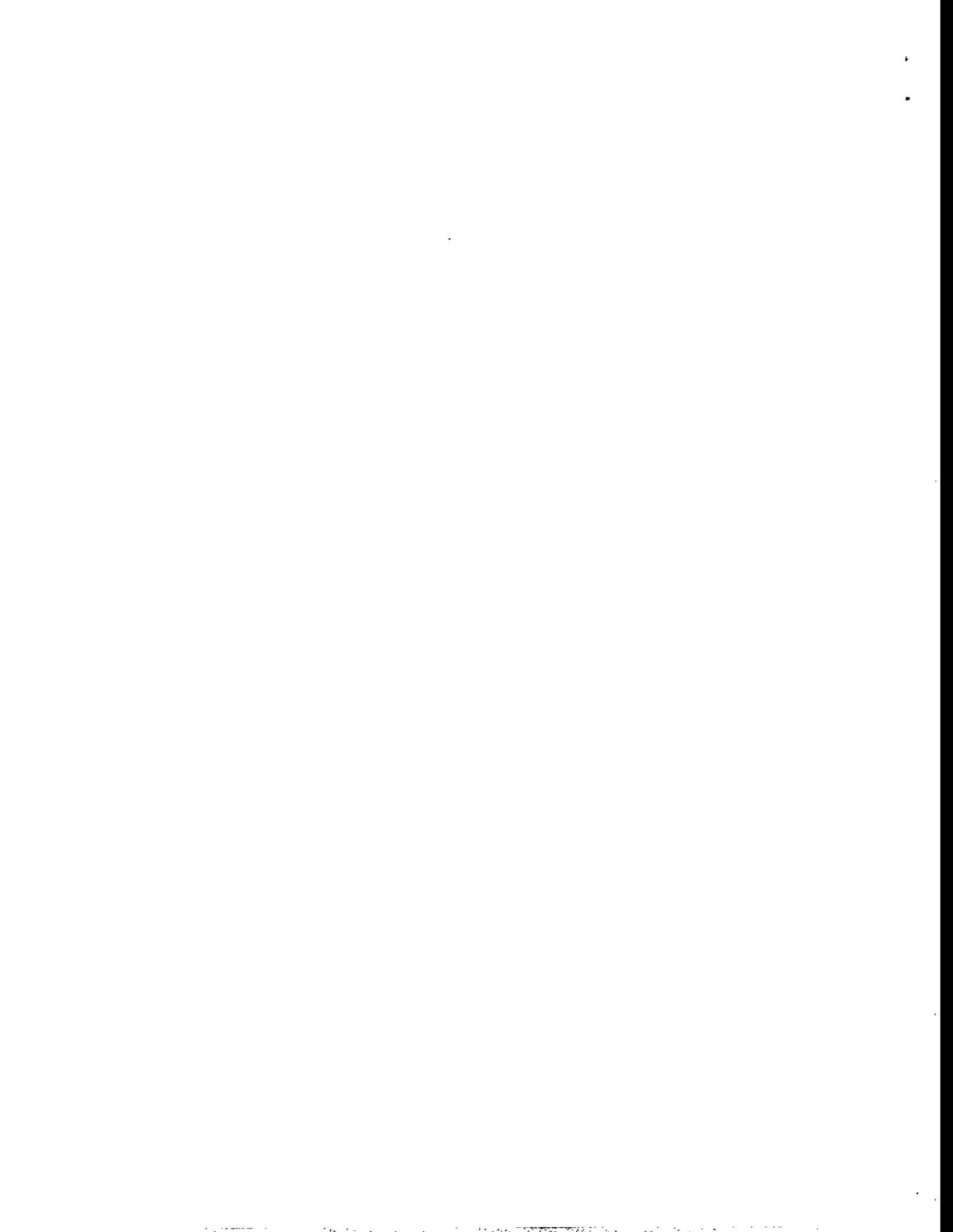
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This technical evaluation was performed by a group of in situ vitrification project personnel with significant input from Brian Spalding, Mike Nancy, Steve Cline, and Mary Anna Bogle of the Environmental Sciences Division, Oak Ridge National Laboratory; John Tixier of Battelle Pacific Northwest Laboratory; and Craig Timmerman of Geosafe, Inc.

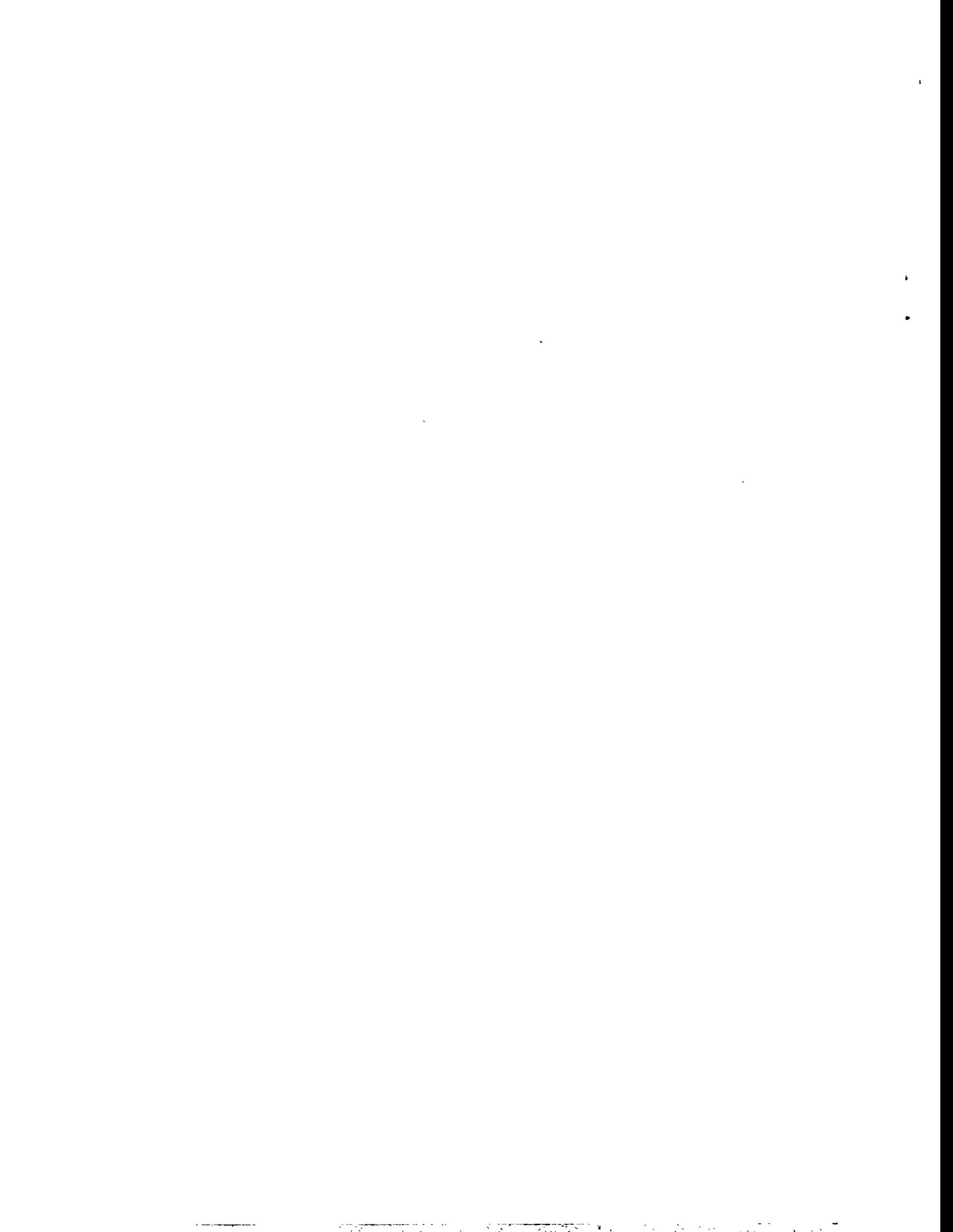


PREFACE

This Technical Evaluation of the In Situ Vitrification Melt Expulsion at the Oak Ridge National Laboratory on April 21, 1996, was prepared at the request of the Department of Energy as a supporting reference document for the Final Unusual Occurrence Report to fully explore the probable causes that lead to the subject incident.

This work was performed under Work Breakdown Structure 1.4.12.6.1.07 (Activity Data Sheet 3307, "Waste Area Grouping 7 In Situ Vitrification"). This document provides the Environmental Restoration Program with the information with the technical information on the performance of the in situ vitrification treatability study operations at ORNL pit 1 up to and including the time of the melt expulsion incident

This document also attempts to diagnose the causes of the melt expulsion event, the consequent damages to equipment, the radiological impacts of the event, and the equipment design modifications and procedural changes necessary for future safe ISV operations. A companion document, *Environmental Health and Safety Independent Investigation of the In Situ Vitrification Melt Expulsion at the Oak Ridge National Laboratory, Oak Ridge, Tennessee* (ORNL/ER-371) has also been issued that focuses on the results of an independent team's investigation of the project's operation, management, and oversight activities, which did not strongly affect such a melt event scenario.



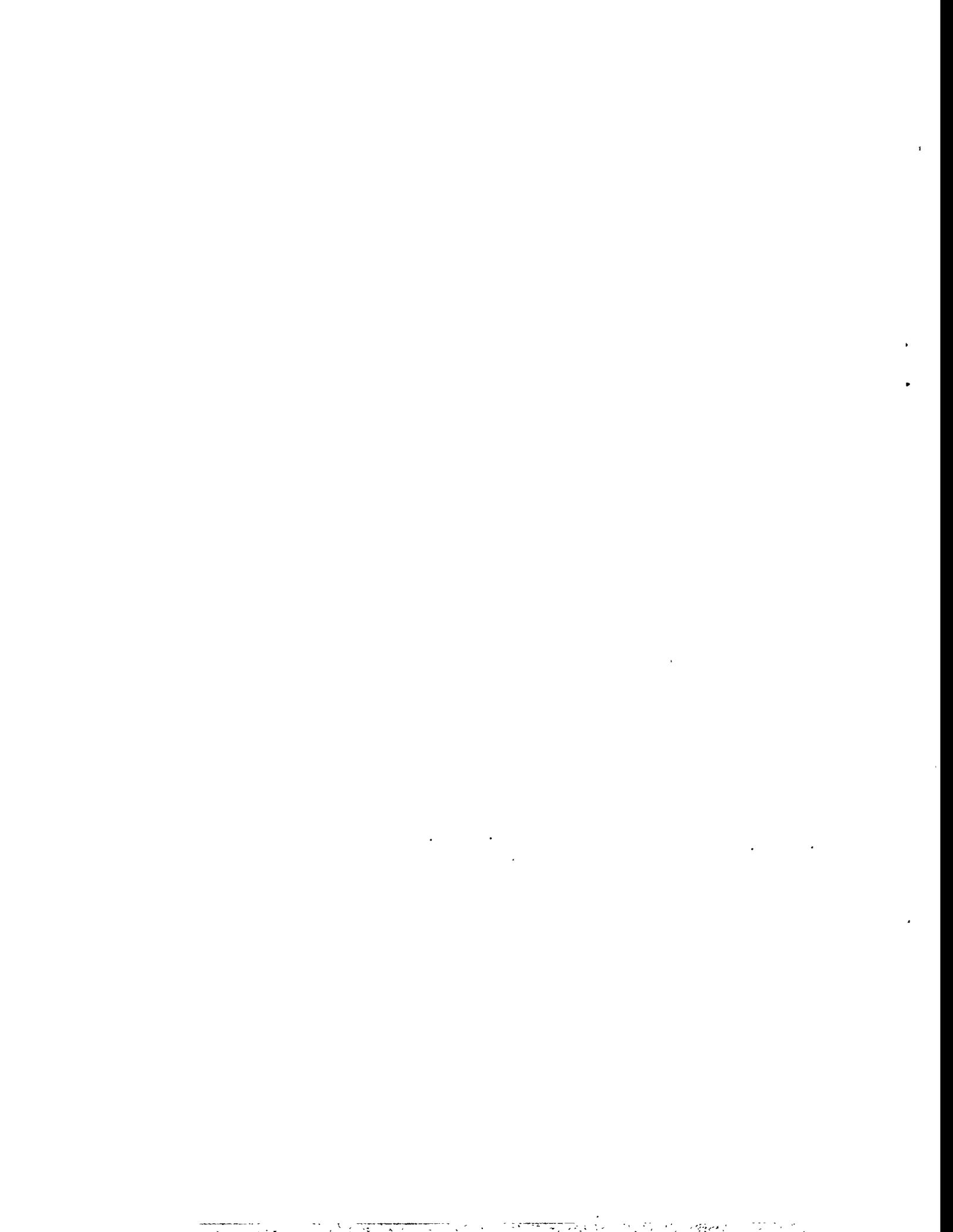
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ABBREVIATIONS

DAS	data acquisition system
DOE	Department of Energy
EDT	Eastern Daylight Time
EPA	Environmental Protection Agency
HEPA	high efficiency particulate air
ISV	in situ vitrification
kWh	kilowatt-hour
LMES	Lockheed Martin Energy Systems
MAS	material addition system
MMS	modified method 5
MW	megawatt
NGVD	National geodetic vertical datum
OAT	Operational Acceptance Test
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
T100P	temperature of 100 poise viscosity
UST	underground storage tank

EXECUTIVE SUMMARY

On April 21, 1996, at 6:12 p.m., approximately 20 tons of molten glass were expelled from a 216-ton body of molten (approximately 1600°C) radioactively contaminated soil (containing 2.4 Ci of ^{137}Cs) at a field site at the Oak Ridge National Laboratory in Oak Ridge, Tennessee.

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 in situ vitrification (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 and covered with a stainless steel hood maintained under negative pressure to collect, filter, scrub, and monitor off-gas.

Off-gas into the hood was rapidly heated by the melt expulsion from a typical operating temperature of 250°C to over 1000°C with an associated surge of pressure sufficient to lift the 15,000-lb hood approximately 12 in. off the ground. 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 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). 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 failed to detect any airborne 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 0.13 μCi of ^{137}Cs could have been released. This activity of ^{137}Cs could have delivered a hypothetical and unmeasurable dose of 0.02 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 have contained 99.7% of all off-gas radioactivity. Moreover, the residual molten material was found to contain 99.9981% 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 pool of molten glass. Many light pieces of fiberglass were apparent as well as a few globular clusters. Subsequent cleanup efforts revealed a total of only a few pounds of these contaminated fibers at the site.

All expelled glass particles were found to have a uniform specific activity (1.2E-08 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 were 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 \$150,000 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 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 will 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. Personnel protective clothing for thermal stress will be required for this task.

The off-gas hood itself, in addition to repairs, will be modified to handle future melt expulsion events in a controlled manner without lifting from the ground. Vents will 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 will 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 the melt body, will be protected by a guard to prevent damage by splashes of molten glass.

The root cause of the melt expulsion incident was inadequate design for project operations. The melt expulsion scenario was clearly not considered very probable; thus, its potential effects were not addressed in either the equipment design or the project procedures. Although similar melt expulsions events had been experienced in 3 of the previous 70 large-scale ISV melts, previous incident investigations have implicated man-made subterranean structures (e.g., tanks, concrete barriers, drums), which were thought to constrict the normal flow and dissipation of off-gas around the growing molten body.

Off-gas from ISV melts is composed mostly of steam as soil moisture is distilled due to its 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 contributed to constrain off-gas (steam) movement around the melt body in the soil-filled pit during ISV. Although several corrective actions are planned 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 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.

Several 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 ~10 ft below the regularly monitored elevation of standing water in the pit within 20 lateral ft of the melt body. 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, no 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.

Second, flow-monitored and curved vent pipes need to be installed 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 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 in the present incident.

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 can 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 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 video monitoring capability due to fouling of windows, which resulted in extremely poor to entirely indistinct video images.

1. EVENT SUMMARY DESCRIPTION

An old seepage pit, last used for the disposal of radioactive liquid waste in 1951, was being converted from its present condition of untreated contaminated residual soil into an improved glass waste form as part of an in situ vitrification (ISV) demonstration project. Approximately 2 MW of electrical power was being supplied to the ground, and an estimated 216 tons [196 metric tons (Mg)] of molten soil, containing 2.43 Ci of radioactivity of which more than 99% was ^{137}Cs , was being processed at the time of the melt expulsion incident. The ISV melting operations had been occurring normally at the site since April 4, with several planned interruptions for equipment testing and sampling and had been in continuous normal operations for about 72 h immediately prior to this melt expulsion incident.

At about 6:12 p.m. EDT, Sunday, April 21, 1996, a significant melt expulsion incident occurred during field operations of an ISV project at Oak Ridge National Laboratory (ORNL). Apparently, a large expulsion of steam and molten glass occurred causing the overlying off-gas collection hood to displace, vertically releasing the hot pressurized steam (Fig. 1). No personnel were injured nor were any personnel contaminated as a result of this melt expulsion incident. However, within seconds of the hot gas and/or molten glass release, peripheral combustible equipment (electrical insulation, rubber hoses, fiberglass trays, etc.) on and around the off-gas hood caught fire due to the intense heat (Fig. 2). Emergency personnel were notified and were on site by 6:15 p.m. All electrical power to the ISV equipment was turned off at the emergency switch at the site. But fire-fighting actions were not recommended or taken due to the unknown potential for large steam releases from the still hot hood and surrounding equipment. The small smoldering fires were allowed to self-extinguish as the source of intense heat dissipated quickly.

Samples of air and smoke from within the site, taken during the residual fires, revealed no radioactive contamination other than natural radon, which emanates from any heated soil. However, later that evening, numerous pieces of radioactive glass were found on-site, apparently ejected from the ISV melt during the melt expulsion incident. As a precaution, the Melton Valley Access gate (Post 24) was closed to all traffic until more detailed surveys were completed. As a further precaution, site personnel present during the melt expulsion incident underwent whole body assays and urine analyses, which determined that no low-level contamination had occurred. It appears that radioactivity was well contained within the ISV glass and 0.13 μCi of ^{137}Cs was emitted to the air during the melt expulsion incident. This amount of activity, even if channeled to the nearest residence on the perimeter of the Oak Ridge Reservation, would not result in a measurable or detectable dose, i.e., about 0.02 μrem .

2. MAJOR CONCERNS DURING AND AFTER THE MELT EXPULSION INCIDENT

Major concerns for the ORNL ISV project were raised by this melt expulsion incident and break down into three categories: personnel safety, environmental contamination, and equipment damage. These are discussed by category although many concerns overlap categories.

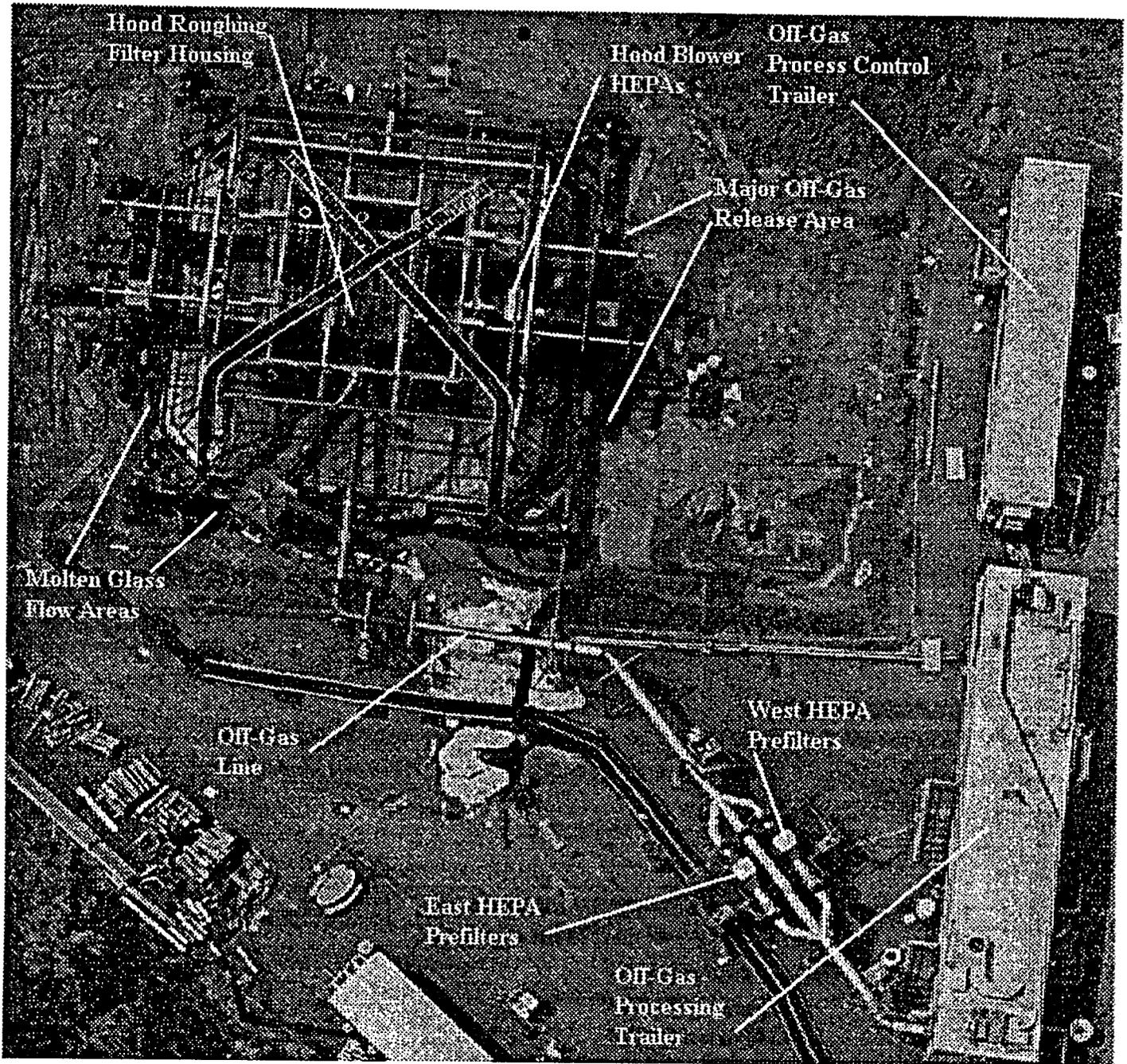


Fig. 1. Aerial photograph of ORNL ISV site on April 22, 1996, with notations showing locations of key equipment and pertinent incident areas.

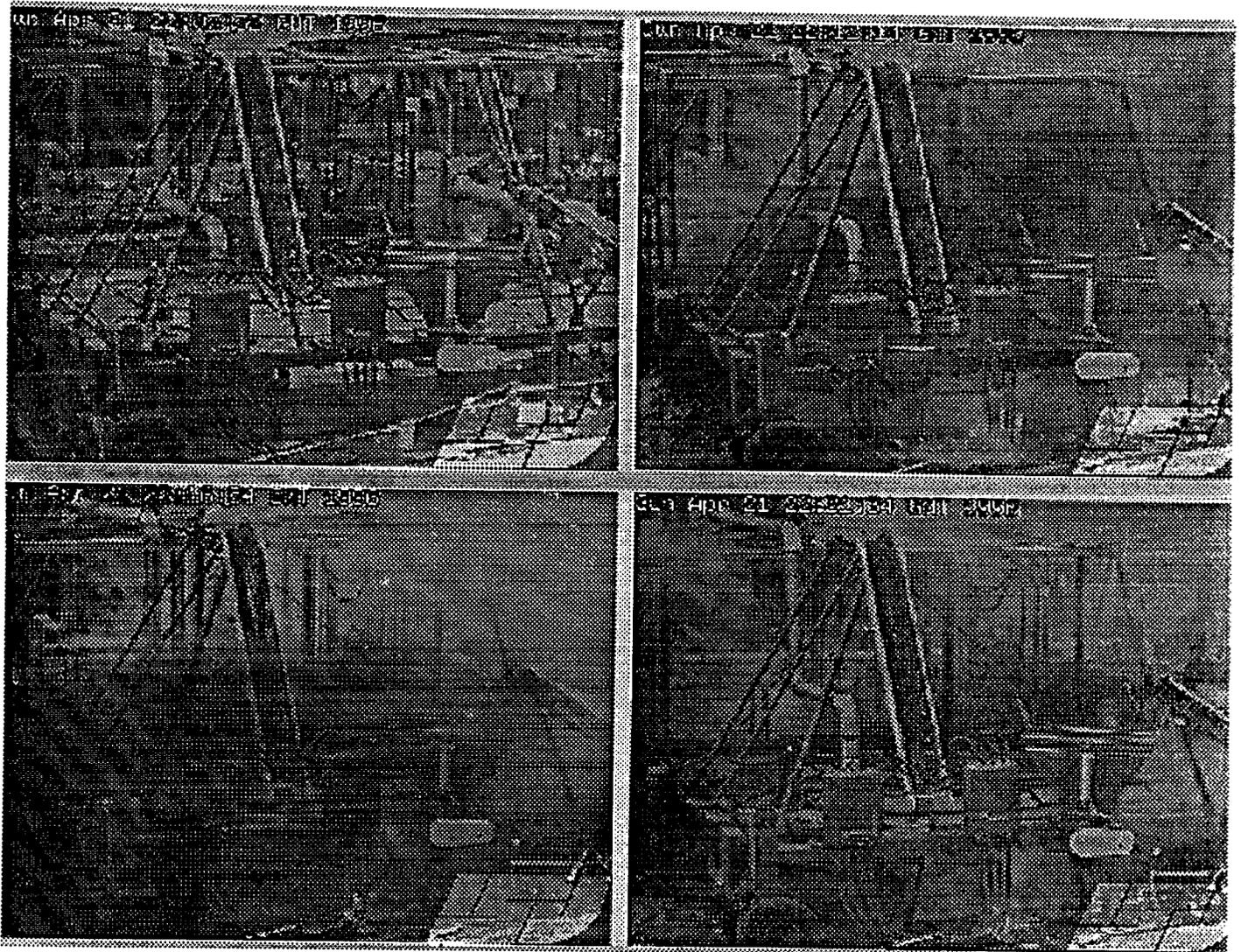


Fig. 2. Sequence of video monitoring images captured at 5-min intervals immediately before to 10 min after the ISV incident of April 21, 1996.

2.1 PERSONNEL SAFETY

During the ISV melt expulsion incident, four personnel were on site. The shift engineer and one operator were in the process control trailer monitoring process parameters during the melt expulsion incident. The second ISV operator was on a ladder outside preparing the off-gas sampling apparatus downstream of the west prefilter housing (Fig. 1) just to the northeast of the hood. A radiation protection technician was in the portable office/break building just east of the off-gas hood.

The outside ISV operator reported hearing a thud-like sound followed by a "ka-whoom." He reported seeing the north end of the off-gas hood raise about a foot from the ground and glowing hot gases issuing from the opening beneath the raised panels. The glowing jet of gases appeared to extend about 6 ft to the north. The jetting lasted only a few seconds and the hood returned to the ground surface. He then climbed down the ladder and ran to the east of the site meeting the radiation protection technician who had exited on hearing the unusual sounds from the off-gas hood. Both these personnel proceeded to the small rise just to the east of the site on Melton Valley Access road. They both reported that the hood panels appeared to glow cherry-red when they looked back within the first minute of the melt expulsion incident.

The other ISV operator and the shift engineer reported observing a strong glow to the video image from the off-gas hood; the video image from the side camera was completely indistinguishable due to rapid accumulation of particles on its window through the hood wall. But it had been used as a kind of "optical pyrometer" over the previous several days, glowing more or less as the surface of the melt heated or cooled.

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. He reported feeling a slight tremor and hit the emergency electrode power switch (this engineer had been on duty during a previous ISV melt expulsion incident in Richland, Washington, in 1991 and recognized the melt expulsion incident's symptoms as identical to that previous event). He immediately called 911 for emergency assistance and then the ORNL project team leader, who was approximately a half-mile away in his office in ORNL Bldg. 1505.

While on the telephone, the shift engineer reported viewing the off-gas through the window on the south side of the process control trailer. He also reported seeing the same jet of hot gas discharging directly towards him and the off-gas process control trailer. He moved away from the window expecting to feel a strong blast but did not. Subsequent viewing of the areas charred by the jet gas revealed that the steep 4-ft high embankment between the off-gas hood and control trailer deflected the hot gases up into the atmosphere rather than into the process control trailer. The ISV operator, who was in the process control trailer with the shift engineer at the time of the melt expulsion incident, left to check on the safety and location of the outside ISV operator and the radiation protection technician. All site personnel eventually met at the designated assembly point near the Melton Valley Access gate slightly after the arrival of emergency responders.

About this same time, both the ORNL project team leader and the Pacific Northwest National Laboratory (PNNL) project manager arrived on site from their offices in Bldg. 1505. Fire department personnel were preparing to fight the fires in peripheral combustible equipment (electrical cables, plastics, fiberglass walkways, etc.) on and around the off-gas hood. The ORNL project team leader cautioned them to wait until power was completely turned off at the site before spraying any water onto these small fires. He then proceeded to turn off power at the emergency switch on the site power pole and, following the startup of the emergency generator, proceeded to turn off the emergency generator. He met the shift engineer

leaving the process control trailer on the way to the portable generator trailer. Upon returning to fire department personnel and consulting with the PNNL program manager, it was decided not to fight the small fires on the hood perimeter as a large amount of steam would likely be generated with unknown effects on possibly continuing or further release of radioactive off-gas.

No personnel were injured during the melt expulsion incident because no personnel were in the danger zones on or immediately around the hood. However, such a scenario of off-gas release was not addressed in personnel safety planning for this project; had project personnel been performing any of several routine tasks on or around the off-gas hood, they would have been at considerable risk of injury. Previous ISV off-gas pressurization and melt expulsion incidents had all involved buried structures in the soil subsurface, which were believed to constrain off-gas flow away from and around the melt bodies. In the present ISV operations, no man-made structures were contained in ORNL pit 1, thus, it was believed that such a off-gas constraint scenario would not be possible there.

As an additional precaution for off-gas pressurization and, thus, a tacit admission that it might occur, vent pipes were installed at various depths and angles beneath the predicted melt geometries at various times; these pipes were to provide reduced-resistance conduit for ISV off-gas to the collection hood rather than relying completely on the natural porosity of the soil in pit 1. Whether these vent pipes functioned or not during the ISV melt is presently unknown as the visual inspection technique using the video image of the interior of the hood was not available.

It should also be pointed out that the region of the melt near contact with the denser undisturbed rock at the pit 1 bottom could not be vented via such pipes, which could not be driven into this dense material. Thus, although project planing activities weighted heavily the hazards of hot surfaces, high voltage, and radioactive contamination associated with ISV, little attention was placed on the perceived unlikely event of off-gas pressurization and its associated risks.

All four personnel on-site during the uncontrolled release of ISV off-gas were monitored for contamination of skin and clothing before leaving the site; none was detected. The next day, all four were subjected to whole-body and lung assays of any internal contamination that may have been inhaled or ingested during the melt expulsion incident. All four personnel also submitted urine samples over the next two days in a further effort to identify any possible contamination. All assays exhibited no detectable radioactive contamination. Obviously, this is not surprising given subsequent air monitoring data and the fact that no project personnel were directly in the off-gas release from the hood. Considering the unknown nature of contaminant release during and immediately following the melt expulsion incident, such personnel monitoring was an extremely prudent precaution.

Many of the tasks that project personnel had been performing put them in the potential danger zone during ISV operations. These tasks are discussed in the following sections.

2.1.1 Electrode Additions

Electrode additions require about an hour once every 3 to 4 days. Because of differential progress, all electrodes are not added at once. This task requires 3 to 4 personnel on the hood platform.

2.1.2 Radiation Surveys

Once, about 2 hr before the melt expulsion, we entered the hood work platform to perform an area radiation survey, which required 2 people about 30 min to complete.

2.1.3 Adjustments to Roughing Filter Blowback Equipment and Hood Spray Suppression System

Performed periodically whenever hood power was turned off for another reason, e.g., electrode lowering or additions, this task required one person about 30 min to complete.

2.1.4 Melt Sampling and Observation

Once at the end of the OAT, 3 persons were used to sample the molten body and view and photograph electrode conditions (i.e., oxidation) and melt surface. The electrode eccentric ports were opened, a metal rod was inserted into the melt with a thermocouple, and a glass sample was collected on the rod after withdrawal. This required about 2 hr to complete with full level-C protective clothing and Health Physics coverage. In addition, several smears of inside surfaces of the hood panels were taken.

2.1.5 Material Addition System (MAS) Use

After the OAT, the MAS was used to add limestone (2 yd³) and 4,800 ft³ of Firelite insulating aggregate. This required about 6 hr with 4 personnel working within 10 ft of the hood.

2.1.6 Roughing Filter Blowback Control Adjustments

One person for about 10 min once or twice a day adjusted the blowback pressure settings from the superstructure perimeter on the east side.

2.1.7 Groundwater Level Measurements

Twice a day, one person would measure the level of ground water in the two wells immediately north and south of the off-gas hood. This activity required approximately 15 min to complete.

2.1.8 Off-Gas Sampler Checks

Every 2 hr, one person would check the operation of the Graseby-Andersen paper tape sampler attached to the south superstructure. This usually required only 10 min except when the paper tape jammed or broke, requiring up to 30 min to repair.

2.1.9 Air-Compressor Reset

The air compressor, used to run the roughing filter blowback system, periodically tripped and required an operator to go to the west side of the hood to push a reset button. After several days of operation, this was eventually set correctly and required no further resets.

2.1.10 Turning Lights On/Off

The photoswitch to automatically turn on the hood's floodlights at night had not functioned correctly. An operator was required to go to the breaker panel on the east side every evening to reset this switch.

2.1.11 Clean Viewing and Video Camera Windows

The glass windows periodically required cleaning. This operation was performed every other day by two personnel and required about 30 min to complete each window. Later in the test, after the OAT,

cleaning any windows or video ports was discontinued because their condition seemed to deteriorate within several hours of cleaning.

2.1.12 Equipment Maintenance

During the interval between the OAT and resumption (start) of melt 1, many maintenance personnel (electricians, fitters, millwrights, etc.) worked to repair many problems on and around the hood. Sampling the roughing filter bags was probably the most time-consuming activity and, from the perspective of the melt expulsion, the most vulnerable period; this operation took 6 people about 2 hr in full level-C PPE.

2.1.13 Electrode Lowering

During the OAT phase of the melt, one of the four electrode hoists (a manually operated type) required 1 to 2 people to go onto the hood work platform about once a shift (8 hr) for 10 min to relieve tension by lowering the hoist. This hoist was replaced during the downtime after the OAT with a repaired electric hoist so that further entry onto the hood for this operation was not required.

Corrective measures to modify or eliminate these tasks are discussed in Chap. 9, which discusses all safety improvements needed for the project.

2.2 ENVIRONMENTAL CONTAMINATION

Environmental contamination was of concern after the melt expulsion incident in three different areas: the uncontrolled release of radioactivity to the air, the distribution of radioactively contaminated glass within and outside the hood, and the planned/expected contamination of off-gas processing equipment. Perhaps the most critical information, which had to be reconstructed after the melt expulsion incident, was the amount of radioactivity that may have escaped from the off-gas hood during the uncontrolled release period when it was open to the atmosphere. Such a calculation is critical for future ISV operations as it will allow for design of safe radiological operations during a potential recurrence of such an uncontrolled release.

2.2.1 Activity of ^{137}Cs in Samples of Glass Expelled From ISV Hood

Glass samples were collected on the day after the melt expulsion incident from around the ISV off-gas hood on the south and southeast sides. In addition, on April 26, 1996, two samples of glass, dangling from roughing filter elements, were obtained during sampling of these filter fabrics. Using NaI gamma spectroscopy on crushed specimens, the activity of ^{137}Cs was assayed; other radionuclides (^{90}Sr , ^{238}U , and ^{239}Pu) were not assayed at this time (but will be later as part of the evaluation of the overall ISV project) because these radionuclides do not have sufficient volatility from melts to be detected in ISV off-gas. Results are presented in Table 1. The average activity for all samples of the ISV product was $1.22\text{E-}08$ Ci/g and exhibited little variation between the expelled and internally splashed glass.

Previous product samples, taken directly from the melt after the OAT phase on April 19, 1996, averaged 2500 dpm/g or $1.129\text{E-}09$ Ci/g. At the time of the melt expulsion incident, molten material being processed amounted to about an order-of-magnitude more radioactivity than during the OAT. If the melt size were 196 Mg (metric tons), at the time of the melt expulsion incident, then the total inventory in the melted mass would be 2.43 Ci of ^{137}Cs .

Table 1. Activity of ^{137}Cs in samples of pit 1 ISV product after the melt expulsion incident of April 21, 1996

Sample ID	Activity (dpm/g)	Activity (Ci/g)
ESE Hair 5'	26,500	1.194E-08
ESE 15'	24,900	1.123E-08
ESE 4" Thick		
Flow	30,700	1.383E-08
S 2' 3" Thick		
Flow	27,800	1.253E-08
Dangling Glass on		

It also found that the samples of hair-like fiber glass, taken at some distance from the hood, were approximately the same specific activity of ^{137}Cs as the bulk glass that flowed from under the hood or was splattered onto the roughing filter. Thus, the thin threads of glass around the site must also have originated from the melt. Observations of the molten glass flow at the southeast corner revealed many fiber strands frozen in the process of formation; apparently, ISV off-gas as it escaped through the narrow gap between the hood foot and the ground surface was of sufficient velocity to entrain glass, which rapidly cooled to solid fibers as it traveled a short distance into the cooler surrounding air.

2.2.2 Off-gas system contamination

Major components of the ISV off-gas system handling equipment were sampled to determine the distribution of ^{137}Cs subsequent to the melt expulsion. By normalizing the distribution of ^{137}Cs relative to the entire inventory being processed by the molten body, the perspective of contaminant distribution can be gleaned for any future processing inventory and the environmental consequences of possible future incidences assessed. Major off-gas system components include 1) the hood's roughing filter at the central off-gas intake, 2) the two banks of high efficiency particulate air (HEPA) prefilters in the off-gas line between the hood and the off-gas processing trailer, 3) the HEPA filter bank for the hood's backup blower, 4) the off-gas scrub system solutions, and 5) various hood panel and pipe internal surfaces on which off-gas particulate contamination may have been deposited.

The HEPA prefilters included the bank in use at the time of the melt expulsion incident as well as the bank that had been in use for several days before the melt expulsion incident. These HEPA prefilters had been changed eight times over the pit 1 melting operations whenever particulate buildup was sufficient to result in a differential pressure greater than about 8 psi. The HEPA filters in use during the melt expulsion incident were significantly deformed, but otherwise apparently functional, due to a pressure surge through the off-gas line. The HEPA filters on the hood backup blower were sampled because, although the hood blower was not on during or after the melt expulsion incident, it would have received a pressure surge of off-gas and may have contained some contamination.

Results of the distribution of ^{137}Cs are depicted in Fig. 3. Most notably, 99.9981% of the ^{137}Cs was retained in the ISV molten body subsequent to the melt expulsion incident. Of the 0.0019% of the ^{137}Cs activity that was released into the process off-gas, most was retained on the hood's roughing filter. Of the fraction that passed the roughing filter, all was retained on the HEPA prefilters as no ^{137}Cs was detected in the off-gas scrub system solutions. Measurable activity, found on the HEPA prefilters switched out of the off-gas flow about two days prior to the melt expulsion incident, indicates that ^{137}Cs was being incorporated into the growing ISV molten mass for several days prior to the melt expulsion incident. The HEPA filters on the hood's off-gas backup blower also contained a significant fraction of the total off-gas inventory. Field surveys of the smear samples from various hood panels and the off-gas pipes revealed no detectable activity; these samples will be assayed in the low-background laboratory environment for quantification of their low-level activity. Their contribution to the total off-gas inventory and distribution would be trivial compared to the various filter samples, which yielded readily detectable activities with field survey instruments and during short (10 min) counting intervals in the low-background laboratory environment.

2.2.3 Off-Gas Monitoring and Sampling

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, which pulled off-gas from the intake of the roughing filter; this sampler would yield the best representative sample of the off-gas

Distribution of ¹³⁷Cs
Following ISV "Burp" of April 21, 1996

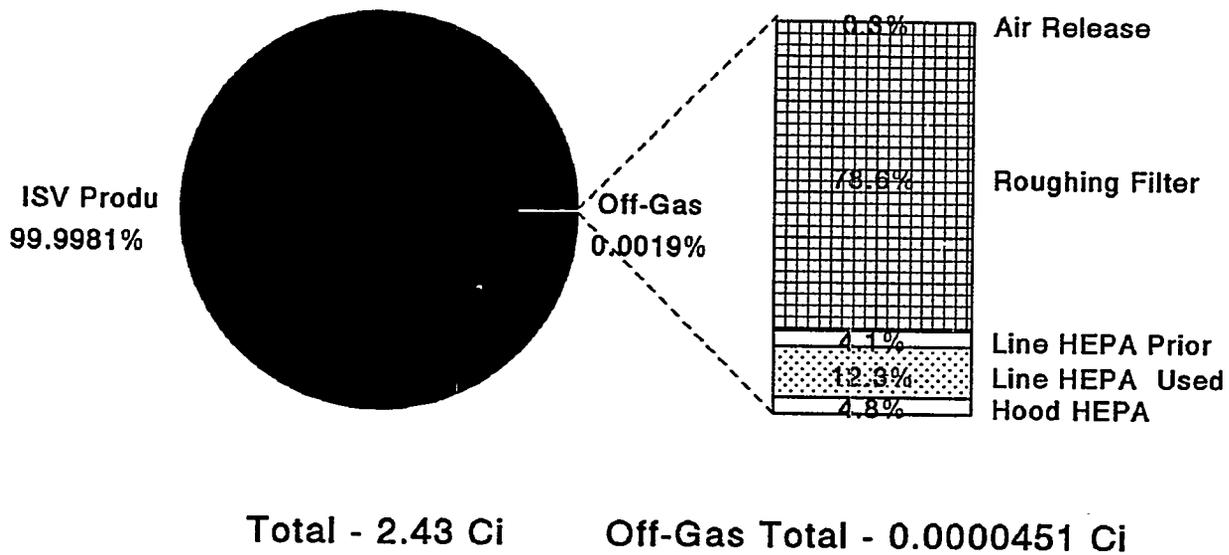


Fig. 3. Distribution of ¹³⁷Cs in ISV off-gas and equipment following the incident of April 21, 1996.

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 and causing its paper tape to fall apart regularly, the sampler was functioning correctly and its performance verified during a regular field check about 80 min before 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 18:30, within 20 min of the start of the melt expulsion incident. A total of 49 dpm of ^{137}Cs were detected on the segment of the paper tape in operation at the time of the melt expulsion incident. Assuming the sample was collected over the entire 20 min preset sampling interval, the off-gas activity concentration of ^{137}Cs was 1.229 dpm/L of gas. Any pressure surge into the sampling line during the melt expulsion incident would result in a lower activity concentration and, hence, the reported activity concentration is conservative, i.e., tending towards a probable higher number. This activity concentration will 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.

The other functional off-gas sampler was located immediately upstream of the HEPA prefilters and functioned to sample off-gas which had passed through the roughing filter. This sampler was also functioning at the time of the melt expulsion incident; it exhibited low detectable activities of ^{137}Cs , which did not differ from those before the melt expulsion incident. This lack of difference in activity points to the continued functioning of the roughing filter during the melt expulsion incident.

2.2.4 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; thus, they 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 that 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 switched to an ambient air monitor after the OAT because of continued 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. 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. On his arrival, the project team leader noticed that the smoke cloud from the subsequent hood perimeter fires had risen quite high before slowly moving to the northeast of the site. Therefore, 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 filter samples.

2.2.5 Uncontrolled Air Release Estimate

To estimate the volume of off-gas released during the period of unconfined and pressurized hood, 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 concentration in the off-gas was calculated as discussed above; using this measured concentration of activity and the estimated total volume of off-gas released, the total release of ^{137}Cs activity can be calculated.

2.2.5.1 Pre-event conditions

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:

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

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

$$T_1 = 250^\circ\text{C} = 523^\circ\text{K},$$

$$V_1 = \text{combined volume of hood, startup trench, and subsidence crater}$$

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

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

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

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

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

2.2.5.2 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 test of 1991). Actually our 15,000-lb hood (just the panels) plus adhering soil, needs 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.

2.2.5.3 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. H₂O) and temperature (298°K), this volume would be 230,000 L or 8,120 ft³. I have not corrected for any off-gas withdrawal from this total 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.

2.2.5.4 Uncontrolled release of ¹³⁷Cs

The calculated concentration of ¹³⁷Cs activity in the off-gas was 1.229 dpm/L. This activity was measured on the last spot on the Graseby-Andersen tape sampler of off-gas within the hood and 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 $1.229 \times 230,000 = 282,670$ dpm or 1.27E-07 Ci of ¹³⁷Cs.

2.2.5.5 Maximum pressure possible inside hood

Assuming that all off-gas was instantaneously contained inside hood as the gas was heated from 523°K to 1773°K, both the volume and moles of gas remain constant and the new pressure, P_4 , would be:

$$P_4 = (P_1 \times T_2) / T_1 = 406.3 \text{ in. H}_2\text{O} \times 1773^\circ\text{K} / 523^\circ\text{K} = 1377 \text{ in. H}_2\text{O or}$$

970.6 in. H₂O above ambient (1 atmosphere). In other units, this would be 2.385 atmospheres or 35.1 psi. Obviously, the hood would yield or move upward long before such a pressure was approached. But, this calculation demonstrates that there is plenty of heating to produce a pressure wave or exhaust jet from the uplifting hood.

2.2.6 Distribution and Dispersion of ISV Glass

2.2.6.1 Glass Flow Outside Hood

Major amounts of ISV glass product flowed outside the hood panels but almost all of it was confined to the southeastern corner of the hood (Fig. 4).

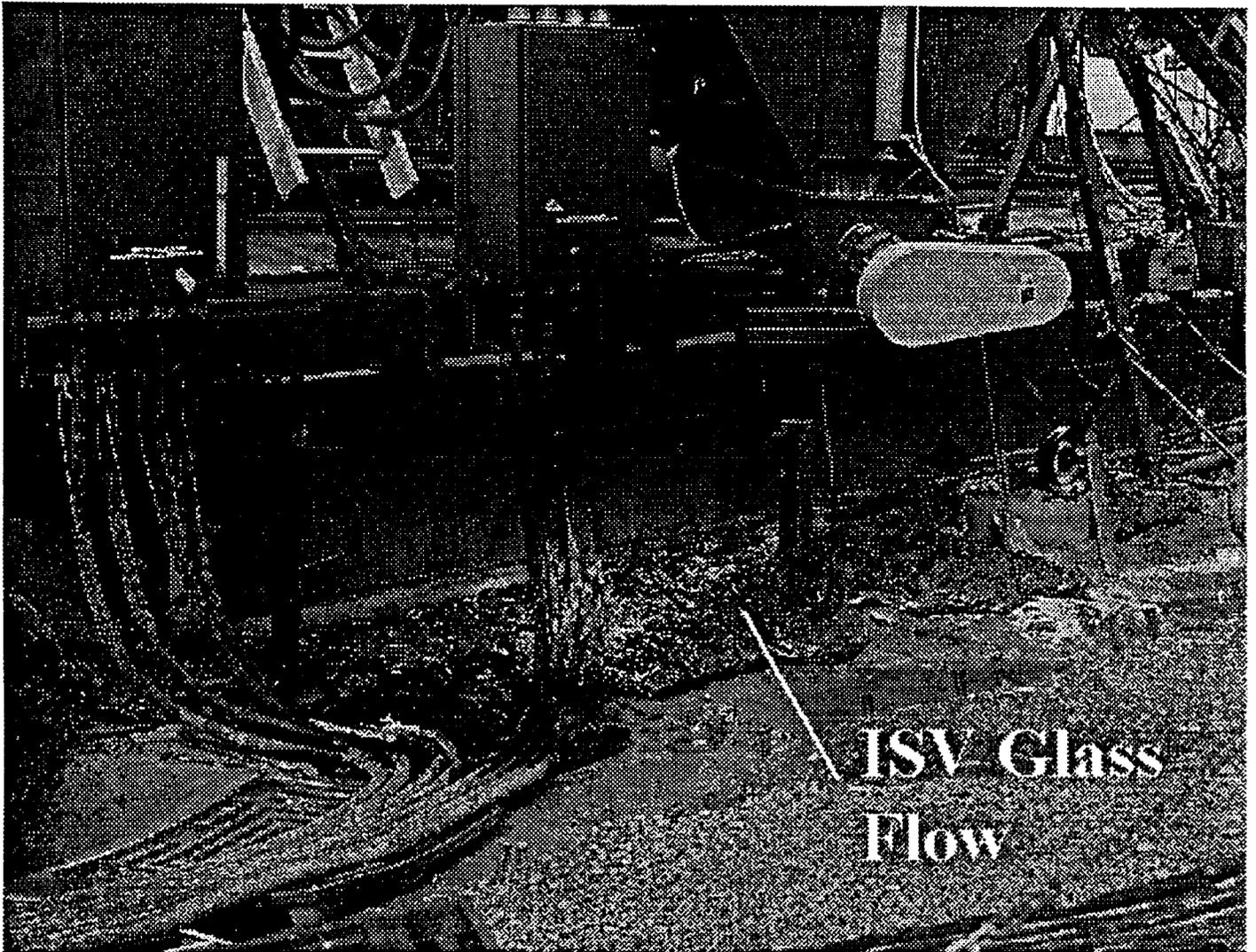


Fig. 4. Flow of ISV glass from under off-gas containment hood following incident of April 21, 1996.

2.2.6.2 Morphology of Expelled Glass Particles

Two types of glass particles were observed around the off-gas hood unconnected with the bulk flow of glass under the hood panels. These were generally in the form of irregular globs (Fig. 6) (most within 20 ft of the hood), and fibers, some quite thin (Fig. 7), which occurred up to 300 ft away from the hood and must have had some aerodynamic attributes to be carried so far. Both types of expelled glass appear to have been formed by high velocity off-gas jetting over a molten surface from just underneath the hood panel foot. Actual glass fibers and globs, in the process of forming when pressurizing and lifting of the hood had ceased, can be seen on the south side of the off-gas hood (Fig. 5).

2.2.6.3 Distribution of Expelled Glass

The distribution of expelled glass within and around the hood is summarized in Fig. 8. This distribution estimate was based on visual examination as personnel entry into the hood is presently precluded. In the SW quadrant, the glass flow extends approximately 10 ft from the starter pit and appears to be about 2 in. thick. Most of the surface immediately in front of the SW corner hood panel is only sparsely scattered with glass (the Cerwool blanket, which was placed over the entire ground surface inside the off-gas hood prior to ISV operations, is still visible).

The entire SE quadrant appears to be covered with glass. The once "level" ground surface under the hood appears to be depressed by about 4-5 in. immediately south of the starter pit. This depression extends approximately 10 ft out from the starter pit. From the NE corner hood opening, the glass flow appears to be 10-15 ft out from the starter pit and nominally 2 in. thick. The glass on the ground surface north of the starter pit has several hundred 2- to 3-in.-tall stalagmites/spikes present.

2.3 EQUIPMENT DAMAGE

When the melt expulsion incident occurred, the hood was observed to have broken its seal with the ground and lifted around the base about 6 to 12 in. As a result, on all sides the ground seal is broken and the base of the hood panels remains lifted up about 6 in. On the north end, a blast of hot gas was observed to be emitted. This blast burned up most of the combustible matter in its path, including several cardboard boxes (containing noncombustible materials) and vegetation on the graded slope to the present pit surface. A section of fiberglass grating had been placed on the ground under the catwalk on the hood to act as a walkway across the muddy soil surface of the pit. When this grating burned, it contributed to much of the damage to hood equipment on the north side. Damage includes the control panel for the hydraulic system (Fig. 9) and all hood instrumentation (wires, valedines, magnehelic, heat flux pad, etc.). Other damage on the north side includes the Remtron antenna signal panel (apparent short in the signal wires), the window view port (the glass is broken, and the window shield will not rotate due to warpage of the housing), and the light and electrical insulation (melted). The paint on the drive panel is burned but there is no obvious damage to the inside electrical equipment; further troubleshooting is required to confirm functional status of the drive system.

2.3.1. Damage on Hood Perimeter

On the east side, a pile of gravel covered about the north half of the area between the hood and the graded slope of the pit. The gravel pile extended down to within about 1 ft of the base of the hood and was under all the electrical panels on the north end of the east side. There is melt flow out from under the hood on the south half of the east side. It extends out from the edge of the hood panels about 3 to 5 ft and is about 4 to 6 in. thick. The insulation on the high voltage cables is burned (about the last 10 ft

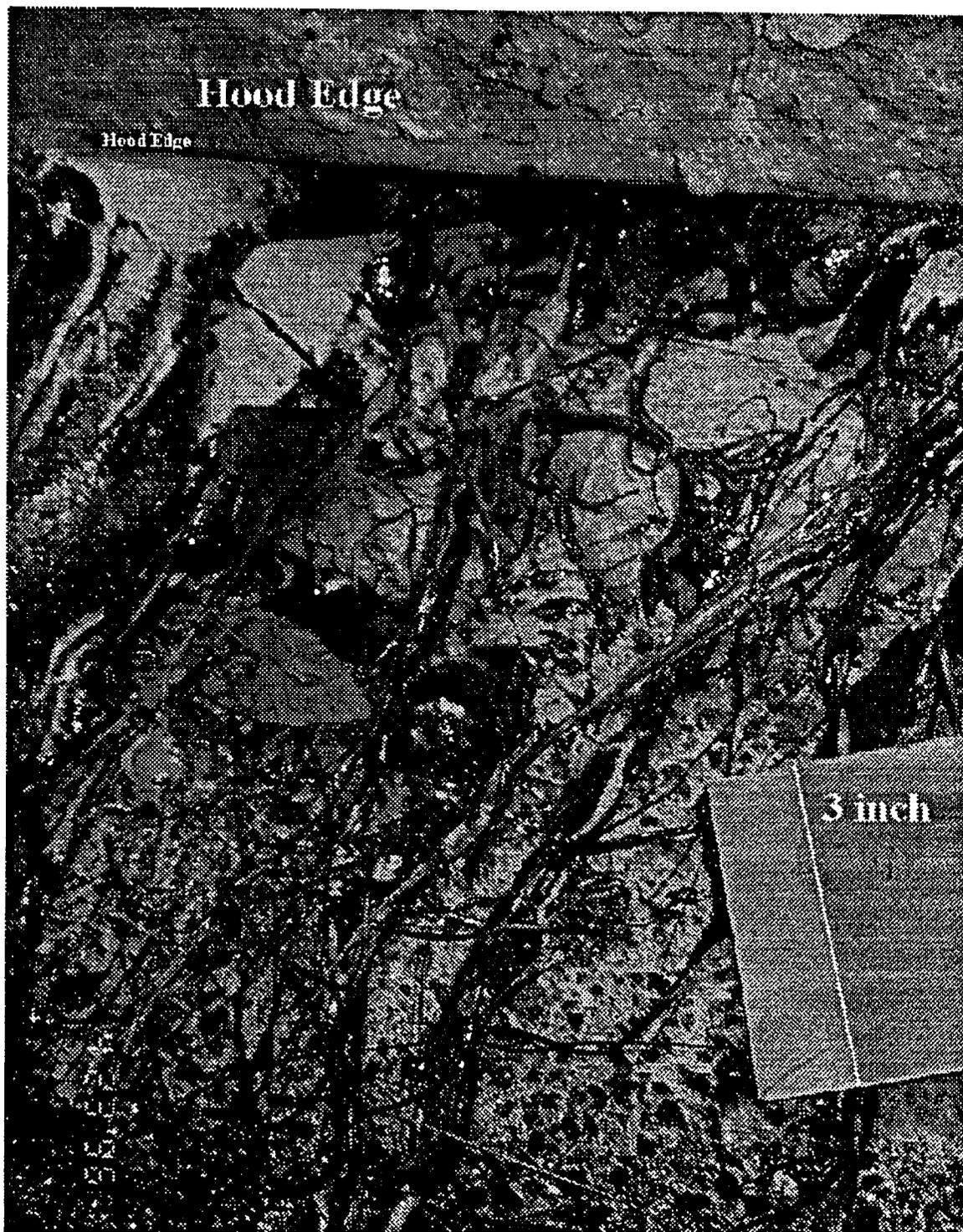


Fig. 5. ISV glass fibers frozin in forming proceess on ground surface near edge of off-gas hood panel foot.

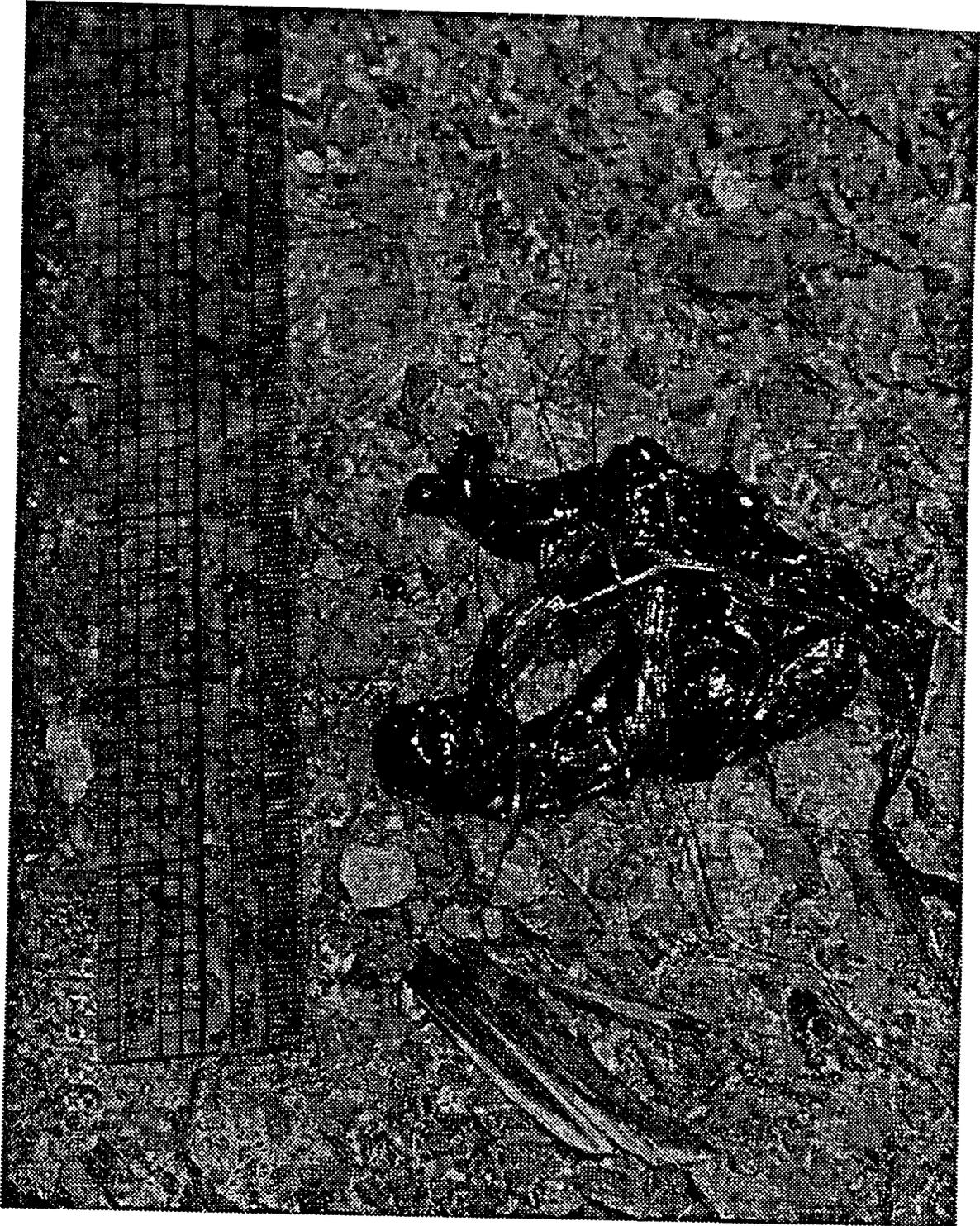


Fig. 6. Expelled ISV glass glob on ground surface just to east of off-gas hood.



Fig. 7. Hair-like form of ISV glass expelled approximately 20 ft east of off-gas collection hood during incident of April 21, 1996.

**Area of Major
Off-Gas Release**

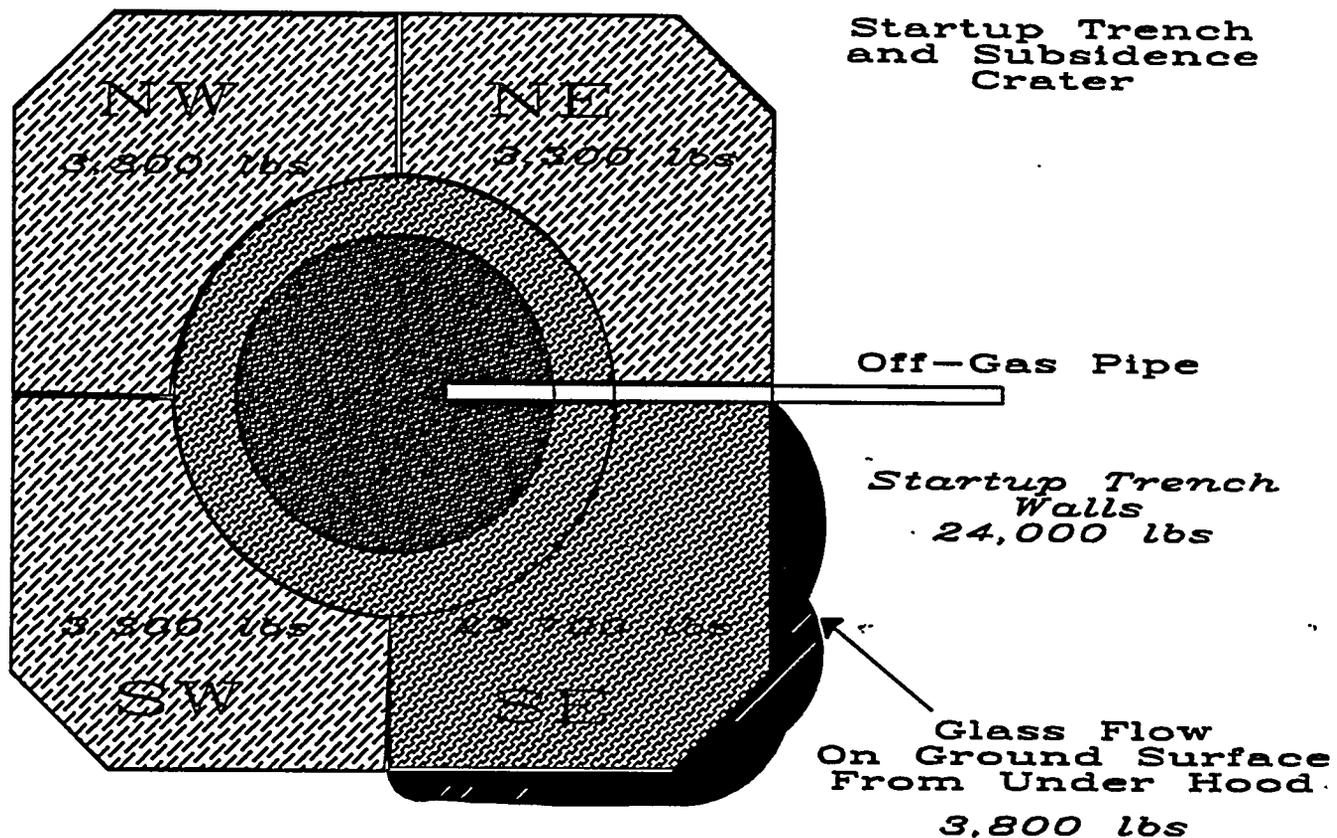


Fig. 8. Estimation of distribution of ISV expelled glass within and around off-gas collection hood after April 21, 1996, incident.

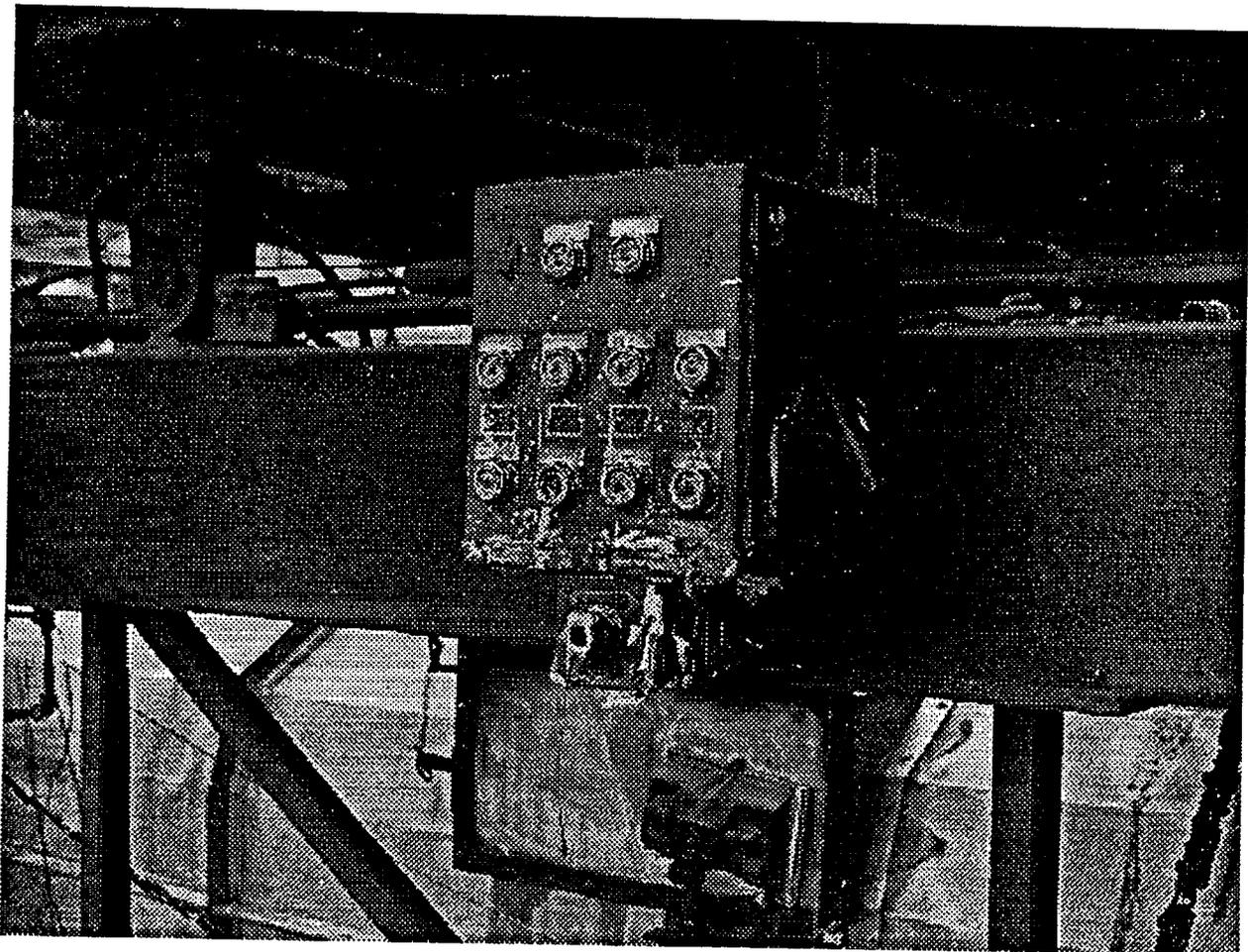


Fig. 9. Damage to the ISV hood's travel system hydraulic lift controller resulting from the fire of April 21, 1996.

of each of the 8 cables as they run into the junction boxes (Fig. 10). The MAS pneumatic lines and controls were melted. The wheel on the feed conveyor toward the hood was burned. The support leg to the MAS hopper is sitting in glass and appears to be warped, the east leg of the SE landing gear jack is also sitting in glass and warped, and the gear box appears to be adversely heat affected. These mechanisms need to be repaired or replaced. The paint on the backs of all the electrical panels has been scorched, but the interiors of most appear to be unaffected, except for the roughing filter control panel and the hoist remote control panel. All electrical wires running to the hood system appear to be unaffected except the hoist remote control cable and any instrumentation wiring adjacent to the hood panels in the area.

The window view port on the east side is in similar condition as the one on the north. Inside the roughing filter control panel, the plastic tubing for pressure monitoring is melted, and the bulk of wires that were resting on the bottom of the panel are melted, shorting the wires to ground. These can be easily repaired. The blow back control board does not appear to be damaged but will require further troubleshooting. The hoist remote control cable outer insulation is melted about 8 to 10 ft from the junction box. It can be cut off and reconnected to the junction box. All hoist control cable (yellow vinyl) insulation routing from the junction box to the hoists is melted and will need to be replaced. The condition of the 480 to 208/120 volt transformer is unknown and will need to be inspected, but it appears to be in good condition.

On the south side, melt flowed out of the east two-thirds of the hood, extending out 1 to 2 ft at thicknesses of 4 to 6 in. Fiberglass grating in the area was burned but not as damaged as that found on the north side. All hydraulic and pneumatic rubber hoses in the SE corner are heat affected and will need to be replaced. The inner tire on the SE travel system has some charred tread and should probably be replaced. The sidewall appears to be in good condition. Since this was the most heat-affected tire, it should at least be removed and the tube and inside of the tire examined. If it is in good condition, the others should be as well.

The window viewport and light are in the same condition as the others. The MAS control panel appears to be heat affected. There are no shorts to ground in the supply power wiring, but all the controls and fuses appear to be damaged. The push buttons and switches appear to function, but the lenses are melted. The fiberglass housing for the Graseby-Andersen tape sampler is slightly heat affected but not scorched and could be reused. The tape sampler itself and radiation monitor need additional troubleshooting.

On the west side, there were no adverse thermal effects and all the equipment appears to be in good condition (however, the west side is the side with the fewest components). The compressor, inlet air control valve, and the camera control junction box all seem to be in good condition. The condition of the camera on the west window view port needs to be further evaluated.

2.3.2 Damage on Hood Work Platform

Most of the combustible items on the work platform were heat-affected. The hood blower over the grating that burned on the north side is slightly scorched. The wiring was pulled from its connection to the hood structure and reconnected (to pull vacuum on the hood during observations inside the panels) and works well. In fact, the wiring that was pulled from the conduit running along the north side of the hood structure appears unaffected (good news with regard to the wiring contained in conduit in general).

All of the water spray pressure suppression system electrical controls are melted and would need to be replaced if the system is to be used again. All of the hoist control cable (yellow vinyl) insulation

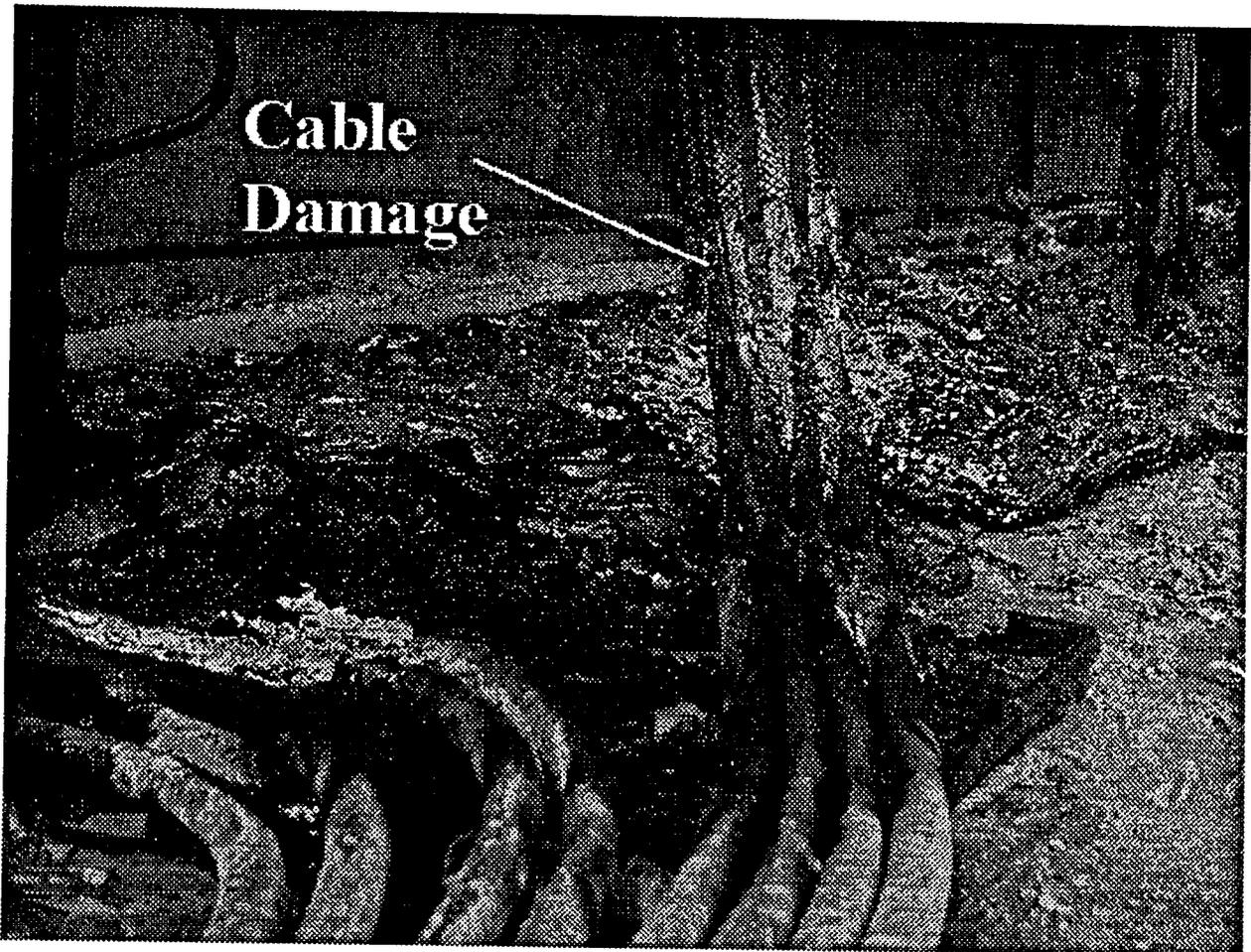


Fig. 10. Fire damage to ISV electrode power cables on the east side of off-gas hood resulting from expelled glass.

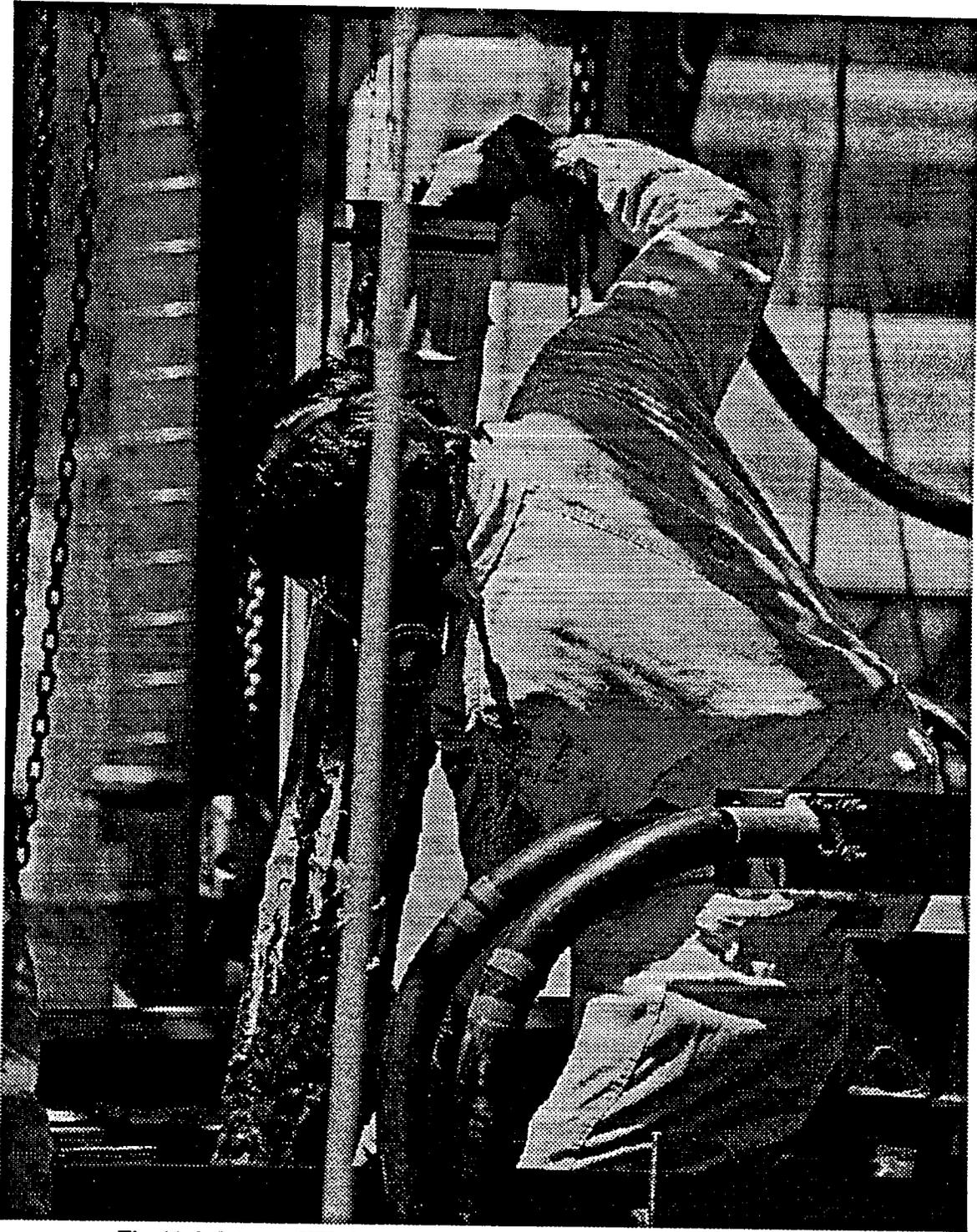


Fig. 11. Splattered ISV glass adhering to one of the 128 roughing filter elements during removal for sampling.

needs to be replaced because the vinyl is melted and some of the twist lock plugs are damaged. One local hoist controller is melted and needs to be replaced. All of the nylon in the clamps were affected by the heat; some are completely burned. All sections need to be replaced and the clamps repainted. This could be an opportunity to improve the design and operation of the clamp (which was heavy and very awkward to handle). About 12 of the 16 electrode cables are heat affected at the bottom of the festoon loop (the four western-most cables were unaffected); they will need to be cut off and the lugs will need to be recrimped. There should be enough cable slack to not have to replace or even extend the cable with splice kits. Most of the grating has burned and peeling paint and should be repainted.

The roughing filter housing was highly damaged by the heat and somewhat warped; this can probably be reworked in place so that the lids will fit properly. All bags and hardware (clamps, gaskets, etc.) will need to be replaced. The cages appear to be bent somewhat and may be able to be reworked or else replaced. (Note: it appeared that during operation, the roughing filter was undersized for the minimum flow being pulled; longer bags may be necessary to improve the efficiency of the bag filters if the flow cannot be further reduced.) Railing around the work platform was made of steel cable with plastic cover which has melted in some places. It may be possible to clean this railing and leave it uncoated or just paint it; otherwise, the cable rail will have to be replaced. The phenolic insulators and the phenolic and Nextel electrode seals on the electrode cradle are scorched and need to be replaced.

2.3.3 Damage Cost Estimate

Estimates for repair of hood damage range from \$142,000 to \$544,000; the actual cost will depend on how much functional damage to electrical equipment is finally determined. Presently, electrical power to the hood is shut off and systematic testing of circuits, breakers, switches, lights, motors, and control and instrument circuits will take some time and effort to complete. The cost for replacing each possibly damaged component has been determined, but whether actual replacement is necessary is not presently known. However, a systematic evaluation of the electrical system will be the only method to firm up repair estimates and schedules. Much of this work is planned for the early part of June. It is anticipated that actual repairs can be completed by the end of August.

3. AMOUNT (MASS) OF MELTED SOIL PRESENT DURING THE MELT EXPULSION INCIDENT

Three somewhat independent methods are available to estimate the mass of glass present in the ISV melt body at the time of the melt expulsion incident. Melt mass estimation is important to perform a process assessment using a mass balance to describe the distribution of contaminants and to estimate the fraction of pit 1 already treated and to plan the additional ISV melts required to complete treatment of all source contamination. Melt mass was estimated from 1) determining the total amount of electrical energy applied to the melt assuming certain melting efficiencies, 2) determining the size of the melted or solidified body and assumptions about product density and 3) measuring the final concentrations of the conservative tracers in the product and dividing this into their known additions to the soil.

3.1 ESTIMATE FROM APPLIED ELECTRICAL POWER

The two-hour manually recorded data showed that the total energy consumed by the pit 1 OAT and melt 1 site was 546 kWh. Integrating the incremental power data from the Bailey, a more accurate value of 526 kWh is obtained and will be used in the following analysis.

According to the draft site characterization report (Spalding et al. 1994, p 32) the following data are used:

Soil void volume = 43%

Pit 1 backfill soil density (dry basis) = 1500 kg/m³

Pit 1 native formation density = 2000 kg/m³

For every cubic meter of dry soil having a mass of 1500 kg/m³, another .43 m³ of water could be added, having a mass of 430 kg. Therefore, the moist density of saturated pit 1 backfill soil is 1930 kg/m³. On a mass basis, a cubic meter of saturated soil is 78% soil and 22% water (1500/1930 and 430/1930, respectively). Assuming that the energy to melt soil is about the same as the energy to remove water, 78% of the energy applied was used to melt soil, or 426,000 kWh. Using a standard energy efficiency conversion for soil melting, based on previous experience, of 1 kWh/kg, the mass of soil melted was 426,000 kg. However, in the 1991 ORNL pilot-scale ISV demonstration (Spalding et al., 1991), 2.41 kWh/kg of product was calculated under similar extremely moist soil conditions; using this less efficient ISV conversion for the present melting operation would yield an estimated mass of only 177,000 kg. This value will be affected by the actual energy required to melt the pit 1 soil vs removing water and the actual energy efficiency. Given the rate at which the energy was applied (power levels vs down time), this is a reasonable assumption at this time.

Conversely, 22% of the energy applied was used to remove water, or 120,000 kWh, the equivalent of 120,000 kg, the equivalent of 120,000 L (31,700 gal). This value is similar to the volumes of off-gas scrub solution collected (99,443 L or 26,273 gal); further data (including water vapor transmitted through the off-gas processing system) will need to be evaluated and considered to refine the water balance.

3.2 ESTIMATE FROM MEASURED MELT SIZE AND DENSITY

The mass of the melt can be calculated from estimates of its size, shape, and density. A number of assumptions need to be made concerning each of these parameters as well as the techniques employed to gather actual measurements of each parameter.

3.2.1. Melt Geometric Assumptions and Model

The melt was started at 12.00 ft below the reference elevation, i.e., the top of the hood's working platform). The recorded measurements averaged 12.33 ft to the top of starter path tubes but should be reduced by 0.33 ft for the additional starter sand added later to cover starter tubes. The final melt surface was measured at 17.74 ft below the same reference elevation. These final melt surface measurements were obtained on 5/15/96 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. Therefore, the melt cone section (Fig. 12) was 8.97 ft thick (i.e., 12.00 ft + 14.71 ft - 17.74 ft = 8.97 ft). The melt density was assumed to be 2.83 Mg/m³ (177 lb/ft³) with a melt thickness of 8.97 ft, and a cone section geometry was used to calculate the melt volume. [The assumed melt density of 2.83 g/cm³ comes from ORNL/TM-12201 (Spalding et al. 1992), the final report of the 1991 ISV radioactive pilot-scale test.]

A minimum bottom radius equal to 1 ft outside the equivalent electrode radius, i.e., 8.07 ft, was assumed. The minimum equivalent electrode diameter was 10 ft × √2. A minimum top radius equal to the startup trench radius, i.e., 10.00 ft, was assumed. It was further assumed that relative variation in the

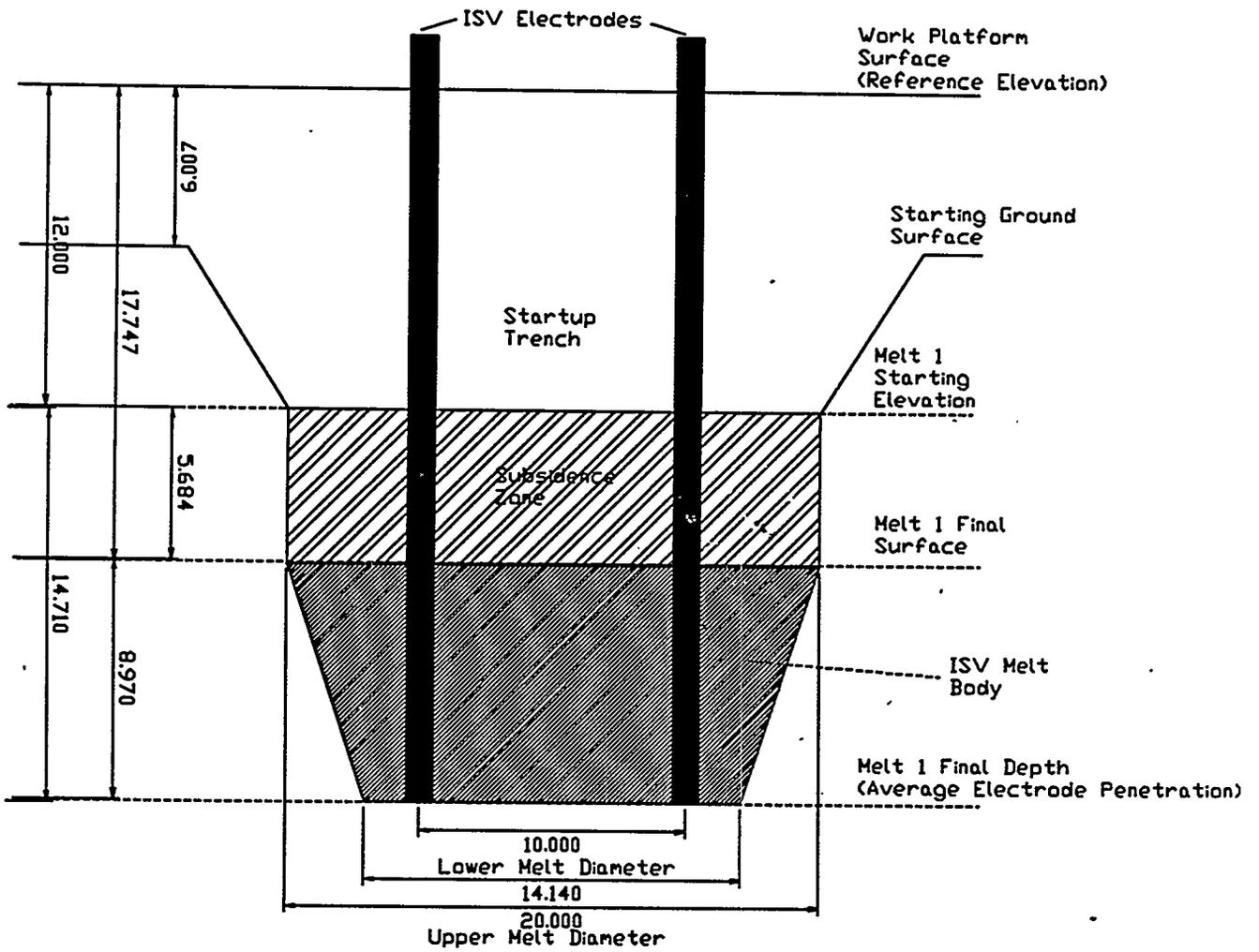


Fig. 12. Geometric configuration and dimensions assumed for calculation of ISV melt body size.

bottom and top melt radii would increase linearly from these assumed minimum radii. The calculated melt mass as a function of top and bottom radii are presented in Table 2.

3.2.2 Side Wall Probing

The location of edge of the melt was determined by probing for hard, dense, sintered sidewall using a 1-in.-dia. Geoprobe rod. This rod was driven to refusal using the electric vibratory hammer that had been employed in drill rod probing of the pit bottom during site characterization; driving techniques were identical to those described in the project procedure (ISV-TS-P01). Rods were driven at targeted and measured angles, using a digital reading level placed on the extended drill rod train once the angle had been firmly constrained by driving several 3- or 4-ft lengths of drill rod horizontally. Refusal was interpreted as the edge of the sintered zone or, for steeper angles, the original pit 1 bottom. Probing was not attempted from either the west or east sides of the hood; refusal by undisturbed wall material would have been encountered almost immediately because the 50-ft-wide off-gas hood projected well beyond the 25-ft width of pit 1. Knowing the drive angle, the total length of rod in the hole at refusal, and the distance of the starting point from the center of the melt, the radius of the refusal point from the center of the melt could be calculated. A total of 13 probings were completed at various angles and melt/hood centerline offsets, although all starting points were positioned 6 ft from the hood wall and, therefore, 31 ft from the melt center.

Before withdrawing the drill rod train, a type-K thermocouple was inserted to the bottom of the drill rod train to determine temperature of the refusal contact. Temperatures above 100°C were interpreted as evidence of refusal at the sintered zone boundary. The thermocouple was then withdrawn in 2-ft intervals to profile the temperature of the region through which the drill rod had been driven. Maximum temperatures were often observed at depths less than refusal, particularly for probe paths that met refusal on the pit bottom but traveled through peripheral, thermally affected but unsintered, zones around the melt body. Because the probing activities were carried out over several weeks during which the melt was cooling, direct comparisons of maximum temperatures cannot be inferred directly as isotherms.

The wall probing results do not yield a symmetrically simple picture of melt width. The apparent radius of the upper portion of the melt body on the north side was 14.1 ft; however, the best estimate of the radius on the south side was only 6.6 ft. Assuming the south side radius was not an artifact of either probing into a fissure or into a subsidence failure zone, an average top radius of 10.35 ft is the most likely melt body radius. As can be seen from Table 2, such a size would contain a melt mass between 186 and 229 Mg. This is somewhat less than the estimated mass of 426 Mg estimated from electrical power consumption under optimistic energy conversion assumptions but similar to the 177 Mg estimated with more likely energy conversion efficiency. However, the estimated range, based on such probing, encloses the ISV mass estimate based on rare earth tracer dilution discussed subsequently.

3.3 MELT MASS ESTIMATE BY SPIKED TRACERS

Lutetium, holmium, and cesium tracers were placed into the soil zone, which was eventually incorporated into the ISV melt body. By measuring their concentrations in the final melt product and dividing the average concentration into the known measured mass of tracer placed into the melt, a somewhat direct calculation of melt mass is possible. Actually, a small correction for the trace ambient concentrations of these spiked elements in the pit 1 soil is made, but its magnitude is quite small. Two independent samples of each of two ISV product samples, the east-southeast and south flows collected

Table 2. Calculated mass of the pit 1 ISV melt body for differing final widths.

Top Radius (ft)	Bottom Radius (ft)	Melt Volume (ft ³)	Melt Volume (m ³)	Melt Mass (tons)	Melt Mass
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

outside the hood (Table 3) were analyzed by neutron activation and required several weeks for other induced radioactivity to decay before the Lu and Ho activation products could be assayed. The best estimate of the mass of ISV product formed is about 196 Mg. This measurement of melt mass is free of assumptions about melt geometry (necessary in the probing method) and electrical energy conversion (necessary in the power conversion method).

4. CHEMICAL ANALYSIS OF ISV PRODUCT

Two samples each of the expelled glass after the melt expulsion incident and the ISV product sampled after the OAT were pulverized and dissolved using the $\text{LiBO}_2\text{-HNO}_3$ technique described in the Quality Assurance Project Plan. The elemental composition of the glass should set the ISV operating temperature. The results of these analyses are presented in Table 4. Although the composition of the ISV glass was similar at the end of the OAT and after the melt expulsion incident, significant minor differences are apparent. Calcium increased between the OAT and final melt due to addition of limestone with the MAS. The sodium content decreased between the OAT and final composition because of continued dilution of the initial charge of sodium provided in the feldspar starter sand.

5. TEMPERATURE OF THE ISV MOLTEN BODY

The elemental composition of the pit 1 ISV melt was input into a model of silicate melt viscosity as a function of temperature (Fig. 13). The model of melt viscosity versus temperature (Shaw 1972) is based on a limited range of elemental compositions and may not provide the best estimate of ISV operating temperatures. It is usually assumed that ISV operating temperature is approximately the temperature of 100 poise viscosity (T100P). However, the model, which predicts a T100P of over 2000°C for the pit 1 melt composition, must be significantly incorrect.

First, Shade and Piepel (1990), using a sample of ORNL soil virtually identical in composition to the pit 1 soil, measured a T100P of 1735°C. Second, pit 1 soil was used previously in an engineering-scale test melt in 1995 where a type-C thermocouple measured an ISV operating temperature of 1750°C.

Third, when a type C thermocouple was pushed into the pit 1 melt immediately after the OAT, it approached 1475°C as a maximum reading after about 5 min of immersion in the melt body. It should be noted that the thermocouple was inside a steel Geoprobe drill rod, which may have buffered the apparent temperature reading near the melting point of the steel (ca. 1500°C). However, when the thermocouple/rod was pulled from the melt, the steel rod had been melted from the end of the thermocouple.

Fourth, the melting code also predicts a T100P for the feldspar starting sand of over 1900°C whereas laboratory crucible tests have shown the feldspar sand to be completely melted after an hour of exposure to 1200°C; the supplier of the feldspar sand specifies a melting point of just under 1200°C for the product. A redeeming aspect of the melting code, however, is that it accurately predicted the T100P of the melt composition used in the 1991 ORNL pilot-scale test, which was a mixture of soil and limestone; the model predicted a T100P of about 1400°C, whereas the measured ISV operating temperature was slightly over 1500°C. Thus, assuming that the model overpredicts pit 1 ISV operating temperature and T100P by approximately 300°C, an actual ISV operating temperature for pit 1

Table 3. Analyses of lutetium and holmium tracers in ISV product from ORNL pit 1 after the melt expulsion event and the OAT.

Sample	Concentration of		Calculated ISV Mass Based on	
	Lu	Ho	Lu	Ho
	($\mu\text{g/g}$)	($\mu\text{g/g}$)	(Mg)	(Mg)
ESE Flow	6.94	19.1	196	196
S Flow	7.06	19.5	193	192
OAT	10.7	25.0	127	150
Pit 1 Soil	0.40	1.0	-	-

The mass of Lu added was 1,361 g and the mass of Ho added was 3,743 g; masses are corrected for actual analyses of materials used and are expressed on elemental (oxide-method).

Table 4. Elemental composition of ISV product at ORNL pit 1 after the OAT and the melt expulsion incident.

Major Component Oxide	Melt-1 Glass (%)	OAT Glass (%)
Al ₂ O ₃	19.8	20.6
CaO	2.9	2.5
Fe ₂ O ₃	6.5	6.7
K ₂ O	2.0	2.0
MgO	1.6	1.5
MnO ₂	0.06	0.06
Na ₂ O	1.0	1.3
SiO ₂	65.0	67.3
TiO ₂	0.8	0.8
Total	99.6	103.0

Table 4. Although the composition of the ISV glass was similar at the end of the OAT and after the melt expulsion incident, significant minor differences are apparent. Calcium increased between the OAT and final melt due to addition of limestone with the MAS. The sodium content decreased between the OAT and final composition due to continued dilution of the initial charge of sodium provided in the feldspar starter sand.

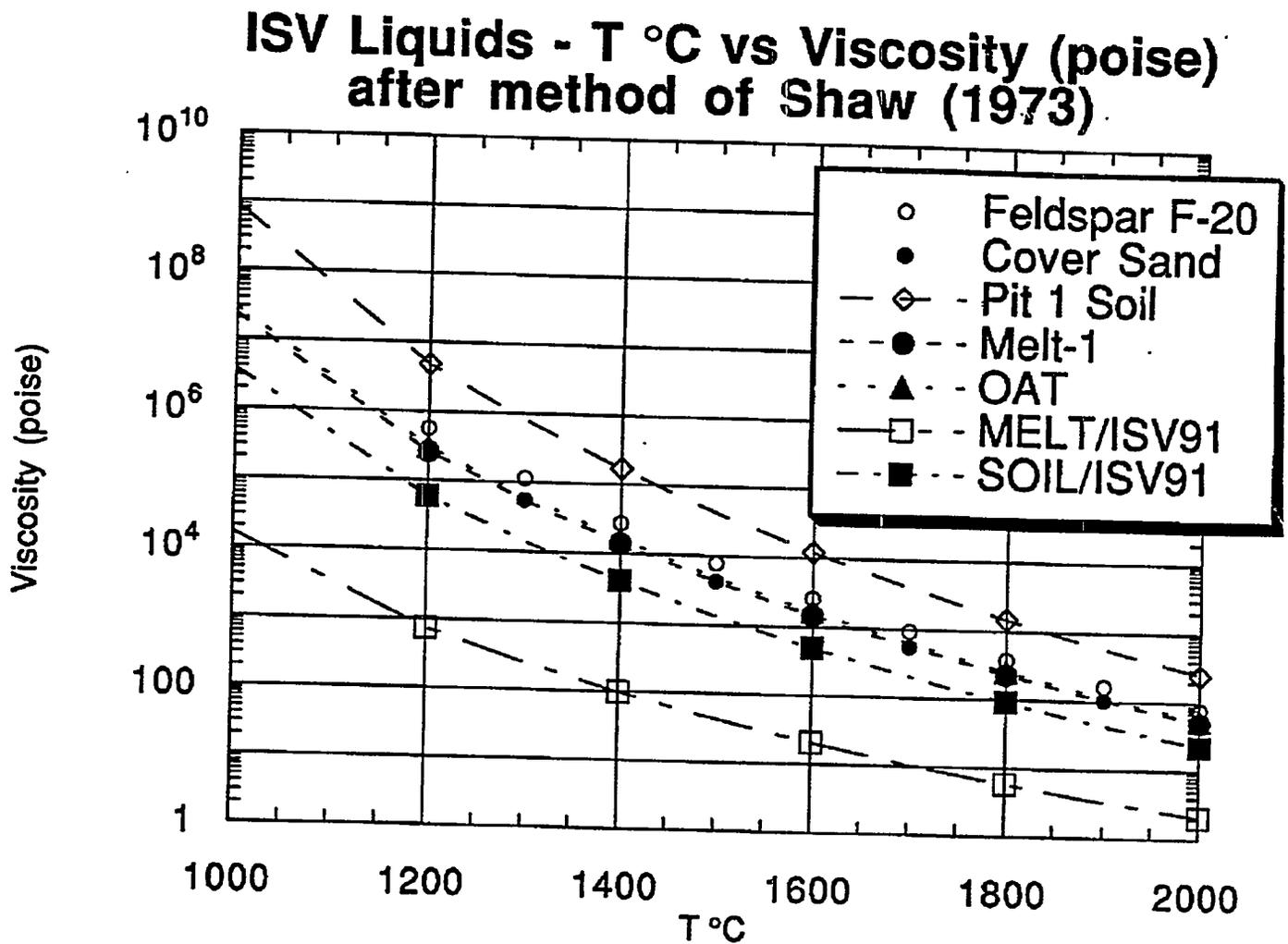


Fig. 13. Relationship between melt viscosity and temperature as calculated using model of Shaw (1973) for various ORNL elemental compositions.

operations is predicted to be approximately 1600°C. This is consistent with the general conclusion that an unamended pit 1 soil would process at about 1750°C and that the ISV processing temperature would be lowered by the addition of a sodium- and potassium-rich silicate like the feldspar sand.

To finally determine the actual ISV operating temperature of the pit 1 melt composition, samples of the product can be heated in laboratory crucibles (platinum) to a temperature at which the molten contents can be easily poured out. The condition of pourability would occur well above the T100P. Alternately, a melt composition like the 1991 ISV product could be heated to its ISV operating temperature in laboratory crucibles to determine its pour test characteristics; the unknown pit 1 could be heated to various temperatures until a pouring viscosity similar to the 1991 known product is duplicated. Test apparatus for experimental measurement of silicate melt viscosity is costly and would require purchase for this sole need due to its subsequent contamination.

6. PROCESS PERFORMANCE AND PERFORMANCE DATA SUMMARY

6.1 PRIOR ISV OPERATIONS DESCRIPTION

ISV melt operations at pit 1 were initiated on April 3 at about 10 a.m. At that time the off-gas treatment system was started and final operational readiness checklist items were addressed and completed throughout the day. At about 9:45 p.m., power delivery to the soil was achieved to initiate the Operational Acceptance Test portion of the project. The OAT was planned to run until the melt was determined to have reached a depth of no less than 2 ft above the known radioactive contamination layer (at a depth of 24 ft from original pit 1 grade). The melt progressed at a downward rate of about 1 ft per day (1/2 in. per hr) as measured by electrode depth. The target depth for the OAT was reached at about 12 p.m. on April 15 at which time the OAT evaluation portion of the project was initiated. The OAT evaluation lasted about 3 days, with melt 1 (melting the remainder of the setting into the radioactive zone) being initiated at about 6 p.m. on April 17. The depth objective of melt 1 was primarily to incorporate the radioactive zone, so melting to a depth of at least 26 ft below original grade was desired.

As a secondary objective, it was desired to continue melting in an attempt to determine the depth limit to which such ORNL sites could expect to be melted.

During melt operations, there were always at least four people on site. There were three operators required for the ISV process system. The operations schedule was divided into 3 overlapping 8-hr shifts. On each shift there was a shift engineer, who was very familiar with the ISV equipment and experienced in the ISV process. The other two ISV personnel were operators, usually having minimal direct ISV operations experience. All ISV operations staff were trained via classroom and hands-on training, which was approved and documented by the ISV equipment supervisor. During operations, at least one staff member is required to remain in the control trailer at all times to monitor the process control equipment. Other staff members may be found at various locations around the site at various times, consistent with their job responsibilities, adjusting equipment, collecting data, or just making observations about the process. The fourth staff member was a health physics technician (HP) assigned for 24-hr coverage of the project, provided in two 12-hr shifts per day.

Routine activities that required entry to the exclusion zone (and thus proximity to the hood) included water level monitoring, off-gas sample monitoring, and roughing filter adjustments. There were no "routine" (i.e., regular) activities on the hood working platform, except for adding electrode sections to the electrode column, which required about 4 people. Two or three electrode sections were added to each electrode column at different times during the course of the run.

The purpose of the OAT was to observe equipment and operator performance and to make any adjustments as required or necessary. Since there were numerous new equipment components as well as an operational crew with minimal ISV experience on the DOE large-scale ISV system, it was expected that some equipment, procedural, or personnel changes would be necessary. However, the assessment of the operations during the OAT showed that there were no major issues to be addressed or resolved by the time the OAT evaluation portion was begun. Several relatively minor problems/issues were encountered during the OAT; a description of the situation and its resolution follows:

6.1.1. Acute Issues

6.1.1.1. Stepdown Voltage Potentials

Because of the high voltages used in ISV melt operations, it may be possible to generate step down potentials some distance from the ISV hood system. It has been measured on several previous ISV melts at all scales that such a step down voltage potential does not actually exist. It is also standard procedure as a safety precaution for operators working near the hood system when melt power is applied to wear high voltage boots and gloves. However, it was thought by some that the different conditions at pit 1 relative to past ISV operations could lead to step down potentials that had not been observed previously. Therefore, an array of rods was driven into the ground so that the step down potentials could be measured. The measurements were obtained during the early stages of the OAT when the voltage levels were at their peak (about 1000 volts per phase on this test). Step down potentials were measured in the millivolt range and it was determined that there would not be a risk of electrical shock due to a step potential (i.e., >50 volts within a 3-ft distance).

6.1.1.2. Loss of Independent Phase Voltage Control

On April 7 at about 6 a.m. (Easter Sunday morning), a problem occurred with the B phase of the 3750 kVA transformer secondary. The problem manifested itself with loss of voltage control at the B phase controller and a temperature on the B phase saturable core reactor that reached the high alarm (90°C, with normal operations being at about 40° - 50°). After a day of trouble shooting, the problem was temporarily repaired/resolved at about 4 p.m., and full power was again restored to the melt. Over the course of the next several days, the suspect components were removed for evaluation. The problem has still not been completely resolved.

6.1.1.3. Scrub System 1 Pump Repair

On April 8 at about 4 p.m., a problem with the #1 scrub system pump motor was experienced. The problem manifested itself with 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.

None of these acute issues contributed to any increased personnel stay time in the exclusion zone near or on the hood system.

6.1.2 Chronic Issues

6.1.2.1. Off-Gas Sampler Problems

Throughout the OAT portion of the melt and into the melt 1 portion, trouble was experienced with the various off-gas samplers being used on the test. These are discussed in the following sections.

The tape on the Graseby/Andersen tape samplers drawing a sample from the off-gas line between the roughing filter and the prefilters and the sampler on the hood broke because of moisture. The problem was finally remedied by installing a hand-held hair dryer to blow across the sample collection area to keep the tape dry. It was the Graseby-Andersen tape sampler drawing samples from the hood plenum that was located on the base frame of the hood in the exclusion zone that contributed to the increased stay times. The difficulties associated with the Modified Method 5 (MM5) samplers or any of the other samplers did not contribute to increased stay times.

The MM5 samplers that were drawing a sample from the off-gas before and after the HEPA prefilters continued to draw moisture from the impingers back through the particulate filter, compromising the sample. The problem was never completely solved although the last attempted remedy of cleaning the check valve was not tested because of the melt expulsion incident.

The AMS-4 sampler drawing samples from the off-gas stack continued to experience spurious alarms due to radon collection, in spite of its inherent capability to correct for radon (alpha radiation). This problem may have been related to the excess moisture impinging on the sample filter resulting in discharge of the unit's proportional detector.

6.1.2.2 Roughing Filter

The roughing filter employed on the new ISV off-gas hood was a bag house designed to shake the particulate off the bags and drop it back to the melt surface. There are 128 individual bags (8 rows of 16 bags each). Each bag assembly consists of a high temperature ceramic fabric (Nextel by 3M Corp) clamped to a 4-ft-long, 6-in.-dia. support cage. Each cage has a flange on top and is inserted vertically into a tube sheet and restrained and sealed by a hold-down mechanism. The bags are shaken by a pulse of air blown into the bag assembly from a pulse pipe, one of which is arranged over each row of bags. The pulse of air is controlled for pressure, duration, and interval. Since this was a prototypical application of the bag house design, it was expected that some adjustments would be required.

It turned out that experimental adjustments were made frequently to the roughing filter pulse controls. During the many days of the OAT, an operational procedure 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. w.c. When this occurred, it appeared that the air pulse system was unable to sufficiently clean the bags so the roughing filter had to be bypassed for a short period (usually 15 to 30 min) to allow the bags to be sufficiently cleaned. It became operational procedure 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 the compressor air supply pressure contributed to increased stay times in the exclusion zone.

6.1.2.3. Electrode Feed Hoists

Electrode feeding was accomplished via a system that employs an electromechanical chain hoist to support and vertically position the electrode. One hoist is used at each of the four electrode stations. One of the hoists was damaged by water infiltration at the control panel on the hoist before the OAT was initiated. A manual chain fall was obtained and used in its place so that the melt could start. This necessitated access to the working platform to adjust the manual hoist and lower the electrode. This was typically accomplished about once per shift (8 hr) and usually in combination with other activities requiring access to the working platform.

6.1.2.4. Hood Viewing Ports

The ISV hood was designed with 6 view port access locations, 1 on the middle of each side wall and 2 on the top of the hood. Two locations were selected to install a high temperature video camera. One of the camera ports was located on the top of the hood near the center, while the other was located at a view port on the side wall of the hood. This left 3 viewports on the side and 1 on the top for direct observation.

The use of the cameras was intended to reduce, if not eliminate, the need for personnel to access the hood for routine viewing purposes. The cameras included an air sweep system designed to keep the glass protecting the camera lens free of particulate. The three remaining viewports on the side of the hood included a damper mechanism that was also designed to minimize particulate buildup on the windows. However, neither the air sweep on the cameras nor the mechanical damper on the viewports were able to keep the windows adequately free of particulate for a clear view of the melt. Also, the camera system on the top of the hood, looking directly down onto the melt, apparently malfunctioned early in the run and could not be repaired at the time.

The particulate generation on the windows hindered the collection of visual data from the melt. It was possible to view the melt from the top sight glass when personnel were on the working platform and occasionally through small apertures in the side viewports where the particulate loading was low. Efforts were made to clean the view port windows occasionally during the run but the clear view was typically short lived. As a consequence of the lack of visual data collection capability, very little data were collected on the performance of the vent pipes because the position of the vent pipe socks could not be readily ascertained.

6.1.2.5. Off-Gas Flow Rate Design Uncertainty

Over the course of operations, an issue related to the off-gas flow rate developed. It appears that the flow rate being drawn from the hood is about twice that for which the prefilter and roughing filter systems were designed. That is, the off-gas system is designed to pull a maximum of about 104 standard scm/min of air. However, according to design data and information available at the time the filter systems were designed, the off-gas system is designed to operate normally at between 40 and 60 scm/min. Therefore, the filter systems were designed for a maximum flow of about 60 scm/min. It should be made clear that exceeding the design flow rate does not compromise any safety aspects of the equipment, it merely reduces 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 current conditions. It

contributed to an increased usage of HEPA filters in the prefilter system since the ΔP increased more rapidly than otherwise would have been experienced. The actual flow rates as well as potential modifications to the filtering hardware will be examined before the next run is initiated.

6.1.2.6 Melt Monitoring Thermocouple Array Malfunctioning

During the site preparation activities of the preceding year, an array of type K and type C thermocouples was installed in the soil surrounding the projected region of the first melt. For various reasons, almost all of the thermocouples failed during the early stages of the OAT. After that, there was no accurate indication of the melt front thermal profile or the melt temperature as was designed to be obtained by the thermocouple array. While this did not contribute to increased stay times in the exclusion zone, it did contribute greatly to a lack of understanding of the melt temperature, melt growth, and moisture profiles in and around the melt region. The failure also required the placement of an additional four thermocouples on the north and south sides of the off-gas hood at a depth where an enlarged melt body could be detected before it might undercut the perimeter of the off-gas hood. The placement of these extra thermocouples is discussed subsequently.

6.1.2.7 Caustic Solution Preparation Problems

The addition of caustic solution became complicated when the supply of liquid sodium hydroxide was depleted after only a few days. The intention was to add concentrated liquid caustic solution to the scrub tanks via the caustic tank addition procedure and avoid handling solid caustic pellets. Once the liquid caustic supply was depleted, the standard procedure was to mix solid caustic pellets and water to form the caustic solution to be added to the scrub tanks. It is recommended that sufficient supply of liquid caustic be obtained for the next runs. (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.) At one point in the run, the transfer linkage for the piston pump on the caustic addition system broke. It was temporarily repaired but needs to be replaced. The use of solid caustic material did not contribute to an increased stay time in the zone; it did, however, create an additional safety hazard for ISV operators, which had to be managed and can be avoided.

6.1.2.8. Hood Compressed Air Supply Problems

The hood system compressor developed a problem in which the compressor would not automatically start up once it reached its low pressure set point. For several days, this was an intermittent problem. Operators would have to judge when the compressor was depleted and go out and reset the compressor so it could recharge. The problem was eventually solved by one of the shift engineers. Since the compressor provided the pulse air for the roughing filter blowback cycles, the malfunction of the compressor contributed to the poor performance of the roughing filter during this period. The compressor control is mounted on the hood frame and required an entry to the exclusion zone for trouble shooting and reset procedure.

6.1.2.9 ISV Vent Pipe Monitoring System Inoperability

The subsurface vent pipe operational assessment technique provided no information on vent pipe performance. The movement of ceramic wind socks attached to the tops of various vent pipes was to provide visual evidence of their conducting off-gas into the hood from the subsurface. During the entire

OAT, only one wind sock could be seen from the north viewport window. It was lying on the Cerwool-covered ground surface and appeared bloated or rigid with what could possibly be expelled mud from the vent pipe. When the off-gas hood is moved, an effort will be made to systematically find and evaluate the condition of all socks and determine the residual open intervals of all pipes. As discussed subsequently, a better system to determine vent pipe performance must be identified for future ISV operations so their functional status can be evaluated in real time.

6.1.3 OAT Evaluation

During the "down time" of the OAT evaluation period, several planned procedures were conducted. These included removing several bags from the roughing filter for sampling (and replacing them with clean ones), inserting a rod into the melt to remove a sample of the glass and taking smear samples of the inside of the off-gas hood and piping equipment, as available. An overall evaluation of the process and operations showed that they were working very well, and in that light, the above listed problems were considered minor.

An effort was made to repair the damaged electrode hoist, but the repair parts obtained were not correct. Efforts were made to clean off the viewports but they were short lived. An effort was made to remove the malfunctioning camera (to attempt to repair it) but an evaluation of this effort showed that it would take more time and resources than could reasonably be committed at the time so the effort was abandoned. New holes were driven into the pit for thermocouple placement, one each on the north and south ends, in an effort to make up for the lost thermocouple data mentioned above and specifically so that the outward growth of the melt could be monitored relative to the size of the off-gas hood.

During the period of the OAT evaluation, when activities were not being conducted in the vicinity of or on the hood, power was applied to the melt at an "idling" rate of about 1 MW. The basis for applying the low power level was to try to preserve the melt temperature without advancing the melt while the evaluation (of undetermined duration) was being conducted.

Once the evaluation was completed and the approval was given to continue melting, melt 1 was initiated at about 6 p.m. on April 17. All operations and activities continued without additional problems, in spite of the fact that radiation levels in the vicinity of the hood were increasing as expected, until the event occurred at 6:12 p.m. on April 21.

6.2 ISV PROCESS PERFORMANCE DATA BEFORE AND DURING MELT EXPULSION INCIDENT

6.2.1 Electrode Depth Versus Time

The manually collected data on the penetration of the four electrodes into the melt body as a function of time is presented in Fig. 14. At the time of the melt expulsion incident, two characteristics of the electrode penetration information would seem worthy of note. First, the average electrode depth was approximately 10 ft below the elevation of perched groundwater within pit 1 at the two monitoring wells immediately to the north and south of the off-gas hood. Pit 1 ISV melting had been operating under such conditions relative to the pit's perched water since the start of operations when seeping water had to be pumped out of the startup trench.

Second, one electrode had been lagging significantly behind (approximately 1 ft less penetration) the other three electrodes. At the time of the melt expulsion incident, this lagging electrode was continuing to make depth progress, like the others, indicating that it was not stuck or frozen into a cold

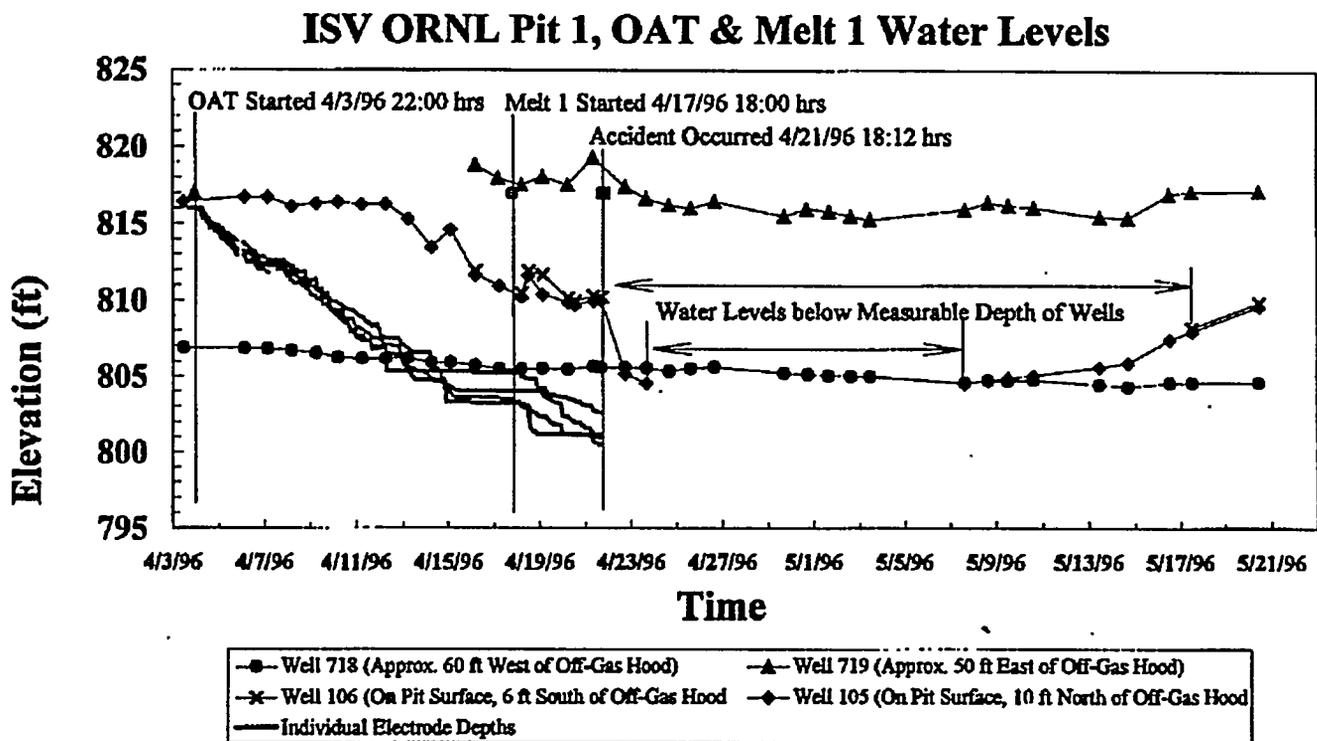


Fig. 14. Depth of ISV electrode penetration into the ORNL melt as a function of time and its relation to groundwater elevation within and around pit 1.

cap on the melt body. Such an electrode penetration profile, as well as the breakage of the other three electrodes during previous operations, was not considered unusual for large-scale ISV melts by the experienced PNNL or Geosafe staff.

6.2.2 Off-Gas Hood Temperature and Vacuum

Two obvious characteristics of the hood were grossly perturbed by the expulsion of glass during the melt expulsion incident: hood vacuum and temperature. The data acquisition system, however, only saves 4-min average characteristics of the data monitored by the process control system (the two Bailey computers). Thus, because both the hood temperature and vacuum (or pressure during the melt expulsion incident) during the incident were quite transient and because power to the DAS and other ISV equipment was turned off shortly after the melt expulsion, the archived data do not provide the necessary resolution of these parameters to understand the dynamics of the melt expulsion incident.

The archived data are useful to determine if trends indicating something unusual was about to occur were apparent. However, the data both in the short term and over the entire length of ISV operations at pit 1 show no obvious indicating trends. For example, the temperature of off-gas in the hood plenum (Fig. 15) indicated quite stable conditions during the 20 hr prior to the event. Small fluctuations like that which occurred around 3:21 p.m. on April 21 were the result of adjustment of the hood's air-intake valve (PIC-101) or a change in HEPA prefilters. There is no trend of increasing or decreasing hood off-gas temperature prior to the melt expulsion. The "spike" in the off-gas temperature near the end of the data collection period shows the influence of increased off-gas temperature on a 4-min average, much-dampened intensity.

The vacuum in the off-gas collection hood obviously went considerably positive (pressure) when the hood was lifted off the ground during the expulsion event. Routinely, the hood was maintained under slight vacuum (i.e., 0.25-0.50 in. of water column). As can be seen from Fig. 16, hood vacuum varied over the duration of the melt operations from operator adjustment of the air-inlet valve or application of water by hose or rainfall to the soil and sand around the hood base to improve its seal to the ground. Examination of detailed data during the 20 hr prior to the melt expulsion (Fig. 17) reveals the same lack of indicating trend prior to the melt expulsion incident.

6.2.3 Electrical Power Characteristics

An obvious question concerning the cause of the melt expulsion was whether electrical power to the melt body had been turned up prior to the melt expulsion incident and, unwittingly, lead to the "boil over" of the melt body contents. Of course, selection of the level of power to the melt involves some ISV process judgment and inherent process and equipment restraints. Voltage to the electrodes is the parameter adjusted by the ISV operations personnel, and the resulting amperage is monitored and kept within the limitations of the power cables to the melt. The resistance of the melt itself determines what current will flow at a given voltage setting.

Power is turned on and off quite frequently during any ISV operation for a variety of equipment adjustments in the electrical safety zone on the hood work platform. The level or amperage and voltage to each of the two phases to the melt body did not show any unusual fluctuation or trend during the entire 18-day interval of ISV operations; the ISV shift engineer, at the time of the melt expulsion incident, did report unquantified fluctuations in the voltage and current immediately before or during the melt expulsion but these are not reflected in the 4-min average parameters collected by the data acquisition system. The power to the melt (the product of current and voltage for both phases) showed an obviously similar trend over the 18-day interval (Fig. 13). It can also be seen that the level of power, which was

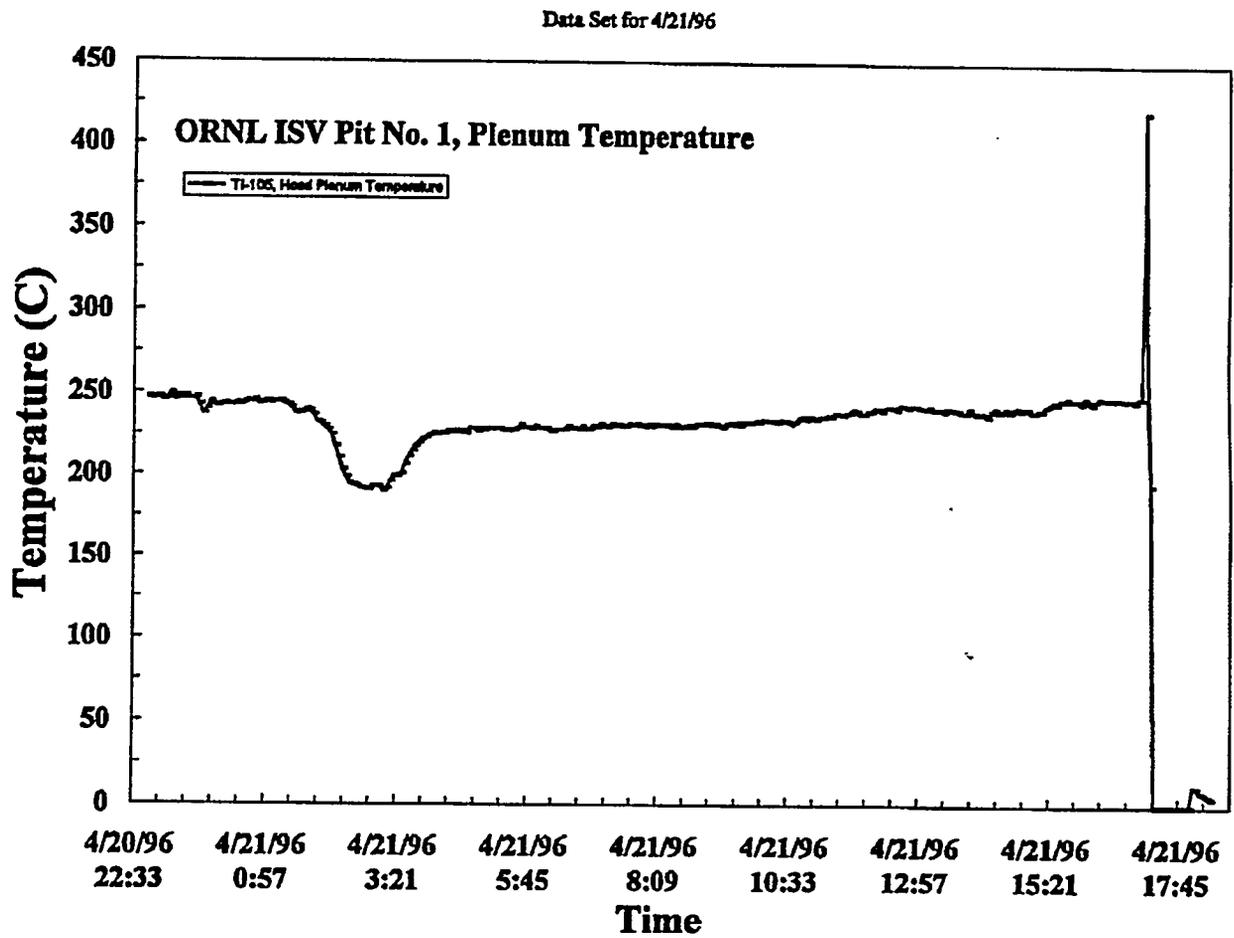


Fig. 15. Off-gas hood plenum temperature during the 20 hr immediately before the ISV melt expulsion incident of April 21, 1996, 6:12 pm.

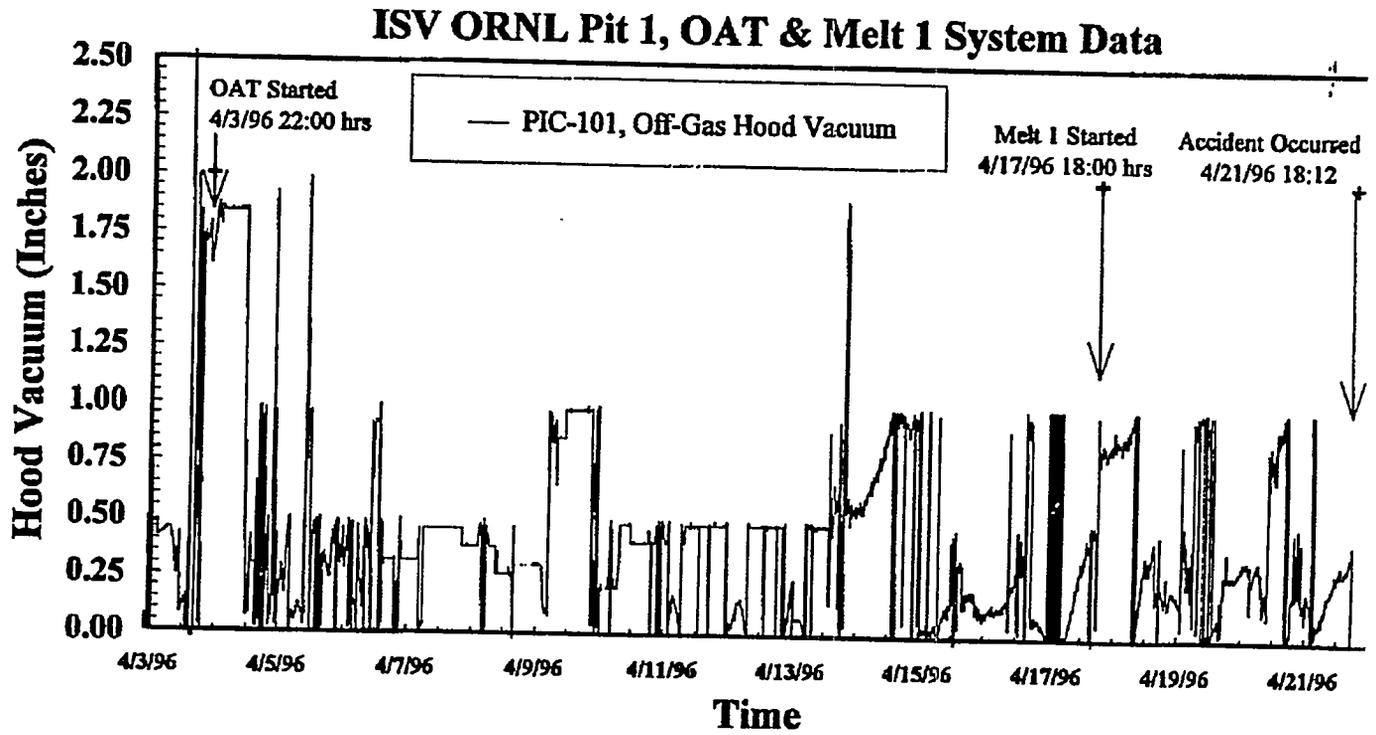


Fig. 16. Vacuum in the ISV off-gas collection hood over the entire duration of the ORNL pit 1 ISV operations.

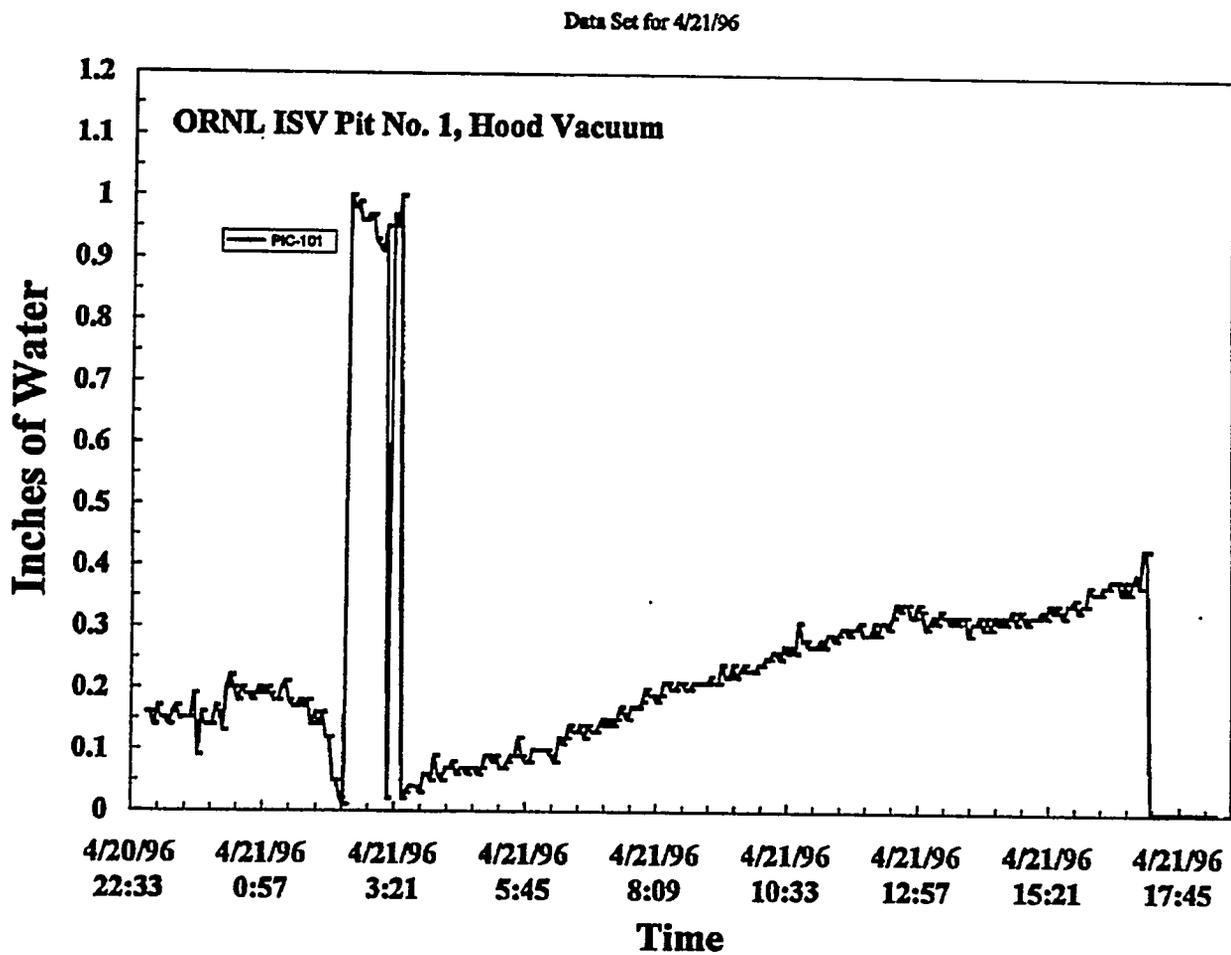


Fig. 17. Vacuum within the ISV off-gas collection hood during the 20 hr preceding the ORNL ISV incident of April 21, 1996, 6:12 p.m.

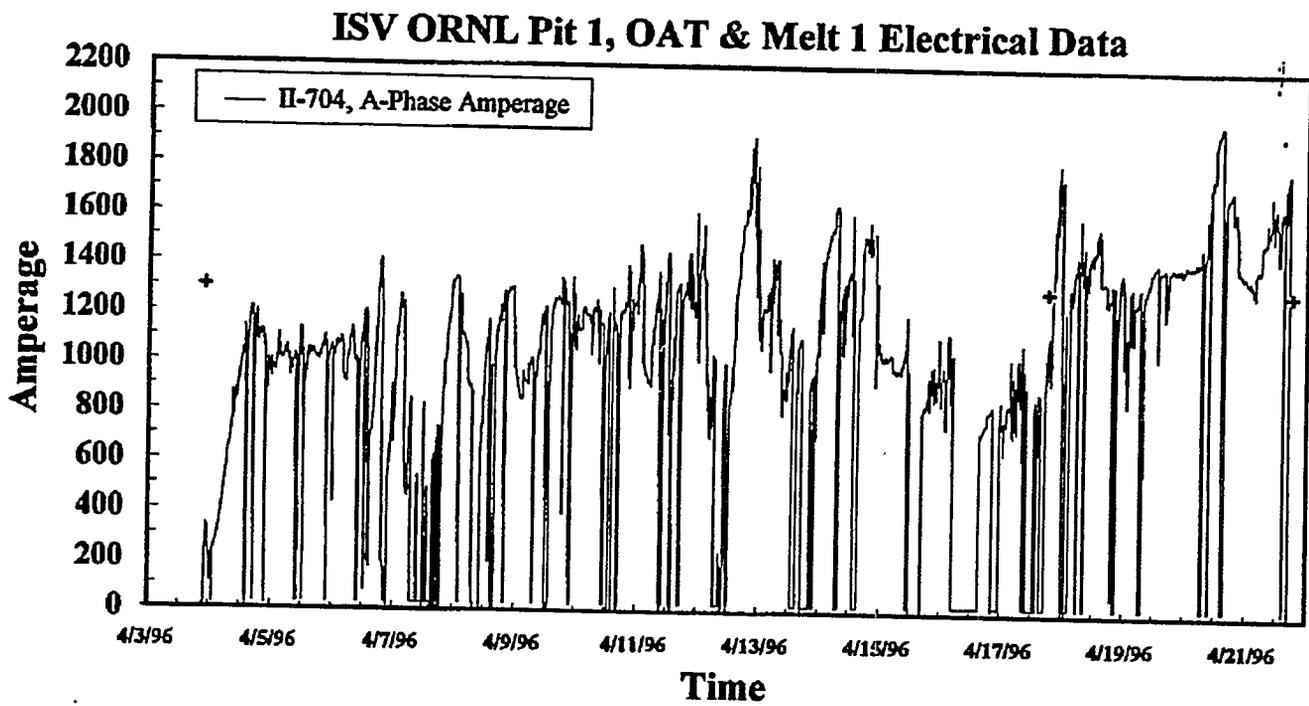


Fig. 18. Amperage in the A-phase supplied to the ORNL iISV melt over the duration of operations; B-phase amperage was identical.

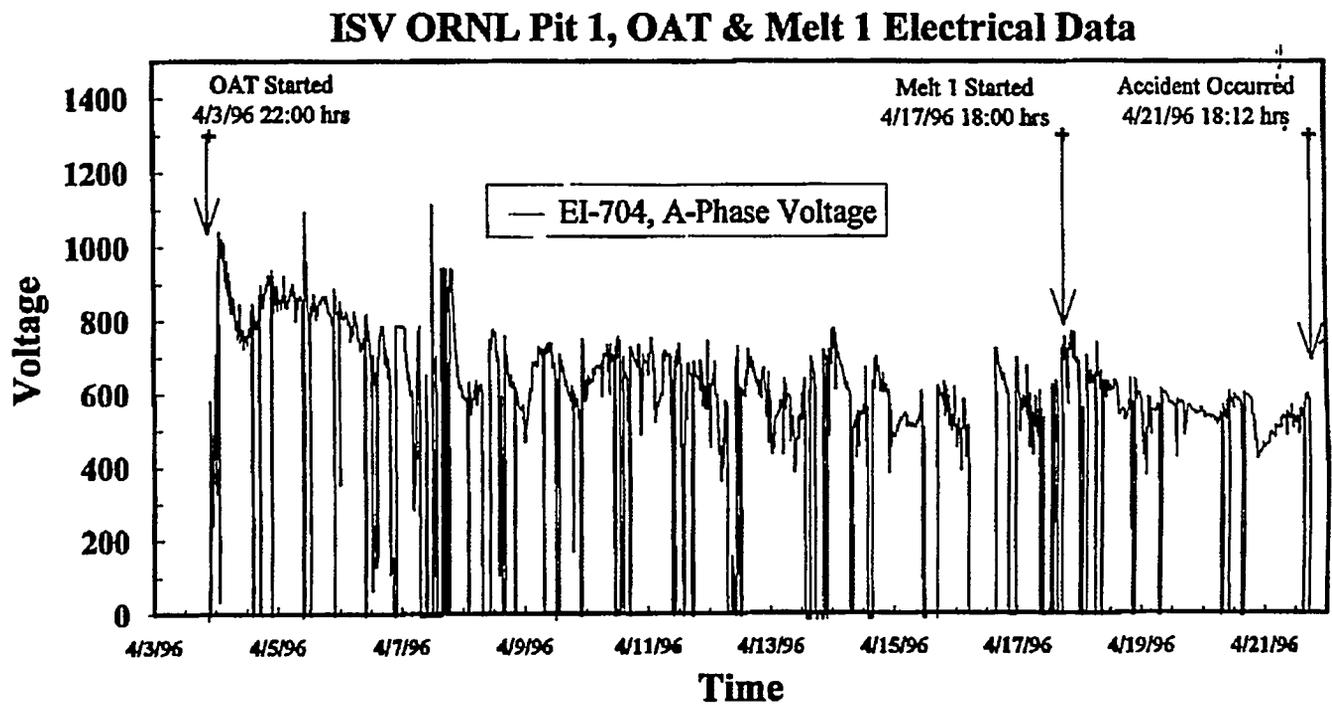


Fig. 19. Voltage applied to the A-phase of the ORNL ISV melt over the duration of operations.

being delivered to the pit 1 melt at the time of the melt expulsion incident, was not the most elevated; many other times previous to the melt expulsion incident, power levels had been significantly higher. Power was usually adjusted in response to hood off-gas temperature; when hood plenum temperatures exceeded about 300°C, power was routinely reduced to a level that would maintain off-gas temperature below that level.

The cumulative power delivered to the melt can also be seen in Fig. 20. As discussed previously, cumulative power is useful for estimating melt mass. More importantly, the slope of cumulative power versus time is a more convenient indicator of energy to the melt because it avoids the shorter-term fluctuations apparent in the actual power data. It can be seen from Fig. 20 that the slope of the cumulative power at the time of the melt expulsion was not significantly different than at other times during the 18-day interval.

Examination of electrical power characteristics during the 20 hr immediately prior to the melt expulsion (Fig. 21) reveals no obvious trend other than a gradual stepping-up of power. The brief period of power outage at about 2 hr before the melt expulsion was due to entry to the hood's work platform to perform a radiation survey and to adjust electrodes. Four personnel were on the work platform at that time, and this graph indicates that they could have selected a slightly later time to complete their tasks and been present during the melt expulsion.

During the periods when the pit 1 melt was operating optimally, a typical total power of 2 MW was being applied. Attempts to raise this power input always resulted in overheating of the ISV off-gas and hood skin temperatures and required power reduction. Actually, when viewed on a power density basis, the pit 1 melt was typical of many large-scale ISV melts that are typically deployed with greater spacing between electrodes. The 10-ft electrode spacing selected for the initial melt in pit 1 corresponds to a power density of 0.02 MW/ft², assuming 100 ft² area (10 × 10 ft) among the four electrodes. Using an identical power density, 4 MW could be applied to an electrode array with a 14.1-ft spacing. Such larger electrode spacings should be considered for the additional ISV melts in pit 1, which would both speed up ISV melt rate (mass per unit time) and result in larger diameter melts.

6.2.4 Water Collected From Melt

The water distilled from the ISV melt zone was condensed by the off-gas scrub system, collected, and transferred to a tanker, which was used to transport it to wastewater disposal facilities at ORNL. The limited capacity of the ISV scrub system collection tank necessitated frequent transfers of accumulated liquid, which generated considerable data on liquid accumulation versus time (Fig. 22 and Fig. 23). The ISV equipment has two identical off-gas scrub systems to provide backup or expanded off-gas processing capacity should a problem develop with one of the two systems. Scrub system 1 had its recirculating pump fail, as discussed previously, during the OAT, and, after repair during the down time between the OAT and start of Melt 1, it was returned to operation. The slope of the cumulative liquid volume collected in Fig. 22 and Fig. 23 is a direct measure of the rate of generation of water from the melt. Although the slope of liquid accumulation indicates a slightly greater generation rate (approximately 505 L of water per hour) during the 2 days immediately prior to the melt expulsion incident, there was no dramatic increase in liquid generation rate which could be interpreted to indicate a major influx of water into the thermally active zone around the melt.

6.2.5 Water Table Responses Before And After Melt Expulsion

As discussed in detail under the section on the mechanism of melt expulsion, the elevation of perched water in pit 1 was being drawn down gradually by distillation over the entire 18-day interval

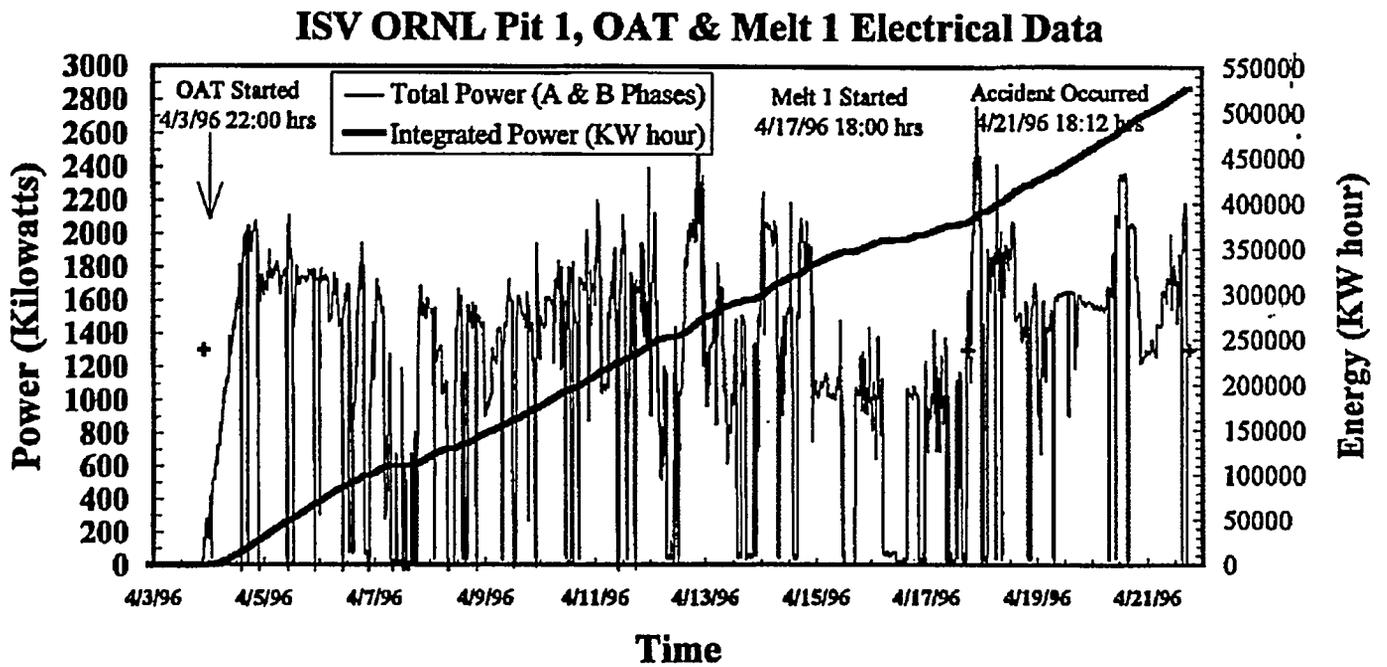


Fig. 20. Electrical power and cumulative energy applied to the ORNL ISV melt over the duration of operations.

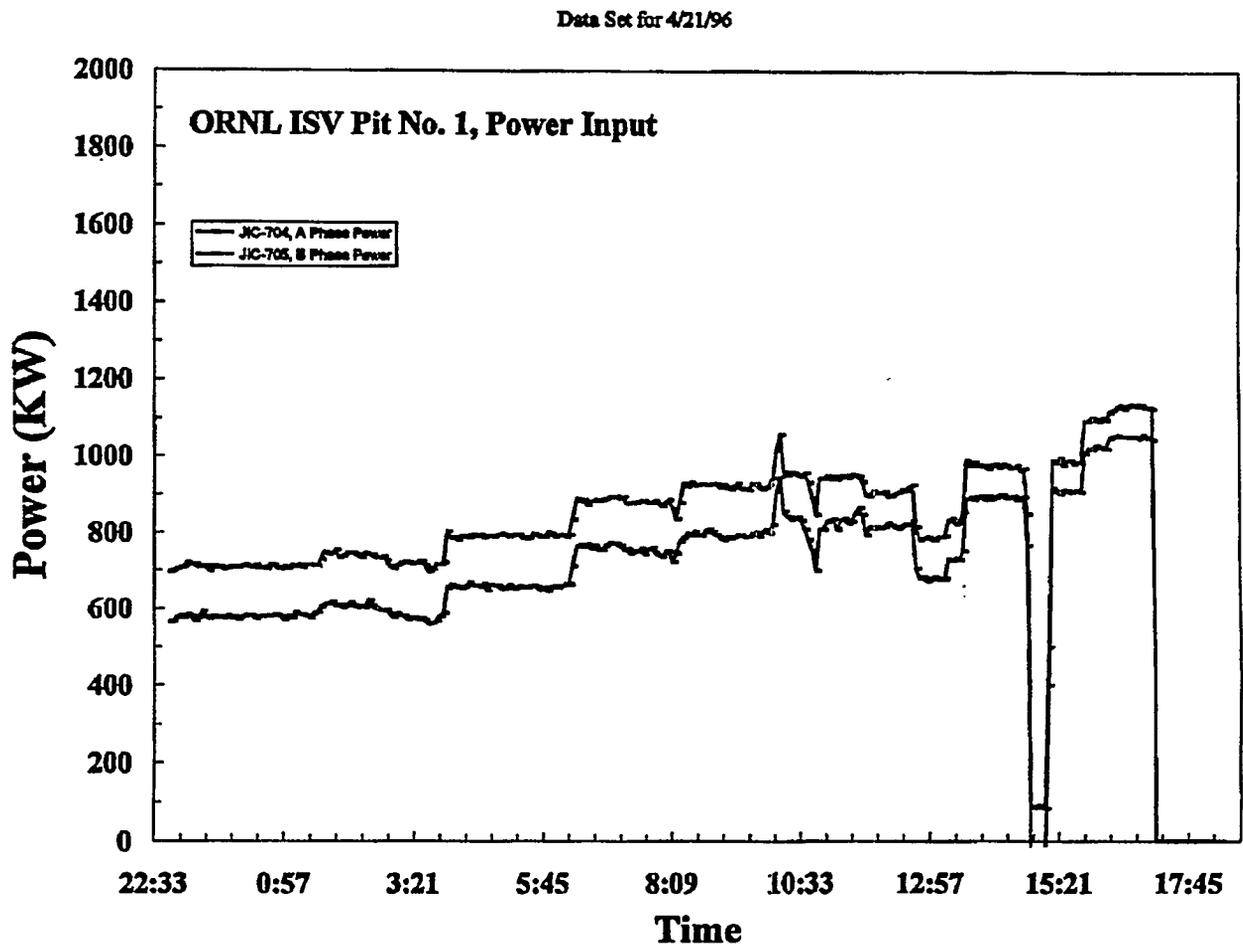


Fig. 21. Electrical power applied to the ORNL ISV melt during the 20 hr preceding the expulsion event of April 21, 1996, 6:12 p.m.

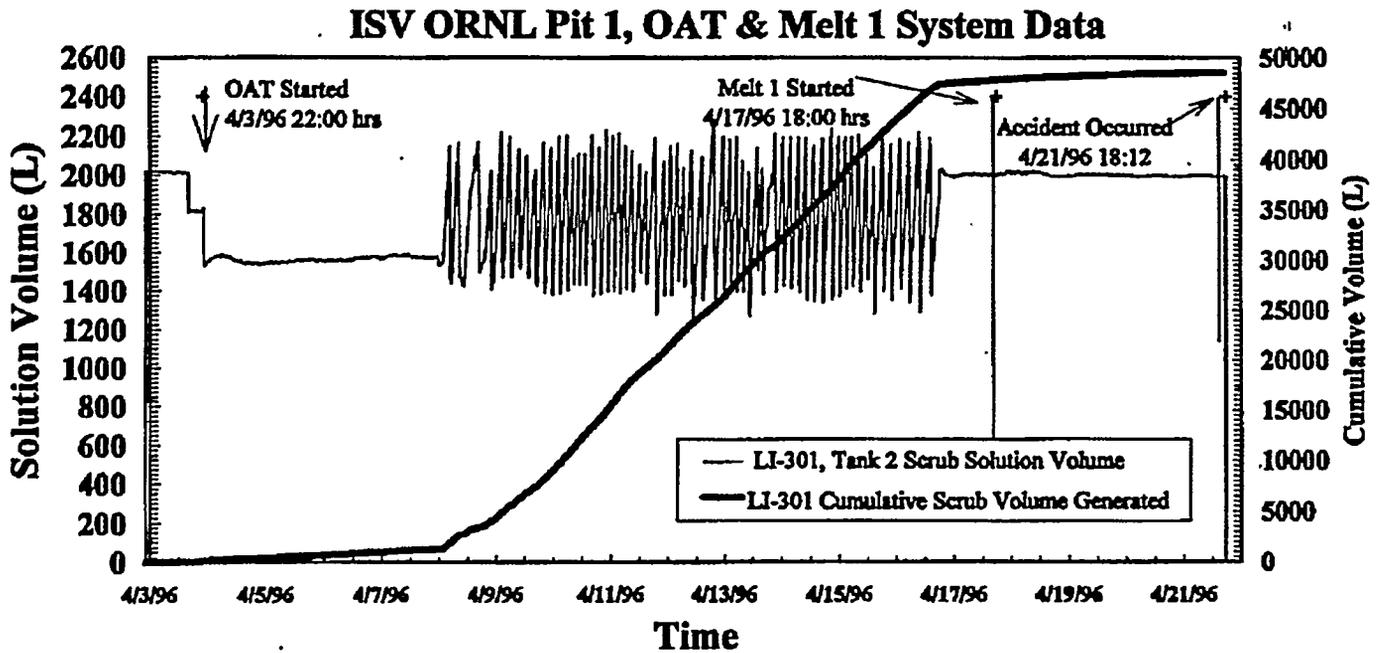


Fig. 22. Cumulative volume and liquid level of off-gas scrub solution in ISV scrub system 2 during the ORNL ISV operations.

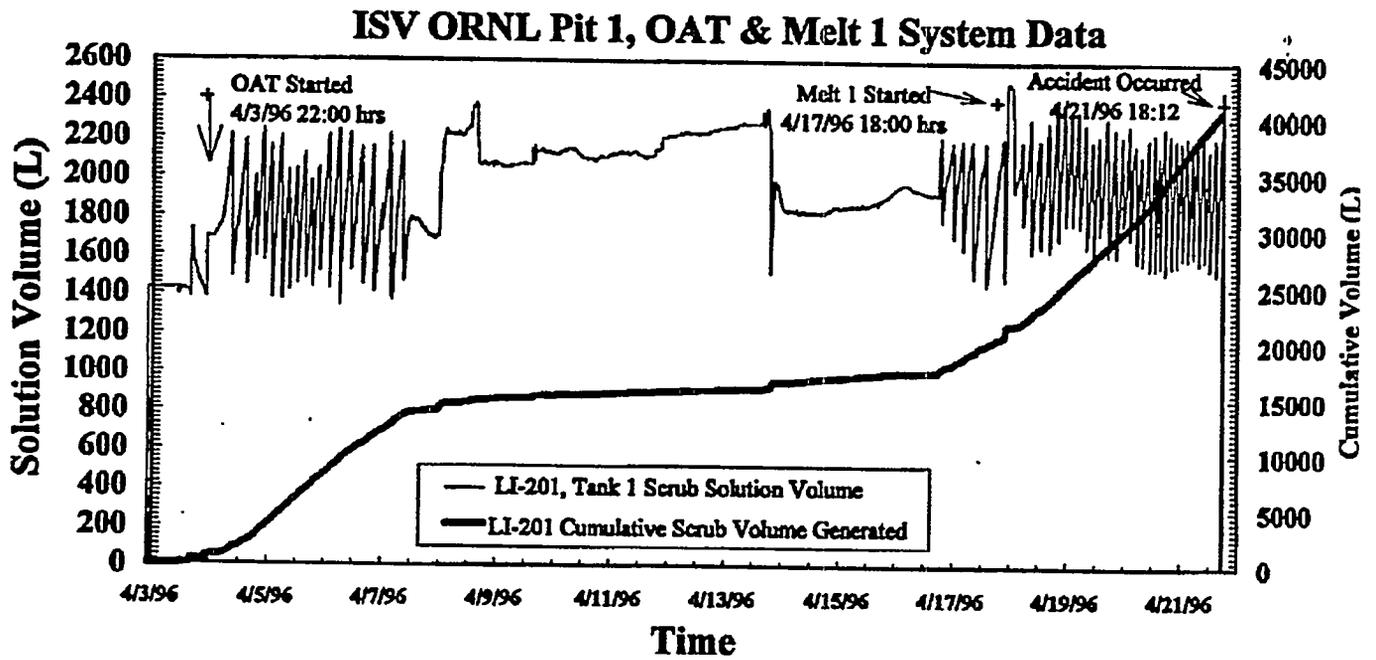


Fig. 23. Cumulative volume and solution levels in ISV off-gas scrub system 1 during operations at pit 1.

leading up to the melt expulsion (Fig. 24). However, when measurements of the water levels in the two wells immediately north and south of the off-gas hood were attempted on the day after the melt expulsion, no water was found in either well indicating that the levels had dropped at least 6 ft since the previous day's measurement to below the bottom of the each well.

In contrast, water levels in the two wells outside pit 1 to the east and west of the pit indicated no fluctuation relative to the melt expulsion incident. Water levels as of May 30, 1996, have now returned high enough to cover the top of the melt surface in the residual startup trench/subsidence crater. The two wells on the north and south sides of the off-gas hood were subjected to several elevation manipulations, (a few sections of Geoprobe rod were removed and the wells were lifted up slightly) required because of the pit 1 surface sculpting in March 1995 and to protect their protruding heads during off-gas hood assembly on the pit surface in July-September 1995. The differences between the original installation elevations and the final configurations are summarized in Fig. 25.

In addition to the observations of water levels in the two wells within pit 1 adjacent to the off-gas hood, the response of several thermocouples, positioned between these wells and the melt body provide additional information on the possible causes for the disappearance of water from these wells. Due to the failure of most of the buried thermocouples around the melt area, after the OAT, two angled Geoprobe rods were driven at angles on the north and south sides outside the off-gas hood. Two type-K thermocouples were then inserted in each Geoprobe rod to two different depths.

The purpose of these additional thermocouples was to provide warning if the ISV melt body were to approach a diameter similar to the width of the off-gas hood. Thermocouples were positioned at approximately 5 and 10 ft inside the wall of the hood at depths of 14 and 22 ft below ground surface, respectively (Fig. 26). All four thermocouples were connected to the data acquisition system in the project office/break area portable building; data from these thermocouples were collected beginning 4 days prior to the event and for about 2 weeks after. Power for this DAS was not interrupted as was the process control trailer's DAS during the fire. None of the four thermocouples indicated any thermal influence from the melt body. Thus, the disappearance of water from these two wells further away from the melt body would not have been caused by hot pressurized steam flowing away from the melt. The disappearance of water must represent flow towards the melt body probably into dried soil around the melt which, prior to the event, must have contained sufficient pressure to counter the hydrostatic head of perched water in these wells.

7. MECHANISM OF MELT EXPULSION

As in past incidences of molten glass expulsions during ISV operations, the ORNL expulsion was caused by steam pressurization at some depth beneath the molten body in excess of the static hydraulic pressure or the molten body plus any structural strength resident in the melt's cold cap and surrounding sintered zone (Geosafe Corp 1993; Roberts et al. 1992). To understand how these various components interact to conduct steam around the melt body rather than through it, the normal ISV melt body conditions need to be reviewed (Fig. 27). As can be seen from Fig. 27, the molten body is believed to have several transition zones between it and unaffected soil usually within a few inches of actual molten product. It is generally thought that the layer or rind of dry soil surrounding the molten body is very important as a conduit for steam and other hot gas to move from beneath and around the molten body to the ground surface where it collected in the ISV off-gas hood. The total soil porosity in this dry rind is thus available for gas conductivity.

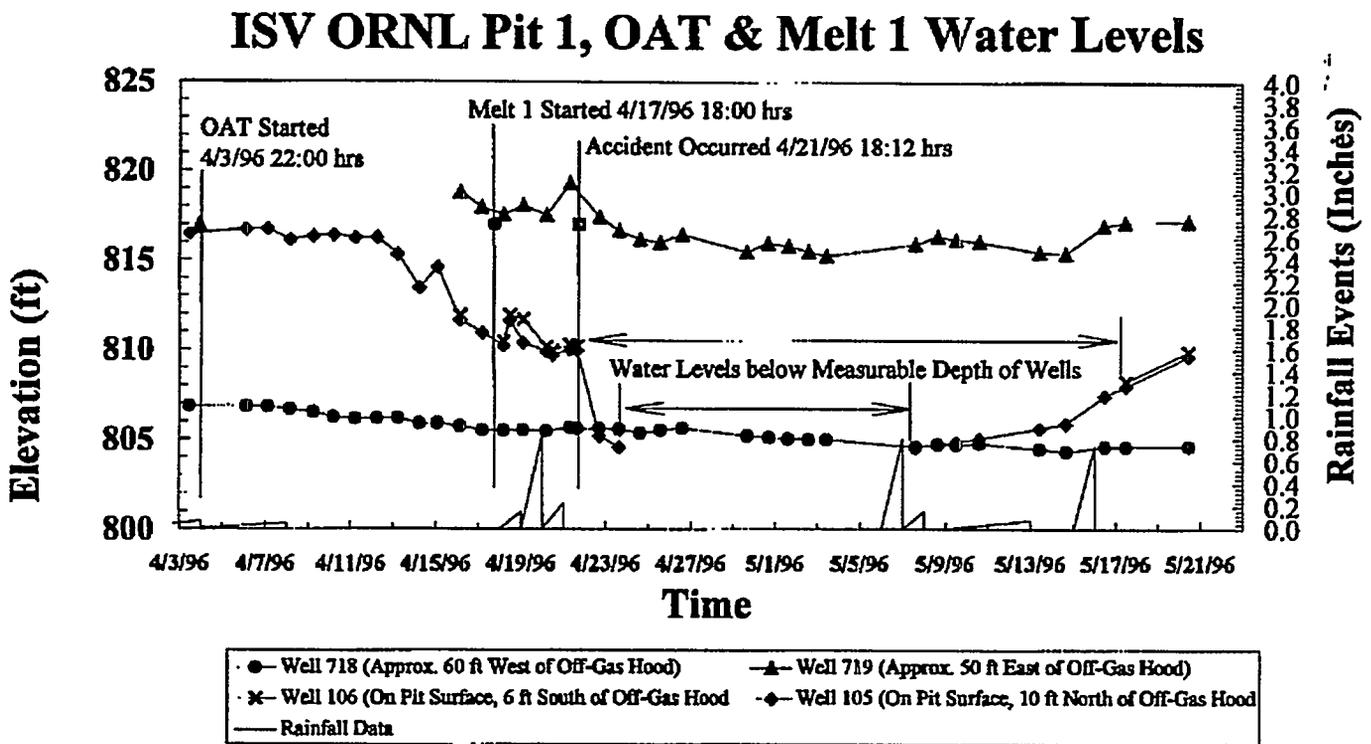


Fig. 24. Water table elevations within and around ORNL pit 1 and precipitation during ISV operation relative to the April 21, 1996, expulsion incident.

ORNL Pit 1, Geoprobe Wells

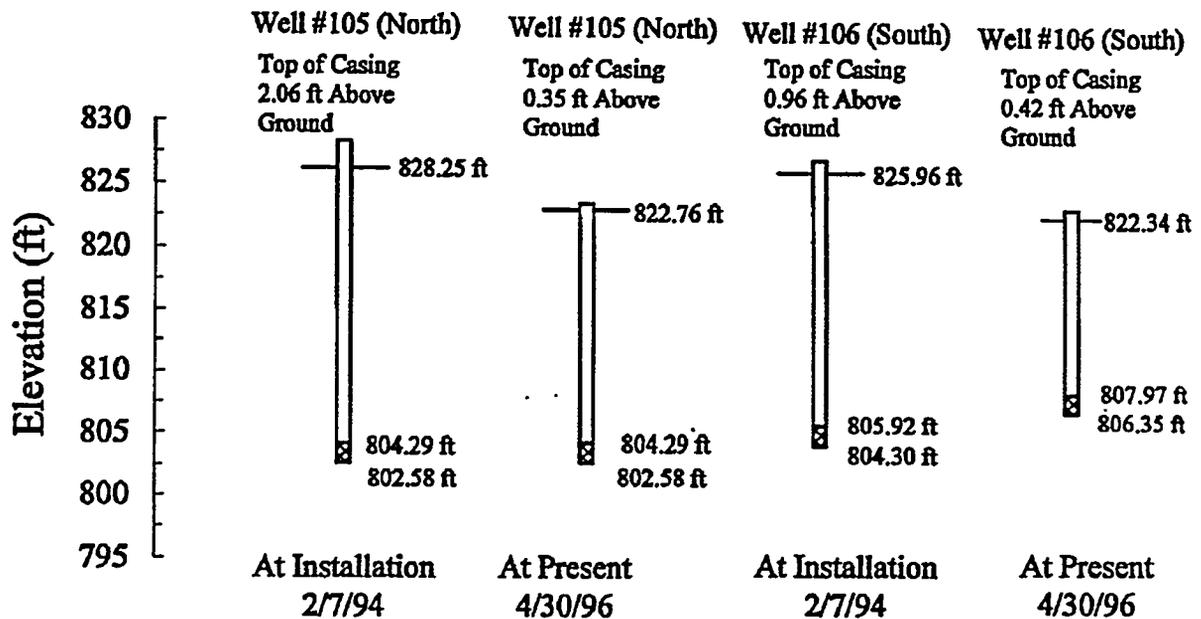


Fig. 25. Variation in configuration between installation and final use of two driven wells in pit 1 immediately north and south of the ISV melt body.

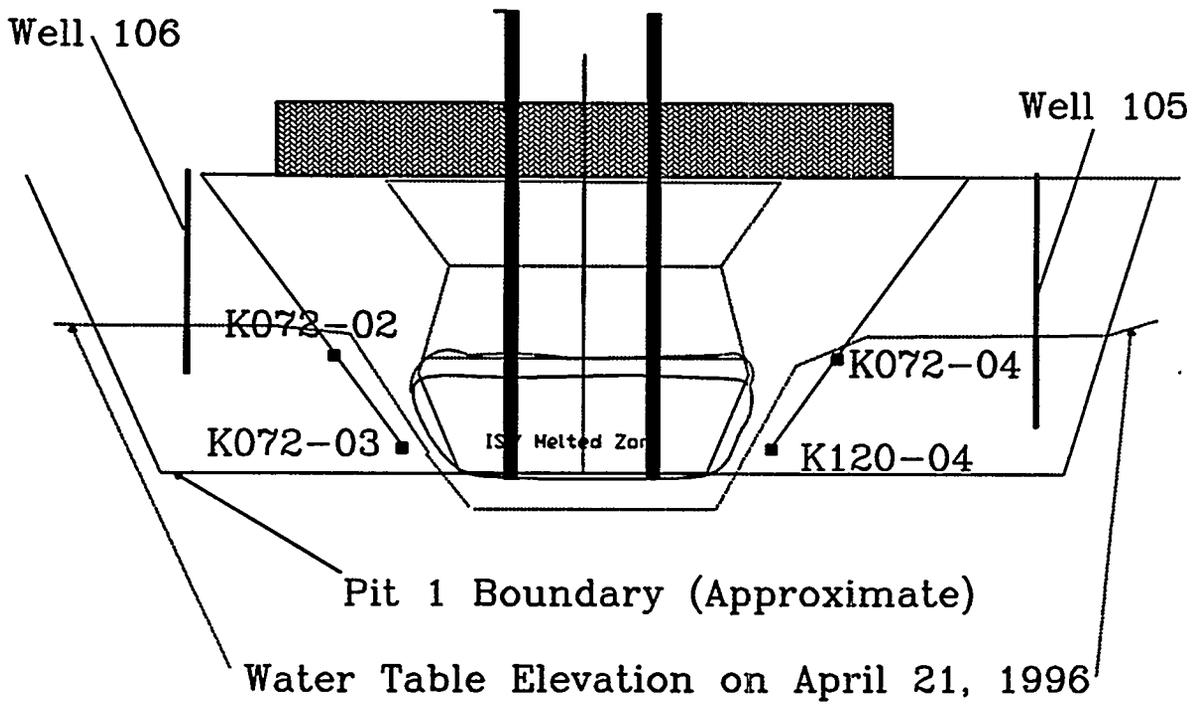


Fig. 26. Cross-section of ORNL pit 1 showing melt depth, perched groundwater, monitoring wells, and thermocouple positions immediately before the incident of April 21, 1996.

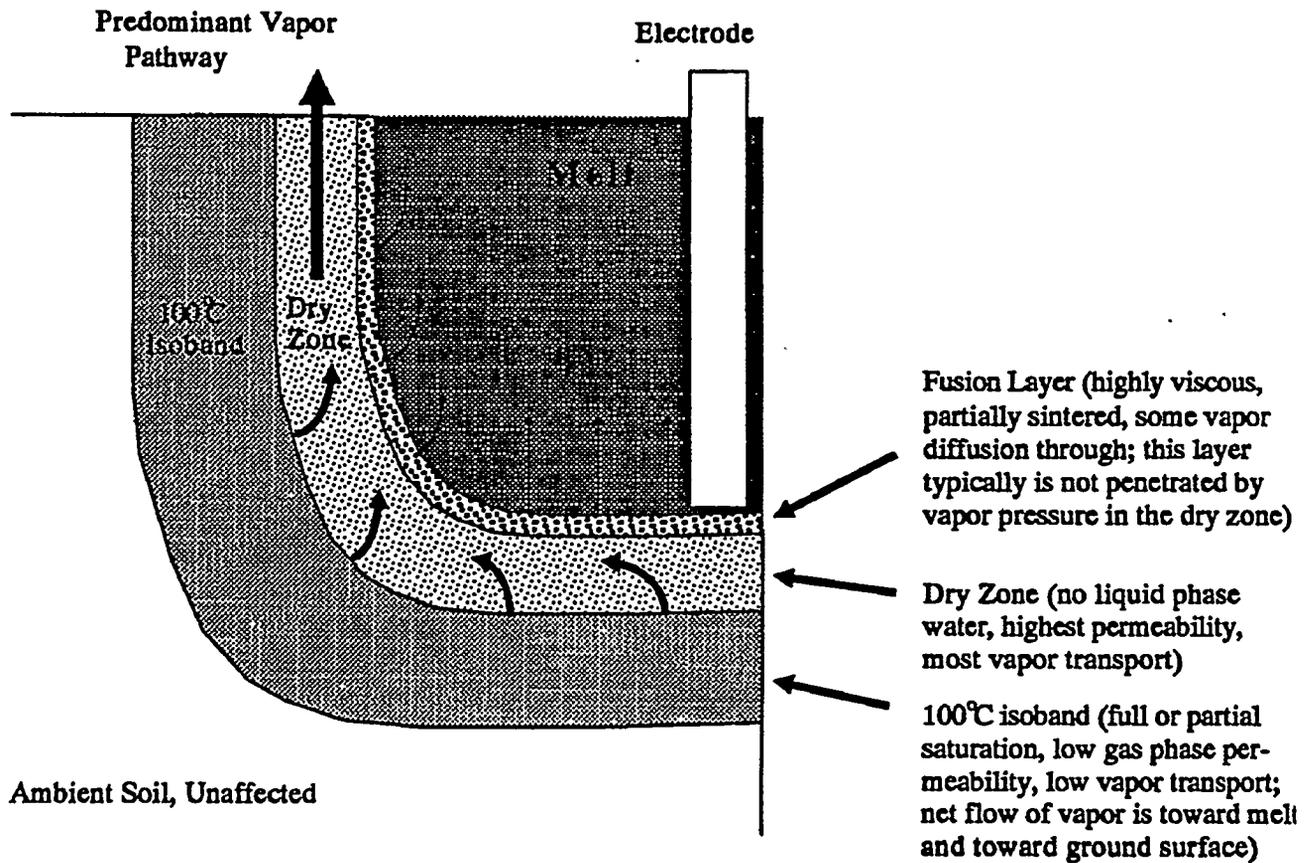


Fig. 27. Conceptual model of ISV off-gas vapor pathways around a body of molten soil.

Perhaps the only salient difference between the conceptual model in Fig. 27 and actual conditions in ORNL pit 1 is that the unaffected soil zone would have been completely saturated with water. This difference could be a significant factor in contributing to the expulsion incident in pit 1. As depicted in Fig. 28, pressurization of steam in the dry zone has an additional potential release through the saturated 100°C isoband zone into ambient unsaturated soil requiring only a nominal pressure to displace the narrow band of water in this limited saturated zone. However, in the case of pit 1, the unaffected soil was saturated; thus, it had no residual gas-filled porosity through which to conduct any steam. Obviously, some residual gas-filled porosity in the unaffected soil, i.e., unsaturated conditions, would be a desirable condition to maintain this potential pressure venting pathway.

7.1 SOIL POROSITY FOR OFF-GAS CONDUCTION

The porosity of pit 1 soil averaged about 43% (soil bulk density of 1.5 g/cm³) to a low of 16% for the denser undisturbed material at the bottom of the original pit (bulk density of 2.2 g/cm³). Of course, the total porosity is not necessarily correlated with or indicative of gas permeability, which is the parameter that limits the gas conductivity of a particular material; but the denser undisturbed material beneath pit 1 is likely to be of significantly lower gas permeability than the overlying less dense fill soil. Thus, as the melt body approached this denser bottom material, restrictions in gas permeability become more likely. In general, if the rate of steam generation is too great for the dry zone to dissipate around the melt body or if the dry zone projects into a zone with man-made obstructions, e.g., a concrete floor, residual tank floor, or extended metal barrier, steam pressure dissipation can be obstructed to the point that the least resistant pressure gradient to the surface would be through the molten body. Such man-made obstructions have been implicated in the three previous ISV melt expulsion events and, assurance of the absence of man-made barriers in pit 1 was thought by the project team to discount the possibility of a melt expulsion.

It would seem obvious in retrospect that the denser undisturbed soil or rock beneath pit 1 could have functioned as a barrier to steam pressure release and contributed to the melt expulsion. However, the pit bottom was judged not to exhibit high integrity as it was frequently penetrated by 0.5-in. diam rod driven from the soil surface with an electric jackhammer. Of the 63 driven rod strings, 15 penetrated up to 39 ft below the surface through the dense pit bottom at 26 ft. None of the other drive rod tests actually encountered refusal on the pit bottom; penetration tests were simply terminated when a change in penetration speed indicated contact with denser material, i.e., the pit bottom. The pit bottom always resulted in penetration refusal when driving the larger diameter (1.75 in.) AQ drill rod; the AQ drill rod strings were used as access holes for in situ radiation detection as part of site characterization. Thus, conceiving of the pit 1 bottom as a monolithic and impermeable strata would be inconsistent with the penetration test data collected during site characterization. However, the bottom of pit 1 is significantly more dense and likely significantly less permeable than the overlying fill soil.

7.2 MELT HYDROSTATIC PRESSURE

Gas permeability in the dry zone around an ISV melt body is not the only factor that restrains steam from entering the melt body. The weight of the molten fluid itself poses a significant barrier to steam entry. The density of molten fluid (2.83 g/cm³ or 177 lb/ft³) provides a calculated hydrostatic pressure of 1.21 psi/ft of melt depth. The pit 1 melt body at the time of the expulsion was 8.97 ft thick and, thus, would have a hydrostatic pressure of about 11 psi at its bottom. Steam could enter the melt body only

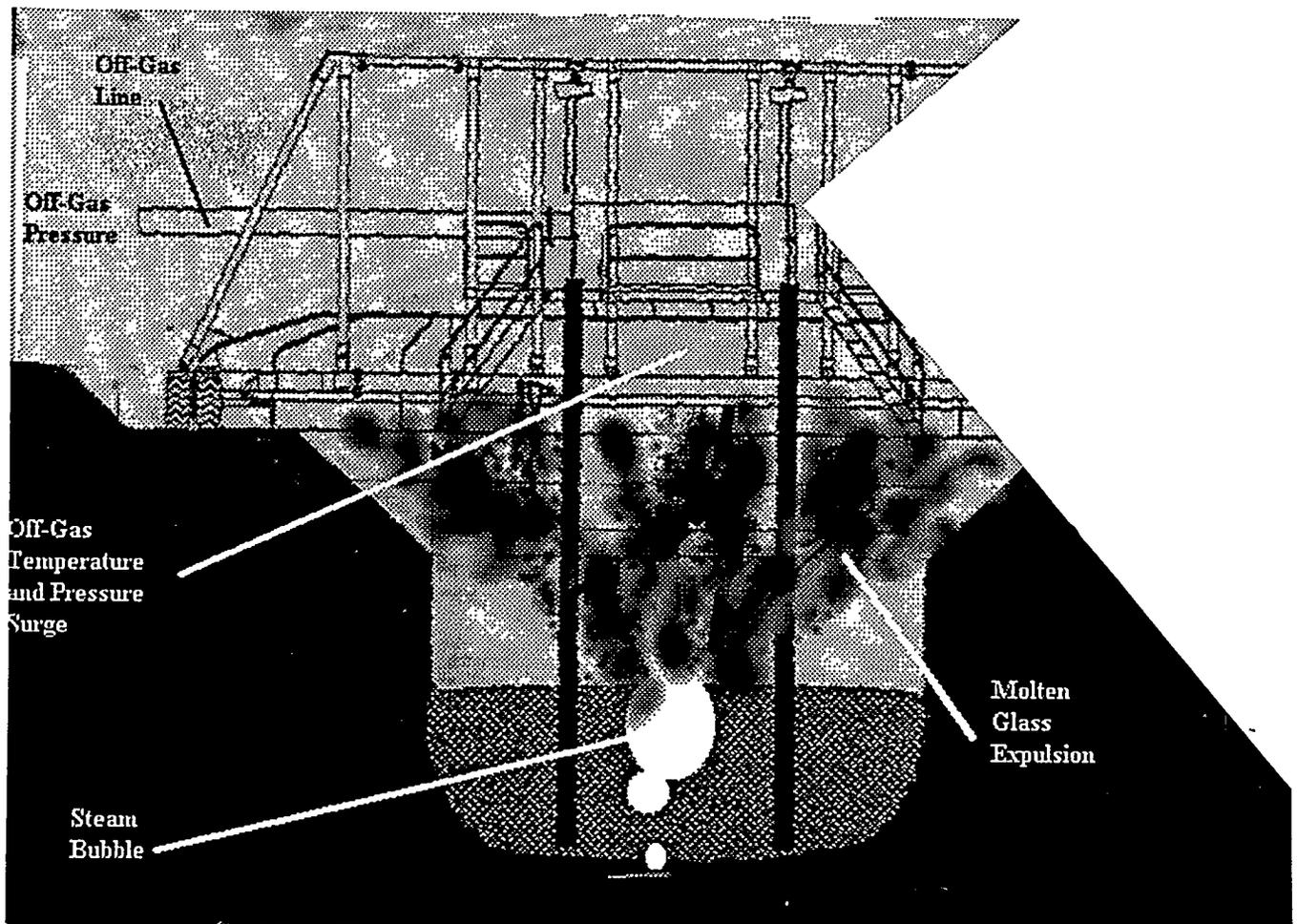


Fig. 28. Conceptualization of steam-bubble mediated expulsion of molten glass during the April 21, 1996 incident at ORNL.

if its pressure were in excess of that hydrostatic pressure. Of course, steam could enter the melt body at lower pressure at a shallower depth and still result in a bubble of significant size which could cause a melt expulsion (Fig. 28).

Assuming that the bottom of the melt is dry, the hydrostatic head difference between the melt bottom and the perched water in pit on the north and south sides of the off-gas hood was approximately 11 ft or 4.76 psi. Such a hydrostatic pressure would not be sufficient to overcome the melt body hydrostatic (more correctly, lithostatic) pressure and result in water movement to the melt body. But, a steam pressure of such magnitude would be quite plausible within the dry zone around the melt body. Of course, if that steam pressure were relieved rapidly, as during the melt expulsion event, then perched groundwater could flow rapidly into the depressurized dry zone. This explanation could account for the disappearance of standing water in the two wells within pit 1 after the melt expulsion.

7.3 SINTERED ZONE PROPERTIES

In addition to the static pressure of the molten body, the sintered layer or rind of thermally altered soil around the melt body poses a barrier to mechanical disturbance and, presumably, to steam entering the melt body. Sintered soil is soil which has not yet completely melted but has fused together into a brick-like material of high structural strength; it is stronger than either the dried or unaltered soil outside or the viscous molten mass inside. It provides some constraint on melt body deformations from pressures outside and inside it. Although the sintered layer is likely still permeable to steam, it likely poses some fluid conduction constraints on steam entry into the melt body.

7.4 COLD CAP FORMATION

Similar to the sintered zone on the sides and bottom of the ISV melt body, a cold cap or solidified layer can form on the upper surface of the ISV melt body. If the cold cap forms sufficient strength, it can function as a confining structure to melt deformation necessary for bubble growth and movement. It, in effect, can function as an additional confining pressure for the melt body. Its subsequent redissolution into the melt with increased heating or partial thinning of seams within, can result in a loss of this additional confining pressure. Such loss of confining pressure could well contribute to bubble growth, particularly if steam was marginally restrained near the melt bottom by its added strength.

7.5 PRESSURIZATION BY STEAM

Several mechanisms exist by which steam pressure could incrementally or rapidly build up somewhere beneath the surface of the molten body and subsequently lead to a rapid melt body expulsion. One mechanism, already alluded to above, involves a blockage in the dry zone conduit as a melt progresses downward into more dense material. A slight concavity to the lower surface of the melt body could result in sealing of the melt body to the dense underlying material with a pocket of trapped moisture. Pressure on this trapped water/steam could then build until it exceeds the structural strength of the sintered layer restraining it. If the sintered layer then fails by fracturing, pressurized steam or water would be brought into contact with the molten body with only its hydrostatic head as a restraint. If the sintered layer provides several hundred to thousand psi of strength, the rapid transition to the melt body's 11 psi of restraining force could easily result in a sudden expulsion of molten glass as the bubble rapidly floats to the surface of the melt body or displaces glass upward.

Similar in result, but slightly different in mechanism, would be a failure or cave-in of the sintered layer on the side wall of the melt body. Here, the fracture, in addition to being caused by steam pressure, could be caused by the collapse of subsidence crater wall material. If a ledge of surrounding soil were undercut by an ISV melt growing outward as it progressed downward, beam failure of such a ledge could propagate a crack downward into the side wall of the sintered and/or dry zone material. Such a fissure could occur at any depth of the side wall. An open fissure would be rapidly filled by any perched groundwater outside the dry zone. The molten material could also flow into the fissure, but its high viscosity, compared to water, would result in most of the fissure being filled with water rather than melted soil. The rapid contact between liquid water and molten soil could result in the rapid production of steam at high pressure which could rapidly displace molten material upwards. Failure of the sintered zone beneath the melt could also result in a similar rapid influx of water and subsequent steam generation and melt expulsion.

The observation that the perched groundwater, observed in the two water level monitoring wells within pit 1 just to the north and south of the off-gas hood, was not present on the day after the expulsion incident (Fig. 14) is pretty good evidence that this water was rapidly transported into the melt region. As can be observed from Fig. 14, at the time of the expulsion incident, the bottom of the ISV melt body as inferred from the depth of electrode penetration was approximately 10 ft lower in elevation than perched groundwater in pit 1 on the north and south sides of the hood. Thus, the hydraulic gradient was quite steep for movement of water into the region of the melt body during the entire period of melting at pit 1. However, it is unknown whether water movement to the melt body was the result rather than the cause of the expulsion incident. If the expulsion event was caused directly by a trapped pocket of moist soil beneath the engulfing melt body, then the fracturing pressure could create a conduit for water into the melt after the actual causative event. Subsequently, this water could contribute to the magnitude of the event and/or be transported into the dry zone where normal venting could evaporate most of it.

7.6 ALTERNATE PRESSURIZATION SCENARIOS

Less probable scenarios exist for alternate mechanisms for the melt expulsion incident in pit 1. The presence of a sealed drum of waste liquid cannot be ruled out with absolute certainty. Neither the disposal records for pit 1 nor the extensive penetration testing of pit 1 with driven drill rods revealed any evidence of buried objects. The excavation of the startup trench for the first melt operation exhumed only one small cedar shrub in the large amount of soil excavated.

Alternately, the presence of a sealed container of some combustible liquid also cannot be ruled out absolutely. The site characterization analyses of perched groundwater in pit 1 found no traces of volatile organic solvents. Nor were any traces of volatile organics or incomplete combustion products found in analyses of ISV off-gas scrub liquids during the melt expulsion incident. Thus, the scenario of a combustion explosion within the hood would seem unlikely.

Samples of the ISV off-gas scrub solution, which were taken immediately before and after the ISV pit 1 melt expulsion incident of April 21, 1996, 18:12, were analyzed for traces of volatile organics. Traces of volatile organics, particularly aromatic species like benzene, toluene, xylene, would be expected to show some detectable concentrations if a fire or explosion occurred during the ISV melt expulsion incident. Such a scenario would encompass the hypothesis that the ISV molten body contacted a pocket or container of a flammable organic unknowingly buried within the zone of vitrification. The site characterization of pit 1 as well as its disposal records make this scenario extremely unlikely; however, such a situation can never be ruled out absolutely.

The analyses requested were for volatile organic analytes (EPA method 8240). ISV scrub system 1 was in operation during the incident. Thus, the last sample immediately before the incident (4/21/96 15:30) was selected as a typical off-gas scrub solution profile; in addition the last sample from scrub system 2 (4/16/96 15:01) was selected as a replicate for typical ISV scrub solution characteristics; scrub system 2 was last used near the end of the OAT but before the melt 1 resumption when the circulating pump for system 1 was repaired. The after sample for scrub system 1 was taken on the day after the incident (4/22/96 14:19) when power was restored to the ISV equipment and the off-gas system was put back into operation. An additional after incident sample of scrub system 1 was taken two days later (4/24/96 14:15) during the final wash out of the scrub solutions in the processing trailer as the equipment was being put into safe standby status. Complete results are tabulated in Appendix A.

8. ROOT CAUSE OF PIT 1 MELT EXPULSION INCIDENT

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 in either the equipment design or the project procedures. All safety analyses addressed only radiological, electrical, and existing equipment hazards (Spalding and Naney 1995; Campbell and Ikenberry 1990; Lamar and McLaughlin 1987).

Although similar melt expulsions events had been experienced in three of the previous 70 large-scale ISV melts, 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. Off-gas from ISV melts is composed mostly of steam as soil moisture is distilled due to its 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 contributed to constrain off-gas (steam) movement around the melt body in the soil-filled pit during ISV.

Although several corrective actions are planned 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 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.

9. TECHNIQUES TO AVOID FUTURE MELT EXPULSIONS

Several techniques have the potential to prevent a repeat of the melt expulsion incident during future ISV operations at pit 1. All techniques of potential value are listed along with a discussion of their potential effectiveness, feasibility of implementation, cost, and implementation schedule, where available, for subsequent operations at pit 1.

9.1 DRAWDOWN PERCHED GROUNDWATER IN PIT 1

As discussed previously in the discussion of the mechanism of the melt expulsion, perched groundwater was, at worst, a likely cause of the driving force for water entering the melt body and, at least, a major contributor to the magnitude of the melt expulsion. Future ISV operations should have a hydraulic gradient for gravitational water movement away from, not towards, the melt body. Thus, the perched water table in pit 1 must be drawn down to about 5 ft below the target and final depth of the melt body (electrode penetration depth). There are a number of approaches to effect drawdown of the perched water and to prevent its recharge during ISV operations.

First, a passive system of water table suppression could be effected by a French drain surrounding the north, east, and south sides of pit 1 and graded to discharge to the east of the site. Although this option is likely to be quite effective, it requires the construction of a maximum 30-ft-deep gravel filled trench of over 400 ft in length to an exit elevation below 800 ft National Geodetic Vertical Datum. Such an exit elevation only occurs about 200 ft to the west of the site and resides in the contaminated wooded area to the west. A similarly-sized French drain in uncontaminated soil was installed in SWSA 6 in 1986 at cost of about \$400,000. This is a major construction project and, thus, is not recommended for pit 1.

Second, a drawdown well or wells could be installed directly into pit 1 and perched groundwater pumped out, collected, monitored for radioactive contamination, and disposed appropriately. The drawdown well(s) would need to penetrate the dense undisturbed soil/rock which forms the bottom of pit 1. Although such well construction is technically feasible, drill cuttings will be quite contaminated as well as the resulting pumped perched water. The pumped water would be expected to contain both ^{90}Sr and ^{137}Cs at activities similar to those found in the characterization activities at pit 1, i.e., 3200 and 1600 Bq/L, respectively. Although the disposal of such contaminated groundwater in the expected amounts (i.e., about 36,000 gallons as determined in the site characterization report) does not pose an overwhelming technical challenge, a potentially less expensive alternative exists. In addition, well(s) placed directly into pit 1 cannot continue to operate through the final melt which, by definition, incorporates all of pit 1 into the three overlapping ISV melts.

Third, drawdown well(s) could be installed near, but outside, pit 1. Aside from the obvious advantage of drilling wells into comparatively uncontaminated soil and having drawdown well(s) out of the way of the ISV melt bodies, such a placement would likely greatly attenuate the radioactive contamination in groundwater draining out of pit 1. Groundwater would be drawn into the well(s) from pit 1, and all other directions as well, by the induced hydraulic gradient. The groundwater from pit 1 would flow through the volume of soil between the pit and the drawdown point(s) where soil adsorption would remove all the ^{137}Cs and most of the ^{90}Sr .

Of course, such adsorption is merely an accelerated natural groundwater movement through pit 1 but in an unnatural direction. However, the drawdown time for such well(s) depends on the hydraulic conductivity and connectivity of the formation and the potential location of the well(s). Such information could be readily determined by a drawdown and recharge test using existing monitoring wells at the site. Based on these pump tests, the size, location, number, and contamination characteristics for drawdown can be determined. A minimum of two wells to a maximum depth of 35 ft below present grade would be required. An additional cost to the project of approximately \$30,000 would be required to complete construction of such well(s).

9.2 EMPLACE MONITORED VENT PIPES BENEATH MELT BODY

Although the pit 1 initial ISV setup employed straight angled vent pipes placed to various depths and at various distances from projected growing melt bodies, the zone of pit 1 immediately above the undisturbed pit bottom was not accessible by this venting technique. Perhaps pertinently, this was the zone of melt body penetration at the time of the melt expulsion incident. The "unventability" of this depth interval by the selected technique results from the combination of angled, straight vent pipes, the requirement for pipes to vent inside the off-gas hood, and the impenetrability of the undisturbed pit bottom to drive rods. Had vent pipes been able to be positioned deeper than the pit's undisturbed bottom, viable venting from this depth interval could reasonably have been expected. But, since vent pipes could not be placed through this dense pit bottom, the only option for a venting technique would have been to drive vent pipes at a near horizontal angle which would have necessitated extremely long vents penetrating the soil surface well outside the off-gas hood perimeter.

Two improvements in subsurface venting techniques can be implemented in future operations at pit 1. First, curved vent pipes could be installed beneath or, at least, at the final melt body depth. These could be emplaced using the same drill rod driving, withdrawal, and placement techniques used previously. Such curved vent pipes would only be required near the bottom of the melt zone while other zones could be vented using the previous straight angled vent pipe technique. Pre-curved drill rods would need to be fabricated for the pilot hole construction while continuously-slotted well screen would probably be flexible enough to conform to the pilot hole without pre-curving. Obviously, vent pipe construction and placement techniques would need to be verified prior to use at pit 1. Previous LMES investigation of directional drilling techniques (ORNL/ER-335, 1995) has neither demonstrated a directly applicable technique nor identified a probable alternate directional drilling strategy which would work at pit 1, particularly at the depth and density of the pit bottom.

Equally important as a credible venting technique for all zones under the melt body is a verification technique that vent pipes are open and remain functional during melt operations. In the previous pit 1 ISV operations, vent pipe performance monitoring became impossible. Ceramic socks were attached to each vent pipe and it was planned to use the video images of the inside of the hood to determine whether the socks inflated during operations and, hence, were functional in conducting off-gas from the subsurface. However, not only were the video images unable to observe any wind socks but attempts to view the socks through the observation windows provided observation on only one sock. Thus, vent pipe operational verification was completely unobtainable by the selected technique.

When the off-gas hood is finally moved, observation of surviving vent pipes and attached socks may provide some fortuitous evidence, e.g., continued venting of hot gas or remaining open to final melt contact, that venting did occur during operations. However, a much more certain vent pipe performance verification technique needs to be developed. Some type of inexpensive and durable flow sensor could probably be incorporated into the vent pipe to provide some remote signal of gas flow and temperature. Alternately, a pressure transducer access tube could be placed in selected vent pipes to determine differential pressure between that point and the hood plenum which would be indicative of gas flow. Filling of vent pipes with refractory material, like the high-temperature Firelite insulating aggregate used for melt body covering, would also seem desirable to prevent pipe collapse when the steel material melts on contact with the melt. This would be particularly important near the projected bottom of the pit where maximum vent functioning is essential.

9.3 SUBSURFACE PRESSURE MONITORING

In addition to improved venting techniques and remote sensor verification of their operation, it would also seem prudent to development and implement a technique to measure gas pressure beneath the melt body particularly in the transition zone between fill and dense undisturbed material at the pit bottom. Regardless of vent pipe operation, such monitoring information would provide early warnings to ISV operators that pressures under the melt were building and electrical power should be attenuated in response. Reduction in melt power when approaching the pit 1 bottom is a strategy (discussed below) similar to that used by Geosafe when ISV melts approach a subsurface concrete barrier. A steel tube, opened or screened near the bottom, would be sufficient to transmit pressure to a surface location where an appropriate transducer could be attached in a less harsh environment. Again, through angled and/or curved tube placement, pressure monitoring access points could be positioned at various depths under the projected melt body. Detailed site-specific designs need to be developed and implemented to provide ISV operators with such real-time information on subsurface pressures.

9.4 HOLD ELECTRODES ABOVE PIT BOTTOM

When the electrodes and, hence, the melt bottom approach the pit 1 dense undisturbed layer, the electrodes could be held from further penetration and power reduced to the melt. Both of these techniques have been used by Geosafe Corp. in operations at their Salt Lake City site after a similar melt expulsion incident. That site had a relict buried concrete floor under the projected melt zone. After the melt expulsion incident, an additional 35 large-scale melts were performed without incident by employing this technique. ORNL pit 1 may have a similar effective "floor" problem at the pit bottom. Such techniques are designed to slow steam generation while maintaining melt progress near such transition zones. By itself, such a technique has no guarantee to prevent future melt expulsions at pit 1 but in combination with the techniques discussed above, particularly subsurface pressure monitoring, has excellent potential to minimize recurrence of the problem. The project test plan and operational procedures could easily be modified to accommodate this approach at minimal cost, perhaps only a few extra days of melt operation.

9.5 CENTRAL VENT PIPE IN MELT

Placement of a central vent pipe or "fifth" electrode in the center of the ISV melt body has the potential to relieve submelt pressure. Such a technique was attempted during the large-scale ISV underground tank demonstration by PNNL in 1991. The central vent pipe appeared to function until it finally fell over shortly before that test ended in a similar melt expulsion event. Such a vent pipe has to be placed prior to melting and be open from that predetermined interval to the surface. The vent pipe used in 1991 was a bored-out graphite electrode column which was vented into the hood plenum. If such a technique is to relieve submelt pressure it must survive the melt conditions (graphite would be the material of choice), remain open (not fill with molten material) between the desired depth and the vent point, and be of sufficient size to conduct the maximum gas flow. Aside from the design changes to the present off-gas hood which would be required to support the vent pipe and the technique for the vent pipe placement to the desired depth in a very contaminated soil layer, too much safety performance would depend on a few untested assumptions. Would the graphite survive any better than the ISV electrodes of which three or four broke and required replacement? Would the internal bore in such a vent remain open throughout the entire melt as required? How would vent operational performance be verified and what operational decision would be required if operational monitoring were not possible? It seems that too many uncertainties exist to rely solely on such a technique for safety protection against

future melt expulsion events. However, it could be applied in combination with other less uncertain techniques to monitor and/or relieve submelt pressure.

9.6 AVOID COLD CAP DEVELOPMENT

As discussed in the section on melt expulsion mechanisms, cold cap formation can result in increased effective confining pressure for the ISV melt body on its submelt zone. As the cold cap collapses or is reincorporated into the melt body, the confining pressure is then afforded only by the hydrostatic head of the melt body and pressurized steam could vent rapidly through the melt body. By preventing cold cap formation, fluctuations in effective confining pressure could be avoided and, possibly, rapid changes in steam venting through the melt body. Techniques to avoid cold caps from developing include maintenance of sufficient electrical power to the melt to prevent the cooling conditions 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 will 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 at this time except that limestone gravel is not visible on the present melt surface. However, the massive mixing during the melt expulsion event is likely to have precluded the possibility of making this determination by examining the present melt.

However, due to the unknown role of cold caps in contributing to submelt pressurization, such techniques cannot be advocated for relief of submelt pressurization although the concept seems desirable. Thus, this technique will not be implemented in future pit 1 ISV operations.

9.7 BURIED ISV START-UP CONFIGURATION

An alternative to keeping the cold cap from forming and redissolving, would be to maintain a large cold cap which would, in turn, maintain a significant confining strength to prevent 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 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. Thus, this technique should probably be avoided for future pit 1 ISV operations.

10. SAFETY IMPROVEMENTS FOR FUTURE ISV MELT EXPULSIONS

Even with implementation of all the techniques discussed in the previous section to prevent ISV melt expulsions, the degree of understanding of melt expulsion mechanism is not sufficient to assure that

it will not occur again. Thus, more attention must be paid to the inherent risk of a recurrence of the melt expulsion incident. First and foremost, personnel must be protected from injury during performance of necessary tasks in the danger zone around 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 this melt expulsion incident and to maintain its operational status.

10.1 PERSONNEL SAFETY CHANGES

The various tasks, performed by ISV operations personnel on and around the off-gas hood, were summarized in section 2.1. Some tasks can be eliminated by providing remote monitoring or adjustment capability outside the danger zone, some tasks can be performed outside a well defined and confined danger zone, and some tasks can be performed within the danger zone using appropriate protective devices.

10.1.1 Predetermined Pressure Relief Zones

The greatest danger zone during the current melt expulsion incident was on the ground surface around the perimeter of the hood; the jetting of hot off-gas and flow of molten material occurred in this zone. Unfortunately, many hood control and monitoring points are mounted on the superstructure base frame clearly within this danger zone. But the danger zone only occurred where the hood lifted, notably on the north side; virtually no damage occurred on the west side. Thus, design of blowout panels or pressure relief structures will be able to confine the hot off-gas to a predetermined section of the hood perimeter for subsequent melts. The least amount of peripheral equipment is located on the west side of the hood; this, then, is the logical place for blowout panels. Alternately, conducting structures could vent off-gas upwards.

10.1.2 Earthen Berms

One of the fortuitous consequences of the off-gas jetting out from under the hood on the north side 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. The steep slope functioned to divert the hot off-gas jet up into the atmosphere rather than into the side of the trailer. The singed grass on the top of this embankment left a direct record of this deflection of hot gas (Fig. 29). This fortuitous result points to the effectiveness of earthen berms in deflecting expelled off-gas from horizontal flow where the potential for personnel injury is greatest. Thus, an earthen berm can be used as a confining engineered barrier for uncontrolled off-gas release and function to protect personnel from injury. The earthen berm can easily be constructed on all sides of the hood. In particular, the west side, which could have blowout panels and, thus, would be expected to accommodate all releases, should be precluded from personnel entry at all times. In other areas outside an earthen berm, personnel can have unrestricted access.

10.1.3 Elimination of Tasks in Danger Zone

Operation of the material addition system (MAS), previously performed by project staff within the danger zone around the hood, will be eliminated in future operations. The MAS was only used at pit 1 after the OAT as a test of its capability to add material under ISV conditions. Approximately, one hopper (2 yd³) load of limestone gravel was added. It was anticipated that significant amounts of limestone would be added throughout the OAT to maintain a lower ISV operating temperature to minimize volatilization of ¹³⁷Cs during the subsequent melt 1 operations into the contaminated layer of pit 1. However, the melt appeared to be operating at relatively low temperature (1600°C) which was ascribed

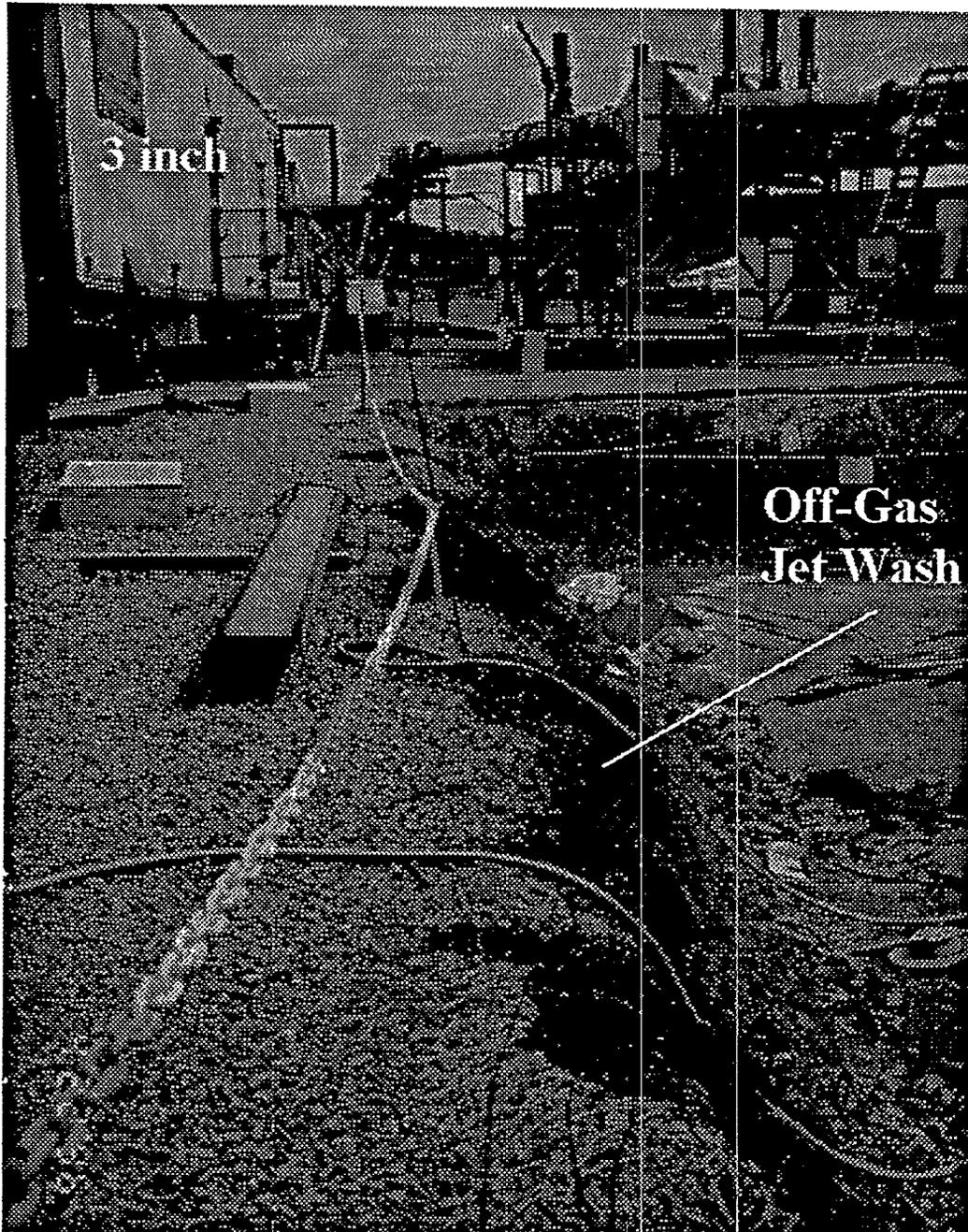


Fig. 29. Vegetation on embankment scorched by hot off-gas expelled from the north side of ISV hood during the incident of April 21, 1996.

to the relatively large amount of sodium and potassium included in the feldspar starter sand used to initiate this first melt. Thus, the use of feldspar starter sand will be employed in future pit 1 ISV melts and will eliminate the need for the MAS to add limestone.

The MAS was also used to add 4,800 lb (nominally 87 ft³) of Firelite 2855LI insulating aggregate after the end of the OAT in an effort to test the concept of an in situ floating barrier/filter on reducing ¹³⁷Cs volatilization from the melt. This floating layer was to be sampled after the termination of melt 1; however, the melt expulsion eliminated this layer even if it had not already been incorporated into the melt body. This aggregate is a 60:40 (weight basis) alumina:silica high temperature (1540°C) light granular material which had been found to dissolve very slowly into pit 1 molten soil. However, the excellent results observed for the behavior of ¹³⁷Cs in the pit 1 ISV test preclude the need to add this insulating aggregate to the melt surface using the MAS.

Another task which can be eliminated to avoid the need for ISV operators to enter a danger zone, is the recharge and adjustment technique for the hood's water spray suppression system. The system had been disabled from automatic process control during the melt 1 phase of ISV operations. It would have been of little or no use in avoiding, mitigating, or recovering from a melt expulsion event of the magnitude experienced by this project.

10.1.4 Automation of Monitoring and Adjustment Tasks

Several operator tasks involve gathering data from instruments, checking dial or indicators, and adjustments to equipment within the danger zone around or on the hood. Most of these can be eliminated by the use of remote sensors or adjustment controls. Such changes in design of existing equipment or project methods include:

- Use of pressure transducers in groundwater level monitoring wells in the danger zone. Previously, an operator walked to the two monitoring wells on each side of the hood and lowered an electronic tape down the well until it encountered the standing water when a audible signal was initiated. The operator manually recorded the depth of the water on a project data sheet. For approximately \$1,000 per well, a pressure transducer can be positioned in the bottom of the well and an electric signal routed back to a remote data acquisition system. Such a system, in addition to completely eliminating the danger to the ISV operator, will result in continuous and automatic data gathering.
- Roughing filter blowback adjustments - Controls for the roughing filter blowback interval, duration, and high and low differential pressure limits can be moved from its present position on the hood frame to remote pendant which can be positioned outside the danger zone like the electrode hoist remote pendant. The extension of electric lines would be relatively easy but flexible pipes/lines for the pressure gauge may require some design consideration. Likewise, both the roughing filter's supplied compressed air dial and regulator will need to be moved for remote operation if their adjustment is anticipated to be more frequent than electrode section addition (i.e., more than three times during a melt).
- Off-gas sampler/monitor - The present Graseby-Andersen paper tape sampler and monitor of the ISV off-gas is attached to the south superstructure frame. An ISV operator visually inspected this apparatus three times a shift. The entire sampler/monitor can be moved outside the danger zone. This will require the extension of the insulated sampling tube (0.5" stainless steel) to the new location and a supply of 110-volt power. Only a few hours of pipe fitter and electrician labor should be required. However, part of the repair of this monitor will include replacement of the burned insulation on the previous sample line between the roughing filter and the edge of the hood.

- **Air-compressor reset and adjustments** - The reset button switch and the air compressor itself on the west side of the hood can be moved to a remote location using a cable extension and sealed switch. This will eliminate the need for an ISV operator to enter the danger zone for this simple task. If adjustments to the compressor's upper and lower pressure set points are required during operation, then this control box will need to be moved outside the danger zone also. Alternately, the entire air-compressor could be moved off the hood to a remote location with the compressed air delivered to the hood via a flexible line.
- **Turning lights on and off** - Remote switches for the hood's overhead lights and for the lower or window lights will need to be provided. This will eliminate the need for operators to approach the circuit breaker panel attached to the east side of the hood frame. Likewise all 480- and 110-volt breakers should be either opened or closed prior to and not changed during operation. Addition of remote switches will eliminate the use of circuit breakers as switches
- **Video camera adjustment and window cleaning** - The present video viewing system was grossly deficient in meeting its stated objectives. Obviously, the air-jet window cleaning technique did not function. 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 be operable during the present melt expulsion incident, extremely valuable information about the size, location, and kinetics of the expulsion event may have been obtained. Positioning of a video camera directly over the melt may also need to 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 cameras should be considered to assure continuity of visual monitoring.
- **Radiation surveys** - Surveys of radiation dose readings by radiation protection personnel walking around and on the hood work platform should be eliminated. Results of the present melting operations have indicated that no contamination was observed outside the hood during operations (excluding the expelled glass product after the incident). Continued confirmation of the lack of surface contamination during ISV operations does not seem worth the risk to personnel safety. Perhaps, dose readings can be obtained using an extended probe arm from outside the danger zone, i.e., from behind an earthen berm.

10.1.5 Protection of Personnel During Necessary Tasks

The major task which requires operating personnel to enter the danger zone is the addition of electrode sections. The present design of the electrode hoist system allows 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 perform this task on the hood work platform. The hoist is disconnected from the electrode column in the melt and used to hoist and attach another section onto the existing column. The electrode stop and electrical power contact are then adjusted up to the top of the new electrode section. The

operation requires 3 persons about 30 min to complete a single electrode section addition; the operations require bolting and unbolting eight fasteners per electrode and more than one person to lift electrode collars and electrode contactors. It is highly desirable to complete this operation with a minimum of time of electrical power shut-off because cold cap formation will ensue and can result in electrode binding at the current position.

The temperature of the work platform environment during the melt expulsion incident must have been quite hot; the hood panels, only a foot below the open grating of the work platform, were reported to be glowing cherry-red (i.e., $>1000^{\circ}\text{C}$). Workers in such a situation would need thermal protection for a period of 20-40 seconds required to effect a controlled walk exit from the platform to outside the danger zone. Thermal protective suits, at a cost of approximate \$1000/set, would seem to offer such protection; consultations with safety specialists will be initiated to determine the best personnel protective clothing for this situation. Likewise, emergency repairs to hood equipment, which cannot be delayed until scheduled downtime, will require the use of such protective equipment in the danger zone.

Several changes in electrode addition procedure should be made to minimize the time necessary on the hood's work platform. First, because a typical melt requires three electrode sections, these sections should be staged on the work platform rather than the previous staging area on the ground surface to the north and south of the hood. These previous staging areas were clearly in some of the worst locations for off-gas jetting. The use of hood pressure vents may make these areas less hazardous but cannot completely eliminate the danger to personnel anywhere on the hood perimeter. Second, the use of power nut drivers to replace the previous hand wrenches would greatly reduce the time spent bolting and unbolting fasteners. Galling of bolt threads in the sometimes warm hood environment often made bolt loosening and tightening a difficult and time-consuming task. Third, a complete set of four electrode additions should be made at one time; if necessary, electrodes can be held on their stops until lagging electrodes catch up. There is an inherent increase in task efficiency and consequently decrease in time per electrode addition if one crew can perform all electrode additions at one time. This will be particularly true when power tools reduce the fatigue factor during bolt loosening which necessitated personnel task sharing during several electrode additions.

10.1.6 Definition of Hazard Zones and Times

It is virtually impossible to predict in an objective theoretical manner an interval of time after shutdown of electrical power to an ISV melt when a melt expulsion incident cannot occur. Such a situation is not too surprising when one considers the scientific efforts and resources which have been invested into predicting natural volcanic eruptions that have met with very limited success. Obviously, as time passes after electrical shutdown, an ISV melt body cools and its surface solidifies at some point to a strength where its molten interior can no longer move or be expelled. It is hoped that the subsurface pressure monitoring technique will provide some objective data from which decisions about personnel entry to the hood platform can be made. Criteria may be possible such as that the pressure must be stable for at least one hour and below a certain threshold before entry can be attempted.

An analogous decision concerning when the off-gas processing system can be shut down following termination of power to a melt has resulted in a generally accepted conclusion that about 4 hours are required before hazardous or radioactive contamination of off-gas can no longer be detected; this 4-hour rule-of-thumb has been ascribed to the time required for the surface of the melt body to form a sufficient cold cap to eliminate further contaminant release from the melt. Perhaps, a similar rule-of-thumb can be deduced for hardening of the melt body's sintered shell which would preclude the possibility of a melt expulsion. Such rules-of-thumb are likely to evolve in the future. But the resumed ISV operations at pit 1 will attempt to devise an indicator of melt stability from submelt pressure measurement stability. For

the foreseeable future, personnel will require protective clothing or equipment whenever entry into the danger zone is required.

The hazard or danger zone around the ISV hood will be maintained at the planned electrical safety exclusion zone, i.e., an arbitrary 20 ft away. However, earthen dikes or berms will be constructed at or inside this boundary. A mandatory exclusion zone will be maintained immediately outside the pressure relieving vents. These zones will be marked with the entrance requirements and danger indications.

10.2 EQUIPMENT PROTECTION

It would be quite expensive to relocate all the hood vulnerable equipment outside the danger zone. Just about all of the damage to the equipment on the hood's superstructure base was caused by secondary fires. Removal of all possible combustible material from the danger zone would greatly minimize most of the secondary fires. Items such as wooden cribbing and fiberglass grated walkways would be quite simple to accomplish. 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 wrapping 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 can be protected by rigid thermal insulation boards or removal. Additional insulation of the superstructure's main beam and components will be required above any blowout panel or vent area on the hood.

In addition to insulation and/or removal of peripheral equipment, a great deal of damage could have been prevented by the use of a small soil berm inside the hood to contain molten material flow from contacting the hood walls and flowing out underneath. Such containment would prevent much of the thermal warping of hood panels and the secondary fires on the southeast corner of the hood which were caused by direct contact with molten glass.

A hood-cooling external water spray system, similar to that designed by Geosafe Corp. for another ISV off-gas hood, could provide excellent 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. Such a system, in addition to heat suppression, would function as an in situ fire-fighting system.

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. Practically all the 128 filter elements were splashed with molten glass which adheres well to the ceramic fabric. More importantly, when sampling the fabric, it was extremely brittle and friable. One could poke a finger through it just in attempting to hold the filter. Initially, the fabric was quite flexible and durable; when sampled after the OAT, it was still pretty tough 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. As part of the estimated hood repairs, all the fabric sleeves on all 128 fingers will need to be replaced. This represents a cost of \$19,000 for the bags (material only) with a total repair cost of \$26,680 including labor (assuming all bag cages can be reused). It is not known whether the brittleness of the ceramic fabric after the event was the result of the proximity to and contact by molten glass or a result of the general thermal surge within the hood. Regardless, the roughing filter bags need to be protected from melt splashes in the future. If the redesigned hood can vent off-gas well, not lifting off the ground, and endure

the thermal shock without damage to wires, air, and hydraulic lines, then down time for several weeks solely to replace the roughing filter bags, which would be covered with very radioactive glass, would not be desirable.

For relatively little design and fabrication effort, a splash guard (which might also function as a thermal shield) can be placed between the bottom of the housing and the melt body lying directly below it. This shield or guard can be a sheet of stainless steel suspended from bars projecting down from the corners of the housing. It will need to be low enough to allow adequate open area for off-gas to flow around without significant drop in pressure. It will need to be wide enough to intercept any molten projectiles from the maximum width of the underlying melt body. And it will need to be sloped downward from middle to outside edges to facilitate the return of particles to the melt as the filter is shaken during normal blowback operations. Perhaps a four-sided tent configuration could meet these requirements. Hopefully, if cited correctly, this tent would not experience enough differential pressure to be under any significant stress; thus, it may not require a great deal of reinforcement or support.

10.3 EMERGENCY RESPONDER TRAINING AND PROCEDURES

The major consideration in the decision to advise the emergency responders (firemen) not to fight the secondary fires around the hood perimeter was the uncertainty in radioactive emissions and contamination of external hood surfaces at the time. It seemed logical that pouring water on these very hot surfaces would result in rapid steam generation and an unknown entrainment of radioactive contamination into the subsequent plume of steam. Having determined the degree of radioactive contamination after the incident such fire fighting efforts even with water could have saved a great deal of equipment damage with little or no effect on radioactive contamination containment. Even a better fire fighting strategy could have employed carbon dioxide extinguishers on the several small fires which caused much of the electrical insulation damage. Thus, in the unlikely event of future fires, fire fighters will be briefed on materials and methods for fighting such fires. They will also be briefed on the radioactive contamination conditions to which they will be exposed.

In addition, the decision to turn off all power to the site for the hood perimeter fire was not wise for the protection of equipment or minimization of environmental contamination. Again, the decision was made for the protection of fire fighting personnel. In virtually the same amount of time required to open the line circuit and turn off the emergency generator, power to the hood blower and the hood system could have been shut down at the control trailer; the off-gas system could thus have continued in operation. Power to the electrodes was already shut off by the shift engineer action of pushing the emergency power switch. With shut off of three switches all power to the hood would have been off and fire fighting efforts could have proceeded without fear of electrical hazards. These conclusions will be incorporated into the modified emergency plan for the project.

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Appendix A

**VOLATILE ORGANIC SPECIES IN SAMPLES
OF ISV OFF-GAS SCRUB SOLUTION**

Volatile Organic Species in Samples of ISV Off-Gas Scrub Solution

The reported data qualifiers are:

- U - Indicates compound was analyzed for but not detected. The sample quantitation limit is listed.
- J - Indicates that the quantitation value is estimated. Usually this qualifier will appear after a value that is below the quantitation limit (i.e., the compound was detected at some level below the quantitation limit). The qualifier may also appear after a tentatively identified compound (TLC) for which no specific calibration was available.
- B - This qualifier appears for a compound that was detected in both the sample and its associated blank.
- Y - Indicates that the value was obtained after dilution of the sample.

Results - The results of the volatile organic analyses are presented in the attached tabular data. The only detected organics in any samples were traces of butanone and acetone which appeared in all samples and exhibited their maximal concentration in the "before" melt expulsion incident samples particularly of scrub system 1. Apparently, trace concentrations of these species must be normal background characteristics of ISV off-gas from soils like those in pit 1 and may also contribute to the characteristic odor of ISV scrub solutions. More importantly, none of the fire-indicating aromatic species were detectable in any of the samples. Thus, this evidence would support the conclusion that a fire or combustible explosion of any organic species was not involved in the pressurization-temperature incident at pit 1.

Customer Id: SS-1-58 ORNL Sample No: 960502-125
 (Sample taken 4/21/96 15:30, last sample before melt expulsion incident)

Analysis	Result	Error	UNITS
1,1,1-trichloroethane	U	5.00 +-	µg/L
1,1,2,2-tetrachloroethane	U	5.00 +-	µg/L
1,1,2-trichloroethane	U	5.00 +-	µg/L
1,1-dichloroethane	U	5.00 +-	µg/L
1,1-dichloroethene	U	5.00 +-	µg/L
1,2-Dichlorobenzene	U	5.00 +-	µg/L
1,2-dichloroethane	U	5.00 +-	µg/L
1,2-dichloroethene (cis)	U	5.00 +-	µg/L
1,2-dichloroethene (total)	U	5.00 +-	µg/L
1,2-dichloroethene (trans)	U	5.00 +-	µg/L
1,2-dichloropropane	U	5.00 +-	µg/L
1,3-Dichlorobenzene	U	5.00 +-	µg/L
1,4-Dichlorobenzene	U	5.00 +-	µg/L
2-butanone	B	25. +-	µg/L
2-hexanone	U	10. +-	µg/L
4-methyl-2-pentanone	U	10. +-	µg/L
acetone	Y	350. +-	µg/L
benzene	J	3. +-	µg/L
bromodichloromethane	U	5.00 +-	µg/L
bromoform	U	5.00 +-	µg/L
bromomethane	U	10. +-	µg/L
carbon disulfide	U	5.00 +-	µg/L
carbon tetrachloride	U	5.00 +-	µg/L
chlorobenzene	U	5.00 +-	µg/L
chloroethane	U	10. +-	µg/L
chloroform	U	5.00 +-	µg/L
chloromethane	U	10. +-	µg/L
cis-1,3-dichloropropene	U	5.00 +-	µg/L
dibromochloromethane	U	5.00 +-	µg/L
ethylbenzene	U	5.00 +-	µg/L
methylene chloride	U	5.00 +-	µg/L
styrene	U	5.00 +-	µg/L
tetrachloroethene	U	5.00 +-	µg/L
toluene	U	5.00 +-	µg/L
trans-1,3-dichloropropene	U	5.00 +-	µg/L
trichloroethene	U	5.00 +-	µg/L
vinyl acetate	U	10. +-	µg/L
vinyl chloride	U	10. +-	µg/L
xylene (m&p)	U	5.00 +-	µg/L
xylene (o)	U	5.00 +-	µg/L
xylene (total)	U	5.00 +-	µg/L

Customer Id: SS-1-59 ORNL Sample No: 960502-126

(sample taken 4/22/96 14:19, first sample of scrub system 1 solution after melt expulsion incident)

Analysis	Result	Error	UNITS
1,1,2,2-tetrachloroethane	U	5.00 +-	µg/L
1,1,2-trichloroethane	U	5.00 +-	µg/L
1,1-dichloroethane	U	5.00 +-	µg/L
1,1-dichloroethene	U	5.00 +-	µg/L
1,2-Dichlorobenzene	U	5.00 +-	µg/L
1,2-dichloroethane	U	5.00 +-	µg/L
1,2-dichloroethene (cis)	U	5.00 +-	µg/L
1,2-dichloroethene (total)	U	5.00 +-	µg/L
1,2-dichloroethene (trans)	U	5.00 +-	µg/L
1,2-dichloropropane	U	5.00 +-	µg/L
1,3-Dichlorobenzene	U	5.00 +-	µg/L
1,4-Dichlorobenzene	U	5.00 +-	µg/L
2-butanone	B	12. +-	µg/L
2-hexanone	U	10. +-	µg/L
4-methyl-2-pentanone	U	10. +-	µg/L
acetone	180. +-	µg/L	
benzene	U 5.00 +-	µg/L	
bromodichloromethane	U	5.00 +-	µg/L
bromoform	U	5.00 +-	µg/L
bromomethane	U	10. +-	µg/L
carbon disulfide	U	5.00 +-	µg/L
carbon tetrachloride	U	5.00 +-	µg/L
chlorobenzene	U	5.00 +-	µg/L
chloroethane	U	10. +-	µg/L
chloroform	U	5.00 +-	µg/L
chloromethane	U	10. +-	µg/L
cis-1,3-dichloropropene	U	5.00 +-	µg/L
dibromochloromethane	U	5.00 +-	µg/L
ethylbenzene	U	5.00 +-	µg/L
methylene chloride	U	5.00 +-	µg/L
styrene	U 5.00 +-	µg/L	
tetrachloroethene	U	5.00 +-	µg/L
toluene	U 5.00 +-	µg/L	
trans-1,3-dichloropropene	U	5.00 +-	µg/L
trichloroethene	U	5.00 +-	µg/L
vinyl acetate	U	10. +-	µg/L
vinyl chloride	U	10. +-	µg/L
xylene (m&p)	U	5.00 +-	µg/L
xylene (o)	U	5.00 +-	µg/L
xylene (total)	U	5.00 +-	µg/L

Customer Id: SS-1-60 ORNL Sample No: 960502-127

(Sample taken 4/24/96 14:15, second sample of scrub system 1 after incidnet)

Analysis	Result	Error	UNITS
1,1,2,2-tetrachloroethane	U	5.00 +- $\mu\text{g/L}$	
1,1,2-trichloroethane	U	5.00 +- $\mu\text{g/L}$	
1,1-dichloroethane	U	5.00 +- $\mu\text{g/L}$	
1,1-dichloroethene	U	5.00 +- $\mu\text{g/L}$	
1,2-Dichlorobenzene	U	5.00 +- $\mu\text{g/L}$	
1,2-dichloroethane	U	5.00 +- $\mu\text{g/L}$	
1,2-dichloroethene (cis)	U	5.00 +- $\mu\text{g/L}$	
1,2-dichloroethene (total)	U	5.00 +- $\mu\text{g/L}$	
1,2-dichloroethene (trans)	U	5.00 +- $\mu\text{g/L}$	
1,2-dichloropropane	U	5.00 +- $\mu\text{g/L}$	
1,3-Dichlorobenzene	U	5.00 +- $\mu\text{g/L}$	
1,4-Dichlorobenzene	U	5.00 +- $\mu\text{g/L}$	
2-butanone	B	24. +- $\mu\text{g/L}$	
2-hexanone	U	10. +- $\mu\text{g/L}$	
4-methyl-2-pentanone	U	10. +- $\mu\text{g/L}$	
acetone	Y 290.	+- $\mu\text{g/L}$	
benzene	U 5.00	+- $\mu\text{g/L}$	
bromodichloromethane	U	5.00 +- $\mu\text{g/L}$	
bromoform	U	5.00 +- $\mu\text{g/L}$	
bromomethane	U	10. +- $\mu\text{g/L}$	
carbon disulfide	U	5.00 +- $\mu\text{g/L}$	
carbon tetrachloride	U	5.00 +- $\mu\text{g/L}$	
chlorobenzene	U	5.00 +- $\mu\text{g/L}$	
chloroethane	U	10. +- $\mu\text{g/L}$	
chloroform	U	5.00 +- $\mu\text{g/L}$	
chloromethane	U	10. +- $\mu\text{g/L}$	
cis-1,3-dichloropropene	U	5.00 +- $\mu\text{g/L}$	
dibromochloromethane	U	5.00 +- $\mu\text{g/L}$	
ethylbenzene	U	5.00 +- $\mu\text{g/L}$	
methylene chloride	U	5.00 +- $\mu\text{g/L}$	
styrene	U 5.00	+- $\mu\text{g/L}$	
tetrachloroethene	U	5.00 +- $\mu\text{g/L}$	
toluene	U 5.00	+- $\mu\text{g/L}$	
trans-1,3-dichloropropene	U	5.00 +- $\mu\text{g/L}$	
trichloroethene	U	5.00 +- $\mu\text{g/L}$	
vinyl acetate	U	10. +- $\mu\text{g/L}$	
vinyl chloride	U	10. +- $\mu\text{g/L}$	
xylene (m&p)	U	5.00 +- $\mu\text{g/L}$	
xylene (o)	U	5.00 +- $\mu\text{g/L}$	
xylene (total)	U	5.00 +- $\mu\text{g/L}$	

Customer Id: SS-1-61 ORNL Sample No: 960502-128

(sample taken 4/16/96 15:01, last sample of scrub system 2 before melt expulsion incident, scrub system 2 was not in use during melt expulsion incident)

Analysis	Result	Error	UNITS
1,1,2,2-tetrachloroethane	U	5.00 +- 5.00	µg/L
1,1,2-trichloroethane	U	5.00 +- 5.00	µg/L
1,1-dichloroethane	U	5.00 +- 5.00	µg/L
1,1-dichloroethene	U	5.00 +- 5.00	µg/L
1,2-Dichlorobenzene	U	5.00 +- 5.00	µg/L
1,2-dichloroethane	U	5.00 +- 5.00	µg/L
1,2-dichloroethene (cis)	U	5.00 +- 5.00	µg/L
1,2-dichloroethene (total)	U	5.00 +- 5.00	µg/L
1,2-dichloroethene (trans)	U	5.00 +- 5.00	µg/L
1,2-dichloropropane	U	5.00 +- 5.00	µg/L
1,3-Dichlorobenzene	U	5.00 +- 5.00	µg/L
1,4-Dichlorobenzene	U	5.00 +- 5.00	µg/L
2-butanone	JB	7. +- 7.00	µg/L
2-hexanone	U	10. +- 10.00	µg/L
4-methyl-2-pentanone	U	10. +- 10.00	µg/L
acetone		14. +- 14.00	µg/L
benzene	U	5.00 +- 5.00	µg/L
bromodichloromethane	U	5.00 +- 5.00	µg/L
bromoform	U	5.00 +- 5.00	µg/L
bromomethane	U	10. +- 10.00	µg/L
carbon disulfide	U	5.00 +- 5.00	µg/L
carbon tetrachloride	U	5.00 +- 5.00	µg/L
chlorobenzene	U	5.00 +- 5.00	µg/L
chloroethane	U	10. +- 10.00	µg/L
chloroform	U	5.00 +- 5.00	µg/L
chloromethane	U	10. +- 10.00	µg/L
cis-1,3-dichloropropene	U	5.00 +- 5.00	µg/L
dibromochloromethane	U	5.00 +- 5.00	µg/L
ethylbenzene	U	5.00 +- 5.00	µg/L
methylene chloride	U	5.00 +- 5.00	µg/L
styrene	U	5.00 +- 5.00	µg/L
tetrachloroethene	U	5.00 +- 5.00	µg/L
toluene	U	5.00 +- 5.00	µg/L
trans-1,3-dichloropropene	U	5.00 +- 5.00	µg/L
trichloroethene	U	5.00 +- 5.00	µg/L
vinyl acetate	U	10. +- 10.00	µg/L
vinyl chloride	U	10. +- 10.00	µg/L
xylene (m&p)	U	5.00 +- 5.00	µg/L
xylene (o)	U	5.00 +- 5.00	µg/L
xylene (total)	U	5.00 +- 5.00	µg/L

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