RECEIVED

APR 01 1996

OSTI

**Process System Evaluation - Consolidated
Letter Reports. Volume 1 - Alternatives
for the Off-Gas Treatment System for the
Low-Level Waste Vitrification Process**

**L. M. Peurrung
T. J. Deforest
J. R. Richards***

March 1996

**Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest National Laboratory
Richland, Washington 99352**

***Air Control Techniques, P.C., Cary,
North Carolina**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**Process System Evaluation - Consolidated
Letter Reports. Volume 1 - Alternatives
for the Off-Gas Treatment System for the
Low-Level Waste Vitrification Process**

L. M. Peurrung
T. J. Deforest
J. R. Richards*

March 1996

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

*Air Control Techniques, P. C., Cary, North Carolina

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

The document was printed on recycled paper.

Summary

This report provides an evaluation of alternatives for treating off-gas from the low-level waste (LLW) melter. The study used expertise obtained from the commercial nonradioactive off-gas treatment industry. It was assumed that contact maintenance is possible, although the subsequent risk to maintenance personnel was qualitatively considered in selecting equipment. Some adaptations to the alternatives described may be required, depending on the extent of contact maintenance that can be achieved.

This study was conducted before data was available on the off-gas characteristics of specific melter systems. Therefore, estimates have been made to arrive at approximate off-gas streams for a joule-heated melter and a combustion-fired melter. These estimates are then used as the basis for identification and evaluation of five candidate options for a melter off-gas system. This evaluation identified key issues for the off-gas system design. To provide background information, technology reviews were assembled for various classifications of off-gas treatment equipment, including off-gas cooling, particulate control, acid gas control, mist elimination, NO_x reduction, and SO_2 removal. An order-of-magnitude cost estimate for one of the off-gas systems considered is provided using both the off-gas characteristics associated with the Joule-heated and combustion-fired melters. The key issues identified and a description of the preferred off-gas system options are provided below.

Five candidate treatment systems were evaluated. All of the systems are appropriate for the different melting/feed preparations currently being considered. The lowest technical risk is achieved using option 1, which is similar to designs for high-level waste (HLW) vitrification in the Hanford Waste Vitrification Project (HWVP) and the West Valley Demonstration Project. Option 1 uses a film cooler, submerged bed scrubber (SBS), and high-efficiency mist eliminator (HEME) prior to NO_x reduction and high-efficiency particulate air (HEPA) filtration. However, several advantages were identified for option 2, which uses high-temperature filtration. Based on the evaluation, option 2 was identified as the preferred alternative. The characteristics of this option are described below.

- The melter off-gas is subjected to a natural gas reburner (for NO_x reduction) and evaporative cooling to a temperature of 700°F (371°C) before passing the gas through a high-temperature filtration unit. This treatment obtains the advantages of high-temperature filtration while avoiding the concerns associated with higher temperatures. Filtering very close to the melter in this manner limits the concentration of radionuclides in downstream units, and may allow halides in the elemental or acid gas forms to pass through the filter, thus allowing their collection in a downstream scrubber and rejection from the melter system. However, the ability of this filter to operate reliably without plugging and the ability to recycle the dry dust material back to the process represent significant uncertainties.

- The high NO_x concentrations are reduced by a methane reburner at the melter exit (mentioned above) and a selective catalytic reduction (SCR) unit at the exit of the high-temperature filter, eliminating the need for a preheater for the SCR unit.
- Acid gases are controlled in a packed bed scrubber. This system also efficiently collects the intentionally high ammonia slip emissions from the SCR units.
- A conventional mist eliminator and a HEME are used in series to protect the downstream HEPA filters. The cleaned gas stream is heated to approximately 200°F in an indirect heat exchanger prior to entering the HEPA filter.
- The HEPA filters are used as a final protection against particulate radionuclide emissions.
- A separate emergency treatment system is included to minimize radionuclide emissions during severe gas surges from the melter.

Either option 1 or option 2 satisfies all of the performance criteria identified in this evaluation and could be used successfully for the off-gas streams considered. The preferred option (option 2) has advantages and additional uncertainties compared to the more conventional approach described in option 1.

Key Issues

A number of key issues were identified as a result of the identification and evaluation of the off-gas treatment system options.

- High nitrogen oxide emissions from the melter create significant economic problems. If possible, the LLW feed should be pretreated to minimize nitrates and other nitrogen compounds in the feed. Preliminary results from melter vendor testing indicate that NO_x concentrations may be lower than assumed, although still in the thousands of ppm.
- Both the installed costs and operating costs of the off-gas treatment system will be high. It is very possible that these costs will exceed costs for the melter and its associated feed preparation system. The off-gas treatment costs can be minimized by selecting a melter system which has a low off-gas generation rate since the costs for the off-gas system are strongly dependent on gas flow rate.
- Phosphorus emissions from the melter may poison the catalyst for SCR systems for nitrogen oxides control. The emission rates for phosphorus should be determined during the pilot plant testing of the melter.

- The maximum hydrogen emissions and oxygen concentrations in the melter off-gas should be quantified during pilot plant testing. Hydrogen gas has a broad explosive range, and the presence of potentially explosive conditions may prevent the use of a reburn unit to control nitrogen oxides emissions.
- The present candidate systems do not account for the gas streams from the LLW feed preparation system. The gas flow rates and pollutant characteristics of these systems should be determined so the feasibility of controlling these emissions in the main off-gas treatment system can be determined.
- The off-gas treatment stream should be designed to handle a routine gas surge. Excess capacity equivalent to 1.4 times the average gas flow rate at the maximum melting rate would be consistent with design practices for air pollution control systems used on other types of sources with highly variable waste feed quality. The actual excess capacity for a particular system will need to be determined based on the operating characteristics of the selected melter.
- The present system does not include control of tritium, carbon-14 (in the form of CO_2), or mercury. The present and anticipated regulatory requirements should be reviewed to determine if the anticipated facility boundary line concentrations are acceptable. It is conceivable that future risk assessment-based requirements would demand more stringent control of volatile radionuclides. Control of the volatile radionuclides such as tritium could be accomplished most economically in the feed preparation system rather than in the off-gas treatment system.
- The decontamination factors for halogens and the NO_x yield from nitrites and nitrates in the melter should be determined. These factors will strongly influence the capability to recycle the waste stream generated by the acid gas control devices.
- The total SO_2 emissions expected from the melter and sulfur processing (if used) should be determined. This information is needed to confirm that a separate sulfur dioxide control module is not needed.
- The accumulation of solids at the entrance of the off-gas cooling system should be evaluated as part of pilot plant tests. The transition section between the melter exit and the initial off-gas quenching stage should be designed to minimize vulnerability to solids accumulation.

Acronyms

ACFM	Actual Cubic Feet per Minute
ALARA	As Low As Reasonable Achievable
BACT	Best Available Control Technology
BIF	Boiler and Industrial Furnaces
CEM	Continuous Emission Monitor
CFR	Code of Federal Regulations
DCG	Derived Concentration Guides
DF	Decontamination Factor
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic Precipitator
FGD	Flue Gas Desulfurization System
FRP	Fiberglass Reinforced Plastic
HEME	High Efficiency Mist Eliminator
HEMF	High Efficiency Metal Filter
HEPA	High Efficiency Particulate Absolute Filter
IAEA	International Atomic Energy Agency
LERF	Liquid Effluent Retention Facility
LFCM	Liquid Fed Ceramic Melter
LLW	Low Level Wastes
MACT	Maximum Achievable Control Technology
MEI	Maximum Exposed Individual
NAAQA	National Ambient Air Quality Standards
NESHAPS	National Emissions Standards for Hazardous Pollutants
NSPS	New Source Performance Standards
Op	Opacity
PM ₁₀	Particulate Matter having An Aerodynamic Diameter Less than 10 micrometers
PSD	Prevention of Significant Deterioration
RCRA	Resource Conservation Recovery Act
SBS	Submerged Bed Scrubber
SCFM	Standard Cubic Feet per Minute
SCR	Selective Catalytic Reduction
SIP	State Implementation Plan
SNCR	Selective Noncatalytic Reduction
WDOE	Washington Department of Ecology
WHC	Westinghouse Hanford Company

Conversion Factors

$$1 \text{ meter (m)} = 3.281 \text{ feet}$$

$$1 \text{ meter}^2 \text{ (m}^2\text{)} = 1.076 \times 10^1 \text{ ft}^2$$

$$1 \text{ meter}^3 \text{ (m}^3\text{)} = 3.532 \times 10^1 \text{ ft}^3$$

$$1 \text{ meter/second (m/s)} = 196.8 \text{ ft/min}$$

$$1 \text{ meter}^3\text{/second (m}^3\text{/s)} = 2.119 \times 10^3 \text{ ft}^3\text{/min}$$

$$1 \text{ meter}^3\text{/minute (m}^3\text{/min)} = 35.32 \text{ ft}^3\text{/min}$$

$$1 \text{ kilogram (kg)} = 2.205 \text{ lb}$$

$$1 \text{ kilopascal (kPa)} = 4.019 \text{ inches of water}$$

$$1 \text{ pascal (Pa)} = 0.001 \text{ kilopascal}$$

$$1 \text{ inch of water (in. W.C.)} = 0.0361 \text{ lb}_f\text{/in}^2$$

$$1 \text{ U.S. gallon} = 3.785 \text{ liters}$$

$$1 \text{ U.S. gallon} = 0.1337 \text{ ft}^3$$

$$1 \text{ mg/SCF} = 0.0154 \text{ grains/SCF}$$

Contents

Summary	iii
Acronyms	vii
Conversion Factors	ix
1.0 Introduction	1.1
1.1 Purpose and Scope of the Alternatives Evaluation	1.1
1.2 Limitations	1.1
1.3 Selection Criteria of Off-Gas Treatment Systems	1.1
2.0 Off-Gas Stream Characteristics	2.1
2.1 Off-Gas Characteristics of the Liquid-Fed Combustion Melter	2.1
2.2 Off-Gas Characteristics of the Liquid-Fed Ceramic Melter	2.3
3.0 Regulatory Requirements	3.1
4.0 Candidate Off-Gas Treatment Systems	4.1
4.1 Off-Gas Treatment System 1	4.1
4.2 Off-Gas Treatment System 2	4.7
4.3 Off-Gas System 3	4.11
4.4 Off-Gas Treatment System 4	4.16
4.5 Off-Gas Treatment System 5	4.19
4.6 Summary of Off-Gas Treatment System Options	4.23
5.0 Component Control System Characteristics	5.1
5.1 Off-Gas Cooling	5.1
5.1.1 Film Coolers	5.1
5.1.2 Water Quenching	5.2

5.1.3	Heat Exchangers	5.3
5.1.4	Cryogenic Gas Injection	5.3
5.2	Particulate Control	5.3
5.2.1	High-Temperature Filters	5.5
5.2.2	Low Temperature, Dry Particulate Control Devices	5.7
5.2.3	Low Temperature, Particulate Wet Scrubbers	5.10
5.2.4	High-Efficiency Particulate Filtration	5.17
5.3	Acid Gas Control	5.19
5.4	Mist Eliminators	5.24
5.4.1	Conventional Mist Eliminators	5.24
5.4.2	High Efficiency Mist Eliminators	5.25
5.5	NO _x Reduction	5.26
5.5.1	Selective Catalytic Reduction	5.26
5.5.2	Selective Noncatalytic Reduction	5.29
5.5.3	Natural Gas Reburning	5.30
5.6	Sulfur Dioxide Control Systems	5.30
5.6.1	Lime or Limestone Nonregenerable Systems	5.31
5.6.2	Copper Oxide Process	5.32
5.6.3	Other Sulfur Dioxide Scrubbing Technologies	5.32
5.7	Volatile Radionuclide Removal	5.32
5.8	Carbon Dioxide Control	5.33
5.9	Iodine Control	5.33
6.0	Costs for the Off-Gas Treatment System	6.1
7.0	References	7.1

Appendix A - Vendors of Air Pollution Control Equipment	A.1
---	-----

Figures

2.1 Frequent Gas Surges in Tests With a Ceramic Melter	2.5
4.1 Flowchart for Off-Gas System 1	4.3
4.2 Flowchart for Off-Gas System 2	4.8
4.3 Flowchart for Off-Gas System 3	4.12
4.4 Flowchart for Off-Gas System 4	4.17
4.5 Flowchart for Off-Gas System 5	4.20
5.1 Pulse Jet Filter Configuration	5.6
5.2 Reverse Air Fabric Filter	5.8
5.3 Submerged Bed Scrubber	5.11
5.4 Venturi Scrubber Throat	5.12
5.5 Hydrosonic Scrubber	5.14
5.6 Wet Ionizing Scrubber	5.15
5.7 Ejector Scrubber	5.16
5.8 Impingement Tray Scrubber	5.21

Tables

2.1	Estimated Off-Gas Characteristics for a Combustion Melter Fed With 6M Liquid Feed	2.2
2.2	Estimated Off-Gas Characteristics for a Ceramic Melter Fed With 6M Liquid Feed	2.4
3.1	PSD Threshold Emission Rates, Tons/Year	3.1
3.2	Present and Future Regulatory Requirement	3.4
3.3	Dose Rates Calculated for Release of Volatile Radionuclides in Tank Inventory	3.5
4.1	Differences in the Candidate Off-Gas Treatment Systems	4.2
5.1	Effect of Melter Type and Gas Cooling Method on the Off-Gas Flow Rate	5.2
5.2	Decontamination Factors for a Liquid-Fed Ceramic Melter and a Combustion-Type Melter	5.20
6.1	Order-of-Magnitude Capital Cost Estimate for Off-Gas Treatment System 2, Including Emergency Vent System	6.3

1.0 Introduction

1.1 Purpose and Scope of the Alternatives Evaluation

The primary purpose of this project is to evaluate possible off-gas treatment systems that could be used to control emissions from the low-level waste (LLW) vitrification process. The necessary characteristics and costs of the off-gas treatment system may have a major impact on the types of melters and waste feed preparation systems selected. Furthermore, this study identifies areas requiring further investigation so the overall project will not be delayed by unexpected issues concerning the off-gas treatment system.

1.2 Limitations

At the time this study was conducted, the type of melter and the type of feed preparation system had not been selected. In fact, seven different types of melters are being actively investigated. These melter systems potentially generate off-gas streams with substantially different pollutant characteristics and gas flow rates. Accordingly, it was not possible to develop alternatives for a specific type of system.

Virtually all of the previously designed radioactive waste treatment systems have been developed for high-level waste (HLW) vitrification or LLW incinerators. The off-gases from these systems differ in the concentrations of radionuclides, concentrations of conventional air pollutants, gas temperatures, and gas flow rates. Accordingly, the off-gas treatment system design for the LLW vitrification system cannot be a simple extrapolation of existing off-gas treatment systems.

1.3 Selection Criteria for Off-Gas Treatment Systems

The candidate treatment systems and the system components have been selected based on the criteria listed below. These are listed in their approximate order of importance.

1. Air pollutant emissions must be below the applicable U.S. Environmental Protection Agency (EPA), U.S. Department of Energy (DOE), and Washington Department of Ecology (WDOE) requirements.
2. The system must be safe to operate.
3. The off-gas system must be reliable.
4. The off-gas system must be maintainable with minimum risk to personnel.

5. Capital costs and operating costs of the off-gas treatment system must be as low as possible.
6. The off-gas treatment system must be flexible to account for process variations in gas flow rates, types of pollutants, pollutant concentrations, gas temperatures, and gas oxygen concentrations.
7. Liquid and solid waste streams generated by the off-gas treatment system must be minimized, and these wastes must not create unmanageable environmental hazards.
8. The components used in the off-gas system must be based on the manufacturer's experience in previous similar applications. Thus, only established technologies are considered.
9. It must be possible to effectively monitor the system to certify compliance with operating requirements and to optimize operating conditions.
10. The off-gas treatment system should be as simple as possible.

2.0 Off-Gas Stream Characteristics

The off-gas stream characteristics are a direct function of the waste composition, type of melter, and type of LLW feed preparation system being used. Presently, there are seven different melters under consideration. There are also several different configurations of the feed preparation system. The melter and feed system characteristics significantly affect the off-gas composition, temperature, and flow rate.

To provide a basis for evaluating possible off-gas treatment system options, two different types of melter systems have been assumed. One of these is a liquid-fed combustion melter with a six molar sodium waste feed stream. The other is a liquid-fed ceramic melter (LFCM) also fed with a six molar sodium waste stream.

2.1 Off-Gas Characteristics of the Liquid-Fed (6M) Combustion Melter

The estimated off-gas characteristics of a liquid fed combustion melter are summarized in Table 2.1. These estimates are based on waste composition data provided by Westinghouse Hanford Company (WHC) (Orme 1994) and data provided by Vortec (1993) for a similar melter. It is assumed that there will be a 14-year processing lifetime. It is also assumed that the decontamination factors (DF) for the full-scale melters will be roughly equivalent to those found in pilot-scale studies; that is, a DF^(a) of unity is assumed for sulfur and nitrogen compounds. No data are available for quantifying the retention of halogens, carbon, or mercury, so a DF of unity is also assumed for these compounds. Sulfur dioxide levels could be higher, depending on the sulfur content of the fuel. Reduction of nitrates and nitrites to nitrogen either in the melter or by pretreatment of waste feed is not considered when estimating NO_x concentrations. The phosphorus DF is unknown and is assumed to be 50 [LFCM figure, from Perez et al. (1993)]. The gas flow rate has been scaled up based on the rate reported in Vortec (1993). Air is used as the oxidant. Actual gas flow rates will depend heavily on the fuel chosen, the air/fuel ratio, and the use of air versus pure oxygen as an oxidant.

The water vapor concentration in the off-gas is the combined effect of vaporization of moisture in the LLW feed stream and the formation of water due to the combustion of fuel. Some water also enters the system as ambient water vapor in infiltrating air. Due to the high water vapor content, it is important to keep the off-gas stream well above the moisture dew point until the corrosive halogens and sulfur dioxide are removed.

(a) The decontamination factor (DF) is calculated as inlet/outlet so that a DF = 1 indicates that all of these compounds exit with the off-gas rather than being included in the glass.

Table 2.1. Estimated Off-Gas Characteristics for a Combustion Melter Fed With 6M Liquid Feed (100 ton/day glass production)

Off-Gas Characteristics	Value
Gas Stream Characteristics	
Gas flow rate	14,000 SCFM
Gas stream temperature	1204°C (2200°F)
Gas Stream Composition	
Water vapor	20%
Oxygen	2%
Nitrogen	70%
Carbon dioxide	8%
Pollutants	
NO _x	16,000 ppm
SO ₂	140 ppm
Fluorine (as HF)	600 ppm
Chlorine (as HCl)	150 ppm
Iodine (as HI)	0.02 ppm
Mercury	0.06 ppm
Phosphorus	6 ppm
Carbon monoxide	60 ppm
Particulate	50 mg/SCF (0.77 gr./SCF)

Reducing the moisture content of the feed stream could significantly decrease the size of the off-gas treatment system because of a reduction in the fuel requirement to provide the latent heat of evaporation for water in the feed. It could also minimize problems with tritium recovery, if tritium recovery is required by future regulatory requirements.

The estimated nitrogen oxide (NO and NO₂) concentration of 16,000 ppm is very high. For comparison, the typical nitrogen oxide (NO_x) emissions from coal-fired boilers and hazardous waste incinerators range from 300 to 1,000 ppm. The high nitrogen oxides levels may present major problems with the off-gas system design, especially since these emissions are accompanied by particulate matter that could mask or poison the catalysts used to reduce nitrogen oxides. The nitrogen oxides concentrations that are generated should be minimized by pretreating the waste feed stream or by using techniques to chemically reduce the nitrogen compounds before their emission from the melter.

The estimated HCl and HF concentrations of the off-gas stream are high. These compounds can cause severe corrosion of metals and severe acid attack of filter elements used in the air pollution control system. HCl and HF emissions should be minimized to the extent possible by pretreating the waste feed system.

Presently there is no information on the frequency and severity of gas surges from the liquid-fed combustion melter. These surges must be accounted for during the design of the off-gas system so that positive pressure excursions in the melter do not overcome the radionuclide containment of the melter.

The estimated total particulate content of the off-gas is 50 mg per SCF (0.77 gr./SCF). This figure is based on Orme (1994). The particulate loading reported for a Vortec melter (Vortec 1993) was even higher at 150 mg/SCF (2.3 gr./SCF). For comparison, coal-fired boilers and hazardous waste incinerators have particulate loadings in the range of 30 to 150 mg per SCF (0.45 to 2.3 gr./SCF). The particulate will probably consist of 1) dried feed material entrained in the off-gas stream and 2) nucleated particles formed from vapor phase metal compounds. The radionuclides in the off-gas stream are expected to be present primarily as part of the particulate matter that has nucleated (Vortec 1993). Essentially all of the nucleated particles will be in the submicrometer size range.

2.2 Off-Gas Characteristics of the Liquid-Fed (6M) Ceramic Melter

The estimated off-gas characteristics of a liquid-fed ceramic melter (LFCM) are summarized in Table 2.2. As in the case with the combustion melter, these estimates are based on the waste composition data provided in the WHC flowcharts (Orme 1994), and it is assumed there will be a 14-year processing lifetime. The estimates presented in Table 2.2 are based on current waste inventory, the LFCM-8 report (Perez et al. 1993), and the simulant recipes in the LLW-Vit Statement of Work (Wilson 1994). An assumed air inleakage rate of 1,000 SCFM is included in the total off-gas flow rate of 4,400 SCFM. The assumed DFs for nitrogen, iodine, carbon, and mercury are 1; for fluorine and chlorine, 4; for sulfur, 10; and for phosphorus, 50 (Perez et al. 1993).

Due to the lack of combustion gases in this type of melter, the total off-gas flow rate from the ceramic melter is less than one-third of the estimated flow for the combustion melter. The reduced gas flow rate would significantly benefit the total cost of the off-gas treatment system.

The benefits provided by the small gas flow rate may be partially offset by the high pollutant concentrations. For example, the nitrogen oxides level of 50,000 ppm is one hundred times more concentrated than typical gas streams treated in nitrogen oxides control systems. Pretreating the waste to minimize nitrogen oxides emissions would be very helpful for the LFCM.

The HF and HCl concentrations are very high due in part to the low gas flow rate. Exotic materials of construction will be needed throughout the portion of the off-gas treatment system exposed to these pollutants. It will be important to maintain the off-gas system above the temperature of the moisture dewpoint to prevent absorption of these highly soluble contaminants in water layers on metallic surfaces.

Table 2.2. Estimated Off-Gas Characteristics for a Ceramic Melter Fed With 6M Liquid Feed (100 ton/day glass production)

Off-Gas Characteristics	Value
Gas Stream Characteristics	
Gas flow rate	4,400 SCFM
Gas stream temperature	982°C (1800°F)
Gas Stream Composition	
Water vapor	70%
Oxygen	4%
Nitrogen	20%
Carbon dioxide	0.2 to 0.8%
Pollutants	
NO _x	50,000 ppm
SO ₂	40 ppm
Fluorine (as HF)	500 ppm
Chlorine (as HCl)	120 ppm
Iodine (as HI)	0.06 ppm
Mercury	0.2 ppm
Phosphorus	20 ppm
Carbon monoxide	100 - 1000 ppm
Particulate	3 - 10 mg/SCF (0.046 - 0.15 gr./SCF)

Gas surges can occur with LFCMs because of the breakdown of the cold cap on the surface of the molten glass. This breakdown allows the pooled liquid feed to contact the surface of the molten glass. Surging is often a response to overfeeding and is more severe with alkaline feeds (Goles and Sevigny 1993). Frequent surges when feeding an alkaline liquid feed are illustrated in Figure 2.1. There are short-term gas flow rate surges of 50% to 100% of the average gas flow rate in this case (Goles and Sevigny 1993). To design a reasonably economical off-gas treatment system, it is important to operate a melter in a manner that minimizes gas surging. It will also be necessary to include excess gas flow capacity in the off-gas system to handle surges in the range of 125% to 140% of the normal gas flow rate at maximum melting rates.

Severe gas surges can be handled only with an emergency bypass system. It would be extremely expensive to attempt to contain and control these severe surges with the main off-gas treatment system. Furthermore, a severely oversized off-gas treatment system would not perform efficiently during routine operating periods. For this reason, a separate emergency treatment system is needed.

Figure 2.1. Frequent Gas Surges in Tests With a Ceramic Melter

3.0 Regulatory Requirements

This chapter addresses regulations that may influence the performance requirements that will impact the design and operation of the off-gas system. The off-gas emissions from the LLW vitrification system will be subject to numerous DOE, EPA, and WDOE regulatory limits. Gretsinger and Colby (1994) gives a broader discussion of all regulations that may impact the design and operation of the LLW vitrification plant.

Due to the potential emission of radionuclides, the melter will be subject to the EPA regulation titled *National Emission Standards for Hazardous Air Pollutants* (40 CFR Part 61, Subpart H). This regulation limits the exposure level at the facility boundary line to less than 10 mrem/yr. This exposure limit is similar to that in DOE Order 5400.5. This radiation exposure limit implicitly limits the particulate emissions from the facility since most of the radionuclides emitted from the melter are in the form of particulate matter.

If any of the pollutant emissions exceed the threshold emission rates shown in Table 3.1, the melter will be subject to the Prevention of Significant Deterioration (PSD) regulations. These emissions are calculated based on the "potential-to-emit," which means that the air pollution control efficiencies are assumed to be zero, and the melter operates 8760 hr/yr at full capacity. The "potential-to-emit" emission rates estimated for the two types of melters are shown in Table 3.1.

Table 3.1. PSD Threshold Emission Rates, Tons/Yr (potential to emit)

		Potential-to-Emit, Tons/yr	
Pollutant	PSD Threshold Emission, Tons/yr	Combustion Melter	Ceramic Melter
Particulates	25	410	8 - 26
Sulfur dioxide	40	86	8
Nitrogen oxides (as NO ₂)	40	6,900	6,900
Carbon monoxide	100	16	8 - 84
Mercury compounds	0.1	0.1	0.1
Hydrogen fluoride	3	120	30
Hydrogen chloride	NA	52	13
(Source of PSD threshold levels: 40 CFR 51.166; see also 173-400 WAC.			

The off-gas system will have to demonstrate Best Available Control Technology (BACT) to satisfy the PSD requirements. Furthermore, the emissions of criteria pollutants (PM_{10} , SO_2 , NO_2 and Pb) cannot be allowed to cause significant increases in the ambient concentrations at the facility boundary line. The main effect of this regulation will be to limit nitrogen oxides emissions. To achieve BACT, the radiation exposure limits will require particulate control that is much more efficient than necessary.

The melter will process wastes that include both radionuclides and hazardous chemicals. Accordingly, the melter may be subject to 1) EPA Resource Conservation and Recovery Act (RCRA) requirements for hazardous incinerators in 40 CFR Part 264, Subpart O, or 2) EPA RCRA requirements for boilers and industrial furnaces (BIF) in 40 CFR Part 266. These regulations limit hydrogen chloride emissions to less than four pounds per hour or to a control efficiency of 99%. If these regulations are judged to apply, the organic constituents will have to be destroyed in the melter or removed in the off-gas system to 99.99% efficiency. In that case, pollution control equipment beyond that specified in this report may be necessary to reach that efficiency. These regulations also include limitations on total particulate (both regulations) and on metal emissions (BIF). However, the previously discussed radiation exposure limits will require particulate control beyond the requirements necessary to comply with these regulations. These regulations have comprehensive requirements regarding waste analyses, monitoring, and testing.

The melter will be defined as "major" with respect to the Title V^(a) operating permit requirements and the EPA-proposed enhanced monitoring requirements. The operating permit issued by the State of Washington will have to include all of the regulatory requirements applicable to the melter system. The enhanced monitoring regulations will require a variety of continuous emission monitors, parameter monitoring systems, or alternative compliance monitoring techniques to certify compliance.

The melter is subject to WDOE Regulation 460, an air toxic emission regulation applicable to new sources. This limits the allowable facility boundary line concentration of a number of pollutants present in the off-gas stream of the melter.

In the future, the melter off-gas system could be subject to a future EPA-promulgated Maximum Achievable Control Technology (MACT) standard.^(b) This will require stringent control of the pollutants included on the list of 189 chemicals and groups of chemicals included in Title III of the Clean Air Amendments of 1990. These air pollutants include the following:

- radionuclides
- hydrogen chloride
- hydrogen fluoride

(a) Clean Air Act Amendments of 1990. 40 CFR 70, as implemented by WAC-173-401.

(b) No citation is available at this time. If issued, citation will probably be included under 40 CFR 63.

- nickel compounds
- chromium compounds
- various aromatic organic compounds
- various halogenated organic compounds.

The MACT regulatory standards may become the dominant factor limiting the hydrogen chloride and hydrogen fluoride emissions.

The various overlapping regulatory requirements are summarized in Table 3.2. This table includes the future regulatory requirements that will probably be retroactively applied to the melter system.

Due to the radiation limitations included in several of the regulatory limits, particulate emissions must be very low. Efficiencies well beyond 99.9% will be needed. The hydrogen chloride and hydrogen fluoride levels will have to be reduced more than 99% if compliance with BIF limits and potential future MACT limits is required. If such controls are implemented, hydrogen iodide will be controlled with similar efficiency since this compound behaves chemically like hydrogen chloride and hydrogen fluoride. Also, systems used to collect the halogens will capture most of the relatively low sulfur dioxide emissions from the melter system. Hazardous organic compounds (most solvents) included in the waste stream will have to be destroyed by more than 99.99% if the melter system is permitted as an incinerator or miscellaneous unit. This permitting designation has not yet been determined. The effect on system design could be significant.

The emissions from the plant will be controlled to meet the 10 mrem/yr radionuclide dose limit at the site boundary for all sources from within the site (note that any radionuclide release triggers PSD review). The estimated site boundary doses are developed in Table 3.3. The second column provides the estimated inventory of radionuclides of interest, and the third column indicates an order-of-magnitude decontamination factor. From this data, and operating assumptions, an off-gas concentration is determined (column 4). A comparison to WHC administrative controls is provided, although these limits would be applied at the stack rather than to the treated melter off-gas concentrations. Dose factors (column 6) for unit radionuclide release are used to calculate the dose contribution at the site boundary (column 7). These preliminary calculations indicate that the site boundary dose would be under 10 mrem/yr.

The off-gas treatment flowsheets shown in Chapter 4.0 of this report will remove the radionuclides that take the form of particulates. However, there are several radionuclides (^{129}I , ^{14}C , ^3H) that will emerge from the melter as room-temperature gases and vapors (e.g., HI, CO_2 , and H_2O). Calculations summarized in Table 3.3 indicate that these gases and vapors may be released to the environment untreated without exceeding the present 10 mrem/yr dose rate. While iodine may be retained and treated by the off-gas system, retaining and treating carbon dioxide and water would be very costly and would produce extremely large quantities of secondary waste. However, allowing those materials to

Table 3.2. Present and Future Regulatory Requirement

Presently Applicable Regulations	
Prevention of Significant Deterioration (PSD), WAC 173-400	Prevents worsening of air quality due to construction of a new source in an area attaining the National Ambient Air Quality Standards (NAAQS)
National Emission Standards for Hazardous Pollutants (NESHAP), EPA, 40 Part 61 Subpart H	Minimizes the emissions of toxic air pollutants from new and existing facilities, limits exposure to 10 mrem/yr to the public at the site boundary
Boiler and Industrial Furnace (BIF) Regulation, EPA, 40 Part 266 Subpart H (potentially applicable)	Minimizes the emissions of toxic air pollutants from sources processing hazardous waste, limits HCl emissions to <4 pounds per hour or a control efficiency of 99%, limits particulate emissions to 0.08 grains per dry standard cubic foot (DSCF) @ 7% O ₂
DOE Order 5400.5	Limits exposure to 10 mrem/yr to the public at the site boundary, compliance determined by means of Derived Concentration Guides (DCG)
DOE Order 5480	Limits concentrations for individual radionuclides, limits maximum annual doses to 500 mrem, stipulates ALARA
Controls for New Sources of Toxic Air Pollutants, WAC 173-460	Limits plant boundary line concentrations of toxic air pollutants
Future Regulations	
Enhanced Monitoring, EPA 40 Part 64	Requires monitoring of air pollutants for which a source is defined as major in accordance with the Title V operating permit (regulation to be in effect no later than mid-1995)
Operating Permit EPA 40 Part 70 and the State of Washington	Requires major sources subject to State Implementation Plan (SIP), NESHAP, MACT, New Source Performance Standards (NSPS) and other regulations to have a comprehensive operating permit issued by the State of Washington
Maximum Achievable Control Regulations (MACT), EPA 40 Part 63	These regulations are an extension and expansion of the NESHAPs regulations. The MACT regulation will limit the toxic air pollutant emissions from a variety of specific processes. Pollutants subject to MACT requirements include HCl, HF, chromium compounds, mercury compounds, various halogenated organic compounds, and radionuclides. The MACT standard applicable to the melter will probably be in effect around 1997 to 2000.

vent to the stack would release virtually the entire inventory of ³H and ¹⁴C contained in the tanks to the environment. Such a release would probably have a small impact, but this practice may not be acceptable to stakeholders. Furthermore, future radiation exposure limits based on risk assessment approaches could be substantially lower than the present 10 mrem/yr level. This could result in the need to control tritium and carbon dioxide. This potential should be determined as far in advance of system construction as possible since control of tritium and carbon dioxide would significantly affect the off-gas treatment system, would be expensive, and would generate large quantities of secondary wastes.

Many of the regulations require comprehensive monitoring and reporting. The system will have to include a number of continuous emission monitors (CEM) and other instrumentation systems to satisfy

Table 3.3. Dose Rates Calculated for Release of Volatile Radionuclides in Tank Inventory

Radionuclide	Estimated Curie Content of Melter Feed Over LLW Plant Lifetime, Ci	Estimated Total DF, Including Melter and Off-gas Treatment	Off-gas Concentration, $\mu\text{Ci}/\text{Ml}^{(a)}$	WHC Administrative Control Value, $\mu\text{Ci}/\text{Ml}^{(b)}$	Exposure Factor, rem/Ci (89-m Stack, Site Boundary) ^(c)	Contribution to Dose at Site Boundary, mrem/yr
$^3\text{H}^{(d)}$	6.19E+02	1	6.38E-07	1.00E-07	7.00E-09	3.10E-04
$^{14}\text{C}^{(a)}$	5.33E+03	1	5.49E-06	5.00E-07	1.50E-06	5.71E-01
$^{99}\text{Tc}^{(f)}$	3.21E+04	2000	1.65E-08	2.00E-09	1.30E-06	1.49E-03
$^{106}\text{Ru}^{(f)}$	2.24E+05	1.00E+08	2.31E-12	8.00E-08	4.70E-06	7.52E-07
$^{129}\text{I}^{(f)}$	3.06E+01	100	3.15E-10	700E-11	2.90E-04	6.34E-03
$^{137}\text{Cs}^{(g)}$	3.49E+05	1.00E+07	3.60E-11	4.00E-10	7.70E-06	1.92E-05
Total	5.73E+05		3.54E-10			5.79E-01
(a) At STP; 24-hour operation for 14 years at 4400 SCFM. (b) Westinghouse 1993 (WHC-CM-7-5). (c) From Nickels (1991). (d) DST only; from Boomer et al. (1993). (e) Westinghouse (1994) (internal memo 7E360-94.015). (f) DST - Boomer et al. (1993); SST - Westinghouse (1994) (internal memo 7E360-94.015). (g) WHC memo inventory reduced by 99% pretreatment efficiency.						

these requirements. Sophisticated data acquisition systems will be needed to compile and reduce this monitoring data. Also, detailed reports will have to be submitted to WDOE semi-annually.

Stack emissions at Hanford are subject to an administrative control set at one times the derived concentration guideline shown in Table 3.3 [Westinghouse 1993 (WHC-CM-7-5)]. The calculated stack concentrations for the plant are almost uniformly above these control values. (The exceptions are cesium and ruthenium.) However, the melter off-gas would probably exit the stack after being combined with ventilation air, which may reduce these concentrations to acceptable levels.

4.0 Candidate Off-Gas Treatment Systems

Off-gas treatment is necessary to comply with regulatory requirements, protect facility operating personnel, and protect the melter system. Because of the number of pollutants generated by the melter, the off-gas treatment system will consist of several separate subsystems, as listed here:

- Off-gas cooling
- Nitrogen oxides reduction
- Particulate control
- Acid gas control
- Emergency release protection.

In addition to these major subsystems, the off-gas treatment system will have several separate waste treatment handling operations, fans, and continuous emission monitoring instruments.

The entire off-gas train may be built with a redundant system to facilitate maintenance and permit continued operation of the melter if one or more of the off-gas treatment systems fail.

The off-gas treatment system will be very large and complex. It potentially could cost more to construct than the melter and its associated feed preparation system.

Melter selection, design, and operation will have a profound impact on the design and performance of the off-gas system. The type of melter chosen, for example, may determine whether certain system components will even be necessary. As indicated in Tables 2.1 and 2.2, the off-gas flow rates vary substantially for the various types of melters.

Five off-gas trains were chosen as candidate systems for the melter off-gas. These are shown in Figures 4.1 through 4.5 (these figures are presented in the following subsections as part of the discussions of the respective off-gas trains). All of the off-gas trains have the same type of emergency bypass system for gas surges and melter upsets. The main differences are in the methods used for particulate control and acid gas control, as indicated in Table 4.1.

4.1 Off-Gas Treatment System 1

A flowchart for off-gas treatment system 1 is shown in Figure 4.1. This is a conventional system for a HLW vitrification process. It is very similar to systems at the West Valley Demonstration Project

Table 4.1. Differences in the Candidate Off-Gas Treatment Systems (components listed in sequence of flowchart)

Flowchart	Gas Cooling	Particulate Control	Nitrogen Oxides Control	Acid Gas Control
1	1. Film Cooler	1. Submerged Bed Scrubber 2. HEME 3. HEPAs	1. SCR	1. Submerged Bed Scrubber
2	1. Evaporation Cooler 2. Evaporation Cooler	1. Metallic Filter 2. HEME 3. HEPAs	1. Reburn 2. SCR	1. Packed Bed Absorber
3	1. Film Cooler 2. Absorber	1. HEME 2. Metallic Filter 3. HEPAs	1. SNCR 2. SCR	1. Spray Absorber
4	1. Evaporation Cooler 2. Particle Scrubber	1. Particle Scrubber 2. HEME 3. HEPAs	1. Reburn 2. SCR	1. Packed Bed Absorber
5	1. Evaporation Cooler	1. Fabric Filter 2. HEPAs	1. Reburn 2. SCR	1. Dry Scrubber

(WVDP) and the system designed for Hanford [the Hanford Waste Vitrification Plant (HWVP)]. Since these components have been used to treat melter emissions in the past, there is less technical risk associated with off-gas treatment system 1 than for other proposed systems.

Gas is cooled using a conventional film cooler. The cooler is sized to reduce the gas temperature to a range of 93°C to 149°C (200°F to 300°F) to prevent the submerged bed scrubber (SBS) from being damaged and to convert vapor-phase pollutants to particulate matter. The film cooler significantly increases the total gas flow rate through the addition of dilution air.

A SBS is used to capture large diameter particulate matter entrained in the melter effluent gases. Acid gases are also absorbed in this system. Solids collected in the scrubber liquids are occasionally purged from the vessel by means of a flush system (stream 11 in Figure 4.1). An overflow stream (stream 8) is used to remove excess water condensed from the gas stream.

Most of the larger particulates are captured in the SBS. However, submicron particulates containing much of the radionuclide content will pass through this unit.

A high efficiency mist eliminator (HEME) is used downstream of the SBS to remove entrained liquid droplets and collect the <3-micrometer particles penetrating the SBS. The particulate matter must be removed to avoid masking or poisoning the catalyst beds in the downstream selective catalytic reduction units (SCRs). Sprays mounted in the HEME are used to intermittently remove solids from the filter elements.

A fan is needed after the HEME to minimize the negative static pressure in the effluent gas stream. The estimated static pressure at the discharge of the HEME is -60 inches of water. This fan increases the static pressure to approximately -1 inches of water to avoid air infiltration problems and structural problems in the downstream heat exchangers, SCR's, and high efficiency particulate air (HEPA) filters.

An indirect heat exchanger is used to heat the gas from the HEME to temperatures ranging from 550°F to 700°F. Temperatures in this range are needed for the nitrogen oxides reduction reactions in the SCR unit. The SCR units and their associated heat exchanger are the one part of this system that differs from the HWVP and WVDP systems. Projected nitrogen oxides emissions are substantially higher in this LLW vitrification process than in HLW processes. A series of SCR's is needed since the inlet concentrations of nitrogen oxides could be as high as 16,000 ppm to 50,000 ppm (see Table 2.1 and 2.2). However, absorption of nitrogen dioxide in the SBS may slightly reduce the NO_x concentrations at the SCR inlet.

The ammonia injection rates to the SCR's are controlled by a NO_x CEM in the stack (as shown in Figure 4.1) or immediately downstream of the last SCR. Ammonia CEM's are not used since these are extremely expensive and not commercially proven. Following the SCR's, the gas stream is cooled to approximately 150°F to 250°F in an indirect heat exchanger.

The gas stream passes through a series of HEPA filters for final removal of particulate radio-nuclides. Each of the HEPAs has a prefilter to extend its service life. Finally, the treated gases are vented to the atmosphere through the plant stack.

Off-gas treatment system 1 has been evaluated against the selection criteria discussed in Chapter 1. The results of this comparison are summarized in the following paragraphs.

Criteria 1 - Air pollutant emissions must be below the applicable EPA, DOE, and WDOE requirements.

The overall particulate emissions would be reduced by more than 99.999% in the off-gas treatment system. The main risk to overall effectiveness of particulate control is the ability to adequately contain emissions from the melter. Short-term gas stream surges could cause pressurization of the melter if the emergency treatment system is inadequate. Also, the high negative pressures downstream of the SBS and HEME could lead to air infiltration into the ductwork and vessels. Should infiltration become severe, it may be difficult to maintain a negative static pressure in the melter.

The acid gas removal efficiencies would exceed 99% for all of the halogens and would be 60% to 90% for sulfur dioxide. These removal efficiencies should be adequate.

The nitrogen oxide removal efficiency should range from 90% to >99%, depending on the number of SCR units used in series. Based on a 90% removal efficiency per SCR, it would

probably be necessary to use at least three SCRs in series to adequately reduce nitrogen oxides emissions. There is some risk of high ammonia emissions. There are no downstream scrubbers or absorbers in this system to collect unreacted ammonia.

The radionuclides present in the particulate form are adequately collected. However, some of the tritium and most of the carbon-14 are emitted with the stack gases.

Criteria 2 - The system must be safe to operate.

Overall, the system is safe to operate. However, some particulate radionuclides will penetrate to the HEME and quarterly replacement of these filter elements may be necessary. The operation of the heat exchanger upstream of the SCRs is very important. Sudden loss of steam to the heat exchanger could reduce gas temperatures in the SCRs below the level where the ammonia reacts with NO_x . In extreme cases, the ammonia concentrations could approach the explosive range. For this reason, it would be necessary to discontinue the ammonia feeds when the SCR inlet gas temperature is too low.

The ductwork, SBS vessel, and HEME vessel would have to be designed to withstand both the high negative static pressure and the corrosive attack of the off-gases. Sudden failure of the ductwork or vessels could cause contaminants to be released from the melter. Furthermore, the emergency treatment must be designed to respond very rapidly to maintain containment during melter gas surges or other upsets.

It would be important to design the components properly to minimize worker exposure during maintenance.

Criteria 3 - The off-gas system must be reliable and have a redundant system.

Off-gas system 1 has an emergency system that is relatively similar to the main treatment system. Only the nitrogen oxides control equipment has been left out of the emergency system.

System reliability may be reduced by particulate penetration to the HEME. The particulate loadings from some types of melters may be high and the SBS has a very limited capability for removing particles of less than approximately 3 micrometers. Accordingly, the HEME may require frequent servicing.

Criteria 4 - The off-gas system must be maintainable with minimum risk to personnel.

All of the control units included in this system can be designed to minimize the risk to operations and maintenance personnel.

Criteria 5 - Capital costs and operating costs of the off-gas treatment system must be as low as possible.

The cost of this system would be high because of the high gas flow rate created by the film cooler. Also, it would be necessary to reheat the gas leaving the HEME to facilitate nitrogen oxides reduction. It is also necessary to cool the gas stream leaving the SCR's.

Exotic materials of construction such as Inconel® would be needed in the SBS and HEME because of the presence of halogens and radionuclides.

Criteria 6 - The off-gas treatment system must be flexible to account for process variations in gas flow rates, types of pollutants, pollutant concentrations, gas temperatures, and gas oxygen concentrations.

Off-gas system 1 satisfies this criteria.

Criteria 7 - Liquid and solid waste streams generated by the off-gas treatment system must be minimized, and these wastes must not create unmanageable environmental hazards.

The SBS and HEME purge streams would have to be concentrated in an evaporator. This would cause tritium emissions. Furthermore, the liquids would be extremely corrosive and difficult and expensive to treat. The HEPA filter units and SCR catalyst units would have to be disposed of as hazardous, radioactive solid wastes.

Criteria 8 - The components used in the off-gas system must be based on the manufacturer's experience in previous similar applications.

All of the component control devices used in this system are used in a conventional manner.

Criteria 9 - It must be possible to effectively monitor the system to certify compliance with operating requirements and to optimize operating conditions.

The CEM equipment and radiation monitoring equipment downstream of the HEPA units satisfy this criteria.

Criteria 10 - The off-gas treatment system must be as simple as possible.

Because of the diversity of the pollutants, none of the off-gas treatment systems would be very simple. This system is relatively complicated compared to other possible systems because of the need to cool and reheat the gas several times while it passes through off-gas treatment system 1.

4.2 Off-Gas Treatment System 2

This treatment system would be appropriate for all types of melter systems regardless of the particulate concentration in the off-gas. It uses high-temperature filtration as the primary means of controlling particulate emissions. A HEME and a set of HEPA filters provide additional particulate control. A flowchart for off-gas treatment system 2 is shown in Figure 4.2.

The off-gas from the melter is treated in a natural gas reburning chamber mounted directly above the melter. This unit uses off-stoichiometric combustion conditions to chemically reduce approximately 60% of the nitrogen oxides to molecular nitrogen. Overfire air ports in the reburn chamber are used to complete combustion. In addition to its use for NO_x control, the reburn unit could conceivably be used to preheat the off-gas treatment system during startup periods.

Gas is then cooled using a conventional evaporative cooler. This cooler uses spray water with low suspended and dissolved solids to avoid generating submicrometer particles during droplet evaporation.

A sintered metal filter system with a pulse jet configuration is used as the main particulate control device. By operating at 371°C (700°F), most of the particles formed by nucleation from metal or organic vapors are captured. Only the highly volatile metal chlorides and mercury compounds should pass through this unit in the vapor state. If cesium in the off-gas is present as cesium chloride (rather than as cesium oxide), some CsCl may penetrate this unit as a vapor. Most of the radionuclides are captured in this unit. Therefore, contamination of downstream equipment and waste streams is minimized. The solids from the metallic filter can be returned to the melter feed preparation system or disposed as a relatively low volume hazardous-radioactive waste stream. By operating at a relatively low temperature of 371°C (700°F), the filter unit is not subject to severe thermal expansion and contraction problems. However, the temperature is sufficiently hot to minimize corrosive attack from the acid gas compounds.

The off-gas discharged from the metallic filter system is in the range of 343°C to 371°C (650°F to 700°F). This is an appropriate operating temperature for a set of SCR units. Nitrogen oxides should be reduced approximately 99% in a set of two SCRs. The service life of the catalysts should be relatively long (1 to 2 years) because of the removal of phosphorus in the upstream metallic filter unit. The ammonia injection rates to the SCRs are controlled by a NO_x CEM in the stack (as shown in Figure 4.2) or immediately downstream of the last SCR. Ammonia CEMs are not used since they are extremely expensive and not commercially proven.

The acid gases are collected in a conventional absorber system consisting of an evaporative cooler for reducing the gas temperature to approximately 121°C (250°F) prior to the absorber. Reducing the gas temperature is important since the first mass transfer step in absorption is very temperature sensitive. Because of the reduction in particulate concentrations in the upstream metallic filter, essentially all types of absorbers could be used. These include conventional packed beds, submerged beds, impingement trays, sieve trays, and spray towers. An alkaline scrubbing liquid with a pH between 6 and 9 would be used to ensure high-efficiency absorption of HF , HCl , HI , and SO_2 . The

Figure 4.2. Flowchart for Off-Gas System 2

required liquid-to-gas ratio in the absorber recirculation stream would range from as low as 5 to more than 30 gallons per thousand actual cubic feet per minute (ACFM). A liquid purge stream of approximately 5% of this recirculation liquid flow rate would be needed to maintain the quality of the recirculation liquid. This purge stream would have to be treated in an evaporator before its disposal as a hazardous and radioactive waste. The waste stream would include the particulate radionuclides penetrating the metallic filter, the HI absorbed in the system, and tritium that condensed in the absorber.

In addition to acid gas control, the absorber system would be effective in capturing ammonia slip emissions from the SCR unit. Ammonia slip emissions occur because of the incomplete reaction of the ammonia and the gas stream nitrogen oxides.

The effluent gas stream from the absorber would be treated in a conventional mist eliminator to remove most of the large-diameter droplets entrained in the absorber vessel. The gas stream is then treated in a Brinks® type (or equivalent) HEME to remove droplets and particulate in the 0.1- to 10 micrometer size range. The particulate matter collected by the HEME would include particles that nucleated from vapor phase materials exposed to the relatively cold conditions in the absorber vessel.

The primary purpose of the HEME is to extend the service life of the downstream HEPA filters by reducing particulate loadings and eliminating entrained water droplets that could blind the HEPAs.

A heat exchanger using steam as a heat source would be used before the HEPAs to heat the off-gas stream to the 66°C to 121°C (150°F to 250°F) temperature range. Heating the off-gas stream eliminates problems with moisture condensation on the HEPA filter units. The set of HEPA filters provides the final protection against radionuclide emissions.

Off-gas treatment system 2 has been evaluated against the selection criteria discussed in Chapter 1. The results of this comparison are summarized in the following paragraphs.

Criteria 1 - Air pollutant emissions must be below the applicable EPA, DOE, and WDOE requirements.

The overall particulate emissions would be reduced by more than 99.999% in the off-gas treatment system. The main risk to overall effectiveness of particulate control is the ability to adequately contain emissions from the melter. Short-term gas stream surges could cause pressurization of the melter if the emergency treatment system is inadequate.

The acid gas removal efficiencies would exceed 99% for all of the halogens and would be 60% to 90% for sulfur dioxide. These should be adequate.

The nitrogen oxide removal efficiency should be in the range of 99.6% (60% in the reburn unit and 99% in a set of two SCRs).

The radionuclides present in the particulate form will be adequately collected. However, some of the tritium and most of the carbon-14 would be emitted with the stack gases.

Criteria 2 - The system must be safe to operate.

Overall, the system would be safe to operate. By removing the particulate radionuclides early, this system would be safer to maintain than the systems shown in the other flowcharts (Figures 4.1, 4.3, 4.4, and 4.5).

It is important to design the components properly to minimize worker exposure during maintenance. Furthermore, the emergency treatment must be designed to respond very rapidly to maintain containment during melter gas surges or other upsets.

Criteria 3 - The off-gas system must be reliable.

Off-gas system 2 satisfies this criteria. However, there are uncertainties regarding the ability of the metal filter not to plug and the ability to convey solids to the feed preparation area.

Criteria 4 - The off-gas system must be maintainable with minimum risk to personnel.

This system should be relatively easy to maintain. The sequence of control devices in this system creates highly favorable operating conditions. The removal of particulate in the metallic filter minimizes operating problems for the SCR and absorber. The absorber serves as a collector for any secondary pollutant emissions from the SCR. The high efficiency demister effectively protects the HEPAs.

Criteria 5 - Capital costs and operating costs of the off-gas treatment system must be as low as possible.

Capital costs of this off-gas treatment system would be the lowest of any of the systems evaluated in this study. The low costs are due to the use of evaporative cooling to minimize the gas flow rates of the cooled gas stream and the use of the particulate filter in the initial part of the treatment system.

Waste treatment costs would be minimized by recycling the metallic filter solids to the melter feed system.

As with all the systems, exotic materials of construction, such as Inconel®, would be necessary because of the presence of halogens and radionuclides. In this system, these expensive materials would be needed from the evaporative cooler to the absorber.

Criteria 6 - The off-gas treatment system must be flexible to account for process variations in gas flow rates, types of pollutants, pollutant concentrations, gas temperatures, and gas oxygen concentrations.

Off-gas system 2 satisfies this criteria.

Criteria 7 - Liquid and solid waste streams generated by the off-gas treatment system must be minimized, and these wastes must not create unmanageable environmental hazards.

Four separate waste streams would be generated in this system: 1) the absorber/mist eliminator liquid purge stream, 2) the metallic filter solids stream, 3) waste HEPA filter units, and 4) waste SCR catalyst units. Off-gas system 2 has a high fraction of the particulate radionuclides in the metallic filter solids stream. This should allow for recycling the radionuclides to the melter preparation system and minimize radionuclide levels in the liquid streams purged from the downstream absorber.

The absorber purge stream would have to be concentrated in an evaporator. This would cause tritium emissions. Furthermore, the liquids would be extremely corrosive and difficult and expensive to treat. The HEPA filter units and SCR catalyst units would have to be disposed of as hazardous, radioactive solid wastes.

Criteria 8 - The components used in the off-gas system must be based on the manufacturer's experience in previous similar applications.

All of the component control devices used in this system are used in a conventional manner.

Criteria 9 - It must be possible to effectively monitor the system to certify compliance with operating requirements and to optimize operating conditions.

The CEM equipment and radiation monitoring equipment downstream of the HEPA units satisfy this criteria.

Criteria 10 - The off-gas treatment system must be as simple as possible.

Because of the diversity of the pollutants, none of the off-gas treatment systems would be very simple. This system is the least complex system included in the scope of this study.

4.3 Off-Gas System 3

This system uses a conventional particulate scrubber for control of particulate matter. It is an expanded version of the current flowchart proposed for the LLW vitrification facility (Orme 1994). This system is most appropriate for a melter that generates a low gas flowrate and low particulate loadings. For example, this off-gas treatment system would be more effective and economical for the LFCM than the combustion melter system because of the particulate loadings generated by the combustion melter. The flowchart for off-gas system 3 is shown in Figure 4.3.

Because of high nitrogen oxides levels, the off-gas stream from the melter is treated in a selective noncatalytic reduction system (SNCR) to convert 30% to 50% of the nitrogen oxides to molecular nitrogen. This system must be closely coupled to the melter since the gas temperature must range from

Figure 4.3. Flowchart for Off-Gas System 3

871°C to 1093°C (1600°F to 2000°F) to ensure that the proper reactions occur. Below 871°C (1600°F), most of the ammonia does not react and must be collected downstream as an additional pollutant. Above 1093°C (2000°F), most of the ammonia oxidizes to form additional nitrogen oxides rather than chemically reducing the nitrogen oxides from the melter.

A film cooler is included for initial gas cooling. This substantially increases the gas flow rate throughout the remainder of the off-gas treatment system. An emergency quench system is included downstream of the film cooler since short-term temperature excursions may not be adequately attenuated by the slow-responding film cooler.

The film cooler shown in this flowchart would reduce the gas temperature to approximately 288°C to 371°C (550°F to 700°F). This is the normal operating range for an SCR unit used as the main nitrogen oxides control system. The SCR would be fed an aqueous ammonia stream or a diluted ammonia gas-carrier gas stream generated in a preparation system not included on the flowchart.

The off-gas leaving the SCR unit would be further cooled in the acid gas absorber. The absorber would use a sodium-based alkaline scrubbing liquid to remove HF, HCl, HI, and SO₂. Typical types of absorbers appropriate in this type of system include spray towers, submerged beds, sieve trays, impingement trays, and wet ionizing systems. The sieve tray and impingement trays absorbers would not be appropriate if the particulate loadings were high, such as those estimated for the combustion melter system. Most of the particulate matter larger than approximately 3 microns would be collected along with the acid gases in the absorber. This would include most of the radionuclides. Because of the low gas temperature of 49°C to 60°C (120°F to 140°F) in the absorber, a large fraction of the water vapor emitted from the melter would be collected in the absorber recirculation liquid. A portion of this liquid would be purged from the system and treated to concentrate the radionuclides for eventual disposal.

Water droplets would be removed in a conventional mist eliminator downstream of the particulate scrubber. This would be a fiber bed system, mesh pad system, or other inertial device for removing large-diameter droplets. The primary function of this mist eliminator is to protect the downstream HEME and HEPA filters.

The composite fiber bed-type mist eliminator would be used to remove droplets below 10 microns. These usually penetrate conventional mist eliminators. The primary purpose of the fiber bed unit is to protect the downstream metallic filter and HEPA filters from entrained water droplets and high particulate loadings. The outlet gas temperature from the fiber bed unit would be approximately 49°C to 60°C (120°F to 140°F). The gas stream would be saturated with moisture. Accordingly, it would be necessary to heat the gas stream well above the dewpoint to avoid blinding the metallic filter and the first HEPA filter. Hot gas injection is used instead of a heat exchanger to minimize maintenance requirements caused by corrosion and/or scaling of the gas side of the heat exchanger. The outlet temperature would be kept below 121°C (250°F) to avoid damage to the HEPAs and revolatilization of radionuclides still in the gas stream.

The metallic filter would use cylindrical sintered metal filters in a pulse jet-type baghouse configuration. This unit would have a high efficiency for the submicrometer particles that nucleated from vapor phase metal and organic compounds. Some of the semi-volatile radionuclides would be captured in the metallic filter. This unit would also serve to extend the service time of the downstream HEPA units by minimizing the particulate loadings and stopping entrained droplets from penetrating the mist eliminators. The double HEPA system would be the last line of protection against the emission of radionuclides. These units would be conventional HEPA systems.

A double fan arrangement is used in this system to minimize the negative static pressures inside the equipment. The inlet static pressure to the first centrifugal fan would be approximately -30 to -40 inches of water. Structural reinforcement of the vessels and ductwork would be needed because of these negative pressures.

Off-gas treatment system 3 has been evaluated against the selection criteria discussed in Chapter 1. The results of this comparison are summarized in the following paragraphs.

Criteria 1 - Air pollutant emissions must be below the applicable EPA, DOE, and WDOE requirements.

The overall particulate emissions would be reduced by more than 99.999% in the off-gas treatment system. The main risk to overall particulate control effectiveness is the ability to adequately maintain emissions from the melter. Short-term gas stream surges could cause pressurization of the melter if the emergency system is inadequate.

The acid gas removal efficiencies would exceed 99% for all of the halogens and would be 60% to 90% for sulfur dioxide. These should be adequate.

The nitrogen oxide removal efficiency should be in the range of 99.3% (30% in the SNCR and 99% in two SCRs).

The radionuclides present in particulate form will be adequately collected. However, some of the tritium and most of the carbon-14 will be emitted with the stack gases.

Criteria 2 - The system must be safe to operate.

Overall, the system would be safe to operate. However, it is important to design the components properly to minimize worker exposure during maintenance. Furthermore, the emergency treatment must be designed to respond very rapidly to maintain containment during melter gas surges or other upsets.

Criteria 3 - The off-gas system must be reliable.

Off-gas system 3 satisfies this criteria.

Criteria 4 - The off-gas system must be maintainable with minimum risk to personnel.

The presence of the SCR systems on the inlet side of the off-gas system would cause relatively high maintenance requirements. In this location, the catalyst is not protected from the particulate, which can mask and poison the catalyst. The remainder of the system components can be maintained if the component units are designed properly.

Criteria 5 - Capital costs and operating costs of the off-gas treatment system must be as low as possible.

Capital costs of this unit would be very high because of the number of separate control units needed. Also, exotic materials of construction, such as Inconel®, would be needed from the film cooler to the metallic filter because of the presence of the halogens and radionuclides.

The use of the film cooler substantially increases the cost of this system because of the increased gas flow rates.

Criteria 6 - The off-gas treatment system must be flexible to account for process variations in gas flow rates, types of pollutants, pollutant concentrations, gas temperatures, and gas oxygen concentrations.

Off-gas system 3 satisfies this criteria.

Criteria 7 - Liquid and solid waste streams generated by the off-gas treatment system must be minimized, and these wastes must not create unmanageable environmental hazards.

Four separate waste streams will be generated in this system: 1) absorber/mist eliminator liquid purge stream, 2) metallic filter solids stream, 3) waste HEPA filter units, and 4) SCR catalyst units. The liquid stream would have to be concentrated in an evaporator. This would cause tritium emissions. Furthermore, the liquids would be extremely corrosive and would be contaminated with radionuclide particulate matter. Liquid treatment would be very difficult and expensive.

Conversely, the small solids stream from the metallic filter can be returned to the waste feed system. The HEPA filter units and SCR catalyst units would have to be disposed of as hazardous, radioactive solid wastes.

Criteria 8 - The components used in the off-gas system must be based on the manufacturer's experience in previous similar applications.

Most of the component control devices used in this system are used in a conventional manner. However, the SCR system would be challenged by the high nitrogen oxides concentrations and the high metals levels. Significant developmental work may be needed to successfully operate a SCR system in this type of application.

Criteria 9 - It must be possible to effectively monitor the system to certify compliance with operating requirements and to optimize operating conditions.

The CEM equipment and radiation monitoring equipment downstream of the HEPA units will satisfy this criteria.

Criteria 10 - The off-gas treatment system must be as simple as possible.

Because of the diversity of the pollutants, none of the off-gas treatment systems would be very simple. This system is more complex than off-gas treatment system 2.

4.4 Off-Gas Treatment System 4

Off-gas system 4 is similar to system 3 with the exception that the primary particulate control device is a scrubber rather than a metallic filter. This system would be less appropriate for a melter generating a relatively high particulate loading. The selective catalytic unit is in a vulnerable location if the particulate loadings are high. The flowchart for off-gas system 4 is shown in Figure 4.4.

Initial nitrogen oxides reduction is performed using a reburn chamber directly above the melter, followed by an evaporative cooler to decrease the gas temperature to the 288°C to 371°C (550°F to 700°F) range.

Selective catalytic reduction units are used as the primary means to minimize nitrogen oxide emissions. The overall nitrogen oxides control efficiency in off-gas system 4 would be similar to the 99.4% level in off-gas system 2.

The off-gas leaving the SCR unit could be cooled either in an evaporative cooler (as shown in item 5 on Figure 4.4) or using a presaturator on the particulate scrubber. The inlet gas temperature to the particulate scrubber should be less than approximately 121°C (250°F).

A conventional particulate scrubber such as an adjustable throat venturi, a collision scrubber, or a wet ionizing scrubber could be used. The venturi scrubber and collision scrubbers would have to operate at very high static pressure drops of 30 to 50 inches of water to efficiently collect the submicron particulate matter generated by the melter. Because of the high static pressure drops, it may be necessary to move the first centrifugal fan from the position shown in item 4 on Figure 4.4 to immediately downstream of the first mist eliminator. This would be needed to minimize the amount of equipment and ductwork subjected to very high negative static pressures. The wet ionizing scrubber would operate at much lower static pressure drops and thereby avoid the extreme negative static pressure condition.

However, because of its limited efficiency in the submicron size range, several modules would have to be located in series. Even with this arrangement, the wet ionizing scrubbers would not have an overall efficiency as high as the adjustable throat venturis or collision scrubbers.

JR 003/1-95

Figure 4.4. Flowchart for Off-Gas System 4

A packed bed absorber (or other type of absorber) would be used for acid gas control. This absorber would have a liquid recirculation system which is separate from the particulate scrubber to minimize solids loadings in the absorber liquid. The packed bed scrubber is vulnerable to solids accumulation. Following the absorber, a conventional mist eliminator and a HEME would be used to remove entrained droplets. The gas stream would then be heated prior to the HEPA filters.

Off-gas treatment system 4 has been evaluated against the selection criteria discussed in Chapter 1. The results of this comparison are summarized in the following paragraphs.

Criteria 1 - Air pollutant emissions must be below the applicable EPA, DOE, and WDOE requirements.

This system is capable of the same pollutant removal efficiencies as the previously discussed systems.

The radionuclides present in particulate form are adequately collected. However, some of the tritium and most of the carbon-14 would be emitted with the stack gases.

Criteria 2 - The system must be safe to operate.

Overall, the system would be safe to operate. However, the system would have to be carefully designed because of the extremely high negative static pressures that could exist downstream of the particulate scrubber.

It is important to design the components properly to minimize worker exposure during maintenance. Particulate radionuclides would contaminate essentially all of the control devices and the connecting ductwork. Furthermore, the emergency treatment must be designed to respond very rapidly to maintain containment during melter gas surges or other upsets.

Criteria 3 - The off-gas system must be reliable.

Off-gas system 4 satisfies this criteria.

Criteria 4 - The off-gas system must be maintainable with minimum risk to personnel.

This system would be difficult to maintain because of the ability of particulate radionuclides to penetrate to the particulate scrubber. This increases the maintenance requirements of the SCR unit.

Criteria 5 - Capital costs and operating costs of the off-gas treatment system must be as low as possible.

Capital costs of this off-gas treatment system would be high because of the exotic materials of construction and the large number of separate particulate scrubber and absorber vessels in the

system. Operating costs would be high because of the high static pressure drop of the particulate scrubber, the need to treat a large volume wastewater stream, and the need to frequently replace the SCR catalysts.

Criteria 6 - The off-gas treatment system must be flexible to account for process variations in gas flow rates, types of pollutants, pollutant concentrations, gas temperatures, and gas oxygen concentrations.

Off-gas system 4 satisfies this criteria.

Criteria 7 - Liquid and solid waste streams generated by the off-gas treatment system must be minimized, and these wastes must not create unmanageable environmental hazards.

The wastewater treatment costs for off-gas treatment system 4 would be high because of the large volume of waste from the particulate scrubber and the absorber. Costs for the disposal of the SCR catalyst as hazardous waste would be higher than those for system 2 since the catalyst will have a reduced service life.

Criteria 8 - The components used in the off-gas system must be based on the manufacturer's experience in previous similar applications.

Most of the component control devices used in this system are used in a conventional manner. However, the SCR system would be challenged by metal-containing particulate matter.

Criteria 9 - It must be possible to effectively monitor the system to certify compliance with operating requirements and to optimize operating conditions.

The CEM equipment and radiation monitoring equipment downstream of the HEPA units satisfy this criteria.

Criteria 10 - The off-gas treatment system must be as simple as possible.

All of the off-gas systems are relatively similar with respect to their complexity.

4.5 Off-Gas Treatment System 5

Off-gas treatment system 5 uses a spray dryer-type dry scrubber for acid gas control and a fabric filter as the primary particulate control system. This system is most appropriate for melters generating low particulate concentrations. A flowchart for off-gas system 5 is shown in Figure 4.5.

The off-gas from the melter is first treated in a reburn chamber for nitrogen oxides reduction. The gas stream is then cooled to the 288°C to 371°C (550°F to 700°F) temperature range. A set of SCR units is then used to complete the chemical reduction of nitrogen oxides.

A spray dryer absorber would be used for collection of HF, HCl, HI, and sulfur dioxide. A lime slurry would be injected into a large spray dryer vessel having a gas residence time between 6 and 20 seconds. The lime would be injected as a slurry having a solids content of 5% to 15% by weight. The quantity of lime would be 1.5 to 2.0 times the stoichiometric requirement to react with the halogens and sulfur dioxide. High-pressure nozzles or air-assisted spray nozzles would be used to ensure that the lime slurry droplets are sufficiently small to evaporate to dryness before leaving the absorber vessel.

The fabric filter is used to collect the dried reaction products from the spray dryer and the particulate matter emitted from the melter. Most of the solids would be recycled through the spray dryer to improve the use of the lime reagent. This is useful for minimizing the quantity of solids that must be disposed as hazardous-radioactive wastes.

The gas stream is reheated in a heat exchanger (or by hot gas injection) prior to the HEPA filters. The HEPA filters provide the final protection against emission of radionuclides.

Off-gas treatment system 5 has been evaluated against the selection criteria discussed in Chapter 1. The results of this comparison are summarized in the following paragraphs.

Criteria 1 - Air pollutant emissions must be below the applicable EPA, DOE, and WDOE requirements.

The overall particulate emissions would be reduced by more than 99.999% in the off-gas treatment system. The main risk to overall particulate control effectiveness is the ability to adequately maintain emissions from the melter. Short-term gas stream surges could cause puffing from the melter if the emergency treatment system is inadequate.

The acid gas removal efficiencies would exceed 99% for all of the halogens and would be 60% to 90% for sulfur dioxide. These should be adequate.

The nitrogen oxide removal efficiency would be in the range of 99.6% (60% in the reburn unit and 99% in two SCRs).

The radionuclides present in particulate form will be adequately collected. However, some of the tritium and most of the carbon-14 will be emitted with the stack gases.

Criteria 2 - The system must be safe to operate.

Solids accumulation in the spray dryer absorber could present major safety problems since these materials must be removed manually, a very time-consuming process. Particulate radionuclides and tritium would be present in these solids deposits.

Criteria 3 - The off-gas system must be reliable and have a redundant system.

Off-gas system 5 may be subject to frequent outages because of the vulnerability of the spray dryer absorber. Variations in the inlet gas flow rate or inlet gas temperature can result in buildup of sticky solids because of incomplete drying of the slurry droplets. Furthermore, the SCR may be subject to masking or catalyst poisoning because of the particulate matter in the gas stream.

Criteria 4 - The off-gas system must be maintainable with minimum risk to personnel.

This system should be extremely difficult to maintain because of the vulnerability of the spray dryer absorber. In addition to solids buildup, frequent replacement of the nozzles may be needed. The high moisture levels in the off-gas stream may complicate proper drying of the solids. Furthermore, it may be difficult to maintain the fabric filter solids recycle stream back to the waste feed preparation system. The high solids loadings to the baghouse also may require frequent maintenance.

Criteria 5 - Capital costs and operating costs of the off-gas treatment system must be as low as possible.

Capital costs of this off-gas treatment system would be high because of the complexity of the spray dryer absorber. Operating costs may be low if a major portion of the solids collected in the fabric filter can be returned to the melter feed preparation system. There are no liquid effluent streams that must be treated with this system.

Criteria 6 - The off-gas treatment system must be flexible to account for process variations in gas flow rates, types of pollutants, pollutant concentrations, gas temperatures, and gas oxygen concentrations.

Off-gas system 5 satisfies this criteria.

Criteria 7 - Liquid and solid waste streams generated by the off-gas treatment system must be minimized, and these wastes must not create unmanageable environmental hazards.

The main advantage of off-gas system 5 is the lack of liquid effluent. Furthermore, a portion of the solids collected in the fabric filter could be returned to the melter.

Criteria 8 - The components used in the off-gas system must be based on the manufacturer's experience in previous similar applications.

Most of these component control devices used in this system are used in a conventional manner. However, the SCR system would be challenged by metals-containing particulate.

Criteria 9 - It must be possible to effectively monitor the system to certify compliance with operating requirements and to optimize operating conditions.

The CEM equipment and radiation monitoring equipment downstream of the HEPA units satisfy this criteria.

Criteria 10 - The off-gas treatment system must be as simple as possible.

Off-gas system 5 has relatively few components. However, it would be difficult to operate. The spray dryer absorber would be very sensitive to variations in the off-gas flow rate and temperature.

4.6 Summary of Off-Gas Treatment System Options

Off-gas treatment system 2 is preferable to the other four types of systems. The use of a high-temperature filter in the early portions of the treatment system improves the reliability of the downstream control devices and minimizes the radionuclide contamination of the absorber liquid stream. The SCR units can be operated efficiently without concern about ammonia slip since the downstream absorber will capture any ammonia emissions. The HEME and the heat exchanger provide a high degree of protection for the HEPA filter units. Off-gas treatment system 2 is most consistent with the selection criteria presented in Chapter 1.

5.0 Component Control System Characteristics

This section provides information concerning some of the component systems included in the five off-gas treatment systems discussed in Chapter 4. Information is also provided concerning some of the control devices that could conceivably be used as alternatives to the units included in the flowcharts.

5.1 Off-Gas Cooling

The off-gases exit the melter at temperatures of approximately 982°C to 1204°C (1800°F to 2200°F). Cooling these gases is necessary to protect temperature-sensitive air pollution control equipment downstream and to condense vaporized pollutants such as metal oxides and chlorides. Techniques used for off-gas cooling include 1) air dilution using a film cooler, 2) water quenching in a spray tower, 3) transfer of heat through a shell-and-tube heat exchanger, and 4) cryogenic gas injection.

Particulate nucleation and accumulation on the off-gas side of the heat exchangers usually makes these techniques inappropriate for LLW vitrification processes. Materials which may accumulate in the heat exchanger include semi-volatile metal compounds such as cesium and ruthenium compounds. The buildup of solids in the inlet side of the heat exchanger could block gas flow out of the melter and thereby create containment problems. Also, the removal of these materials could present safety hazards for the maintenance personnel. The susceptibility of film coolers and evaporative coolers to particulate buildup is less severe but, nevertheless, must be considered in selecting the method of gas cooling.

One of the main factors to be considered in selecting the method of gas cooling is the resulting gas flow rate which must be treated in the downstream air pollution control equipment. Table 5.1 illustrates that the cooled gas flow rates are substantially lower when evaporative cooling is used rather than air dilution in a film cooler.

5.1.1 Film Coolers

Film coolers have been used to quench off-gases from thermal treatment of radioactive waste both at PNL and in a number of operating plants (Perez et al. 1993, IAEA 1989). They are a reliable, proven technology. The gas is cooled simply by the addition of cold air, generally introduced at the walls parallel to the flowing gas stream to keep particulates from aggregating on the unit walls. These units are usually simple and inexpensive and have low maintenance requirements. Their chief disadvantage is that they substantially increase the off-gas flow rate, as indicated in Table 5.1. This increases the cost of the downstream equipment.

**Table 5.1. Effect of Melter Type and Gas Cooling Method
on the Off-Gas Flow Rate**

Type of Melter and Method of Gas Cooling	Off-Gas Flow Rate (Stream 6, Figures 4.1 - 4.5)	
	SCFM	ACFM @ 371°C (700°F)
Ceramic Melter		
Film Cooler	14,410	31,650
Water Evaporation	6,170	13,560
Combustion Melter		
Film Cooler	60,160	13,200
Water Evaporation	22,520	49,480

The outlet temperature is controlled by the amount of ambient air added. Therefore, temperature and air velocity cannot be controlled independently. Since the only material added to the off-gas is air, no secondary waste is produced by this process.

5.1.2 Water Quenching

Spray towers are also a proven technology in the treatment of mixed wastes (IAEA 1989) and other high-temperature processes. Spray nozzles inject water droplets into the tower, and the gases are cooled by evaporation of the water. The primary advantages of spray towers are 1) the ease of temperature control, and 2) the low maintenance requirements. Outlet temperature is controlled by controlling the rate of water addition.

The evaporative cooling towers must be designed for a relatively long residence time (5 to 10 seconds) to allow for complete droplet evaporation. Adequate droplet evaporation may be difficult to sustain during low gas flow periods typical of melter idling. Several separate sets of spray nozzles would be needed so that the liquid flow rate could be reduced without significantly reducing the nozzle pressure. Significant changes in the nozzle pressure could cause increased droplet sizes, and these droplets may not evaporate properly within the evaporative cooler.

Exotic materials of construction would be needed because of the acidic conditions in droplets collected at the bottom of the evaporative cooler. The quantity of unevaporated liquid would be largest during low gas flow periods and during system startup.

One of the disadvantages of evaporative cooling systems is the quantity of water added to the off-gas stream. If the off-gas remains above its dewpoint for the remainder of the off-gas treatment system, the added water vapor will simply be sent up the stack. If the spray water is condensed in the

downstream control system, it will be sent back to the waste evaporators where additional energy will be required for its re-evaporation. If it becomes necessary to retain and treat the tritiated portion of the waste stream, the added water will become a secondary waste.

Another possible disadvantage of evaporative cooling is the accumulation of solids at the entrance of the cooler from the condensation of semi-volatile materials. The design of the entrance section should be evaluated during pilot tests of the melter. One possible option involves the use of a short film cooler section between the melter and the evaporative cooler. This would initiate the off-gas stream cooling while providing an air sweep along the walls of the transition section.

The spray water used in the evaporative cooler must have low suspended solids and/or dissolved solids. During droplet evaporation, these solids can be released as submicrometer particulates which increase the burden on downstream particulate control equipment in the off-gas treatment system.

5.1.3 Heat Exchangers

Shell-and-tube heat exchangers are not appropriate for the initial cooling of the melter off-gases. The gas temperatures of 982°C to 1204°C (1800°F to 2200°F) are too hot for conventional metals used in fabricating the heat exchangers. Furthermore, the nucleation and deposition of solids on the heat exchange surfaces would severely reduce heat transfer efficiency, and it would be very difficult to remove these solids.

5.1.4 Cryogenic Gas Injection

Cryogenic gases such as liquid nitrogen could be injected into the gas stream. This would be an effective means to cool the gas stream since heat is taken up by the evaporation of the liquid nitrogen and by the heating of the gaseous nitrogen from -196°C (-320°F) to the cooler outlet gas temperature. Furthermore, the nitrogen gas would not generate wastes that would have to be processed.

The main disadvantage of this approach is that liquid nitrogen would be expensive and the demand would be high due to the large off-gas flow rates. This economic penalty is partially offset by the reduction in the total off-gas flow rate that must be treated throughout the off-gas treatment system.

5.2 Particulate Control

The particulate matter contains a substantial fraction of the radioactive species in the off-gas. At least two particle removal stages will be required in the off-gas train because the gas stream must be sent through a set of HEPA filters before it can be sent to the stack, and the particle loading in the off-gas is too high to be sent directly to HEPAs. A sophisticated particulate control device or combination of units must be used to minimize the particulate loading reaching the HEPA filter.

The solids-handling equipment associated with the particulate control device is especially important since it will be necessary to maintain containment by avoiding fugitive emissions (Dalton et al. 1992). To the extent possible, the solids should be returned to the melter feed preparation system so that the radionuclides can be returned to the melter. This will maximize the quantity of radionuclides ultimately disposed with the vitrified waste.

It is also important to remove the majority of the particulate early in the treatment system so that the radionuclides are not at high concentrations in the subsequent waste streams from the scrubbers and other cold systems. Because of the presence of the radionuclides and other materials, all of the air pollution control equipment waste streams will be classified as hazardous wastes. Furthermore, the particulate matter that remains in the off-gas stream can mask and poison the catalyst used in nitrogen oxides control systems and can plug packed beds used in scrubbers.

Particle separation can be done at high temperatures [260°C to 816°C (500°F to 1500°F)] or at moderate temperatures [260°C (<500°F)]. Below 260°C (500°F), conventional fabrics such as acid-resistant coated fiberglass and Gore-tex membrane-coated fiberglass can be used. There is extensive industrial experience with the low-temperature filters since they are used in many types of hazardous waste incinerators and fossil fuel combustion applications. At the low temperatures, all of the vapor phase metal compounds with the exception of the mercury compounds would have nucleated to form filterable particulate matter. Furthermore, low-temperature units are not as vulnerable as high-temperature units to air infiltration from the problems associated with the repeated thermal expansion and contraction. However, low-temperature units can be subject to corrosion from the condensation and absorption of acid gases in localized cold zones of the unit. Also, the salt-containing particulate matter collected in low-temperature fabric filters can be sticky at temperatures below 216°C (420°F) (Dalton et al. 1992) in part because of the high water vapor content of the off-gas.

Above 260°C (500°F), sintered metal filters, woven ceramic fabrics, and sintered metal filters can be used. The metal filters can be composed of a wide variety of the metals, depending on the maximum temperature limits and the corrosive conditions potentially present in the gas stream. One of the main advantages of the high-temperature units is that the particulate matter can be removed in the early portion of the off-gas system without unnecessarily increasing gas flow rates because of dilution and/or evaporative cooling. There is no need to reheat the off-gases to achieve the necessary operating temperatures of the SCR system. Another advantage of high-temperature filtration is that it reduces the likelihood of the formation of dioxins and furan compounds because of heterogenic catalytic reactions on the surfaces of the particulate matter. The dioxin and furan compounds are suspected carcinogens that can form from partially oxidized organic compounds and chlorinated compounds when the gas stream temperature is between 279°C and 341°C (535°F and 645°F) (Dalton et al. 1992). High-temperature filtration removes most of the particulate matter before the off-gas is cooled into the temperature range where dioxins and furans can form. Once formed, these compounds would not be adequately collected by any of the downstream control devices included in the various off-gas treatment systems discussed in Chapter 4.

- The significant advantages offered by high-temperature filtration are partially offset by their inherently high cost. They are also more difficult to maintain because of thermal expansion and contraction problems.

5.2.1 High-Temperature Filters

Sintered Metal Filters

Sintered metal filters are frequently used in thermal treatment of radiological wastes. The cylindrical filter elements are usually 6 to 12 inches in diameter and several feet long. They are composed of sintered metal (fused particles) with pores less than approximately 3 micrometers. The filters should be made out of Inconel® or similar material having very good resistance to both halogen compounds and radiation. The Inconel® filters can be used up to temperatures of 600°C (1110°F) (IAEA 1989), well above the temperature range required for the off-gas systems discussed in Chapter 4. Accordingly, the unit could handle short-term temperature surges caused by gas flow surges or problems with the gas cooling system. The static pressure drop varies from 1 to 3 kPa (4 to 12 inches of water).

The cylindrical filters are installed in a pulse jet-type configuration. The filters are hung from a tube sheet mounted near the top of the collector. The filter elements must be welded or otherwise sealed to the top side of this tube sheet to prevent gas from shortcircuiting around the filter elements. The particulate-laden gas enters from the outside of the filter element, and clean gas passes up the center. The clean gas accumulates in the plenum at the top of the unit. Figure 5.1 shows a standard pulse jet-type filter configuration. However, a metallic filter uses rigid metal filters rather than the cage support fabric filters shown in the figure.

The cylindrical filters should be installed in a number of separate compartments equipped with poppet-type isolation dampers. The compartments should be isolated from the gas stream during filter cleaning to facilitate gravity settling of the solids into the hoppers.

The sintered metal filter unit should be designed with a relatively low air flow-to-media area ratio of less than 2.5 ft³ per minute per ft² of filter. Due to the high gas flow rate (in ACFM), several separate filters elements would be needed in the unit.

The filter elements are cleaned by a compressed air system. A compressed air pulse is delivered to the top center of each filter element using a compressed air tube mounted across each row of elements. Compressed air flow is controlled by means of a diaphragm valve and a solenoid valve. Compressed air pressure is usually more than 60 psig. However, the short-term cleaning pulses only slightly increase the absolute pressure in the baghouse, and these pulses would not compromise containment of radionuclides. The absolute pressure would remain substantially below atmospheric pressure at all times during cleaning.

Figure 5.1. Pulse Jet Filter Configuration

The compressed air system should include a drier and a coalescing filter. These are needed to minimize condensed water-related blinding of the filter elements.

The clean gas plenum should have top access hatches and a large vertical plenum so that the filter elements could be removed without the need for personnel to enter the filter housing. Filter element sleeves should be included so that dust emissions can be minimized during the removal of filters. It should be noted, however, that filter replacement will rarely be needed since these units are not subject to wear and flex failure. Problems which could require filter element replacement are limited to corrosion or irreversible blinding. These two conditions can be avoided by proper startup practices, by proper operation of the evaporative coolers upstream of the filter unit, and by proper maintenance practices of identifying and correcting air infiltration problems upstream of the filter unit.

The hoppers should be steeply sloped. Thermal insulation, air gaps, and hopper heaters should be used to keep the solids warm as they are being discharged to the solids-handling equipment. A pneumatic conveying system could be used to transport the solids back to the melter feed preparation system.

Ceramic Filters

A ceramic filter system could be used instead of the sintered metal filter described above. This system uses cylindrical ceramic filters made of silicon carbide which can be used at temperatures of up to 1100°C (approximately 2000°F) (IAEA 1989). The static pressure drop can vary from 2 to 6 kPa (8 to 24 inches of water) (IAEA 1989). The filter unit is very similar to the type that uses sintered metal filters.

The ceramic filter is not appropriate because the filter is more vulnerable to blinding than the sintered metal filter and because there is no need to operate at extremely high gas temperatures. In fact, most of the particulate emitted from the melter would still be in the vapor state at this temperature. Furthermore, it would be difficult to minimize air infiltration because of the thermal expansion and contraction that would occur during startup, shutdown, and melter feed interruptions.

Conventional Fabric Filters with Woven Ceramic Fabric

A conventional fabric filter using woven ceramic fabric could also be used as an alternative to the sintered metal filter. These fabrics would be used in a reverse air-type configuration to minimize flex-related damage. The cylindrical bags would be hung from a top assembly and attached to a tube sheet immediately above the hoppers. Particulate-laden gas enters the hopper area and passes into the center of the bags. Cleaned gas passing through the bags accumulates in the gas cleaning compartment surrounding the bags.

The bags would be tensioned to minimize flexing during filtering and cleaning. The bags would be arranged in a number of separate compartments and cleaned by isolating a compartment and passing filtered air backwards through the bags. A typical reverse air-type fabric filter is shown in Figure 5.2.

This type of high-temperature fabric filter is not recommended for this application since manual handling is necessary to replace failed bags. Flex failure could cause frequent failure. Furthermore, the chemical resistance of the ceramic fabrics to fluorides is not known.

5.2.2 Low Temperature, Dry Particulate Control Devices

Conventional Fabric Filter

A conventional fabric filter is used downstream of the spray dryer in off-gas system 5. This unit could be either a pulse jet unit similar to the one described above or a reverse air fabric filter. A typical reverse air fabric filter was shown previously (see Figure 5.2).

Figure 5.2. Reverse Air Fabric Filter

This unit would be especially vulnerable to solids plugging in the hopper because of the inherently hygroscopic nature of the calcium chloride reaction product formed in a dry scrubber. Hopper heaters and thermal insulation are very important to avoid solids buildup in the hoppers.

The air-to-cloth ratio should be approximately 1 ft^3 per minute per ft^2 . This means that the unit would be relatively large.

Fiberglass bags are usually used in dry scrubber-type applications. However, the uncollected fluorides in the gas stream could severely damage the fiberglass material. It would be necessary to test a variety of specialty fabrics in order to select a fabric that could withstand the corrosive conditions caused by incomplete acid gas removal in the spray dryer.

The baghouse tube sheet, shell, isolation dampers, bypass ducts, and other metallic components should be constructed of Inconel® or other highly corrosion-resistant material. These expensive materials of construction are needed since the spray dryer will occasionally be subject to short-term malfunctions that could allow HCl and HF to penetrate to the fabric filter. Furthermore, the spray dryer may not be able to respond to short-term spikes in the HCl and HF generation rates in the melter.

One of the main disadvantages of the reverse air fabric filter is the need to enter the clean gas compartment to remove failed bags and reinstall new bags. During this time, the maintenance personnel would be surrounded by tall bags containing large amounts of particulate matter. Radiation exposure could be high because of the dusty conditions during the maintenance work and the fact that personnel would be surrounded by radionuclide-containing dust.

Pulse Jet Fabric Filters

As an alternative to the reverse air fabric filter, a pulse jet system could be used to capture the solids from the spray dryer and melter. This baghouse would be similar to the one shown in Figure 5.2. The fabric would be a 20 oz/yd² woven fiberglass with acid-resistant coating or Teflon-B coating. However, it should be noted that the fiberglass cloth is vulnerable to fluoride attack, and radiation will cause Teflon to break down. Accordingly, it would be necessary to evaluate alternative fabrics for this type of application.

Electrostatic Precipitators

Particle-gas separation by electrostatic precipitation is a well-established process in industry for treating fly ash or other industry-specific powders. Particles entering the precipitator are electrically charged. They then migrate toward an electrically grounded vertical collection plate because of the strong, nonuniform electrical field. These collection plates and discharge electrodes are cleaned by mechanical hammers.

Electrostatic precipitators (ESP) have very low pressure drops of less than one inch of water. Collection efficiencies are usually greater than 99%. However, lower efficiencies occur when most of the particulate is in the submicrometer range.

In order to achieve high particulate removal efficiencies, the dust layers accumulating on the collection plates and discharge electrodes must have moderate resistivity. If the resistivity is too low, the electrical charge on the particles is dissipated too quickly, and the dust layer is only weakly held on the vertical surfaces. During rapping, a major portion of the collected dust can be re-entrained. This off-gas stream generated by the melter would probably be vulnerable to low dust layer resistivities because of the high sodium content in the particulate and the high moisture content in the gas stream.

An electrostatic precipitator is not an ideal choice as the primary particulate control device for the melter off-gas. Many of the maintenance problems associated with precipitators require labor-intensive maintenance work inside the unit. Even when the precipitator is washed out prior to the work, it is difficult to remove all of the solids. Radionuclide levels in the solids trapped in the precipitator could be relatively high.

An electrostatic precipitator is not flexible with respect to the dust layer composition. Variations in the feed characteristics could cause a significant change in the dust layer resistivities. This would have a direct impact on the particulate removal efficiency.

Cyclone Separators

Cyclone separators have modest removal capability for large particles. For particles larger than 10 micrometers in diameter, removal efficiency can exceed 85% (IAEA 1989). However, only about 50% of the particles in the 1 to 10 micrometer size range and 10% to 20% of the particles in the

submicrometer size range are usually collected. Cyclones use inertial force for separating the particles from the spinning gas stream. The cyclones themselves have no moving parts, making them reliable and easy to maintain. The operating temperature range is limited only by the materials of construction used in the cyclone body and the solids-handling equipment at the bottom of the unit. There is some wear from abrasion. However, the units are generally quite durable. Operating difficulties arise primarily in the dry handling of the collected particles, especially in the hopper.

5.2.3 Low Temperature, Particulate Wet Scrubbers

There are numerous types of high-efficiency particulate wet scrubbers. The types used most often for sources similar to the melter (such as hazardous waste incinerators and medical waste incinerators) include submerged bed scrubbers (SBS), adjustable throat venturis, ejector scrubbers, collision scrubbers, hydrosonic scrubbers, and wet ionizing scrubbers. The performance of essentially all of these types of particulate scrubbers can be enhanced by including equipment within the scrubber system to provide for condensation growth of submicrometer-sized particles prior to the particulate scrubber vessel.

Submerged Bed Scrubbers

A SBS vessel is illustrated in Figure 5.3. The inlet gas stream enters through a center duct. The gas stream turns 180° above the surface of the scrubbing liquor at the bottom of the vessel. This part of the scrubber operates much like an orifice scrubber and particulate matter larger than approximately 3 micrometers is collected. The turning gas stream then enters a submerged bed mounted in an annular arrangement. Particle impaction and gas absorption occur as the dispersed gas bubbles pass upwards through the bed. The gas stream and entrained water droplets collect at the top of the vessel and are exhausted to a mist eliminator.

Static pressure drop through the bed depends on the liquid head in the scrubber. Usually, SBSs have pressure drops between 30 and 40 inches of water.

The main advantages of the SBS are its low maintenance requirements and the limited vulnerability to operating problems. Furthermore, large particulate matter and acid gases are collected simultaneously.

The main disadvantages of the SBS include its limited capability to remove particles less than 3 micrometers in diameter and the high static pressure drop. It may also be necessary to custom design and fabricate this type of scrubber since all of the wet scrubber manufacturers contacted during this study no longer offer this type of scrubber system.

Figure 5.3. Submerged Bed Scrubber

Adjustable Throat Venturi Scrubbers

A venturi scrubber uses primarily inertial impaction to capture particulate. The particulate-laden gas stream entering the venturi throat is accelerated to a velocity ranging between 10,000 and 25,000 feet per minute. Recirculated scrubbing liquid is introduced near the inlet to the throat. This liquid is accelerated and atomized by the high-velocity gas stream. Before the droplets reach the same velocity as the particles, they serve as excellent impaction targets. In fact, near the entrance of the throat, the particles can be moving at a velocity that is more than 150 mph faster than the large, slowly accelerating droplets.

A typical throat section of an adjustable throat venturi scrubber is shown in Figure 5.4. The movable blades can constrict the throat and thereby change the gas velocity through the throat. The static pressure drop across the throat increases with the square of the average gas velocity. Particulate removal efficiency usually (but not always) increases as the static pressure drop increases.

Figure 5.4. Venturi Scrubber Throat

Static pressure drops in the range of 30 to 50 inches of water are usually required to achieve high-efficiency removal of particulate matter generated by combustion systems. Even higher static pressure drops may be needed if a large quantity of the particulate matter is in the 0.1 to 0.5 micrometer range, which is especially difficult to capture by inertia and Brownian displacement in the venturi throat.

The liquid recirculation rate needed for effective particulate removal is in the range of 15 to 76 L (4 to 20 gal) per thousand ACFM. A liquid recirculation rate of 38 L (10 gal) per thousand ACFM has been found to be optimal for a wide variety of adjustable throat venturis.

Several practical problems can limit the performance of the venturi scrubber. Poor liquid distribution across the inlet of the venturi throat can create dry zones. Particles passing through these dry zones cannot be captured since there are no water droplets to serve as impaction targets. Once the gas stream exits the throat (approximately 0.002-second treatment time), the droplets and particles are moving at the same velocity, and impaction is no longer possible. Accordingly, particles passing through a dry zone usually will not be captured. If even one percent of the throat remains "dry," the scrubber system may not achieve its performance requirements. Venturi scrubbers with poor liquid distribution conditions can have dry zones that represent more than 10% of the inlet area.

A similar gas-liquid maldistribution problem can occur because of the physical erosion and chemical corrosion of the throat dampers. Even though they are constructed of erosion-resistant materials, it is difficult to withstand the 46- to 116-m/s (100- to 250-mph) particle-laden gas stream.

The presence of corrosive compounds such as HCl and HF would accelerate damage to the throat dampers. These dampers must be inspected and replaced whenever the static pressure drop data shifts from baseline conditions.

Gas-liquid maldistribution can also be created by a poor inlet duct configuration, by poor recirculation liquid supply header design, by poor liquid spray nozzle/injection pipe design, or by the accumulation of solids at the point where the liquid is introduced into the scrubber (termed the "wet-dry line"). All of these problems can be minimized by purchasing a system from an experienced scrubber manufacturer.

The recirculation liquid must have a pH between approximately 6 and 9 to avoid a variety of operating problems. Below a pH of 6, the dissolved chlorides and fluorides are extremely corrosive. Above 9, calcium and magnesium compounds dissolved in the liquid precipitate out in the piping, supply headers, recirculation tanks, mist eliminators, and other parts of the scrubber system. These deposits would adversely affect particulate removal efficiency and would eventually create the need for an extended maintenance outage. Removal of the deposits would be labor intensive and involve close contact with the radionuclide-containing solids. Proper pH levels can be maintained by proper pH monitoring of the recirculation liquid stream.

Collision-Type Particulate Scrubber

A collision scrubber is simply two venturi throats in an opposed arrangement. The inlet gas stream is split and sent to the two venturis. The gas stream exiting one of the venturi sections collides with the gas stream leaving the other venturi. This provides a second opportunity for particle impaction into water droplets.

The collision scrubber uses a gas recirculation system to maintain adequate velocities in the throat. Accordingly, it does not have adjustable throat dampers. However, this does not mean that it is free of routine maintenance problems. The gas recirculation fan and dampers must be inspected and repaired routinely.

The remainder of the scrubber system is virtually identical to the adjustable throat venturi described above.

Hydrosonic Scrubber

There are actually four different types of units sold under this name:

- fan drive
- fan drive tandem nozzle

- supersub fan/ejector drive
- steam or air ejector drive.

They have different gas velocities and liquid injection velocities. The throat portion of a hydrosonic scrubber is shown in Figure 5.5.

Inertial impaction of particles into liquid droplets occurs in the area immediately downstream of the liquid injection system. The liquid is injected through a ring of nozzles around the gas inlet. The high-velocity gas stream atomizes the liquid, which then serve as impaction targets. The particle-containing droplets are then removed in a mist eliminator (not shown).

The static pressure drop levels and liquid-to-gas ratios used in free jet scrubbers are similar to those used in adjustable throat venturis.

Wet Ionizing Scrubbers

These units collect particulate matter primarily by electrostatic forces. The particles in the gas stream are electrically charged as they pass through the short gas passages in the preionizer section. This section consists of a set of vertical discharge wires suspended between electrically grounded discharge plates. A voltage of 20 to 25 kV is applied to the discharge electrodes. The particles are charged with negative ions created in the coronas on these discharge electrodes. A typical wet ionizing scrubber is shown in Figure 5.6.

Figure 5.5. Hydrosonic Scrubber

It should be noted that wet ionizing scrubbers are usually constructed of fiberglass-reinforced plastics (FRP). This may not be desirable for radioactive service since FRP can burn readily if there is a severe gas temperature surge. This could eliminate containment of the radionuclides. It would be possible to construct these units out of metal. However, this would be considerably more expensive than the standard units. Furthermore, these units would be vulnerable to corrosion because of the dissolved chlorides and fluorides and the presence of the captured particulate radionuclides.

One of the main advantages of this type of scrubber is the relatively low static pressure drop. Typical static pressure drops are in the range of 4 to 10 inches of water. The liquid-to-gas ratios are usually in the range of 10- to 20-gallons per thousand ACFM.

The acid gas removal efficiencies can be very high.

Particulate removal efficiencies are usually greater than 99% for particles larger than 1 micrometer and are in the range of 50% to 95% for particles in the 0.5- to 1-micrometer size range. If necessary, several wet ionizer modules can be used in series to increase the overall particulate removal efficiency.

The electrically charged particles enter a conventional packed-bed scrubber. As the charged particles pass around the wetted packing, they induce an opposite electrical charge in the polar water layer. Accordingly, the particles are attracted to and captured by the water layer on the packing. The packed bed is also used for the removal of soluble acid gases such as HF, HCl, HI, and SO₂.

Figure 5.6. Wet Ionizing Scrubber

Ejector Scrubbers

A typical ejector scrubber vessel is shown in Figure 5.7. This type of scrubber has a venturi section with a high-pressure liquid spray nozzle. The low-pressure area around the high-velocity liquid stream induces gas flow through the unit. This type of scrubber usually creates a negative pressure of 1 to 3 inches of water. Liquid-to-gas flow ratios are usually in the range of 5 to 30 gallons per thousand ACFM. Liquid spray pressures can be over 80 psig.

Particles are captured by impaction on the high-velocity droplets in the liquid stream. The droplets are captured in the downstream area of the ejector scrubber vessel and/or a mist eliminator (not shown in Figure 5.7) downstream of the scrubber.

One of the main disadvantages of this type of scrubber is the energy requirements for the pump. The pump is subject to severe physical erosion and chemical erosion if the scrubbing liquid must be recirculated. The service life of the ejector spray nozzle is also limited because of erosion and corrosion.

Ejector scrubbers are usually used as gas absorbers on gas streams having particulate levels of relatively low concentration.

Figure 5.7. Ejector Scrubber

Condensation Growth Pretreatment

Submicrometer particulate matter generated by the melters is difficult to collect since it is not subject to strong inertial forces even in high-velocity gas streams. The collection efficiency for these particles can be increased by the heterogeneous condensation of water on the particle surfaces. Water-coated particles are collected more efficiently because of their increased mass.

Condensation growth can be achieved by cooling the high water vapor content (20% to 70%) off-gas streams in a spray tower scrubber, packed bed scrubber, or other contacting vessel. The scrubber is essentially being used for heat transfer from the gas stream to the liquid stream. To achieve outlet gas temperatures below the adiabatic saturation temperature, the recirculated liquid stream is cooled in a heat exchanger or cooling tower to remove sensible heat from the liquid stream. The outlet gas temperature is usually in the range of 100°F to 120°F.

Alternatively, condensation growth can be achieved by injecting steam into the gas stream. The gas stream is then cooled rapidly to cause the water vapor to heterogeneously nucleate on the surfaces of the submicrometer particles. Steam injection systems usually require between 0.5 to 1.0 pounds of steam per pound of off-gas treated. Accordingly, it is necessary to have a relatively large steam source.

5.2.4 High-Efficiency Particulate Filtration (HEPA)

High-efficiency particulate filtration (often termed HEPA) units are used to minimize radionuclide emissions. At least two separate HEPA units are installed in series at the end of the off-gas treatment system to capture radionuclides in particulate form. Each of the filtration units must have a rated efficiency exceeding 99.97% for the most difficult-to-collect particles (0.3 micrometer diameter particles). There are three main types of HEPA filters: 1) conventional panel filters, 2) sintered metal filters, and 3) sand filters.

Conventional Panel Filters

Conventional panel filter-type HEPA units are used extensively in the nuclear industry and in other applications in which ultraclean air is required. They are extremely effective; however, they cannot be cleaned and the panel filters must be disposed of when loading produces an unacceptably high pressure drop to protect against rupture. Changing out the filters frequently is undesirable because of worker exposure, downtime, cost, and secondary waste generation. The maximum recommended dust content of the gas to be treated is 3 mg/m³ (0.0013 gr./ft³). The maximum dust loadings of the filters are approximately 10 to 15 pounds of dust for a 2-foot by 2-foot panel filter (Dalton et al. 1992). Change-out of panel-type HEPA filters is prescribed when accumulated dust exceeds a dose threshold or when the pressure drop across them becomes too high (3 - 6 inches of water) (Dalton et al. 1992). The HEPA panel filters can fail mechanically if the pressure drop exceeds approximately 16 inches of water (Schmel 1990). Pressure drops are relatively low (1 to 1.5 inches of water when new).

Panel filter-type HEPA filters are made of a pleated paper composed of nonwoven glass fibers 1 to 4 microns in diameter. They are held in housings with seals. Stainless steel and carbon steel frames are often used for the panel filters (IAEA 1989, Dalton et al. 1992). Typical face velocities range from 0.77 to 2.6 m/s. (150 to 500 ft/min) (Dalton et al. 1992, Schmel 1990).

The maximum operating temperature is limited to approximately 121°C (250°F) (Dalton et al. 1992). However, acid-resistant and high-temperature [up to 282°C (540°C)] fibers and seals are available.

Up to 95% humidity can be tolerated, but water droplets cannot since these would blind the filtering surface. For this reason, mist eliminators are routinely installed in front of HEPAs as well as heat exchanges to raise the temperature of the gas well above its moisture dewpoint [usually 66°C to 82°C (150°F to 180°F)].

HEPA filters must be discarded and are thus a source of secondary waste. It may be possible to vitrify them. Because they are critical to the purity of the off-gas leaving the plant, HEPAs require careful installation and monitoring.

The HEPA units should include test ports for the use of tracer gas to evaluate each filter unit. There should also be a detector in the outlet ducts to check for leakage around the HEPA panel filters or through pinholes in the HEPA unit.

High-Efficiency Metal Fiber (HEMF) Filters

HEMFs have recently been developed as a cleanable, reusable alternative to HEPAs. These filters are made of sintered metal fibers with pore sizes as low as 0.5 microns (Mott Metallurgical 1993). In addition to being cleanable, they have high abrasion resistance, are nonflammable, are radiation resistant, and have extremely wide operating ranges for pressure drop and temperature. Particle removal efficiencies meet those of HEPAs. The initial cost for such filters is higher than for HEPAs, but since they are reusable, the long-term costs may be less.

Sand Filters

Sand filters use multiple layers of sand with a gradation of sizes from the inlet to outlet (Schmel 1990). The advantages of sand units include low maintenance cost, inertness to chemical attack, and flexibility regarding pressure or temperature fluctuations (Schmel 1990). The disadvantages include a high static pressure drop, uncertain service life of the sand, high capital cost, large size, and high sand disposal cost. No information was found demonstrating that sand filters have high particulate removal efficiencies in the difficult-to-control size range of 0.1 to 0.5 micrometers.

Because of the scale of the equipment, sand filters would be difficult to use in this type of off-gas treatment system. Furthermore, the entire sand bed would have to be disposed as hazardous waste once there is sufficient particulate buildup to increase the static pressure drop across the sand filter.

5.3 Acid Gas Control.

Several acid gases will be present in the melter off-gas, including hydrofluoric (HF), hydrochloric (HCl), and iodic (HI) acids. When exposed to water, the SO_3 and NO_2 in the off-gas form sulfuric (H_2SO_4) and nitric (HNO_3) acids, respectively. Sulfuric acid will form to a lesser extent even in the absence of condensed water because of the presence of catalytic metals (iron, manganese) in the off-gas. Phosphoric acid (H_3PO_4) probably will be present as well.

Acid gases are removed by both wet or dry scrubbers. In a wet scrubber, the alkaline liquid is kept at a pH between 6 and 9 for most effective removal of acids. The efficiency of acid gas removal is dependent on the gas-liquid mixing and the gas phase concentration of the acid gas compound. The solubility of the compound in a high pH liquid and the rate of dissociation of the acid gas compound in the liquid also affect removal efficiency. In the case of the various halogen compounds, the efficiency of HI removal will be slightly lower than that for HCl and HF because of its rate of dissociation in the liquid phase. Acid compounds are converted to salts in the scrubbing liquid.

Retention depends on melter type; however, little data are available for the various melters currently considered for the LLW plant. Data (Wilson 1994) show that for an LFCM, the decontamination factors (DFs) are approximately those shown in Table 5.2. Vortec (Vortec 1993) figures indicate a DF of unity for nitrogen in a combustion-type melter. No data for other elements or for other melter types are available. Vendor tests should include analyses for these elements in the glass and off-gas in order to determine their DFs. Melter selection should reflect retention of these acid-gas forming elements since improved retention leads directly to a less costly off-gas treatment system.

Iodine and nitrogen (which appear in the waste as nitrite and nitrate ions) are not significantly retained in the glass by an LFCM, though some fraction of the nitrogen may be converted to N_2 . For a combustion-type melter, potentially none of these elements will be retained. While nitrogen and sulfur oxides could be treated by the technologies discussed in this report, treatment of the halogens would be more difficult. The purged scrubbing liquid cannot simply be discarded because of the radionuclides. To remove the halogens, a portion of the acid gas control system waste stream would have to be removed, treated, and disposed as a hazardous-radioactive waste.

All of the acid gases and vapors can be controlled in either absorbers or dry scrubbers. Common types of systems are listed below.

Absorbers

- Spray towers
- Impingement tray

Table 5.2. Decontamination Factors for a Liquid-Fed Ceramic Melter and a Combustion-Type Melter

Element	Decontamination Factor	
	LFCM ^(a)	Combustion Melter
Cl	4	— ^(b)
F	4	— ^(b)
I	1	— ^(b)
S	10	— ^(b)
N	1	1 ^(c)
P	50	— ^(d)
(a) Perez et al. 1993. (b) Unknown; assumed = 1. (c) Vortec 1993. (d) Unknown; assumed = 50.		

- Packed beds

Dry scrubbers

- Spray atomizer dry scrubbers
- Dry injection dry scrubbers

In addition to controlling the halogen acid gases and vapors, these systems can simultaneously collect sulfur dioxide. The operating characteristics of each of these acid gas control systems are discussed briefly in the sections below.

Spray Towers

A spray tower absorber is an open chamber with an array of spray nozzles. The absorbing vessel can be arranged either horizontally or vertically. The superficial gas velocity is usually kept below 10 feet per second to allow time for absorption of the pollutants and to avoid re-entrainment of the droplets. The liquid-to-gas ratios vary from 38 to 189 L (10 to 50 gal) per thousand ACFM, depending on the solubility of the contaminants, the extent of contaminant reaction in the liquid phase, the liquid temperature, and the required contaminant removal efficiency. Approximately 5% to 10% of

this recirculation liquid flow must be purged from the absorber system to maintain reasonable solids levels and dissolved contaminant concentrations in the recirculation liquid.

One of the main advantages of spray tower scrubbers is that they are not highly vulnerable to scaling. The main disadvantage is that they use relatively large quantities of scrubbing liquid. They are usually not as efficient as other types of absorbers.

Impingement Scrubbers

An impingement tray scrubber is shown in Figure 5.8. The scrubber consists of a vertical vessel with two or more horizontal trays. The trays have several .48-cm to .635-cm (3/16-in. to 1/4-in.) holes to permit the gas to pass through. Scrubbing liquid flows across each of the trays. Weirs and downcomers are used to direct the liquid flow through the absorber and prevent the gas stream from

Figure 5.8. Impingement Tray Scrubber

shortcircuiting around the trays. As the gas stream passes through the small orifices in the trays, the water above the tray is atomized and entrained. Mass transfer occurs from the gas stream to the droplets formed above the tray.

The liquid-to-gas ratio used in impingement tray scrubbers varies from 2 to more than 20 gallons per thousand ACFM. The quantity of water depends on the liquid temperature, the pollutant concentrations, and the required control efficiencies. Approximately 5% to 20% of this recirculation liquid flow rate is purged to a wastewater treatment system to minimize solids levels. The small-diameter orifices through the trays plug quickly if the suspended solids levels exceed approximately 0.5% by weight.

The liquid depths on the trays vary from 1 inch to 1.5 inches. Depth is controlled by overflow weirs on the feed side and downcomer side of the trays.

One of the main advantages of impingement tray absorbers is that they have relatively high acid gas removal capability combined with moderate particulate removal capability. Acid gas removal efficiencies can exceed 99%. Particulate removal efficiencies for material larger than one micrometer are also above 99%. However, impingement tray absorbers are not highly efficient for particles in the submicrometer size range.

These high particulate and acid gas removal efficiencies can only be achieved if the gas-liquid distribution is uniform. Maldistribution problems can be caused by sloped trays, bowed trays, and partially plugged trays.

Packed Bed Scrubbers

Packed bed scrubbers have also enjoyed popularity in vitrification practice, particularly the SBS. In these scrubbers, particle-laden off-gas is sent into a tower containing a packing material with co-current (as in the SBS) or countercurrent liquid flow. Particles are lost to the liquid phase as the gas traverses the packing. Gas quenching is also provided by these scrubbers. Submerged bed scrubbers have been operated at inlet gas temperatures up to 570°F at PNL.

One disadvantage of the conventional packed beds is their vulnerability to pluggage. However, this is not a common problem with submerged bed systems. The disadvantage of the submerged bed designs is the relatively high static pressure drop of 30 to 40 inches of water.

Spray Atomizer-Type Dry Scrubbers

This type of dry scrubber uses a finely atomized alkaline slurry to absorb the acid gases. The slurry has a solids content that can vary from 5% to 20% (Donnelly et al. 1986, Ferguson et al. 1986, Sedman and Bina 1987). The slurry droplets are evaporated to dryness and then collected in a fabric filter or electrostatic precipitator. Additional acid gas removal continues even after the droplets are

fully dried. Chemisorption occurs on the dried particles as they are transported to the fabric filter and as they remain in the dust cake on the fabric filter bags.

Calcium hydroxide ($\text{Ca}(\text{OH})_2$) is the most common alkali used since it is relatively inexpensive and easy to handle. However, other alkali materials could conceivably be used. Calcium hydroxide is added at a rate equivalent to 1.5 to 2.0 times the stoichiometric requirement. The excess calcium hydroxide is needed since a portion of the material is not used efficiently.

The calcium hydroxide feed rates are minimized by recycling a portion of the solids from the fabric filter and all of the solids collected in the bottom of the spray dryer vessel. Recycling of the partially reacted alkali is difficult since a number of hygroscopic compounds, such as calcium chloride, are present in the solids as reaction products.

There are two means of atomizing the calcium hydroxide slurry: 1) high-pressure spray nozzles, and 2) rotary atomizers. The high-pressure nozzles operate at pressures ranging from 60 to more than 100 psig. Both high-pressure liquid and air-assisted nozzles are used. Rotary atomizers are mechanically complex spinning disk-type systems operating at 10,000 to 17,000 rpm. They are usually not economical for the relatively small-scale gas flow rates anticipated for the melter.

The spray dryer absorber vessels must be very large to ensure the slurry particles completely evaporate to dryness. The gas residence times vary from 6 to 20 seconds (Donnelly et al. 1986, Ferguson et al. 1986).

The main operating problem associated with spray atomizer-type dry scrubbers is the failure to completely dry the particles before they exit the spray dryer vessel. The moist, sticky particles can quickly accumulate in the spray dryer vessel and cause an unscheduled shutdown of the entire off-gas treatment system. To avoid this problem, spray dryer absorbers are usually operated with exit gas temperatures 20°F to 50°F above the moisture dewpoint. It is also important to have relatively hot inlet gas temperatures since the sensible heat of the inlet gas stream is the source of energy used to evaporate the slurry droplets to dryness.

A portion of the solids collected in the fabric filter would have to be treated and disposed as hazardous-radioactive waste. This would be necessary to purge the off-gas treatment system of halogens and other absorbed materials with DFs of unity in the melter.

Dry Injection Scrubbers

This type of dry scrubber uses finely divided alkali particulate for the chemisorption of acid gases. The dry material is usually at least 90% less than 325 mesh (74 micrometers) (Foster et al. 1987). The injection rate of the alkali is usually 3 to 3.5 times the stoichiometric requirement (Foster et al. 1987, Moller and Christiansen 1985). This high addition rate is needed since a large fraction of the alkali is trapped with the particle and is not available for the adsorption of acid gas vapors. Calcium hydroxide is the most common alkali used in dry injection scrubbers.

Because of the temperature sensitivity of the adsorption step, the inlet gas temperature must be maintained at approximately 250°F. A heat exchanger may be needed to achieve this low gas temperature.

The main advantage of this system is low capital cost. There is no need for a large and expensive spray dryer vessel. The main disadvantage is the high operating cost associated with purchasing the alkali and disposing of the incompletely reacted material.

The acid gas removal efficiencies for both spray atomizer and dry injection dry scrubbers are usually more than 99%. The removal efficiencies for sulfur dioxide are usually 60% to 90%. Spray atomizers are more efficient than dry injection scrubbers for sulfur dioxide.

5.4 Mist Eliminators

Mist eliminators are used to remove entrained water droplets that could overload or blind downstream equipment in the off-gas treatment system. There are two categories of mist eliminators: 1) conventional, and 2) high efficiency.

5.4.1 Conventional Mist Eliminators

Conventional mist eliminators are used to collect the 100- to 1000-micrometer droplets formed in most types of particulate wet scrubbers and acid gas absorbers. They use inertial impaction for droplet collection. The types of conventional mist eliminators include

- cyclonic vessels
- rod decks
- multi-pass chevrons
- mesh pads
- fiber beds.

The cyclonic vessels have a tangential gas inlet. These are rarely used on modern systems since they are large, expensive, and relatively inefficient. They are moderately effective only when the gas flow rate is within 80% to 110% of the design capacity.

The other types of mist eliminators provide good removal efficiencies for large droplets. However, it is important to maintain the gas velocities through the unit below the maximum rated levels. These maximum velocities range from 7 feet per second to 20 feet per second, depending on the type and design of the mist eliminator.

High localized velocities are often caused by the partial pluggage of the mist eliminator elements. This can be caused primarily by precipitation of solids from the scrubber droplets. These deposits may be routinely flushed from the mist eliminator using a set of intermittently operated spray nozzles. Clean water is usually used in these nozzles to ensure complete solids removal. Mist eliminators are usually cleaned at least once per shift. Cleaning may be needed much more frequently in some systems. It can be initiated by a timer or by a differential pressure sensor across the mist eliminator.

Typical static pressure drops across conventional mist eliminators are 0.5 to 4 inches of water. High static pressure drops usually indicate partial pluggage. If this condition is not corrected, the static pressure drop can increase to the point that the gas flow from the melter is reduced or the mist eliminator fails mechanically.

Most conventional mist eliminators are constructed of fiberglass-reinforced plastic or other synthetic material. Many of these use glues to retain the mist eliminator elements in the mounting frames. The ability of these synthetic materials and glues to withstand the radionuclides should be carefully evaluated.

5.4.2 High Efficiency Mist Eliminators

The conventional mist eliminators are not effective for small-diameter (< 10 micrometer) droplets formed by atomization or nucleation in the scrubber or absorber. These small droplets include water, condensed organics, and condensed acids. These droplets can blind and/or corrode the HEPA filters used at the discharge end of the off-gas treatment system. The droplets can be collected efficiently using a high efficiency mist eliminator (HEME).

In a HEME, the gas stream passes through a series of concentric screens holding a packing of randomly oriented fiberglass or polypropylene fibers. The filter elements are usually 2 feet in diameter and 6 to 8 feet long. The droplets are collected by inertial impaction as the gas stream moves through the densely packed filter element. The droplets coalesce and drain into the sump at the bottom of the HEME. This type of mist eliminator has efficiencies exceeding 90% even for submicrometer droplets. The removal efficiencies for droplets in the 1- to 10-micrometer size range exceed 99%. The static pressure drop varies from 4 to 20 inches of water, depending on the specific type of filter element and the available superficial velocity through the filter. The face velocities are usually less than 5 feet per minute.

The HEME provides a "back-up" collector for submicrometer particulate penetrating a scrubber. However, high particulate concentrations in the gas stream can blind the filter element since there is no means for completely removing the solids with the spray nozzles used for routine cleaning.

As in the case with conventional mist eliminators, the materials of construction for the filter element should be selected to be compatible with the radiation levels in the liquids collected.

5.5 NO_x Reduction

Prevention of significant deterioration (PSD) limits specify annual NO_x emissions from the site of less than 40 tons per year. Current estimates for NO_x in the gases vented by the melter range from 10,000 to 50,000 ppm and from 10 to 20 tons per day. Therefore, without obtaining special exemptions, removal efficiencies for NO_x may need to exceed 99%. The potential to emit large quantities of NO_x will almost certainly trigger BACT requirements.

Some melters may convert part of the nitrates and nitrites in the waste to molecular nitrogen. If that capability can be verified by a melter vendor, it would be a favorable factor in selecting a melter of that type.

The redox potential of the waste can be altered by adding materials such as sugar. No such additives were assumed in the calculations of the off-gas content in Tables 2.1 and 2.2 of this report. Reductive additions would be quite favorable from the perspective of off-gas treatment.

There are currently three widely used technologies for NO_x control for fossil fuel-fired boilers, waste incinerators, and gas turbines: 1) selective catalytic reduction (SCR), 2) selective noncatalytic reduction (SNCR), and 3) natural gas reburn. It is likely that one or more of these will need to be applied to control the very high NO_x emissions from the melter.

5.5.1 Selective Catalytic Reduction

Selective catalytic reduction systems use ammonia or urea to chemically reduce NO_x to molecular nitrogen. They typically achieve reduction efficiencies exceeding 90% (Kokkinos et al. 1992). Ammonia is prepared either as an aqueous solution or as a dilute gaseous mixture. The dilute gas mixture is usually 3% to 5% by volume ammonia. The ammonia-containing stream is then injected into the flue gas through an array of nozzles to obtain a uniform mixture of the ammonia in the gas stream. As the mixture passes through the reactor, the catalyst facilitates the chemical reaction between NH₃ and NO_x to produce nitrogen and water. The principal chemical reactions which occur when ammonia is used as the reducing agent are listed below.

The catalysts use noble metals deposited on an alumina substrate. They are usually prepared in a honeycomb arrangement and can be arranged for either horizontal or vertical gas flow, depending on the particulate loadings and size distributions in the gas stream [Makansi 1993, Donnelly and Brown 1989, Durilla et al. (date unknown)].

System performance depends on the following factors:

- flue gas temperature
- residence time
- NO_x concentration
- NH₃ injection rate
- gas mixing efficiency
- catalyst activity.
- catalyst quantity (cells per inch).

Ammonia injection can be controlled automatically to account for variations in inlet NO_x concentrations. Operating temperatures usually range from 550°F to 700°F (Donnelly and Brown 1989). However, higher temperatures will be possible once new catalysts being developed become commercially available.

High temperatures can damage the catalyst. Because of the exothermic nature of nitrogen oxides reduction, it may be necessary to include heat exchangers between the first and second SCR modules in series to remove the heat generated. The need for the SCR depends on the inlet concentration of nitrogen oxides released by the vitrification system.

At low gas temperatures, the nitrogen oxides reduction efficiency decreases. Ammonium bisulfate and ammonium sulfate can also form at low operating temperatures. This can cause scaling of the catalyst bed and scaling of downstream equipment in the off-gas treatment system.

Static pressure drop through the SCR vessel and catalyst bed usually ranges from 4 to 10 inches of water. This depends primarily on the design of the catalyst and the residence time of the gas stream in the catalyst.

One of the main disadvantages of the SCR approach for NO_x control is the vulnerability of the catalyst to phosphorus (Makansi 1993) and other elements potentially present in the off-gas stream. Phosphorus can cause irreversible poisoning of the catalyst. If this happens, the catalyst unit must be replaced. A number of other elements and compounds in the off-gas stream could potentially mask the catalyst bed and thereby reduce its activity. These materials can be removed by manually washing the catalyst bed with alkaline and/or acid wash solutions. Before selecting an SCR system for the off-gas treatment system, a complete evaluation should be made of all the elements potentially in the off-gas stream. This is necessary so that the SCR manufacturer and the catalyst supplier can determine if the unit will be able to maintain reasonable activity for NO_x reduction.

The ammonia is usually injected at a rate equivalent to approximately 90% of the stoichiometric rate (Kokkinos et al. 1992). This is necessary to avoid ammonia slip (emission), which can cause a high opacity plume in fossil fuel boiler and waste incinerator applications. However, in the case of the melter, the SCR unit will be upstream of a particulate scrubber or acid gas absorber. Any unreacted ammonia will be efficiently collected in this unit. Accordingly, it should be possible to use ammonia injection rates that are equal to or above the stoichiometric levels. This should allow for higher NO_x control efficiencies than in other types of applications.

It should be noted that the ammonia feed preparation system has not been included on the flow-charts presented earlier in this report. If anhydrous ammonia is being used, there must be a storage vessel for the ammonia and a hot carrier gas stream. The ammonia is usually diluted to a concentration less than 25% of its lower explosive limit to avoid explosion hazards. Also, it is necessary to have an emergency scrubber to ventilate the ammonia storage area in case the storage vessel develops a leak or ruptures.

In the case of aqueous ammonia preparation systems, the ammonia preparation system is relatively simple. The material is stored in an aqueous form and is fed directly to the SCR unit at a rate dependent on the NO_x concentration. No emergency scrubber is needed in this case.

SCR systems can also be operated with urea. The urea is fed to the gas stream as an aqueous solution. The feed preparation system for urea is analogous to that for aqueous ammonia.

One of the primary advantages of an SCR system is the high removal efficiency. SCR processes generally operate in excess of 90% removal of NO_x and can operate up to 98% efficiency if units are used in series. Because of the high removal efficiencies, the SCR process is generally considered a "best available control technology" (BACT). However, it should be noted that SCR units have never been applied on a gas stream with as many potential masking agents and poisons as the melter off-gas stream. Accordingly, it may be difficult to achieve the removal efficiencies that have been observed in other types of SCR applications.

The disadvantage of SCR systems is the high catalyst cost. The high catalyst cost leads to a much higher initial capital cost and to higher operating costs because of catalyst replacement. Replacement frequency is affected by the specific catalyst used as well as the operating conditions (masking agent and poison concentrations, temperature, NO_x concentration). Due to the presence of a variety of potential catalyst poisons in the off-gas stream, it is unlikely that the catalyst will have a service life exceeding one year. Advanced catalysts are being developed that do not use noble metals and are therefore much less expensive. These will probably be commercially available by the time the full-scale melter is built.

SCR units can generate several wastes. Nitrous oxide (N_2O), considered a greenhouse gas, is an undesirable reaction product formed during the reduction reactions. SCR units can also generate ammonium bisulfate and ammonium sulfate from the reaction of ammonia with vapor phase sulfuric acid.

The spent catalyst is considered a hazardous waste. In other applications, this catalyst is returned to the SCR manufacturer for recovery of the valuable catalysts. Returning the catalyst would not be possible in the case of the melter system since radionuclides would be present.

5.5.2 Selective Noncatalytic Reduction

Selective noncatalytic reduction systems use essentially the same approach as SCR systems, i.e., reacting NH_3 with NO_x to form molecular nitrogen and water. The reaction is a homogeneous, gas phase reaction, however, and no catalyst is required. The following are typical SNCR reactions.

As with SCR, other reducing agents such as urea are also used. However, ammonia is the most commonly used reducing agent. The reactions work only in the 871°C to 1093°C (1600°F to 2000°F) range (Hastings and Schaefer 1980, Pachaly et al. 1991, Jones et al. 1990, Makansi 1990). At temperatures above 1093°C (2000°F), NH_3 may react with oxygen to produce additional NO, making the reducing compounds counterproductive. At temperatures below 871°C (1600°F), ammonia does not react and is emitted with the off-gas stream (Hastings and Schaefer 1980).

SNCR systems remove 20% to 60% of the NO_x at inlet NO_x concentrations of 150 to 300 ppm when ammonia is injected into the flue gas in the proper temperature range (Kokkinos et al. 1992). No information has been found for the performance of SNCR systems at the extremely high concentrations expected from the LLW vitrification facility (10,000- to 50,000-ppm NO_x).

To reduce NO_x efficiently, the ammonia must be uniformly mixed into the gas stream at a point in the process where the gas temperature is in the necessary range. Several sets of injection nozzles are used for this purpose. Temperature sensors are used to select the most appropriate set of nozzles for ammonia injection.

The main factors that determine the removal efficiency of SNCR are the same as those for SCR:

- flue gas temperature
- ammonia-gas stream distribution
- NH_3 injection rate
- residence time in the necessary temperature range
- NO_x concentration.

Ammonia is usually injected at a rate below stoichiometric requirements. However, this may not be necessary in the melter off-gas treatment system since an absorber downstream will capture any unreacted ammonia.

The low initial cost of noncatalytic reduction systems makes them attractive. As there are no catalysts that could be poisoned by off-gas contaminants, the maintenance requirements are relatively low.

The primary disadvantage of this system is that it is typically only 20% to 60% effective in reducing NO_x . Furthermore, these efficiencies are obtained only when the gas temperature at the injection point is in the 1600°F to 2000°F range:

Essentially no secondary wastes are generated by this process. However, N_2O can form in some cases (Kokkinos et al. 1992). In practice, a small portion of the ammonia may pass through the system unreacted.

5.5.3 Natural Gas Reburning (Nonstoichiometric Firing)

Natural gas reburning (reburn) is a fuel-rich combustion process. Burner combustion air is fired at a rate equivalent to 0.9 to 1.0 of the stoichiometric requirement (Kokkinos et al. 1992). Overfire air is used to complete the oxidation of the organics formed in the burner flame. As the natural gas burns, the NO_x is reduced to molecular nitrogen by organic free radicals generated in the burner flame.

Reburn systems used on oil and coal-fired boilers generally provide 50% to 70% reduction efficiencies for NO_x [Gas Research Institute (undated), U.S. EPA 1992]. No systems have been operated at the very high NO_x concentrations anticipated in the melter system. It is anticipated that performance of a reburn unit on the melter would be less efficient than for other applications since there are safety limits regarding the extent of off-stoichiometric firing conditions that could be maintained. An explosion could occur if the burner is operated in an excessively fuel-rich condition.

As with SNCR, reburn is a relatively low-cost technology. Operating the reburner during melter downtime would allow the rest of the off-gas train to remain at operating temperatures, reducing the detrimental effects caused by cycling.

The disadvantages of reburn to reduce NO_x emissions include possible low efficiencies for high NO_x concentrations and the combustion air flow and heat load added to the off-gas stream.

5.6 Sulfur Dioxide Control Systems

Site PSD limits for annual SO_x emissions are 40 tons per year. Current estimates for SO_x emissions from the LLW melter are between 40 and 140 ppm and up to 95 tons SO_2 per year. To exceed the PSD standards, at least 60% of the SO_x must be removed, either in the melter or in the off-gas treatment system. If there are other SO_x -generating processes on site, the removal efficiency will

need to be even greater. These estimates are well within the typical operating parameters of standard SO_x control technologies and should not be a major concern.

Some of the SO_x will likely be removed by other processes in the off-gas train such as cooling towers and scrubbers for particulates and acid gases. Moreover, depending on melter type, sufficient sulfur may be retained by the glass to eliminate the need for a SO_x treatment stage. As shown in Table 5.2, LFCMs have a sulfur DF of about 10, which would bring emissions below the regulatory limit even before they reach the wet scrubbing stages. Additional sulfur scrubbed out of the off-gas could simply be returned to the evaporators and ultimately to the melter. If the glass does not retain any sulfur, however, sulfur in scrub liquids would need to be treated to avoid merely cycling the sulfur between the melter and off-gas systems.

Using a separate process to eliminate residual SO_x will generate considerable amounts of secondary waste (either liquid or solid). Melter choice and performance will affect the cost of equipment and, potentially, of secondary waste disposal.

Industry uses a wide variety of flue-gas desulfurization processes. These processes are generally classified as wet or dry scrubbers (absorbers) and can be either regenerable or nonregenerable. Many of these systems achieve over 90% removal of SO_x . The most common wet and dry scrubbing techniques are described in detail below; less common techniques are mentioned briefly.

5.6.1 Lime or Limestone Nonregenerable Systems

The most common wet scrubbing system uses lime or limestone to absorb SO_2 . The process is nonregenerable, which means the scrubbing materials are not recovered and sulfur dioxide is not converted into a salable product. The overall reactions are those of SO_2 with lime (CaO) or limestone (CaCO_3) to form calcium sulfite (CaSO_3), with some oxidation of the sulfite to form calcium sulfate (CaSO_4).

The calcium sulfite and sulfate crystals precipitate in a reaction vessel or hold tank designed for solids precipitation and dissolution of the alkaline additive. The hold tank effluent is recycled to the scrubber to absorb additional SO_2 . A slipstream from the hold tank is sent to a liquid-solid separator to remove the precipitated solids from the system.

Additives such as MgO , Na_2CO_3 , and NH_3 can be used to improve performance, improve reliability and operating flexibility, and reduce costs for new and existing flue gas desulfurization (FGD) systems.

A major advantage of nonregenerative lime or limestone scrubbers is that they are a relatively simple design. The primary disadvantage is that large amounts of secondary waste are generated in the form of sludge.

5.6.2 Copper Oxide Process

The copper oxide process is a dry, regenerable process that removes SO_2 from the flue gas using CuO and can be used to produce byproduct sulfur (Martin 1981, Yeh et al. 1987). The CuO reacts with SO_2 according to the mechanism shown below.

The copper is then regenerated and SO_2 is evolved by passing a reducing gas, usually hydrogen, over the copper sulfate. Passing the exhaust-reducing gas through a Claus reactor produces commercial-grade sulfur as a byproduct.

The process can also remove NO_x when NH_3 is added. The NH_3 reduces NO over CuO or CuSO_4 according to the following reaction.

The process can achieve 90% removal of SO_2 regardless of inlet SO_2 concentrations. The system operates at about 750°F.

The primary advantages of the CuO process are that it can be used for simultaneous SO_2 and NO_x removal, and it can produce valuable byproducts. Radiological concerns make it unlikely that any of the byproducts produced by using this process on the Hanford Site could be marketed. However, sulfur may be used to encapsulate the glass produced by the melter. If that is not feasible, the byproducts would most likely be disposed of as radioactive waste. The disadvantages of the CuO process are that it is very complex, very expensive, and requires hydrogen.

5.6.3 Other Sulfur Dioxide Scrubbing Technologies

The dual alkali and Wellman-Lord processes are also common wet scrubbing techniques. The dual alkali process is a regenerable process that consists of scrubbing the SO_2 with a sodium solution, then contacting this solution in an external reactor with a calcium solution to produce a calcium sludge. The Wellman-Lord process is also a regenerative process. In this process, SO_2 is absorbed and reacted with a sodium sulfite solution to produce sodium bisulfite. Thermal decomposition causes the reaction to reverse, producing a rich SO_2 stream that can be treated in a Claus reactor to produce elemental sulfur. Both processes can achieve over 90% removal of SO_2 .

5.7 Volatile Radionuclide Removal

The vast majority of the curie content in the off-gas will be in the particulates. The particulates are removed very effectively by the particulate control systems (including the HEPA filters). Technetium is a somewhat volatile heavy metal, but keeping the temperature of the off-gas processing line low

should minimize its escape. However, virtually all of the three radionuclides, ^{129}I , ^{14}C , and ^3H , will emerge from the melter as gases. Iodine-129 will appear primarily as HI; ^{14}C will appear as CO_2 and some CO , and ^3H will appear as H_2O .

Calculations shown previously in Table 3.1 indicate that these three materials could be released from an 89-m stack over the 14-year life cycle of the plant with less than a 1-mrem/year exposure to the public at the site boundary. The carbon and iodine are each responsible for about half of that dose, while the tritium dose is negligible.

While this small dose would be less than the 10-mrem/year dose allowable under environmental regulations, the plant operators and stakeholders may wish to further reduce these emissions. Some processes for removing iodine from waste streams are described below. They can be quite expensive to implement because of the silver content in the required materials. Retaining the $^{14}\text{CO}_2$ and the $^3\text{H}_2\text{O}$ are more problematic, not because of technological challenges but because of the large volumes of carbon dioxide and water, most of it nonradioactive, in the off-gas.

The tritium contributes virtually nothing to dose. However, if necessary, it can be easily condensed out of the off-gas and handled in the same manner as the vapors from the evaporators. Presumably, most of the tritium inventory will be either sent up the stack or to the Liquid Effluent Retention Facility (LERF).

5.8 Carbon Dioxide Control

Only about 1 ppm of the carbon content in the tank waste is ^{14}C . Carbon in the tanks is largely present as carbonates, organic compounds, and chelators. If a combustion-type melter is used, all of the fuel will be converted to carbon dioxide and water. This source of carbon would far outweigh the carbon from the waste. Carbon dioxide can be scrubbed using a caustic scrubber in the manner discussed for acid gases. The scrubbing solution would then have to be treated to fix the carbon in a more permanent form, typically done by converting the carbon to calcium carbonate or other carbonate in a secondary treatment step. The carbonate is then grouted (Scheele and Burger 1982).

5.9 Iodine Control

Several iodine treatment technologies are available. A 1983 PNL report (Burger and Scheele 1983) surveyed the technologies and recommended gas-phase absorption using an amorphous silica bead impregnated with silver nitrate. This material, developed by the German company Bayer-Leverkusen, is known as AC-6120[®]. Its silver content is 7 to 12 weight percent. Typically, two beds are operated in series at elevated temperatures (110°C to 160°C) to achieve better than 99.99% removal of iodine. Eventually the material is spent and cannot be regenerated; however, silver recovery by secondary treatment is possible. Loading is possible until 95% of the silver has been converted to silver iodide. The process is effective on a wide array of iodine compounds and is tolerant of other species (such as NO_x) in the off-gas. It is also relatively simple to build and operate. It is quite expensive because of the cost of silver; in addition, other halogens are known to compete with iodine for retention, which

could further increase material costs. The process was demonstrated at a PUREX-type pilot plant. More details are given in Burger and Scheele (1983).

Placement of such a unit in the off-gas train might be problematic. Normally, the whole off-gas stream would be routed through the packed bed iodine treatment unit before passing through any wet or dry scrubbing stage in order to treat the iodine before it is scrubbed out. Early in the off-gas train, however, the temperature and dewpoint may be too high, and particulates re-entrained from the melter might plug the bed.

Other technologies known to retain iodine are caustic scrubbing, PUREX silver reactor, Mercurex, Iodox, silver zeolites, organic resins, activated carbon, solvent scrubbing, and electrolytic scrubbing. These technologies are also discussed in Burger and Scheele (1983).

6.0 Costs for the Off-Gas Treatment System

Order-of-magnitude estimates of capital cost have been prepared for off-gas treatment system 2 (described in Chapter 4). Because of the differences in the gas flow rates, different estimates were needed for off-gas treatment systems handling the liquid fed ceramic melter and the combustion melter. The purpose of preparing these estimates is to provide general indications concerning the impact of melter and feed preparation characteristics on the cost of the off-gas treatment system.

The capital cost estimates have been based on the melter gas flow rates presented in Table 6.1. The gas flow rates have been increased by a factor of 1.4 to account for routine gas surges. Very high costs for the construction materials have been assumed for the control device components between the evaporative cooler and the acid gas removal scrubber (absorber). It has been assumed that Inconel® or an equivalent material is needed in these areas because of the moderate temperatures [371°C (<700°F)] and the presence of high concentrations of chlorides, fluorides, and radionuclides.

The estimated costs of purchased equipment have been multiplied by an installed cost factor. This method accounts for costs associated with the following items.

Direct Installation Costs

- Foundations and supports
- Handling and erection
- Electrical
- Piping
- Ductwork
- Instrumentation
- Insulation
- Painting and coating

Indirect Installation Costs

- Engineering
- Construction and field experience

Table 6.1. Order-of-Magnitude Capital Cost Estimate for Off-Gas Treatment System 2, Including Emergency Vent System

Unit	Gas Flow Rate, ACFM		Material of Construction Multiplier	Purchased Equipment Cost		Number of Units	Installed Cost Multiplier	Installed Cost	
	LFCM	Combustion Melter		LFCM	Combustion Melter			LFCM	Combustion Melter
Reburn	24,000	100,000	3	400,000	1,100,000	1	2.5	1,000,000	2,750,000
Cooler	20,000	70,000	3	400,000	1,100,000	1	2.5	1,000,000	2,750,000
Metallic Filter	20,000	70,000	7	1,500,000	3,600,000	1	2.5	3,750,000	9,000,000
SCRs	22,000	75,000	7	1,000,000	2,500,000	2	3.0	6,000,000	15,000,000
Cooler-Absorber	12,500	42,500	7	600,000	1,400,000	1	3.0	1,800,000	4,200,000
Submerged Bed Scrubber	24,000	100,000	7	1,000,000	2,700,000	1	3.0	3,000,000	8,100,000
Demister	12,500	42,500	3	50,000	120,000	1	2.0	100,000	240,000
HEME	12,500	42,500	3	200,000	450,000	2	3.0	1,200,000	2,700,000
Heat Exchanger	12,500	42,500	3	100,000	240,000	1	2.0	200,000	480,000
HEPAs	12,500	42,500	3	300,000	900,000	2	2.0	1,200,000	3,600,000
Fans	12,500	42,500	3	200,000	500,000	2	3.0	1,200,000	3,000,000
CEMs	-	-	-	500,000	500,000	1	3.0	1,500,000	1,500,000
Totals								21,950,000	53,320,000

- Contractor fee
- Start-up
- Performance testing
- Contingencies

Other Costs

- Site preparation
- Buildings

The capital cost estimates do not include a redundant control system train following the evaporative cooler. A redundant train permits continued operation of the melter even when extensive maintenance on one of the control device components in the off-gas treatment system is necessary.

Costs for an emergency treatment system (SBS, HEME, and dual HEPAs) have been included. The system has been sized for a gas flow rate approximately equal to that of the main off-gas treatment system.

The summarized cost estimates are presented in Table 6.1. These estimates are strictly order-of-magnitude estimates. No attempt has been made to obtain budgetary cost estimates from possible equipment vendors because of the uncertainties regarding the melter characteristics and the off-gas streams to be generated by the melter.

The cost estimates indicate the significant impact of the gas flow rate generated by the melter. A melter with a low gas flow rate, such as the LFCM, may permit the use of an off-gas treatment system as much as 80 million dollars less expensive than a melter with a very high gas flow rate. Furthermore, the installed costs could be lower if the routine gas surge rates were less than the 140% (40% above maximum) assumed in these calculations.

The costs for nitrogen oxides control are extremely high. These costs include the 9 to 21.6 million dollars for the SCRs and the 3 to 9 million dollars for the reburn systems. A reduction in the nitrogen levels in the melter feed would greatly benefit the overall treatment system costs.

A reduction in the fluoride and chloride levels would reduce the need for exotic materials of construction, such as Inconel®, for several components of the off-gas treatment system, potentially reducing off-gas system treatment costs by 5 to 10 million dollars.

7.0 References

Boomer, K.D., S.K. Becker, A.L. Boldt, and J.S. Garfield. 1993. *Tank Waste Technical Options Report*. WHC-EP-0616, Westinghouse Hanford Company, Richland, Washington.

Burger, L.L. and R.D. Scheele. 1983. *The Status of Radioiodine Control for Nuclear Fuel Reprocessing Plants*. PNL-4689, Pacific Northwest Laboratory, Richland, Washington.

Dalton, J.D., R.L. Gillins, T.L. Harris, and A.L. Wollerman. 1992. *Assessment of Off-Gas Treatment Technologies for Application to Thermal Treatment of Department of Energy Waste*. DOE/MWIP-1, ORNL/M2323, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Donnelly, J.R. and B. Brown. 1989. *JOY/Kawasaki Selective Catalytic Reduction De-NO_x Technology*. Paper presented at the Air & Waste Management Association 82nd Annual Meeting, Anaheim, California, June 25-30, 1989.

Donnelly, J.R. et al. 1986. *Equipment Design Considerations for Resource Recovery Spray Dryer Absorption Systems*. Paper presented at the 79th Annual Meeting of the Air Pollution Control Association, Minneapolis, Minnesota, June 1986.

Durilla, M., J.M. Chen, B.K. Speronello, and R.M. Heck. Undated. *Composite SCR Catalysts for NO_x Reduction*. Paper prepared by Engelhard, Inc.

Ferguson, W.B. et al. 1986. *Equipment Design Considerations for the Control of Emissions from Waste-to-Energy Facilities*. Paper presented at the 79th Annual Meeting of the Air Pollution Control Association, Minneapolis, Minnesota, June 1986.

Foster, J.T. et al. 1987. *Design and Start-up of a Dry Scrubbing System for Solid Particulate and Acid Gas Control on a Municipal Refuse-Fired Incinerator*. Paper presented at the Air Pollution Control Association Specialty Conference on Thermal Treatment of Municipal, Industrial, and Hospital Waste, Pittsburgh, Pennsylvania, November 1987.

Gas Research Institute. Undated. *Natural Gas Reburning, Cost Effective Reduction for Utility Boilers*. Gas Research Institute, Chicago, Illinois.

Goles, R.W. and G.J. Sevigny. 1993. *Off-Gas Characteristics of Defense Waste Vitrification Using Liquid-Fed Joule Heated Ceramic Melters*. PNL-4819, Pacific Northwest Laboratory, Richland, Washington.

Gretsinger, W.T. and J.M. Colby. 1994. *Low-Level Waste Vitrification Plant Environmental Permitting Plan*. WHC-SD-WM-PLN-090 Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Hastings, A. and M. Schaefer. 1980. *Controlling Nitrogen Oxides*. EPA 600/8-80-004. Prepared by Science Applications, Inc. for the U.S. Environmental Protection Agency, Washington, D.C.

International Atomic Energy Agency (IAEA). 1989. *Treatment of Off-Gas from Radioactive Waste Incinerators*. Technical Report Series No. 302, International Atomic Energy Agency, Vienna.

Jones, D.G., S. Negrea, G. Lautenschlager, G. Rose, R.A. Smith, and G.H. Shiimoto. 1990. *Urea Injection NO_x Removal in European Coal-Fired Boilers and MSW Incineration Plants*. Paper 90-32.3. Paper presented at the 83rd Annual Meeting of the Air and Waste Management Association, Pittsburgh, Pennsylvania, June 24-29, 1990.

Kokkinos, A., J.E. Cichanowicz, D. Eskinaze, J. Stallings, and G. Offen. 1992 (November). "NO_x Controls for Utility Boilers: Highlights of the EPRI July 1992 Workshop." *J. Air Waste Management Association*, pp. 1498-1505.

Makansi, J. 1983 (May). "Special Report: Reducing NO_x Emissions from Today's Power Plants." *Power*, pp. 11-28.

Makansi, J. 1990 (January). "Focus of NO_x Removal Shifts from Process Design to Optimization." *Power*, pp. 47-49.

Martin, A.E. 1981. *Emission Control Technology for Industrial Boilers*. Noyes Data Corporation, Park Ridge, New Jersey. pp. 118-122.

Moller, J.T. and O.B. Christiansen. 1985. *Dry Scrubbing of MSW Incinerator Flue Gas by Spray Dryer Absorption: New Developments in Europe*. Paper presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, Michigan, June 1985.

Mott Metallurgical. 1993. *Precision Porous Metals Engineering Guide*. Mott Metallurgical Product Literature, Farmington, Connecticut.

Nickels, J.M. 1991. *Unit Dose Calculation Methods and Summary of Facility Effluent Monitoring Plan Determinations*. WHC-EP-0498, Westinghouse Hanford Company, Richland, Washington.

Orme, R.M. 1994. *TWRS Process Flowsheets*. WHC-SD-WM-TI-613 Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Pachaly, R., J.E. Hofmann, and W.H. Sun. 1991. *The NO_xOUT[®] Process for the Control of the NO_x Emissions from Waste Incinerators*. Paper 91-34.6. Paper presented at the 84th Annual Meeting of the Air and Waste Management Association, Vancouver, British Columbia, June 16-21, 1991.

Perez, J.M. et al. 1993. *Draft HWVP Pilot-Scale Melter Campaign LFCM-8 Summary Report*. PHTD-93-04.15D/K963, Pacific Northwest Laboratory, Richland, Washington.

Scheele, R.D. and L.L. Burger. 1982. *Selection of a Carbon-14 Fixation Form*. PNL-4447, Pacific Northwest Laboratory, Richland, Washington.

Schmel, G.A. 1990. *A Review of Potential Alternatives for Air Cleaning at the Hanford Waste Vitrification Plant*. PNL-7391, Pacific Northwest Laboratory, Richland, Washington.

Sedman, C.B. and T.G. Bina. 1987. *Municipal Waste Combustion Study: Flue Gas Cleaning Technology*. EPA 503-SW-87021d. Prepared in cooperation with the U.S. Environmental Protection Agency, Air and Energy Engineering Research Lab, Research Triangle Park, North Carolina.

U.S. Environmental Protection Agency. 1992. *Summary of NO_x Control Technologies and Their Availability and Extent of Application*. EPA-450/3-92-004. U.S. Environmental Protection Agency, Emission Standards Division, Research Triangle Park, North Carolina.

Vortec Corporation. 1993. *Phase I Test Results: High Capacity Melter Test Services for Westinghouse Hanford Company*. Vortec Corporation, Collegeville, Pennsylvania.

Westinghouse Hanford Company. 1993 (March 1, 1993). *Environmental Compliance: Section 2.0, Air Quality*. WHC-CM-7-5, Westinghouse Hanford Company, Richland, Washington.

Wilson, C.N. 1994. *Evaluation of Melter System Technologies for Vitrification of High Sodium Content Low-Level Radioactive Liquid Wastes: Statement of Work*. WHC-SD-WM-RD-044 Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Yeh, J.T., C.J. Drummond, and J.I. Joubert. 1987. "Process Simulation of the Fluidized-Bed Copper Oxide Process Sulfation Reaction." *Environmental Progress* 6(1):44-50.

Appendix A

Vendors of Air Pollution Control Equipment

Appendix A

Vendors of Air Pollution Control Equipment

Baghouses Fabric Filters

ABB Flakt
Environmental Systems
Knoxville, Tennessee
615-693-7550

American Air Filter
215 Central Avenue
Louisville, KY 40232
502-637-0710

Bundy Environmental Services
Reynoldsburg, Ohio
614-861-2500

CECO Filters
Conshohocken, Pennsylvania
800-220-8021

Crawford Equipment & Engineering
Orlando, Florida
800-228-0884

Environmental Elements Corp
Baltimore, Maryland
410-368-7000

Emtrol
Hauppauga, New York
516-582-9700

Fuller Company
Lehigh Valley, Pennsylvania
215-264-6011

General Electric
Environmental Services
Lebanon, PA 17042

Griffen Environmental Co, Inc.
Syracuse, New York
315-451-5300

Interel Corporation
Englewood, CO 80155
303-773-0753

Joy Environmental Systems
Monrovia, CA 91016
800-666-7684

MikroPul Environmental Systems
102 American Road
Morris Plains, NJ 07950
201-606-5900

Pall Trinity Micro Corp.
Cortland, NY 13045
607-753-6041

Research Cottrell
Somerville, NJ 08876
201-685-4000

United McGill
Columbus, OH 43216
614-443-0192

ZURN Air Systems
Birmingham, Alabama
205-252-2181

HEPA Filters

BACT Engineering, Inc
Arlington Heights, IL 60004
708-459-3580

Cambridge Filter Co.
Syracuse, New York
315-457-1000

Flanders Filters, Inc.
Washington, NC 27889
919-946-8081

Dry Scrubbers

Bundy Environmental Services
Reynoldsburg, Ohio
614-861-2500

Interel Corporation
Englewood, CO 80155
303-773-0753

Joy Environmental Systems
Houston, Texas
800-528-1159

KRCumwelttechnik
Federal Republik of Germany
0931-903-05

Research Cottrell
Somerville, NJ 08876
201-685-4000

Electrostatic Precipitators

ABB Flakt
Environmental Systems
Knoxville, Tennessee
615-693-7550

Beltran Associates
1133 East 35 Street
Brooklyn, NY 11210
718-338-3311

Environmental Elements Corp.
Baltimore, Maryland
410-368-7000

General Electric
Environmental Services
200 North Seventh Street
Lebanon, PA 17042

Lurgi
Baltimore, Maryland
410-664-1307

Research Cottrell
Somerville, NJ 08876
201-685-4000

United McGill
Columbus, OH 43216
614-443-0192

Wheelabrator Frye
Pittsburgh, Pennsylvania
412-562-7300

Particulate Wet Scrubbers

AirPol, Inc.
Teterboro, New Jersey

Anderson 2000
Peachtree City, Georgia
404-997-2000

Calvert Environmental
San Diego, California
619-272-0050

Compliance Systems International
San Diego, California
619-431-1602

Croll-Reynolds
Westfield, New Jersey
908-232-3200

Emtrol Corp.
Hauppauga, New York
516-582-9700

Environmental Elements Corp
Baltimore, Maryland
410-368-7000

Interel Corporation
Englewood, CO 80155
303-773-0753

John Zink
Tulsa, Oklahoma
918-747-1371

Koch
Wichita, Kansas
316-832-5110

Monsanto Enviro-Chem Systems, Inc.
St. Louis, Missouri
314-275-5700

Research Cottrell
Somerville, NJ 08876
201-685-4000

Wheelabrator Frye
Pittsburgh, Pennsylvania
412-562-7300

United McGill
Columbus, OH 43216
614-443-0192

ZURN Air Systems
Birmingham, Alabama
205-252-2181

NOx Control Systems

ABB Flakt
Environmental Systems
Knoxville, Tennessee
615-693-7550

Allied Signal
Tulsa, Oklahoma
918-266-1400

ARI Technologies
Palatine, Illinois
708-359-7810

Deutsche Babcock E&U AG
Federal Republik of Germany
208-8330

Englehard
Carteret, New Jersey
908-205-5723

Exxon Research and Engineering Co.
Florham Park, New Jersey
201-765-6742

Foster Wheeler
Clinton, New Jersey
908-236-1250

Johnson Matthey
Environmental Products
Wayne, Pennsylvania
610-971-3100

Noxso
Bethel Park, Pennsylvania
412-854-1200

Wahlco
Santa Ana, California
714-979-7300

Wheelabrator Air Pollution Control
Pittsburgh, Pennsylvania
414-562-7055

Tri-Mer Corp.
Owosso, Michigan
517-723-7844

W. R. Grace
Thermal & Emission Control Div.
Baltimore, Maryland
800-638-3844