Performance Evaluation of the Pilot-Scale, Double-Shell Tank Ventilation System Using Simulated Aerosol Streams

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SUMMARY

In FY 1988 and FY 1989, Pacific Northwest Laboratory (PNL) conducted tests using a pilot-scale prototypic ventilation system to obtain performance data at a variety of test conditions. The performance data will be used in the design and operation of the full-scale, double-shell tank ventilation system. A one-twentieth scale tank ventilation system was fabricated and installed. The system includes a refrigerated condenser to remove condensible vapors and a high-efficiency mist eliminator (HEME) to capture aerosol particles and entrained water before the off gas enters the final high-efficiency particulate air (HEPA) filters. PNL conducted tests to 1) determine the effectiveness of the system for removal of condensible vapors, 2) determine the effectiveness for removal of soluble and insoluble aerosols, and 3) estimate the operating life of the HEME.

The evaluation of the pilot-scale ventilation system was separated into four experimental areas: 1) identification of the primary factors affecting performance, 2) water vapor removal, 3) aerosol removal, and 4) HEME life expectancy. Performance was defined in terms of a decontamination factor (DF) for each component of the ventilation system. The DF is the ratio of inlet aerosol concentration to outlet aerosol concentration. Higher DF values indicate greater efficiency for removal of aerosols.

The primary factors affecting the DF for the condenser were flow rate, humidity and temperature, aerosol species, and aerosol concentration. Higher flow rates resulted in higher DFs when the relative humidity was at the high test level. Soluble aerosols resulted in significantly higher DFs than the insoluble aerosols when the relative humidity was high. When the relative humidity was low, there was no significant difference between the DFs for the soluble and insoluble aerosols. At higher concentrations of aerosols, the effect of flow rate becomes more significant. Higher flow rates result in a higher DF at high aerosol concentrations. The DF across the system was significantly affected by the aerosol species and the humidity and temperature. The DF across the system for the soluble aerosols was greater than for the insoluble aerosols. The DF for soluble aerosols was a factor of three greater at high humidity than when the humidity was low.

The water vapor removal tests were conducted to identify the parameters that affected carryover of water vapor from the condenser to the HEME. The system removed 100% of the theoretical water that could be removed based on psychrometrics. At high flow rates, the amount of water carried to the HEME was dependent on the absolute humidity. At low absolute humidities, approximately 100% of the condensed water was carried over to the HEME. However, at high absolute humidities, more than 85% of the condensed water drained from the condenser. At low flow rates, condensed water was not carried from the condenser to the HEME. This indicates that carryover of water to the HEME is dependent primarily on the residence time through the condenser, rather than the temperature or humidity. Calculated heat transfer coefficients agreed with published literature for this type of condensing system.

The pilot-scale ventilation system was successful in removing aerosols in the size range tested, which corresponds to the size data collected in the field. System DFs ranged from 5.8 to 37 depending on humidity, temperature, aerosol species, and inlet aerosol concentration. The HEME DFs were higher in the submicron particle sizes and the DFs increased as the inlet concentration increased.

Less than a 15% increase in the pressure drop (ΔP) was observed during each of the three, 30-day, HEME life expectancy tests with soluble, insoluble, and mixed soluble and insoluble aerosols. The results of the mixed soluble and insoluble aerosol test indicated that less than an 8% increase in the ΔP through the HEME was achieved with an inlet concentration of $537 \mu\text{g}/\text{m}^3$. Based on these results, an estimated average full-scale aerosol concentration of $16.5 \mu\text{g}/\text{m}^3$, and similar operating conditions (i.e., HEME face velocity, humidity), the HEME will operate for more than 900 days $[(537/16.5)(30 \text{ days})]$ without an appreciable ($>15\%$) increase in the ΔP . Water spray was effective at washing soluble aerosols from the filter and partially effective at washing insoluble aerosols from the filter. Continuous water spray, at the flows tested, did not affect aerosol removal in the HEME. Intermittent washing of the HEME filter with a water spray would be beneficial in removing collected aerosols and regenerating the filter.

The pilot-scale ventilation system has been successfully demonstrated for the removal of condensible vapors and soluble and insoluble aerosols from the off-gas stream. Therefore, the full-scale ventilation system has the potential to reduce the release of radioactive aerosols and to effectively reduce the load on the existing HEPA filters in the tank farm ventilation system.

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1.0 INTRODUCTION

Radioactive waste slurries are currently being stored in underground tanks on the Hanford Site. The slurries that are being stored in the double-shell tanks (DSTs) are various mixtures of radioactive solids, liquids, and aqueous wastes. The tanks must be maintained at a negative pressure relative to atmospheric pressure to safeguard against pressurization and the subsequent leakage of entrained radioactive aerosols to the environment. A ventilation system must be capable of withdrawing the total volume of off gas generated from the tanks while maintaining the tanks at a negative pressure. Westinghouse Hanford Company (WHC) has identified a need to improve the efficiency of the ventilation system being used on the tank farms to meet the more restrictive release limits for radioactive isotopes. Kaiser Engineers Hanford Company (KEH) has been contracted by WHC to design the new ventilation system for the existing tank farms. WHC contracted the Pacific Northwest Laboratory (PNL) to fabricate and test the prototypic pilot-scale design prior to finalizing the design of the ventilation system. The PNL has conducted tests to determine 1) the effectiveness of the system for removal of vapors condensable at 35°F, 2) the effectiveness for removal of soluble and insoluble aerosols, and 3) the life span of the mist eliminators to be used in the new system. The results of extensive testing of the pilot-scale system with condensibles and both soluble and insoluble aerosols are presented in this report.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations based on extensive testing of the pilot-scale DST ventilation system are provided below.

- The pilot-scale ventilation system was successful in removing vapors condensable at 35°F and soluble and insoluble aerosols from the process off gas. Therefore, the full-scale ventilation system has the potential to reduce the release of radioactive vapors and aerosols and to effectively reduce the load on the existing high-efficiency particulate (HEPA) filters in the tank farm ventilation system.
- Flow rate, humidity and temperature, aerosol species, and aerosol concentration were significant factors affecting aerosol decontamination through the condenser. Higher flow rates resulted in higher condenser decontamination factors DFs, especially when the relative humidity was at the high level. The effect of flow rate was more significant at higher aerosol concentrations. Condenser DFs for soluble aerosols were significantly higher at high relative humidity. When the relative humidity was low, there was no significant difference between the condenser DFs for soluble and insoluble aerosols.
- Decontamination through the high-efficiency mist eliminator (HEME) is not affected by the water spray at the range of spray flow rates tested. However, HEME decontamination does appear to be affected by aerosol concentration. Higher HEME DFs were obtained at higher concentrations of both soluble and insoluble aerosols.
- Decontamination across the overall system was significantly affected by the aerosol species and the humidity and temperature. The overall system DFs were greater for the soluble aerosols than for the insoluble aerosols, especially at high relative humidity. At low relative humidity, system DFs were primarily dependent on the efficiency of the HEME.
- Decontamination of sodium chloride (NaCl) and ammonium nitrate (NH_4NO_3) soluble aerosols occurred in both the condenser and HEME. At high absolute humidity (0.07 to 0.08 lb H_2O /lb air), condenser DFs ranged from 3 to 16 with a feed concentration of 30 to 51 $\mu\text{g}/\text{m}^3$. Condenser DFs generally increased with the off-gas flow rate. At a lower absolute humidity, condenser DFs ranged from 1 to 2, and decontamination was primarily controlled by the HEME. System DFs for soluble NH_4NO_3 aerosols based on total mass concentrations were between 5.8 and 37 with an average of 19. System DFs averaged 18 for NH_4NO_3 aerosols in the 0.05 to 0.1- μm size range and 7.1 for aerosols in the 1.6 to 3.2- μm size range at an inlet concentration of 120 $\mu\text{g}/\text{m}^3$.

- Decontamination of insoluble titanium dioxide (TiO_2) aerosols was primarily controlled by the HEME and appeared to be affected by the aerosol concentration. HEME DFs for insoluble aerosols averaged 5.9 at an inlet concentration of $68 \mu\text{g}/\text{m}^3$. At a higher inlet concentration of $188 \mu\text{g}/\text{m}^3$, the average HEME DF increased to 25. An average system DF of 13 was obtained during tests with a system inlet concentration of $153 \mu\text{g}/\text{m}^3$ and a HEME inlet concentration of $68 \mu\text{g}/\text{m}^3$. System DFs averaged 22 for TiO_2 aerosols in the 0.05 to $0.1\text{-}\mu\text{m}$ size range and 12 for aerosols in the 1.6 to $3.2\text{-}\mu\text{m}$ size range at an inlet concentration of $153 \mu\text{g}/\text{m}^3$.
- Condensible water vapor removal is dependent on the psychrometrics of the process gas. The pilot-scale ventilation system effectively removed 100% of the water that could theoretically be condensed based on a saturated stream at the HEME outlet conditions. Condensed water that was not collected by the condenser was removed by the HEME. When the flow rate was at the high test level (150 scfm) and the absolute humidity was high, condensate was collected by the condenser. At the low humidity, the condensate was carried to the HEME before collection. At the low test flow rate of 80 scfm, condensate was collected by the condenser at all absolute humidities.
- Heat transfer coefficients for the condenser ranged from 7 to $31 \text{ BTU}/\text{ft}^2\text{-hr-}^\circ\text{F}$ depending on the flow rate and absolute humidity of the off-gas stream. These values are within the range of expected values based on published literature for forced-convection cooling of gases.
- HEME life expectancy tests with soluble, insoluble, and mixed soluble-insoluble aerosols obtained less than a 15% increase in the pressure drop over the 30-day test periods. The results of the mixed soluble-insoluble aerosol test indicated that less than an 8% increase in the pressure drop (ΔP) through the HEME was achieved with a system inlet concentration of $537 \mu\text{g}/\text{m}^3$. Based on these results, an estimated average full-scale aerosol concentration of $16.5 \mu\text{g}/\text{m}^3$, and similar operating conditions (i.e., HEME face velocity, humidity), the HEME will operate for more than 900 days $[(537/16.5)(30 \text{ days})]$ without an appreciable ($>15\%$) increase in the ΔP . Water spray was effective at washing soluble aerosols from the HEME filter and partially effective at washing insoluble aerosols. Intermittent washing of the HEME filter with a water spray would be beneficial in removing collected aerosol and regenerating the filter, especially during periods of low absolute humidity.
- The proposed ventilation system has been tested for the removal of soluble and insoluble aerosols and condensible water vapor. Decontamination of aerosols in the 0.05 to $2\text{-}\mu\text{m}$ size range has been demonstrated. Decontamination factors and operating longevity are enhanced when the process stream contains condensible water vapor. Tests have not been conducted with highly corrosive or abrasive

off-gas streams; therefore, the suitability or applicability of the process to these streams would require additional evaluation and selection of materials of construction.

- Spray or flush nozzles should be incorporated in the full-scale design to allow for flexibility in operation and extended life span of the HEME filters. Water spray should be operated on a periodic basis, especially during periods of low humidity to minimize fouling of the HEME filter. A water spray flow rate of 0.25 gph/ft² filter surface was effective during pilot-scale testing.
- The full-scale ventilation system should be equipped with temperature and ΔP monitoring equipment and sampling ports that would allow for aerosol sampling at the inlet and outlet of each operable unit. A reliable means of humidity (dew point) measurement may be advantageous for evaluating the frequency at which HEME filter spray is required.
- Pilot-scale testing was conducted with HEME face velocities of 0.4 to 0.8 ft/sec. The full-scale system flow rates should be designed for a similar or lower face velocity through the HEME.
- The pilot-scale refrigerated condenser was operated with a coolant temperature of 35 to 37°F. Lower temperatures resulted in ice formation and a subsequent decrease in the heat transfer coefficient. The full-scale system should be designed to operate above 35°F to protect against ice formation.
- Based on performance test results with condensible vapor and soluble and insoluble aerosols, the proposed ventilation system could be effectively applied to other off-gas systems. This technology should be considered for application at other Hanford tank farms, vessel ventilation systems, and processing facilities.

3.0 AEROSOL REMOVAL PROCESSES

In the nuclear industry, condensers, demisters, heaters, and HEPA filters have traditionally been used to remove moisture and aerosols from off-gas systems. In addition, gravitational or centrifugal settlers, electrostatic precipitators, and wet scrubbers have been used in industry for aerosol removal. The primary goal of the tank farm ventilation system is to remove aerosols and condensible vapors that are generated through agitation, heating, and mixing of the wastes stored in the DSTs. Currently, the ventilation system consists of water-cooled condensers, demister pads, heaters, and HEPA filters to remove contamination in the off-gas stream. The water-cooled condensers remove a portion of the condensible vapors from the off-gas stream. The demister pads aid in the removal of water mist and large particulate matter by providing surface area for impaction. Prior to atmospheric release, the air stream is heated and then passed through a series of HEPA filters to remove the residual aerosol contamination. Because the HEPA filters act as the principle particulate removal operation, frequent replacement of the filters is required. The expense of frequent filter replacement and increased exposure to operating personnel warrants reevaluation of the current off-gas treatment system. In addition, the efficiency for removal of condensible vapors such as tritium will not satisfy current regulatory standards based on estimates of future tank loadings. Therefore, a new ventilation system was proposed with an emphasis on aerosol removal prior to HEPA filtration and increased efficiency for removal of condensible vapors.

An evaluation of the existing off-gas system was conducted by WHC(a) to identify the characteristics of the aerosol contamination for use in development of a new ventilation system design. Sampling of the off-gas system downstream of the existing water-cooled condensers and demister pads resulted in identification of two separate mass size distributions, one at a mass mean aerodynamic diameter of $0.073\ \mu\text{m}$ and the other at approximately $2\ \mu\text{m}$. Most

(a) Powell, W. J. 1989. Memo to N. R. Kerr, WHC, "Aging Waste Off-Gas Sampling Status Report." April 21, 1989.

of the beta and gamma activity was concentrated in the smaller size range of 0.05 to 0.4 μm . The mass concentration ranged from 0.9 to 64.8 $\mu\text{g}/\text{m}^3$ with an average of 16.5 $\mu\text{g}/\text{m}^3$.

Based on these results, the proposed system would require water-cooled condensers for first-stage removal of condensible vapors, a refrigerated condenser to remove additional condensible vapors, demisters to remove mist downstream of the condensers, and a component capable of removing entrained aerosols prior to heating and HEPA filtration. The use of gravitational or centrifugal settlers for non-condensable aerosol removal would be unwarranted because they are not effective at removing submicron particles (Hidy 1984, p. 698 and p. 701). Wet scrubbers could remove entrained aerosols; however, these units were eliminated from consideration because they would add substantial volumes of water to the process and would result in re-entrainment of condensible vapors in the off gas. Electrostatic precipitators would also be effective at removal of submicron particles; however, mechanical rapping or wet washing to remove collected aerosols from the precipitator surface could result in re-entrainment of condensible and noncondensable aerosols. Re-entrainment would cause increased loading of the HEPA filters. A HEME that acts as both a demister and submicron aerosol removal unit was selected. The HEME uses a washable fiber filter capable of removing both condensible and noncondensable aerosols (Hidy 1984, p. 719). By positioning downstream of the condensers, the HEME will replace demisters and effectively remove a portion of the entrained aerosols prior to HEPA filtration. The HEMEs have undergone extensive development for vitrification process application and have been successfully tested in off-gas treatment systems at PNL (Scott, Goles, and Peters 1985, Goles and Anderson 1986), Savannah River (Randall and Sabatino 1986), and West Valley Nuclear Services. They are currently in the reference design for these vitrification facilities.

The proposed tank farm ventilation system, shown in Figure 3.1, will include first- and second-stage heat exchangers to reduce the temperature of the off-gas stream, a refrigerated condenser to maximize removal of condensible vapors, and a HEME to capture aerosol particles and entrained water before entering the final HEPA filters. The refrigeration unit will enhance the ventilation system's ability to remove condensibles while the HEME

FIGURE 3.1. Schematic of the Proposed DST Ventilation System

utilizes a washable fiber filter to remove both aerosols and water mist. Captured particles can be rinsed from the filter material with a water spray to partially regenerate the HEME filter. By removing the primary particulate contamination at the HEME, there will be less duty on the HEPA filters, resulting in longer use of the HEPA filters before replacement. The HEME will replace the current de-entrainers, serve as the principle demister, and increase the aerosol removal efficiency prior to HEPA filtration.

4.0 EXPERIMENTAL APPARATUS

A one-twentieth-scale DST ventilation system, shown in Figures 4.1 and 4.2, was fabricated and installed at PNL. Table 4.1 contains the key for the symbols used in Figure 4.2. Ambient air is pulled through a HEPA filter by an existing off-gas blower into the 4-in.-diameter, pilot-scale off-gas line. Aerosols are injected into the line to simulate test conditions. Steam can be injected into the aerosol-containing off-gas stream through a metered injection port to adjust the absolute humidity. The stream then passes through a heat exchanger that is used to adjust the relative humidity and temperature of the off gas. The simulated off gas then passes through the primary components of the pilot-scale system: the refrigerated condenser and HEME, and out through the off-gas blower. Temperature, pressure, and flow rate sensors are mounted throughout the test system to monitor, adjust, and record operating parameters. The system was designed to allow for simulation of a variety of conditions expected in a full-scale ventilation system. The individual components in the pilot-scale ventilation system are described in detail in the following sections.

4.1 AEROSOL GENERATION

Aerosols were produced by VirTis® SG-40 aerosol generators. This apparatus uses a Laskin-type nozzle that shears a liquid solution with sparged air to create a liquid aerosol. Air at 20 psi was provided to generate the aerosols. Aerosol production rate was controlled by selecting an appropriate combination of the six nozzles and by varying the air flow rate to the generator. Aerosol composition was controlled by the composition of the solution used in the generator. Soluble aerosols were produced using a NaCl or NH_4NO_3 solution. Insoluble aerosols were produced using a suspension of TiO_2 in water. The solution for generating soluble aerosols was a mixture of 40 g of NaCl or NH_4NO_3 in 3 L of demineralized water. Insoluble aerosols were generated using a mixture of 80 g of TiO_2 in 3 L of water. Mixed soluble-insoluble tests were conducted by using two aerosol generators, one

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FIGURE 4.1. Photograph of the Pilot-Scale DST Ventilation System

FIGURE 4.2. Schematic of the Pilot-Scale DST Ventilation System

TABLE 4.1. Equipment Descriptions

<u>ID #</u>	<u>Description</u>
CSAS	Classical scattering aerosol spectrometer
QCM CI	Quartz crystal microbalance cascade impactor
TI-T7	Type K thermocouples - temperature
H1	Hygrometer - ambient air dew point
P1	Barometer - ambient pressure
P2	Pressure gauge - steam pressure
P3	Differential pressure transducer - HEME operating pressure
P4	Differential pressure transducer - CSAS operating pressure
OR1	Orifice plate (4 in.) - inlet flow rate
OR2	Orifice plate (1/2 in.) - injection steam flow rate
OR3	Orifice plate (1 in.) - CSAS flow rate
PT1	Pitot tube - water/glycol coolant flow rate
PT2	Pitot tube - HEME outlet flow rate
DP1	Differential pressure transducer - OR1
DP2	Differential pressure transducer - OR2
DP3	Differential pressure transducer - heat exchanger press. drop
DP4	Differential pressure transducer - PT1
DP5	Differential pressure transducer - HEME pressure drop
DP6	Differential pressure transducer - OR3
DP7	Differential pressure transducer - HEME condensate level
DP8	Differential pressure transducer - HX condensate level
V1	Regulating valve - steam injection control
V2	Regulating valve - steam heater control
V3	Ball valve - inlet aerosol sample manifold
V4	Ball valve - HEME inlet aerosol sample manifold
V5	Ball valve - HEME outlet aerosol sample manifold
V6	Control valve (4 in.) - system air flow control
V7	Regulating valve - CSAS sample flow control
V8	Diverter control valve - process gas temperature control
V9	Regulating valve - water cooler control
V10	Diverter valve - cooling water drain
R1	Flowmeter and control valve - HEME water spray
POG	Primary off-gas system blower

for soluble NH_4NO_3 and the other for insoluble TiO_2 . Each generator was adjusted separately to obtain the desired aerosol production rate. Aerosol sizes in the 0.05 to 25- μm size range were measured.

4.2 PROCESS GAS LINE HEATER OR COOLER

The incoming process gas stream could be heated above or cooled below the ambient temperature using the heater or cooler. This unit is a 15-ft² stainless steel shell and tube heat exchanger that uses either 30-psig steam or process water. The control valves on both the steam and process water lines were used to vary the steam or cooling water flow rate to the heat exchanger, which determined the temperature of the process gas. The process gas temperatures that were used in testing ranged from 60°F to 150°F.

4.3 HIGH-EFFICIENCY MIST ELIMINATOR

The HEME unit, shown in Figure 4.3, is a mist eliminator designed to eliminate submicron particles from the process gas stream. The process gas enters the top and center of the HEME, and then passes through a 30-cm diameter cylindrical filter (Flexifiber® type BD-PFF) consisting of approximately 8 cm of 8 to 10- μm -diameter glass fibers. The filter captures aerosol particles by impaction and by Brownian diffusion. A water spray (FullJet® 1/4 G) full cone nozzle positioned 3.2 cm above the filter sprays directly at the filter and can be used to wash the filter free of captured particles. Wash solution and mist removed from the off-gas stream are collected and metered via a dip leg connected to the bottom of the HEME. The dip leg is routed to a water and condensate collection system. It is necessary to provide adequate water height in the dip leg to provide a seal against the vacuum existing inside the HEME. This vacuum will pull a column of water up the dip leg equal to the operating pressure of the HEME while allowing the wash solution to flow into the collection vessel. This collection rate is monitored and necessary for material balance calculations.

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FIGURE 4.3. Schematic of the High-Efficiency Mist Eliminator

4.4 PROCESS GAS CHILLER

The process gas chiller consists of an air/glycol condenser coupled to a glycol/refrigerant heat removal system. The chiller is designed to cool the process gas stream such that condensable vapors in the process gas are condensed. The chiller is shown in Figure 4.2. A refrigerant evaporator cools the 50 wt% water-glycol mixture, which is maintained at -3.6°C (30°F) to $+1.7^{\circ}\text{C}$ (35°F) in a 380-L storage tank. This mixture is pumped through the three-way splitter valve (V8), which diverts a portion of the mixture back to the storage tank and a portion of the mixture to the air/glycol condenser. The three-way splitter valve is adjusted to maintain the temperature of the process gas stream leaving the condenser. The air/glycol condenser is a four-pass shell and tube heat exchanger, with the process gas passing through the shell side of the exchanger and the water-glycol mixture passing through the tube side. The unit has a total surface area of 6.35 m^2 (68.3 ft^2). The positioning of the three-way valve is manipulated by a pneumatic actuator tied to a set point temperature controller. With this system, it is possible

to cool 150 acfm of saturated air at 100°F to 35°F, saturated. Condensate from the condenser was collected and monitored using a dip leg arrangement similar to that described above for the HEME. The condenser was positioned to allow for flow of condensed vapors to a shell-side drain port connected to the dip leg.

4.5 CONDENSATE COLLECTION SYSTEM

The water collection system consists of two 70-gal steel tanks to contain condensate from the condenser and HEME. Dip legs from the condenser and HEME are terminated several inches above the bottom of each tank. Instrument air is purged through tubing to the top and bottom of each tank. Rotameters are used to set and adjust the purged air flow rate. Differential pressure transducers are connected between the top and bottom air lines to measure the liquid head in each tank. The corresponding millivolt signal from each transducer is transmitted to the existing data acquisition system, converted to a volume reading, and recorded for later analysis.

4.6 CSAS/SAMPLING MANIFOLD

The classical scattering aerosol spectrometer (CSAS) (Particle Measuring Systems, Inc., Boulder, Colorado, model CSAS-100) system uses light-scattering theory to measure aerosol particle diameters. A 5-mW classical He-Ne laser tube is used to create a light beam that is passed through windows mounted on the side of the sample tube. The process gas is drawn through the sample tube, and any entrained aerosols will scatter the light beam. The scattered light is collected by optics and focused onto the photodetector where the energy of the scattered light is measured. The energy of the pulse of scattered light is proportional to the size of the aerosol that scattered the light; thus, the CSAS can count the number of aerosols passing through the beam and determine the aerosol "optical" or equivalent geometric size distribution. However, the CSAS measures aerosols in a limited, predetermined size range. The instrument was calibrated for aerosols in the 0.32 to 0.755- μm size range; therefore, aerosols below 0.32 μm or above 0.755 μm were not measured by the CSAS.

The sampling manifold allowed for samples to be drawn from three locations in the system. Sample flow rates through the CSAS were maintained at 10 acfm to minimize anisokinetic losses (resulting from difference between process and sample flow rates) and optimize the accuracy of the CSAS. This flow was monitored by an orifice plate meter and controlled by a throttling valve. By appropriate valve switching, samples were taken and analyzed from 1) the inlet line to the system, 2) the entrance to the HEME, and 3) the exit from the HEME. The inlet sample line consisted of 11 ft of 1-in. outside diameter (OD) stainless tubing with three 90°, 3 1/4-in. radius bends. The HEME inlet and outlet sample lines were each 9-ft long with two 90° (3 1/4-in. radius) bends and one 90° elbow. All sampling probes were constructed of 1-in. OD stainless tubing with a 30° bevel knife edge. Losses in aerosol concentrations resulting from the length of sample line and number of 90° bends were estimated based on standard correlations (Liu et al. 1985). Less than a 1% loss through each bend would be expected for aerosols less than 3 μm in diameter; however, greater than 80% of the aerosols in the 12.5- μm size range or greater would impact on the tubing or elbow wall and not be detected. In general, results of aerosol sampling are expected to be quite accurate for particles less than 3 μm and inaccurate for larger particles. Aerosol data from each sample port were used to determine the efficiency and the DF for the heat exchanger, the HEME, and the overall system. It was necessary to allow sufficient time for thermal equilibrium within the sampling chamber before initiating the CSAS sampling sequence. It was also necessary to maintain the temperature of the gas flowing through the sampling chamber above saturation in order to avoid condensation on the optics of the CSAS. Eight inches of heat tape on each sample line was provided for this purpose to maintain sample temperatures greater than the process temperature. Data were not collected when sample lines were at a temperature lower than the process gas.

4.7 QUARTZ CRYSTAL MICROBALANCE CASCADE IMPACTOR

In addition to the CSAS, a quartz crystal microbalance cascade impactor (QCM CI) (California Measurement, Inc., Sierra Madre, California, model PC-2) was used to measure aerosol particle size distribution and concentration.

While the CSAS measures a particle number distribution, the QCM CI measures a mass concentration distribution. This type of instrument was used for field sampling of the existing tank farm ventilation system. Use of the QCM CI in series with the CSAS allowed comparison between the two methods and obtained data which could be directly compared to field data.

The QCM CI pulls process gas at 240 mL/min from the CSAS sampling manifold through an isokinetic [0.027-in. inside diameter (ID) knife edge] sampling probe into the sensing stack, which comprises 10 impactor stages. Particles of sufficient size and mass impact on a piezoelectric crystal microbalance (PCM) present on each stage of the impactor. Smaller particles escape impaction on the first stages but are captured later as the velocity of the process gas is increased through smaller orifices. The sensing stack segregates particles into ten 50% efficiency cut-off sizes (Dp50) between aerodynamic diameters of 25 and 0.05 μm . Assuming a particle density of 2 g/mL, the Dp50s are shown in Table 4.2. Water condensate that may collect on an impactor stage causing high readings is eliminated by pulling dry, aerosol-free filtered air through the column after particle impaction but prior to frequency measurement to evaporate any condensed water. The impacted particles on each stage result in a change in frequency of the quartz crystal that is proportional to the mass of particles collected. All sampling was conducted over a time period sufficient to obtain a minimum of

TABLE 4.2. QCM CI 50% Cut-Off Sizes

<u>Stage</u>	<u>Dp50, μm</u>
1	25.00
2	12.50
3	6.40
4	3.20
5	1.60
6	0.80
7	0.40
8	0.20
9	0.10
10	0.05

5 Hz frequency change per stage, as recommended by the manufacturer. The change in crystal frequency and the calculated concentration of particles present in the process stream for each Dp50 is output from the control unit of the QCM CI. Because the QCM CI measures particle size distribution over a wider size range than the CSAS, it is better suited to broadly distributed aerosols. The CSAS is more precise in a narrower distribution but inaccurate for broadly distributed aerosols.

4.8 DATA ACQUISITION SYSTEM

The data acquisition system (DAS) consists of a Hewlett-Packard (HP) 9000/200 computer system (Hewlett-Packard Company, Houston, Texas) interfaced to a Fluke 2240B data logger (John Fluke Manufacturing Company, Everett, Washington), a Validyne SPM 380 digital scanning panel meter (Validyne Engineering Corporation, Northridge, California), and the CSAS. All temperature measurements were provided by Type K thermocouples interfaced to the Fluke data logger. Flow rates were measured using orifice plates and pitot tubes with all pressure drops and operating pressure measurements determined using Validyne pressure transducers interfaced to the Validyne panel meter. Temperatures, pressure drops, flow rates, and aerosol size and count in each of the 15 channels of the CSAS were collected by the HP 9000/200 computer system and were stored on its hard disk. All pressure transducers, thermocouples, and the dew point hygrometer were calibrated before use and checked at completion of the experiments. QCM CI measurements were output on thermal paper, referenced in the laboratory record book, and stored for later analysis.

5.0 EXPERIMENTAL APPROACH

The evaluation of the pilot-scale ventilation system was separated into four experimental areas: 1) identification of the primary factors affecting performance, 2) water vapor removal, 3) aerosol removal, and 4) HEME life expectancy. The primary factors affecting performance were first identified to determine the operability of the system and to define the parameters that would require further evaluation. Performance was defined in terms of the DF for each component of the ventilation system. The DF is the ratio of inlet aerosol concentration to outlet aerosol concentration as defined below.

$$DF_{HX} = \frac{HX \text{ inlet particle concentration}}{HX \text{ outlet particle concentration}}$$

$$DF_{HEME} = \frac{HX \text{ outlet particle concentration}}{HEME \text{ outlet particle concentration}}$$

$$DF_{SYSTEM} = \frac{HX \text{ inlet particle concentration}}{HEME \text{ outlet particle concentration}}$$

where HX = heat exchanger (condenser)

HEME = high-efficiency mist eliminator

DF = decontamination factor.

Higher DF values indicate greater efficiency for removal of aerosols. Water vapor removal and aerosol removal tests were conducted to further evaluate the performance of the system as a function of the primary variables. A water material balance was used to determine the water removal performance and the DF was used for aerosol removal performance measurements. HEME life expectancy tests were conducted to ensure that the proposed system would function properly for an extended period without requiring maintenance. This was a primary concern because of the frequency at which HEPA filters were being replaced in the current ventilation system. The approach for each area of experimentation is presented in detail in the following sections.

5.1 PRIMARY FACTORS AFFECTING PERFORMANCE

To identify the primary factors affecting performance, six ventilation system variables were selected for evaluation. These variables represented the primary adjustable parameters in the proposed ventilation system and all variables known to fluctuate in the current ventilation system. The objective of initial testing of the pilot-scale ventilation system was to determine the overall efficiency of the system and identify the primary parameters that affect this efficiency. The variables that were selected for investigation in this study were:

- water spray rate
- off-gas flow rate
- inlet gas temperature
- inlet relative humidity
- inlet aerosol concentration
- aerosol species.

Because of the number of parameters of interest, a test matrix was developed using a partial factorial experimental design to allow for estimation of all main effects and the two- and three-factor interactions that were of significant interest. The test matrix is shown in Table 5.1. All variables were investigated at a high and a low level. The two- and three-factor interactions that were estimated from this experimental design are listed in Table 5.2. The run numbers are used to reference each set of conditions as specified in Table 5.1. The run numbers and operating conditions of the tests were completely randomized to allow an unbiased estimate of the statistics. However, the tests were run in the order shown in Table 5.1 from top to bottom. This allowed for tests with each aerosol species to be conducted together without disruption. The first block of runs contained all soluble aerosols using NaCl, and the second block included all the insoluble runs with TiO₂. The matrix was designed to allow for estimation of the six main variables, 11 two-way interactions, and one three-way interaction, with six replicate runs providing an estimate of the standard deviation.

TABLE 5.1. Experimental Design Matrix

<u>Run No.</u>	<u>Water Spray, gal/hr</u>	<u>Inlet Flow, scfm</u>	<u>Inlet Temp., °F</u>	<u>Inlet Rel. Humidity</u>	<u>Concentration, particles/mL</u>	<u>Species</u>
1	0.8	150	90	25	500	NaCl
2	0	150	90	25	1000	NaCl
3	0	80	90	25	1000	NaCl
4	0	150	120	95	500	NaCl
5	0	80	90	95	1000	NaCl
6	0	150	120	25	500	NaCl
7	0.8	80	120	95	500	NaCl
8	0.8	80	120	25	1000	NaCl
9	0.8	150	90	95	1000	NaCl
10	0.8	150	120	95	1000	NaCl
11	0	150	90	95	1000	NaCl
12	0	80	120	25	500	NaCl
13	0.8	80	90	25	500	TiO ₂
14	0.8	150	120	25	500	TiO ₂
15	0	80	120	95	500	TiO ₂
16	0.8	150	120	95	500	TiO ₂
17	0.8	80	90	95	500	TiO ₂
18	0.8	80	120	95	1000	TiO ₂
19	0.8	150	90	25	1000	TiO ₂
20	0	150	90	95	1000	TiO ₂
21	0	150	90	25	500	TiO ₂
22	0	80	120	25	1000	TiO ₂
23	0.8	150	90	95	500	TiO ₂
24	0	150	120	95	1000	TiO ₂

The variables were controlled as closely as possible to the specified levels. Temperature, pressure, particle concentration from the CSAS, humidity, and flow rate data were collected every 30 sec and stored on the hard disk. A hard copy of the data and plots was obtained for data analysis. The temperature, pressure, and particle concentration data from the CSAS were used to determine the DFs as a function of the test parameters.

TABLE 5.2. Estimated Interactions

<u>Two-Factor Interactions</u>		
Water Spray Rate	vs. Inlet Flow Rate	
	vs. Inlet Humidity	
	vs. Aerosol Concentration	
	vs. Aerosol Species	
Inlet Flow Rate	vs. Inlet Temperature	
	vs. Inlet Humidity	
	vs. Aerosol Concentration	
	vs. Aerosol Species	
Inlet Temperature	vs. Inlet Humidity	
Inlet Humidity	vs. Aerosol Species	
Aerosol Concentration	vs. Aerosol Species	
<u>Three-Factor Interactions</u>		
Inlet Flow Rate	vs. Inlet Temperature	vs. Inlet Humidity

A statistical analysis was conducted to identify the parameters or interactions that significantly affected decontamination through the process.

5.2 WATER VAPOR REMOVAL

The water removal tests were conducted to evaluate the ventilation system's efficiency for removal of condensible vapors and to determine the condenser heat transfer coefficients and cooling requirements. Removal of the condensibles from the full-scale process will be dependent on the psychrometrics of the refrigeration system and the performance of the condenser. Heat transfer coefficients were desired for use in scale up and for comparison to literature values to ensure that the system was operating in the expected range.

Two sets of experiments were conducted: one at 150 scfm and the other at 80 scfm. Each set consisted of six or seven tests at varying relative humidity, absolute humidity, and temperature. The objective was to

cover the range of operating conditions expected in the full-scale ventilation system; therefore, the inlet off-gas stream was adjusted to obtain both saturated and less-than-saturated conditions between 60°F and 150°F. The absolute humidity of the inlet stream was adjusted by varying the rate of steam injection into the process after accounting for the ambient humidity of the inlet air. Relative humidity was controlled by adjustment of the heater/cooler after setting the desired absolute humidity. The refrigeration unit was set to control the condenser outlet temperature at approximately 39°F by automatically adjusting the flow rate of the coolant through the heat exchanger. The rate of condensate collection during each test was determined to perform a material balance on the water entering and exiting the system. Flow, temperature, humidity, and condensate collection data were used to estimate heat transfer coefficients and water removal efficiencies.

5.3 AEROSOL REMOVAL

Experiments were conducted to determine DFs through the condenser, HEME, and the overall pilot-scale system. The primary objective of these tests was to determine DFs for both soluble and insoluble aerosols over a range of operating conditions that would be expected in the full-scale system. Decontamination factors, defined as the ratio of inlet aerosol concentration to outlet aerosol concentration, are necessary for design calculations of a full-scale ventilation system to ensure that the proposed process will meet discharge requirements. Sodium chloride and ammonium nitrate aerosols were generated to simulate the soluble aerosols expected in the actual off gas. Soluble species such as sodium, ammonium, nitrate, and chloride are primary components of the DSTs. Therefore, these components would be expected as aerosols in the off-gas stream. Titanium dioxide aerosols were generated to simulate insoluble aerosols in the off-gas stream. Aerosol concentrations at the condenser inlet, HEME inlet, and system outlet were measured with the CSAS and QCM CI. Absolute and relative humidity, temperature, off-gas flow rate, and aerosol concentration were varied to obtain DFs over a wide range of expected operating conditions.

5.4 HEME LIFE EXPECTANCY

Loading tests were conducted to estimate the life expectancy of the HEME glass-fiber filter through extended operation with a concentrated feed stream. Experiments were performed with NH_4NO_3 aerosols, TiO_2 aerosols, and with a 50:50 mixture (number based) of NH_4NO_3 and TiO_2 aerosols. Each test was run for approximately 1 month, 24 hr per day, with continuous generation of aerosols. To maximize the loading of the HEME, NH_4NO_3 and TiO_2 loading tests were conducted at 150 scfm and 80% relative humidity without operation of the refrigerated condenser. Because of evidence that entrained water mist was condensing in the HEME and washing the fiber filter, the mixed NH_4NO_3 - TiO_2 loading tests were conducted at 80 scfm and 80% relative humidity with the refrigerated condenser in operation to reduce the volume of water or water vapor carried to the HEME. The pressure drop through the HEME was recorded prior to initiation of each test and monitored continuously as the loading progressed. The flow rates, aerosol generation rates, and steam injection rates were adjusted daily to correct for fluctuations in the off-gas vacuum, aerosol generator liquid level, and ambient absolute humidity. The CSAS was used to set and adjust the aerosol concentration in the feed and the QCM CI was used to measure mass concentrations throughout the system several times weekly. Tests were designed to simulate full-scale operation; however, the concentration of aerosols entering the process were elevated by a factor of 8 to 30 to shorten the duration of the tests. An approximate life span of the HEME filter was estimated based on these test results and aerosol concentration data from the field.

6.0 EXPERIMENTAL RESULTS

Experimental results for each area of testing described in Section 5.0 are presented in Sections 6.1 through 6.4.

6.1 PRIMARY FACTORS AFFECTING PERFORMANCE

Decontamination factors were used as the basis for identification of factors affecting aerosol removal performance of the pilot-scale system. During these tests, the CSAS was used to measure count-based aerosol concentrations. These concentrations were used to calculate DFs as defined in Section 5.0.

During data analyses, it was determined that the interaction between temperature and humidity could not be differentiated. Because the vapor pressure of water changes with temperature, the relative humidity of the gas stream will change with temperature even though the absolute humidity remains constant. Therefore, for analysis, temperature and relative humidity were grouped to account for changes in absolute humidity. Three levels were defined, high, medium, and low. The high level (high) corresponds to the condition of high relative humidity (>90% of saturation), high absolute humidity (>0.07 lb H₂O/lb air), and high temperature (120°F). The intermediate level (medium) represents the condition of high relative humidity, low absolute humidity (<0.03 lb H₂O/lb air), and low temperature (90°F). The low level (low) corresponds to the condition of low relative humidity (<30% of saturation) and low absolute humidity at either high or low temperature. With this grouping variable, it was still possible to analyze the effect the variables have on the DFs. This grouping variable provided a better fit to the model by eliminating the estimation of the interaction between temperature and humidity.

Experimental data in the form of DFs for the condenser, HEME, and system as a function of test variable were used in a statistical analysis to identify all parameters and interactions that may affect decontamination. Sections 6.1.1 through 6.1.3 describe the results of the statistical analysis for condenser, HEME, and system DFs, respectively.

6.1.1 Decontamination Across the Condenser

Statistical analysis of the condenser DFs resulted in identification of three significant interactions. A regression coefficient (R^2) value of 0.96 was obtained. R^2 indicates the fraction of the total variability in the DF that can be explained by the significant parameters. R^2 values close to 1.00 indicate a good estimation of the interactions.

As shown in Figure 6.1, a significant interaction exists between the flow rate and the grouping variable. The higher flow rate resulted in higher DFs when the relative humidity was at the high level, but not when the relative humidity was low. The data indicate that the effect of the flow rate may be influenced by the steam injection rate or temperature at the high relative humidity level. At the higher flow rate, the steam injection rate must be increased to maintain the same absolute humidity. Increased steam injection or poor temperature control could artificially increase DFs.

FIGURE 6.1. Effect of Flow Rate, Humidity, and Temperature on Decontamination Through the Condenser

A significant interaction also exists between the species type and the grouping variable. As shown in Figure 6.2, significantly greater DFs were obtained with soluble aerosols than with insoluble aerosols when the relative humidity was high. When the relative humidity was low, there was no significant difference between the DFs for the soluble and insoluble aerosols. The values of DF for the condenser were highest at the intermediate level (medium) of the grouping variable (high relative humidity and low temperature). It was expected that the highest DF would be experienced at high relative humidity and high temperature. Unusually high DFs reported for two of the runs, both at the intermediate level of the grouping variable, skewed the condenser results. Poor temperature control during these two runs produced higher relative humidities resulting in greater DFs. Therefore, it was not possible to determine the significance of temperature on the condenser DF. It was possible to conclude that high relative humidity yields high DFs.

FIGURE 6.2. Effect of Humidity, Temperature, and Aerosol Species on Decontamination Through the Condenser

The third significant interaction existed between aerosol concentration and flow rate. Condenser DFs were higher at the higher flow rate, as shown in Figure 6.3. At higher flow rates, the off gas is in a more turbulent mixing range resulting in higher heat transfer rates and increased likelihood of impaction on the cooling tubes. Therefore, better decontamination results. The effect of flow rate appears to be more pronounced at the higher aerosol concentration.

6.1.2 Decontamination Across the HEME

The test matrix was designed to determine the effect of the six variables on the DFs of the condenser and the overall system. It was not possible to evaluate the HEME performance in the same manner as the condenser and the overall system. The test conditions at the inlet of the HEME depended on the performance of the condenser. For example, with a high aerosol concentration and a high relative humidity test condition, the DF across the condenser would be high. This resulted in a low inlet

FIGURE 6.3. Effect of Flow Rate and Aerosol Concentration on Decontamination Through the Condenser

concentration to the HEME, when the test matrix was set up for a high concentration. Therefore, test results could not be evaluated to determine the effect of concentration on HEME DF.

The effect of water spray rate is important in evaluating how the HEME should be operated. The effect of water spray rate can be determined by looking at the DFs for the overall system. In the range of water spray rates tested, there was no increase in the DFs for the overall system. Therefore, the water spray rate did not affect aerosol removal in the HEME. If the water spray rate had increased the efficiency of the HEME, this would have been reflected in the DF for the entire system. This conclusion is only valid for the range of the water spray rates tested. These results indicate that continuous water spray may not be necessary. Intermittent water spray will probably be required to regenerate the HEME filter, as indicated in the results of loading tests presented in Section 6.4.

6.1.3 Decontamination Across the System

The DF across the system was significantly ($R^2 = 0.93$) affected by the aerosol species and by the level of the humidity and temperature. The DFs for the system as a function of the species and grouping variable are shown in Figure 6.4. There is no statistically significant difference between the DFs at the high and medium levels of the grouping variable for NaCl, and only marginal difference (90% confidence level) between the DFs at the low level of the grouping variable for NaCl and TiO_2 . None of the other variables tested (i.e., water spray, inlet flow rate, or aerosol concentration) had a significant effect on the DF for the system. The DFs for the soluble aerosols were greater than for the insoluble aerosols. Hidy (1984) confirms that soluble, hygroscopic particles reduce the vapor pressure of water at the gas-solid interface, increasing the take up of water vapor, whereas insoluble particles do not behave in this manner. The marginal difference between system DFs for the soluble and insoluble aerosols at the low level of the grouping variable is evidence that in the absence of water vapor, the aerosols behave similarly.

The effect of different absolute humidities at the high level of relative humidity (resulting from the change in vapor pressure with

FIGURE 6.4. Effect of Humidity, Temperature, and Aerosol Species on Decontamination Through the System

temperature) was clearly seen in Figure 6.4 for the insoluble aerosols. When both the temperature and relative humidity were at the high level (i.e., high absolute humidity), the DF was a factor of three greater than when the relative humidity was high but the temperature was low. For the soluble aerosols, there was not a statistical difference between DFs at the high and medium levels of the grouping variable.

6.2 WATER VAPOR REMOVAL

Because removal of condensibles such as tritium is dependent on the ability of the ventilation system to remove water vapor, tests were designed to study condensation and water and mist removal. Testing indicated that a substantial volume of condensed vapor was being carried to the HEME; therefore, tests were also conducted to identify the parameters that affected this carryover. Tests were performed at several temperatures, absolute and relative humidities, and off-gas flow rates.

The results of tests conducted at 150 scfm are summarized in Table 6.1. The test numbers shown are for reference only. During these tests the glycol/water coolant was maintained at a temperature between 35°F and 37°F. Steam was injected into the off-gas stream to obtain absolute humidities of 0.01, 0.03, and 0.08 lb H₂O/lb dry air. The temperature of the off-gas stream was adjusted with the overhead heater/cooler to obtain stream temperatures coinciding with either saturated or less than saturated (i.e., 40% to 60% relative humidity) air. As indicated in Table 6.1, the percentage of water condensed but carried to the HEME appears to be dependent on the absolute humidity. At 0.01 and 0.03 lb H₂O/lb dry air, approximately 100% of the condensed water was carried over to the HEME. However, at 0.08 lb H₂O/lb dry air, more than 85% of the condensed water drained from the condenser. The data shown as "Relative % Carryover to HEME" are calculated from the volume of water collected by the HEME and the total volume of water collected by both the HEME and the condenser. A water balance, shown as "% of Theoretical Removed," indicates good ($\pm 15\%$) agreement between theoretical and actual water removal for tests conducted at 0.03 and 0.08 lb H₂O/lb dry air. However, greater than 100% deviation between actual and theoretical removal was obtained for tests conducted at the low absolute humidity of 0.01 lb H₂O/lb dry air. Because very low steam injection rates are required for the low absolute humidity test condition, there is a high potential for condensation in steam lines. This would result in much higher water injection rates than indicated by the steam flowmeter and in large errors in the material balance. However, the indication of carryover is justified by the relative difference between collection rates for the condenser and HEME.

Data from tests conducted at 80 scfm are shown in Table 6.2. Unlike tests conducted at 150 scfm, results indicate that condensed water is not carried from the condenser to the HEME. At all absolute humidities (0.01, 0.03, and 0.08 lb H₂O/lb dry air), less than 12 wt% of the condensed water was collected by the HEME. This indicates that carryover of water to the HEME is dependent on the residence time through the condenser, rather than the temperature or humidity.

Cooling loads or duties and approximate heat transfer coefficients are shown in Tables 6.1 and 6.2 and in Figure 6.5. The ΔT used to calculate the

TABLE 6.I. Summary of Water Removal Tests Conducted at 150 scfm

Operating Condition	Test Number						
	1	2	3	4	5	6	7
Off-Gas Flow Rate, scfm	148	150	149	150	150	151	151
Inlet Temperature, °F	89.8	119	142	120	115	59.8	77.6
Outlet Temperature, °F	41.9	42.0	46.1	44.8	45.8	38.4	39.4
Coolant Temperature, °F	37.0	36.2	35.6	35.0	36.8	35.8	36.2
HEME Outlet Temperature, °F	44.4	44.1	48.2	47.2	48.4	41.2	42.4
HEME Collection, gal/day	52.3	58.1	14.6	7.5	18.5	29.1	20.7
HX Collection, gal/day	2.2	1.1	120	130	122	-2.1	2.2
Absolute Humidity, lb/lb air	0.324	0.0322	0.0808	0.0803	0.0805	0.0107	0.0109
Relative Humidity, %	100	44	56	99	100	92	50
HEME Outlet Absolute Humidity	0.0062	0.0062	0.0072	0.0069	0.0073	0.0055	0.0057
Theoretical Removal, gal/day	51.0	51.5	145	146	145	10.3	10.3
% of Theoretical Removed	107	115	93	94	97	260	222
Relative % Carryover to HEME	96	98	11	5	13	108	90
Cooling Load, BTU/lb dry air	39.7	48.8	106	101	98.1	10.8	14.8
Cooling Load, BTU/min	449	557	1200	1156	1120	124	170
ΔT , log mean	20.2	29.0	41.3	34.7	31.9	9.7	15.0
U_0 , BTU/ft ² -hr-°F	19.5	16.9	25.5	29.3	30.8	11.2	10.0

TABLE 6.2. Summary of Water Removal Tests Conducted at 80 scfm

Operating Condition	Test Number					
	1	2	3	4	5	6
Off-Gas Flow Rate, scfm	80	80	80	81	81	81
Inlet Temperature, °F	91.5	120	120	58.1	80.3	96.2
Outlet Temperature, °F	38.8	38.9	42.2	37.4	38.1	37.9
Coolant Temperature, °F	35.9	35.4	36.2	36.0	36.0	35.7
HEME Outlet Temperature, °F	45.3	44.9	46.5	43.6	44.3	45.1
HEME Collection, gal/day	-1.1	4.4	3.3	2.1	-4.5	1.1
HX Collection, gal/day	29.1	34.9	71.6	20.0	22.8	10.8
Absolute Humidity, lb/lb air	0.0316	0.0318	0.0805	0.0121	0.0122	0.0135
Inlet Relative Humidity, %	99	42	99	100	56	37
HEME Outlet Humidity Ratio	0.0064	0.0063	0.0067	0.0060	0.0062	0.0064
Theoretical Removal, gal/day	26.4	26.9	77.9	6.6	6.3	7.7
% of Theoretical Removed	106	145	96	338	287	157
Relative % Carryover to HEME	-4	11	4	10	-25	9
Cooling Load, BTU/lb dry air	41.6	48.1	101	12.7	18.1	23.7
Cooling Load, BTU/min	253	294	616	78	112	146
ΔT , log mean	17.9	25.5	29.5	7.5	13.9	17.5
U_0 , BTU/ft ² -hr-°F	12.4	10.1	18.4	9.2	7.1	7.4

FIGURE 6.5. Heat Transfer Coefficients as a Function of Absolute Humidity

heat transfer coefficient is a log mean temperature difference (Perry and Chilton 1973, pp. 10-23):

$$\Delta T_L = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$

where: T = temperature, °F

ΔT_1 = T off-gas inlet - T coolant outlet

ΔT_2 = T off-gas outlet - T coolant inlet

The change in temperature of the glycol/water is assumed to be negligible (i.e., coolant temperature is used for both inlet and outlet). The condenser is of the four-pass configuration with a surface area of 68.3 ft². The ΔT does not account for the phase change of steam condensing to water; therefore, the heat transfer coefficient (U_o) is larger for those cases of high

absolute humidity. Heat transfer coefficients ranged from 7 to 31 BTU/ft²-hr-°F and are within the "order of magnitude" expected range of 2 to 50 BTU/ft²-hr-°F for forced convection cooling of gases (Bird, Stewart, and Lightfoot 1960; Perry and Chilton 1973).

6.3 AEROSOL REMOVAL

Results of testing to identify the parameters affecting performance indicated a significant interaction between humidity, temperature, and both condenser and system DFs. Aerosol removal tests were conducted to further evaluate this interaction and to determine DFs for both soluble and insoluble aerosol over the expected range of operating conditions. Because HEME DFs were not clearly identified during initial testing, removal tests were also designed to obtain data on HEME performance.

To determine aerosol removal efficiencies, aerosol concentrations and particle size distributions were measured using both the CSAS and QCM CI. The CSAS is capable of measuring particles within a narrow range of diameters (0.32 to 0.755 μm). The QCM CI measures particle mass over a broader range of 0.05 to 25 μm . The CSAS will not count particles outside the preselected range. The range of the CSAS was selected to include a majority of the particles. Consequently, DFs based on CSAS measurements may be higher if particles are generated over a wide size range and are not detected by the CSAS. A comparison of the aerosol concentrations and DFs based on outputs from each of the instruments was made using NaCl particles. These results are included in Section 6.3.1 with a summary of NH₄NO₃ and NaCl soluble aerosol removal tests. Results of insoluble TiO₂ removal tests are summarized in Section 6.3.2.

6.3.1 Soluble Aerosol Removal

Soluble NaCl aerosols were introduced into the process gas line at a concentration of approximately 1000 particles/mL of gas at a process gas flow of 150 scfm. This inlet concentration corresponded to a QCM CI reading of 51.1 $\mu\text{g}/\text{m}^3$. Steam was injected into the system to maintain an absolute humidity of 0.0228 lb H₂O/lb dry air. This resulted in an inlet temperature of 88°F and a relative humidity of 78%. The condenser cooled the process gas

to 39°F. The process gas at the outlet of the condenser contained 17.5 particles/mL based on the CSAS and $4.22 \mu\text{g}/\text{m}^3$ based on the QCM CI. The DF based on CSAS measurements was 56.5 and the QCM CI measurements gave a DF of 12.1. As shown in Figure 6.6, the aerosols generated included a significant concentration of particles outside the CSAS range of 0.32 to $0.755 \mu\text{m}$. In addition, off-gas measurements conducted by WHC indicated a significant mass size range below $0.32 \mu\text{m}$. Therefore, the lower DF based on QCM CI measurements is more reliable. As discussed in Section 4.0, Experimental Apparatus, aerosol concentrations for particles above $3.0 \mu\text{m}$ are likely to be erroneous based on estimates of losses due to bends in the sample lines. Particles in the size ranges above $3 \mu\text{m}$ are also most likely to be removed by impaction through bends in the primary off-gas lines.

The relative humidity was then decreased to approximately 5% by heating the inlet stream while maintaining a constant absolute humidity. At this lower relative humidity, the decontamination was greatly decreased. A condenser DF of 1.53 was obtained based on the CSAS, and a DF of 1.63 was obtained based on the QCM CI. As shown in Figure 6.7, the majority of particles in the 0.05 to $0.40\text{-}\mu\text{m}$ range were not removed by the condenser at the

FIGURE 6.6. Soluble Aerosol Size Distribution, RH = 78%

FIGURE 6.7. Soluble Aerosol Size Distribution, RH = 5%

lower humidity. Because of the reduced decontamination of the smaller particles at the lower humidity, errors in the CSAS measurement were not significant.

Ammonium nitrate removal tests were also conducted to determine whether NH_4NO_3 aerosols would be removed by the pilot-scale system over the expected operating range of 60°F to 120°F. Tests were conducted at approximately 150 and 80 scfm at varying temperatures, absolute humidities, and relative humidities. Results of the tests conducted at 80 to 90 scfm are shown in Table 6.3. Inlet aerosol concentrations ranged from 31 to 51 $\mu\text{g}/\text{m}^3$ with system outlet concentrations between 1.5 and 6.3 $\mu\text{g}/\text{m}^3$. Previous tests indicated that high absolute humidity and relative humidity increased condenser DFs. These results show that high relative humidities do not appear to dramatically increase DFs through the condenser. However, an apparent increase in the condenser DF with increasing absolute humidity was observed. These results indicate that DFs through the condenser are more dependent on absolute humidity than relative humidity. An increase in the condenser DF was observed as the relative humidity was increased; however, this increase

TABLE 6.3. Summary of NH_4NO_3 Removal Tests Conducted at 80 to 90 scfm

Operating Condition	Test Number						
	1	2	3	4	5	6	7
Off-Gas Flow Rate, scfm	88.9	78.7	87.5	88.5	90.5	89.4	89.2
Inlet Temperature, °F	90.5	118	108	112	123	60.7	88.8
HX Outlet Temperature, °F	38.3	38.4	40.5	42.1	41.2	38.2	38.3
HEME Outlet Temperature, °F	43.6	45.1	46.6	46.9	45.8	42.8	43.0
Absolute Humidity, lb/lb air	0.0278	0.0314	0.0733	0.0737	0.0719	0.0106	0.0107
Inlet Relative Humidity, %	90	44	110 ^(a)	105 ^(a)	82	92	37
Inlet Concentration, $\mu\text{g}/\text{m}^3$	50.8	45.8	30.8	30.9	43.2	42.5	49.6
HX Outlet Concentration, $\mu\text{g}/\text{m}^3$	24.2	35.5	7.05	10.5	20.8	27.8	36.1
Outlet Concentration, $\mu\text{g}/\text{m}^3$	1.45	1.25	2.8	5.33	2.42	1.5	2.23
Condenser DF	2.1	1.29	4.37	2.94	2.08	1.53	1.37
HEME DF	16.7	28.3	2.52	1.97	8.61	8.51	6.2
System DF	35.0	36.6	11.0	5.79	17.9	28.3	22.3

(a) Relative humidities above 100% indicate super-saturation. The percentage is a relative approximation based on the difference between the off-gas temperature and the saturation temperature.

was not significant at low absolute humidities. Overall, an increase in system DFs as a result of higher condenser DFs was not observed.

Experimental data for NH_4NO_3 removal tests conducted at 150 scfm are shown in Table 6.4. Data at the higher flow rate confirm tests conducted at 80 to 90 scfm with regard to the effect of absolute and relative humidity on condenser DFs. On the average, condenser DFs were higher at 150 scfm;

TABLE 6.4. Summary of NH_4NO_3 Removal Tests Conducted at 150 scfm

Operating Condition	Test Number						
	1	2	3	4	5	6	7
Off-Gas Flow Rate, scfm	147	148	146	148	151	148	147
Inlet Temperature, °F	89.8	119	118	129	60.5	60	92
HX Outlet Temperature, °F	40.8	39.7	42.9	43.3	39.1	36.7	38
HEME Outlet Temperature, °F	43.7	43.2	45.8	46.1	41.6	40.1	41.3
Absolute Humidity, lb/lb air	0.0315	0.0314	0.0830	0.0819	0.0110	0.0113	0.0114
Inlet Relative Humidity, %	100	43	105 ^(a)	80	97	100	35
Inlet Concentration, $\mu\text{g}/\text{m}^3$	37	41.4	46	42	37.3	42.6	40.7
HX Outlet Concentration, $\mu\text{g}/\text{m}^3$	10.5	16	2.8	4.8	25.5	19.2	21.1
Outlet Concentration, $\mu\text{g}/\text{m}^3$	2.71	6.29	2.4	3.15	3.44	2.69	1.55
Condenser DF	3.51	2.58	16.5	8.75	1.46	2.22	1.93
HEME DF	3.89	2.55	1.16	1.52	7.42	7.13	13.6
System DF	13.7	6.58	19.2	13.3	10.8	15.8	26.3

(a) Relative humidities above 100% indicate super-saturation. The percentage is a relative approximation based on the difference between the off-gas temperature and the saturation temperature.

however, HEME DFs and system DFs were higher at the lower flow rate. The average system DF at 80 to 90 scfm was 22.4; at 150 scfm, the system DF averaged 15.1. This apparent decrease in system DF with flow rate is not conclusive because both inlet and condenser outlet aerosol concentrations were higher at the lower flow rate than at the higher flow rate, potentially inflating the HEME and system DFs. In addition, no significant relationship

between flow rate and system DF was indicated from initial testing with the factorial design. The overall conclusion based on removal tests is that the pilot-scale ventilation system was effective at reducing NH_4NO_3 aerosol concentrations, primarily by removal through the HEME. Substantial removal through the condenser will also occur when the absolute humidity exceeds 0.08 lb H_2O /lb air or at higher flow rates. HEME DFs averaged 9.3 with a system DF average of 19 for tests conducted between 80 and 150 scfm.

Tests were also conducted with NaCl and NH_4NO_3 aerosols without operation of the condenser to obtain higher HEME inlet concentrations. These tests were conducted as part of the HEME loading or life expectancy tests described in detail in Section 6.4.1. The DFs are shown here for comparison to the previously described data.

Sodium chloride aerosols were generated to an average HEME inlet concentration of $39.3 \mu\text{g}/\text{m}^3$ at a process gas flow rate of 150 scfm. The off-gas temperature and humidity were at ambient conditions of approximately 75°F and 0.006 lb H_2O /lb air ($\approx 32\%$ relative humidity). The HEME outlet concentration averaged $6.65 \mu\text{g}/\text{m}^3$ for a mass-based HEME DF of 5.9. The average HEME DFs as a function of particle size are shown in Figure 6.8.

Ammonium nitrate aerosols were also studied without condenser operation. Steam was injected into the process off gas to maintain a relative humidity of 80% at an ambient temperature of 80°F (≈ 0.018 lb H_2O /lb air). An average process inlet concentration of $133 \mu\text{g}/\text{m}^3$ was maintained. Although the condenser was not operating during these tests, a condenser DF of approximately 2 was observed, thereby reducing the average HEME inlet concentration to $63.5 \mu\text{g}/\text{m}^3$. This decontamination is likely a result of impaction on the condenser tubes and pipe wall as the off-gas stream passes through the heat exchanger.

An average HEME outlet concentration of $13.3 \mu\text{g}/\text{m}^3$ was obtained for a HEME DF of 4.8. Figure 6.9 shows the condenser, HEME, and system DFs for each channel (size range) of the cascade impactor. DFs for the 25-, 12.5-, and 6.4- μm size ranges should not be considered accurate because of aerosol losses through the sampling lines. Based on soluble aerosol removal tests with NaCl and NH_4NO_3 , HEME DFs ranged from 1.2 to 28. Low HEME DFs in the

FIGURE 6.8. Average NaCl Aerosol DFs at an Inlet Concentration of $39.3 \mu\text{g}/\text{m}^3$

FIGURE 6.9. Average NH_4NO_3 Aerosol DFs

1 to 2 range were observed when HEME inlet concentrations were lower than $5 \mu\text{g}/\text{m}^3$. This may be partially a result of the difficulty in obtaining accurate QCM CI measurements (i.e., frequency change >5 Hz per stage) at very low outlet concentrations or a result of reentrainment of aerosols from the HEME filter. Reentrainment would be independent of HEME inlet aerosol concentrations; therefore, at a low inlet concentration, the effect on HEME DFs would be more significant. As HEME inlet concentrations rose, HEME DFs also increased. The highest HEME DFs were obtained when HEME inlet concentrations were greater than $100 \mu\text{g}/\text{m}^3$. During extended tests with HEME inlet concentrations of 40 to $64 \mu\text{g}/\text{m}^3$, the HEME DF was consistently within 10% of 5.3. As indicated in Figures 6.8 and 6.9, HEME and system DFs for aerosol particles in the 0.05 to $0.4\text{-}\mu\text{m}$ size range were generally higher than DFs for the larger particles.

6.3.2 Insoluble Aerosol Removal

Initial testing indicated that humidity and temperature had little effect on removal of insoluble TiO_2 aerosols except at very high absolute humidities. Tests were conducted to determine the level of absolute humidity necessary to significantly affect insoluble aerosol removal through the condenser. The CSAS was used to estimate DFs based on particle counts in the 0.32 to $0.755\text{-}\mu\text{m}$ size range. Mass-based QCM CI measurements were not obtained during this testing because of technical problems with the instrument. Steam was injected into the 150 scfm process gas to obtain an absolute humidity of 0.023 lb $\text{H}_2\text{O}/\text{lb}$ air. At a condenser inlet temperature of 88°F , the relative humidity was approximately 80%. The process gas was cooled to 39°F . The DF for the heat exchanger was 1.86. As heat was supplied to lower the relative humidity at a constant absolute humidity, the DFs decreased. At a relative humidity of 20%, no decontamination of insoluble particles through the condenser occurred. The steam injection rate was increased to obtain DFs at higher humidities. DFs above 2 were not achieved until the process gas became saturated at temperatures above 100°F . A maximum count-based DF of 16.2 was obtained with insoluble aerosols at 122°F and 0.096 lb $\text{H}_2\text{O}/\text{lb}$ air.

Off-gas temperatures at the condenser inlet are expected to be maintained below 100°F in the full-scale process. Therefore, insoluble aerosol

removal will be primarily controlled by the HEME. HEME DFs for TiO_2 aerosols were obtained as part of loading tests described in Section 6.4. The DFs are detailed here for comparison to soluble aerosol DFs.

Initial testing with insoluble aerosols was conducted at 150 scfm with an average HEME inlet concentration of $60.0 \mu\text{g}/\text{m}^3$. The off-gas temperature and humidity were at ambient conditions of approximately 75°F and 0.006 lb $\text{H}_2\text{O}/\text{lb}$ air ($\approx 32\%$ relative humidity). The HEME outlet concentration averaged $3.88 \mu\text{g}/\text{m}^3$ for a mass-based HEME DF of 15.5. The average HEME DFs as a function of particle size are shown in Figure 6.10. Higher HEME inlet concentrations were also obtained as a result of buildup of residual TiO_2 in the aerosol generator. The HEME inlet and outlet concentrations averaged $188 \mu\text{g}/\text{m}^3$ and $7.43 \mu\text{g}/\text{m}^3$, respectively, for a HEME DF of 25.3. Similar to results of NH_4NO_3 removal tests, these tests indicate that HEME DFs increase as the inlet concentration increases. The average HEME DFs as a function of particle size for tests at $188 \mu\text{g}/\text{m}^3$ are shown in Figure 6.11.

FIGURE 6.10. Average TiO_2 Aerosol DFs at an Inlet Concentration of $60.0 \mu\text{g}/\text{m}^3$

FIGURE 6.11. Average TiO_2 Aerosol DFs at an Inlet Concentration of $188 \mu\text{g}/\text{m}^3$

Tests were also conducted with TiO_2 at a higher relative humidity to more closely approximate the full-scale system. The off-gas flow rate was maintained at 150 scfm and steam injection was used throughout the test period to obtain an inlet off-gas stream with an absolute humidity of 0.0178 lb H_2O /lb air. The refrigeration system was not operated during these tests; therefore, the HEME inlet temperature was approximately 75°F. An average system inlet aerosol concentration of $153 \mu\text{g}/\text{m}^3$ was obtained. Approximately 83% of the total aerosol mass was between the 0.05- and 1.6- μm size range. A condenser DF of approximately 2 reduced the HEME inlet concentration to $68.0 \mu\text{g}/\text{m}^3$. The HEME outlet concentration ranged from 5.35 to $16.0 \mu\text{g}/\text{m}^3$, with an average of $11.6 \mu\text{g}/\text{m}^3$ for a HEME DF of 5.9. The average HEME DFs as a function of particle size are shown in Figure 6.12.

6.4 HEME LIFE EXPECTANCY

Extended loading tests of the HEME were conducted to estimate the life expectancy of the HEME filter and to determine the effect of water spray on

FIGURE 6.12. Average TiO_2 Aerosol DFs at an Inlet Concentration of $68 \mu\text{g}/\text{m}^3$, 80% Relative Humidity, 75°F, and No Refrigeration

regeneration. Soluble and insoluble aerosol particles were tested separately and then combined for a mixed soluble-insoluble loading tests. Initially, tests with NaCl and then TiO_2 were conducted for a period of 3 to 6 days to determine if an increase in the pressure drop through the HEME would be observed. Month-long testing was then conducted with NH_4NO_3 , then TiO_2 , and finally a mixture of both aerosols. After each extended test, the ability of water spray to regenerate the filter and lower the pressure drop was studied.

6.4.1 Soluble Aerosol Loading

Initial soluble aerosol loading tests were conducted with NaCl at a system inlet concentration greater than 1000 particles/mL in the 150 scfm process gas stream. The refrigeration system was not operated to maximize the particle counts to the HEME and to reduce the amount of water vapor carried over from the condenser. The process was operated continuously for 3.5 days, at which time a 3% increase in the pressure drop was observed. The QCM CI was used to monitor the HEME inlet and outlet mass concentrations and distributions on a daily basis. Figure 6.13 shows the average soluble

FIGURE 6.13. Average Soluble Aerosol Size Distribution

aerosol particle size distribution for the inlet and outlet HEME streams over the full test period. The majority of particles were generated in the 0.05 to 0.8- μm range. The HEME inlet concentration averaged $39.3 \mu\text{g}/\text{m}^3$ and outlet concentrations averaged $6.65 \mu\text{g}/\text{m}^3$.

To ensure that the increase in pressure drop was a result of aerosol loading rather than water loading, the filter was allowed to dry by pulling warm air through the filter without aerosol generation. No decrease in the pressure drop was observed. Water spray was operated at 50 mL/min for 116 min to attempt to wash the filter of entrained soluble particles. Again, the filter was dried by passing air through the filter. The filter pressure drop decreased after washing and drying to its original value of 6.60-in. water. This test indicated that water spray is effective in regenerating the HEME filter when it is loaded with soluble aerosol particles.

Loading tests were then conducted with NH_4NO_3 to attempt to foul the HEME filter and obtain life expectancy data. During loading tests, the off-gas flow rate was maintained at 150 scfm. Steam injection was maintained

throughout the test period to obtain an inlet off-gas stream at approximately 80% relative humidity. This corresponded to an absolute humidity of 0.0178 lb H₂O/lb dry air. During the 29-day test, an average inlet aerosol concentration of 133 $\mu\text{g}/\text{m}^3$ was maintained. Although the condenser was not operating during the loading tests, a condenser DF of approximately 2 was observed, thereby reducing the average HEME inlet concentration to 63.5 $\mu\text{g}/\text{m}^3$. This decontamination is likely a result of impaction on the condenser tubes and pipe wall as the off-gas stream passes through the heat exchanger. An average HEME outlet concentration of 13.3 $\mu\text{g}/\text{m}^3$ was obtained. The average size distribution for the NH₄NO₃ aerosols is shown in Figure 6.14.

The change in pressure drop (ΔP) over the 29-day period is shown in Figure 6.15. At the start of the test, the ΔP through the HEME was 7.26 in. of water. This increased to a maximum of 9.99 in. of water on day 25; however, during the entire test period, the ΔP fluctuated up and down as indicated in Figure 6.15. Although the ΔP was affected by a varying off-gas flow rate, an increase in the volume of condensate collected from the HEME is

FIGURE 6.14. Average NH₄NO₃ Aerosol Size Distribution During Loading Test

FIGURE 6.15. HEME Pressure Drop During NH_4NO_3 Loading Test

indicative of a washing of the filter from condensed steam. An average of 2.3 gal/day of steam condensate was collected by the HEME. This volume accounts for approximately 10% of the total steam injected into the system to raise the relative humidity to 80%. Because of this steady washing of the filter through mist removal, the HEME ΔP did not increase substantially (i.e., >100%) during the 29-day test. Approximately 21 g of NH_4NO_3 aerosols was loaded on the filter during the test; however, most of this was probably washed from the filter as a result of condensate. The filter was washed at the end of the test with the water spray at approximately 0.8 gal/hr for 1 hr. The spray appeared to be effective at washing additional NH_4NO_3 from the filter as the ΔP decreased below 7.2 in. of water to 6.91 in. of water.

6.4.2 Insoluble Aerosol Loading

Initial testing with insoluble aerosols was conducted for 6 days by generating TiO_2 aerosols at concentrations greater than 200 particles/mL at 150 scfm. Insoluble aerosol generation rates fluctuated depending on the liquid level in the generator, the solution concentration, and the generator air pressure. While particle counts were frequently maintained near

300 particles/mL, counts of 3000 particles/mL were also observed. Mass-based concentrations and size distributions are shown in Figure 6.16 for the first 3 days of operation. The average HEME inlet and HEME outlet concentrations were 60.0 and 3.88 $\mu\text{g}/\text{m}^3$, respectively. Higher concentrations were obtained during the last 3 days because of buildup of residual TiO_2 in the generator. The average distribution for this time period is shown in Figure 6.17. The HEME inlet and outlet concentrations averaged 188 and 7.43 $\mu\text{g}/\text{m}^3$, respectively. The pressure drop increased from 6.60 to 6.80 in. of water during the duration of the test. By averaging mass-based concentrations over the entire test period, a total aerosol loading was estimated. The cumulative mass loading based on these estimates is 4.58 g of TiO_2 .

The HEME filter was dried by pulling warm air through the system to ensure that the pressure drop was a result of insoluble particle loading rather than water vapor. The water spray was operated for 40 min at 50 mL/min to attempt to wash the HEME. Unlike the regeneration achieved with soluble aerosols, no decrease in the pressure drop was observed after water spray.

FIGURE 6.16. Average Insoluble Aerosol Size Distribution for Days 1 to 3

FIGURE 6.17. Average Insoluble Aerosol Size Distribution for Days 4 to 6

Extended loading tests were then conducted with TiO_2 to obtain data suitable for estimating life expectancy. As with NH_4NO_3 loading tests, the off-gas flow rate was maintained at 150 scfm. Steam injection was used throughout the test period to obtain an inlet off-gas stream with an absolute humidity of 0.0178 lb H_2O /lb air. The refrigeration system was not operated to minimize aerosol removal through the condenser. An average system inlet aerosol concentration of $153 \mu\text{g}/\text{m}^3$ was obtained. Approximately 83% of the total aerosol mass was between the 0.05- and $1.6\text{-}\mu\text{m}$ size range. Similar to soluble aerosol loading tests, a condenser DF of approximately 2 reduced the HEME inlet concentration to $68.0 \mu\text{g}/\text{m}^3$. The HEME outlet concentration ranged from 5.35 to $16.0 \mu\text{g}/\text{m}^3$ with an average of $11.6 \mu\text{g}/\text{m}^3$. The average size distribution for TiO_2 aerosols is shown in Figure 6.18.

The change in ΔP over the 35-day test is shown in Figure 6.19. Initially, the ΔP through the HEME equaled 6.93 in. of water. This increased to a maximum of 10.1 in. of water on day 30. The rapid increase in the ΔP at the beginning of the test is evidence of the effect of filter wetting and also indicates that fluctuations in the ΔP may be a result of water retention

FIGURE 6.18. Average Insoluble Aerosol Size Distribution for Extended 35-Day Test

FIGURE 6.19. HEME Pressure Drop During Extended TiO_2 Loading Test, 150 scfm

rather than aerosol loading. After stopping aerosol generation and steam injection on day 33, the HEME filter dried to a ΔP of 7.55 in. of water. After the filter was washed with water at 50 mL/min for 192 min and dried with warm air, the ΔP decreased to 7.29 in. of water. This indicates that washing of the filter is partially effective at removing insoluble TiO_2 . Therefore, fluctuations in the ΔP during the test period are most likely a result of changes in the volume of water retained in the filter fibers, washing from condensing water vapor, and variations in the off-gas flow rate.

Condensate collection during the first 20 days of testing was stable at approximately 9.7 L/day. The rate of condensate collection decreased at day 24, increased on day 25, decreased again, and increased rapidly to more than 18 L/day from days 29 to 30. This variation in condensate collection coincides with fluctuations in the HEME ΔP . As collection rates increased due to a decrease in room temperature, increase in steam injection rate, or increase in the humidity of the ambient air, the ΔP through the HEME decreased.

6.4.3 Mixed Insoluble-Soluble Loading

An extended test was conducted to closely simulate the expected full-scale operating conditions by generating a mixed insoluble-soluble aerosol stream. Two aerosol generators were used, one for soluble NH_4NO_3 and the other for insoluble TiO_2 . Daily, the generation rate of each aerosol was adjusted to maintain approximately an equal count-based concentration of each aerosol in the inlet to the system. High generation rates were used to increase the concentration of aerosols and attempt to accelerate loading of the HEME. Steam injection was used to maintain an inlet off-gas absolute humidity of 0.0178 lb H_2O /lb air (approximately 80% relative humidity at 80°F). The refrigeration unit and condenser were operated to simulate the full-scale ventilation system by cooling the off-gas stream to approximately 37°F. During loading tests with NH_4NO_3 and TiO_2 , condensed water vapor was collected by the HEME and resulted in continuous washing of the filter. In addition, water removal tests indicated that carryover of condensed water vapor from the condenser to the HEME was dependent on the off-gas flow rate.

To minimize washing of the HEME filter from condensing water vapor during the mixed loading test, the process was operated at 80 scfm.

The average system inlet concentration for the 30-day test was $537 \mu\text{g}/\text{m}^3$ of mixed aerosols. Several mass-based concentrations were measured with only one of the two generators operating at a time to determine the ratio of each aerosol in the off-gas stream. Although the count-based concentrations of each aerosol were approximately equal, soluble NH_4NO_3 aerosols represented approximately 66% of the total mass-based concentration. The condenser outlet concentration averaged $193 \mu\text{g}/\text{m}^3$ for a condenser DF of 2.8. The average HEME outlet concentration was $7.87 \mu\text{g}/\text{m}^3$. The average size distribution during the mixed loading test is shown in Figure 6.20. A high concentration of particles in the 12.5 to $25\text{-}\mu\text{m}$ size range was generated during these tests and is probably a result of the high generation rates used in this test. When higher generation rates are attempted, large water droplets are easily formed from bubbling of the liquid in the aerosol generator.

FIGURE 6.20. Average Mixed Soluble-Insoluble Aerosol Size Distribution for Extended 30-Day Test

As indicated in Figure 6.20, most of the larger aerosols were removed by the condenser through either impaction or condensation and did not add significantly to the loading of the HEME.

The change in ΔP over the 30-day test is shown in Figure 6.21. Because the test was conducted at 80 scfm, the ΔP through the HEME was much lower than achieved during prior testing at 150 scfm. Initially, the ΔP through the HEME equaled 3.60 in. of water. This increased to a maximum of 4.76 in. of water on day 24. During the first 9 days of testing, steam injection was not used because of a mechanical problem with the steam regulating valve. The increase in the ΔP on day 9 coincides with the start of steam injection. Although there is no indication that the HEME began collecting condensate at this time, it is likely that the stream exiting the condenser became saturated with water vapor when steam injection was started. This may have resulted in a wetting of the HEME fibers and an increase in the ΔP . Water collection by the condenser was steady at approximately 77 L/day from day 9 through day 30. Fluctuations in the ΔP during the test period are most

FIGURE 6.21. HEME Pressure Drop During Mixed Soluble and Insoluble Extended Loading Test, 80 scfm

likely a result of changes in the volume of water retained in the filter fibers and variations in the off-gas flow rate. After stopping aerosol generation and steam injection on day 30, the HEME filter dried to a ΔP of 4.10 in. of water. After the filter was washed with water at 50 mL/min for 70 min and dried with warm air, the ΔP decreased to 3.90 in. of water or approximately 8% above the initial ΔP .

Based on results of the mixed soluble-insoluble loading test and an estimated average full-scale aerosol concentration of $15 \mu\text{g}/\text{m}^3$, the HEME will operate for more than 1000 days without an appreciable increase in the ΔP . Intermittent washing of the HEME filter with a water spray would be beneficial in removing collected aerosols and regenerating the filter. The frequency of washing and optimum water spray conditions such as pressure and temperature were not evaluated during pilot-scale testing.

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