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DRAFT

EXPERIMENTAL RESULTS OF ACE VENT FILTRATION, POOL SCRUBBER TESTS AA1-AA4 AND DOP1-DOP5

JANUARY 1989

J. D. McCormack

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ABSTRACT

A series of four aerosol scrubbing tests were done with a sparger at submergences of 1.6 to 4.6 m in a buffered pool and are reported in detail. Aerosols used were formed from the vapor phase using Cs, Mn, and I and had AMM diameters of about 2 μm. The tests were done with pool temperatures at about 25 and 82°C and with steam volume fractions in the carrier gas from 0.01 to 0.42. The aerosol carrier gas temperatures ranged from 130 to 150°C. Superficial gas velocity in the pool based on the outlet gas volume ranged from 0.034 to 0.119 m/s. Entrainment measurements were made. Also, ambient temperature scrubbing tests were done using dioctylphthalate (or dioctyl sebacate) aerosol. Decontamination factors reported ranged from 11 to 3000, were highest for soluble aerosols and varied with pool depth

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We are grateful to the approximately 15 people who participated directly in the performance of the experiment and the others doing the necessary work of consulting, equipment design, crafts, chemical analysis, electron microscopy, and stenography.

The ACE program is supported by a multinational consortium whose membership is listed on the cover of this report. EPRI provided the necessary liaison between the sponsors and the test performer.

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ACRONYMS

ACE	Advanced Containment Experiments
ADL	Aerosol Delivery Line
AMMD	Aerodynamic Mass Median Diameter
AMV	Aerosol Mixing Vessel
ANSI	American National Standards Institute
BWR	Boiling Water Reactor
CSTF	Containment Systems Test Facility
CV	Containment Vessel
DAS	Data Acquisition System
DEMONA	Demonstration of Nuclear Aerosol Behavior
DF	Decontamination Factor
DOP	Dioctylphthalate
DOS	Dioctyl Sebacate
DP	Differential Pressure
EPRI	Electric Power Research Institute
FTV	Filter Test Vessel
GSD	Geometric Standard Deviation
HI	Hydrogen Iodide
LACE	LWR Aerosol Containment Experiment
LWR	Light Water Reactor
PNL	Pacific Northwest Laboratory
SEM	Scanning Electric Microscope
SGS	Submerged Gravel Scrubber
TAC	Technical Advisory Committee
TTW	Through-The-Wall
WHC	Westinghouse Hanford Company
XRD	X-Ray Diffractometry

Section 1

INTRODUCTION

An Advanced Containment Experiments (ACE) Program is being funded by an international consortium (members listed on inside cover). The objectives of the ACE program are: 1) to provide a comparative experimental basis for aerosol removal techniques (e.g., submerged gravel beds, water pools, filters etc.), 2) to provide data for modeling transport of radioactive iodine species, 3) to determine fission product releases from molten "corium" concrete reactions, and 4) to develop and validate applicable computer codes and models. The first of these objectives is being done as Phase A of the ACE Program. In Phase A, testing is being done to compare the means of controlling the fission product release using passive filtering devices such as are being employed or considered for use in light water reactors in many countries.

One method of filtering the gases that would be exhausted while venting the containment of an LWR is to use a pool scrubber. This is one of the simplest methods and/or proposed devices, which ranges from sand and gravel beds to filters and venturi scrubbers.

This report discusses the first series of Phase A tests of the aerosol removal techniques. These were done with a pool scrubber configuration. The purposes of the pool tests were:

- to expand the data on removal of aerosols by pools to CsOH, CsI, and MnO (i.e., some typical representative soluble and insoluble aerosol species)
- to obtain decontamination factor data that can be indexed to data obtained by others
- to measure carryover (entrainment) from the pool
- to obtain pool effects data apart from later tests with a submerged gravel scrubber and a submerged venturi scrubber, which use a pool together with other devices
- to demonstrate and calibrate apparatus to be used to test other vent cleanup devices.

The tests were done at the Containment Systems Test Facility (CSTF) at Hanford by Battelle-PNWL and Westinghouse Hanford Company. The program is utilizing the apparatus and expertise developed for the recently completed LWR Aerosol Containment Experiments (LACE) Program.

1.1 BASIS OF TEST

Venting of containment is a risk reduction strategy which could be carried out after some time in the course of a major Loss-of-Coolant Accident in an LWR.(2) The design flow rates required to arrest the pressure increase in the containment depend on the accident assumptions and the filtering devices can be sized to give the required efficiency for the flowrates needed. Therefore, these ACE-phase A tests are designed to use realistic flowrates scaled to the size of the experimental apparatus.

The aerosols to be used are 1) an insoluble aerosol to simulate those insoluble aerosols that may be generated from overheated fuel and cladding, core-concrete interactions, etc., 2) a soluble aerosol, cesium hydroxide, and 3) an iodine containing aerosol, specifically cesium iodide. The concentrations of radioactive aerosols in the containment at the time of venting determines the necessary decontamination to give a certain release, and knowledge is needed of both the concentration and the decontamination to determine a risk. The tests are designed to determine decontamination factors for these three types of aerosols. The aerosol concentrations for the experiment are determined by the available generation methods, the time period of the experiments, sampling times, and sensitivity of the analysis techniques.

1.1.1 Steam/Gas Mixture and Flowrate

Most accident scenarios result in considerable steam being present in the containment at the time of venting. The German design for the Brokdorf filter assumed mainly steam flow with up to 25% air and other gases flowing at 0.3 m/s at 0.12 MPa and 132°C in the filter. The French use 29% steam with 33% air and 33% CO_2 and 5% CO and an aerosol concentration of 0.1 g/m^3 as design values for their vent/filter system (1).

Since no prototype pool scrubbers for containment venting use have been proposed, the flow rate of the gas through the ACE test Pool Scrubber is based on a typical design of sparging pools and pressure suppression pools of BWR's, and is of typical

depth. The area of the pool is smaller than it would be in an actual reactor but the size is large enough to remove any significant effects of the walls since the diameter is much larger than the bubble size.

Section 2

SUMMARY

One method of filtering the gases that would be exhausted while venting the containment of an LWR is to use a pool scrubber. This is one of the simplest methods and/or proposed devices which range from sand and gravel beds to filters and venturi scrubbers. Many of these methods have been designed and tested individually and they are being installed in some European reactor complexes. A series of four aerosol experiments were performed in which an aerosol mixture of MnO, CsOH, and CsI were sparged through a water pool. A representative mix of steam, nitrogen, and aerosol were bubbled through a scrubbing pool of water at a lower temperature (25°C) and at a higher temperature (82°C) and the decontamination factors for the aerosols were measured. The particle sizes of the aerosol mixture were typically of 2 μm AMMD, GSD = 2. Decontamination factors were obtained for the three different aerosols. With no aerosol flowing, reentrainment of liquid from the pool was also measured at the selected flow rates. In addition to the tests using the aerosol mixture, a standard filter efficiency test was made with dioctylphthalate (DOP) to provide a means of independent comparison with results from other sites.

Section 3

DESCRIPTION OF EXPERIMENTAL ARRANGEMENT

3.1 FACILITY DESCRIPTION

The test facility is the Containment System Test Facility (CSTF) at 221T building at the Hanford Site. The ACE-Phase A tests utilized an existing water tank as a filter test vessel (FTV). With the FTV partly filled with water, a pool type scrubber was simulated by bringing the steam-aerosol mixture from the existing mixing vessel into the pool through a pipe and sparger and then exhausting the scrubbed gases to the existing outlet scrubber and fan [not shown] (Figure 3-1). Aerosol sampling ports at the inlet and outlet of the FTV were used to obtain the inlet and outlet aerosol concentrations from which the decontamination factor could be calculated. A hydrogen iodide feed system was added to the previously existing cesium hydroxide and manganese oxide aerosol generating apparatus to produce an aerosol of cesium iodide.

3.1.1 Building Arrangement

The FTV that was used to test the sparger (pool scrubber) arrangement for these experiments is located inside the CSTF - Containment Vessel (CV). The CSTF itself is located within a concrete building that also includes office space, chemical laboratory space, maintenance facilities, effluent disposal facilities and utility services. The building arrangement is shown in Figures 3-2 and 3-3.

3.1.2 Filter Test Vessel

The FTV was built by modifying the internal tank, which held the flashing pool in LACE 5 and 6 Experiments. A dimensional sketch of the FTV location is shown in Appendix A and a sketch of the experimental arrangement is shown in Figure 3-1.

The FTV is a vertical cylinder, with a 1.5 m inside diameter and height of 6.1 m. It contains a steam heating coil, thermocouples, and level sensors. It is insulated and the upper one meter is heated electrically to minimize heat loss through the wall.

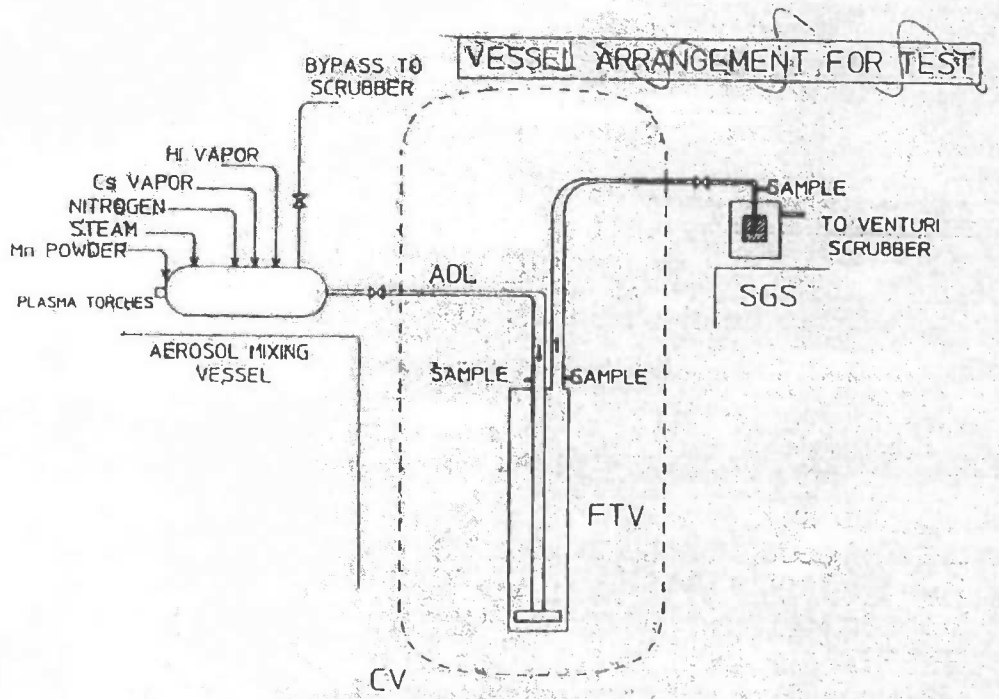

Figure 3-1. Vessel Arrangment for the Test

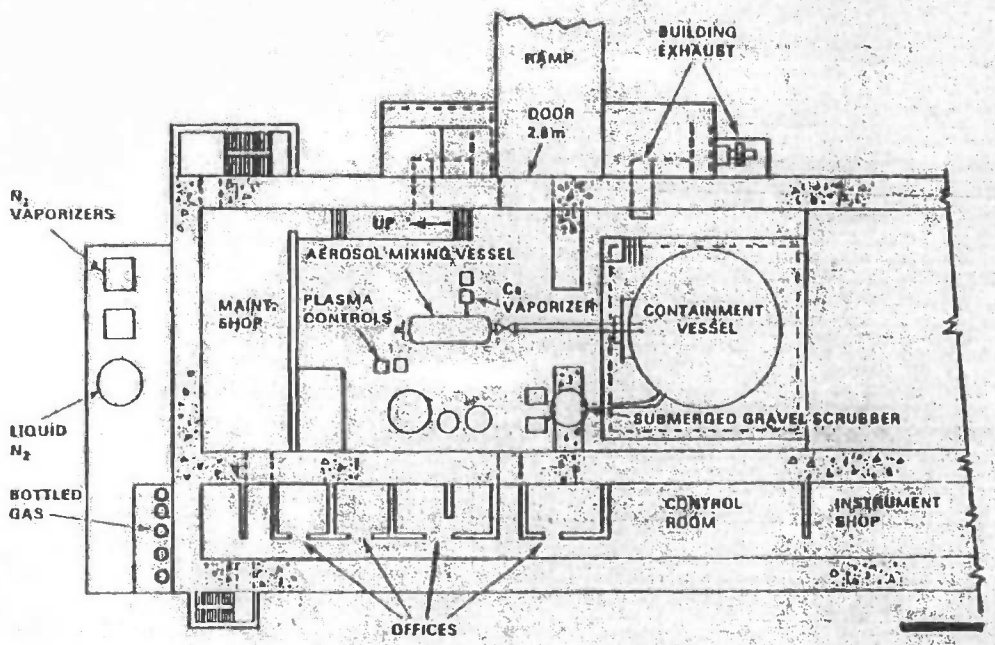

Figure 3.2. Plan View of CSTF Building Arrangement

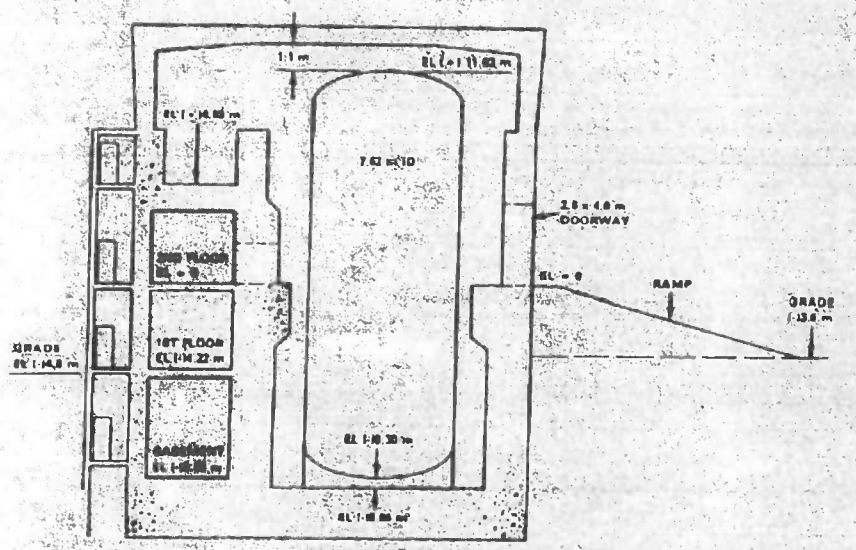

Figure 3-3 CV Arrangement in the CSTF Building

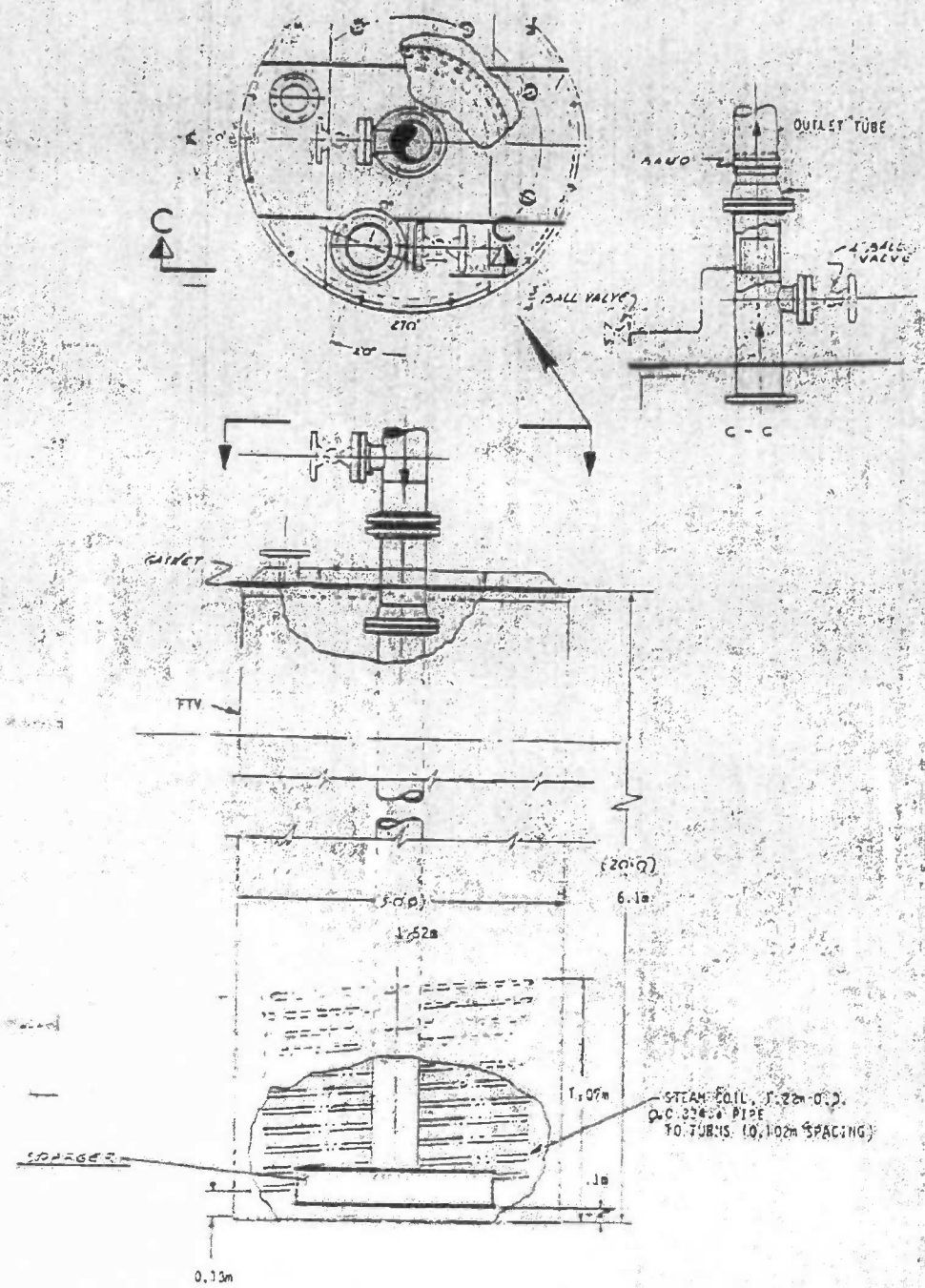

Figure 3-4. Filter Test Vessel Arrangement

3.1.3 Building Services

Steam is supplied to the CSTF from a nearby boiler house by two steam lines. One is a low-pressure line (0.6 MPa) designed to provide a 0.8 kg/s flow rate and the other is a high-pressure line (1.5 MPa) designed to provide a 0.2 kg/s flow rate. Inline 15-kW and 30-kW electrical heaters are provided to produce the required superheat.

The CSTF is equipped with a liquid nitrogen supply tank and atmospheric evaporators designed to maintain a flow rate of 0.25 standard m^3/s. The existing nitrogen gas delivery line is adequate for flow rates to ~0.2 m^3/s. The 11.4-m^3 liquid nitrogen supply is equivalent to ~7800 standard m^3 of N_2 gas. A 75-kW electric heater in the nitrogen gas line provides the capability of preheating the nitrogen when this is necessary. In addition, a compressed air supply line designed to maintain a flow rate of 0.05 standard m^3/s at 0.6 MPa is available.

3.2 POOL SCRUBBER DEVICE

Figure 3-5 is a sketch of the sparger, which was located in the FTV pool to break up the gas flow into bubbles.

The sparger consisted of a vertical, insulated, downcomer pipe attached to the lid of the FTV and through which the aerosol was sent into a round, flat chamber near the bottom of the pool. The chamber had a total of 51, 9.5 mm (3/8") holes drilled vertically through the top plate (details are listed in Table 3-1). Thirty of these holes were at a radius of 419 mm and 21 were on a second circle of 368 mm radius. There were also four, 12.7 mm weep holes through the bottom plate of the sparger to allow drainage when the FTV is emptied. The sparger downcomer pipe had standoff spokes (with foot plates on the ends) to stabilize the hanging sparger in case of chugging or vibration when the system was running.

3.2.1 Rationale of Sparger Design

This test had the following purposes:

- to measure the decontamination of test aerosols (simulating aerosols in containment) by a scrubbing pool
- to provide the pool data to validate the ACE testing methods by comparing with tests by others
- to obtain pool scrubbing decontamination separate from other decontamination phenomena that are combined with pool scrubbing in devices such as submerged gravel scrubbers and submerged venturi scrubbers. These combined devices are to be tested later in the program.

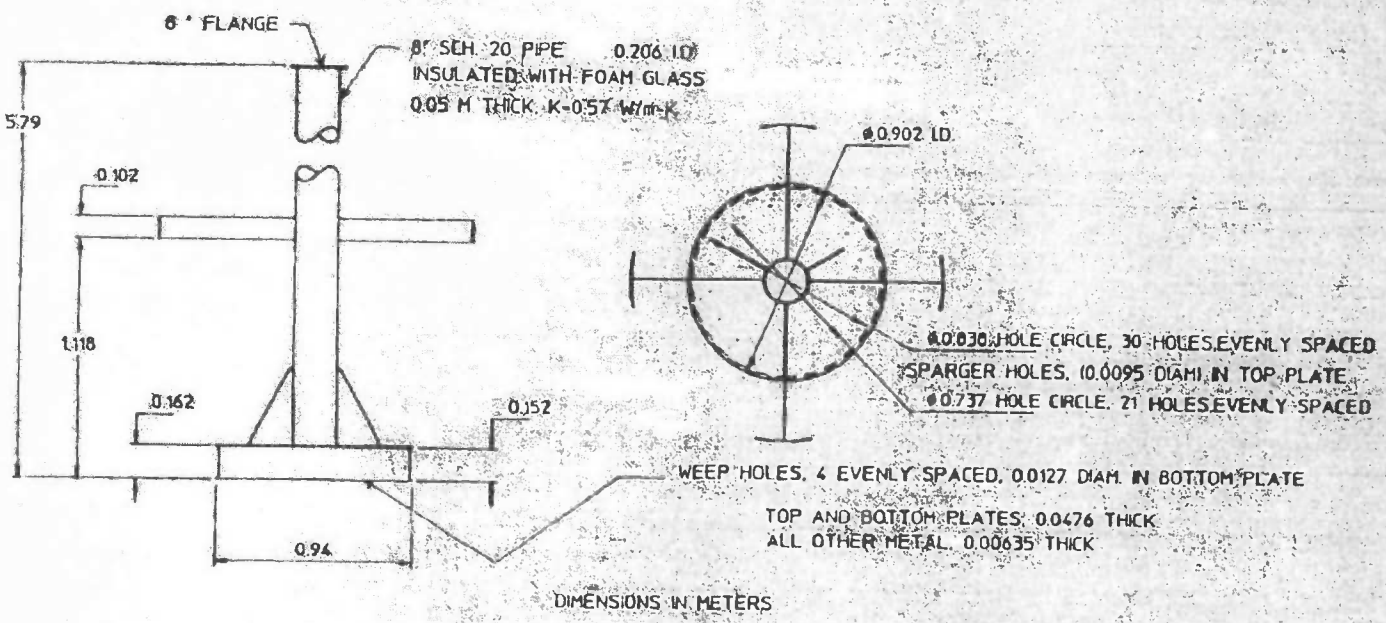

Figure 3-5. Sparger Insert

Table 3-1

SPARGER GEOMETRY

Thickness of insulation on vertical pipe, foamglass, m	0.009525
Inside diameter of fiber test vessel, m	1.524
Inside diameter of sparger pan, m	0.902
Inside diameter of sparger inlet pipe, m	0.206
Inside depth of sparger pan, m	0.1524
Diameter of sparger holes, m	0.009525
Diameter of outer circle of 30 holes, m	0.838
Diameter of inside circle of 21 holes, m	0.737
Number of sparger holes	51
Total area of sparger holes, m^2	0.00363
Diameter of sparger drain holes, m	0.0127
Number of sparger drain holes	4
Height of sparger hole from bottom of FTV, m	-0.263
Thickness of insulation on vertical pipe, foamglass, m wrapped with stainless steel jacket	0.05
Thermal conductivity of foamglass insulation, W/m-K	-0.57

The flow rates, hole diameters, steam contents, and pool depths were chosen to be compatible with these purposes. The entry pipe into the sparger was insulated to minimize condensation on the pipe wall (condensation would actually occur in a prototype that would not be insulated) because the condensation would carry aerosol with it, change the steam content and generally make it difficult to assess the effect of the pool scrubbing action only. Although pool scrubbers are not currently being used for containment venting, the principle is utilized in BWR pressure suppression systems. For these a typical hole size is about 1 cm. To get small bubbles, orifices of this size are usually operated at Reynolds numbers above 6000. For the sparger design, a Reynolds number of 10,000 implies a velocity through a 1 cm hole of about 20 m/s. This, and the desired total flowrates of about 0.085 m^3/s determined the number of holes for the sparger. The velocity head pressure drop across such an orifice at about 20 m/s velocity is about 152 Pa or about 1.5 cm water

head. This head could easily be accommodated by the 15 cm depth of the sparger pan such that no gas would pass through the drain holes on the bottom of the pan.

3.3 AEROSOL GENERATING SYSTEM

Aerosols were generated separately by vaporization/ condensation processes and mixed in the 5-m^3 Aerosol Mixing Vessel (AMV), to provide some agglomeration, chemical reaction, and fallout of oversize particles before sending the combined stream to the FTV. Cesium hydroxide (CsOH) was used as a water soluble species. Manganese oxide (MnO) was used for the insoluble species. The method of generating these two aerosols had been demonstrated in the LACE tests. Hydrogen iodide was used to provide iodine to the aerosol. Most of the HI will react in the AMV to form CsI, which is the primary form of iodine predicted in severe reactor accidents (Gieseke et al. (8). HI was provided to give a Cs:I ratio of 10:1, as is indicated by fuel release calculations. Other iodine compounds are predicted to be formed in lesser amounts. But these are highly dependent on oxidation-reduction conditions, radiation, and pH, and were not added in the these tests.

3.3.1 CsOH Aerosol Generation System

CsOH aerosol was generated by reaction of cesium vapor with steam. Elemental cesium was heated in a pressurized supply vessel and discharged into a heated vaporizer coil at a controlled flow rate. The vaporized Cs and a low flow rate of nitrogen sweep gas flowed through a heated line to the AMV. The reaction products were hydrogen gas and particles of CsOH. A schematic diagram of the system is shown in Figure 3-6. In some tests the steam was supplied in minimum (stoichiometric) amount by metering water into the AMV. A fraction of the Cs will react to form CsI, as noted above.

3.3.2 MnO Aerosol Generation System

Manganese powder transported by argon gas was vaporized in a 50-kW helium-argon plasma torch and discharged to a reaction chamber filled with a mixture of steam and nitrogen as was done in the LACE tests. The Mn reacts with steam to form MnO aerosol particles and H_2. A schematic diagram of the system is shown in Figure 3-7. (In some tests, the steam was supplied in minimum (stoichiometric) amount by metering water into the AMV.)

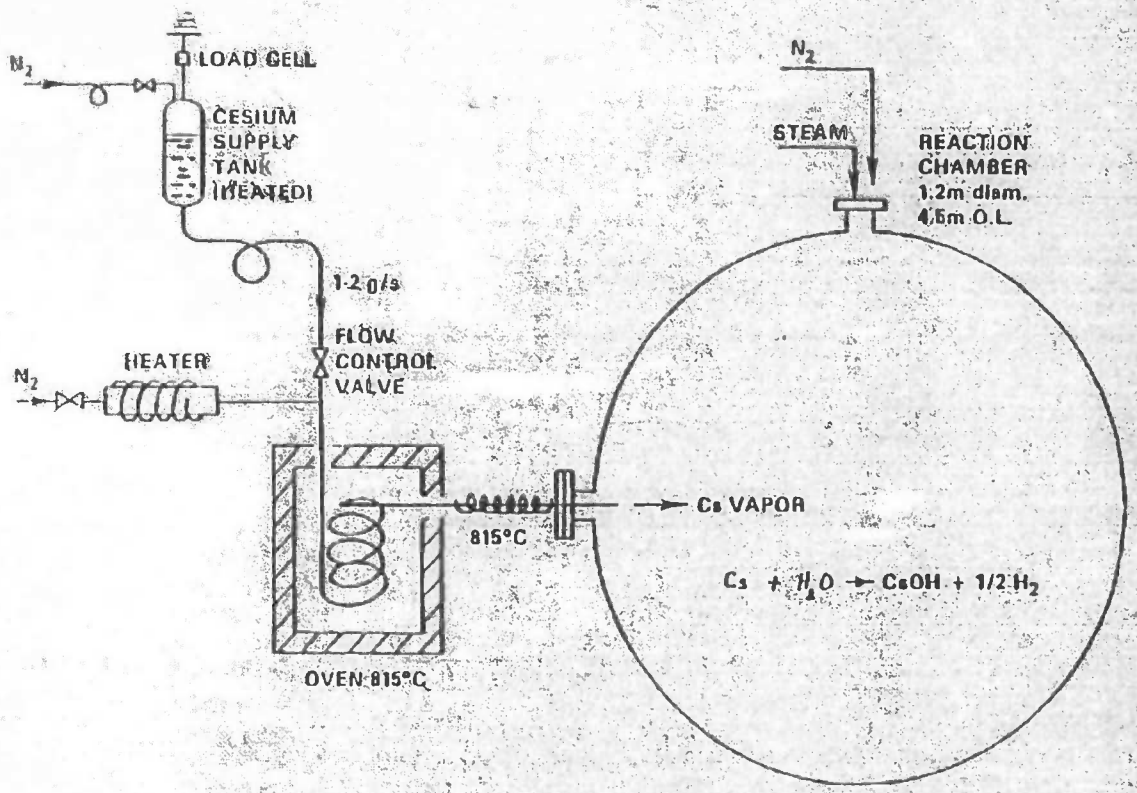

Figure 3-6. Schematic Diagram of CsOH Aerosol Generation System

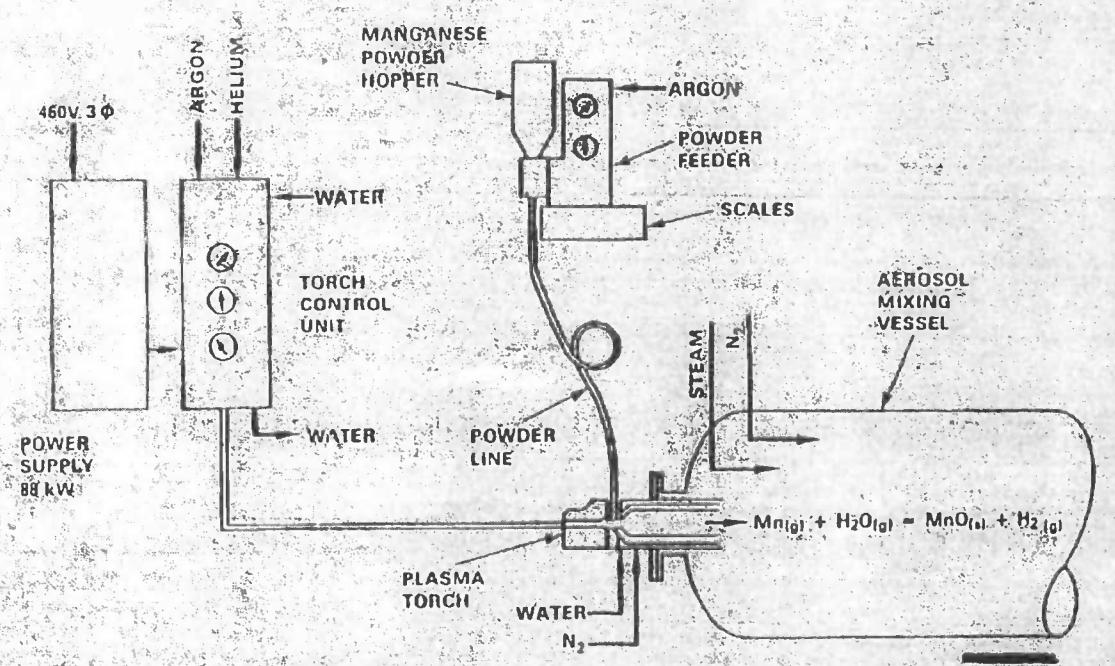

Figure 3-7. Schematic Diagram of MnO Aerosol Generation System

3.3.3 Iodine Injection System

Anhydrous hydrogen iodide gas in a pressurized cylinder was metered at a controlled pressure into the aerosol mixing vessel. The meter calibration was initially calculated from theory and the rotameter air calibration. Since the weight of the HI fed was measured, the early tests themselves were used to correct the rotameter calibration in subsequent tests. The HI vapor passing into the AMV reacts with the CsOH to produce CsI. Analyses of the tests showed that cesium and iodine were closely associated in the piping and scrubbing system. A schematic diagram of the system is shown in Figure 3-8.

3.3.4 Aerosol Mixing Vessel (AMV) and Delivery System

The mixing of the aerosol forming vapors with the steam/nitrogen carrier gas was done in the AMV (shown schematically in Figure 3-1). The 5.2 m^3 AMV is 1.22 m in diameter by 4.57 m overall length and is fabricated from carbon steel. The AMV is oriented horizontally, with the plasma torches located at the opposite end from the ADL nozzle. Steam (if used) and nitrogen were injected into the AMV through separate ring manifolds located near the plasma torches. Cesium vapor was injected through a side nozzle at a distance of 2.3 m from the outlet of the plasma torches. Water (if used) was injected into the hot N_2 pipe at the entry to the AMV (see Figure 3-9).

The wall of the AMV was heated electrically by exterior rod heaters and is insulated. A filtered liquid drainage system is provided to recover aerosol deposited in the AMV during post-test cleanup operations.

The aerosol delivery line (ADL) from the AMV to the FTV was connected to a 200 mm ball valve which was located just outside the AMV. It is a carbon steel pipe, 203 mm in ID and about 7.6 m in overall length. The pipe continued horizontally from the valve for about 4.7 m and then bent down at a 0.3 m radius (Sch. 40, 8" LR elbow) to become vertical for about 2.7 m before its attachment to the aerosol sampling section (TTW) on the FTV lid. The entire length of the ADL was insulated.

A TTW aerosol sample station (T5) was installed on the entry pipe which extended 0.48 m below the lid of the FTV where the insulated sparger downcomer was attached. Two thermocouples were installed at the same location, one in the gas stream and one on the outer wall of the pipe beneath the insulation.

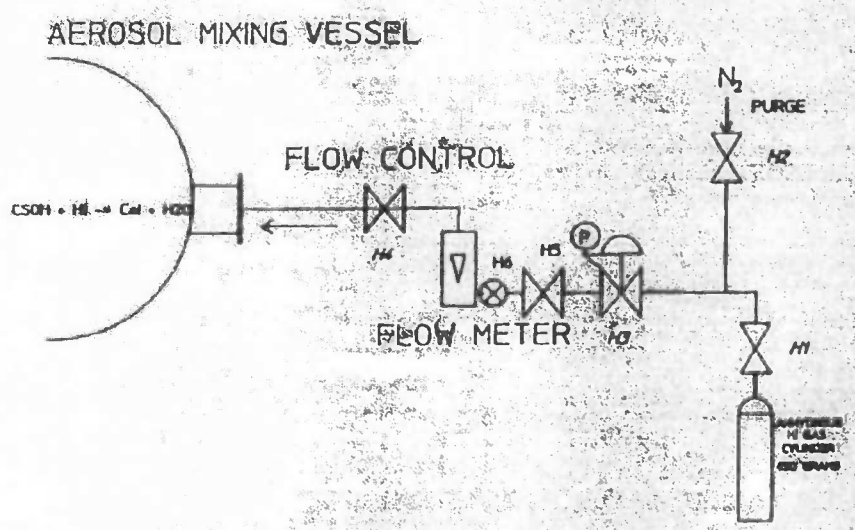

Figure 3-8. Schematic Diagram of HI Injection System

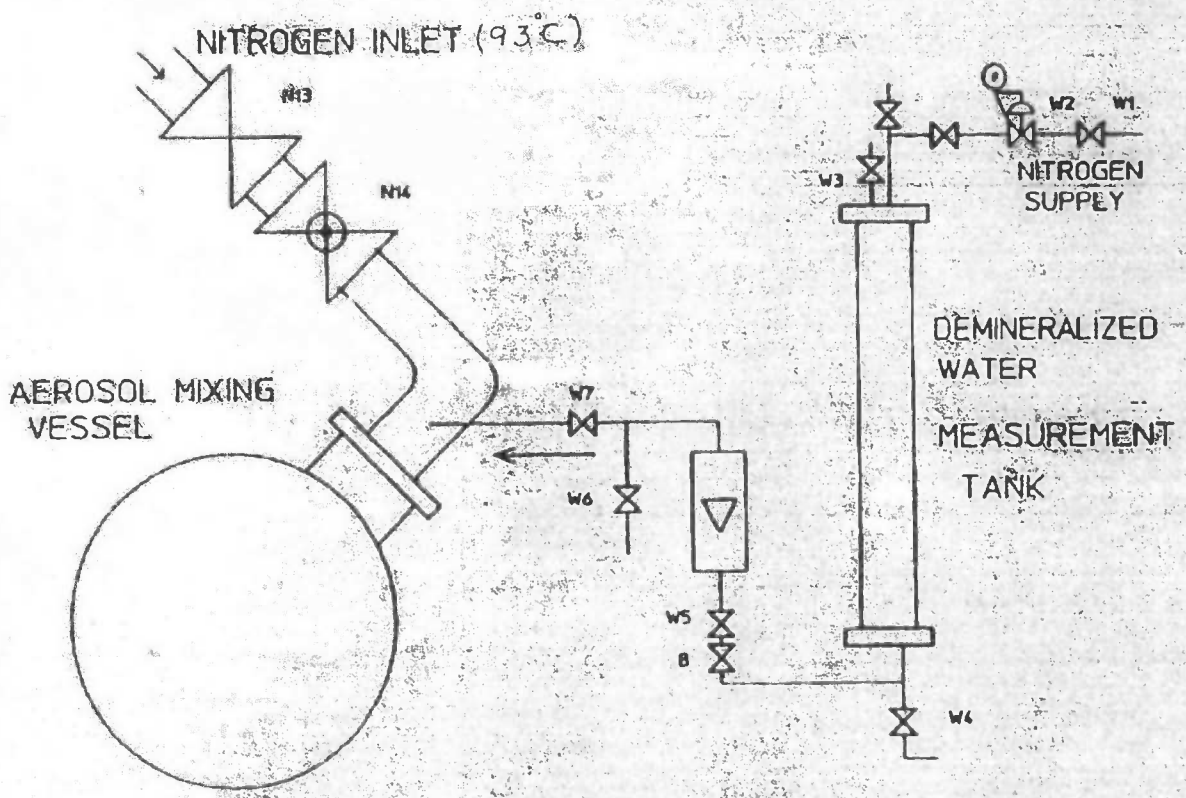

Figure 3-9 Schematic Diagram of Water Injection System

3.4 INSTRUMENTATION

Much of the instrumentation used in the ACE A series of tests was used previously in the LACE tests. A detailed description of these instruments is given by Albiol and McCormack (10). A list of the principal instruments and measurement methods is provided in Table 3-2, together with estimates of uncertainties associated with each measurement.

3.4.1 Through-the-Wall (TTW) Sample Stations

Three TTW sample stations were used, one (designated T5) on the ADL near the entry to the FTV. One (T6) on the exit line from the FTV and one (T7) at the inlet to the containment vessel vent scrubber (see Figure 3-10).

Each TTW station consisted of a 100-mm-diameter air lock chamber attached to the sampling point. By opening the air lock ball valve, various types of sampling devices were inserted directly into the containment atmosphere. The devices were attached to a hollow push rod that had a sliding seal at the end of the air lock chamber. Sampling gas was withdrawn through the sampler via the hollow push rod.

Three types of samples were taken at the TTW station: filters, cascade impactors, and etched Nuclepore filters for SEM. The filter and impactor samples required accurate control and measurement of the gas/steam flow rate. This was accomplished by condensing the steam downstream of the sample and measuring the flow rate of noncondensible gas with a rotameter.

To prevent condensation in the sampler, the sampling devices were preheated in an oven to a temperature slightly (1-5°C) greater than that of the sampled environment.

3.4.2 TTW Filter Samples

The TTW filter samples were taken on 47-mm diameter glass-fiber filters* mounted on stainless steel filter holders. After cooling, some of the filter papers were weighed and all of them were analyzed chemically for Cs and Mn mass. The inlet surfaces of the filter holder were washed and analyzed also. These washes and any aerosol material on the backup charcoal paper were combined and the total was used to determine the aerosol concentration (Section 6.2.2). Both contributions to the totals were usually small.

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*Gelman type A/E, manufactured by Gelman Instrument Co., Ann Arbor, Michigan

Table 3-2

EXPERIMENTAL MEASUREMENTS AND ACCURACY

Measurement	Number of Loc.	Target No. of Times	Accuracy	Method
Suspended aerosol CsOH and MnO mass concentration in ADL	1	5	±25%	TTW filter samples, analysis for Cs, Mn, I
Suspended aerosol CsOH and MnO mass concentration in FTV exit gas	1	3		TTW filter samples, analysis for Cs, Mn, I
Aerosol particle size distribution in ADL	1	3	±25%	Cascade impactor; analysis for Cs, I, Mn, weighing
Aerosol particle size distribution in FTV exit gas	2	3	±25%	Cascade impactor; analysis for Cs, I, Mn, weighing
Primary particle morphology in aerosol in ADL suspended in FTV exit gas	1	1	N/A	SEM
Aerosol chemical composition in test ADL	1	1	N/A	Chemical analysis of filter sample; XRD
Volumetric flow rate of steam to AMV	1	a	±5%	Orifice meter
Volumetric flow rate of N_2 to AMV	1	a	±5%	Turbine meter
Volumetric flow rate of other gases to aerosol generator	1	a	±10%	Flow meter
Composition of noncondensible gas in ADL (vol %)	1	2	±20%	Mass spectrometry grab samples after condensing steam
Temperature of outer wall of ADL	2	a	±5°C	Thermocouple
Aerosol mixing chamber pressure	1	a	±1%	Transducer
Overall Cs mass balance	N/A	1	±10%	Weighing, washing, volume analysis for Cs
Overall Mn mass balance	N/A	1	±15%	Weighing, washing, volume analysis for Mn

Table 3-2

(continued)

Measurement	Number of Loc.	Target No. of Times	Accuracy	Method
Cs instantaneous feed rate	1	a	±20%	Load cell, weight loss of feed tank
Overall I mass balance	N/A	a	±10%	Weighing, washing, volume analysis for I
Total Cs mass fed to vaporizer	1	1	±4%	Weight difference
Mn instantaneous feed rate	1	a	±20%	Load cell, weight loss of feed tank
Total Mn fed to torches	1	1	±4%	Weight difference
Vent rate of gas from FTV	1	a	±5%	Orifice meter
HI feed rate	1		±10%	Weight difference, rotameter

[a]Data logger frequency.

3.4.3 Charcoal Backup

At stations T5 and T6 a charcoal loaded backup paper* was used on filter samples. The backup paper was chemically analyzed for I and Cs.

3.4.4 Cascade Impactors

Two types of cascade impactors were used: Anderson Mark III and Sierra Series 220 **. Glass fiber stage collection filters were used to facilitate unloading so that each impactor could be quickly reloaded for repeated use during each experiment. The glass fiber collection surface also retained any liquid aerosol. Most of the impactors were 8-stage, but some had only 6 stages.

*Schleicher & Schuell, Keene, New Hampshire. (S & S 910)

**Manufactured by Anderson Samplers, Inc., Atlanta, Georgia.

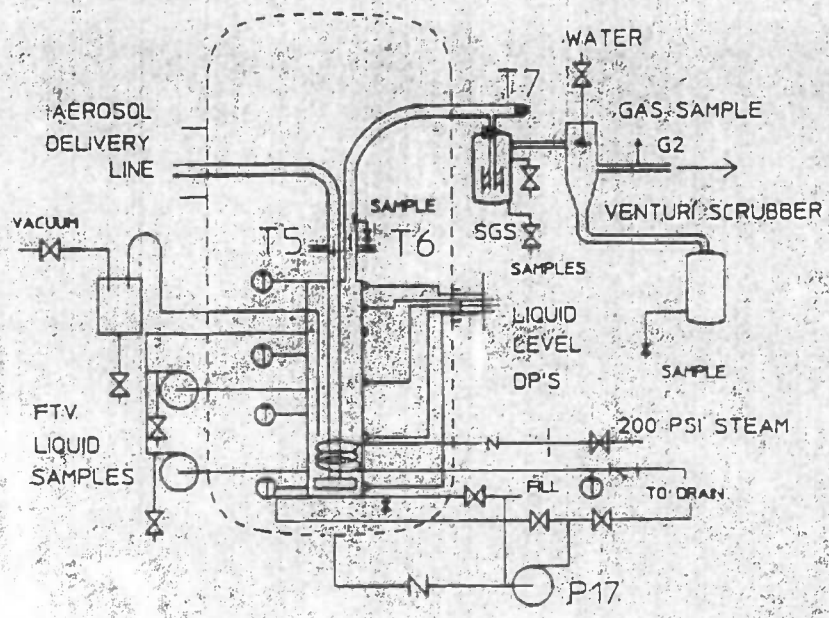

Figure 3-10. Filter Test Vessel and Sampling Locations

The two types of impactors used in these tests were calibrated with ammonium fluorescein and polystyrene latex particles with room temperature air by Cushing et al. (4). The sampling conditions and stage cutoff diameters obtained by Cushing are listed in Table 3-3. The procedures in these tests called for sampling at flow rates close to those used by Cushing. The cutoff diameters listed in Table 3-3 were adjusted for actual sampling conditions by use of Eq. 3-1:

$$d_{50} = (d_{50})_{ref} \left[\left(\frac{\mu}{\mu_{ref}} \right) \left(\frac{Q_{ref}}{Q} \right) \right]^{0.5} \qquad (3\text{-}1)$$

where d_{50} = aerodynamic cutoff diameter at sampling conditions

μ = viscosity of gas at sampling conditions

Q = gas flow rate at sampling conditions

ref = subscript indicating value of parameter under calibration or reference conditions.

Table 3-3

STAGE CUTOFF DIAMETERS FOR CASCADE IMPACTORS USED IN TEST AA1-4

Number	$(d_{50})_{ref}$ (μm) Andersen III[a]	Sierra 226[b]
1	13.2	18.0
2	8.3	11.0
3	5.64	4.4
4	3.8	2.65
5	2.45	1.7
6	1.25	0.95
7	0.77	0.53
8	0.52	0.32[c]
9	--	0.16[c]

[a]Size of unit density spheres removed with 50% efficiency at 21°C, 1 atm pressure, and 14.2 ℓ/min at flow conditions.

[b]Size of unit density spheres removed with 50% efficiency at 28°C, 1 atm pressure, and 7.15 ℓ/min at flow conditions.

[c]From manufacturer's catalogue.

Particle size distributions were constructed from the sample data using the method described by Mercer (5).

3.4.5 Steam and Gas Flow Rate Measurement

The flow rates of steam to the CV and AMV were measured by sharp-edged orifice meters. A moisture separator in the supply line minimized the amount of liquid carried by the saturated steam. The temperature and pressure of the steam upstream of each meter were measured. For low steam-fraction tests, water was injected into the heated nitrogen line and controlled using a rotameter (Figure 3-9). After the test, the total water was determined from changes in the supply tank amount.

Nitrogen flow rate was measured by a turbine meter with an electronic output signal to the data acquisition system (DAS). The temperature and pressure at the meter were also measured.

Miscellaneous small gas flows which were measured by rotameters were read and recorded manually. These include the plasma torch gas feeds, the Cs evaporator carrier gas, the ADL nitrogen purge, and the gas flow rates at the TTW sampling stations. The temperatures and pressures at the rotameters were measured.

3.4.6 FTV Liquid Level and Sampling

The method of liquid level measurement was by a bubble tube system. The setup used in tests AA1 and AA2 (Figure 3-11) was changed for greater accuracy to that shown in Figure 3-12 for tests AA3 and AA4.

3.4.7 Noncondensible Gas Composition

The composition of aerosol carrier gas flowing from the AMV to the FTV was calculated from the measured volumetric flow rates of steam and gases fed to the AMV. In addition, the composition of noncondensible gas was measured by taking two gas samples from the AMV (after condensing the steam) and analyzing by mass spectrometry.

3.4.8 Temperature Measurement

Temperature measurements were made by stainless-steel sheathed American National Standards Institute (ANSI) Type K thermocouples. Locations of the junctions are indicated in Figure 3-10. The temperature of gas flowing through the aerosol sample stations was measured with bimetallic dial thermometers.

3.4.9 Pressure Measurement

Static and differential pressures were measured by pressure transducers. Locations of measuring points are shown on Figures 3-11 and 3-12.

3.5 DATA ACQUISITION SYSTEM

Many of the key experimental measurements were made manually and periodically, e.g., filter samples, cascade impactor samples, electron microscope samples, steam fraction measurements, and samples for chemical analyses. The data associated with these manual samples were logged by technicians onto data sheets or recorded in notebooks. The online instrumentation included thermocouples, pressure transducers, steam and nitrogen flow meters, Cs and Mn feed weights, FTV vent orifice meter, and FTV liquid level. The output of these sensors was recorded in parallel on strip chart recorders

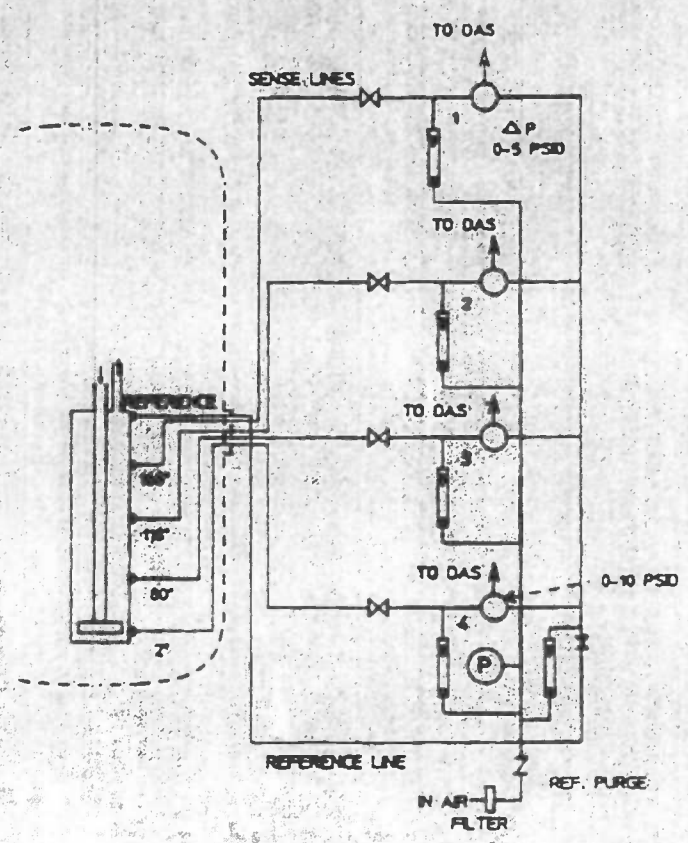

Figure 3-11. FTV Pool Level Arrangement, Tests AA1 and AA2

and on a 200-channel DAS.* The DAS output recorded on a hard disk by interfacing a personal computer** to the paper tape. The normal scan rate on the paper tape was one complete scan per minute.

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*Datalogger Model 2280A, John Fluke Manufacturing Co., Inc., Mountlake Terrace, Washington.

**Model Kaypro-II, Non-Linear Systems, Inc., Solana Beach, California

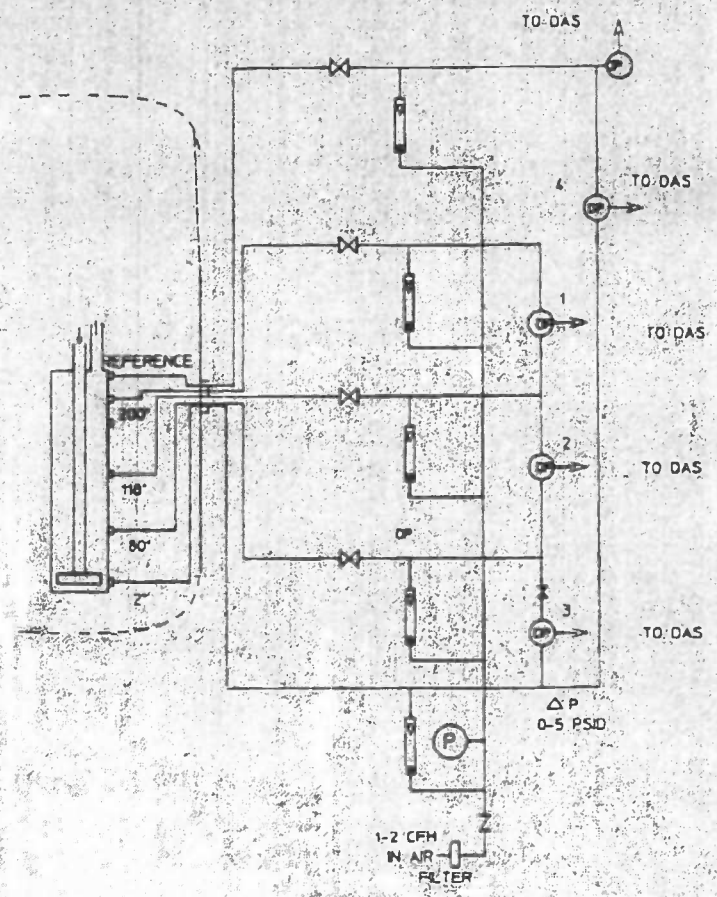

Figure 3-12. FTV Pool Level Arrangement, Tests AA3 and AA4

3.6. CHEMICAL ANALYSIS

The samples taken on filters, liquids, and cascade impactors were analyzed for Cs and Mn using the methods which were previously used in the LACE program. For each test, approximately 800 samples were analyzed for Cs, Mn, and I. All samples after iodine analysis were treated with either HCl or disodium ethylene

diamine tetra acetate (EDTA) to dissolve the Mn compounds. Cs was measured by flame emission spectroscopy. Mn was measured by flame atomic absorption spectroscopy. Iodide was determined by specific ion electrode. Descriptions of analytical procedures are given in Appendix A.

Section 4

TEST PROCEDURE

4.1 PRETEST ACTIVITIES

The following was done in preparation for the actual testing:

1. Agreement was reached on the conditions for each test through meetings of the ACE Technical Advisory Committee and discussions with EPRI as the representative of the test sponsors.

2. A Test Plan was written and approved, which stated the objectives and basic parameters for these tests.

3. The internal tank used in LACE Tests LA5 and LA6 was modified to serve as the Filter Test Vessel (FTV) for the ACE tests. A lid was installed on the tank to create a closed vessel and piping was added from the AMV to the FTV and from the FTV to the existing SGS.

4. The sparger (described in Section 3.2) was designed, fabricated, and installed in the FTV for these tests. Leak tests and DOP efficiency measurements were made.

5. Test Procedures were written and approved which specified in detail for each pair of the tests the preparatory work to be done, the steps to be followed during testing, the sampling schedules, and the post-test cleanup and chemical analyses.

6. The effectiveness of the pool in removing a DOP aerosol was measured using standard DOP measurement procedures. This provided a comparison to a recognized standard.

7. A practice test, duplicating all steps of Tests AA1 and AA2 except for actual aerosol generation, was conducted to check out the equipment and instrumentation, to train test operators, and to assure against unexpected problems in the main tests.

4.2 PROCEDURE DURING TEST

Two tests were performed during a single day of continuous facility operation. The two tests with a low-temperature pool (AA1 and AA2) were performed first, and those with a high-temperature pool (AA3 and AA4) later. One of the two available plasma torches was operated during each test, as this was found to be the limit for efficient torch operation before disassembly and cleaning was required. Hence, two tests were the maximum possible to run at one time.

Each day of testing included the following steps:

1. Start electrical preheat of the AMV, ADL, FTV, and Cs system several hours before the test.

2. Establish heated nitrogen flow to the AMV and FTV.

3. Turn on plasma torch (without Mn feed) in dry atmosphere and bring up to power.

4. Establish steam flow to AMV and FTV. For the higher steam flow rates (AA2 and AA4) steam was fed from the building supply. For lower rates (AA1 and AA3) steam was generated by introducing water into the hot nitrogen entering the AMV.

5. Establish reasonably steady temperatures in the system. The plasma torch gave a major heat addition to the AMV, so the AMV heaters were generally turned off and the nitrogen preheat reduced when the plasma torch was on. Even so, the gas temperature at the FTV inlet unavoidably rose when the plasma torch was on.

6. Divert flow from FTV to bypass 5 min before start of test. This permitted the three aerosol generation systems to be brought on line before aerosol was introduced to the FTV.

7. Start Cs flow to vaporizer and AMV. Start Mn powder to plasma torch. Start HI flow to AMV.

8. Restore gas and aerosol flow from bypass to FTV to start test.

9. Take samples during 30 minute test. Aerosol samples were taken from the ADL near the entrance to the FTV (location T5), from the vent line just above the FTV outlet (location T6), and from the vent line near the inlet to the SGS (location T7). The flowing gas was sampled for total suspended aerosol using filter samples, for particle-size distribution using cascade impactors, and for scanning electron microscopy (SEM) using Nuclepore filters. Liquid samples were taken from the FTV, the sparger, the vent-line condensate, and the SGS. Gas samples for mass spectrometry were taken from the AMV.

10. Stop Mn, Cs, and HI flow at end of test. Continue steam and nitrogen flow.

11. Wait 10 minutes to clear suspended aerosol from the system.

12. Sample for resuspension of aerosol material from FTV pool. Retain same nitrogen and steam flows.

13. Adjust gas flows and FTV pool depth to conditions for second test.

14. Repeat Steps 5-12 for second test.

15. Shut off gas flows and shut down facility.

The timing of the above events for Tests AA1-4 is given in Table 4-1.

Table 4-1

CHRONOLOGY OF KEY EVENTS

	AA1, 2	AA3, 4
Start electric preheat of AMV, ADL, FTV	-340 min	-345 min
Start electric preheat of cesium system	-270	-230
Start steam heating of FTV pool	Not Required	-115
Start hot nitrogen flow to AMV	-75	-75
Divert nitrogen flow from bypass to FTV	-50	-55
Start plasma torch No. 1 without Mn feed	-40	-40
Start water injection to AMV	-30	-27
Divert flow from FTV to bypass	-5	-5
Start Cs feed to AMV	-4	-4
Start HI feed to AMV	-1	-2[a]
Start Mn feed to AMV	-1	-1
Divert flow from bypass to FTV, start test	0	0
Stop Mn, Cs, and HI feed. Turn off plasma torch No. 1. End test. Maintain gas flow.	30	30
Start resuspension test	40	40
End resuspension test, stop water injection	65	65
Raise FTV pool level	80-100	80-95
Start blowdown of steam lines	131	125
Start plasma torch No 2.	140	141
Start steam flow to AMV and FTV	150	150
Divert flow from FTV to bypass	175	175
Start Cs feed to AMV	176	176
Start HI feed to AMV	178.5	178
Start Mn feed to AMV	178	178
Divert flow from bypass to FTV, start test	180	180
Stop Mn, Cs, and HI feed. Turn off plasma torch No. 2. End test. Maintain N_2 and steam flow	210	210

Table 4-1

(continued)

	AA1, 2	AA3, 4
Start resuspension test	220	220
End resuspension test	280	283
Stop steam and nitrogen flows to FTV	281	285

[a]In Test AA3 the HI flow was shut off from 15 to 19 min to change the HI gas bottle.

4.3 POST TEST CLEANUP

The test components were cleaned after each pair of tests to determine how much aerosol material had collected in each component and thus provide input for a mass balance.

The two plasma torches were removed from the AMV, and the torch liners and residue were removed and weighed, to determine the mass of Mn remaining on each of them.

The AMV, the ADL, and the bypass piping were each cleaned by a high pressure water spray. The water was passed through polypropylene filters to remove insoluble material. The filters and samples of filtrate were sent to the laboratory for chemical analysis. The liquid in the FTV was similarly filtered and analyzed, although it was not possible to recover all the precipitated MnO.

Liquid samples for chemical analysis were taken from the SGS while the liquid in it was well agitated by gas flow, and the SGS was drained and cleaned.

Chemical analyses of the recovered aerosol material, the aerosol samples, and the liquid samples were performed by the PNL analytical laboratories using the methods described in Section 3.6.

4.4 DOP EFFICIENCY TESTS

The pre-test measurements of the sparger-pool efficiency were made using a standard ANSI N510-1980(7) DOP test. This is a standard test method for field testing of high efficiency air cleaning systems using a dioctyl phthalate (DOP) aerosol

produced by compressed air using Laskin nozzles. The specification requires that the aerosol have a light-scattering mean droplet-size 99% less than 3 μm, 50% less than 0.7 μm and 10% less than 0.4 μm.

The size of the test aerosol is not specifically defined by the standard except as a "light scattering mean." Hinds (9) has reported DOP aerosol size distributions obtained using a Laskin generator to have a count median diameter of 0.25 μm with a geometric standard deviation, GSD of about 1.53. From the count size distribution he calculated a typical mass median diameter of 0.70 μm. For the measurements made on the pool scrubber dioctyl sebacte (DOS) (which is thought to have reduced health effects) was used to form the aerosol. Hinds(9) reports the MMD size of this DOS aerosol to be 0.56 μm only slightly smaller than the size obtained using DOP, hence no distinction between the two aerosols will be made in this discussion.

The aerosol concentration upstream and downstream of the test item was measured with a near forward light scattering photometer. This device responds closely to the mass concentration. The test aerosol was injected into the AMV, inlet and outlet samples were taken at T5 and T6 sample stations previously described. For these tests the inlet aerosol concentration was 60 to 120 mg/m^3, depending on the scrubber air flow. A schematic of the test set-up is shown in Figure 4-1.

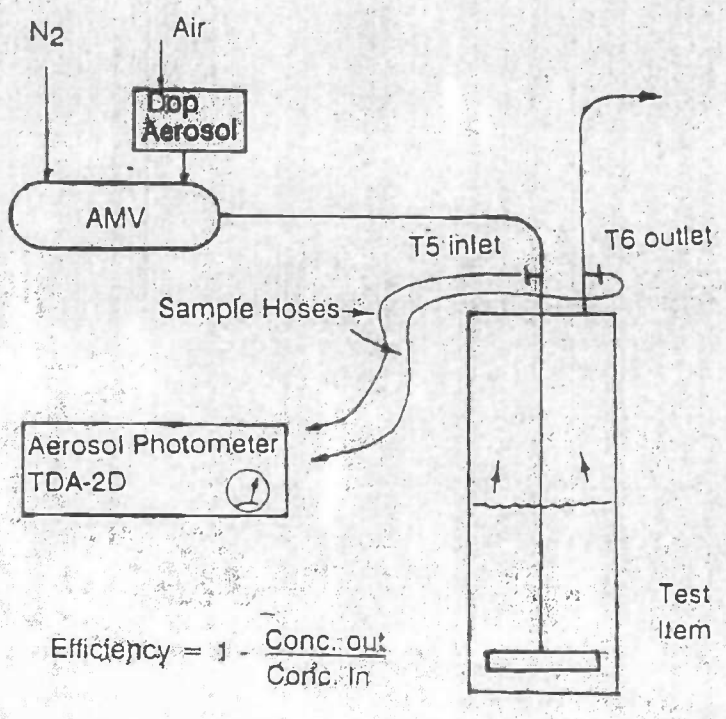

Figure 4-1. DOP Test Arrangement

Section 5

TEST CONDITIONS

The desired conditions for this series of tests are shown in Table 5-1.

5.1 INLET AND INITIAL THERMAL HYDRAULIC CONDITIONS

The conditions of the inlet gas flowing to the FTV are summarized in Table 5-2 for each of the four tests performed. The principal variation in gas flow between tests was in the inlet steam fraction. The volumetric steam fraction was about 1% in Tests AA1 and AA3, 19% in AA2, and 41% in AA4. The total mass gas flow rate ranged from 77 to 110 g/s, which gave actual volumetric flow rates of 0.07 to 0.11 m^3/s. In Test AA2, the steam flow rate was only one-third of that intended because the proper orifice was not installed in the steam flow meter during this test. The inlet gas temperature ranged from 138 to 150°C. It was difficult to keep the gas temperature as low as desired because of the high heat input from the plasma torches. The inlet pressure was approximately atmospheric plus the head of the FTV pool.

Table 5-1

DESIRED TEST CONDITIONS

	Water Temperature[a]	Submergence, m	Steam in Nitrogen, w%
AA1	20 - 30°C	1.6	Low
AA2	20 - 30°C	4.6	30
AA3	70 - 80°C	2.6	Low
AA4	70 - 80°C	4.6	30

[a]The exact temperature conditions attainable with the apparatus were not known.

Table 5-2

SUMMARY OF ACTUAL TEST CONDITIONS

	AA1	AA2	AA3	AA4
Inlet Gas (at T5)				
Total flow, g/s	110	77	110	93
Temperature, °C	138	142	150	141
Pressure, kPa	121	150	132	150
Actual volumetric flow, m^3/s	0.113	0.069	0.106	0.091
Steam fraction by volume	0.012	0.185	0.013	0.410
Average Aerosol Flow Rates, g/s				
Cs	0.531	0.654	0.613	0.653
Mn	0.597	0.263	0.887	0.499
I	0.0761	0.0683	0.0694	0.0586
Inlet Aerosol Conc. (at T5), g/m^3 actual				
Cs	4.70	9.51	5.78	7.19
Mn	5.28	3.82	8.36	5.50
I	0.673	0.993	0.654	0.645
Duration of aerosol flow, min	30	30	30[a]	30
Pool				
Submergence of sparger, m	1.38	4.52	2.62	4.61
Temperature, °C	26	24	82	83
pH	9.8	10	8.9	8.9

[a]26 min for I. There was no flow of HI during the interval from 15 to 19 min, when the HI bottle was being changed.

The principal parameters of the FTV water pool are also listed in Table 5-2. Both the temperature and depth of the pool were varied between tests. The pool temperature was 25°C in Tests AA1 and AA2, 83°C in AA3 and AA4. The submergence of the sparger holes below the water surface was 1.4 m in AA1, 2.8 m in AA3, and 4.6 m in AA2 and AA4. The pH of the pool was maintained at 9-10 by buffering with 0.05M boric acid and NaOH (0.047M, Test AA 1/2; 0.021M Test AA 3/4).

The thermal hydraulic data are discussed in greater detail in Section 6-1.

5.2 AEROSOL SOURCE TO FILTER TEST VESSEL

Aerosols of Mn, Cs, and I were generated as discussed in Section 3.3. In each test all three aerosol species were introduced simultaneously over a test duration of 30 min; i.e., from 0 to 30 min in AA1 and AA3 and from 180 to 210 min in AA2 and AA4. (An exception occurred in AA3 where the HI input was valved off during the interval from 18 to 19 minutes to change the HI bottle).

The flow rate and the concentration (expressed per actual cubic meter of gas at the temperature and pressure existing at the T5 sampling station) of each of these three aerosol species in the inlet gas are listed in Table 5-2. These values are averages over the 30-min test duration for aerosol entering the sparger and FTV as calculated from mass balance data, as discussed in Section 6.2.1.

The aerosol generation systems were operated under the same nominal conditions in each of the four tests to provide the same aerosol source in each. Target rates were 0.6 g/s of Cs, 1.0 g/s of Mn, and 0.06 g/s of I. The actual rates varied from 0.53 to 0.65 g/s for Cs, 0.26 to 0.89 g/s for Mn, and 0.059 to 0.076 g/s of I. The large variation of the Mn rate is due to the varying efficiency of the plasma torch in converting Mn powder to aerosol. Similar variability was encountered with these plasma torches in the LACE tests. The variation of the Cs flow rate is due to operational control tolerances, and that of the I to adjustment of the calibration factor for the HI flowmeter based on data from the preceding tests.

The ratio of Cs to Mn was 2.5 in Test AA2, which is 2 or 3 times as high as in the other tests. Since CsOH is very hygroscopic, the aerosol in AA2 was more moist than in other tests and may have been, therefore, more susceptible to agglomeration.

The measurements of particle size distribution, chemical form, and variation of inlet concentration with time are discussed in Section 6.2.

Section 6

EXPERIMENTAL RESULTS

6.1 THERMAL-HYDRAULIC RESULTS

6.1.1 Gas Flow Rates and Velocities

The inlet gas flow rates for the FTY are given in Table 6-1. The values given in this and the following tables of thermal-hydraulic data are averages over the testing (sampling) interval. The data for the resuspension tests are treated separately and are designated by a suffix R following the test number. Gas flow rates are given both on a mass basis (g/s), or a standard volume basis (standard* m^3/s) and/or an actual volume basis (actual m^3/s) based on the gas temperature at T6 and the AMV pressure. The helium and argon flows are those introduced in the operation of the plasma torches.

The steam flow rate in Test AA2 was only one-third of that intended because the proper orifice was not installed in the steam flow meter during this test. Volume steam fractions were about 1% in Tests AA1 and AA3, 19% in AA2, and 41% in AA4. The total gas flow rate was about 0.09 standard m^3/s in all tests, except AA2 where the total flow was low because of the low steam flow.

The inlet flow rates were held nearly constant over the period of each test.

The average velocity of the gas through the discharge holes in the sparger (total area 0.00363 m^2) listed in Table 6-1 is a nominal value calculated from the inlet gas volume at T5. This velocity is typically in the range of 20 to 30 m/s. The actual velocity will be somewhat less because of cooling and condensation of steam in the sparger inlet pipe beyond the temperature measuring point.

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*Standard m^3 is volume of gas at 0°C, 101.3 kPa.

Table 6-1

INLET GAS FLOW RATES TO ETV

Test	AA1	AA1R	AA2	AA2R	AA3	AA3R	AA4	AA4R
Time, start, min	0	40	180	220	0	40	180	220
Time, end, min	30	65	210	280	30	65	210	283
Mass Flow Rates, g/s								
Nitrogen	107.6	107.7	65.6	59.7	107.6	107.1	62.6	61.3
Helium	0.3	0	0.3	0	0.3	0	0.3	0
Argon	0.8	0.4	0.8	0.4	0.8	0.4	0.8	0.4
Total noncondensible	108.7	108.1	66.7	60.1	108.7	107.5	63.7	61.7
Steam	0.85	0.85	9.97	9.83	0.93	0.93	29.2	29.4
Total	109.5	108.9	76.7	9.9	109.6	108.4	92.9	91.1
Volumetric Flow, std m^3/s								
Total noncondensible	0.0883	0.0867	0.0547	0.0483	0.0883	0.0859	0.0523	0.0492
Steam	0.00106	0.00106	0.0124	0.0122	0.00116	0.00116	0.0363	0.0366
Total	0.0894	0.0878	0.0671	0.0605	0.0895	0.0870	0.0886	0.0858
Total Volumetric Flow Actual m^3/s	0.1131	0.1090	0.0688	0.0607	0.1061	0.0998	0.0908	0.0854
Volume Steam Fraction	0.01191	0.0121	0.185	0.202	0.0130	0.0133	0.410	0.427
Velocity through Sparger Holes, m/s	31.2	30.0	19.0	16.7	29.2	27.5	25.0	23.5

The outlet gas flow rates from the FTV pool are given in Table 6-2. The gas flow is assumed to reach equilibrium with the water in the pool, and the outlet steam flow fraction is that calculated on the assumption that all gas becomes saturated with water vapor at the pool temperature. The outlet volume steam fraction is 50% for the hot pool (Tests AA3 and AA4) and about 3% for the cool pool (Tests AA1 and AA2).

The superficial velocity of the gas rising through the FTV pool (1.72 m^2 in cross section) is based on the outlet gas volume, since the temperature and vapor content of the gas would be expected to come rapidly into equilibrium with the pool. The superficial gas velocity ranges from 0.03 to 0.12 m/s.

The chemical composition of the noncondensible inlet gas is shown in Table 6-3. These data are based on gas samples taken from the AMV and analyzed by mass spectrometry.

6.1.2 Temperatures

The average temperatures measured in each test at various locations are listed in Table 6-4. Elevations used to define thermocouple location are measured from the bottom of the FTV.

Inlet gas temperatures (measured 150 mm downstream from the T5 inlet aerosol sampling station) were 130 to 150°C. The pool temperature was 25°C in Tests AA1 and AA2, 83°C in AA3 and AA4.

There was a significant cooling of the inlet gas passing down through the 20-cm sparger inlet pipe within the FTV. The inlet pipe wall at 5.59-m elevation (0.51 m below the top of the FTV) was 20° to 30° cooler than the gas at sample station T5 just above the top of the FTV. Thermocouples were installed to measure the wall and gas temperatures in the sparger; however, there were problems with them and neither performed reliably.

The gas temperature in the FTV above the pool shows a thermal stratification. The gas temperature at 3.35 m agrees well with the water temperature at 0.15 m. The top 0.61 m of the FTV wall (above 5.49 m) was heated to prevent condensation, and the gas temperature at 5.79 m was at a temperature intermediate between that of the heated wall and the cooler water pool.

Table 6-2

AVERAGE OUTLET GAS FLOW RATES TO FTV

Test	AA1	AA1R	AA2	AA2R	AA3	AA3R	AA4	AA4R
Volumetric Flow, std m^3/s								
Total noncondensible	0.0883	0.0867	0.0547	0.0483	0.0883	0.0859	0.0523	0.0492
Steam	0.0026	0.0028	0.0015	0.0016	0.0801	0.0800	0.0546	0.0477
Total	0.0909	0.0895	0.0562	0.0499	0.1684	0.1659	0.1069	0.0969
Total Volumetric Flow Actual m^3/s	0.0943	0.0933	0.0585	0.0524	0.205	0.201	0.132	0.119
Volume Steam Fraction	0.0286	0.0311	0.0267	0.0316	0.476	0.482	0.511	0.492
Superficial Velocity in Pool m/s	0.055	0.054	0.034	0.030	0.119	0.117	0.077	0.069

Table 6-3

AEROSOL CARRIER GAS ANALYSIS BY MASS SPECTROMETER[a]

Gas	Volume %			
	AA1	AA2	AA3	AA4
N_2	97.0	95.4	97.1	95.2
He	1.87	2.86	1.84	2.96
Ar	0.80	1.28	0.80	1.33
O_2	0.16	0.04	0.08	≤ 0.01
H_2	0.18	0.36	0.17	0.52
CO_2	< 0.01	< 0.01	0.02	< 0.01
CO	< 0.10	< 0.10	< 0.10	< 0.10

[a]Taken from AMV - after condensing the steam.

The saturation temperature of the inlet gas is that calculated for the inlet composition given in Table 6-1 at the inlet (AMV) pressure. In all tests the inlet gas temperature was well above saturation.

6.1.3 Pressure, Pool Depth, and Void Fraction

The average pressures measured in each test are listed in Table 6-5. The inlet pressure is taken as that measured in the AMV; the outlet pressure as that measured at the inlet to the SGS. The pressure drops through the large-diameter pipes are negligible. The FTV outlet was near atmospheric pressure. The difference between inlet and outlet pressures was due principally to the head of liquid in the FTV.

The FTV was provided with pressure taps at four elevations (see Figures 3-11 and 3-12). The differential pressure between the lowest tap and the gas space above the pool was used to calculate the liquid depth in the pool and the submergence of the sparger discharge holes. These values are given in Table 6-5 for a collapsed pool;

Table 6-4

AVERAGE TEST TEMPERATURES, °C

Test	AA1	AA1R	AA2	AA2R	AA3	AA3R	AA4	AA4R
Time, start, min	0	40	180	220	0	40	180	220
Time, end, min	30	65	210	280	30	65	210	283
Inlet gas, (T5)[c]	138.3	130.3	142.3	133.6	150.0	136.9	141.4	130.3
Inlet pipe wall, 5.59 m elevation	104.7	111.0	110.5	110.2	--	--	--	--
FTV 0.15 m elevation	25.7	27.1	24.5	27.1	82.2	82.8	81.8	83.7
FTV 2.74 m elevation	25.9	27.2	24.5	27.2	82.3	82.9	83.8	83.0
FTV 3.35 m elevation	26.0	27.4	24.5	27.2	82.2	82.9	83.8	83.0
FTV 5.79 m elevation	47.4	46.6	39.4	43.7	86.5	87.5	84.1	83.2
FTV heated wall, 5.49 m elevation	67.6	64.1	49.7	53.9	100.0	100.3	84.2	88.1
Outlet gas (T6)[a]	38.4	39.3	29.7	32.7	83.1	84.2	84.0	83.3
SGS inlet gas (T7)[b]	33.8	34.0	28.6	29.8	81.9	82.7	82.9	82.1
SGS water	25.0	25.3	25.4	25.5	58.6	72.6	72.2	77.3
Inlet saturation temperature (T5)[c]	14.0	14.3	67.8	69.8	16.7	17.2	86.8	87.9

[a]Thermocouple located 340mm downstream of T6

[b]Thermocouple located 260mm downstream of T7

[c]Thermocouple located 150mm downstream of T5

i.e., for one with no bubbles. The sparger submergence (i.e., the depth of the discharge holes below the pool surface) was 1.4 m in Test AA1, 2.6 m in AA3, and 4.6 m in AA2 and AA4.

A comparison of the pressure differential measured between two adjacent pressure taps with that calculated for void-free water permits a calculation of void fraction.

Table 6-5

PRESSURE, LIQUID, DEPTH, AND VOID FRACTION

Test	AA1	AA1R	AA2	AA2R	AA3	AA3R	AA4	AA4R
Pressures, kPa								
Inlet gas (AMV)	120.6	120.5	150.3	150.2	132.4	132.8	150.1	150.4
Outlet gas (SGS inlet)	106.8	106.8	106.1	106.0	108.1	109.2	106.9	107.4
Collapsed pool depth, m	1.64	1.63	4.77	4.80	2.88	2.81	4.87	4.85
Sparger submergence, m	1.38	1.38	4.52	4.55	2.62	2.55	4.61	4.59
FIV water volume, m^3	2.78	2.77	8.17	8.22	4.47	4.35	7.89	8.31
Void fraction:								
5.08 to 3.00 m	--	--	0.115	0.090	--	--	0.090	0.083
3.00 to 2.03 m	--	--	0.103	0.070	--	--	0.067	0.061
2.03 to 0.25 m	--	--	0.040	0.078	0.038	0.034	0.016	0.014
5.08 to 0.25 m	--	--	0.104	0.082	--	--	0.058	0.053
Contact time, s	--	--	14	12	--	--	3.5	3.5

$$f_v = 1 - \frac{\Delta P}{(d)(h)}$$

where f_v = void fraction

ΔP = pressure difference measured between taps

d = density of void-free water at pool temperature

h = vertical distance between taps.

This calculation assumes that the measured pressures are uniform over the cross section of the tank. The contact time of rising bubbles with the liquid may be estimated as:

$$t = \frac{(s)(f_v)}{V_s}$$

where t = contact time, s

s = submergence of sparger below pool surface, m

V_s = superficial velocity of gas through pool (Table 6-2)

The void fraction and contact time are given in Table 6-4. Meaningful void fraction measurements were possible only for the tests with the deep pool. An average void fraction of 10% was measured for AA2, 6% for AA4. The corresponding contact times are 14 and 3.5 s, respectively. The measured void fraction was higher at the top of the pool than at the bottom.

6.1.4 Heat Loss and Condensation

The hot inlet gas passes down to the sparger through an inlet pipe surrounded by the cooler pool in the FTV. Although this pipe is insulated to reduce heat loss, some cooling of the inlet gas and condensation of steam from it will occur. Since steam condensation can remove part of the suspended aerosol, an estimate of the amount of inlet cooling and condensation is useful. Unfortunately, the thermocouples installed in the sparger failed, and temperatures at this location are not known. Therefore, heat loss must be estimated by heat transfer calculations. For example, the main insulation is 0.05 m of Foamglas® with a thermal conductivity of 0.57 W/m·K at 93°C. Considering this thermal resistance only, a 0.08 kg/s nitrogen flow at 125°C temperature difference across the insulation would allow a 5 to 6°C temperature change of the gas or condense 0.7 to 2% of the steam flow.

6.2 AEROSOL RESULTS

6.2.1 Aerosol Mass Balance

A mass balance on each of the three aerosol materials was made using the measured mass fed and the measured mass recovered from various components at the end of the tests. These mass balances are shown in Table 6-6 for Tests AA1 and AA2, and in Table 6-7 for AA3 and AA4.

The quantities listed in Tables 6-6 and 6-7 were determined as follows:

- The "total fed" was obtained from the net mass of Mn supplied to the powder feeder and the weight losses of the Cs and HI reservoirs.
- The "torch residue" is the mass of unvaporized Mn collected from the plasma torch liner.
- "AMV," "Bypass," and "ADL" designate, respectively, the mass recovered at the end of each pair of tests from the AMV, from the bypass pipe plus the venturi scrubber water, and from the ADL. These quantities did not enter the sparger or FTV. The mass recovered was arbitrarily divided between the two tests of the pair in proportion to the mass supplied to the AMV.
- "Fed to FTV" is "Total Fed" minus that recovered upstream of the FTV.
- "SGS" designates the mass collected in the SGS as calculated from liquid samples drawn at the beginning and end of each test. It also includes a small amount in the condensate recovered from the vent pipe that runs from the FTV to the SGS. For AA2 and AA4 this measurement involved taking a small difference between two larger concentrations, and is, therefore, subject to considerable uncertainty.
- "Retained in FTV" is that fed to the FTV minus that collected in the SGS.
- "Measured in FTV" designates the mass collected in the FTV as calculated from liquid samples drawn at the beginning and end of each test. It also includes material collected from the sparger after each pair of tests. This measure excludes the MnO which settled out during the test. Therefore, it is generally somewhat less than the mass "Retained in FTV," and is considered to be a less accurate measure of the amount actually supplied for the FTV.
- "Total Recovered" is the sum of that recovered from, or measured in, the torch residue, AMV, bypass, ADL, SGS, and FTV.
- "% Recovered" is the ratio of the total recovered to the total fed.
- "DF" is the decontamination factor calculated by dividing the mass fed to the FTV by the mass measured in the SGS.
- "Rate to FTV" is the average flow rate of aerosol entering the FTV as calculated by dividing the mass fed to the FTV by the test duration of 30 minutes.

Table 6.6

MASS BALANCE AA1, 2

	Cs, g			Mn, g			I, g		
	AA1	AA2	Total	AA1	AA2	Total	AA1	AA2	Total
Total Fed	1006	1240	2246	3056	1249	4305	144	129	273
Torch Residue	--	--	--	1876	730	2606	--	--	--
AMV	26	32	58	67	30	97	4.4	3.9	8.3
Bypass	17	20	37	26	11	37	0.7	0.6	1.3
ADL	8	10	18	12	5	17	1.5	1.4	2.9
Fed to FTV	955	1178	2133	1075	473	1548	137	123	260
SGS	6.0	0.6	6.6	33	-0	33	1.80	0.03	1.8
Retained in FTV	949	1177	2126	1042	473	1515	135	123	258
Measured in FTV	893	1180	2073	817	444	1261	139	119	258
Total Recovered	950	1243	2193	2831	1220	4051	147	125	272
% Recovered	94%	100%	98%	93%	98%	94%	102%	97%	100%
DF	160	2000		33	high		80	high	
Rate to FTV, g/s	0.531	0.654		0.597	0.263		0.0761	0.0683	

Table 6-7

MASS BALANCE AA3, 4

	Cs, g			Mn, g			I, g		
	AA1	AA2	Total	AA1	AA2	Total	AA1	AA2	Total
Total Fed	1165	1240	2405	2799	1816	4615	114.2	111.2	225.5
Torch Residue	--	--	--	1063	859	1902	--	--	--
AMV	29	31	60	102	57	159	3.2	3.1	6.3
Bypass	23	24	47	24	13	37	1.8	1.8	3.6
ABL	10	10	20	13	8	21	0.9	0.9	1.8
Fed to FTV	1103	1175	2278	1547	899	2496	108.3	105.4	213.8
SGS	3.3	0.4	3.7	11.2	4.0	15.2	0.60	0.04	0.64
Retained in FTV	1100	1174	2274	1586	895	2481	107.7	105.4	213.2
Measured in FTV	919	1084	2003	1207	1016	2223	103	112	215
Total Recovered	984	1149	2134	2420	1937	4354	109.5	117.8	227
% Recovered	84%	93%	89%	86%	107%	94%	96%	106%	101%
DF	330	3000		140	220		180	2600	
Rate to FTV, g/s	0.613	0.653		0.887	0.499		0.0602	0.0586	

The total mass of each aerosol material recovered varies from 93 to 102% of the total mass fed to the aerosol generator in Tests AA1 and AA2, and from 84 to 106% in AA3 and AA4. This agreement is better than had been obtained previously in the LACE tests using similar generation and measurement techniques for CsOH and MnO aerosols. Since the comparison is of measured weights vs. chemical analyses, the agreement confirms the validity of the chemical analyses.

6.2.2 Aerosol Concentration Measurements

The aerosol concentrations in the gas entering and leaving the FTV were measured several times during each test by filter samples inserted into the inlet (T5) and outlet (T6) piping. In addition, background samples were taken before each test and a single sample was taken during each resuspension test. The concentrations measured at the FTV inlet are listed in Table 6-8; those at the outlet in Table 6-9. The aerosol concentrations are given per standard cubic meter of noncondensible gas (NCG). This reference is used because it does not change as the gas passes through the system with varying temperature, pressure, and steam content. The time at which the sampling started and the duration of the sampling are also given in Tables 6-8 and 6-9.

Inlet samples F1 through F5 and outlet samples F1 through F3 were taken during the 30-min period of aerosol release. The averages during aerosol release of the inlet samples and of the outlet samples are listed in Table 6-10 for each of the three aerosol materials. These average concentrations were calculated by integrating the measured values over the 30-min aerosol input period using linear interpolation between sampling times and assuming a constant rate before first and after the last sample. The decontamination factor is the ratio of the inlet to outlet (averaged) concentration.

The variation of the inlet aerosol concentrations with time is plotted in Figures 6-1 to 6-4 for Tests AA1 to AA4, respectively. The Cs aerosol concentration is fairly constant, except for the first sample in Test AA1. The Cs feed data, as obtained from measurements of the weight of the Cs feed tank, also show an abnormally low initial rate for this test. The Mn aerosol concentration shows a somewhat greater variation, particularly in Test AA3 where the concentration falls off during the test. This behavior has been encountered previously with these plasma torches; the aerosol output is reduced as a crust builds up over the torch outlet. The variation of the I aerosol concentration is surprising since the measured flow of HI

Table 6-8

INLET AEROSOL CONCENTRATION (T5)

Test	Sample	Time, min Start	Time, min Δt	Concentration, g/std m³ Cs	Concentration, g/std m³ Mn	NCG I
AA1	F0	-15	1	0.002	0.003	0.000
	F1	1	1	1.9	7.2	0.49
	F2	5	1	6.8	5.7	0.82
	F3	17	1	7.8	5.6	1.04
	F4	21	1	7.2	5.4	0.87
	F5	29	1	7.6	6.2	0.97
	F6	40	25	0.026	0.0008	0.00003
AA2	F0	165	1	0.004	0.012	0.0009
	F1	181	1	12.3	5.2	1.02
	F2	185	1	11.8	6.3	1.27
	F3	197	1	15.0	5.2	1.50
	F4	201	1	14.2	4.7	1.42
	F5	209	1	14.6	3.3	1.57
	F6	220	60	0.0073	0.0023	0.00004
AA3	F0	-15	1	0.004	0.02	0.0001
	F1	1	1	5.4	74[a]	0.84
	F2	5	1	6.4	20.4	0.77
	F3	17	1	6.9	12.5	0.14[b]
	F4	21	1	7.4	10.7	0.57
	F5	29	1	7.4	9.3	0.86
	F6	40	25	0.038	0.0010	0.00244
AA4	F0	165	1	0.007	0.012	0
	F1	181	1	11.3	12.7	1.09
	F2	185	1	13.1	13.4	1.26
	F3	197	1	12.3	14.8	1.33
	F4	201	1	11.5	18.9	1.24
	F5	209	1	10.5	15.1	0.26
	F6	220	60	0.0033	0.0007	0.00002

[a]Excluded from average (Table 6.10) as too high to be credible.

[b]HI flow was off during the interval from 15 to 19 min.

Table 6-9

OUTLET AEROSOL CONCENTRATION (T6)

Test	Sample	Time, min Start	Time, min Δt	Concentration, g/std m³ NCG Cs	Concentration, g/std m³ NCG Mn	Concentration, g/std m³ NCG I
AA1	F0	-15	4	1.0	0.6	0.05
	F1	1	4	35	560	13.9
	F2	13	4	45	510	23.7
	F3	25	4	59	490	16.2
	F4	40	25	5.1	0.2	0.01
AA2	F0	165	4	0.1	0.6	0.06
	F1	181	4	21.6	18	0.91
	F2	193	4	11.2	23	0.93
	F3	205	4	17.8	17	0.84
	F4	220	25	1.06	0.03	0
AA3	F0	-15	4	0.6	1.2	0.03
	F1	1	4	15.5	230	2.95
	F2	13	4	23.3	300	3.10
	F3	25	4	--	--	--
	F4	33	25	12.7	2.0	0.99
AA4	F0	165	4	0.4	0.5	0
	F1	181	4	4.3	88	1.05
	F2	193	4	4.1	105	0.96
	F3	205	4	3.5	52	0.47
	F4	220	25	0.45	2.3	0

gas was nearly constant. The low I value of concentration in Test AA3 at about 21 minutes was due to interruption of HI flow during the interval between 15 and 19 minutes.

A measure of the average aerosol flow rate has been calculated in Table 6-10 as the product of the average aerosol concentration and the gas flow rate. The ratio of this quantity to the average aerosol flow rate calculated from the mass balance data (Tables 6-8 and 6-9) is also given. For Cs and Mn this ratio has values between 0.96 and 1.14, indicating good agreement between the flow and mass balance methods.

Table 6-10

AVERAGE AEROSOL CONCENTRATIONS

Test	AA1	AA2	AA3	AA4
Inlet Concentration, g/std m³ NCG				
Cs	6.66	13.62	6.77	11.98
Mn	5.85	5.11	15.6	15.0
I	0.872	1.377	0.666	1.10
Outlet Concentration, mg/std m³ NCG				
Cs	46	16.3	21.0	4.0
Mn	519	20	280	84
I	18.5	0.90	3.06	0.84
Decontamination Factor				
Cs	145	836	322	3000
Mn	11.3	256	56	180
I	47	1530	218	1320
Inlet Aerosol Flow, g/s				
Cs	0.588	0.745	0.598	0.627
Mn	0.517	0.280	1.378	0.784
I	0.0770	0.0753	0.0588	0.0578
Ratio of Aerosol Flow from Concentration to that by Mass Balance				
Cs	1.11	1.14	0.98	0.96
Mn	0.87	1.06	1.55	1.57
I	1.02	1.10	0.98	0.99

of measurements. For Mn the variation is greater, between 0.87 and 1.57. The aerosol flow rates calculated from the mass balance are judged to be the more accurate, and are used as the basic reference in this report.

6.2.3 Decontamination Factor

The decontamination factor (DF) is the ratio of the amount of aerosol entering the FTV to that leaving it. The DF may be calculated either from the mass balance data

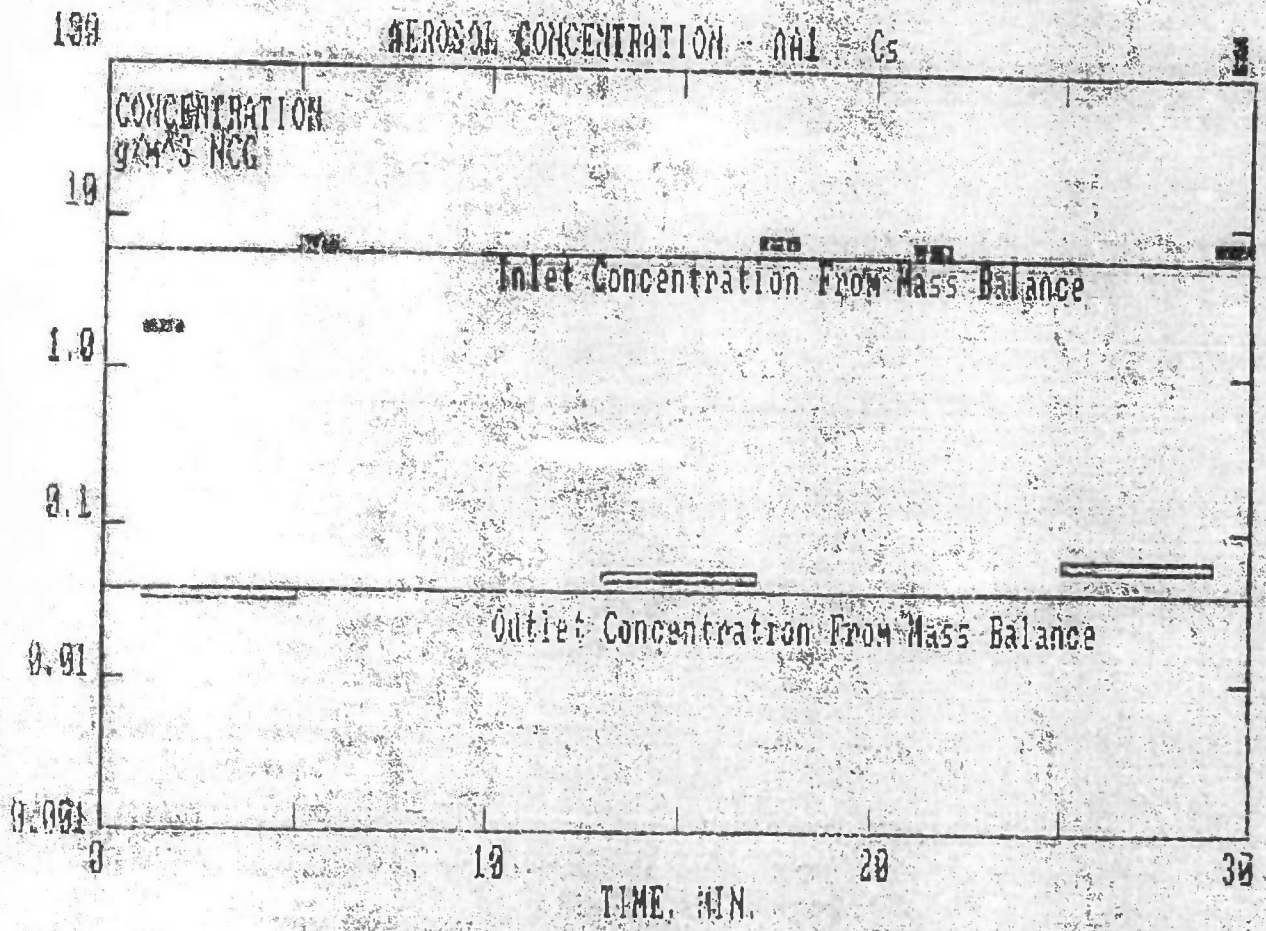

Figure 6-1a. Aerosol Concentration - AA1 - CS

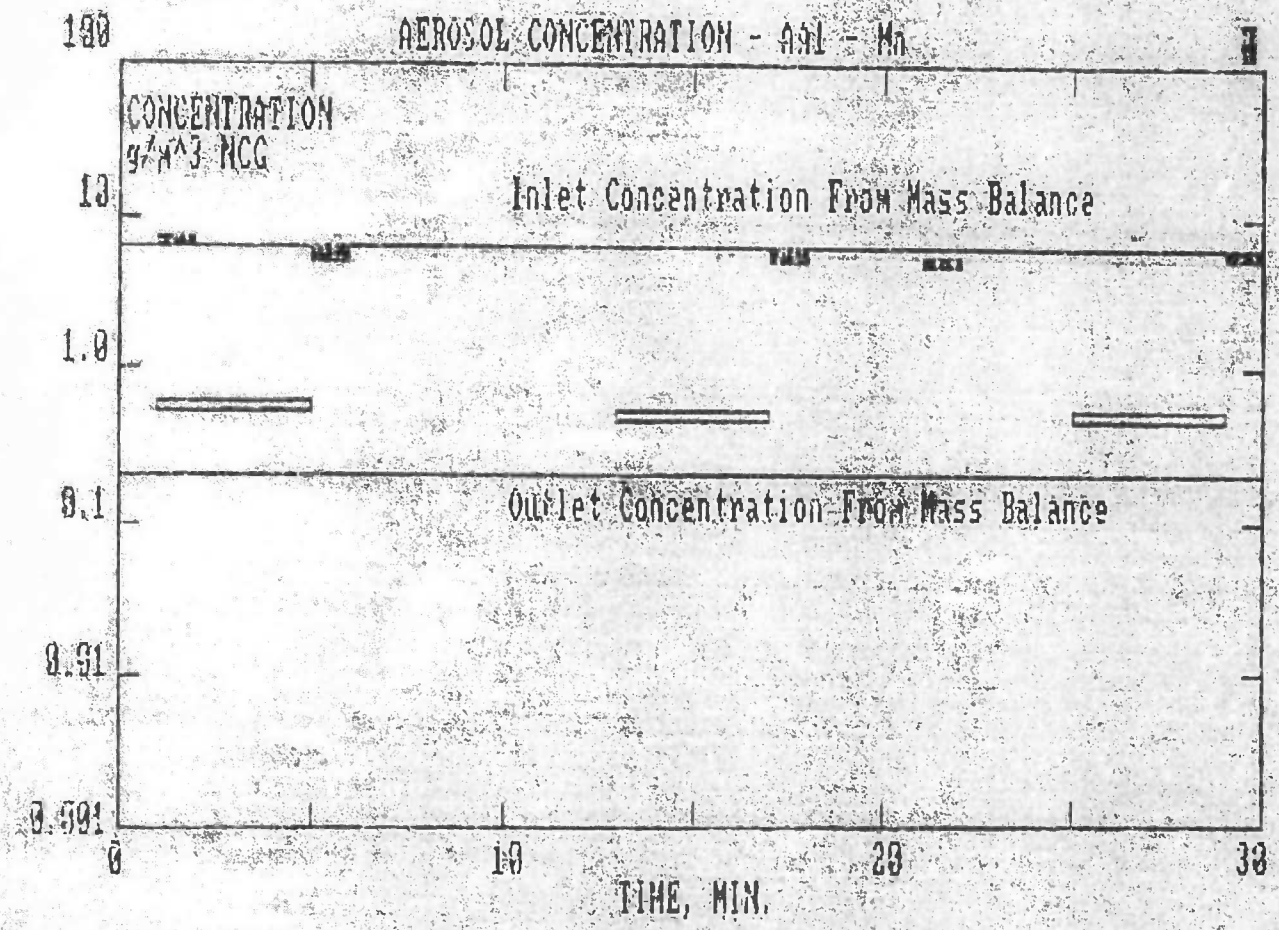

Figure 6-1b. Aerosol Concentration - AA1 - MN

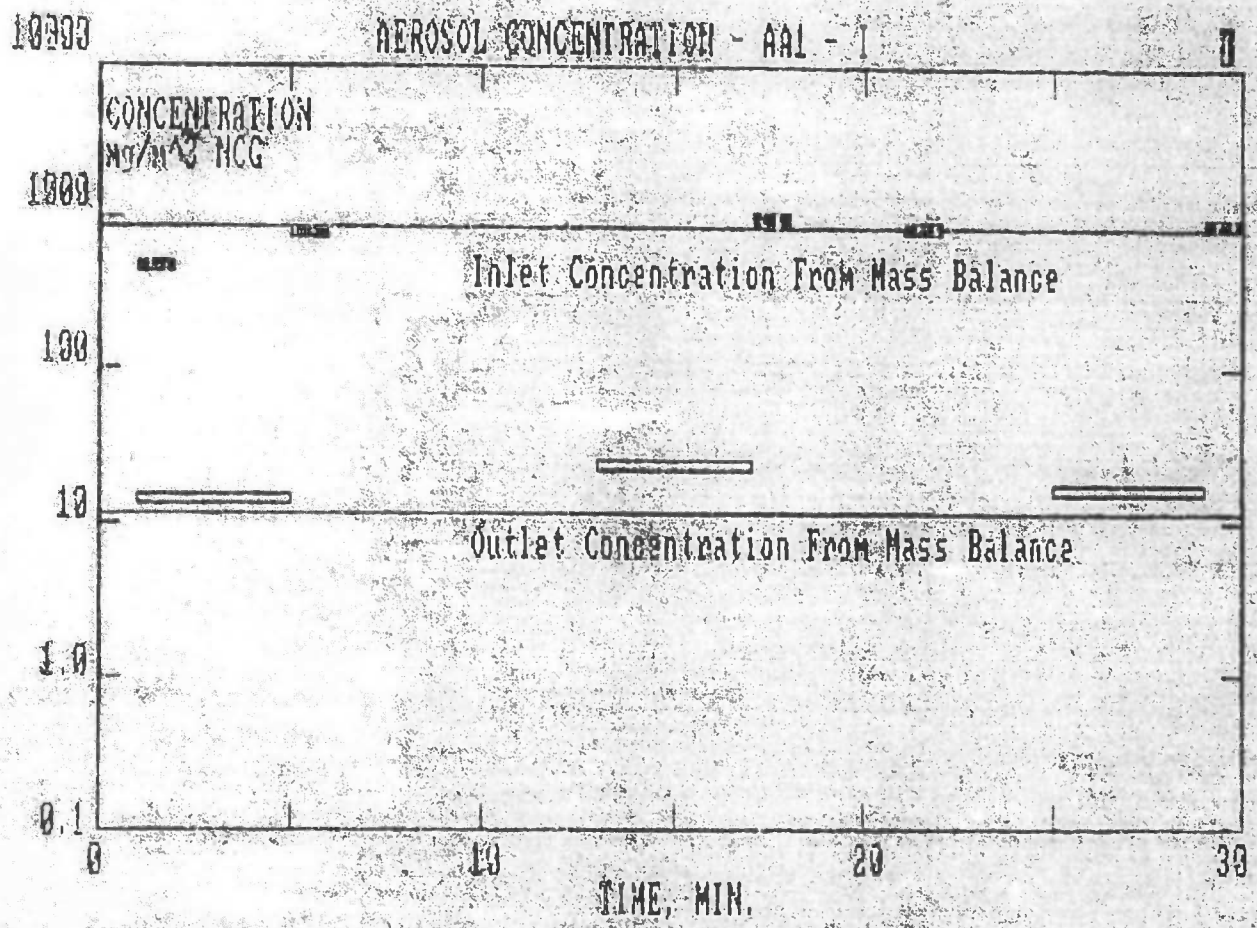

Figure 6-1c. Aerosol Concentration - AA1 - I

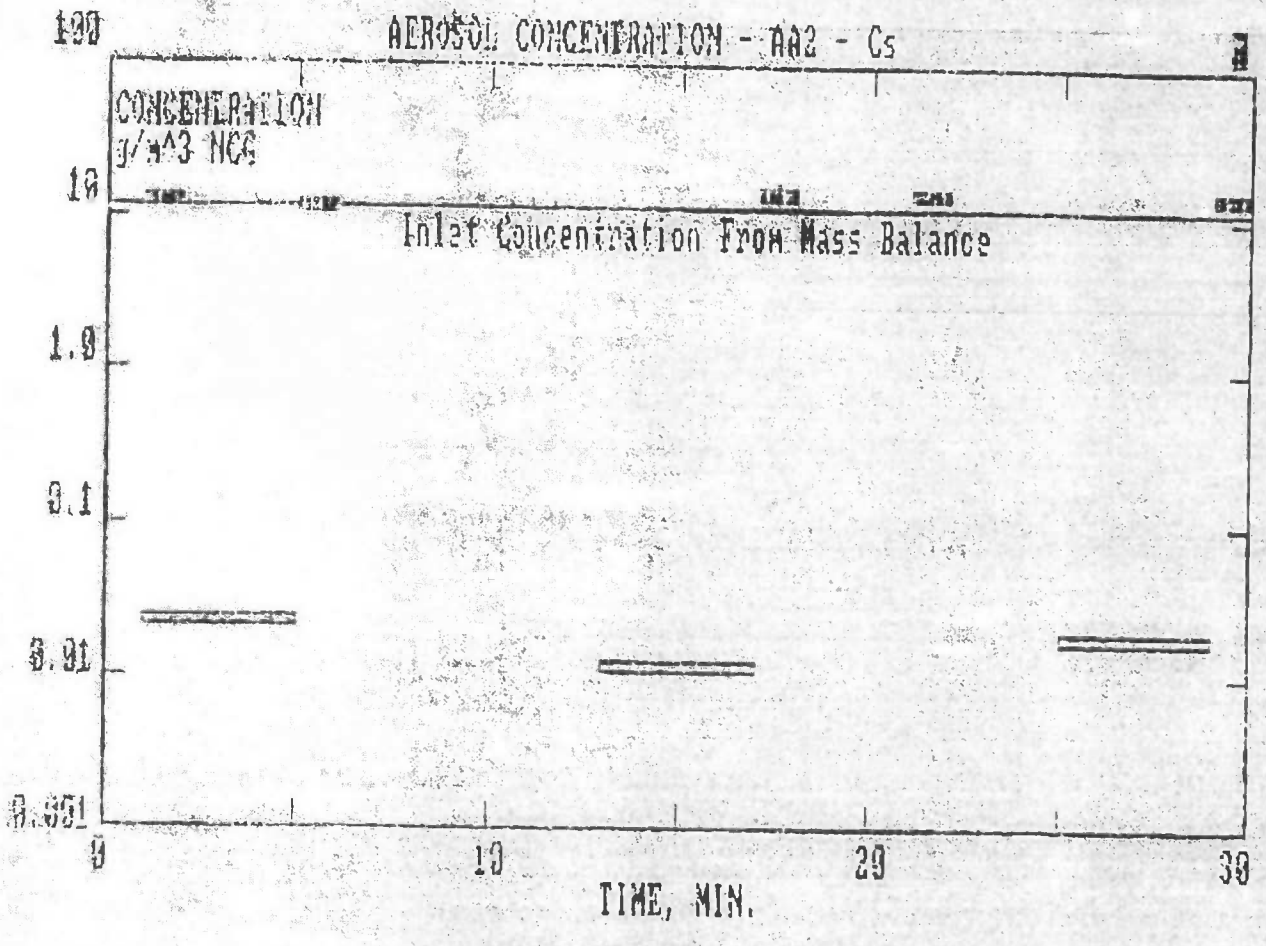

Figure 6-2a. Aerosol Concentration - AA2 - CS

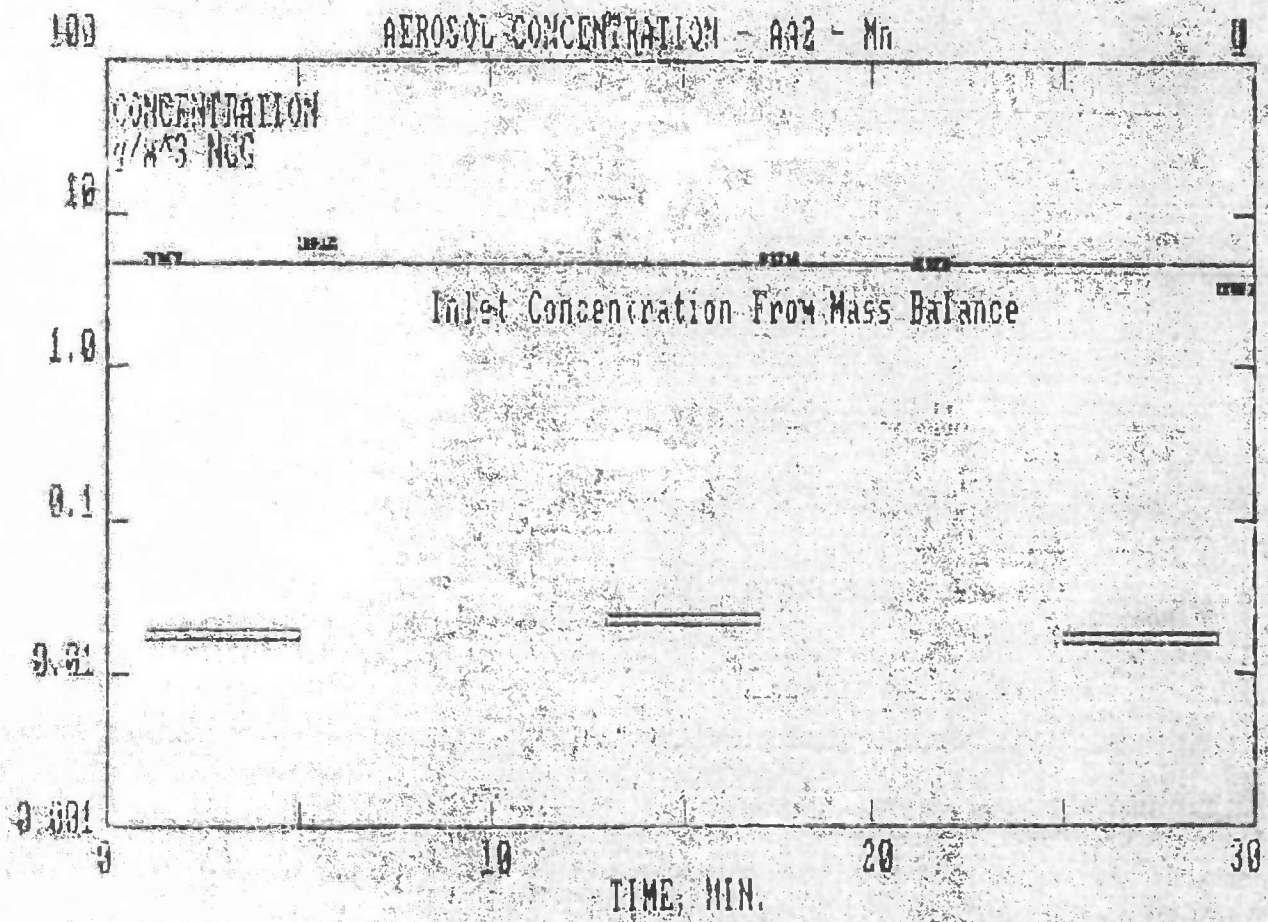

Figure 6-2b. Aerosol Concentration - AA2 - MN

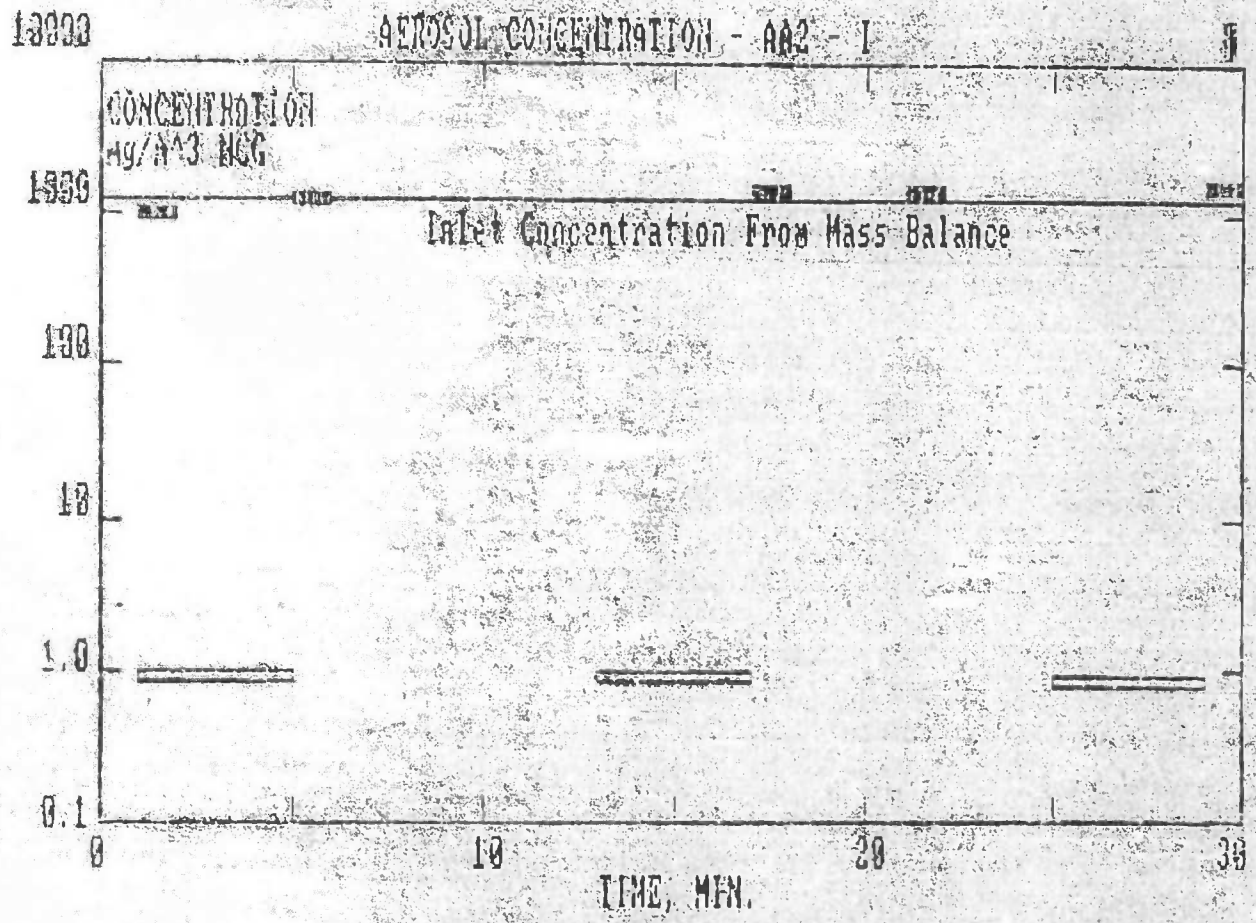

Figure 6.2c, Aerosol Concentration - AA2-I

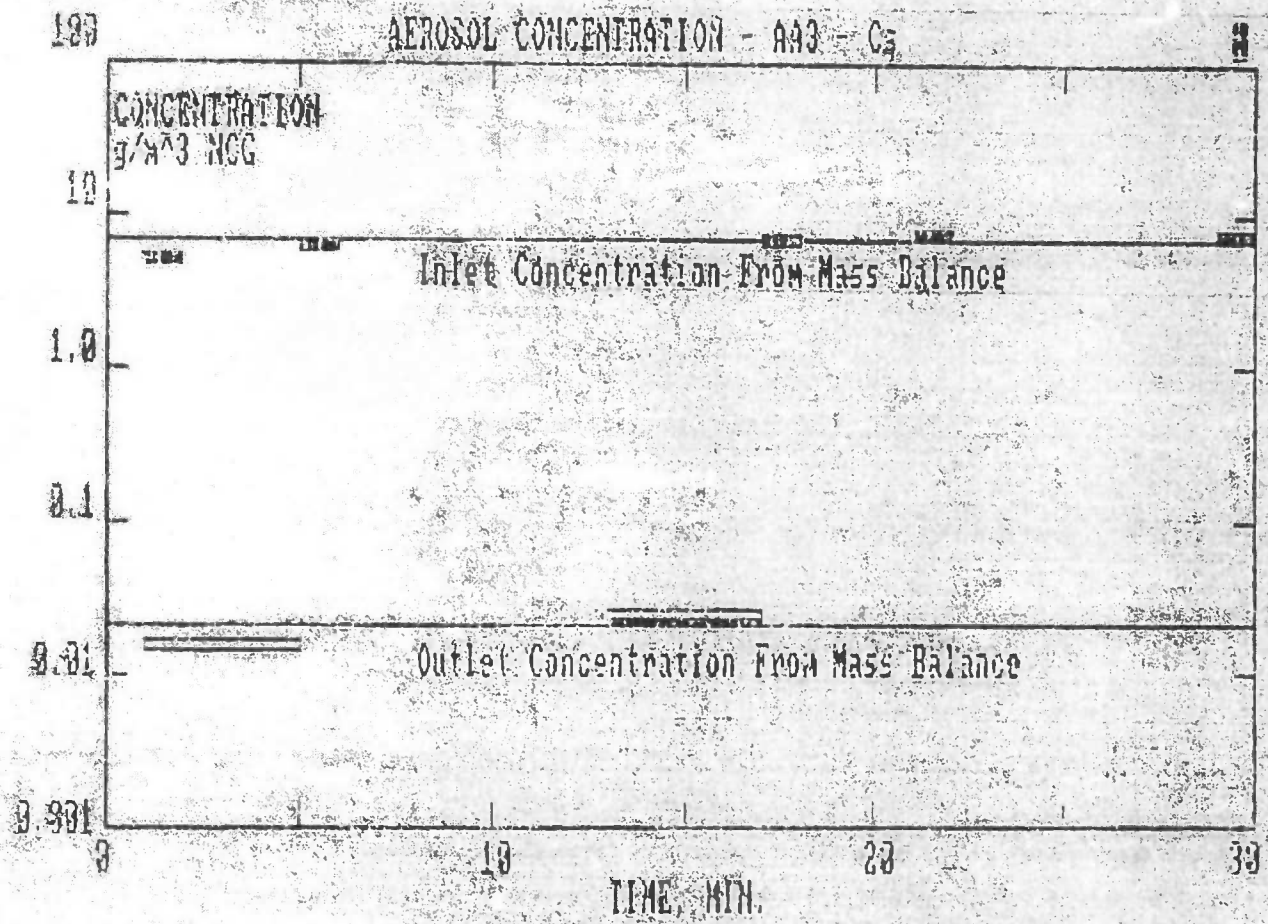

Figure 6-3a. Aerosol Concentration - AA3 - CS

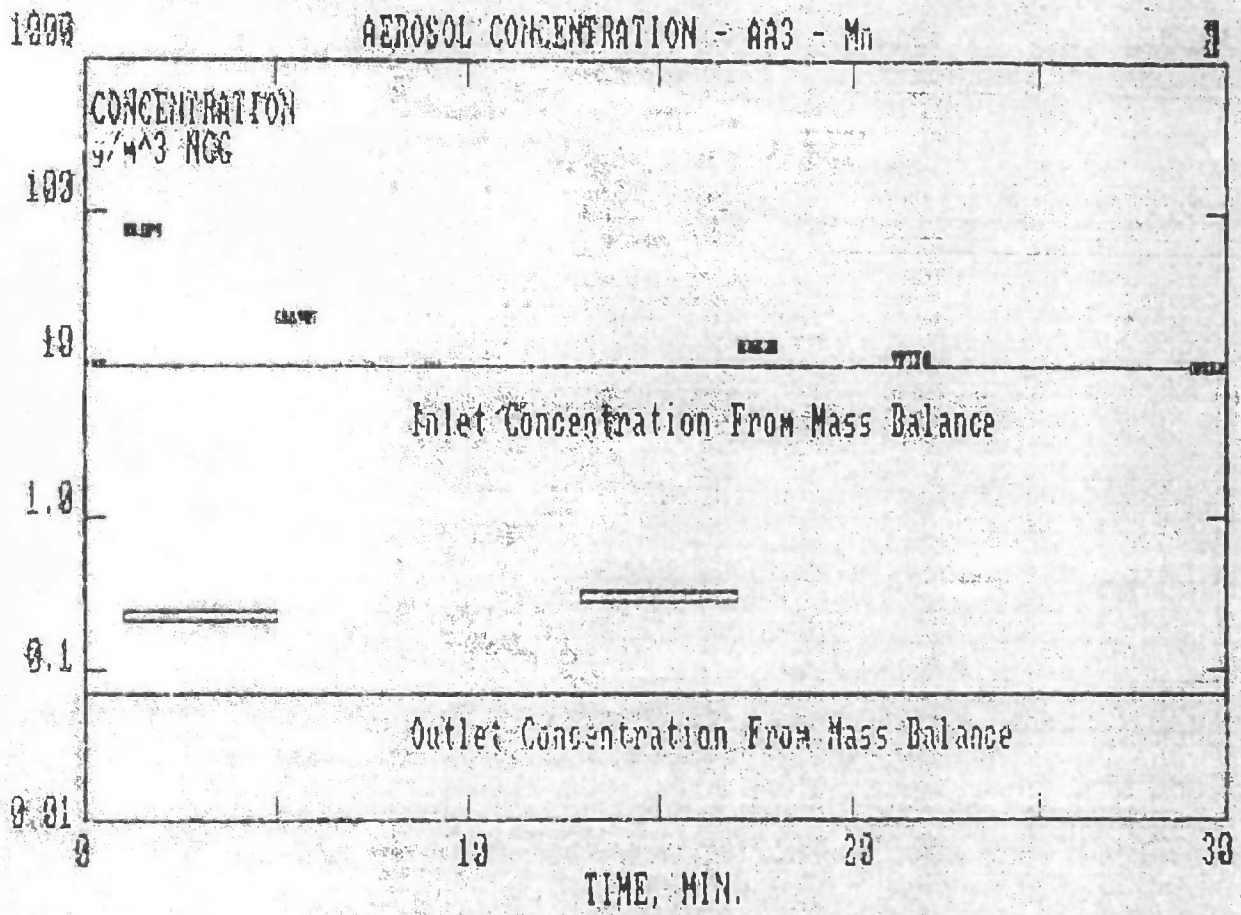

Figure 6-3b. Aerosol Concentration - AA3 - MN

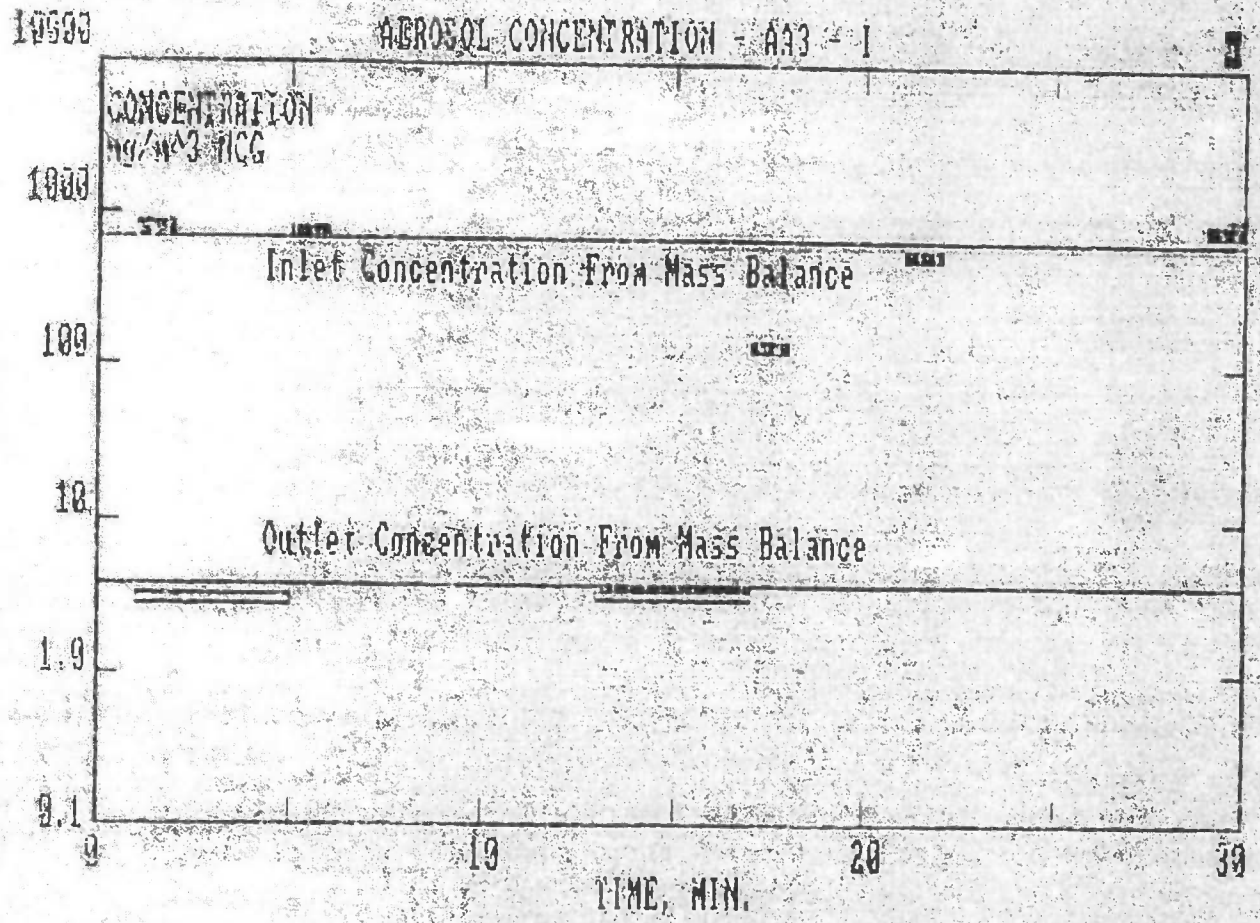

Figure 6-3c. Aerosol Concentration - AA3 - I

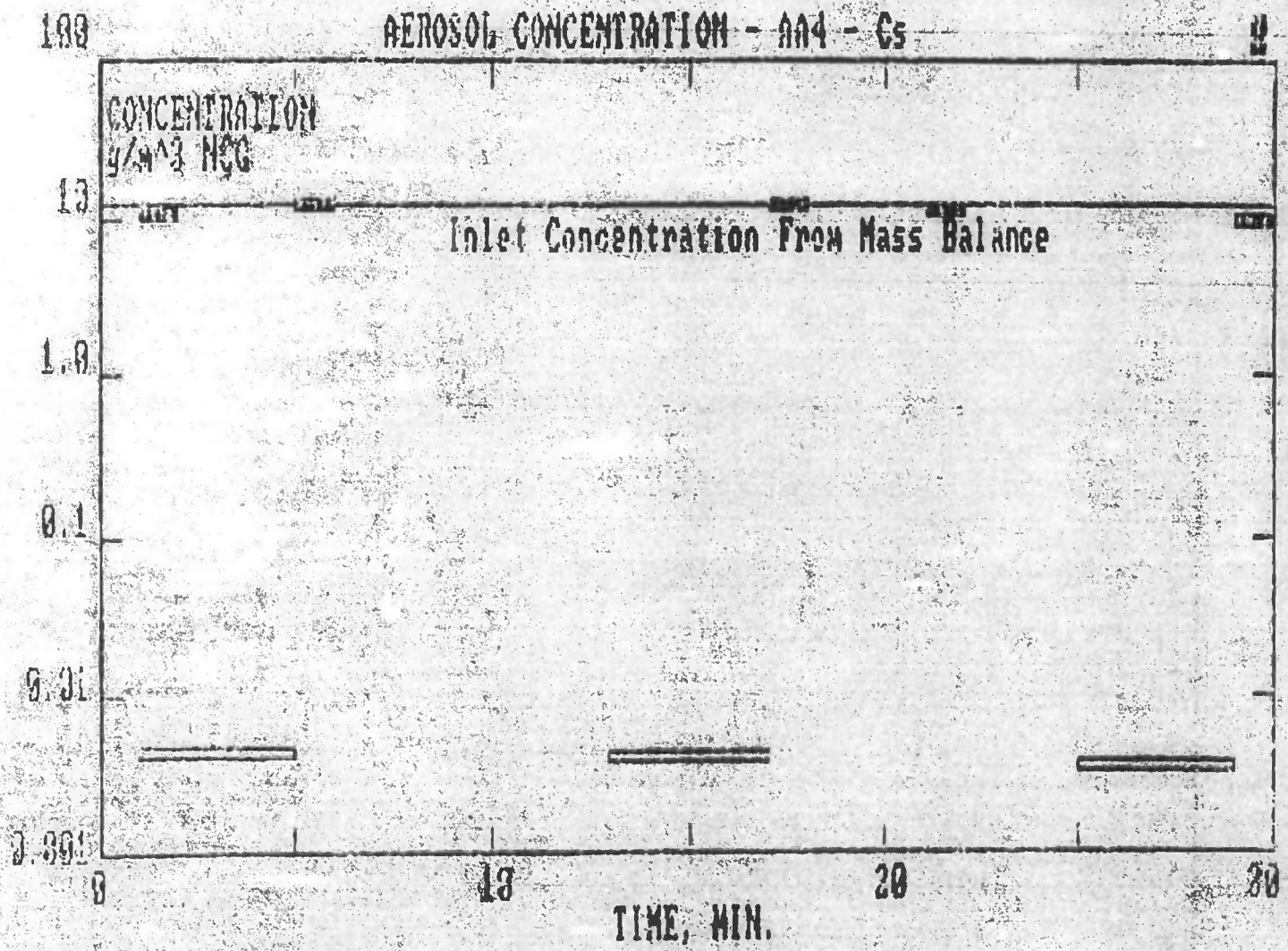

Figure 6-4a. Aerosol Concentration - AA4 - CS

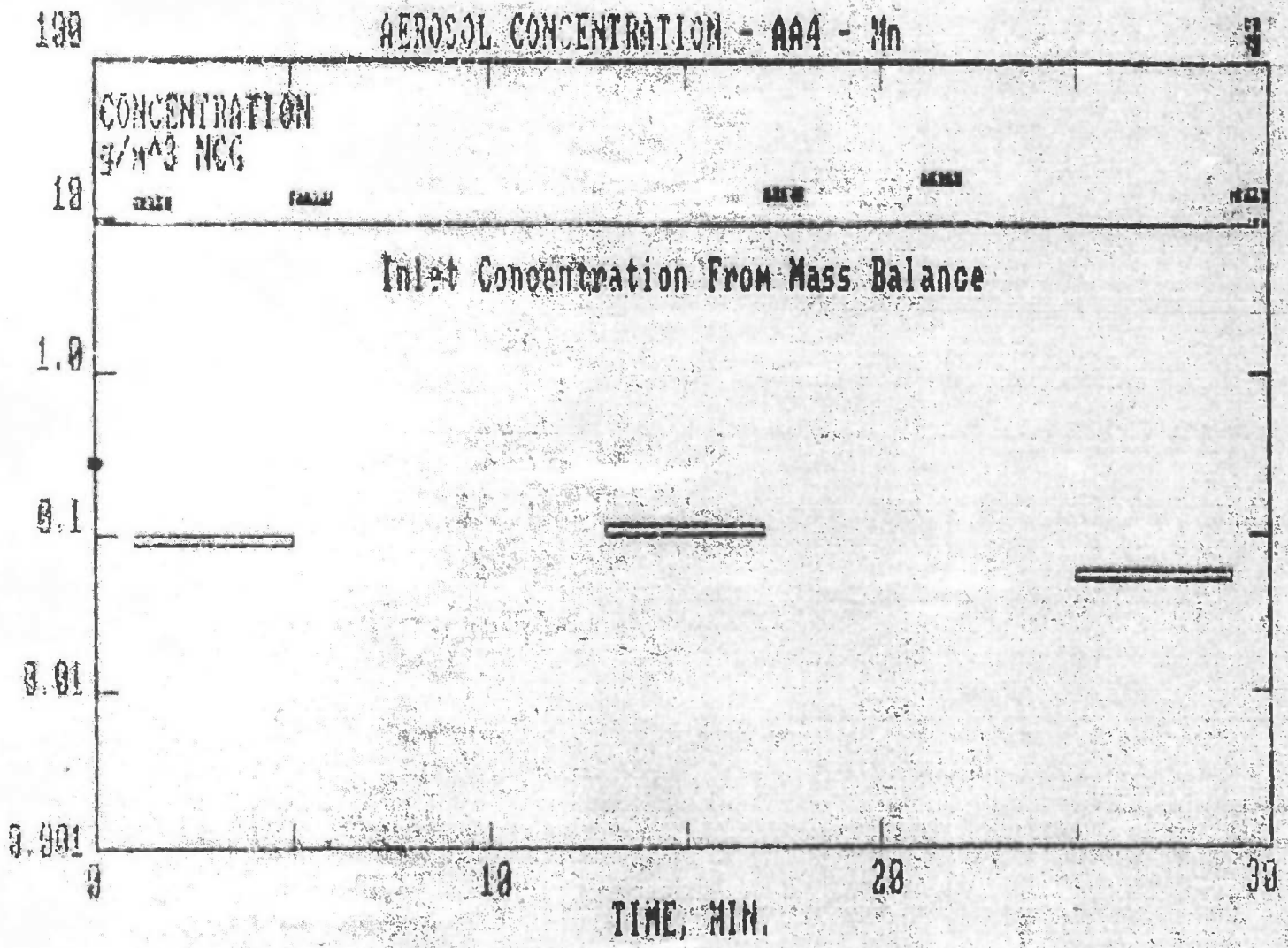

Figure 6-4b Aerosol Concentration -- AA4 - MN

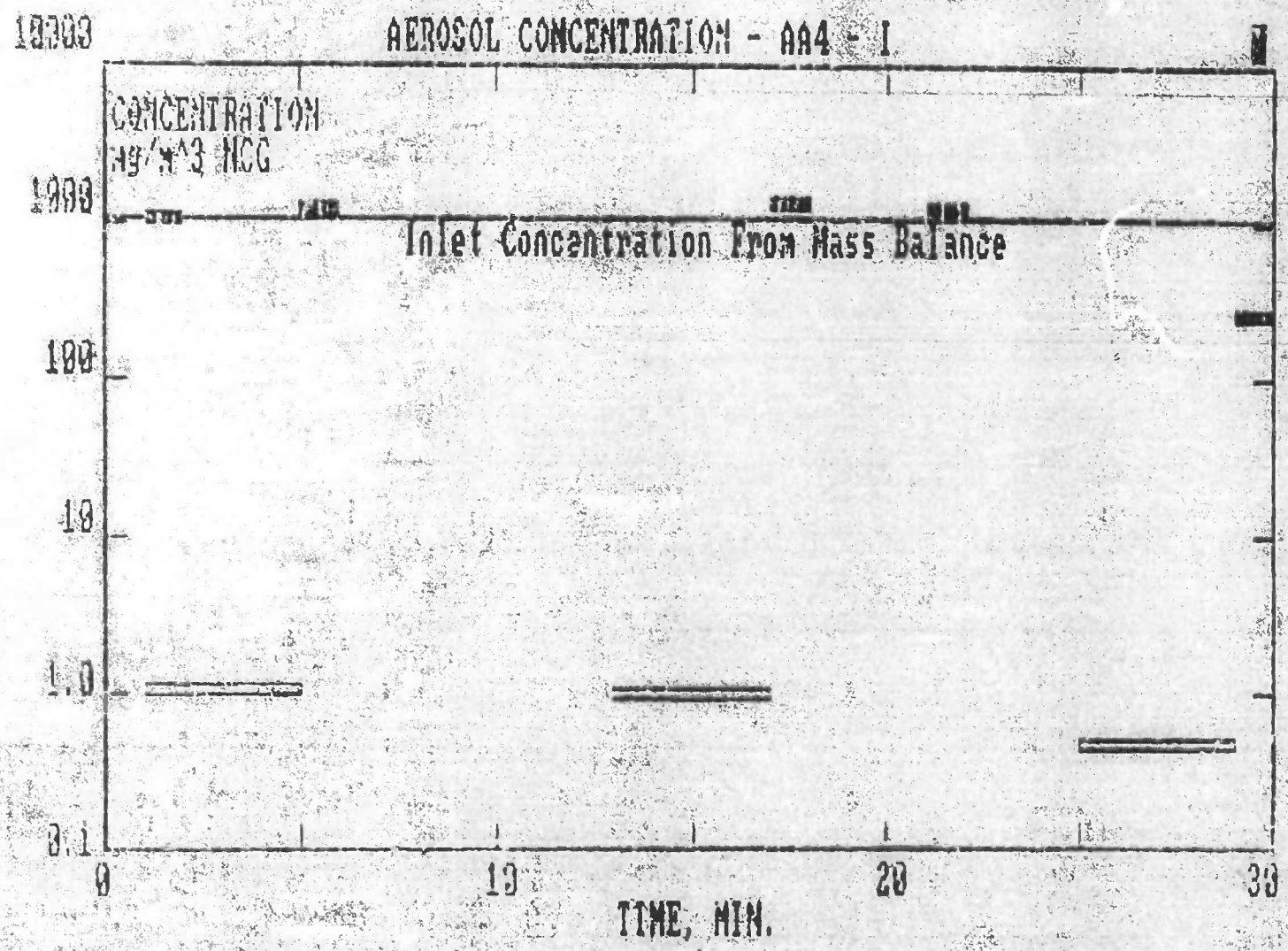

Figure 6-4c. Aerosol Concentration - AA4 I

as shown in Tables 6-6 and 6-7, or from the average aerosol concentrations, as shown in Table 6-10. Both sets of values are listed and compared in Table 6-11.

There is a wide variation of measured DF, from 11 to 3000, depending on aerosol material and test conditions, as discussed more fully below. There is generally fair to good agreement between the two types of measurement. The DFs from mass balance data for Tests AA2 and AA4 are subject to considerable uncertainty because the change in backup SGS liquid concentration is a small difference between two rather large measured concentrations. The DFs calculated for Mn from the mass balance data may be high; the water in the SGS was agitated by the gas flow during the test, but some MnO may have settled out and not been included in the liquid samples.

The dependence of DF on test conditions may be summarized as follows:

- The DF is much higher in the tests with higher steam fraction and deeper submergence of the sparger (AA2 and AA4 compared to AA1 and AA3). The higher steam fraction will promote aerosol flow to the bubble surface due to condensation there. The greater submergence increases contact time with the pool.

- The DF is higher in Tests AA3 and AA4, which had a hot pool, than in Tests AA1 and AA2, respectively, which had a cold pool. However, the submergence was higher in AA3 than in AA1 and the inlet steam fraction was higher in AA4 than in AA2. These differences would be expected to product a higher DF in AA3 than in AA1 and a higher DF in AA4 than in AA2. Thus, it is difficult to draw any conclusions as to the effect of pool temperature.

- The DFs are highest for Cs (145 to 3000) and lowest for Mn (11 to 260). This dependence on aerosol material suggests that the three materials were present, at least in part, as separate particles.

6.2.4 Entrainment from FTV Pool

As the gas passes up through the FTV pool, some water and accompanying aerosol material will be entrained and carried up with it. Entrainment from the pool was measured by collecting an aerosol filter sample at the FTV outlet (Station J7) during a 25-min period starting 10 min after the end of aerosol input from the AMV (Sample F4 in Table 6-9). The data of Table 6-9 show that the concentrations of resuspended aerosol material were negligible compared to those measured during aerosol input to the AMV, and therefore, that resuspension did not significantly affect the results of these tests. However, re-entrainment could reduce the efficiency of a pool scrubber if the pool concentrations became sufficiently high.

Table 6-11

DECONTAMINATION FACTORS

Test	AA1	AA2	AA3	AA4
Inlet Steam Fraction	0.0119	0.185	0.0130	0.410
Sparger Submergence, m	1.38	4.52	2.62	4.61
Pool Temperature, °C	26	25	82	84
DF from Mass Balance				
Cs	160	2000	330	3000
Mn	33	high	140	220
I	80	high	180	2600
DF from Aerosol Concentration				
Cs	145	840	320	3000
Mn	11	260	75	180
I	47	1500	220	1300

The data relevant to the entrainment measurements are summarized in Table 6-12. The pool concentrations were obtained by chemical analysis of liquid samples drawn from the FTV during this portion of the testing. The outlet aerosol concentrations are those from Table 6-9 for sample F4. The entrainment ratio expressed as grams of entrained liquid per standard m^3 of noncondensible gas, is the aerosol concentration divided by the pool concentration. The data for Test AA3 are not included in Table 6-12 because inadvertently the F4 sample was started only 3 minutes after the end of aerosol generation, and this did not allow sufficient time to flush the aerosol from the mixing vessel, so aerosol was probably still being fed to the FTV.

The estimate of liquid entrainment derived from these tests depends greatly on which of the three tracer materials (Cs, Mn, I) is used in the calculation. The outlet aerosol concentrations on which the entrainment estimates are based are generally small and subject to error due to contamination from material from sources other than pool entrainment. It is quite possible that the higher values of entrainment in Table 6-12 arise from such effects. The entrainment data should, therefore, be regarded only as an upper bound on possible entrainment rather than as accurate measurement. However, the data do demonstrate that the re-entrainment of aerosol

Table 6-12

ENTRAINMENT OF LIQUID FROM POOL IN FTV

Test	AA1R	AA2R	AA4R
Pool temperature, °C	27	27	83
Sparger submergence, m	1.38	4.55	4.59
Superficial gas velocity over pool, m/s	0.054	0.030	0.069
Inlet Aerosol Concentration (T6) mg/std m^3 NCG			
Cs	26	7.3	3.3
Mn	0.8	2.3	0.7
I	0.01	0.04	0.02
Outlet Aerosol Concentration (T6) mg/std m^3 NCG			
Cs	5.1	1.06	0.45
Mn	0.2	0.03	2.3
I	0.01	0	0
FTV Pool Concentration, mg/ml			
Cs	0.32	0.24	0.24
Mn	0.28	0.14	0.26
I	0.059	0.036	0.023
Entrainment, g liquid/std m^3 NCG			
Cs basis	16	4.4	1.9
Mn basis	0.7	0.2	9
I basis	0.2	0	0

from the pool is small compared to that passing through, as shown in Table 6-9 by the small concentrations of the F4 resuspension samples compared to F1, F2, and F3.

6.2.5 Aerosol Particle Size Distribution

The particle size distribution of the inlet and outlet aerosols was measured with cascade impactors, as described in Section 3.4.4. Detailed data are given in Appendix C in the form of tables of mass collected at each stage of the impactor as a function of the aerodynamic cut diameter of that stage. These data were then

expressed as a log-normal distribution using a least-squares curve fit, as described in Appendix C. The aerodynamic mass median diameter (AMMD) and the geometric standard deviation (GSD) so obtained are listed in Tables 6-13 to 6-16 for Tests AA1-AA4, respectively.

Tables 6-13 to 6-16 also give the total mass of Cs, Mn, and I on all stages of the filter. If the mass is less than 0.1 mg, there is not enough material for a good measurement; values greater than 0.5 mg are desirable. These tables also include values of r^2, where r is the correlation coefficient for a log-normal distribution. Values of r^2 close to 1.00 indicate a good fit of the data; values below 0.90 suggest significant departure from a log-normal relationship.

The particle-size distribution data of Tables 6-13 to 6-16 are summarized in Table 6-17 as average values of AMMD and GSD at the inlet and outlet of the FTV. The inlet values are averages of the two samples taken at Station T5. The outlet measurements made at Stations T6 and T7 are shown separately, since there appears to be a significant difference between them. The T6 outlet values are averages of the two samples taken; those at T7 are for the single sample taken during aerosol release. Questionable values, as noted on Tables 6-13 to 6-16, were excluded from the averages. In all cases the values based on measurements of Cs, Mn, and I were averaged together.

A large reduction in aerosol particle size was observed in passing through the FTV pool. The average inlet AMMD in Table 6-17 ranged from 1.7 to 2.6 μm; the outlet from 0.5 to 0.9 μm. This shift to a smaller median size is expected, since the scrubber removes the larger aerosol particles more efficiently than the smaller ones.

The particle sizes measured at outlet Station T6 are generally smaller than measured at T7. This difference may result from particle growth due to agglomeration or absorption of moisture between T6, a short distance above the FTV, and T7 which was ~16 m downstream and at a slightly lower temperature (see Table 6-4). It should also be noted that for these tests, different types of impactors were used at the two stations.

The aerosol particle size showed only a small dependence on whether size was based on measurements of Cs, Mn, or I. The average inlet AMMD, averaged over four tests and two inlet samples per test, was 2.37 μm for Cs, 2.04 μm for Mn, and 2.46 μm for I. The average outlet AMMD measured at T7 was 0.92 μm for Cs, 0.84 μm for Mn, and 0.89 μm for Cs.

Table 6-13

AEROSOL PARTICLE SIZE DISTRIBUTION, AA1

Location	Time, min Start[a]	Time, min ΔT	Material	Total Mass mg	AMMD μm	GSD	r^2[e]	Notes
Inlet (T5)	9	0.5	Cs	5.8	2.43	1.75	0.94	
			Mn	8.3	2.08	1.90	0.97	
			I	1.4	2.50	1.88	0.97	
	25	0.66	Cs	9.7	2.45	1.79	0.91	
			Mn	12.6	2.05	1.90	0.96	
			I	2.0	2.67	1.92	0.96	
Outlet (T6)	7.5	4	Cs	1.5	0.92	2.02	0.98	
			Mn	12.9	0.97	1.80	0.96	
			I	0.8	0.93	1.87	0.98	
	19	4	Cs	1.6	0.88	2.17	0.96	
			Mn	13.7	1.00	1.68	0.93	
			I	0.7	0.93	1.88	0.95	
Outlet (T7)	1	25	Cs	12.9				b
			Mn	143.0				b
			I	6.2				b
	40	25[c]	Cs	2.8	0.38	2.13	0.80	
			Mn	0.08	d	d	d	
			I	0.003	d	d	d	

[a]Time after start of aerosol release.

[b]Impactor overloaded.

[c]Reentrainment test.

[d]Insufficient mass on filter for valid measurement.

[e]r = correlation coefficient.

Table 6-14

AEROSOL PARTICLE SIZE DISTRIBUTION - AA2

Location	Time, min Start[a]	Time, min ΔT	Material	Total Mass mg	AMMD μm	GSD	r^2[c]	Notes
Inlet (T5)	9	0.5	Cs	14.1	1.58	2.12	0.98	
			Mn	8.9	1.49	2.13	0.99	
			I	1.9	1.93	1.87	0.99	
	25	0.5	Cs	13.5	1.90	2.04	0.99	
			Mn	5.6	1.95	2.06	0.99	
			I	1.3	1.45	2.21	0.96	
Outlet (T6)	7	4	Cs	0.6	0.75	2.23	0.92	
			Mn	1.4	0.67	2.34	0.97	
			I	0.06	b	b	b	
	19	4	Cs	0.5	0.60	2.44	0.92	
			Mn	1.5	0.53	2.60	0.94	
			I	0.04				
Outlet (T7)	1	25	Cs	5.8	0.84	1.52	0.97	
			Mn	8.0	0.80	1.65	0.92	
			I	0.4	0.93	1.51	0.98	
	40	60[c]	Cs	0.4	0.32	2.07	0.97	
			Mn	0.12	b	b	b	
			I	0.004	b	b	b	

[a]Time after start of aerosol release.

[b]Insufficient mass on filter for valid measurement.

[c]r = correlation coefficient.

Table 6-15

AEROSOL PARTICLE SIZE DISTRIBUTION - AA3

Location	Time, min Start[a]	Time, min ΔT	Material	Total Mass mg	AMMD μm	GSD	r^{2d}	Notes
Inlet (T5)	9.1	0.33	Cs	8.0	2.89	1.90	0.94	
			Mn	11.6	2.18	2.27	0.89	
			I	1.1	2.79	2.03	0.95	
	25	0.33	Cs	9.7	2.55	1.79	0.93	
			Mn	14.4	1.99	2.17	0.96	
			I	1.4	2.58	1.99	0.96	
Outlet (T6)	7	4	Cs					
			Mn	SAMPLE COULD NOT BE TAKEN				
			I					
	24.2	4	Cs	0.3	0.38	2.02	0.94	
			Mn	2.2	0.50	3.07	0.92	
			I	0.06	0.40	2.04	0.98	b
Outlet (T7)	1	25	Cs	4.1				c
			Mn	42.0				c
			I	0.7				c
	41	25[d]	Cs	1.1	0.40	1.58	0.85	
			Mn	0.005	--	--	--	c
			I	0.16	0.40	1.44	0.95	c

[a]Time after start of aerosol release.

[b]Insufficient mass on filter for valid measurement.

[c]Stage assembly error.

[d]r = correlation coefficient.

Table 6-16

AEROSOL PARTICLE SIZE DISTRIBUTION - AA4

Location	Time, min Start[a]	ΔT	Material	Total Mass mg	AMMD μm	GSD	r^{2d}	Notes
Inlet (T5)	9.1	0.33	Cs	4.6	2.34	2.17	0.90	
			Mn	4.2	2.11	2.33	0.91	
			I	0.5	2.56	2.21	0.91	
	25.2	0.33	Cs	16.9	2.81	2.34	0.87	
			Mn	19.6	2.50	2.03	0.91	
			I	1.6	3.20	2.50	0.88	
Outlet (T6)	7	4	Cs	0.06	0.44	2.17	0.98	b
			Mn	1.8	0.42	2.33	0.99	
			I	0.01				b
	19.4	4	Cs	0.04	0.41	2.68	0.96	b
			Mn	1.5	0.54	2.16	0.96	
			I	0.004				b
Outlet (T7)	1	25	Cs	0.6	1.01	1.91	0.97	
			Mn	12.4	0.89	2.28	0.86	
			I	0.14	0.85	1.69	0.98	
	40	60[d]	Cs	0.10	c	c	c	c
			Mn	0.5	c	c	c	
			I	0.000	c	c	c	

[a]Time after start of aerosol release.

[b]Insufficient mass on filter for valid measurement.

[c]Last four impactor stages were wet, invalid sample.

[d]r = correlation coefficient.

Table 6-17

AEROSOL PARTICLE SIZE DISTRIBUTION - AVERAGE VALUES

		AA1	AA2	AA3	AA4
Inlet Volume Steam Fraction		0.012	0.185	0.013	0.410
Sparger Submergence, m		1.38	4.52	2.62	4.61
Pool Temperature, °C		26	24	82	83
AMMD, μm:	Inlet (T5)	2.36	1.72	2.50	2.59
	Outlet (T6)	0.94	0.64	a	0.45
	Outlet (T7)	a	0.86	a	0.92
GSD:	Inlet (T5)	1.86	2.07	2.02	2.26
	Outlet (T6)	1.90	2.40	a	2.34
	Outlet (T7)	a	1.56	a	1.96

[a]Insufficient mass for valid measurement.

The data in Tables 6-13 to 6-16 for the second sample taken at Station T7 apply to the aerosol reentrained from the FTV pool after the end of aerosol release. These measurements suffer generally from a sample mass that is too small for good measurement. The most reliable data are those for Cs, which show an AMMD from 0.24 to 0.40 μm. The cascade impactors used at T7 had a cut diameter for the last stage of 0.38 or 0.46 μm. Therefore, over half of the aerosol was collected on the backup filter, and the calculated AMMD and GSD are based on only the size data of the larger particles (measurements at T6 had a minimum cut diameter of 0.2 μm).

6.2.6 Physical and Chemical Characteristics of Aerosol

The aerosol forming materials are released as vapors into the humid nitrogen AMV atmosphere using the methods described in Section 3.3. The expected reactions are:

$$Cs + H_2O \rightarrow CsOh + 1/2\ H_2 \quad (a)$$

$$CsOH + HI \rightarrow CsI + H_2O \quad (b)$$

$$Mn + H_2O \rightarrow MnO + H_2 \quad (c)$$

Reactions (a) and (b) are fast and should go to completion at the test conditions. Evidence of these reactions is found from the hydrogen formed in the AMV atmosphere, Table 6-3, and from x-ray diffraction (XRD) analysis of the T5 inlet sampling, Table 6-18.

It should be noted that CsOH is hygroscopic and is not expected to be crystalline at the sample analysis conditions, and hence would not be detected by the x-ray method.

Before chemical analysis of the sample, the filters were weighed. The comparison of the measured weights and the weights calculated from the chemical analysis, assuming the aerosol materials were CsOH, CsI, and MnO, is presented in Table 6-19 for Tests AA3 and AA4.

These ratios show that all the sample weight can be accounted for using the expected chemical forms, and that no large amount of water is associated with the aerosol. This finding is somewhat surprising because at the test humidities a CsOH atom would be expected to retain one or two atoms of water, thus producing a typical sample weight ratio of about 1.05 to 1.1.

The formation of soluble iodine or cesium compounds with manganese can also be proposed. Tests for soluble manganese were not made during Tests AA1-4, but the soluble Mn fraction was found to average only 0.02% in FTV liquid samples analyzed during later ACE tests. This indicates that no important quantities of these compounds were formed.

Scanning electron microscope (SEM) examination of particles taken on Nuclepore® filters at stations T5, T6 and T7 have been made in some cases. Sampling to obtain usable particle loading on the filter material has been difficult because of the high aerosol mass concentration at the inlet (T5) samples, and because of the unknown (at least before the test) concentrations expected at the test pool outlet.

Photos were obtained and are shown in Figures 6-5, 6-6, and 6-7. In Figures 6-5 and 6-6 it can seem that the primary particles are mostly spherical or blocky in shape and that the larger agglomerates are also compact blocky shapes. No long chains are seen. The outlet particles are smaller than the inlet particles. Figures 6-7 shows some unusual shapes were found on the T5 inlet filter in Tests AA2 and AA4. The needle shape particles (Test AA2) are rich in cesium compared to the spherical particles which are rich in manganese. Particle sizing from the SEM photos has not, in general, given satisfactory results, due to the high particle concentrations.

Table 6-18

CRYSTALLINE FORMS FOUND AT T5 INLET SAMPLE BY X-RAY DIFFRACTION

Test Number:	AA3	AA4
Compounds:	CsI (s)	CsI (s)
	MnO (s)	MnO (s)
	$Mn(IO_3)_2$ (w?)	Mn_2O_3 (w)

(s) Strong

(w) Weak

(?) Questionable

Table 6-19

COMPARISON OF AEROSOL MASS ON FILTERS BY CHEMICAL ANALYSIS AND WEIGHING

Run and Sample Location	No. of Samples	Ratio Total Weight/Chemical Analysis[a]
AA3 Inlet (T5)	3	0.94 ± 0.01[b]
Outlet (T6)	2	0.98 ± 0.01
AA4 Inlet (T5)	5	0.98 ± 0.11
Outlet (T6)	2	1.34 ± 0.4

[a]Weight calculated from chemical analysis assuming aerosol compounds to be CsOH, CsI, and MnO.

[b]± Standard Deviation.

6.2.7 ITW Sampling Errors

Expected accuracy of the various ACE measurement is discussed in Section 3.4 and Table 3-2. An additional source of variation is due to non-isokinetic sampling of the FTV ducts. A second possible sample error can arise from not aligning the

Figure 6.5. SEM photo of inlet and outlet filter aerosol deposits, test AA1.

AA1 SEM

1 µm

AA1 T5-Nu 1 Inlet

1 µm

AA1 T7-Nu 1 Outlet

Figure 6.X SEM Photos of Inlet and Outlet Filter Liquid Deposits, T5-T7 AA1

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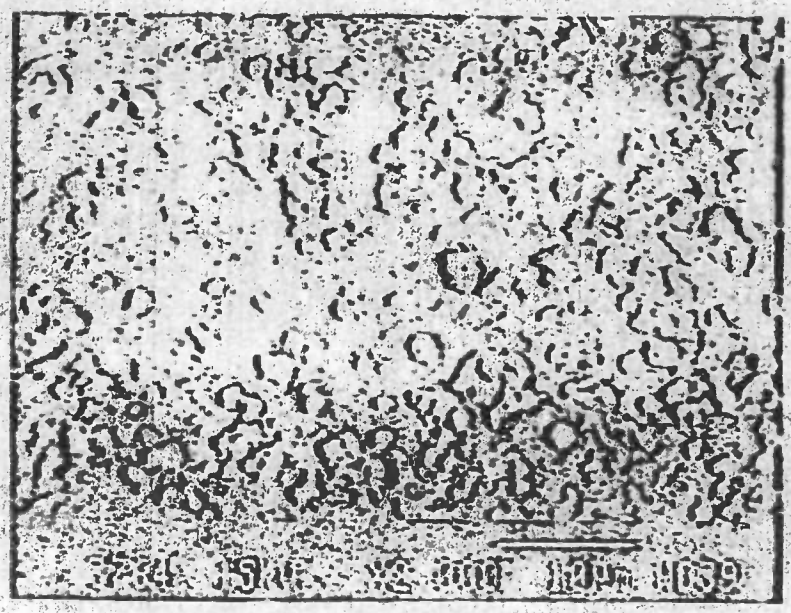
Figure 6.6. SEM photo of inlet and outlet filter aerosol deposits, test AA2.

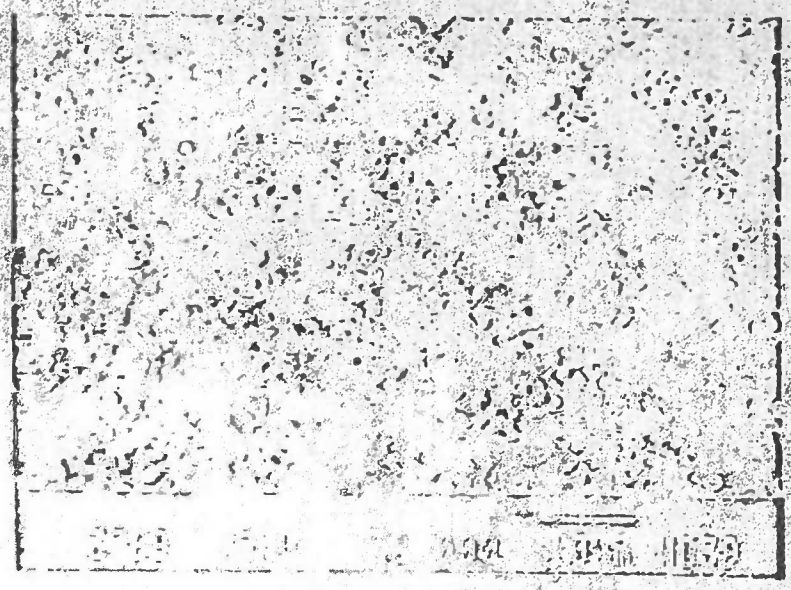
AA2 SEM

10 µm



AA2 T5-Nu 1 Inlet

10 µm



AA2 T7-Nu 1 Outlet

Figure 6 SEM Photo of Inlet and outlet from Reverse Osmosis Test AA2

BEST AVAILABLE COPY

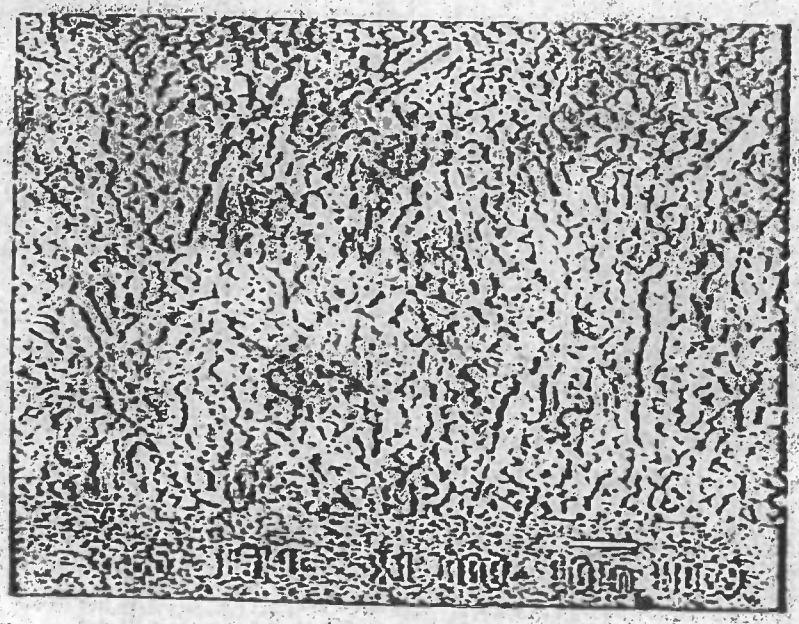
Neg No 8808626-2

FIG 6

Figure 6.7. SEM photo of unusual inlet filter aerosol deposits.

AA2 SEM

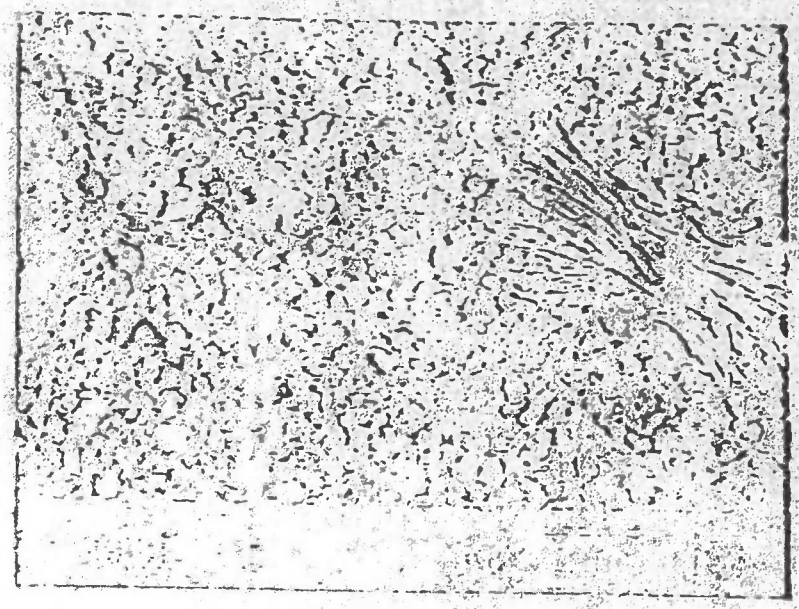
10 µm



AA2 T5-Nu 1 Inlet

AA4 SEM

10 µm



AA4 T5-Nu 1 Inlet

Figure 6.xxx SEM Photo Rinsed Neg No 88035261
Filter Remove Deposit
Fig 6.7

BEST AVAILABLE COPY

sample inlet probe with the duct axis. Both of these sample errors, as discussed by Hinds(6) are affected by the Stokes number and the system velocities and are most severe for larger particles.

For the ACE Tests AA 1-4 where the average inlet particle size at T5 was about 3 μm, a probe misalignment of 45° would give a sample concentration of 98% of the true value. At the pool outlet (T6) sample the average particle size is less than 1 μm and the error even at a 90° misalignment is less than 1%.

TTW sampling at isokinetic velocities is not always possible because of the need to operate the equipment to obtain optimum loadings, because of calibration restraints, and because of limited probe inlet sizes. This error for the worst case velocities, using the above partical sizes, has been estimated for the T5 (inlet) location to be less than 5% (low). For the T6 (outlet) location this error is less than about 10% (high), thus decontamination factors will be slightly underestimated.

For the ACE Tests AA 1-4 where the average inlet particle size at T5 was about 3 μm, a probe misalignment of 45° off the flow direction would give a sample concentration of 98% of the true value. At the pool outlet (T6) sample the average particle size is less than 1 μm and the error even at a 90° misalignment is less than 1%. Sampler operators generally kept misalignment to less than 20°, hence errors due to this effect are probably negligible.

6.3 DOP EFFICIENCY TESTS

As discussed in Section 4.4, pre-test measurements of the sparger-pool efficiency were made using a standard ANSI N510-1980(7) DOP test.

DOP test results are given in Table 6-20 for several flowrates of dry nitrogen and sparger submergences at ambient conditions (24°C pool temperature) and are expressed as percent efficiency and DF (inlet/outlet).

For this small sized test aerosol (see Section 4.4) the scrubbing efficiency is relatively low and the measurements do not show any strong dependence on flow or submergence over the conditions tested. Outlet sampling with the photometer during times when the input aerosol was not being generated showed that pool entrainment carryover was negligible.

Table 6-20

POOL SCRUBBER DOP TEST EFFICIENCY
(Pool Temperature - 24°C)

DOP Test No.	Gas Flow (M^3/s) STP	Submergence (m)	Removal Efficiency (%)	(DF)
1	0.084	4.5	86	7.1
2	0.047	4.5	90	10.0
3	0.042	2.6	84	6.2
4	0.083	2.6	89	9.1
5	0.134	2.6	92	12.5

Section 7

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Appendix A

PROCEDURE USED FOR ANALYSIS OF AAX SAMPLES

Appendix A

PROCEDURE USED FOR ANALYSIS OF AAX SAMPLES

pH is determined with a combination pH electrode in a portion of well-shaken liquid samples.

Total solids are determined by drying and weighing a 50 ml aliquot of well-shaken liquid.

LIQUID SAMPLES

Remove 50 ml of well-shaken liquid and add 5 ml of reagent B or D. Measure iodine by specific ion electrode within 1 hour using 20 ml of the mixture. Fill a plastic scintillation vial with remainder of the mixture for Cs, Na, and B determination by AA or ICP. Digest the rest of the original liquid sample with HCl and return to starting volume for Mn determination by AA. Reagents containing K_2SO_3 were very high in Na. Reagents containing NH_2OH were lower in Na, but the reagent blank was still too high for meaningful Na results from the experiment. Reagent D was used for all samples after Na analyses were canceled.

AEROSOL FILTERS

Add 50 ml of reagent C or E to reduce iodine. Measure iodide by specification electrode within 1 hour using 20 ml. Transfer 10 ml to a plastic scintillation vial for Cs, Na, and B determination by AA or ICP. Digest the remaining 20 ml and the filter with HCl and make up to 20 ml for Mn determination by AA. (Dark color stays on the filter or settles.) Reagent E was used for all samples after Na analyses were canceled.

WATER FILTERS (USED DURING POST-TEST CLEANUP)

Remove the filter from the plastic housing. Cut out a weighed (small) portion and treat with a known volume of reagent E. Measure iodide by specific ion electrode within 1 hour and determine Cs, Na, and B by AA and ICP. Weigh the large remaining portion and digest it with HCl for Mn and Fe determination by AA.

Reagent B: 0.5 M K_2SO_4 + 0.1 M $NH_2OH.H_2SO_4$ adjusted to pH 8.5 with NH_4OH made from gas.

Reagent D: 0.5 M K_2SO_4 + 0.02 M $NH_2OH.H_2SO_4$ adjusted to pH 8.5.

Reagent E: 0.04 M K_2SO_4 + 0.018 M K_2SO_3 (pH is 8.7).

These reagents are made fresh daily.

Appendix B

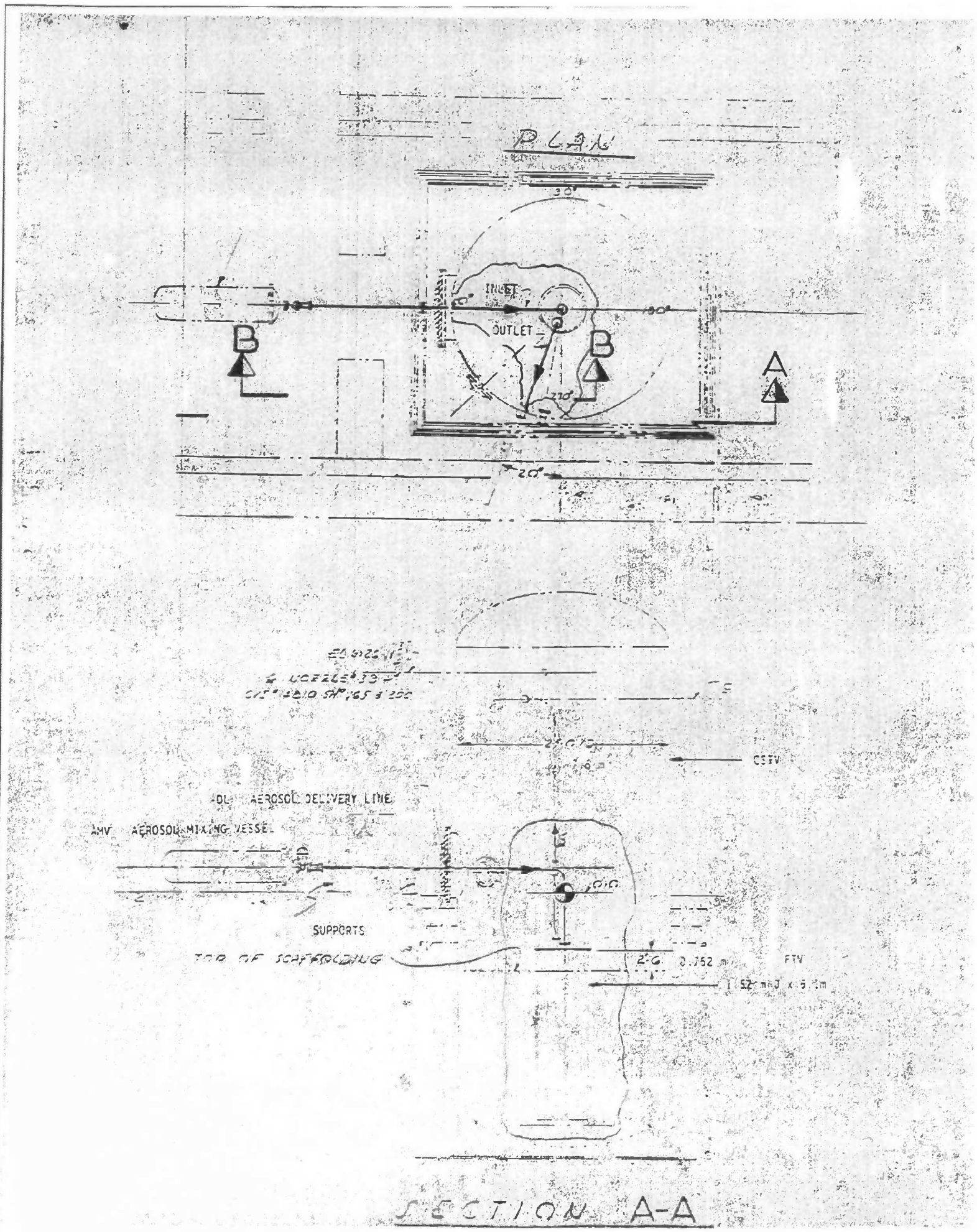
DETAILED SKETCHES OF SPARGER EQUIPMENT

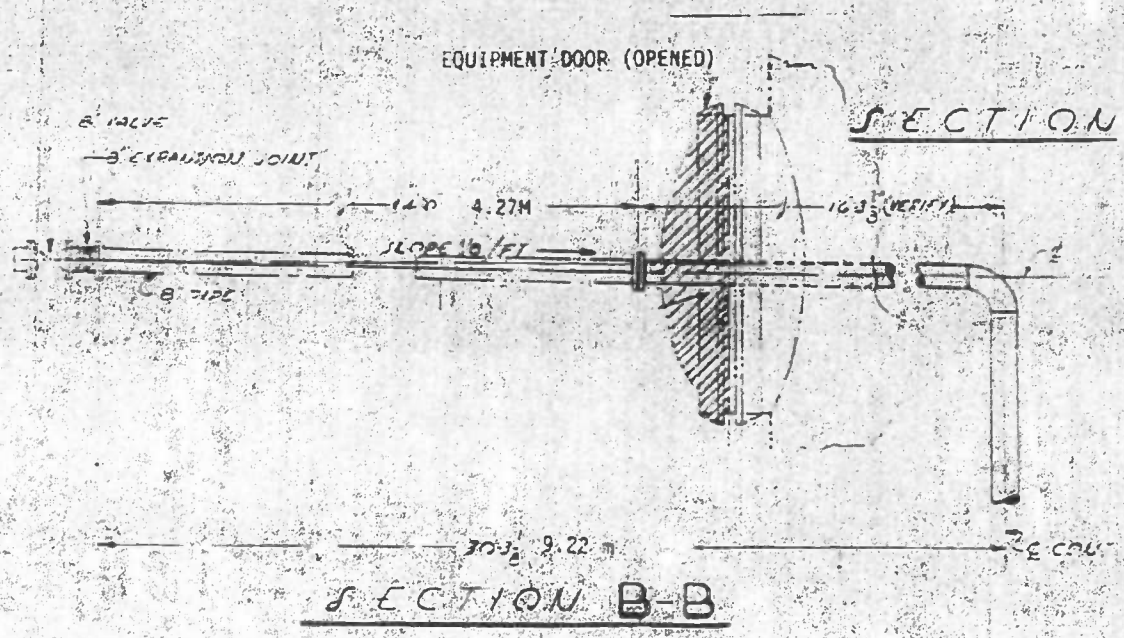
Appendix B

DETAILED SKETCHES OF SPARGER EQUIPMENT

Figure B-1.

Figure B-2.


PLAN
INLET
OUTLET
B
B
A
CSTV
AEROSOL DELIVERY LINE
AMV AEROSOL MIXING VESSEL
SUPPORTS
FTV
SECTION A-A


EQUIPMENT DOOR (OPENED)
SECTION
8" VALVE
8" EXPANSION JOINT
14'0"
4.27M
16 1/3" (VERIFY)
SLOPE 1/8" FT
8" PIPE
30 1/3" 9.22 m
℄ CPU
SECTION B-B

Appendix C

CASCADE IMPACTOR DATA

TABLE C.1

Cascade Impactor Data - Sample AA1-T5-I1

TYPE: 6 STAGE SIERRA TIME: 9.25 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	26.6976	0.0290	0.0529	0.0097	0.9950	0.9936	0.9930
2	16.3152	0.0800	0.0899	0.0207	0.9812	0.9827	0.9780
3	6.5261	0.2400	0.2489	0.0207	0.9398	0.9527	0.9267
4	3.9305	0.5700	0.8889	0.1897	0.8415	0.8453	0.7893
5	2.5214	1.7200	1.5989	0.3797	0.5449	0.6521	0.5141
6	1.4090	2.5500	3.3989	0.4997	0.1052	0.2415	0.1520
FILTER		0.6100	1.9985	0.2097			
TOTAL		5.7987	8.2769	1.3799			

TABLE C.2

Cascade Impactor Data - Sample AA1-T5-I2

TYPE: 6 STAGE SIERRA TIME: 25.38 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	26.7379	0.0670	0.0959	0.0137	0.9931	0.9924	0.9930
2	16.3398	0.1900	0.1489	0.0457	0.9736	0.9806	0.9697
3	6.5359	0.3700	0.3689	0.1097	0.9355	0.9513	0.9136
4	3.9364	0.8500	1.0989	0.2697	0.8480	0.8642	0.7759
5	2.5252	3.4200	2.5989	0.6297	0.4960	0.6581	0.4543
6	1.4112	3.9100	5.1989	0.6097	0.0936	0.2457	0.1429
FILTER		0.9100	3.0985	0.2797			
TOTAL		9.7167	12.6089	1.9579			

TABLE C.3

Cascade Impactor Data - Sample AA1-T6-I1

TYPE: 8 STAGE SIERRA TIME: 9.5 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	14.6091	0.0040	0.0509	0.0037	0.9973	0.9960	0.9968
2	8.9278	0.0040	0.0479	0.0037	0.9946	0.9923	0.9923
3	3.5711	0.0170	0.1289	0.0092	0.9830	0.9823	0.9813
4	2.1508	0.0670	0.6289	0.0287	0.9374	0.9335	0.9470
5	1.3797	0.3300	2.2989	0.1697	0.7122	0.7550	0.7440
6	0.7710	0.5000	5.8989	0.3297	0.3711	0.2974	0.3495
7	0.4302	0.3000	2.2989	0.1797	0.1664	0.1186	0.1345
8	0.2597	0.2300	1.4989	0.1097	0.0095	0.0022	0.0032
FILTER		0.0140	0.0285	0.0027			
TOTAL		1.4656	12.8807	0.8358			

TABLE C.4

Cascade Impactor Data - Sample AA1-T6-I2

TYPE: 8 STAGE SIERRA TIME: 21 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	14.8717	0.0006	0.0239	0.0017	0.9997	0.9983	0.9975
2	9.0883	0.0030	0.0359	0.0027	0.9978	0.9956	0.9936
3	3.6353	0.0130	0.1189	0.0057	0.9896	0.9870	0.9852
4	2.1894	0.0740	0.3789	0.0177	0.9429	0.9594	0.9593
5	1.4046	0.3200	2.3989	0.1297	0.7410	0.7845	0.7695
6	0.7849	0.5700	7.4989	0.2997	0.3812	0.2380	0.3309
7	0.4379	0.2500	1.7989	0.1197	0.2234	0.1069	0.1557
8	0.2644	0.2600	1.2989	0.0877	0.0593	0.0123	0.0274
FILTER		0.0940	0.1685	0.0187			
TOTAL		1.5842	13.7217	0.6833			

TABLE C.5

Cascade Impactor Data - Sample AA1-T7-I1

TYPE: ANDERSEN

TIME: 13.5 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0025 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	12.7837	0.1400	1.3975	0.0347	0.9891	0.9902	0.9944
2	8.0137	0.1800	1.5975	0.0677	0.9751	0.9790	0.9835
3	5.4379	0.2400	1.8975	0.0857	0.9565	0.9657	0.9697
4	3.7206	0.4000	2.6975	0.1697	0.9254	0.9468	0.9423
5	2.3850	1.7000	11.9975	0.7397	0.7933	0.8627	0.8230
6	1.1448	5.6000	82.9975	2.6597	0.3582	0.2808	0.3940
7	0.7346	2.6000	19.9975	1.3497	0.1562	0.1406	0.1763
8	0.4961	1.1000	13.9975	0.6697	0.0709	0.0425	0.0683
FILTER		0.9100	6.0585	0.4237			
TOTAL		12.8696	142.6385	6.2003			

TABLE C.6

Cascade Impactor Data - Sample AA1-T7-I2

TYPE: ANDERSEN

TIME: 52.5 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0025 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	11.8078	0.0100	0.0085	0.0004	0.9965	0.8903	0.8750
2	7.4019	0.0110	0.0005	0.0006	0.9927	0.8839	0.6875
3	5.0227	0.0110	0.0015	0.0004	0.9888	0.8645	0.5625
4	3.4366	0.0150	0.0005	0.0003	0.9836	0.8581	0.4688
5	2.2029	0.0190	0.0015	0.0003	0.9770	0.8387	0.3750
6	1.0574	0.0570	0.0145	0.0002	0.9570	0.6516	0.3125
7	0.6785	0.2100	0.0315	0.0004	0.8834	0.2452	0.1875
8	0.4582	0.9200	0.0145	0.0003	0.5609	0.0581	0.0938
FILTER		1.6000	0.0045	0.0003			
TOTAL		2.8526	0.0775	0.0032			

TABLE C.7

Cascade Impactor Data - Sample AA2-T5-I1

TYPE: 6 STAGE SIERRA TIME: 9.25 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	26.1972	0.0650	0.0429	0.0067	0.9954	0.9962	0.9965
2	16.0094	0.0510	0.0359	0.0087	0.9918	0.9911	0.9920
3	6.4038	0.2100	0.2189	0.0407	0.9769	0.9664	0.9709
4	3.8568	1.0000	0.6689	0.1497	0.9059	0.8909	0.8931
5	2.4742	2.7900	1.0989	0.4897	0.7078	0.7669	0.6387
6	1.3826	3.8700	2.7989	0.6497	0.4331	0.4512	0.3012
FILTER		6.1000	3.9985	0.5797			
TOTAL		14.0857	8.8629	1.9249			

TABLE C.8

Cascade Impactor Data - Sample AA2-T5-I2

TYPE: 6 STAGE SIERRA TIME: 25.25 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	32.0844	0.0360	0.0199	0.0087	0.9973	0.9964	0.9933
2	19.6072	0.0610	0.0269	0.0067	0.9928	0.9916	0.9881
3	7.8429	0.3100	0.1689	0.0117	0.9699	0.9614	0.9790
4	4.7235	0.9400	0.4289	0.0437	0.9005	0.8847	0.9451
5	3.0302	2.0000	0.7489	0.1297	0.7528	0.7508	0.8446
6	1.6933	4.3700	1.8989	0.3597	0.4299	0.4111	0.5657
FILTER		5.8200	2.2985	0.7297			
TOTAL		13.5367	5.5909	1.2899			

TABLE C.9

Cascade Impactor Data - Sample AA2-T6-I1

TYPE: 8 STAGE SIERRA

TIME: 9 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	15.1823	0.0002	0.0039	0.0002	0.9997	0.9971	0.9964
2	9.2780	0.0002	0.0059	0.0002	0.9995	0.9928	0.9928
3	3.7112	0.0010	0.0089	0.0002	0.9978	0.9863	0.9892
4	2.2352	0.0070	0.0189	0.0002	0.9858	0.9724	0.9855
5	1.4339	0.0640	0.1589	0.0067	0.8749	0.8557	0.8644
6	0.8013	0.2300	0.4189	0.0177	0.4764	0.5481	0.5443
7	0.4470	0.1300	0.3189	0.0047	0.2511	0.3139	0.4593
8	0.2699	0.0710	0.2189	0.0027	0.1282	0.1531	0.4105
FILTER		0.0740	0.2085	0.0227			
TOTAL		0.5770	1.3617	0.0553			

TABLE C.10

Cascade Impactor Data - Sample AA2-T6-I2

TYPE: 8 STAGE SIERRA

TIME: 31 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0011 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	14.8880	0.0060	0.0219	0.0002	0.9884	0.9857	0.9949
2	9.0982	0.0007	0.0119	0.0002	0.9871	0.9779	0.9898
3	3.6393	0.0020	0.0219	0.0002	0.9833	0.9636	0.9847
4	2.1918	0.0040	0.0219	0.0002	0.9756	0.9493	0.9796
5	1.4061	0.0590	0.1189	0.0057	0.8605	0.8717	0.8346
6	0.7858	0.1400	0.3289	0.0137	0.5873	0.6570	0.4860
7	0.4384	0.1000	0.3089	0.0067	0.3923	0.4553	0.3155
8	0.2647	0.1800	0.4989	0.0117	0.0409	0.1296	0.0178
FILTER		0.0210	0.1985	0.0007			
TOTAL		0.5123	1.5317	0.0393			

TABLE C.11

Cascade Impactor Data - Sample AA2-T7-I1

TYPE: ANDERSEN

TIME: 13.5 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0025 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	11.8150	0.0060	0.0205	0.0006	0.9990	0.9974	0.9936
2	7.4064	0.0070	0.0245	0.0007	0.9978	0.9944	0.9970
3	5.0258	0.0120	0.0325	0.0007	0.9958	0.9903	0.9954
4	3.4387	0.0240	0.0755	0.0017	0.9917	0.9809	0.9915
5	2.2043	0.1300	0.1675	0.0117	0.9694	0.9599	0.9645
6	1.0581	1.4000	1.5975	0.1397	0.7301	0.7603	0.6428
7	0.6789	2.5000	3.1975	0.1897	0.3026	0.3607	0.2059
8	0.4585	1.5000	2.4975	0.0787	0.0462	0.0486	0.0246
FILTER		0.2700	0.3885	0.0107			
TOTAL		5.8486	8.0015	0.4342			

TABLE C.12

Cascade Impactor Data - Sample AA2-T7-I2

TYPE: ANDERSEN

TIME: 70 MIN.

STAGE PAPER BACKGROUND: 0.0000 mg Cs 0.0025 mg Mn 0.0003 mg I
FILTER PAPER BACKGROUND: 0.0000 mg Cs 0.0015 mg Mn 0.0003 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	11.7920	0.0007	0.0095	0.0006	0.9985	0.9231	0.8462
2	7.3920	0.0007	0.0125	0.0005	0.9971	0.8219	0.7179
3	5.0160	0.0007	0.0135	0.0007	0.9956	0.7126	0.5385
4	3.4320	0.0020	0.0135	0.0007	0.9913	0.6032	0.3590
5	2.2000	0.0030	0.0135	0.0004	0.9847	0.4939	0.2564
6	1.0560	0.0070	0.0135	0.0003	0.9691	0.3846	0.1795
7	0.6776	0.0430	0.0135	0.0002	0.8729	0.2753	0.1282
8	0.4576	0.0900	0.0125	0.0003	0.6716	0.1741	0.0513
FILTER		0.3000	0.0215	0.0002			
TOTAL		0.4467	0.1235	0.0039			

TABLE C.13

Cascade Impactor Data - Sample AA3-T5-I1

TYPE: 7 STAGE SIERRA TIME: 9.25 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	22.8307	0.0628	0.1480	0.0110	0.9921	0.9873	0.9902
2	13.9521	0.2698	0.4680	0.0391	0.9583	0.9471	0.9553
3	5.5808	0.5298	0.6580	0.0905	0.8920	0.8907	0.8745
4	3.3612	2.0698	0.9580	0.2644	0.6328	0.8085	0.6384
5	2.1562	2.8398	3.8480	0.3554	0.2771	0.4783	0.3211
6	1.2050	1.5998	3.8480	0.2474	0.0767	0.1481	0.1002
7	0.2029	0.5398	1.4180	0.0987	0.0091	0.0264	0.0121
FILTER		0.0728	0.3073	0.0135			
TOTAL		7.9844	11.6533	1.1200			

TABLE C.14

Cascade Impactor Data - Sample AA3-T5-I2

TYPE: 6 STAGE SIERRA TIME: 25.2 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	22.8360	0.0728	0.1580	0.0135	0.9925	0.9890	0.9903
2	13.9553	0.2298	0.3680	0.0408	0.9687	0.9634	0.9608
3	5.5821	0.4998	0.7080	0.1074	0.9171	0.9141	0.8833
4	3.3620	1.6298	1.9480	0.2644	0.7488	0.7785	0.6924
5	2.1567	3.8298	3.1780	0.4384	0.3532	0.5573	0.3759
6	1.2052	2.6098	4.7880	0.3554	0.0836	0.2240	0.1194
FILTER		0.8098	3.2173	0.1654			
TOTAL		9.6816	14.3653	1.3853			

TABLE C.15

Cascade Impactor Data - Sample AA3-T6-I2

TYPE: 8 STAGE SIERRA TIME: 26.2 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	13.4886	0.0010	0.0710	0.0000	0.9962	0.9681	0.9998
2	8.2430	0.0005	0.0010	0.0001	0.9943	0.9676	0.9983
3	3.2972	0.0013	0.0110	0.0001	0.9893	0.9627	0.9967
4	1.9858	0.0012	0.0210	0.0002	0.9848	0.9532	0.9936
5	1.2739	0.0085	0.1880	0.0021	0.9524	0.8687	0.9607
6	0.7119	0.0418	0.5480	0.0126	0.7933	0.6222	0.7632
7	0.3972	0.0558	0.4280	0.0151	0.5809	0.4297	0.5266
8	0.2398	0.1098	0.5280	0.0218	0.1629	0.1922	0.1849
FILTER		0.0428	0.4273	0.0118			
TOTAL		0.2627	2.2233	0.0638			

TABLE C.16

Cascade Impactor Data - Sample AA3-T7-I1

TYPE: ANDERSEN TIME: 13.5 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0190 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0230 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	10.2539	0.3098	3.0610	0.0557	0.9249	0.9272	0.9212
2	6.4278	0.3398	2.8010	0.0640	0.8426	0.8606	0.8306
3	4.3617	0.3398	2.8610	0.0615	0.7603	0.7926	0.7435
4	2.9843	0.3498	2.8210	0.0665	0.6755	0.7255	0.6494
5	1.9130	0.2098	1.9310	0.0391	0.6247	0.6796	0.5941
6	0.9183	2.5398	28.1810	0.4133	0.0092	0.0094	0.0091
7	0.5892	0.0068	0.1810	0.0021	0.0076	0.0051	0.0061
8	0.3979	0.0015	0.0470	0.0003	0.0072	0.0040	0.0057
FILTER		0.0298	0.1680	0.0040			
TOTAL		4.1269	42.0520	0.7065			

TABLE C.17

Cascade Impactor Data - Sample AA3-T7-I2

TYPE: ANDERSEN

TIME: 53.5 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0190 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0230 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	10.1388	0.0015	0.0000	0.0001	0.9987	0.9980	0.9994
2	6.3557	0.0022	0.0010	0.0001	0.9968	0.8008	0.9987
3	4.3128	0.0023	0.0000	0.0001	0.9947	0.7988	0.9981
4	2.9508	0.0035	0.0000	0.0003	0.9917	0.7968	0.9962
5	1.8916	0.0045	0.0040	0.0002	0.9877	0.0079	0.9949
6	0.9080	0.0188	0.0000	0.0021	0.9713	0.0059	0.9816
7	0.5826	0.1198	0.0000	0.0168	0.8664	0.0039	0.8750
8	0.3934	0.4798	0.0000	0.0640	0.4463	0.0020	0.4689
FILTER		0.5098	0.0000	0.0739			
TOTAL		1.1422	0.0051	0.1576			

TABLE C.18

Cascade Impactor Data - Sample AA4-T5-I1

TYPE: 7 STAGE SIERRA

TIME: 9.25 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	21.9255	0.1298	0.1280	0.0160	0.9717	0.9695	0.9687
2	13.3989	0.0808	0.0840	0.0126	0.9541	0.9495	0.9441
3	5.3596	0.2298	0.2280	0.0251	0.9040	0.8952	0.8950
4	3.2279	0.8298	0.5880	0.1154	0.7232	0.7551	0.6694
5	2.0707	1.3898	1.0680	0.1564	0.4204	0.5008	0.3636
6	1.1572	1.5098	1.4880	0.1404	0.0914	0.1463	0.0891
7	0.1949	0.3598	0.5480	0.0391	0.0130	0.0158	0.0127
FILTER		0.0598	0.0663	0.0065			
TOTAL		4.5894	4.1983	0.5115			

TABLE C.19

Cascade Impactor Data - Sample AA4-T5-I2

TYPE: 6 STAGE SIERRA TIME: 25.3 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	20.9467	0.7498	0.4080	0.0905	0.9557	0.9792	0.9428
2	12.8008	0.6198	0.5980	0.0789	0.9191	0.9487	0.8929
3	5.1203	1.6098	1.3380	0.1984	0.8240	0.8804	0.7674
4	3.0838	3.4898	3.8580	0.3554	0.6179	0.6837	0.5426
5	1.9783	5.9998	6.8880	0.5454	0.2634	0.3323	0.1977
6	1.1055	3.7498	5.2880	0.2644	0.0419	0.0626	0.0305
FILTER		0.7098	1.2273	0.0482			
TOTAL		16.9286	19.6053	1.5812			

TABLE C.20

Cascade Impactor Data - Sample AA4-T6-I1

TYPE: 8 STAGE SIERRA TIME: 9 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	Mn	I	FRACTION LESS THAN CUT DIAM. Cs	Mn	I
1	12.9853	0.0000	0.0000	0.0001	0.9998	1.0000	0.9903
2	7.9355	0.0001	0.0020	0.0001	0.9982	0.9989	0.9806
3	3.1742	0.0001	0.0110	0.0000	0.9966	0.9927	0.9796
4	1.9117	0.0005	0.0190	0.0001	0.9885	0.9821	0.9699
5	1.2264	0.0038	0.1080	0.0004	0.9269	0.9218	0.9311
6	0.6853	0.0128	0.3780	0.0026	0.7195	0.7108	0.6790
7	0.3823	0.0208	0.4780	0.0034	0.3824	0.4440	0.3492
8	0.2308	0.0108	0.3780	0.0016	0.2074	0.2330	0.1940
FILTER		0.0128	0.4173	0.0020			
TOTAL		0.0617	1.7913	0.0103			

TABLE C.21

Cascade Impactor Data - Sample AA4-T6-I2

TYPE: 8 STAGE SIERRA TIME: 21.4 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0120 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0126 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	12.9917	0.0000	0.0000	0.0000	0.9997	1.0000	0.9971
2	7.9394	0.0000	0.0000	0.0000	0.9994	1.0000	0.9944
3	3.1757	0.0000	0.0090	0.0000	0.9992	0.9941	0.9915
4	1.9127	0.0005	0.0190	0.0000	0.9852	0.9817	0.9887
5	1.2270	0.0018	0.0880	0.0001	0.9348	0.9240	0.9605
6	0.6857	0.0095	0.4880	0.0016	0.6689	0.6045	0.5085
7	0.3825	0.0071	0.4580	0.0006	0.4702	0.3047	0.3390
8	0.2310	0.0071	0.2280	0.0007	0.2715	0.1554	0.1412
FILTER		0.0097	0.2373	0.0005			
TOTAL		0.0357	1.5273	0.0035			

TABLE C.22

Cascade Impactor Data - Sample AA4-T7-I1

TYPE: ANDERSEN TIME: 13.5 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0190 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0230 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg) Cs	NET MASS (mg) Mn	NET MASS (mg) I	FRACTION LESS THAN CUT DIAM. Cs	FRACTION LESS THAN CUT DIAM. Mn	FRACTION LESS THAN CUT DIAM. I
1	10.0241	0.0046	0.2410	0.0004	0.9929	0.9806	0.9972
2	6.2838	0.0059	0.2310	0.0006	0.9838	0.9620	0.9930
3	4.2640	0.0108	0.3310	0.0004	0.9671	0.9353	0.9902
4	2.9175	0.0178	0.3110	0.0017	0.9397	0.9103	0.9780
5	1.8702	0.0618	0.3710	0.0077	0.8443	0.8804	0.9242
6	0.8977	0.2498	3.4010	0.0499	0.4589	0.6065	0.5740
7	0.5760	0.1998	5.2610	0.0532	0.1506	0.1827	0.3007
8	0.3890	0.0698	1.6910	0.0193	0.0429	0.0466	0.0653
FILTER		0.0278	0.5780	0.0093			
TOTAL		0.6481	12.4160	0.1425			

TABLE C.23

Cascade Impactor Data - Sample AA4-T7-I2

TYPE: ANDERSEN TIME: 70 MIN.

STAGE PAPER BACKGROUND: 0.0002 mg Cs 0.0190 mg Mn 0.0006 mg I
FILTER PAPER BACKGROUND: 0.0002 mg Cs 0.0230 mg Mn 0.0006 mg I

STAGE NO.	AERO. CUT DIAM MICRONS	NET MASS (mg)			FRACTION LESS THAN CUT DIAM.		
		Cs	Mn	I	Cs	Mn	I
1	9.8432	0.0007	0.0440	0.0000	0.9926	0.9085	0.9778
2	6.1703	0.0011	0.1410	0.0000	0.9811	0.6154	0.9556
3	4.1870	0.0016	0.1410	0.0000	0.9642	0.3223	0.9333
4	2.8648	0.0017	0.1010	0.0001	0.9463	0.1123	0.7111
5	1.8364	0.0029	0.0400	0.0000	0.9158	0.0291	0.6889
6	0.8815	0.0035	0.0110	0.0001	0.8789	0.0063	0.4667
7	0.5656	0.0079	0.0020	0.0001	0.7958	0.0021	0.2444
8	0.3820	0.0198	0.0000	0.0000	0.5874	0.0021	0.2222
FILTER		0.0558	0.0010	0.0001			
TOTAL		0.0950	0.4810	0.0005			

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EVALUATION OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGINS

Hanford Engineering Development Laboratory

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A.K. Postma
R.K. Hilliard

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EVALUATION OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGINS

A. K. Postma

R. K. Hilliard

ABSTRACT

Alternative air cleaning concepts were evaluated for possible application to FFTF containment margins. For evaluation purposes, it was assumed that the air cleaning system must process 3.07 m^3/s (6500 ACFM) of gas containing sodium compound aerosols (mainly NaOH) at temperatures up to 407°C (700°F) and pressures up to 0.184 MPa (26.4 psia) and accommodate 5450 kg (12,000 lb) of aerosol material. Three systems designed for 90% efficient removal (a venturi scrubber, a submerged gravel scrubber and a spray scrubber) were compared. The submerged gravel scrubber and the venturi scrubber were rated as prime candidates. Four systems designed for 99% removal efficiency (the two "optimum scrubbers" chosen for 90% removal efficiency fitted with fibrous elements, a sand and gravel filter and a HEPA filter bank) were compared. The two scrubbers were again rated as prime candidates. Both the sand and gravel filter and the HEPA filter bank were found to be excessively large and costly. Considerable experience supports the use of the "optimum" scrubber systems and it is concluded that their use is technically feasible for the FFTF containment margins application.

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EVALUATION OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGINS (WAKVAA)

I. SUMMARY AND CONCLUSIONS

A. SUMMARY

An evaluation of alternative air cleaning systems was made to identify the most promising candidates for application to Fast Flux Test Facility (FFTF) containment margins. Seven candidate systems were selected for detailed comparison. The three systems capable of 90% aerosol removal efficiency were: 1) eductor venturi, 2) spray chamber scrubber and 3) submerged gravel bed. The four systems for 99% efficiency were: 1) eductor venturi/fibrous scrubber, 2) submerged gravel bed/fibrous scrubber, 3) sand and gravel bed and 4) HEPA filters.

A conceptual design was developed for each system to show size and major components, and to allow an approximate cost estimate. The systems within each efficiency class were then compared using a criteria list and candidate ratings were made. The rating process identified two prime candidates from each removal efficiency class. Final selection will be based on trade-off studies beyond the scope of this report.

B. CONCLUSIONS

Specific conclusions drawn from work completed are:

- For the 90% removal efficiency case, two scrubber systems (an eductor venturi and submerged gravel bed) were rated as prime candidates. The submerged gravel bed was superior to the eductor venturi in passivity and mechanical simplicity but it lacks an extensive use-history.
- For the 99% removal case, the eductor venturi and the submerged gravel bed scrubber systems were also prime candidates when upgraded by adding a packed bed back-up stage of polypropylene fibers.

- A spray chamber scrubber designed for 90% efficiency is larger and more costly to construct and to operate than the prime candidates; therefore, it was eliminated from further consideration.

- The sand and gravel bed (the 99% removal case) was found too large and costly to construct for use in the present application. The large aerosol mass load requires a sand bed with a planar area of more than 1 acre and a cost of tens of millions of dollars.

- A system using high efficiency particulate air (HEPA) filters, designed for the 99% removal case, was eliminated. The aerosol mass loading required a large number (9100) of filter units (0.61 m x 0.61 m x 0.3 m deep) enclosed in a pressure boundary, making this system too large and costly.

- Both prime candidates (the eductor venturi and the submerged gravel bed) would require a planar area of less than 150 m^2 (1600 ft^2) and therefore, could be located adjacent to the containment vessel.

- A significant experience base exists for trapping sodium compound aerosols by aqueous scrubbers. The use of aqueous scrubbers is technically feasible for the FFTF containment margins application.

II. INTRODUCTION

Although extensive analyses of hypothetical core disruptive accident (HCDA) events in the FFTF show that the heat transport system would remain intact and the fuel coolable, further safety margins available for a postulated reactor vessel melt-through were assessed[1]. In the assessment, it was assumed that the containment vessel would be vented to relieve overpressure and/or purged to prevent hydrogen buildup. Although the potential site boundary radiation exposures were within 10 CFR 100[2] guideline values (even without the use of a filter system), a cleaning system capable of removing radioactive aerosol from a vented or purged containment atmosphere has some benefit in reducing the calculated radiological consequences[1]. This report presents an analytical evaluation of various air cleaning systems for possible use in the FFTF containment margins.

In the postulated melt-through event, a large quantity of sodium aerosol is assumed to be released along with the radioactive species. These sodium compound aerosols impose a higher aerosol mass loading on the present air cleaning system than on normal applications. Therefore, the results of a recent Liquid Metal Fast Breeder Reactor (LMFBR) air cleaning study[3] are not directly applicable.

Objectives of this study are to identify the air cleaning concepts that enhance FFTF containment margins and judge the feasibility of these systems.

Guidelines that limit the scope of this study are:

- Numerous alternative candidates were eliminated by prescreening on the basis of an earlier study,[3]
- The application does not involve a design basis accident and the system is not required to meet all the requirements of an engineered safety system,
- In-containment cleanup devices were not considered, and
- Engineering trade-off studies necessary for final selection of systems were beyond the scope of this report.

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III. AIR CLEANING REQUIREMENTS

A. BASIS

The design operating conditions used in the present evaluation are described in the following sections of this report. The conditions are arbitrarily specified, but are believed to represent bounding-case accident scenarios as described by Bankert, et al.[1]

All conceptual designs developed in the present study are based on venting requirements alone. Because venting conditions are much more demanding than purging operations, a system designed for venting can easily handle purge cases. Only the purge fan and valving are different, and these differences are unimportant in the present evaluation.

B. THERMAL CONDITIONS

For vent mode operation, gas temperatures can vary from 21°C (70°F) to 371°C (700°F), depending on the energy released to the containment atmosphere. The purge mode involves temperatures in the range of 21°C (70°F) to 121°C (250°F). The upper-limit, temperature-time history shown in Figure 1 is used for thermal analyses in this study.

Because the flow control valve is downstream from the air cleaner, pressure in the air cleaning system is equal to that in the containment vessel after venting is initiated. The expected peak pressure is 0.184 MPa absolute (12 psig). The variation in maxiumum pressure with time is shown in Figure 2.

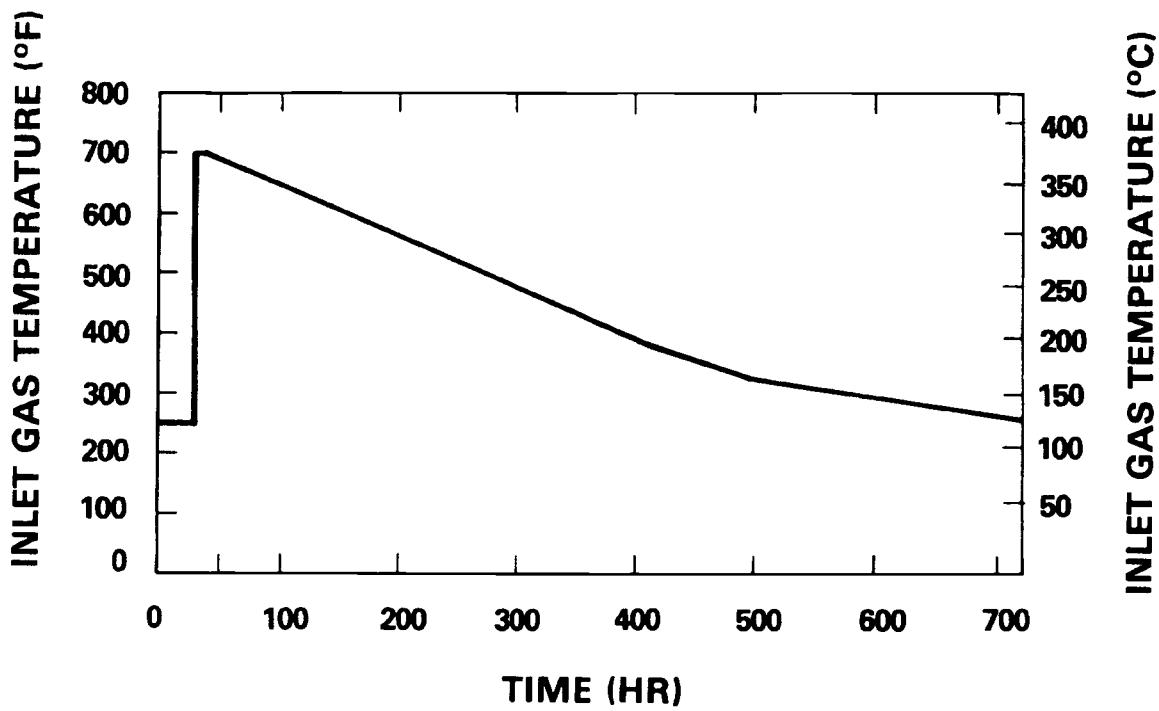

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FIGURE 1. Maximum Temperature of Air Entering the Air Cleaning System. Neg 8009286-10

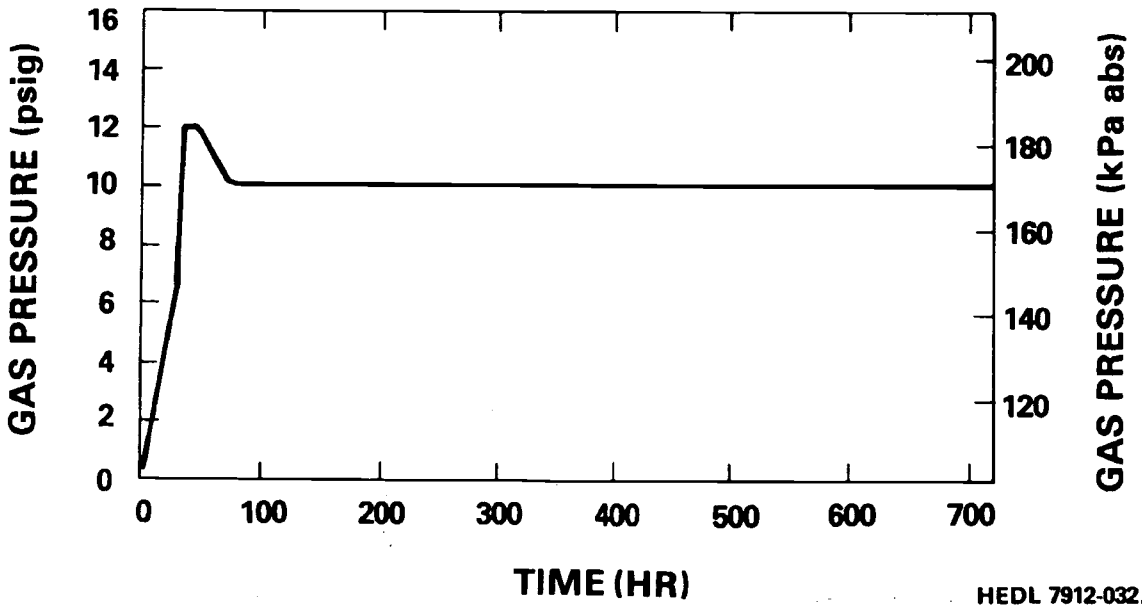

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FIGURE 2. Maximum Gas Pressure in the Air Cleaning System. Neg 8009286-9

C. CHEMICAL FORMS OF GASES AND AEROSOLS

In a hypothetical breach of containment accident, the initial air atmosphere in the containment vessel is altered by water released from heated concrete and by sodium combustion processes. The composition of gases entering the air cleaning system is shown in Figure 3 as a function of time.

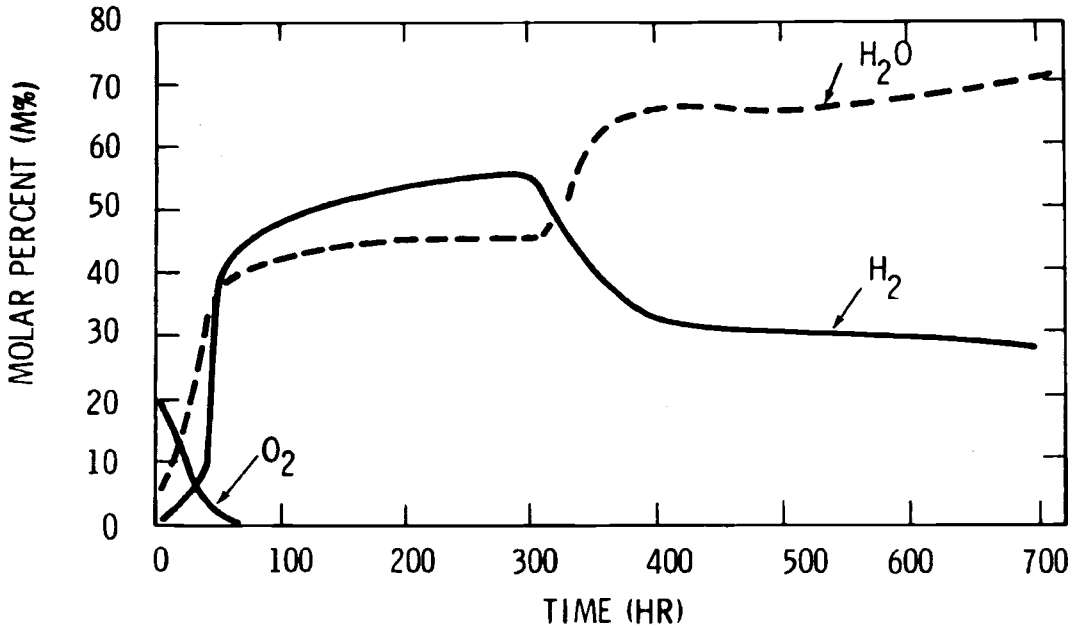

FIGURE 3. Composition of Inlet Gas. Neg 8009286-8

Initially, sodium entering the containment reacts with O_2 to form Na_2O_2:

$$2Na + O_2 \longrightarrow Na_2O_2 \tag{1}$$

By the time the air cleaning system is in operation (30.5 h) appreciable water vapor is present and sodium peroxide is converted to NaOH with the liberation of O_2:

$$Na_2O_2 + H_2O \longrightarrow 2NaOH + 1/2\ O_2 \tag{2}$$

Excess H_2O vapor sorption by the NaOH particles depends on relative humidity:

$$NaOH + xH_2O \rightleftharpoons NaOH \cdot xH_2O \qquad (3)$$

Airborne particles are either dry, sticky or mist drops of NaOH solution, depending on the relative humidity.

Later, when O_2 is depleted, NaOH is formed directly by the reaction between Na and H_2O:

$$Na + H_2O \longrightarrow NaOH + 1/2\ H_2 \qquad (4)$$

Based on the gaseous composition shown in Figure 3, the aerosol particles are composed primarily of NaOH with varying amounts of hydration.

To insure that solubility-based water requirements are not underestimated, 50% of the sodium aerosol is assumed to be present in the air cleaner as Na_2CO_3. Sodium carbonate is formed if CO_2 is released with water from heated concrete,[4] reacting with NaOH:

$$2NaOH + CO_2 \longrightarrow Na_2CO_3 + H_2O \qquad (5)$$

Fifty percent carbonate is probably a conservative value because of the low potential for CO_2 release in the FFTF, but scrubber water volumes designed on this basis will be adequate.

D. AEROSOL PARTICLE SIZE DISTRIBUTION

The particle size distribution of the aerosol entering the air cleaning system is assumed to be log normal, with an aerodynamic mass median diameter (AMMD) of 5.57 μm and a geometric standard deviation of 2.8. The particle size distribution is plotted on log-probability paper in Figure 4.

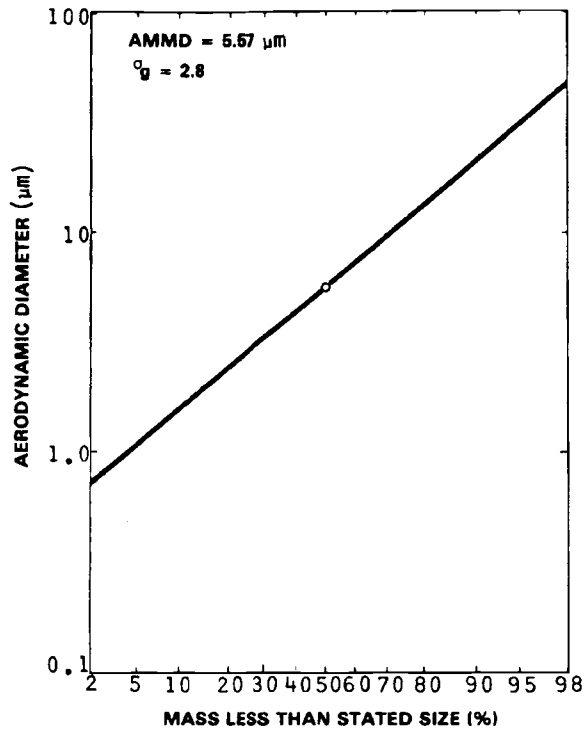

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FIGURE 4. Particle Size Distribution. Neg 8009286-1

E. GAS FLOW RATE

Gas flow rate varies with time according to the pressure buildup rate in containment. The maximum flow rate of 3.07 m^3/s (6500 ACFM) at 371°C (700°F) and 0.184 MPa (12 psig) occurs when venting begins. The flow rate versus time history used for the conceptual designs in this report is shown in Figure 5.

In actual use, the venting would probably be stopped periodically to maintain constant containment pressure. Therefore, Figure 5 should not be used as a basis for estimating total aerosol mass collection by the air cleaning system.

F. AEROSOL MASS COLLECTION

Based on code analyses of venting rates and aerosol concentrations, the maximum aerosol carried into the air cleaning system is projected to be 5440 kg (12,000 lb) anhydrous NaOH.

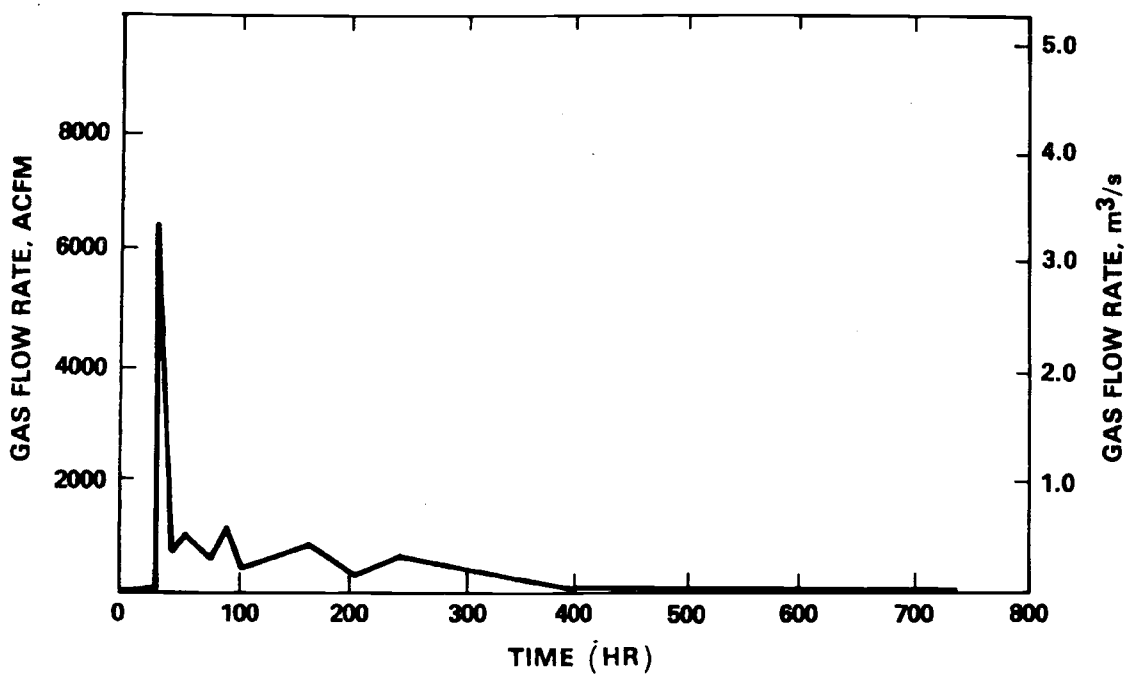

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FIGURE 5. Gas Flow Rate.

G. REQUIRED REMOVAL EFFICIENCY

To provide information on the relative cost and complexity as a function of air cleaning system effectiveness, the study is performed for two classes of systems. For the first class, a 90% aerosol mass removal efficiency is specified; for the second class, a 99% efficiency is required.

H. COMPARISON OF DESIGN PARAMETERS

Air cleaning requirements for the FFTF containment margins application are found to resemble the "containment/confinement" system treated in a recent HEDL evaluation of air cleaning concepts.[3] (See Table 1). However, the higher masses of aerosol and the higher temperatures required by the present study prevent direct utilization of the previous results.

TABLE 1

COMPARISON OF AIR CLEANING SYSTEM REQUIREMENTS

Parameter	Previous Study[3]	FFTF Margins
Aerosol Source	Head Release	Melt-Through and Sodium Boiloff
Maximum Gas Temperature (°C)	150	370
Flow Mode	Constant	Variable
Flow Rate (m^3/s)	7.1	3.1 max 0 min
Aerosol Mass Collected as NaOH (kg)	1000	5450
Max Aerosol Concentration as NaOH at Inlet Conditions (g/m^3)	25	50
Aerosol Particle Properties:		
Mass Median Diameter (μm)	2.0	7.4
Geometric Std Deviation	2.0	2.8
Density, $\alpha\rho$ (g/cm^3)	0.58	0.58
Aerodynamic Mass Median Diameter (μm)	1.5	5.57
Chemical Composition	NaOH	NaOH with Variable NaO_x, Na, Na_2CO_2, Partial Hydration
Start time (h) after HCDA	0	30.5*
Operational Duration (h)	24	720

* Reactor vessel melt-through assumed to occur 3 hours after HCDA initiation.

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IV. PRELIMINARY SCREENING OF AIR CLEANING CONCEPTS

The large list of air cleaning concepts identified in an earlier study[3] was screened to identify prime candidates for FFTF margins application. See Table 2. The following requirements eliminated many candidates:

- Aerosol mass loading is high (5450 kg).
- Concept technology must be at a state of development where hardware design can be started immediately.
- Only one of several apparently equivalent concepts was considered.
- Concepts involving in-containment cleaning were outside the scope of FFTF margins application and therefore were eliminated.
- Systems requiring gas recirculation were not considered.

Seven air cleaning systems were selected for evaluation. Four of these were designed to collect 99% or more of incident aerosol and three were designed to collect 90% or more.

The systems evaluated are:

Case I - 90% Efficient

LE-1 - Eductor Venturi
LE-2 - Spray Chamber
LE-3 - Submerged Gravel Bed

Case II- 99% Efficient

HE-1 - Spray Quench/Eductor Venturi/Fibrous Scrubber
HE-2 - Submerged Gravel Bed/Fibrous Scrubber
HE-3 - Sand and Gravel Bed
HE-4 - HEPA Filters

TABLE 2

PRELIMINARY SCREENING OF AIR CLEANING SYSTEM CONCEPTS

Air Cleaning Concept	Reason Eliminated
Filters:	
Industrial Prefilters	(b)
Deep Bed Graded Media	(a)
Bag Filters	(c)
Sand and Gravel Bed	
High Efficiency Particulate Air (HEPA)	
Cyclone Separator	(c)
Mechanical Separator	(c)
Dry Electrostatic Precipitator	(c)
Wet Electrostatic Precipitator	(c)
Wet Scrubbers:	
Spray Chamber	
Fibrous Packing (low efficiency type)	(d)
High Density Fiber Bed	
Packed Bed (e.g., gravel or Rashig rings)	
Venturi	
Centifugal	(c)
Settling Chamber	(d)
Acoustic Agglomerator	(c)
Fluidized Bed	(b), (c)
Foam Dispersal	(a), (b), (c)

(a) Low Mass Loading Capability
(b) Low or Uncertain Efficiency
(c) Uncertain Behavior for Margins Application
(d) Overall Performance Similar to Other Systems Being Evaluated

V. CRITERIA FOR RANKING ALTERNATIVE SYSTEMS

The criteria used in a previous air cleaning study[3] were modified for application to FFTF containment margins. The six criteria groups are listed in Table 3. Each group contains several individual criteria listed in Table 4. Each criterion is assigned a weight factor to measure its relative importance. The total weight is adjusted to 100.

To rank the various systems, a scoring system was devised as shown in Table 5. A score of 0 to 4 is assigned to each air cleaning system on a criterion-by-criterion basis.

The rating definition is measured by the amount of development work required. However, the same rating factors are used to indicate the acceptability of intrinsic characteristics. For example, the efficiency of a spray chamber is, by the physical forces involved, very dependent on particle size; and no amount of development will change that dependence.

A system score is determined by summing indiviudal criterion scores (the product of the criterion weight and the rating factor). The maximum possible system score is 400.

The following steps summarize the evaluation procedure:

- Definition of the system, including a preliminary conceptual design, utilizing the aerosol and containment atmosphere parameters listed in Section 3.
- The system is evaluated by the criteria listed in Table 4.
- The degree to which the system meets the criteria is quantified by assigning a rating factor ranging from 0 to 4 (to the nearest 0.1), based on criteria described in Table 5.

TABLE 3

AIR CLEANING EVALUATION CRITERIA GROUPS

Group No.	Group Weight	Criterion Description
1	17	System Effectiveness The system shall be effective in reducing the release of radioactive substances to the environment.
2	26	System Reliability The system shall have a high degree of reliability in startup and continuance of operation during the entire accident period.
3	9	Containment Compatibility The presence and operation of the system shall not degrade the normal effectiveness of the containment building.
4	22	Technological Credibility The effectivieness of the system shall be clearly demonstrable by experience, mathematical models and testing.
5	12	System Characteristics and Flexibility The system performance shall not be critically dependent on the accident environment conditions and shall accommodate possible future design changes.
6	14	Fabrication Effort The system shall be readily designed, fabricated and installed at reasonable cost and in a time frame consistent with plant construction.

TABLE 4

EVALUATION CRITERIA FOR AIR CLEANING SYSTEMS

Criteria Description	Weight Factor
1. SYSTEM EFFECTIVENESS	Total: 17
*a. The design decontamination factor can be achieved using design parameters that fall within current state-of-the-art practice.	5
*d. The system can handle dry or sticky particles and particles of varying chemical composition.	5
*c. System effectiveness is not degraded by the radiation dose caused by the accident over the required operating period.	2
d Characteristics inherently favor the system's ability to handle large masses of aerosol.	5
2. SYSTEM RELIABILITY	Total: 26
*a. System shall have a high probability of startup after initiation of the accident.	9
*b. System does not degrade during non-use periods.	6
*c. System shall be capable of dependable operation over a 1000-hour accident period under accident conditions of temperature, humidity, aerosol loading and flow rate.	8
d. System requires simple components, control and conservative design stresses.	3
3. CONTAINMENT SYSTEM COMPATIBILITY	Total: 9
*a. Inadvertent operation shall not harm the containment system or constitute a hazard to personnel.	4
b. Size shall be compatible with installation adjacent to the RCB, and not significantly impact the location of other ancillary plant systems.	5

*Denotes criteria with mandatory acceptable ratings.

TABLE 4 (Cont'd)

Criteria Description	Weight Factor	
4. TECHNOLOGICAL CREDIBILITY	Total:	22
a. Air cleaning concept is based on highly developed technology.	5	
*b. System can be tested in-place for operability and efficiency.	6	
c. System performance can be predicted by verified mathematical models.	5	
d. System equipment scaleup from currently available sizes to LMFBR plant application is small.	3	
e. System concept has been demonstrated with sodium aerosol or the extension of results to sodium aerosol can be made with confidence.	3	
5. SYSTEM CHARACTERISTICS AND FLEXIBILITY	Total:	12
a. System is effective for the entire particle size spectrum expected during the accident.	3	
b. System performance is not highly sensitive to the atmospheric temperature or relative humidity.	3	
c. System energy consumption is low.	3	
d. Post-accident recovery is facilitated by the EACS.	3	
6. FABRICATION EFFORT	Total:	14
a. System costs, capital and maintenance, are low.	10	
b. Materials and techniques used in construction are readily available and easily fabricated.	2	
c. Components and equipment are readily available.	2	
	100	100

*Denotes criteria with mandatory acceptable ratings.

TABLE 5

RATING FACTORS FOR AIR CLEANING SYSTEMS

Rating Factor	Rating Description	
4	Clearly acceptable	Completely satisfies criterion.
3	Probably acceptable	Some development may be required. May not completely meet the criterion but is adequate.
2	Possibly acceptable	A large development effort may be required. Barely meets or falls short of the criterion.
1	Probably unacceptable	Low probably of meeting criterion.
0	Clearly unacceptable	Zero probability of meeting the criterion.

Because certain criteria were considered mandatory requirements, a score of 2.0 or better was required for the system to be considered feasible. Mandatory criteria are listed in Table 6.

TABLE 6

CRITERIA WITH MANDATORY ACCEPTABLE RATINGS*

Criterion No.	Description
1a	Removal efficiency is state-of-art
1b	Dry or sticky particles
1c	Radiation resistance
2a	Reliable startup
2b	Storage life
2c	Reliable long-term operation
3a	Inadvertent operation
4b	In-place testability

*Acceptable is defined as a minimum rating factor of 2.0, as described in Table 5.

- The system score for each individual criterion is obtained by multiplying the criterion weight factor (Table 4) by the assigned rating factor.
- The overall system rating is calculated by summing the scores of the individual criteria. The maximum possible score is 400.
- Systems having a low rating for any individual criterion are examined for possible design changes to improve their rating.
- The systems are ranked according to total score.
- Final ranking is made by considering both the numerical score and the probability of successful application. Because many of the criteria are only semi-quantifiable, the evaluation and rating necessarily entail considerable judgement.

VI. EVALUATION RESULTS

A rudimentary conceptual design was made for each of the seven systems selected in Section IV. Although the designs are not necessarily optimum, this is not expected to have a major influence in comparing systems except where two systems are closely equivalent.

The component and system designs in this study were based on information developed in an earlier study.[3] Where available, equipment performance with sodium or sodium oxide aerosols was used. In the absence of operating performance data specific to LMFBR accident conditions, published information for standard air pollution control equipment was used. Modifications for LMFBR conditions were made according to the authors' judgment.

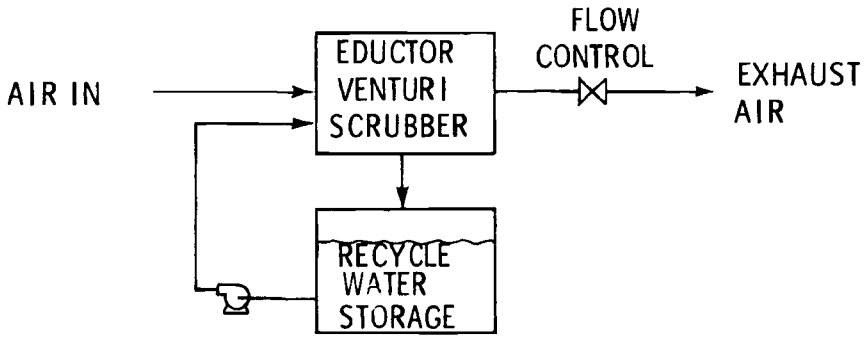
A cost estimate was made for each system based primarily on component costs developed in an earlier study.[3] The costs include engineering, equipment, installation labor, instrumentation and the building needed to house the equipment. The cost estimates are presented as arbitrary units for comparison purposes.

A. DESCRIPTION OF SYSTEMS DESIGNED FOR 90% EFFICIENCY

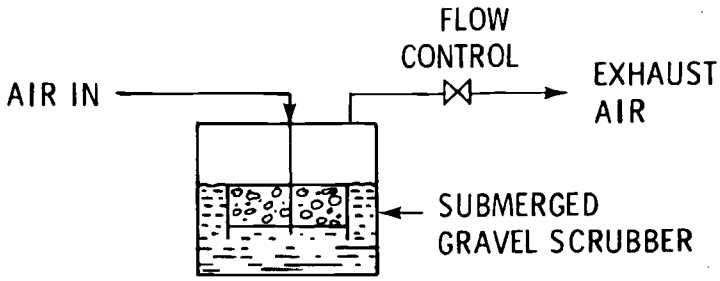
Three air cleaning concepts were selected as candidates for 90% efficient systems. All three are aqueous scrubbers and are judged as the prime candidate systems available for application to FFTF margins. The candidate systems are shown schematically in Figure 6.

1. Venturi Scrubber - System LE-1

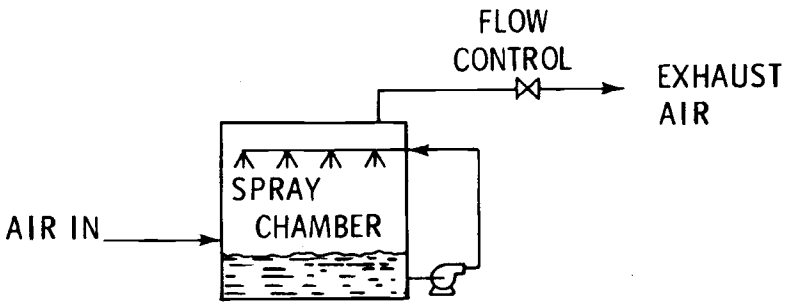
System LE-1 employs an eductor venturi scrubber to remove airborne particles. An eductor-type venturi was selected over a gas-atomized-type venturi because removal efficiency increases as gas flow rate decreases in an eductor unit. In this study the gas flow rate may vary from zero to the design maximum; therefore, use of a gas-atomized venturi would introduce



VENTURI SCRUBBER - SYSTEM LE-1



SUBMERGED GRAVEL SCRUBBER - SYSTEM LE-2



SPRAY CHAMBER SCRUBBER - SYSTEM LE-3

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FIGURE 6. Flow Diagrams For 90% Efficient Candidates. Neg 7913162-12

design complexities that deal with the loss in removal efficiency when flow rate is decreased from the design value.

The main equipment components in this system are: 1) the venturi and separator, 2) the liquid recirculation spray pump and 3) the liquid storage tank. All three components must be designed to withstand an ambient pressure of 0.184 MPa (12 psig) because containment venting rate is controlled by a valve located downstream from the scrubber.

Particle removal efficiency within the eductor was assessed by drop capture models and by comparison with experimental measurements reported for an eductor venturi scrubber studied at HEDL.[5] The size of the venturi was based on a throat gas velocity of 16 m/s (52 ft/s) and the geometrical proportions used by several equipment manufacturers. The venturi unit, complete with entrainment separator, was estimated to be 5.8 m (19 ft) in height and 2.3 m (7.5 ft) in diameter.

The water storage tank holds 30.3 m^3 (8,000 gal). The water volume is stipulated by solubility considerations for the collected aerosol material. An elevation view of equipment layout for the venturi scrubber system is shown in Figure 7. Important design parameters for System LE-1 are summarized in Table 7.

2. Submerged Gravel Scrubber - System LE-2

System LE-2 uses a submerged gravel bed to trap airborne particles. This system is novel because the air flow induces water circulation through the gravel bed and makes a separate water pumping system unnecessary. This concept is currently under development at HEDL and a patent application was filed.

In operation, inlet air is dispersed beneath a gravel bed by means of a submerged downcomer. Buoyant forces cause the air to pass upward through the gravel bed. Appreciable volumes of water are entrained with the air

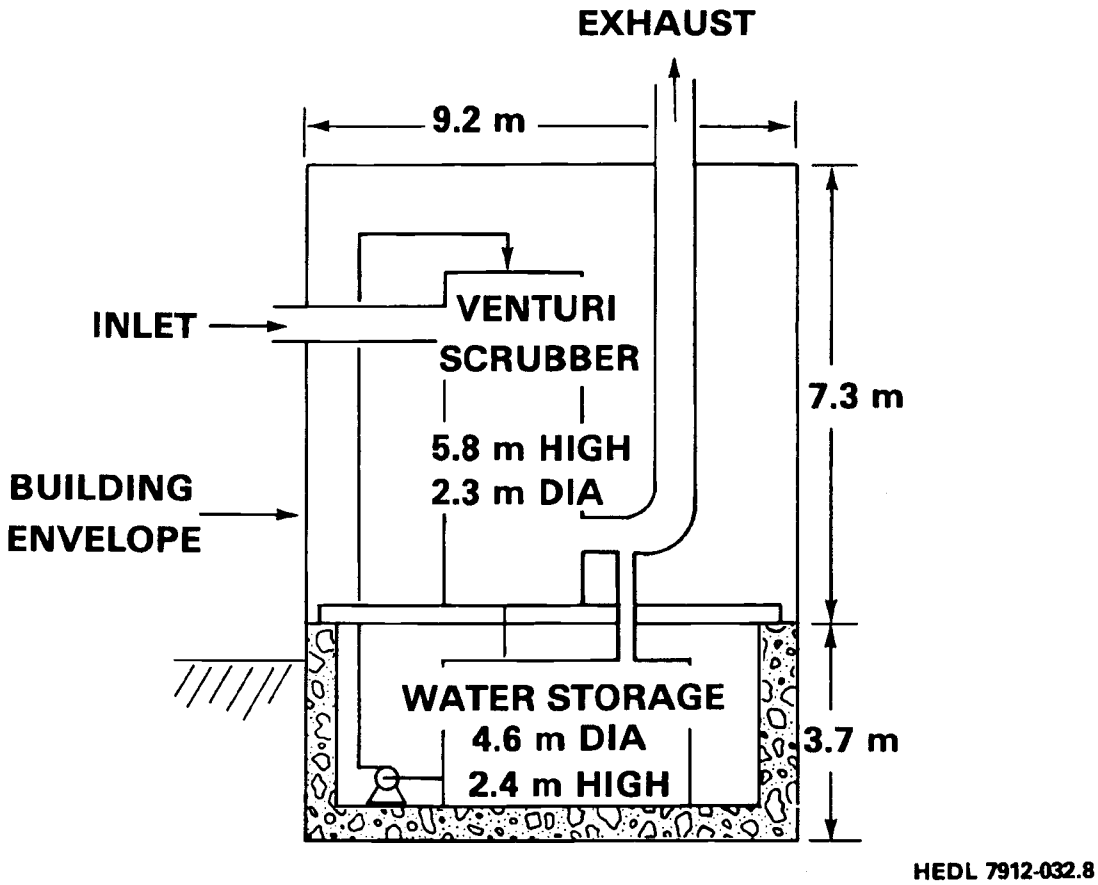

FIGURE 7. Layout For Venturi Scrubber - System LE-1. Neg 8009286-7

TABLE 7

PARAMETERS FOR VENTURI SCRUBBER - SYSTEM LE-1

Water Flow Rate	1.70 m^3/min (450 gal/min)
Water Pressure Drop	0.55 MPa (80 psid)
Throat Gas Velocity	16 m/s (52 ft/s)
Max Gas Flow Rate	3.07 m^3/s (6500 ACFM)
Draft Generated	248 Pa (1 inch water)
Particle Removal Efficiency	90%
Relative Cost Units	0.80

flow. The circulating water keeps the bed clean of particulate debris and assures that water in the system is nearly isothermal. The submerged gravel bed concept is described in Figure 8.

Design of the submerged gravel bed was based on scale-up of results from engineering scale models tested at HEDL. The most important parameters, gas velocity and bed depth, were selected as 0.51 m/s (100 ft/min) and 0.61 m (2 ft), respectively. Particle removal efficiency was analyzed using an equation for packed beds[6] and comparison with HEDL experiments.

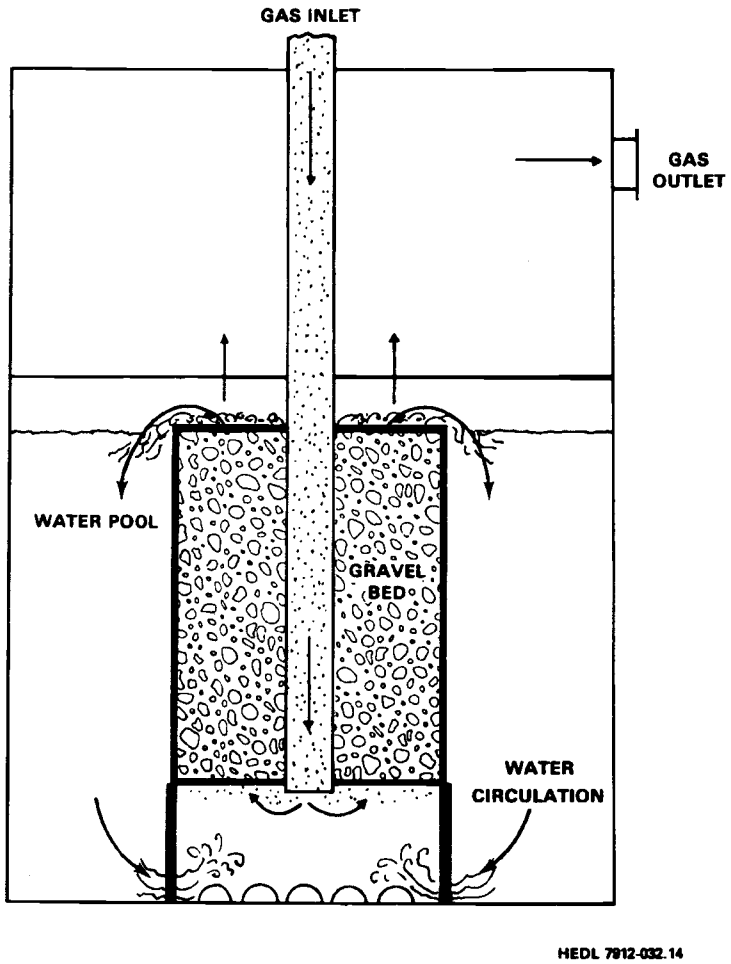

Figure 8. Description of Submerged Gravel Scrubber Concept. Neg 8009286-3

An elevation view showing the layout of the submerged gravel bed is given in Figure 9. Important parameters that describe the design of the submerged gravel bed are summarized in Table 8.

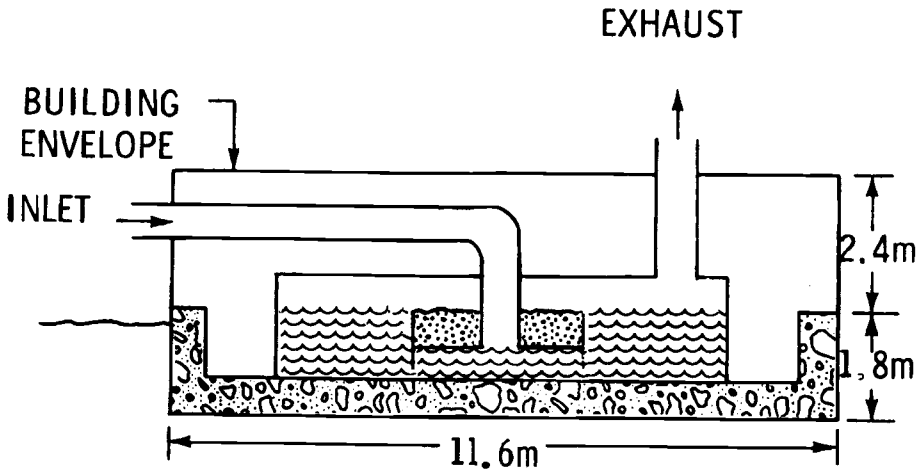

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Figure 9. Layout of a Submerged Gravel Scrubber - System LE-2. Neg 8009286-11

TABLE 8

PARAMETERS FOR SUBMERGED GRAVEL SCRUBBER - SYSTEM LE-2

Gravel Bed OD	3.05 m (10 ft)
Inlet Downcomer Diameter	0.61 m (2 ft)
Gravel Bed Depth	0.61 m (2 ft)
Superficial Gas Velocity in Gravel (maximum)	0.51 m/s (100 ft/min)
Size of Crushed Rock Packing	9.5 to 13 mm (3/8 to 1/2 in.)
Volume of Water	51.1 m^3 (13,500 gal)
Particle Removal Efficiency	90%
Relative Cost Units	0.45

3. Spray Chamber - System LE-3

The spray chamber scrubber is conceptually similar to the eductor venturi in that particle removal is dominated by water drop impaction. The water stream requires higher energy in the venturi but the venturi is smaller in size compared to a spray chamber.

The main component of the spray scrubber is the chamber where falling drops capture suspended particles, mainly by impaction. Due to large size, recirculating water inventory is accommodated within the chamber itself. A recirculating water pump is required to maintain spray flow.

Spray chamber size was determined by the spray rate required to remove 90% of airborne particles and by the maximum spray flux that will avoid significant drop coalescence. It was assumed that the gas phase within the spray chamber was well-mixed. The design approach used is supported by results obtained at HEDL on the removal of sodium compound aerosols within a spray quench chamber.[5]

An elevation view showing the size of the spray scrubber is given in Figure 10. The spray scrubber is appreciably larger than the other two candidates (Figures 8 and 9). Important parameters that describe the design of the spray scrubber are summarized in Table 9.

The significantly higher cost of the spray scrubber is mainly due to the larger size. The higher cost and larger size of the spray scrubber indicate that it will not be competitive with the two other scrubbers unless major off-setting advantages are identified in the detailed evaluation.

B. DESCRIPTION OF SYSTEMS DESIGNED FOR 99% EFFICIENCY

Four systems were selected as candidates for 99% efficiency removal - two aqueous scrubbers candidates from the 90% removal up-graded by adding a packed fiber bed to the outlet of the 90% scrubber; a sand and gravel bed and a bank

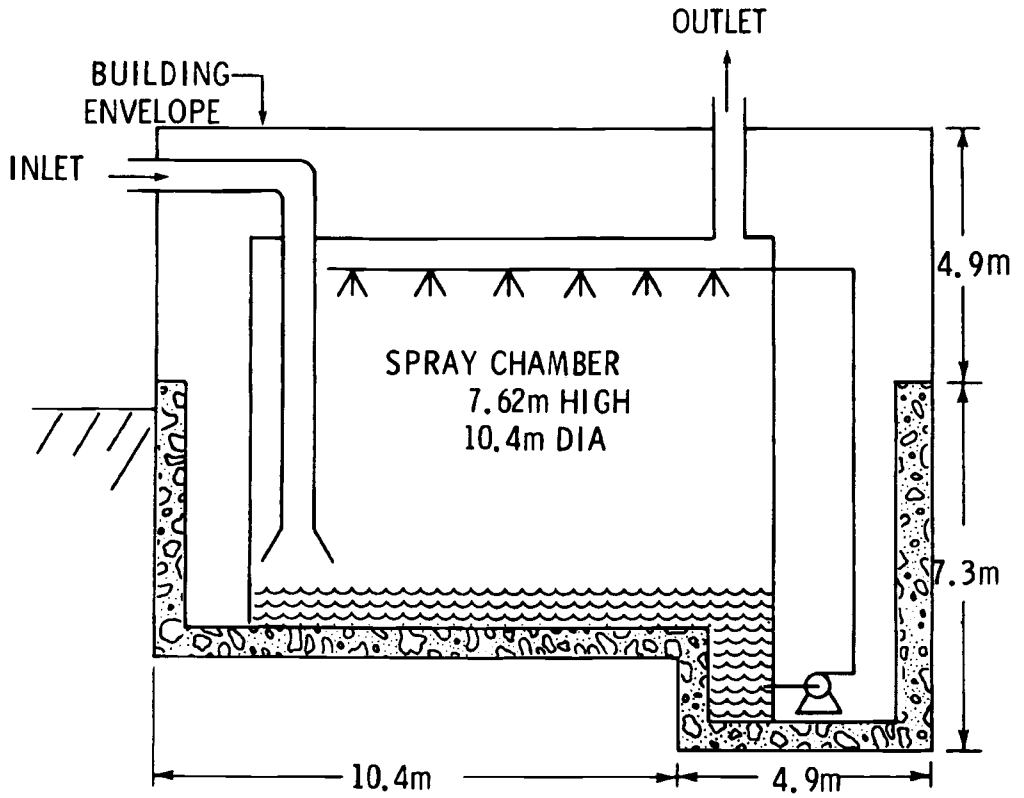

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FIGURE 10. Layout of Spray Scrubber - System LE-3. Neg 8009286-6

TABLE 9

PARAMETERS FOR SPRAY SCRUBBER- SYSTEM LE-3

Diameter of Spray Chamber	10.4 m (34 ft)
Height of Spray Chamber	7.6 m (25 ft)
Spray Flow Rate	1.70 m^3/min (450 gal/min)
Nozzle Pressure Drop	0.28 MPa (40 psid)
Volume of Water	30.3 m^3 (8000 gal)
Effective Drop Diameter	1200 μm
Flow Rate Per Nozzle	0.0473 m^3/min (12.5 gal/min)
Particle Removal Efficiency	90%
Relative Cost Units	1.6

of HEPA filters. Flow diagrams for the candidate systems designed for 99% removal efficiency are shown in Figure 11.

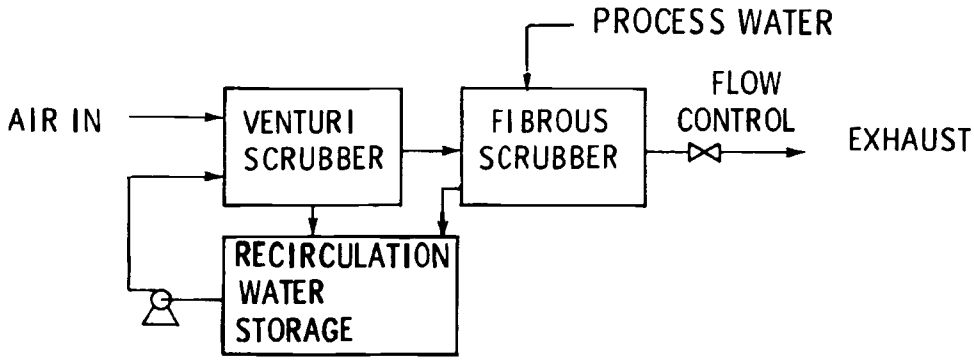
1. Venturi Scrubber with Fibrous Backup - System HE-1

In this system, a packed bed of fibers is added to trap particles that penetrate the venturi. The combined system will yield removal efficiencies well in excess of 99%, as demonstrated in tests performed at HEDL[5]. The design of the venturi pre-scrubber was taken directly from System LE-1 (Figure 7).

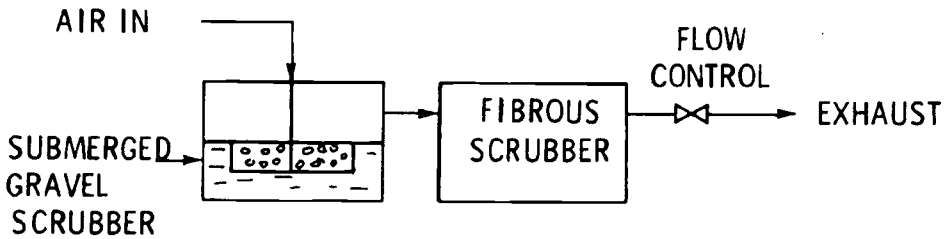
The venturi/fibrous scrubber occupies a space envelope cylindrical in shape, 5.8 m high and 2.3 m in diameter. Other design parameters for the venturi scrubber are listed in Table 7.

The venturi/fibrous scrubber design used annular-shape packed beds of polypropylene fibers. The 72.6-mm (3-in.) thick annulus is 0.59 m (18 in.) inside diameter, 0.79 m (24 in.) outside diameter and 3.05 m (10 ft) in length. Four elements are required to handle the maximum gas flow rate of $1.75/m^3/s$ (3700 ACFM) exiting from the venturi scrubber. Fresh process water mist is applied to the upstream surface of the bed to assure that all soluble material is washed from the fibers. The spray mist flow rate was $20.8\ cm^3/s$ (0.33 gal/min). The venturi/fibrous scrubber elements were enclosed in a carbon steel tank.

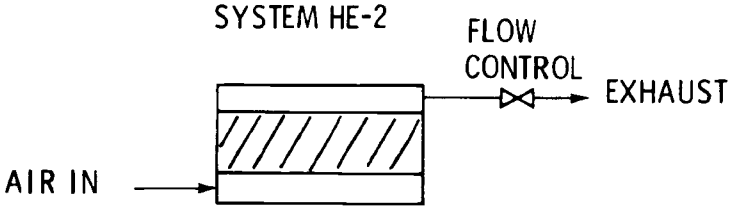
This system requires a recirculation water tank appreciably larger than that used in the 90% design to accommodate the process water used to wet the fiber beds. Over an operating time of 720 hours, $54.5\ m^3$ (14,400 gal) of water would be added as spray mist to the $30.3\ m^3$ (8000 gal) of water required for



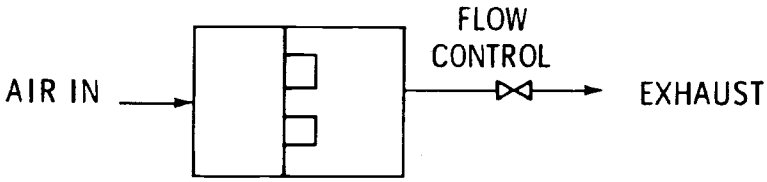
VENTURI SCRUBBER WITH FIBROUS BACKUP - SYSTEM HE-1



SUBMERGED GRAVEL SCRUBBER WITH FIBROUS BACKUP - SYSTEM HE-2



SAND AND GRAVEL FILTER - SYSTEM HE-3



HEPA FILTER BANK - SYSTEM HE-4

HEDL 7912-032.13

FIGURE 11. Flow Diagrams For 99% Efficient Candidate Systems. Neg 8009286-5

solubility for a total minimum liquid capacity of 84.8 m^3 (22,400 gal). A tank having a volume of 113.6 m^3 (30,000 gal) was specified to account for potential condensate accumulation and gas space margin requirements.

An alternative bed washing scheme using recycled water could in principle be used to minimize storage tank capacity. Such a scheme would require a filtration device to avoid plugging the spray nozzle. Only fresh water wash was considered.

An elevation view of the conceptual design for System HE-1 is given in Figure 12. Design parameters for the venturi/fibrous scrubber are summarized in Table 10.

The data of Table 10 show that a cost increment of 25% is added to the 90% efficient venturi scrubber system to increase the removal efficiency to 99%. Also, the spatial requirements are 50% greater. However, this system is less costly than the 90% spray scrubber. Unless a detrimental characteristic is borne out in the detailed ranking process, this 99% system is preferred compared to a lower efficiency, higher cost spray scrubber.

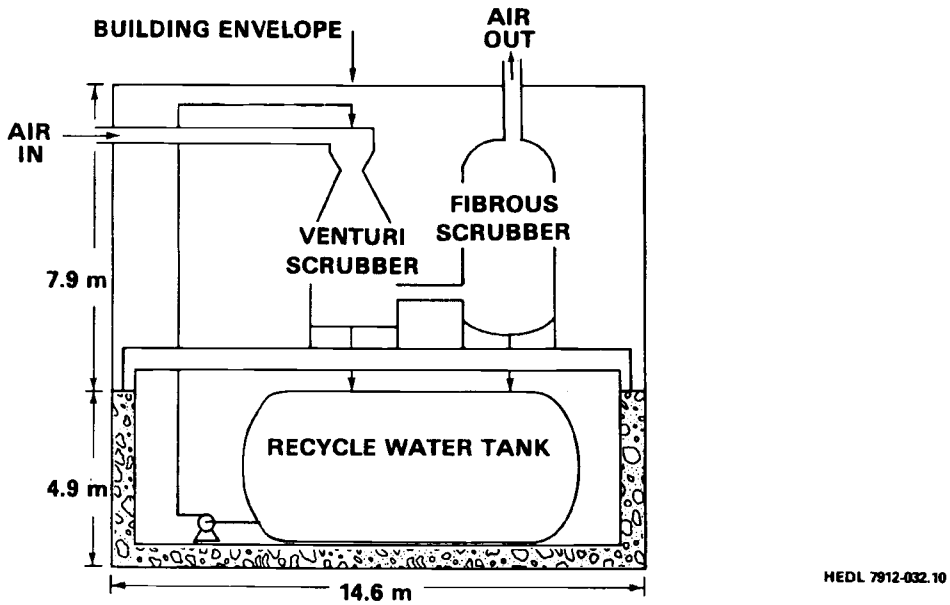


FIGURE 12. Layout of Venturi/Fibrous Scrubber - System HE-1. Neg 8009286-2

TABLE 10

PARAMETERS FOR VENTURI/FIBROUS SCRUBBER - SYSTEM HE-1

Venturi Scrubber Flow Rate	1.70 m^3/min (450 gal/min)
Venturi Water Pressure Drop	0.55 MPa (80 psid)
Venturi Throat Gas Velocity	16 m/s (52 ft/s)
Draft Generated By Venturi	248 Pa (1 in. water)
Length of Fibrous Bed Elements	3.05 m (10 ft)
Diameter of Fibrous Bed Elements	0.79-m (24-in.) OD by 0.59-m (18-in.)ID
Number of Fibrous Elements	Four
Fiber Material	Polypropylene
Fibrous Element Spray Flow Rate	20.8 cm^3/s (0.33 gal/min)
Overall Particle Removal Efficiency	99%
Volume of Recycle Water Tank	113.6 m^3 (30,000 gal)
Relative Cost Units	1.0

2. Submerged Gravel Scrubber with Fibrous Backup - System HE-2

This system combines the submerged gravel scrubber design of System LE-3 with the polypropylene fiber beds described for System HE-1. The combined system is shown conceptually in Figure 13.

The gravel bed size used in this system is identical to that described for the 90% efficient System LE-3 (Table 8). The diameter of water tank and the water depth are the same as specified for System LE-3. The primary difference is the tank height required to accommodate the fibrous scrubber elements. Design parameters for the submerged gravel scrubber with fibrous back-up are listed in Table 11.

The submerged gravel bed with a fibrous backup is low in cost (0.7 relative units) in comparison with the other candidate scrubbers. When combined with passive features, e.g., no liquid pumping system requirement, this system appears to be a strong candidate. One off-setting aspect of this system is lack of a broad use-history.

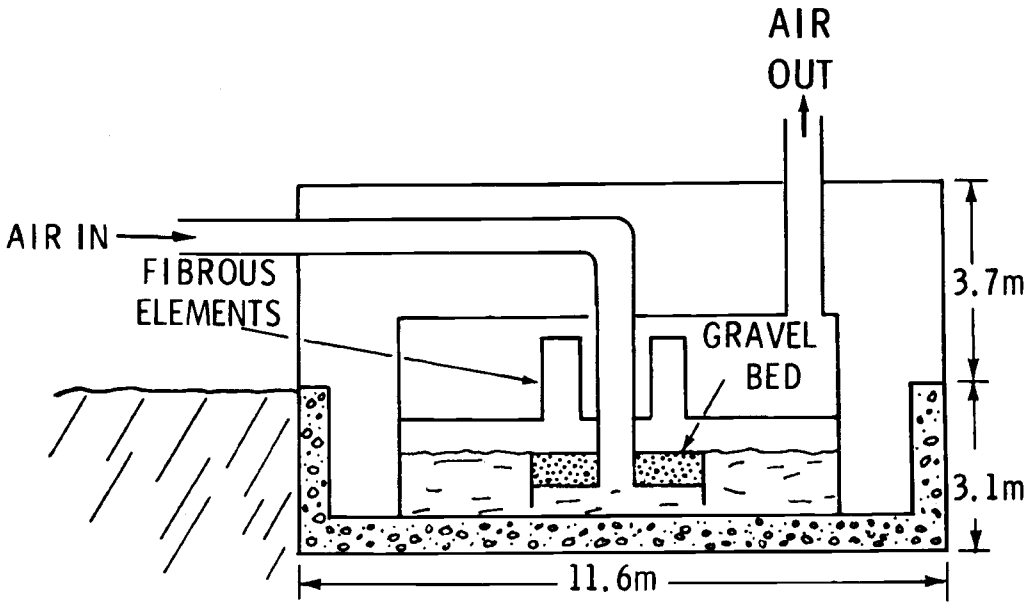


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FIGURE 13. Layout of Submerged Gravel Scrubber with Fibrous Backup - System HE-2. Neg 8009286-4

TABLE 11

PARAMETERS FOR SUBMERGED GRAVEL BED/FIBROUS SCRUBBER - SYSTEM HE-2

Scrubber Tank Overall Size	7.9-m (26-ft) dia x 3.7-m (12-ft) height
Gravel Bed Outside Diameter	3.05 m (10 ft)
Inlet Downcomer Diameter	0.61 m (2 ft)
Gravel Bed Depth	0.61 m (2 ft)
Superficial Gas Velocity in Gravel (max)	0.51 m/s (100 ft/min)
Crushed Rock Packing Size	9.5 to 13 mm (3/8 to 1/2 in.)
Volume of Water	51.1 m^3 (13,500 gal)
Fibrous Bed Elements Length	1.22 m (4 ft)
Fibrous Bed Elements Number	Ten
Fibrous Bed Elements Diameter	0.79-m (24-in.) OD x 0.59-m (18-in.) ID
Fiber Material	Polypropylene
Overall Particle Removal Efficiency	>99%
Relative Cost Units	0.70

3. Sand and Gravel Bed - System HE-3

Sand and gravel bed filters rated high in a previous study[3] because they are passive and can withstand high temperatures and corrosive atmospheres. A major drawback to sand filters is the low mass loading capability.

The sand bed design employed was based on an installation at the Savannah River Laboratory[7] and loading capacity measurements made at HEDL for sodium compound aerosols. The holding capacity of a sand filter is tentatively estimated to be 1.0 kg/m^2 irrespective of air velocity. The superficial flow area required for the present application is

$$5455 \text{ kg} \times \frac{1 m^2}{kg} = 5455 \text{ } m^2 \quad .$$

If square, this unit would be 74 m (242 ft) on a side. This large bed would be difficult to locate close to the FFTF containment building.

A cross-sectional view of the sand and gravel layers is given in Figure 14. As indicated 0.91 m (3 ft) of fine sand is supported by 0.46 m (1.5 ft) of coarser sand and 0.91 m (3 ft) of gravel, yielding a whole bed depth of 2.3 m (7.5 ft). An elevation view of the sand bed filter is presented in Figure 15.

Costs for the sand bed were taken from actual costs incurred at Savannah River Laboratory in 1973. The cost per unit area was increased to account for inflation and design change requirements to meet the 0.184 MPa (12 psig) pressure rating. Parameters that describe the conceptual design of the sand filter are listed in Table 12.

The sand bed is much larger and much more costly than Systems HE-1 and HE-2. These considerations alone would appear to preclude the use of a sand bed filter for FFTF Margins.

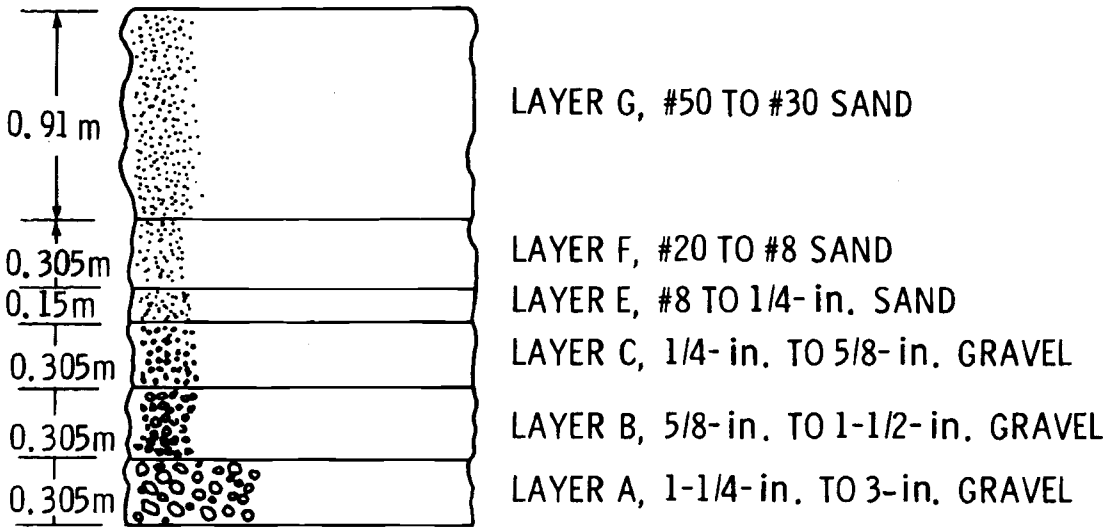

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FIGURE 14. Aggregate Used in Sand Bed Filter - System HE-3 Neg 7913162-11

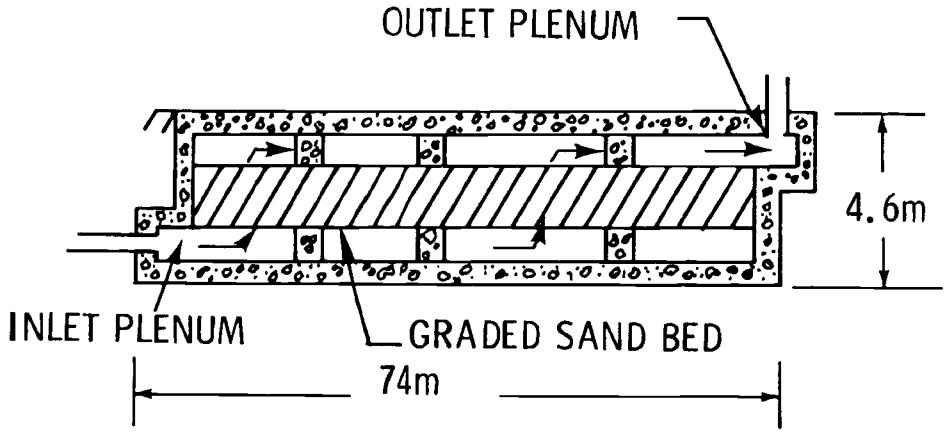

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FIGURE 15. Layout of Sand and Gravel Bed - System HE-3. Neg 7913162-5

TABLE 12

PARAMETERS FOR SAND AND GRAVEL BED - SYSTEM HE-3

Overall Bed Depth	2.3 m (7.5 ft)
Overall Height of Structure	4.6 m (15 ft)
Bed Planar Area	5455 m^2 (58,691 ft^2)
Aerosol Mass Captured (NaOH)	5455 kg (12,000 lb)
Number of Layers of Aggregate	Six
Largest Aggregate	31.8-mm to 75.4-m (1-1/2-in. to 3-in.) Gravel
Finest Aggregate	No. 50 to No. 30 Sand
Basis For Aggregate Layer Design	SRL facility (Reference 7)
Basis For Mass Loading Capacity	HEDL Data
Removal Efficiency	>99%
Relative Cost	16.0

4. HEPA Filters - System HE-4

HEPA filters rated for high temperature service would be installed in banks located inside a pressure building. The size and cost of this system relate directly to the number of individual filter units required.

Loading capacity of HEPA filters for sodium compound aerosols was studied by McCormack, et al.[8] It was found that the mass of aerosol required to plug a filter was a function of humidity. The minimum loading capacity was found to be 0.6 kg per standard HEPA unit. The number of HEPA units required is calculated:

$$5455 \text{ kg} \times \frac{1 \text{ unit}}{0.6 \text{ kg}} = 9092 \text{ units.}$$

This number is very large, and if built, would represent the worlds largest HEPA filter installation. Therefore, no existing commercial HEPA filter banks could be used to cost and size this system.

A conceptual design for this system was developed on the basis of the following premises:

- HEPA filters were used without prefilters.
- The filter units were arranged on horizontal plenums.
- A pressure building was used to house the filter banks.

The layout of the conceptual design is shown in Figure 16. As indicated, the required pressure building is large, approximating a truncated section of the reactor containment building itself. Parameters for this system are summarized in Table 13.

The most notable data of Table 13 are the large size and high cost of the system. Compared to alternatives, this system would appear to be non-competitive because of these two factors.

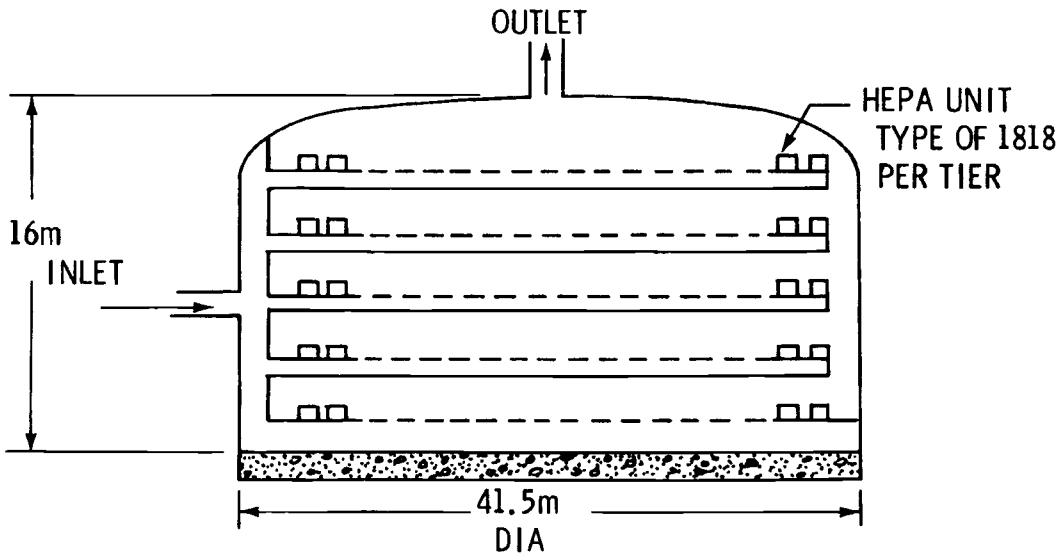

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Figure 16. Layout for HEPA Filters - System HE-4. Neg 7913162-6

TABLE 13

PARAMETERS FOR HEPA FILTERS - SYSTEM HE-4

Number of HEPA Filter Units Required	9090
Aerosol Mass Collected Per HEPA	0.6 kg
HEPA Filter size	0.61 m x 0.61 m x 0.31 m
HEPA Filter Temperature Rating	399°C (750°F)
HEPA Filter Media Composition	Fiber Glass
No. of HEPA Units Per Tier	1818
No. of Tiers In Pressure Building	5
Diameter of Enclosure Building	41.5 m (136 ft)
Height of Enclosure Building	16 m (52.5 ft)
Particle Removal Efficiency	>99%
Relative Cost Units	110

C. COMPARISON OF ALTERNATIVE SYSTEMS

Candidate systems are ranked in terms of criteria described in Section V. The 90% efficient systems are ranked separately from the 99% efficient systems. Choice between the two classes of systems is left to the user who must determine whether the extra cost and complexity of the high efficiency system are justified by the incremental removal efficiency obtained.

1. Ranking of 90% Efficient Candidates

Numerical ranking of the three 90% efficient candidate systems is listed in Table 14. The rationale for assigning the individual scores is described in Appendix A.

From the total scores shown in Table 14, the candidates rank in the following order:

Submerged Gravel Scrubber	(341 points)
Venturi Scrubber	(331.5 points)
Spray Chamber	(309 points)

TABLE 14

NUMERICAL RATINGS OF 90% EFFICIENT SYSTEMS

Criterion	Weight Factor	LE-1 Venturi Scrubber		LE-2 Submerged Gravel		LE-3 Spray Chamber	
		Rating	Score	Rating	Score	Rating	Score
1a*	5	3.5	17.5	3.8	19.0	3.0	15.0
1b*	5	4.0	20.0	4.0	20.0	4.0	20.0
1c*	2	4.0	8.0	4.0	8.0	4.0	8.0
1d	5	4.0	20.0	4.0	20.0	4.0	20.0
2a*	9	3.5	31.5	4.0	36.0	3.5	31.5
2b*	6	3.5	21.0	3.5	21.0	3.5	21.0
2c*	8	3.0	24.0	3.5	28.0	3.0	24.0
2d	3	3.5	10.5	3.5	10.5	3.5	10.5
3a*	4	4.0	16.0	4.0	16.0	4.0	16.0
3b	5	3.0	15.0	3.0	15.0	3.0	15.0
4a	5	4.0	16.0	2.0	10.0	3.0	15.0
4b*	6	2.5	15.0	3.0	18.0	2.5	15.0
4c	5	3.0	15.0	3.0	15.0	3.0	15.0
4d	3	4.0	12.0	2.0	6.0	4.0	12.0
4e	3	4.0	12.0	4.0	12.0	4.0	12.0
5a	3	2.5	7.5	3.0	9.0	2.0	6.0
5b	3	3.5	10.5	3.5	10.5	3.5	10.5
5c	3	2.0	6.0	3.0	9.0	2.5	7.5
5d	3	3.0	9.0	3.0	9.0	3.0	9.0
6a	10	2.5	25.0	3.5	35.0	1.0	10.0
6b	2	4.0	8.0	3.0	6.0	4.0	8.0
6c	2	4.0	8.0	4.0	8.0	4.0	8.0
Total	100		331.5		341.0		309.0

*Mandatory criterion: A rating of 2.0 or better is required to prevent automatic exclusion of concept.

The submerged gravel bed ranks highest due to the favorable rating in reliability (Group 2) and ease of fabrication (Group 6). The weakest aspect of this system is technological credibility (Group 4). While there is little doubt that the system works as designed, lack of a use-history for the submerged gravel scrubber makes it less credible than the other two candidates. The performance of large scale tests on this system could enhance the credibility rating and make it even more desirable than the other candidates.

The venturi scrubber ranked second because the liquid recirculation system (pump & piping) requirement resulted in lower ratings in reliability and cost (Groups 2 and 6, respectively). The broad industrial use-history resulted in the highest rating in technological credibility (Group 4).

The spray chamber ranked last. It is quite similar in many respects to the venturi scrubber, but the large size and attendant high cost make it less desirable. No factors were uncovered that override the low numerical score for the spray chamber and it was eliminated from the viable candidate list.

The two prime candidates had numerically similar scores. Also, it is evident that both system designs are feasible for the FFTF containment margins application. Therefore, a final selection between the submerged gravel scrubber and the venturi scrubber should be based on trade-off studies beyond the scope of this report.

2. Ranking of 99% Efficient Candidates

The numerical ranking of the four 99% efficient systems is listed in Table 15. The rationale for assigning the individual scores is described in Appendix B. From the total scores shown in Table 15, the candidates rank in the following order:

Submerged Gravel/Fibrous Scrubber	(338.1 points)
Venturi/Fibrous Scrubber	(335.9 points)
Sand and Gravel Bed	(282.9 points)
HEPA Filter Bank	(257.7 points)

TABLE 15

NUMERICAL RATINGS OF 99% EFFICIENT SYSTEMS

Criterion	Weight Factor	HE-1 Venturi-Fibrous		HE-2 SGS-Fibrous		HE-3 Sandbed		HE-4 HEPA Filters	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
1a*	5	4.0	20.0	4.0	20.0	3.0	15.0	4.0	16.0
1b*	5	3.5	17.5	3.5	17.0	3.0	15.0	2.5	12.0
1c*	2	3.0	6.0	3.3	6.6	4.0	8.0	3.6	7.2
1d	5	4.0	20.0	4.0	20.0	2.0	10.0	2.0	10.0
2a*	9	3.0	27.0	3.5	31.5	4.0	36.0	4.0	36.0
2b*	6	3.5	21.0	3.5	21.0	4.0	24.0	4.0	24.0
2c*	8	3.0	24.0	3.5	28.0	3.8	30.4	2.0	16.0
2d	3	3.5	10.5	3.4	10.2	2.0	6.0	1.0	3.0
3a*	4	3.6	14.4	3.8	15.2	4.0	16.0	4.0	16.0
3b	5	3.0	15.0	3.0	15.0	0.0	0.0	0.0	0.0
4a	5	4.0	20.0	2.0	10.0	3.0	15.0	3.8	19.0
4b*	6	3.0	18.0	3.1	18.6	4.0	24.0	4.0	24.0
4c	5	3.0	15.0	3.0	15.0	2.0	10.0	2.0	10.0
4d	3	4.0	12.0	2.0	6.0	3.5	10.5	3.0	9.0
4e	3	4.0	12.0	3.0	9.0	2.5	7.5	3.5	10.5
5a	3	4.0	12.0	4.0	12.0	3.0	9.0	4.0	12.0
5b	3	3.5	10.5	3.5	10.5	3.0	9.0	2.0	6.0
5c	3	2.0	6.0	3.0	9.0	3.5	10.5	3.5	10.5
5d	3	3.0	9.0	3.0	9.0	2.0	6.0	0.0	0.0
6a	10	3.0	30.0	4.0	40.0	1.0	10.0	0.0	0.0
6b	2	4.0	8.0	3.0	6.0	3.5	7.0	4.0	8.0
6c	2	4.0	8.0	4.0	8.0	2.0	4.0	4.0	8.0
Total	100		335.9		338.1		282.9		257.7

*Mandatory criterion: A rating of 2.0 or better is required to prevent automatic exclusion of concept.

The low ratings of the sand and gravel bed and HEPA filter systems, as well as their very high costs and large sizes, eliminated these two systems from further consideration.

The two scrubber systems have comparable scores. The submerged gravel/-fibrous scrubber was rated low in technological credibility (Group 4) because it lacks an extensive use-history. In all other categories the submerged gravel scrubber rated superior to the venturi system.

In selecting between the two scrubber systems, the main trade-off is an element of risk in scale-up of the submerged gravel unit versus greater cost and mechancial complexity of the venturi system. Final selection should be made by the system designer following conceptual design studies.

D. ASSESSMENT OF FEASIBILITY OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGINS APPLICATIONS

A review of available information concludes that air cleaning based on aqueous scrubbers is feasible for the FFTF Containment Margins application. Wet systems (scrubbers) are preferred compared to dry systems because the high aerosol mass loading requirements result in very large and costly systems for all dry systems considered.

Extensive testing of scrubber systems at large scale and under realistic aerosol stream conditions has demonstrated the efficient and reliable operation of the candidates. While the design efficiency of the two stage systems was stated as 99% in this study, more detailed analyses(9) and experiments(5) have shown the removal efficiencies to exceed 99.9%.

VII. REFERENCES

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A P P E N D I X A

NUMERICAL RANKING OF 90% EFFICIENT SYSTEMS

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Three candidates (an eductor venturi, a spray chamber and a sumberged gravel bed) are compared on a criterion-by-criterion basis. As noted in Section V, the numerical scores varied from 0 to 4.0. A rating of 4.0 denotes totally acceptable conformance and a rating of 0.0 denotes totally unacceptable conformance.

Criterion 1a. *"The design decontamination factor shall be achieved using design parameters that fall within current state-of-the-art practice."*

For this criterion scores were assigned on the basis of the inherent removal efficiency. The submerged gravel scrubber was rated 3.8. Average removal efficiencies exceeded 99% for a bed design comparable to that developed in this study. This indicates a design removal efficiency of 90% could be met without difficulty.

The venturi scrubber rated 3.5 because Containment Systems Test Facility (CSTF) tests on a 1000 cfm prototype showed that removal efficiencies exceeding 90% could be obtained routinely.[5]

The spray chamber rated 3.0. Calculations and experiments in CSTF show efficiencies of 90% can be otained, but carefully defined operating parameters must be adhered to. The spray chamber is inherently less efficient that the other two scrubbers but is satisfactory for the present application.

Criterion 1b. *"The system shall handle dry or sticky particles and particles of varying chemical composition."*

All three systems rate 4.0 because the physical and chemical composition of the aerosol does not adversely affect performance.

Criterion 1c. *"System effectiveness shall not be degraded by the radiation dose caused by the accident over the required operating period."*

All three systems are rated 4.0 because they use materials and components that could be constructed to easily withstand the radiation exposures encountered.

Criterion 1d. *"System characteristics shall inherently favor the systems with ability to handle large masses of aerosol".*

The three systems are equally efficient in handling large masses of sodium compound aerosols. Each was assigned a score of 4.0.

Criterion 2a. *"The air cleaning system shall have a high probability of startup after initiation of the accident".*

All three systems are equally dependent on a supply of water and on the operation of valves in the vent line. The submerged gravel bed has no active liquid pumping system and was rated 4.0 because it employs no pumps. The other two scrubbers were rated 3.5 because they employ pumps.

Criterion 2b. *"The system shall not degrade during periods of non-use".*

Because all three systems are expected to be "dry" in standby, little degradation would occur during non-use. If rusting of steel does occur, it will affect the venturi and spray chamber because they employ small openings in spray nozzles. On the other hand, biological growths in the gravel bed represent a possible mode of degradation not present in the other two systems. Overall, the systems appear to be equivalent and were assisgned a 3.5 rating.

Criterion 2c. *"The system shall be capable of dependable operation over the 1000-hour accident period under the accident conditions of temperature, humidity, aerosol loading and flow rate."*

For this criterion, scores were assigned on the basis of passivity and the ability to handle changing thermal and flow conditions. All three systems

will require a water source to replace evaporative losses, A system requiring no service during an accident would be more reliable. Because the venturi and spray scrubbers require electrical energy and operation of water pumps, they were assigned scores of 3.0. The submerged gravel scrubber does not employ a liquid pumping system and was rated 3.5.

Criterion 2d. *"The system shall require simple components and control and conservative design stresses.*

The gravel bed is probably the most complex component of the three candidate systems. However, the spray and venturi systems require control systems for liquid pumping. None of the three systems imposes design stress problems. Therefore, the advantages and disadvantages are off-setting and all three systems were assigned scores of 3.5.

Criterion 3a. *"Inadvertent operation of the system shall not harm the containment system (containment vessel and purge system) or constitute a hazard to personnel.*

All three candidate systems are external to the containment vessel and involve no hazard to personnel. No detrimental impacts from inadvertent operation of the system could be identified and all systems were assigned a score of 4.0.

Criterion 3b. *"The size of the system shall be compatible with installation adjacent to the Reactor Containment Building (RCB), and not significantly impact the location of other ancillary plant systems."*

Foot print sizes for the three candidates are comparable and small enough to be located adjacent to the RBC. All systems were rated 3.0 recognizing that an even smaller system would be more desirable.

Criterion 4a. *"The air cleaning concept is based on highly developed technology."*

The eductor venturi scrubber system is widely used in industry and was rated 4.0. The spray chamber was rated 3.0 because spray air washers are widely used but not typically designed for efficiencies as high as this application requires. The submerged gravel scrubber was rated 2.0 because, although many studies of particle capture in a massive packing bed are published, a self-cleaning bed is novel and not yet supported by industrial practice.

Criterion 4b. "The air cleaning system shall be testable in-place for operability and efficiency."

Perodic testing of the aqueous systems involve the following:

1. Fill tank with water
2. Start pumps (venturi and spray)
3. Start fans
4. Inject test particles
5. Collect aerosol samples
6. Measure liquid and gas flow rates
7. Shut down fans and pumps
8. Drain water from system

Because this procedure is more complex than the required procedure for a dry filter system the simpler system (the submerged gravel scrubber) was assigned a score of 3.0. The venturi and spray scrubbers were rated at 2.5 because additional effort is required to operate the liquid pumps and put them into standby condition.

Criterion 4c. "The system performance shall be predictable by verified mathematical models."

Models for predicting particle removal exist for all three candidates. Reasonable agreement between theory and experiment is evident in available comparisons, and a rating of 3.0 was assigned to all candidates.

Criterion 4d. "The equipment scale-up from currently available sizes to FFTF plant application shall be small."

Both the venturi and spray scrubbers are used industrially in sizes larger than required for the application; therefore, no scale-up is required and a score of 4.0 is assigned.

The submerged gravel scrubber would require a scale-up in diameter by a factor of three as compared to engineering scale units operating to date. A rating of 2.0 is assigned because of the scale-up.

Criterion 4e. *"The air cleaning concept shall be demonstrated with sodium aerosol or the extension of results to sodium aerosol can be made with confidence."*

All three system concepts have been extensively tested at HEDL with sodium compound aerosols and a 4.0 score is assigned.

Criterion 5a. *"The air cleaning concept shall be effective for the entire particle size spectrum during the accident."*

All three systems are expected to show moderate to low efficiencies for submicron particles. Ranking was based on the measured sodium compound particle efficiency of each system. The submerged gravel scrubber rated 3.0, the venturi 2.5 and the spray scrubber 2.0.

Criterion 5b. *"The system performance shall not be highly senstive to the atmospheric temperature or relative humidity."*

All three systems process gas at any temperature within design limits and operation is independent of the relative humidity of inlet gas. Since water would have to be added to compensate for evaporation, all systems were rated 3.5.

Criterion 5c. *"The system energy consumption shall be low."*

Energy requirements for the three candidates are modest. Scores were assigned on the basis of horsepower requirements for the conceptual designs, allowing for a possible purge fan operation. Because the gravel scrubber

has no water pump, it was rated 3.0. The spray chamber was rated 2.5 and the venturi scrubber 2.0.

Criterion 5d. "Post-accident recovery shall be facilitated by the air cleaning system."

Contaminants removed from the air stream would be dissolved or entrained in the water of all three systems. After an accident, this water could be processed to put the contaminants into the desired form. This ability is considered satisfactory and a score of 3.0 is assigned to all three systems.

Criterion 6a. "System costs, capital and maintenance, shall be low."

Scores were assigned on the basis of captial costs estimated from the conceptual designs developed. The relative costs and ratings are as follows:

System	Relative Cost Units	Score
Eductor Venturi	0.80	2.5
Submerged Gravel	0.45	3.5
Spray Chamber	1.6	1.0

Criterion 6b. "Materials and techniques used in construction shall be readily available."

All three systems use standard construction materials. The venturi and spray chamber scrubbers use standard construction techniques and were rated 4.0. Since the submerged gravel bed represents a small departure from usual construction techniques, it was given a score of 3.0.

Criterion 6c. "Components and equipment shall be readily available."

All three systems use standard, readily available components and were assigned a score of 4.0.

A P P E N D I X B

NUMERICAL RANKING OF 99% EFFICIENT SYSTEMS

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The four candidates (an eductor venturi with fibrous scrubber, a submerged gravel bed with fibrous scrubber, sand and gravel bed and a HEPA filter system) are compared on a criterion-by-criterion basis. As noted in Section V, the numerical scores varied from 0.0 to 4.0. A rating of 4.0 denotes acceptable conformance and a rating of 0.0 denotes totally unacceptable conformance.

Criterion 1a. *"The design decontamination factor shall be achieved using design parameters that fall within current state-of-the-art practice."*

While all four candidates exhibit efficiencies that exceed the 99% design level, the two scrubber systems and the HEPA filter system are appreciably more efficient than the sand filter. Therefore, the two scrubber systems and the HEPA filter system were assigned scores of 4.0 and the sand and gravel filter was assigned a score of 3.0.

Criterion 1b. *"The system shall handle dry or sticky particles and particles of varying chemical composition."*

The two scrubber candidates are minimally affected by particle chemical composition because solubility considerations dictate minimum water volumes and the dissolution of aerosol trapped in the fibrous elements. A score of 3.5 was assigned to both scrubbers.

The physical characteristics of particles (sticky or dry) appreciably affect the mass loading capability of the sand bed and HEPA filter systems because fiberglass is susceptible to corrosion by moist sodium hydroxide. The sand bed was given a rating of 3.0. The HEPA filter system was rated 2.5.

Criterion 1c. *"System effectiveness shall not be degraded by the radiation dose caused by the accident over the required operating period."*

All four candidates can be designed to accommodate the modest radiation exposures expected. Due to the difference in inherent resistance to radiation

doses, the sandbed filter was rated 4.0, the HEPA filter system 3.6, the submerged gravel scrubber 3.3 and the venturi scrubber 3.0. The submerged gravel scrubber uses polypropylene fibers that are susceptible to radiation damage, although the radiation doses expected for this application do not cause material failures. In addition to the use of polypropylene, the venturi uses pumps and motors not present in the other systems.

Criterion 1d. *"System characteristics shall inherently favor systems with ability to handle large masses of aerosol".*

Because scrubber candidates are able to capture large masses of aerosol without difficulty, they were rated 4.0. Both the sand bed and HEPA systems are inherently inefficient in trapping large aerosol masses. The two dry systems were rated 2.0.

Criterion 2a. *"The system shall have a high probability of start-up after initiation of the accident."*

The two dry scrubbers are rated 4.0 because there are no active components for venting and because no water pools are maintained during the systems shelf life.

The two scrubbers (venturi and submerged gravel bed) require water and introduce a failure mode not present in the dry systems. The venturi scrubber also requires liquid pump start-up. Therefore, the submerged gravel and venturi scrubbers were rated at 3.5 and 3.0 respectively.

Criterion 2b. *"The system shall not degrade during periods of non-use."*

Both dry systems were rated 4.0 because no credible degradation mode could be identified during periods of non-use. The scrubbers were rated 3.5 because of possible corrosion in the water storage tank.

Criterion 2c. *"The system shall be capable of dependable operation over the 1000-hour accident period under the accident conditions of temperature, humidity, aerosol loading and flow rate."*

Scores were assigned to reflect inherent aspects of reliability in each system. The factors and scores are summarized as follows:

TABLE B-1

SYSTEM RELIABILITY RATINGS

System	Score	Judgment Factors
Sand Bed (HE-3)	3.8	No water required, no pumps
Submerged Gravel (HE-2)	3.5	No pump required
Venturi/Fibrous (HE-1)	3.0	Pump required
HEPA Filters (HE-4)	2.0	Possible corrosion of media by NaOH

Criterion 2d. "The system shall require simple components and control and conservative design stresses."

All four candidate systems incorporate simple components but differ in overall design. System scores and judgment factors are summarized as follows:

TABLE B-2

SYSTEM DESIGN RATINGS

System	Score	Judgment Factors
Venturi/Fibrous (HE-1)	3.5	Standard design, modest size
Submerged Gravel (HE-2)	3.4	Modest size, novel gravel bed
Sand bed (HE-3)	2.0	Very large bed, under pressure
HEPA Filter (HE-4)	1.0	Largest pressurized HEPA installation in the world

Criterion 3a. *"Inadvertent operation of the air cleaning system shall not harm the containment system or constitute a hazard to peronnel."*

Because all four candidate systems are external to the containment vessel and could not harm personnel, no major short-comings for any of the systems are envisioned. Both dry systems were rated 4.0. Because effort is required to drain tanks and lines, the submerged gravel and venturi scrubbers were rated 3.8 and 3.6, respectively.

Criterion 3b. *"The size of the air cleaning system shall be compatible with installation adjacent to the RCB, and not significantly impact the location of other ancillary plant systems."*

The two scrubbers are of similar size and appear to fit within available free regions close to the containment vessel. They were given a rating of 3.0. Because dry systems are very large, cannot be located adjacent to the containment vessel and would grossly impact the location of ancillary plant systems, they were assigned scores of 0.0.

Criterion 4a. *"The air cleaning concept shall be based on highly developed technology."*

The venturi/fibrous system uses components that have broad industrial application. The combined system was tested extensively at HEDL with sodium compound aerosols typical of those postulated for margins application.[5] Therefore, this system was rated 4.0.

The HEPA filter system was rated 3.8. Although HEPA filters have very broad industrial application, questionable use with NaOH aerosol and the large installation size detracted from the score. The sand bed rated 3.0 because few sand bed filters are used in industry. The submerged gravel scrubber was rated 2.0 because the system was not demonstrated at full scale.

Criterion 4b. *"The air cleaning system shall be testable in-place for operability and efficiency."*

All systems are external to the containment building and could be tested without significantly impacting other plant operations. However, the scrubber systems would require more effort to operate and put into standby condition. Both the HEPA and sand bed filter systems were assigned scores of 4.0 because the testing procedure would involve only the operation of valves, fans and aerosol testing instruments. The venturi/fibrous scrubber was rated 3.0. The submerged gravel scrubber was rated slightly higher at 3.1 because it has no liquid pumping system to operate.

Criterion 4c. *"The system's performance shall be predictable by verified mathematical models."*

For the scrubbers, particle capture, heat transfer and mass loading capacity can be predicted by available models. Although the models are probably satisfactory, additional verification work would increase confidence. Therefore the scrubbers were rated 3.0.

Dry systems performance, particularly the mass loading capacity, lacks extensive modeling. Off-setting lack of modeling is the availability of empirical information that can be used to design the dry systems. A score of 2.0 was assigned to both the sand bed and HEPA filter systems.

Criterion 4d. *"The scale-up of air cleaning equipment from currently available sizes to FFTF margins application shall be small."*

The venturi/fibrous scrubber was rated 4.0 because no scale-up in size is involved. The sand bed rated 3.5 because, although the required unit would be larger than any presently in existence, there appear to be no technical issues involved in enlarging the planar area. The HEPA filter installation was rated 3.0. While there is no scale-up of the individual filter units, the assembled system would be larger than any existing installation. The submerged gravel/fibrous scrubber was rated 2.0 because a large system was not tested and requires scale-up.

Criterion 4e. *"The system concept shall have been demonstrated with sodium compound aerosol or the extension of results to sodium aerosol can be made with confidence."*

All four candidates were tested with sodium compound aerosols at HEDL and at other laboratories. The venturi/fibrous scrubber rated 4.0. Extensive tests at HEDL have demonstrated the efficiency of this system. The HEPA filter system rated 3.5. Significant experience on trapping sodium compound aerosols was accrued in HEDL test programs. The submerged gravel/fibrous scrubber rated 3.0 because the equipment used in HEDL tests was of a modest size. The sand bed filter rated 2.5 because less information is available on this candidate than for the other candidates.

Criterion 5a. *"The air cleaning system shall be effective for the entire particle size spectrum during the accident."*

The two scrubber systems and the HEPA filter system trap all particles sizes efficiently and rate 4.0. HEDL experiments show that a measurable fraction of fine particles can penetrate a sand bed filter, and this candidate was rated 3.0.

Criterion 5b. *"The system performance shall not be highly sensitive to the atmospheric temperature or relative humidity."*

The two scrubber systems rated 3.5 because their performance is independent of relative humidity and affected by temperature only under extreme conditions when water temperatures approach the safe limit for polypropylene fibers. The sand bed filter was rated 3.0 because loading capacity is dependent on particle stickiness, which in turn depends on relative humidity. The HEPA filter system was rated 2.0 because its loading capacity is dependent on relative humidity and the fiber glass medium is susceptible to corrosion by moist NaOH.

Criterion 5c. *"The system energy consumption shall be low."*

The sand and HEPA filter systems rated 3.5 because they would exhibit low pressure drop and have no water pumping requirements. The submerged gravel/fibrous scrubber rated 3.0 because pressure drop is higher than that of the dry systems. The venturi/fibrous scrubber rated 2.0 because it also requires a liquid pumping system.

Criterion 5d. "Post-accident recovery shall be facilitated by the design of the air cleaning system."

All systems are external to the containment building and have similar characteristics regarding re-entry to containment, but differ in trapped contaminant disposal. In the scrubber systems most of the contaminants would be suspended in the water and could be processed for permanant storage. The scrubbers were assigned scores of 3.0. The sand bed filter was also rated 3.0. It was assumed that the contaminants would be left in place. The HEPA filter system was rated 0.0 because removal and disposal of the large number of HEPA units would involve large expediture of cost and manpower.

Criterion 6a. "System costs, capital and maintenance, shall be low."

Maintenance costs are expected to be low for all candidates. However capital costs vary widely and ratings for this criterion were based on capital cost estimates listed in Tables 7 through 11. Results are tabulated below.

TABLE B-3

SYSTEM RATING BY COST

System	Cost Units	Assigned Score
Submerged gravel (HE-2)	0.7	4.0
Venturi/fibrous (HE-1)	1.1	3.0
Sand bed (HE-3)	16.0	1.0
HEPA filters (HE-4)	110	0.0

Criterion 6b. "Materials and techniques used in construction shall be readily available."

The venturi/fibrous scrubber and the HEPA filter system use standard readily available materials and construction techniques and were assigned scores of 4.0. The sand bed rated 3.5. While construction materials are readily available, only a few large sand bed filters have been constructed. Therefore, construction techniques may require more planning than the "optimum" system. The submerged gravel/fibrous scrubber was rated 3.0. No substantial difficulties in construction techniques are expected, but the design lacks a use-history.

Criterion 6c. "Components and equipment shall be readily available."

Components and equipment required for all systems, except the sand bed are readily available. The two scrubber systems and the HEPA filter are rated 4.0. The fine sand layer used in the sand bed would probably have to be shipped in from the Midwest; therefore a rating of 2.0 was assigned.

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J.D. McCormack
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R.K. Hilliard
J.D. McCormack
A.K. Postma

ABSTRACT

Four large-scale air cleaning tests (AC7 - AC10) were performed in the Containment Systems Test Facility (CSTF) to demonstrate the performance of a Submerged Gravel Scrubber for cleaning the effluent gas from a vented and purged breeder reactor containment vessel. The test article, comprised of a Submerged Gravel Scrubber (SGS) followed by a high efficiency fiber demister, had a design gas flow rate of 0.47 m^3/s (1000 ft^3/min) at a pressure drop of 9.0 kPa (36 in. H_2O). The test aerosol was sodium oxide, sodium hydroxide, or sodium carbonate generated in the 850-m^3 CSTF vessel by continuously spraying sodium into the air-filled vessel while adding steam or carbon dioxide. Approximately 4500 kg (10,000 lb) of sodium was sprayed over a total period of 100 h during the tests.

The SGS/Demister system was shown to be highly efficient (removing ∿99.98% of the entering sodium aerosol mass), had a high mass loading capacity, and operated in a passive manner, with no electrical requirement. Models for predicting aerosol capture, gas cooling, and pressure drop are developed and compared with experimental results.

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SUBMERGED GRAVEL SCRUBBER DEMONSTRATION AS A PASSIVE AIR CLEANER FOR CONTAINMENT VENTING AND PURGING WITH SODIUM AEROSOLS - CSTF TESTS AC7 - AC10

1.0 INTRODUCTION

Although hypothetical core disruptive accidents (HCDAs) are not design basis accidents for breeder reactor plants, extensive assessments of HCDA consequences have been made and design features for providing margins beyond the design base have been considered for future fast reactor plants.[1] One feature proposed for increasing the safety margin is a containment vent and/or purge system which would mitigate the challenge to containment integrity resulting from excessive temperature and pressure or excessive hydrogen. A cleanup system would be provided for removal of vented aerosols and condensible vapors to mitigate radiological consequences to the environment.

A study is in progress at Hanford Engineering Development Laboratory (HEDL) to select and develop a suitable air cleaning system for use in potential breeder reactor containment venting applications. An evaluation of existing air cleaning technology[2] indicated that several types of air cleaning devices have potential for such use, but that all required demonstration under postulated accident conditions and some would be very large and costly. HEPA filters were tested for aerosol mass loading capacity and found to have a low capacity ($\sim$1.6 kg/m^2) before plugging occurred.[3] Dry sand and gravel beds were developed[4] which had an improved capacity ($\sim$4 kg/m^2) and good aerosol removal efficiency (>99%), but were considered impractical from a size and cost standpoint for applications involving a large mass of vented aerosol (to 100,000 kg). Aqueous scrubbers were judged to be the most practical, but no single commercial scrubber could meet the dual requirement of high mass loading and high efficiency. Therefore, a system

comprised of a spray chamber, ejector venturi and high efficiency fibrous scrubber was selected for testing in the Containment Systems Test Facility (CSTF).[5,6]

While the venturi/fibrous scrubber system met all the required design criteria, it had the disadvantage of using active components (pumps); with their attendant failure possibility and electrical demand. A concept was conceived whereby the passiveness and high loading capacity of a water pool scrubber was combined with the high efficiency of a sand and gravel bed. It was termed a Submerged Gravel Scrubber (SGS). The SGS consists of a bed of gravel (or other packing) submerged in a pool of water. Gas, laden with aerosol, is discharged beneath the gravel, where it subsequently flows upward through the bed. The effective density of the two-phase mixture in the gravel region is less than that of the pool outside the gravel bed, and liquid flows upward at a significant rate. This inherent liquid pumping action clears the bed of collected aerosol and provides for a very large mass loading capability.

The SGS concept was developed by performing a series of small-scale experiments, using a 0.3-m diameter gravel bed.[7] The test results were encouraging and a larger scale model was constructed, having a nominal gas handling capacity of 0.47 m^3/s (1000 ft^3/min). A high efficiency demister was incorporated in the design to produce a system with high efficiency for removing particles of all sizes. Four tests were performed in the Containment Systems Test Facility (CSTF) to demonstrate the performance of the SGS/Demister system under postulated breeder accident conditions. This report presents the results of these large-scale tests.

2.0 SUMMARY AND CONCLUSIONS

2.1 SUMMARY

A passive, self cleaning scrubber was demonstrated under conditions simulating containment venting and purging during low-probability accidents in an LMFBR plant. The test article was a Submerged Gravel Scrubber (SGS) with a high efficiency demister. The SGS is a novel device, consisting of a relatively small gravel bed submerged in a pool of water. The function of the scrubber is to remove radioactive aerosols and vapors from vented and purged containment atmosphere with high efficiency (>99.9%) and large mass loading capacity. The features of the SGS which make it attractive for containment venting applications are its passivity (no electrical requirement), its relative small size (low cost and space requirements), its high efficiency, and its high mass loading capacity.

The performance of a 0.47 m^3/s (1000 ft^3/min) model of the SGS/Demister system was demonstrated during four large-scale tests in the Containment System Test Facility (CSTF). The test results showed that the performance was completely satisfactory, with excellent sodium aerosol removal efficiency (>99.98%), absence of pressure buildup due to collected aerosol, and good cooling of the hot containment gas. The passivity of the test article was demonstrated, with no electrical power required except for operation of an exhaust blower during purging operations.

The test aerosols were generated by continuously spraying sodium into the 850-m^3 (30,000-ft^3) CSTF containment vessel. Steam and carbon dioxide were added in some tests to simulate the release of these gases from heated concrete. The dominant aerosol chemical forms were Na_2O_2, NaOH, or Na_2CO_3 in different tests. A total of 4500 kg (10,000 lb) of sodium was sprayed continuously for a total of 102 h during the four tests. An average of 74% of the sprayed sodium formed an aerosol, with suspended concentrations ranging from 2 to 23 g/m^3 and an average particle size of 5.2 μm AMMD (aerodynamic mass median diameter). Twenty percent of the sprayed sodium

(920 kg) was vented to the test air cleaning system and 80% settled or plated on containment surfaces. The temperature of the gas entering the SGS ranged up to 240°C (465°F).

After sodium had been sprayed into the isolated containment vessel for several hours to provide a stable containment environment, the containment atmosphere was vented to the scrubber. The gas flow rate was controlled at 0.5 to 0.6 m^3/s (1060 to 1270 ft^3/min) by modulating a 10-in. butterfly isolation valve. After the 70-kPa (10-psi) overpressure had been relieved, an exhaust blower was started and the containment vessel was purged with air for the duration of the test.

The SGS test article was comprised of a 1.1-m diameter by 0.6-m deep basket of gravel suspended in a 1.8-m diameter tank of water. The pool liquid level was maintained at the same elevation as the top of the gravel bed. Crushed basalt gravel of ~11-mm diameter was used in three tests and 9.5-mm diameter commercially procured ceramic packing was used in one test. The dirty gas flow rate was varied from 0.08 to 0.7 m^3/s (170 to 1460 ft^3/min) and the SGS pool surface level was varied $\pm$90 mm (3.5 in.) during the tests. The scrubber liquid was initially water and accumulated sodium to a maximum of 97 g Na/ℓ (4.2 normal). In one test NaI vapor was injected into the inlet duct to measure the removal of a typical condensible fission product vapor.

Simple mathematical models were developed for use in predicting gas cooling, pressure drop, and aerosol removal. Model predictions agreed closely with experimental measurements for gas cooling and pressure drop, but were overly conservative for predicting aerosol removal.

2.2 CONCLUSIONS

Specific conclusions and summary statements supported by the reported work are as follows:

(1) The overall performance of the Submerged Gravel Scrubber/Demister test article was fully satisfactory, with excellent aerosol removal, good flow control, stable pressure differentials, excellent gas cooling, and high aerosol mass loading demonstrated. The unit operated passively except for water addition to replace evaporation losses.

(2) The performance of the SGS/Demister system compared favorably with that of a previously tested[5,6] system comprised of a water spray quench tank, ejector venturi and fibrous scrubber in series. The particle removal efficiency was slightly better (99.987% vs 99.956%) and pressure differentials were more stable for the SGS unit. The chief advantage of the SGS/Demister over the Quench/Venturi/Fibrous Scrubber system is that the former operates without pumps (no electricity). A possible disadvantage is that it operates at a higher pressure drop (~9.0 kPa vs ~2.0 kPa).

(3) Hydraulic tests on three scale models of the SGS indicate that scaleup to units of 10 to 20 m^3/s (20,000 to 40,000 ft^3/min) may be feasible, but that flow distribution should be verified by large-scale hydraulic testing. Based on a recommended superficial gas velocity of 0.5 m/s, the gravel bed for a 10-m^3/s scrubber would be 5.0-m diameter. Scaleup of the demister could be accomplished by using multiple elements of the size tested in the present work.

(4) The efficiency of the SGS/Demister System for removing sodium fire aerosol particles was excellent, averaging 99.987 , which corresponds to a decontamination factor of 7700.

(5) The removal efficiency of the SGS without the demister was very good, averaging 99.24% (decontamination factor of 130). Only two operating parameters had any detectable effect on the measured efficiency: aerosol particle size and the concentration of sodium in the SGS liquid pool. Variation of particle size of the sodium fire aerosol from 3.4 μm to 8.4 μm AMMD had only a minor effect, but submicron particles were collected with lower efficiency, as expected. High sodium concentration in the scrubber liquid caused the efficiency to decrease slightly, due to entrainment carryover, a characteristic of all scrubbers.

(6) A mathematical model, based on impaction, greatly underpredicted the SGS aerosol removal efficiency. Two mechanisms believed responsible for the higher than predicted performance are: (a) particle growth due to water condensation, and (b) enhanced turbulence due to energy dissipation. The efficiency correlates well with other types of scrubbers on an energy dissipation basis and can be approximated by assigning a cut diameter of 0.4 μm for aerosol capture.

(7) Small particles which penetrated the SGS were captured efficiently (98%) by diffusion in the fiber bed demister. The combination of high mass loading capacity of the SGS and effective small particle retention in the demister produces a highly efficient and flexible air cleaning system.

(8) Hot containment gas was cooled effectively in the gravel bed, with the gas outlet temperature being within 1°C of the pool temperature.

(9) The pressure drop across the scrubber system varied with gas flow rate in a predictable manner and did not change significantly with time. This confirms the ability of the system to capture large masses of aerosol without plugging.

(10) The total mass loading capacity of the system depends on the volume of water provided. Based on solubility considerations, it is recommended that sodium ion concentration in the SGS pool be limited to 115 g Na/ (5 normal).

(11) The efficiency of the system for removing a condensible contaminant, NaI, was appreciably less than for removing the sodium fire aerosol. Approximately 99 of the NaI mass was removed when the NaI was injected as a vapor into the inlet duct. Most of the removal occurred in the fibrous scrubber. These findings support a theoretical prediction based on nucleation and attachment of condensible materials to the sodium fire aerosol particles.

(12) Significant deposition of aerosol occurred in the duct leading from containment to the scrubber. The 10-in. (265-mm) diameter duct was nearly plugged in two of the tests which used NaOH aerosol. An empirical equation relating duct plugging to duct diameter, developed during earlier tests,[5,6] was confirmed.

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3.0 EXPERIMENTAL FACILITY AND INSTRUMENTATION

3.1 FACILITY DESCRIPTION

3.1.1 Containment Vessel

The tests were performed in the Containment Systems Test Facility (CSTF). A schematic plan view of the facility is shown in Figure 1. The chief feature is the containment vessel, which forms the pressure boundary within which the test aerosol is generated and aged. The containment vessel's large size (850 m^3) and height (20.3 m) enable particle agglomeration and chemical reactions to occur on a scale approaching that of an actual plant. It is a carbon-steel vessel with a design pressure of 0.517 MPa gauge (75 psig). It is installed in a concrete cell with the top half extending above the elevation of the main building work area, as shown by the schematic elevation view in Figure 2. All interior surfaces are coated with a modified phenolic paint, and exterior surfaces are covered with a 25.4-mm layer of fiberglass insulation with an outer aluminum vapor barrier. Additional details of the containment vessel are provided in Table 1.

A photograph of the test article as installed in the CSTF is shown in Figure 3. Only the upper half of the containment vessel is visible. The dry, empty venturi and fibrous scrubber housings are visible downstream of the SGS. They remained in the ducting after completion of an earlier test series,[6] but serve no purpose in the present tests except as a duct.

Other features of the CSTF include the sodium supply system for aerosol generation, the instrument and control system, the chemistry laboratory, support services, and a work area adjacent to the containment vessel for installation of the test air cleaning equipment.

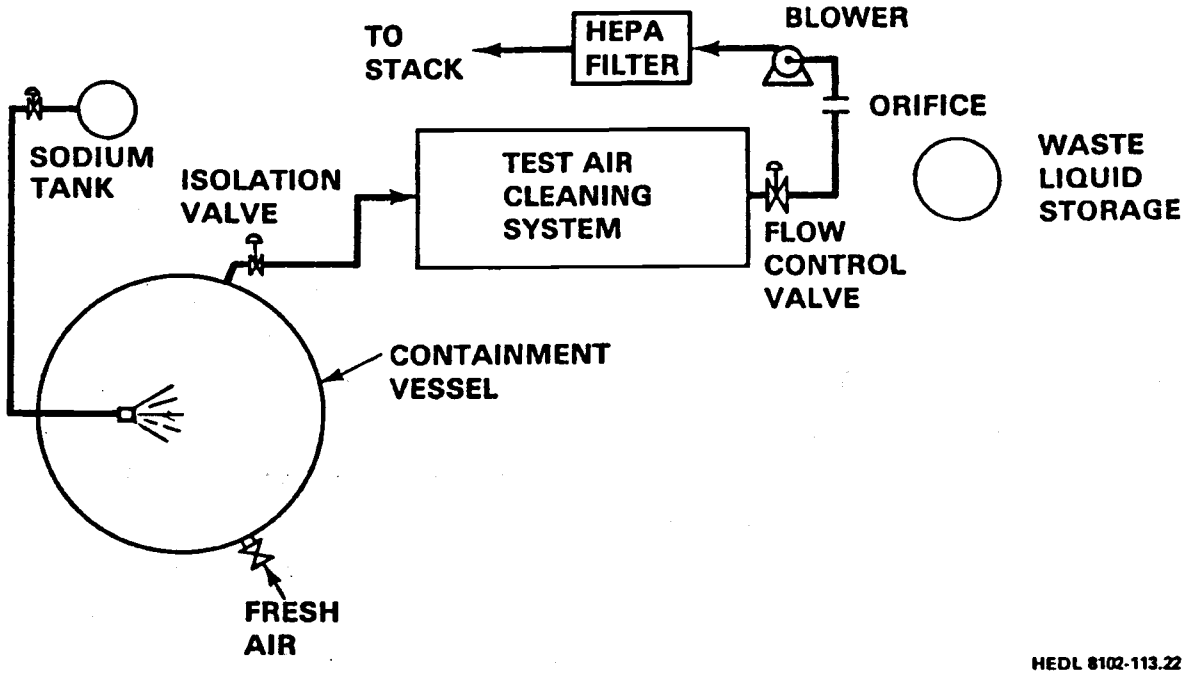

FIGURE 1. Containment Systems Test Facility Schematic Plan View.

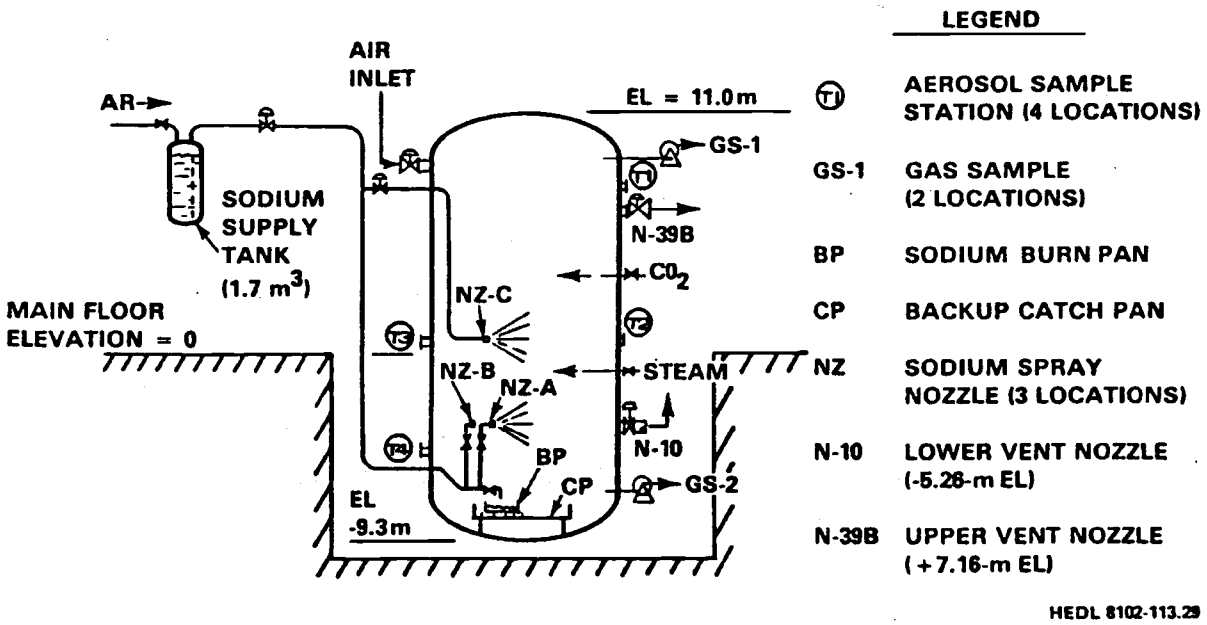

FIGURE 2. Schematic Elevation View of the CSTF Containment Vessel.

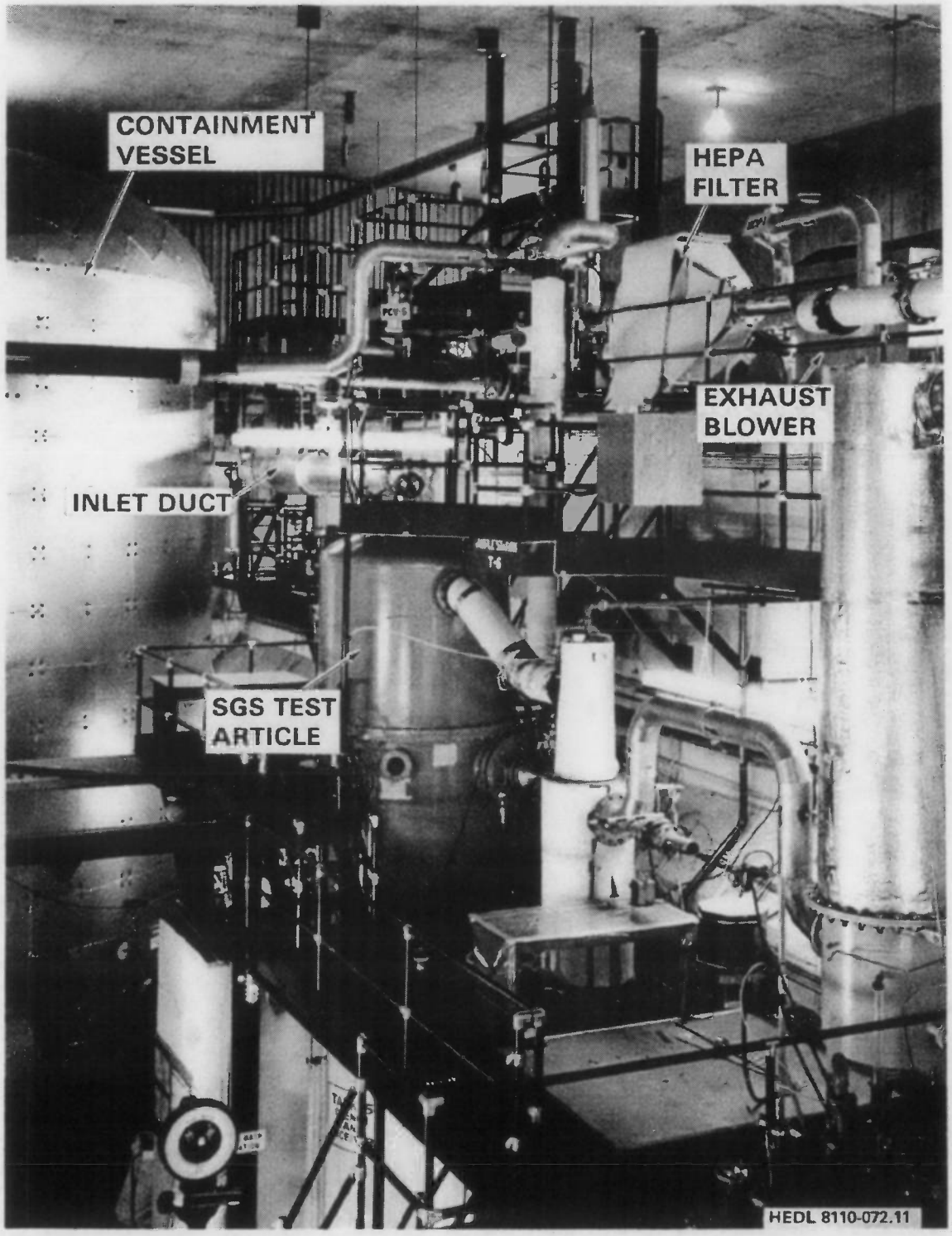

FIGURE 3. Photograph of the SGS Test Article Installed in the CSTF. Neg 8006805-19cn

TABLE 1

CSTF CONTAINMENT VESSEL PROPERTIES

Property	Specification
Code	ASME B&PV Code, Section VIII, 1962[8]
Design Pressure	0.517 MPa at 1600 C (75 psig at 320°F)
Material	Carbon Steel, SA 212-B
Wall Thickness	1.64 mm to 1.90 mm (0.645 in. to 0.75 in.)
Weight	103,000 kg (226,000 lb)
Volume	850 m^3 (30,086 ft^3)
Diameter	7.2 m (25 ft)
Overall Height	20.3 m (66.7 ft)
Internal Surface Area*	1000 m^2 (10,000 ft^2)
Shell Surface Area	520 m^2 (5600 ft^2)
Floor Area	45.6 m^2 (490 ft^2)
Total Horizontal Surface	88 m^2 (900 ft^2)
Nominal Leakage Rate	2.0% per day at 10 psig
Interior Surface Coating	3-Coat Phenolic Paint
Exterior Thermal Insulation	25.4-mm Fiberglass, k=0.0467 W/m°C @ 100°C
Elevation of Backup Catch Pan	(-) 8.5 m (27.8 ft)

* Including shell surface area.

3.2 AEROSOL GENERATION

3.2.1 Sodium Aerosol Generation

Sodium aerosol was generated by spraying sodium continuously from one or more of the three hydraulic spray nozzles shown in Figure 2. The temperature of the sodium at the nozzle ranged from 450°C to 800°C, averaging 580°C. The drop size is thought to be 400 μm mass median diameter with a geometric standard deviation of 1.5, the same as that determined by the nozzle manufacturer for water. The spray drops burned completely before striking any vessel surface.

In each test, sodium delivery was initiated by spilling a small quantity of sodium into a 0.55-m^2 burn pan located at the (-) 8.5 m elevation. This was done to fill the spray line with sodium and to clear the line of any oxide that might have been present, thereby reducing the potential for plugging of the spray nozzle. The spray nozzle was started one minute later. Time zero was defined as the time when the spill to the burn pan occurred. Details of the sodium spray and burn pan spill are given in Table 2.

In test AC9, two nozzles were operated concurrently in order to create a higher aerosol concentration. In test AC9, a leak developed in the spray line, within the pressure boundary of the containment vessel, causing a joint spray and pool fire. The pool fire continued for nearly 5 hr after cessation of spray, albeit at a lower aerosol generation rate than during the period when spray nozzles were operating.

The desired chemical composition of the test aerosol was achieved by injecting steam and carbon dioxide at suitable rates into the containment atmosphere. After an initial period during which the containment vessel was isolated, the containment pressure was vented through the test air cleaning system, and then an exhaust blower was started to draw room air into the containment vessel. This purge air supplied sufficient oxygen to maintain sodium burning for the duration of the entire test.

3.2.2 Sodium Iodide Generation

Sodium iodide vapor was injected into the gas inlet duct 3.8 m upstream from the inlet flange on the SGS test article in Test AC10. The generator consisted of a stainless steel vessel in which liquid NaI was held at an elevated temperature (~870°C) while a nitrogen sweep gas was passed over it. The line leading from the NaI generator to the air cleaning duct was heated to a slightly higher temperature to prevent condensation in the line. As the hot vapor entered the main duct, it cooled rapidly and nucleated to form

TABLE 2

SODIUM AEROSOL GENERATION DETAILS

System	Test No. AC7	AC8	AC9	AC10
Spray Nozzle A				
Type	(a)	(a)	(a)	(a)
Distance above pan (m)	2.7	2.7	2.7	2.7
Time start (min)	1.0	1.0	1.0	1.0
Time stop (min)	1930	1890	490	1520
Na delivered (kg)	1190	1219	308	1193
Avg spray rate (g/s)	10.3	10.8	10.5	13.1
Spray direction	horiz.	horiz.	horiz.	horiz.
Spray Nozzle B	(b)	(b)		(b)
Type			(a)	
Distance above pan (m)			2.7	
Time start (min)			1.0	
Time stop (min)			490	
Na delivered (kg)			308	
Avg spray rate (g/s)			10.5	
Spray direction			horiz.	
Spray Nozzle C	(b)	(b)	(b)	(b)
Burn Pan				
Surface area (m^2)	0.55	0.55	0.55	0.55
Total Na delivered (kg)	20	20	20[c]	5
Time start (min)	0	0	0[c]	0
Time stop (min)	1.0	1.0	1.0[c]	0.25
Number of spills	1	1	1[c]	1
Total Na delivered to CV (kg)	1210	1239	887[d]	1198
Total duration of Na delivery (min)	1930	1890	490[e]	1520
Average Na delivery rate (g/s)	10.4	10.9	30.2	13.1

(a) Spraying Systems Co., type B2 hollow cone.
(b) Not used.
(c) Intentional spill. A leak in spray line resulted in a pool fire lasting 290 minutes after spray nozzle shut off.
(d) Total from spray and Na leak.
(e) Na nozzles shut off at 490 minutes. Pool fire continued until t = 780 minutes.

very small aerosol particles. The airborne concentration of NaI was measured by analyzing for iodine on the same aerosol filter samples that were used for sodium downstream from each scrubber. The liquid solutions and final high efficiency particulate air (HEPA) filter were also analyzed for iodine by the ion selective electrode method. A sketch of the NaI generation system is shown in Figure 4.

3.3 TEST ARTICLE DESCRIPTION

3.3.1 General

A dimensional sketch of the SGS/Demister test article is given in Figure 5. An outer cylindrical steel vessel houses the SGS gravel basket and water pool in the bottom portion. A horizontal tube sheet separates the SGS from the demister section which occupies the upper portion of the test article. A central vertical downcomer penetrates the gravel bed axially and serves as the gas-aerosol inlet. A skirt extends 300 mm below the bottom of the gravel bed, so that gas is confined to the area directly below the gravel and flows upward through the gravel bed to the gas plenum above the surface of the pool. Much of the aerosol is removed during passage through the bed. The partially cleaned gas flows from the plenum above the pool through two 457-mm diameter holes in the tube sheet to the inside of the hollow cylinder fiber demisters. The gas passes through the demisters and exits the test article housing through a side nozzle.

The apparent density of the two-phase mixture of gas and pool liquid in the gravel bed is less than that of the pool outside the gravel bed, and liquid flows upward at a significant rate. This inherent liquid pumping action clears the gravel surfaces of collected aerosol and prevents pressure build-up due to accumulation of deposited aerosol. Liquid pumped through the bed overflows the top of the gravel basket and recirculates to the bottom gravel region through openings in the gravel support skirt.

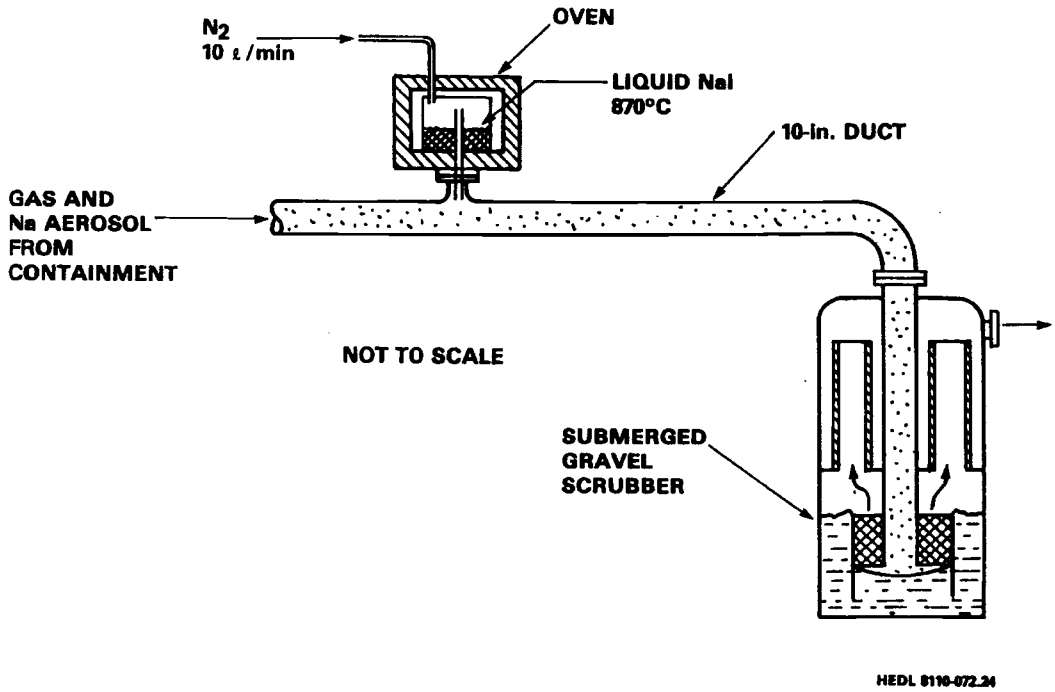

FIGURE 4. NaI Vapor Release Schematic.

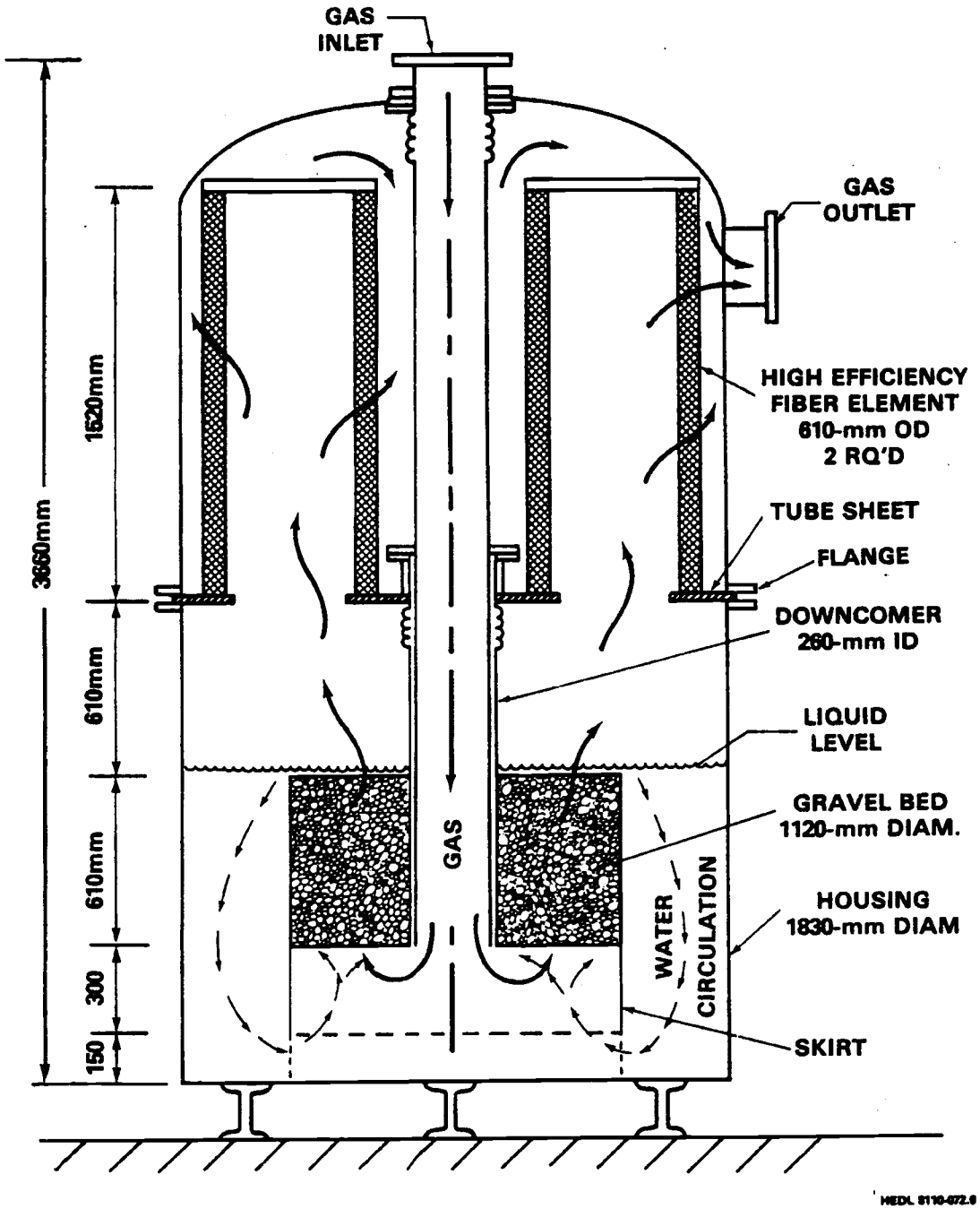

FIGURE 5. Schematic Diagram of SGS/Demister Test Article.

3.3.2 Outer Housing

The housing is a vertical cylinder 1.83 m (6 ft) in diameter and 3.66 m (12 ft) in overall height. It has a flat bottom and dished top head. It is designed, fabricated and tested in accordance with Section VIII, Division 1 of the 1980 ASME Boiler and Pressure Vessel Code.[9] Its design pressure is 103 kPa (15 psig) at 315°C. It is constructed of carbon steel. It is fab- ricated in two sections, joined at the tube sheet by flanges. The gas inlet and outlet nozzles are 265 mm (10 in.) in diameter.

3.3.3 Gravel Basket

A dimensional sketch of the gravel basket is shown in Figure 6. The basket is a cylindrical steel vessel with continuous side walls and open top and bottom. Its inner diameter is 1.12 m and its overall height is 0.927 m. The liquid overflow weir is at the same elevation as the nominal liquid surface level of the water pool. A 0.61-m depth of gravel is supported by grating and screen located 0.45 m above the bottom of the outer housing. A retaining screen is located on top of the gravel. The cross-sectional area of the bed is 0.922 m^2 (9.92 ft^2).

Figure 7 is a photograph of the gravel basket taken before loading with gravel. Figure 8 shows the loaded basket being installed in the bottom section of the test article housing.

3.3.4 Packing for Gravel Bed

In three tests (AC7, AC8 and AC9) the packing was crushed Hanford basalt rock. It was washed and screened to nominal 3/8 to 1/2 inch (9.5 to 12.7 mm) diameter. A sieve analysis is given in Table 3. The material density was 2.84 g/cm and the void fraction was 0.46 $\pm$ 0.02. Pre-test weight and volume measurements gave 823 kg of gravel, occupying 0.533 m^3 of volume. The rock was characterized as having no smooth sides.

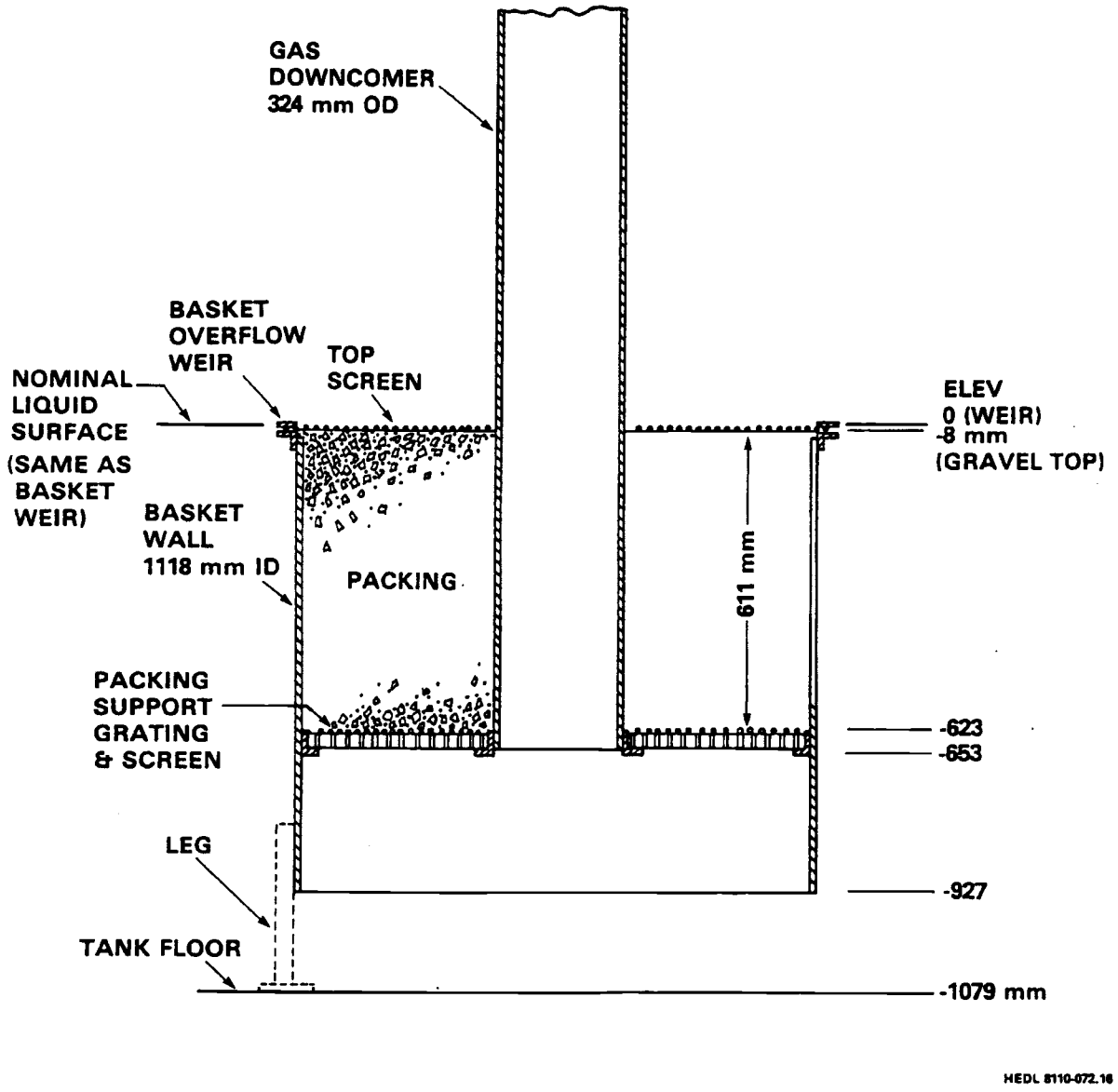

FIGURE 6. Dimensional Sketch of Gravel Basket.

FIGURE 7. View of Gravel Basket Showing Support Screen and Lower Section of Downcomer.. Neg 8005024-8

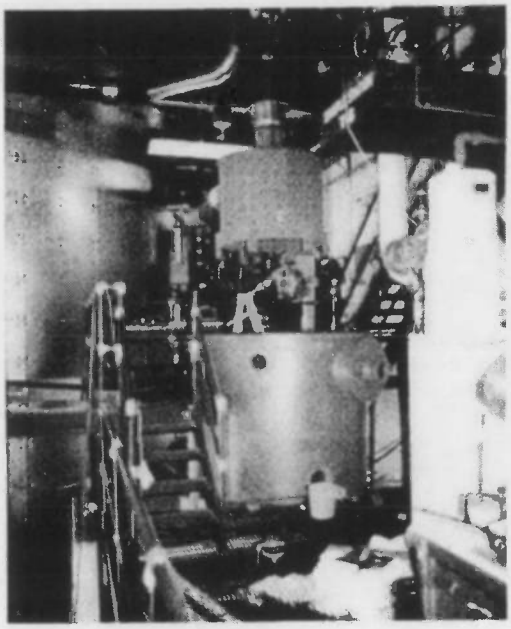

FIGURE 8. Photograph of Loaded Gravel Basket Being Installed in Bottom Housing Section. Neg 8006130-61cn

TABLE 3

SIEVE ANALYSIS OF GRAVEL USED IN TEST ARTICLE[a]

Size of Screen Opening		Retained on Screen	
Inch	mm	kg	wt.%
5/8	15.9	0	0
1/2	12.7	0.213	2.7
7/16	11.1	0.691	8.8
3/8	9.5	4.477	56.5
5/16	7.9	1.864	23.5
(-)5/16[b]	(-)7.9[b]	0.673	8.5
Total		7.918	100.0

(a) Used in tests AC7 through AC9.

(b) Passed through this screen.

In test AC10 the basalt gravel was removed and a commercially available ceramic packing* installed. The packing was 3/8-in. (9.5-mm) diameter balls of approximately spherical shape. The manufacturer states the chemical composition to be approximately 56% SiO_2, 38% Al_2O_3, with small amounts of other materials, and the hardness to measure 6.5 on the Mohs scale.

3.3.5 Gas Downcomer

Gas entered the test article by a vertical downcomer fabricated of 10-in. schedule 20 (260 mm ID) steel pipe. The bottom terminus is open ended and at the same elevation as the bottom of the gravel support grating. Bellows were provided to allow for thermal expansion and ease of assembling the test article.

*Denstone 57™ is manufactured by the Norton Co., Akron, OH.

3.3.6 Demisters

Two high efficiency fiber bed elements* were bolted to the tube sheet. The elements were hollow cylinders fabricated of 20-mm diameter polypropylene fibers compacted to an approximate bulk density of 135 kg/m^3 and held in place between two concentric heavy gauge galvanized steel wire screens. The upper end of each cylinder was closed by a solid plate. Each element was 0.610 m (24 in.) outer diameter and 0.457 m (18 in.) inner diameter and 5 ft high. Total fiber bed surface area of both demisters was 4.38 m^2 (47.1 ft^2) inner and 5.83 m^2 (62.8 ft^2) outer surface.

The design nominal superficial gas velocity recommended by the manufacturer through the bed is 0.0762 m/s (15 actual ft/min). Satisfactory service has been attained over a range of 0 to 0.127 m/s (0 to 25 actual ft/min).[5,6] The design particle removal efficiency is 100% for particles >3 μm and 99 % for particles >3 μm.

The fiber demisters are of the same type tested in earlier tests in the CSTF[5,6] and used in a radioactive waste plant off-gas cleaning system located at Hanford.[10]

3.3.7 Miscellaneous Details

The tube sheet was 3/4-in. (19-mm) thick carbon steel, with four holes: one for the gas downcomer, two for the demisters, and one for the liquid drain. A photograph of the tube sheet is shown in Figure 9.

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*Brink Mist Eliminator Model HE, manufactured by Monsanto-Envirochem Systems, Inc., St. Louis, MO.

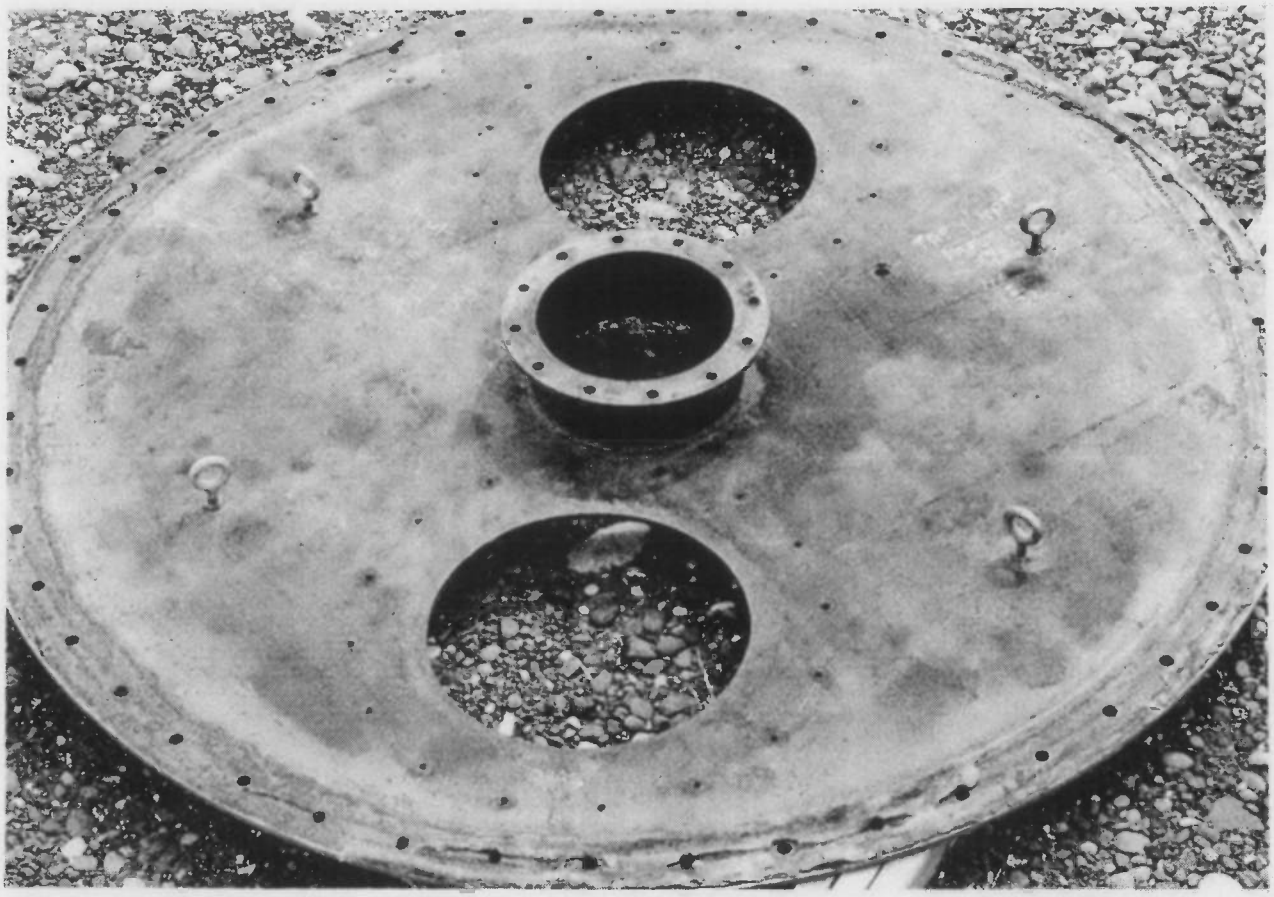

FIGURE 9. SGS Tubesheet. Neg 8005024-9

Two liquid sampling lines were provided from the SGS pool, one from near the surface and one from near the bottom. A drain line from the tube sheet ran to an 18-ℓ receiver tank for the purpose of collecting any liquid entrained through the fiber beds. An aerosol sampling station was provided in the gas plenum above the pool surface. Aerosol samples from the gas stream entering and exiting the test article were provided in the ducts immediately adjacent to the respective nozzles.

Five windows were provided in the outer housing: two windows for observing the pool surface, two for the demister section and one for the pool under-gravel region.

A sight glass was provided for measuring liquid level. A water supply line with meter and manual control valve was used to add process water as needed.

A water spray nozzle was located at the bottom of each demister for the purpose of post-test cleanup. They were not used during the tests.

A steam coil was installed in the SGS pool to provide a means of obtaining a higher liquid temperature than possible with the containment gas. It was used in only one test (AC8) and then only for 3 hours.

3.4 ANCILLARY EQUIPMENT

3.4.1 Exhaust Blower

The purpose of the blower was to induce gas flow through the air cleaning system during containment purging. It was not needed during containment venting, when the pressure within the containment vessel provided the driving force. The blower was of the centrifugal type with a capacity of 0.47 actual m^3/s (1000 actual ft^3/min) at 12 kPa (48 in. H_2O) pressure differential. It is V-belt driven by a 3600 rpm, 20-hp motor. It has a 0.66-m (26-in.) diameter steel impeller.

3.4.2 HEPA Filter

A HEPA filter was provided as a final collection stage to enable a measurement to be made of the overall penetration of aerosol through the test air cleaning system. Two filters were installed in parallel in a side-entering housing located downstream from the blower. The HEPAs were standard units measuring 0.6 m x 0.6 m x 0.3 m, with a rated efficiency of >99.97%.

After each test, the filters were removed and washed to recover the sodium aerosol that had penetrated the air cleaning system and collected on the HEPA filters. Unused filters were also washed to provide information on background sodium content. New filters were used in each test.

3.4.3 Ducts

The inlet duct leading from the containment vessel to the SGS test article was a horizontal, 10-in. diameter, schedule 10 (265 mm ID) type 304 stainless steel pipe, 6.86 m total length. It sloped toward the SGS at 10.4 mm/m. It contained one each 70°, 30°, 90° elbow, a bellows expansion joint and a 10-in. butterfly isolation valve. It was insulated with a 53-mm thick layer of fiberglass with aluminum foil cover.

All duct downstream of the test article was fabricated of 14-gauge (1.9 mm) carbon steel. The dimensions of interconnecting duct are given in Table 4.

3.4.4 Waste Disposal

The gas effluent from the test equipment was sent to a 76-m stack. The work area around the containment vessel and test equipment was ventilated at a rate of 3.8 m^3/s, with HEPA filtered exhaust. Liquid in the test article was drained to a holding tank for analysis before discarding to process sewer.

TABLE 4

DIMENSIONS OF INTERCONNECTING DUCT

Duct Segment	Nom Size (in.)	ID (mm)	Length (m)	No. of Elbows 90°	70°	45°	30°
CV to Test Article Inlet Flange	10	265	6.86	1	1	0	1
Test Article Outlet Flange to VS*	10	265	2.53	0	0	2	0
Venturi to FS*	8	203	4.9	2	0	0	0
FS to Blower	8	203	7.0	4	0	0	0
Blower to HEPA	8	203	1.1	0	0	0	0

*VS and FS are venturi scrubber and fibrous scrubber housing remaining after test AC6.[6]

3.5 EXPERIMENTAL MEASUREMENTS

The methods and instrumentation for the experimental measurements used in this work have been described previously.[11] The measurements are summarized in Table 5.

3.5.1 Aerosol Characterization

The careful characterization of the test aerosol was an important part of the present work. The suspended mass concentration, the particle size distribution, and the chemical composition were measured periodically by direct sampling at various times and locations throughout the tests. In addition, some information on shape and size was obtained by electron and optical microscopy.

The mass concentration of suspended particles was measured as a function of time by periodically passing a measured quantity of gas through small filters

TABLE 5

EXPERIMENTAL MEASUREMENTS AND ACCURACY

Measurement	Locations*	Approx. No. of Samples per test	Method	Accuracy
Suspended aerosol mass concentration	CV atm (4)	120	filter samples	± 14%
	SGS inlet	35	filter samples	± 25%
	SGS outlet	35	filter samples	± 20%
	Demister outlet	35	filter samples	± 20%
Aerosol size distr (aerodynamic)	CV atm (3)	12	Cascade impactor	± 15%
	SGS inlet	5	Cascade impactor	± 15%
	SGS outlet	5	Cascade impactor	± 15%
	Demister outlet	3	Cascade impactor	± 15%
Aerosol particle shape and size	CV atm	1	Electron microscope	***
	SGS outlet	1	Electron microscope	***
Aerosol chemical composition	CV atm	5	Filter, chem analysis	***
	CV floor	1	Spatula, chem analysis	***
	Duct deposit	1	Spatula, chem analysis	***
TOTAL settled aerosol conc	CV (10)	10	Fallout tray	± 10%
TOTAL settled aerosol Na mass	CV	1	Wash CV floor	± 20%
Aerosol Na wall plate-out density	CV (7)	7	Wash patches of wall	± 20%
TOTAL Na sprayed to CV	CV & air cleaning system	**	Wash & steam CV, measure volume, analyze for Na	± 6%
Sodium spray rate	Na supply tank	Continuous	Load cell	± 20%
Pressure across Na spray nozzle	Na supply tank	Continuous	Gauge	± 10%
Static pressure	CV	Continuous	Transducer	± 5%
	Gas flow orifice	Continuous	Gauge	± 5%

*Number in parentheses is number of locations; no number means one location

**Not applicable

TABLE 5 (Cont'd)

Measurement	Locations*	Approx. No. of Samples per test	Method	Accuracy
Pressure differential	Across inlet valve	Continuous	Gauge	± 5%
	Across inlet duct	Continuous	Gauge	± 5%
	Across SGS	Continuous	Gauge	± 5%
	Across demister	Continuous	Gauge and transducer	± 5%
	Across HEPA	Continuous	Gauge	± 5%
	Across Test Article (Total)	Continuous	Transducer and Gauge	± 2%
Gas flow rate	Test article outlet	Continuous	Transducer, Orifice	± 3%
Gas temperature	CV atm (20)	Continuous	Thermocouple	± 5°C
	SGS inlet duct	Continuous	Thermocouple	± 5°C
	SGS outlet plenum	Continuous	Thermocouple	± 1°C
	Demister outlet	Continuous	Thermocouple	± 1°C
	Demister bed	Continuous	Thermocouple	± 1°C
	Gas flow orifice	Continuous	Thermocouple	± 1°C
	Blower out	Continuous	Thermocouple	± 1°C
Liquid temperature	SGS liquid pool (4)	Continuous	Thermocouple	± 1°C
	SGS gravel bed (3)	Continuous	Thermocouple	± 1°C
Steel temperature	CV wall (12)	Continuous	Thermocouple	± 6°C
O_2 conc in gas	CV (2)	Continuous	O_2 analyzer	± 0.3 vol%
H_2 conc in gas	CV (2)	Continuous	H_2 analyzer	± 0.1 vol%
CO_2 conc in gas	CV	Continuous	CO_2 analyzer	± 0.1 vol%
Moisture conc in gas (Dew Point)	CV (2)	Continuous	Dew point meter	± 3°C
	CV (2)	Periodic	Desiccant trap	± 3°C

*Number in parentheses is number of locations; no number means one location.

and subsequently analyzing the material collected on the filters. All samples were taken through wall stations, which enabled the sampler to be inserted directly into the atmosphere being sampled. There were no sampling lines through which aerosol particles must transit. Four of these stations (T1, T2, T3, and T4) were located at various elevations on the containment vessel, one at the inlet to the SGS test article (T5), one at the gas plenum between the SGS pool and the demisters (T6) and one downstream of the test article (T7). Some of the filter papers were analyzed gravimetrically for total mass and all were analyzed for total sodium by either titrimetry or emission spectrometry.

The aerodynamic size distribution was determined by sampling with cascade impactors through the wall stations. Two types of cascade impactors were used: Andersen Mark III 8-stage* and Sierra model 225 6-stage.** Previous tests have shown that these instruments give good agreement when proper calibration data are applied. Glass fiber collection surfaces provided by the manufacturers were used.

Chemical identification of the aerosol was determined at various times during each test by collecting aerosol on a membrane filter paper*** at a wall station and analyzing for various chemical species by x-ray diffraction and wet chemistry. The sample was protected from ambient atmosphere to minimize chemical changes that might occur after the sample was taken.

3.5.2 Temperature Measurement

All temperatures were measured by calibrated Chromel-Alumel® thermocouples with stainless steel sheaths. Readout was in parallel on strip chart recorders, magnetic tape, and paper tape.

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*Andersen Samplers, Inc., Atlanta, GA.
**Sierra Instruments Co., Inc., Carmel Valley, CA.
***Mitex, manufactured by the Millipore Corp., Bedford, MA.
®Chromel-Alumel is a registered trademark of Richmond Machine Products Corp., Staten Island, NY.

3.5.3 Pressure Measurement

Static and differential pressures were measured at the locations listed in Table 5. Diaphragm-type gauges were used in each location. These were supplemented by pressure transducers for the differential pressure across the demisters, the total pressure drop across the SGS/Demister test article, and the containment vessel static pressure.

3.5.4 Gas Composition Measurement

Two parallel sampling systems drew continuous samples from the containment atmosphere, through tubes to a series of on-line gas analyzers that analyzed for O_2, H_2, CO_2, and dew point. Filters were provided at the tube inlet to prevent aerosol from entering the analyzers. One system sampled the upper containment vessel atmosphere (+6.1-m elevation), the other sampled the lower containment vessel atmosphere (-6.7-m elevation). A few grab samples were taken for subsequent analysis by mass spectrometry.

3.5.5 Steam and Carbon Dioxide Injection Rate

In the tests where steam was injected into the containment atmosphere, boiler steam was superheated, metered by an orifice-type flowmeter and the flow rate controlled by a pneumatic valve. Liquid carbon dioxide was vaporized and the rate of injection controlled by a manual valve, with the flow rate measured by a turbine flowmeter.

3.5.6 Air Cleaning System Parameter Measurements

The flow rate of gas through the test air cleaning system was measured by an orifice meter located downstream from the test article. The pressure drop across the orifice plate was measured by an electronic differential pressure transmitter and a square root extractor. The static pressure and temperature of the gas at the orifice were measured so that the flow conditions were known and suitable corrections applied as they varied. Two sharp-edged orifice plates were used with flange taps in the 203-mm ID duct: a plate with 148.31-mm orifice for high flow rate, and a plate with 71.63-mm orifice for low flow rate.

4.0 EXPERIMENTAL PROCEDURE AND TEST CONDITIONS

4.1 EXPERIMENTAL PROCEDURE

The tests were performed in five stages:

- Test preparation
- Containment isolation
- Containment vent
- Containment purge
- Post-test operations

4.1.1 Test Preparation

Test preparation included test article installation and characterization, instrument calibration, sodium spray nozzle installation, sodium system fill and heatup, containment vessel cleanup and sealing, containment vessel leak testing, and containment vessel preheat. Preheating was performed with a portable steam space heater which was removed just prior to isolation of the containment vessel. This was done to reduce the time required to establish containment vent temperature conditions by sodium spray.

4.1.2 Containment Isolation

Sodium flow began by rapidly spilling $\sim$20 kg into a 0.55-m^2 burn pan located at the bottom of the containment vessel. Time zero was defined as the instant the sodium spill valve was opened, and all times in this report are referenced to this time. After one minute, sodium flow was transferred to the spray nozzle(s), and an attempt was made to maintain a constant flow rate for the duration of the test by keeping the pressure drop across the spray nozzle constant.

During the containment isolation period, the containment atmosphere heated up and the aerosol concentration stabilized. Steam or CO_2 flow was started to the containment atmosphere in tests where these gases were called for, and compressed air was added to increase the containment pressure to 70 kPa gauge (10 psig). Aerosol and atmosphere sampling was performed to characterize the atmosphere to be vented. The durations of the isolation periods are listed in Table 6.

4.1.3 Containment Vent

During the containment venting stage, the containment overpressure was reduced to zero by opening the isolation valve and allowing the containment atmosphere to flow from the upper vent nozzle (See Figure 2) through the 10-in. duct to the test air cleaning system. The vent flow rate was controlled at the specified rate by remote manual modulation of the pneumatic 10-in. butterfly isolation valve. See Figure 1.

4.1.4 Containment Purge

After venting was complete, the containment vessel was isolated briefly while liquid and aerosol samples were taken. Then the exhaust blower was started and purging was initiated by opening the 10-in. isolation valve full open and controlling the flow rate with the 8-in. butterfly flow modulating valve located between the air cleaning system and the blower. As soon as the containment pressure was reduced to negative, the fresh-air inlet valve was opened and fresh air was allowed to flow into the containment vessel for the duration of the purge period. The containment vessel pressure fluctuated between 125 Pa and 500 Pa (0.5 in. and 2.0 in. H_2O) negative for the duration of the test. The air entered the containment vessel near the top at approximately 180° azimuth from the outlet to the air cleaning system. The temperature and relative humidity of the purge air are given in Table 6.

TABLE 6

GENERAL TEST CONDITIONS

Condition	Test No. AC7	AC8	AC9	AC10
Initial CV Atmosphere[a]				
Temperature (°C)	59	64	57	63
Pressure (kPa abs)	98.5	98.6	99.7	100.8
Dew point (°C)	17.0	11.0	23.3	5.0
Oxygen concentration (vol%)	20.9	21.0	21.0	21.0
Sodium Spray				
Number of nozzles used	1	1	2	1
Spray drop diam (μm MMD)[b]	400	(f)	(f)	(f)
Spray drop geom std dev (σ_g)[b]	1.5	(f)	(f)	(f)
Avg Na flow rate (g/s)	10.4	10.9	30.2	13.1
Total Na delivered (kg)	1210	1239	887	1198
Spray duration (min)	1930	1890	490[g]	1520
Na temp at nozzle (°C)	540	593	590	650
Steam Injection into CV				
Release point, distance above catch pan (m)	NA[c]	5.5	5.5	5.5
Release point, distance from CV wall (m)	NA	1.83	1.83	1.83
Release orientation	NA	Horiz	Horiz	Horiz
Time start (min)	NA	20	15	20
Time stop (min)	NA	1900	500	1560
Avg rate (g/s)	0	6.0	6.4	7.0
Total injected (kg)	0	677	186	655

Footnotes on p. 35

TABLE 6 (Cont'd)

Condition	Test No. AC7	AC8	AC9	AC10
CO_2 Injection				
Release point, distance above catch pan (m)	NA	NA	1.6	NA
Release point, distance from CV wall (m)	NA	NA	0.45	NA
Release orientation	NA	NA	Horiz	NA
Time start (min)	NA	NA	30	NA
Time stop (min)	NA	NA	782	NA
Avg rate (g/s)	0	0	23.9	0
Total injected (kg)	0	0	108	0
CV Venting				
Time start (min)	180	180	60	180
Time stop (min)	199	196	64	195
CV pressure at start (kPa abs)	166.9	172.1	121.4	176.6
CV pressure at end (kPa abs)	105.5	108.4	108.2	106.9
Avg temp of CV atmos (°C)	114	99.5	157	122
Avg gas flow rate (m^3/s STP)	0.350	0.404	0.317	0.457
Max gas flow rate (m^3/s STP)	0.378	0.434	0.330	0.472
Total gas vented (m^3 STP)	399	388	76	410
CV Purge to Air Cleaning System				
Time start (min)	210	210	70	210
Time stop (min)	2220	2220	1250	2060
Avg temp of CV atmos (°C)	133	145	175	165
Avg temp of air into CV (°C)	23.9	25.5	21.7	24.4
Avg rel humid air into CV (%)	48	49	33	29
Avg gas flow rate (m^3/s STP)[d]	0.297	0.278	0.202	0.228
Total gas purged (m^3 STP)	32,170	29,600	12,890	23,170

Footnotes on p. 35

TABLE 6 (Cont'd)

Condition	AC7	AC8	AC9	AC10
Initial Test Article Conditions				
SGS packing material	gravel	(f)	(f)	Ceramic Spheres
SGS packing size (mm)	9.5-12.7	(f)	(f)	9.5
SGS packing depth (m)	0.610	(f)	(f)	(f)
Gas downcomer submergence (m)[e]	0.650	(f)	(f)	(f)
Packing bed bottom submergence (m)[e]	0.623	(f)	(f)	(f)
Packing bed top submergence (m)[e]	0.013	(f)	(f)	(f)
SGS pool volume (liter)	2470	2500	2420	2330
SGS pool temp (°C)	21.6	26.9	19.4	25.8
SGS pool Na conc (g Na/ℓ)	0.035	0.037	0.14	0.026
Date of Time Zero	6-10-80	9-9-80	11-11-80	2-3-81

(a) CV = Containment Vessel. Initial = at start of Na spray.
(b) Based on nozzle manufacturer's test with water.
(c) NA = not applicable.
(d) Until end of Na spray.
(e) Overflow rim of gravel basket = zero elevation.
(f) Same as Test AC7.
(g) End of Na spray at 490 min, but pool fire continued to t = 780 min.

4.1.5 Post-Test Operations

When the supply of sodium was exhausted, purging with air was continued for several hours while continuing to gather test measurements. When the aerosol concentration in the containment vessel atmosphere had decreased to ~0.1% of its initial value, purging was terminated.

After the containment vessel had cooled to room temperature, it was entered for inspection, photography, and sampling. Following this, the quantity of deposited aerosol was measured by water washing and analyzed for sodium content. The duct leading to the air cleaning system was washed, and a final material balance was made.

4.2 TEST CONDITIONS

General test conditions are summarized in Table 6. The air cleaning system operating conditions were intentionally varied with time so that information could be obtained on the effects of gas flow rate and SGS liquid level. The air cleaning system operating conditions are listed in Tables 7 through 10 for Tests AC7 through AC10, respectively. In these tables, average values are listed for each operating period, during which time conditions were relatively constant. Each operating period differed from the others by a change in at least one of the parameters. An important parameter, C_L, the concentration of sodium dissolved in the SGS pool, is not listed in Tables 7 through 10 because C_L was not a controlled parameter. Tables G1 through G4 (see Appendix G) give the values of C_L as measured at the end of each operating period.

TABLE 7

AIR CLEANING SYSTEM OPERATING CONDITIONS[a] AT VARIOUS OPERATING PERIODS FOR TEST AC7[a]

Operating Period	Time Interval (min)	Gas Flow Rate at SGS Inlet (Std[b] m^3/s)	Gas Flow Rate at SGS Inlet (Actual m^3/s)	Gas Inlet Temp (°C)	SGS Liquid Level[c] (mm)	Aerosol at SGS Inlet: Conc[b] (g Na/m^3 STP)	Aerosol at SGS Inlet: AMMD[d] (μm)	Aerosol at SGS Inlet: σ_g[d]
1	180 - 200[e]	0.350	0.509	105	0	8.38	5.9	2.7
2	210 - 270[f]	0.054	0.081	116	63	12.7	6.0	2.9
3	270 - 330	0.158	0.242	128	35	14.2	6.0	3.1
4	330 - 390	0.299	0.461	132	53	10.5	5.7	3.1
5	390 - 450	0.303	0.469	134	42	10.2	5.2	3.1
6	450 - 510	0.299	0.464	135	75	10.4	5.0	3.1
7	510 - 570	0.308	0.474	133	60	9.5	4.8	3.1
8	570 - 630	0.314	0.491	140	40	10.7	4.7	3.1
9	630 - 690	0.331	0.510	133	-50	9.3	4.7	3.1
10	690 - 750	0.312	0.481	133	130	10.8	4.8	3.1
11	750 - 870	0.314	0.469	119	23	9.2	4.9	3.1
12	870 - 990	0.308	0.481	139	60	11.0	5.0	3.1
13	990 - 1110	0.302	0.470	137	45	9.4	4.8	3.0
14	1110 - 1230	0.310	0.489	142	50	13.3	4.3	2.8
15	1230 - 1350	0.301	0.472	140	25	11.0	4.0	2.7
16	1350 - 1470	0.307	0.480	139	50	11.0	4.0	2.7
17	1470 - 1590	0.308	0.477	135	60	8.5	4.0	2.7
18	1590 - 1710	0.303	0.478	143	60	10.9	4.0	2.7
19	1710 - 1830	0.302	0.476	143	50	11.2	4.0	2.7
20	1830 - 1930[g]	0.302	0.466	134	60	11.3	4.0	2.7
21	1930 - 2050	0.092	0.133	107	70	5.0	4.0	2.7
22	2050 - 2220	0.070	0.097	93	75	0.41	2.5	2.5

(a) Average values for specified time interval

(b) Standard conditions are 0°C and 101.4 kPa.

(c) Distance above top of gravel packing. Add 645 mm to obtain downcomer submergence.

(d) From smoothed curve of cascade impactor data.

(e) Vent from pressurized containment.

(f) Purge from containment, using exhaust fan. Applies to all succeeding operating periods.

(g) End of Na spray at 1930 minutes.

TABLE 8

AIR CLEANING SYSTEM OPERATING CONDITIONS[a] AT VARIOUS OPERATING PERIODS FOR TEST AC8

Operating Period	Time Interval (min)	Gas Flow Rate at SGS Inlet (Std[b] m^3/s)	Gas Flow Rate at SGS Inlet (Actual m^3/s)	Gas Inlet Temp (°C)	SGS Liquid Level[c] (mm)	Aerosol at SGS Inlet: Conc[b] (g Na/m^3 STP)	Aerosol at SGS Inlet: AMMD[d] (μm)	Aerosol at SGS Inlet: σ_g[d]
1	180 - 200[e]	0.403	0.544	79	92	12.0	5.3	3.3
2	210 - 270[f]	0.070	0.098	95	57	11.0	4.2	3.4
3	270 - 330	0.170	0.242	104	62	10.8	4.4	3.4
4	330 - 390	0.328	0.470	107	62	10.7	5.2	3.2
5	390 - 450	0.329	0.476	110	49	13.8	5.2	3.2
6	450 - 510	0.329	0.482	113	36	14.8	4.9	3.2
7	510 - 570	0.332	0.512	132	-27	14.6	4.5	3.3
8	570 - 630	0.324	0.505	138	-15	15.5	4.3	3.4
9	630 - 690	0.301	0.476	142	125	13.7	4.1	3.5
10	690 - 750	0.302	0.481	146	115	15.8	4.0	3.5
11	750 - 810	0.305	0.492	151	49	15.9	3.9	3.6
12	810 - 930	0.303	0.492	155	38	14.2	3.8	3.6
13	930 - 1050	0.303	0.496	159	55	12.4	3.8	3.5
14	1050 - 1170	0.301	0.490	156	48	13.8	3.9	3.4
15	1170 - 1290	0.301	0.486	152	50	12.8	4.1	3.3
16	1290 - 1410	0.302	0.475	142	50	9.9	4.4	3.3
17	1410 - 1530	0.303	0.446	116	50	9.8	4.8	3.1
18	1530 - 1650	0.279	0.390	95	40	10.0	5.1	3.0
19	1650 - 1770	0.221	0.313	101	48	11.2	5.2	3.0
20	1770 - 1890[g]	0.173	0.242	97	55	8.3	5.2	3.1
21	1890 - 2010	0.064	0.092	110	55	2.6	5.1	3.1
22	2010 - 2220	0.069	0.095	94	60	0.2	(h)	(h)

(a) Average values for specified time interval.

(b) Standard conditions are 0°C and 101.4 kPa.

(c) Distance above top of gravel packing. Add 645 mm to obtain downcomer submergence.

(d) From smooth curve of cascade impactor data.

(e) Vent from pressurized containment.

(f) Purge from containment, using exhaust fan. Applies to all succeeding operating periods.

(g) End of Na spray at 1890 min.

(h) Not available.

TABLE 9

AIR CLEANING SYSTEM OPERATING CONDITIONS[a] AT VARIOUS OPERATING PERIODS FOR TEST AC9[a]

Operating Period	Time Interval (min)	Gas Flow Rate at SGS Inlet (Std[b] m^3/s)	Gas Flow Rate at SGS Inlet (Actual m^3/s)	Gas Inlet Temp (°C)	SGS Liquid Level[c] (mm)	Aerosol at SGS Inlet: Conc[b] (g Na/m^3 STP)	Aerosol at SGS Inlet: AMMD[d] (μm)	Aerosol at SGS Inlet: σ_g[d]
1	60 - 64[e]	0.307	0.401	66	50	14.5	5.4	3.4
2	70 - 120[f]	0.073	0.119	150	50	16.0	5.3	3.4
3	120 - 160	0.146	0.258	190	95	14.4	5.4	3.4
4	160 - 220	0.259	0.465	200	95	15.7	5.5	3.3
5	220 - 280	0.254	0.464	209	90	16.3	5.8	3.0
6	280 - 340	0.251	0.467	219	65	17.5	6.1	2.8
7	340 - 400	0.256	0.474	217	35	13.3	5.7	2.8
8	400 - 460	0.274	0.528	238	55	19.3	5.2	3.1
9	460 - 520	0.334	0.622	220	40	8.85	4.6	3.3
10	520 - 580	0.147	0.259	193	50	4.53	4.0	3.4
11	580 - 640	0.146	0.251	182	35	2.82	3.6	3.5
12	640 - 700	0.146	0.245	171	20	2.57	3.4	3.5
13	700 - 780[g]	0.144	0.238	162	0	4.78	3.8	3.3
14	780 - 840	0.063	0.100	145	0	1.11	3.9	3.0
15	840 - 900	0.063	0.099	136	60	0.313	3.6	2.8
16	900 - 960	0.160	0.247	132	60	0.0643	3.3	2.5
17	960 - 1020	0.163	0.247	124	60	0.0411	(h)	(h)
18	1020 - 1140	0.314	0.460	110	50	0.0152	(h)	(h)
19	1140 - 1250	0.066	0.094	101	45	0.0019	(h)	(h)

(a) Average values for specified time interval.

(b) Standard conditions are 0°C and 101.4 kPa.

(c) Distance above top of gravel packing. Add 645 mm to obtain downcomer submergence.

(d) From smoothed curve of cascade impactor data.

(e) Vent from pressurized containment.

(f) Purge from containment, using exhaust fan. Applies to all succeeding operating periods.

(g) End of Na spray at 490 min, but pool fire continued until 780 min.

(h) Not available.

TABLE 10

AIR CLEANING SYSTEM OPERATING CONDITIONS AT VARIOUS OPERATING PERIODS FOR TEST AC10[a]

Operating Period	Time Interval (min)	Gas Flow Rate at SGS Inlet (Std[b] m^3/s)	Gas Flow Rate at SGS Inlet (Actual m^3/s)	Gas Inlet Temp (°C)	SGS Liquid Level[c] (mm)	Aerosol at SGS Inlet: Conc[b] (g Na/m^3 STP)	Aerosol at SGS Inlet: AMMD[d] (μm)	Aerosol at SGS Inlet: σ_g[d]
1	180 - 195[e]	0.457	0.686	117	0	10.3	5.3	2.6
2	210 - 270[f]	0.075	0.116	130	50	17.8	5.0	3.2
3	270 - 330	0.147	0.242	155	25	17.9	4.8	3.4
4	330 - 390	0.293	0.481	158	10	16.1	7.5	3.0
5	390 - 450	0.290	0.482	165	5	17.7	7.3	3.0
6	450 - 510	0.289	0.484	168	35	17.8	6.9	3.1
7	510 - 570	0.282	0.476	172	-40	17.6	6.8	3.2
8	570 - 630	0.287	0.487	174	-50	17.9	7.0	3.3
9	630 - 690	0.269	0.460	178	135	16.0	7.4	3.3
10	690 - 750	0.281	0.484	180	115	15.9	7.8	3.1
11	750 - 870	0.280	0.479	179	30	15.7	8.2	2.8
12	870 - 990	0.276	0.475	180	50	15.4	8.0	2.7
13	990 - 1110	0.280	0.477	176	40	14.6	6.1	2.9
14	1110 - 1230	0.275	0.466	174	25	14.8	6.2	2.9
15	1230 - 1350	0.277	0.466	171	40	13.5	6.0	3.1
16	1350 - 1410	0.041	0.069	173	65	14.4	5.0	3.3
17	1410 - 1470	0.139	0.238	178	80	14.5	4.4	3.3
18	1470 - 1520[g]	0.273	0.439	151	75	7.00	4.1	3.2
19	1520 - 1580	0.078	0.119	126	50	0.690	3.6	2.9
20	1580 - 1640	0.064	0.094	115	60	0.218	3.2	2.7
21	1640 - 1700	0.070	0.101	109	40	0.115	2.7	2.5
22	1700 - 1760	0.168	0.239	103	25	0.043	2.2	2.3
23	1760 - 1820	0.169	0.238	98	15	0.0173	1.8	2.1
24	1820 - 1880	0.342	0.472	92	30	0.0109	1.5	2.0
25	1880 - 1940	0.362	0.492	86	25	0.0017	1.2	1.9
26	1940 - 2000	0.097	0.131	86	-40	0.0010	(h)	(h)
27	2000 - 2060	0.080	0.109	86	-15	0.0007	(h)	(h)

(a) Average values for specified time in intervals.

(b) Standard conditions are 0°C and 101.4 kPa.

(c) Distance above top of packing. Add 645 mm to obtain downcomer submergence.

(d) From smoothed curve of cascade impactor data.

(e) Vent from pressurized containment.

(f) Purge from containment, using exhaust fan. Applies to all succeeding operating periods.

(g) End of Na spray at 1520 min.

(h) Not available.

5.0 EXPERIMENTAL RESULTS

5.1 SODIUM SPRAY OPERATIONS

5.1.1 General Observations

Aerosols of various sodium compounds were generated in the containment vessel by spraying molten sodium into the air atmosphere, where it reacted with oxygen, water vapor and carbon-dioxide to form a mixture of Na_2O_2, NaOH and Na_2CO_3 and their hydrates. Visual and video observations made through windows in the containment vessel wall showed that the sodium self-ignited as soon as it contacted the air atmosphere. A brillantly incandescent spray pattern was visible for approximately one minute before vision was obscured by the dense aerosol cloud. The visible range was reduced to 100 mm to 250 mm for the duration of the spray period.

Difficulties in maintaining a uniform spray rate which were encountered in an earlier test series[5] were largely overcome in the present tests by increasing the sodium spray flow rate. Nodule formation on the spray nozzle did not occur to the extent that it had in the earlier tests, probably because of the higher temperature at the spray nozzle. A jet of high pressure steam was directed onto the nozzle every few hours while sodium flow continued, but this was not thought to be necessary. Figure 10 is a photograph looking down at the bottom head of the containment vessel during post-test AC10 personnel entry. The operator is examining one of the two sodium spray nozzles.

Figures 11 through 14 were also taken during post-test AC10 containment inspection. In Figure 11, the operator is standing on a deposit of NaOH aerosol at the -1.5 m elevation. The deposited aerosol was ~110 mm deep, had a density of ~0.18 g/cm^3, and had sufficient compressive strenth to support the weight of the operator after compacting to ~75% of its original thickness. The grating seen in Figure 11 had been removed from a manway and was leaning against the outer wall of the containment vessel.

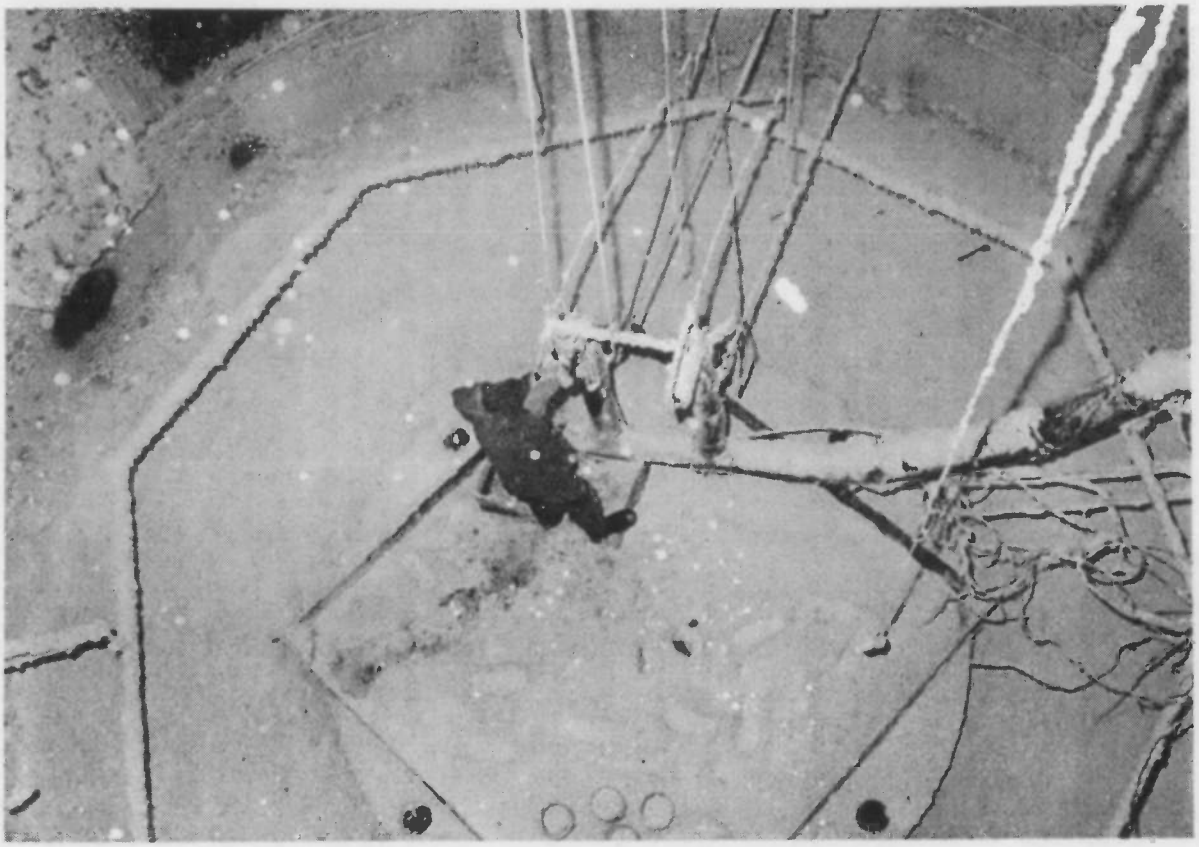

FIGURE 10. Post-test View of Bottom Head of Containment Vessel in Test AC10. Neg 8101097-12cn

FIGURE 11. Close-up View of Settled Aerosol After Test AC10.
Neg 8101097-6cn

The aerosol deposit on the vertical walls was 1 mm to 6 mm thick, with a three-dimensional mottled pattern.

The mottled appearance of the vertical wall aerosol deposit is also shown in Figure 12. Individual spots ranged in size up to ~30 mm diameter. The deposit on a horizontal pipe is seen to be of much less depth than that on the walkway at the same elevation shown in Figure 11, but was still significant (~50 mm).

A phenomenon observed in many of the tests is shown in Figure 13, where a dense row of stalactite-appearing substance is seen hanging from a railing with lengths up to 60 mm. In other tests, the stalactites were more like fragile whiskers.

Another phenomenon is shown in Figure 14, where the wall deposit was very thin in 0.1-m^2 to 0.3-m^2 spots corresponding to areas of the containment vessel where the thermal insulation had been removed. These spots appear black in the photograph, but are actually the dark green paint with which all interior surfaces of the vessel are coated. This is an interesting observation, since a cold surface should collect more aerosol by thermophoresis than hot surfaces--the opposite of the observed effect. One explanation is that the temperature of the vessel wall at these uninsulated areas was sufficiently low to induce condensation of water vapor onto the hygroscopic aerosol particles as they deposited by diffusion and thermophoresis. If enough water were absorbed, the aerosol may become nearly invisible, though present as a thin, dense film. Unfortunately, neither the wall temperature or the deposited density of these spots were measured. This effect may be studied in future tests.

5.1.2 Sodium Mass Balance

Following each test, the containment vessel surfaces were washed to recover the sodium remaining in the containment vessel. Also, the duct leading to

FIGURE 12. View of Aerosol Deposit on Containment Wall After Test AC10. Neg 8101097-24cn

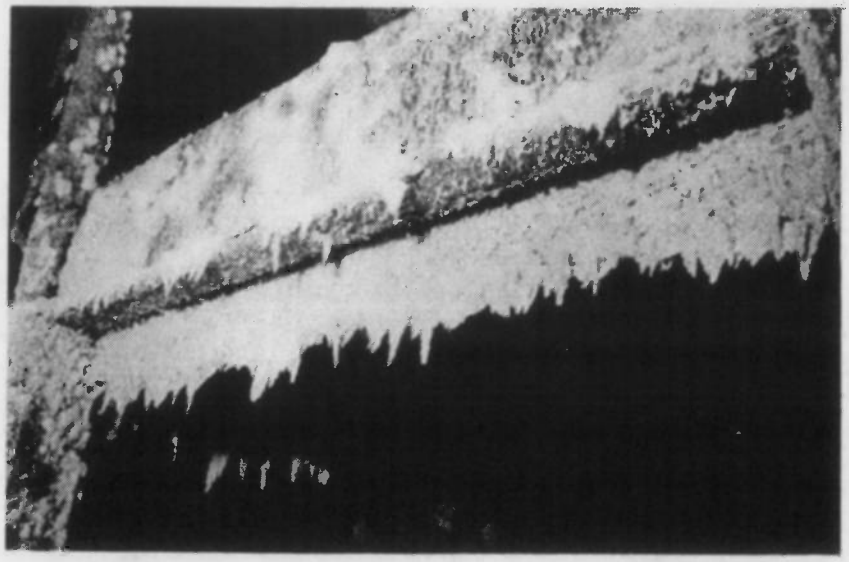

FIGURE 13. Stalactite-Appearing Deposit - Test AC10. Neg 8181097-29cn

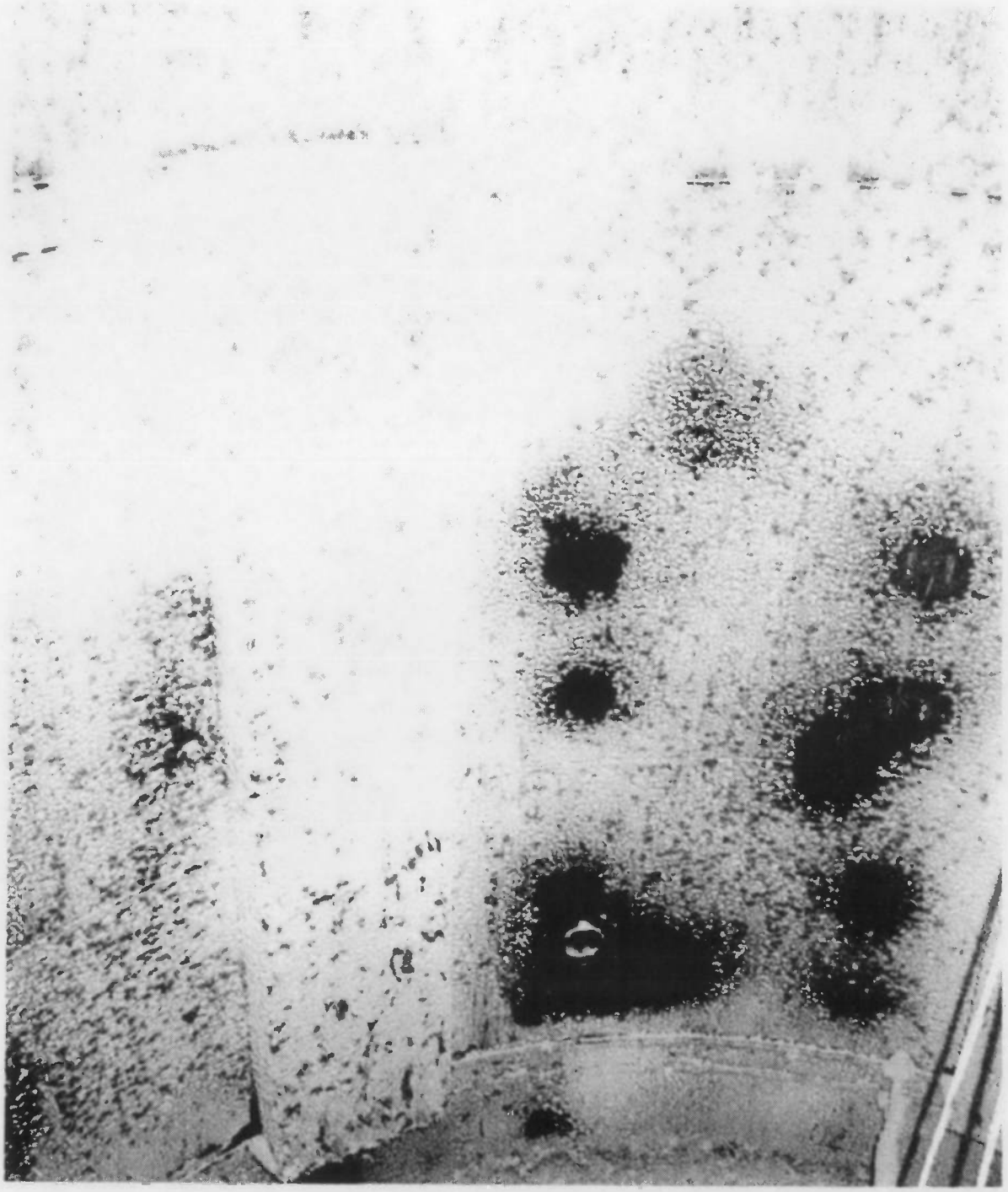

FIGURE 14. View Showing Altered Deposit on Localized Heat Sink Areas - Test AC10. Neg 8101097-9cn

the air cleaning systems was washed and the sodium inventory in the air cleaning system was determined, as described in Section 5.5.2. The total sodium mass accounted for in this manner is compared in Table 11 with the mass determined to have been delivered to the containment by direct weighing of the metallic sodium.

Table 11 shows that good agreement was obtained between recovered and charged mass, with an average recovery 2.2% greater than charged. This is within the experimental error of the measurements.

Table 11 also shows that an average of 20% of the total sodium was vented and purged from the containment vessel, while 80% remained in the containment vessel. The relatively high retention in the containment vessel in test AC9 was due to a sodium leak which resulted in a small pool fire which produced very little aerosol.

5.1.3 Aerosol Generation Rate

An estimate of the quantity of sodium which was converted to an aerosol was made by assuming that any non-aerosolized sodium fell into the 9.3-m^2 catch pan located beneath the spray nozzles. During the post-test cleanup operations, the material in the catch pan was analyzed separately. Sodium found outside the catch pan (including that vented or purged from the containment) was assumed to have been transported as an aerosol. In test AC8, the catch pan deposit was inadvertently washed into the containment vessel washing and so this information was lost for that test. Aerosol generation data for the other tests is summarized in Table 12.

Table 12 shows that the average sodium delivery rate was 12.3 g Na/s, the average aerosol generation rate was 9.15 g Na/s, and the average fraction of sprayed sodium converted to aerosol was 0.741. The lower fraction aerosolized in test AC9 is believed due to the fact that a leak caused some of the sodium to burn as a pool fire, rather than as a spray.

TABLE 11

SODIUM MASS BALANCE

Sodium Mass Description	AC7	AC8	AC9	AC10	All 4 Tests
Delivered to Containment[a] (kg Na)	1210	1239	887	1198	4534
Accounted For Post-Test (kg Na)					
Containment Vessel Washes	1001	822	860	1026	3709
Duct to Air Cleaning System	3.89	47.5	(b)	37.0	88.4[d]
Air Cleaning System	245.04	254.8	80.8[c]	253.3	834.1
Total Accounted For	1249.93	1124.3	940.8	1316	4631.5
Ratio, Accounted For/Delivered	1.03	0.907	1.06	1.10	1.022
Aerosol Mass (kg Na)	854.6	(e)	601.5	1109	2565(f)
Vented & Purged from CV (kg Na)	248.9	302.3	80.8	290.3	922.3
Fraction of Total Vented & Purged	0.199	0.269	0.086	0.221	0.199
Fraction of Aerosol Vented & Purged	0.291	(e)	0.134	0.262	0.242[f]

(a) Average of measurements by weighing drums charged and load cells on heatup tank.

(b) Not measured. Estimated <2 kg Na.

(c) Duct and air cleaning system combined.

(d) Excluding test AC9.

(e) Not measured.

(f) Excluding test AC8.

TABLE 12

SODIUM AEROSOL GENERATION RESULTS

Sodium Mass Description	AC7	AC8	AC9	AC10	All 4 Tests
Total Na Delivered to Containment (kg Na)	1210	1239	887	1198	4534
Duration of Na Spray (min)	1930	1890	780[b]	1520	6120
Avg Na Delivery Rate (g Na/s)	10.4	10.9	19.0[b]	13.1	12.3
Total Aerosol Generated (kg Na)	854.6	794[a]	601.5[b]	1109	3359
Avg Aerosol Generation Rate (g Na/s)	7.38	7.0[a]	12.8[b]	12.2	9.15
Fraction of Delivered Na Aerosolized	0.706	0.64[a]	0.678[b]	0.925	0.741

(a) Estimated.

(b) Combined spray and pool fire.

5.2 CONTAINMENT ATMOSPHERE

5.2.1 Aerosol Concentration

The suspended mass concentration was measured simultaneously at three locations in the containment atmosphere, as described in Section 3.4.1. Three different concentrations were calculated and listed in Tables 13 through 16 for tests AC7 through AC10, respectively, for each sampling time. First, the mean concentration for the three sampling locations was calculated from the test measurements of sodium mass collected on the sample filter paper and the volume of sampled gas measured in standard m^{3*}. This method gives the concentration expressed as g Na/std m^3, and these are listed in column 2 of Tables 13 through 16.

The low values for the standard deviation (1σ, expressed as percent of the mean) listed in column 3 show that the concentration was fairly uniform throughout the vessel.

The temperature and pressure in the containment atmosphere varied throughout the tests. The ratio of standard m^3 to actual m^3 in the containment atmosphere was calculated from temperature and pressure measurements, using the perfect gas law. The factors are listed in column 4 of Tables 13 through 16, and from these factors, the concentration expressed as g Na per actual m^3 was calculated and listed in column 5. The factors are presented for additional times in Appendix D.

The concentrations listed in column 5 correctly express the mass of sodium suspended per unit volume of containment atmosphere. However, the aerosol particles consist of compounds with O, H and C as well as Na. The ratio of sodium mass to total mass was determined by weighing each filter paper

*In this report, standard gas conditions are defined as 0^oC and 101.4 kPa (32^oF and 14.7 psia).

TABLE 13

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC7

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
7	9.76	7.8	0.798	7.79	0.35	22.3
12	16.4	7.6	0.795	13.0	0.43	30.3
16	20.5	2.7	0.792	16.2	0.46	35.3
21	15.2	7.0	0.792	12.0	0.48	25.1
30	14.2	6.1	0.879	12.5	0.49	25.5
40	12.1	9.1	0.955	11.6	0.50	23.1
50	11.6	9.5	1.031	12.0	0.50	23.9
60	10.1	9.3	1.095	11.1	0.505	21.9
80	8.98	10.9	1.149	10.3	0.51	20.2
100	8.32	9.4	1.167	9.71	0.51	19.0
155	7.71	2.3	1.188	9.16	0.515	17.8
170	6.91	8.5	1.186	8.20	0.515	15.9
220	11.9	4.8	0.675	8.03	0.505	15.9
280	11.0	5.8	0.681	7.49	0.495	15.1
345	10.6	3.3	0.675	7.16	0.49	14.6
400	10.1	1.8	0.672	6.79	0.49	13.9
525	10.2	4.2	0.666	6.79	0.495	13.7
600	10.6	11.7	0.662	7.02	0.495	14.2
648	8.85	(d)	0.668	5.91	0.495	11.9
760	8.38	10.7	0.673	5.64	0.50	11.3
813	8.69	7.4	0.672	5.84	0.50	11.7
935	9.19	5.5	0.667	6.13	0.50	12.3
1000	9.55	(d)	0.668	6.38	0.50	12.8
1055	9.63	1.7	0.666	6.41	0.505	12.7
1126	9.15	(d)	0.669	6.12	0.505	12.1

TABLE 13 (Cont'd)

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC7

Sample Time (min)	g Na[a] per Std. m^3	Std. Deviation (%)	Factor[b] Std. m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
1175	11.8	20.0	0.660	7.79	0.505	15.4
1244	11.8	(d)	0.660	7.79	0.51	15.3
1360	10.2	7.5	0.658	6.71	0.51	13.2
1480	8.36	29.1	0.666	5.57	0.51	10.9
1610	10.3	0.56	0.658	6.78	0.515	13.2
1720	9.59	11.4	0.656	6.29	0.515	12.2
1840	10.8	14.1	0.651	7.03	0.52	13.5
1950	7.33	3.9	0.691	5.07	0.52	9.74
2000	4.69	1.3	0.684	3.21	0.52	6.17
2051	0.91	7.8	0.700	0.638	0.52	1.23
2110	0.243	13.4	0.711	0.173	0.525	0.329
2190	0.092	12.0	0.726	0.067	0.525	0.127
2280	0.0269	12.2	0.740	0.0199	0.525	0.038
2560	0.0016	8.1	0.770	0.0012	0.53	0.0023
210-1930	10.0 mean			6.68 mean		13.3 mean

(a) Mean value of three measurements at +6.1 m, +1.8m, and -5.8m.

(b) Factor = 2.70 P/T; P = kPa, T = avg containment temp, °K.

(c) Smoothed data from plot of mass fraction determined by weighing filter paper and analyzing for Na.

(d) Only one sample taken.

TABLE 14

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC8

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
2.2	4.13	(d)	0.789	3.26	0.405	8.05
7.3	8.02	4.1	0.786	6.30	0.430	14.7
12	12.6	8.6	0.782	9.85	0.431	22.9
16	15.4	2.8	0.780	12.0	0.435	27.6
21	17.2	7.0	0.776	13.3	0.440	30.3
30	10.7	20.8	0.815	8.72	0.460	19.0
40	10.8	22.2	0.903	9.75	0.44	22.2
50	9.56	20.9	0.988	9.44	0.445	21.2
60	9.49	14.0	1.075	10.2	0.445	22.9
80	11.0	15.6	1.254	13.8	0.447	30.9
100	12.4	9.8	1.253	15.5	0.445	34.9
155	10.4	7.5	1.244	12.9	0.455	28.4
170	10.2	16.5	1.243	12.7	0.455	27.9
225	12.7	2.2	0.704	8.94	0.450	19.9
285	12.3	6.9	0.703	8.65	0.440	19.6
345	12.6	22.4	0.701	8.83	0.420	21.0
400	9.18	12.6	0.702	6.44	0.412	15.6
520	14.6	(d)	0.660	9.64	0.413	23.3
546	15.1	(d)	0.656	9.91	0.420	23.6
700	15.9	11.5	0.638	10.1	0.455	22.3
825	15.7	15.3	0.626	9.83	0.495	19.8
940	16.1	10.6	0.618	9.95	0.510	19.5
1060	14.8	10.6	0.618	9.15	0.515	17.8
1180	15.6	15.0	0.616	9.61	0.512	18.8
1300	13.8	4.1	0.617	8.51	0.502	16.8

TABLE 14 (Cont'd)

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC8

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
1360	13.5	6.4	0.617	8.33	0.502	16.6
1480	13.7	11.5	0.618	8.47	0.495	17.1
1600	12.8	7.7	0.620	7.94	0.480	16.5
1660	13.2	2.7	0.617	8.14	0.470	17.3
1720	12.9	(d)	0.618	7.97	0.466	17.1
1780	9.53	50.0	0.616	5.87	0.460	12.8
1840	13.4	(d)	0.614	8.23	0.450	18.3
1875	9.49	(d)	0.630	5.98	0.447	13.4
1910	3.95	11.2	0.641	2.53	0.445	5.67
1955	1.27	4.3	0.652	0.828	0.445	1.86
2001	0.457	2.3	0.662	0.303	0.430	0.705
2065	0.194	12.4	0.676	0.131	0.425	0.308
2127	0.077	(d)	0.688	0.0530	0.415	0.128
2190	0.0409	1.9	0.699	0.0286	0.405	0.0706
2247	0.0222	3.8	0.709	0.0157	0.400	0.0392
2305	0.0171	19.4	0.716	0.0122	0.395	0.0309
2520	0.0026	65.0	0.741	0.0019	0.350	0.0054
210-1890	13.3 mean			8.41 mean		18.1 mean

(a) Mean value of three measurements at +6.1 m, +1.8 m, and -5.8 m.

(b) Factor = 2.70 P/T; P = kPa, T = avg containment temp, °K.

(c) Smoothed data from plot of mass fraction determined by weighing filter paper and analyzing for Na.

(d) Only one sample taken.

TABLE 15

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC9

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
2.2	2.47	(d)	0.810	2.00	0.10	20.0
7.2	19.3	1.1	0.787	15.2	0.35	43.4
11	35.3	(d)	0.783	27.6	0.50	55.3
16	29.0	23.9	0.777	22.5	0.505	44.6
21	29.2	(d)	0.774	22.6	0.505	44.7
24	20.9	7.8	0.772	16.1	0.505	28.6
35	17.8	10.3	0.774	13.8	0.50	27.6
40	17.1	7.0	0.778	13.3	0.49	27.1
52	16.1	17.1	0.774	12.5	0.47	26.5
95	14.6	18.1	0.619	9.03	0.443	20.4
185	14.3	20.2	0.583	8.33	0.43	19.4
239	14.9	35.1	0.570	8.49	0.43	19.7
300	16.0	24.3	0.551	8.81	0.43	20.5
308	17.2	6.5	0.549	9.44	0.43	22.0
360	11.7	18.8	0.550	6.43	0.43	15.0
420	16.3	19.7	0.533	8.68	0.43	20.2
488	12.2	24.5	0.535	6.52	0.43	15.2
520	2.49	11.2	0.565	1.40	0.43	3.26
565	3.91	11.1	0.571	2.23	0.43	5.19
620	3.00	37.0	0.584	1.75	0.43	4.07
670	1.16	18.8	0.585	0.678	0.43	1.58
738	5.11	13.6	0.607	3.10	0.43	7.21
795	1.26	13.8	0.624	0.79	0.43	1.84
845	0.464	3.6	0.635	0.294	0.43	0.684
906	0.194	7.8	0.649	0.125	0.43	0.291

TABLE 15 (Cont'd)

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC9

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
951	0.0649	13.4	0.660	0.042	0.43	0.0977
1034	0.0197	49.5	0.681	0.0134	0.43	0.0312
1133	0.00444	16.4	0.707	0.00313	0.43	0.00728
1250	0.00345	36.3	0.721	0.00249	0.43	0.00579
60-780	10.2 mean			5.76 mean		13.4 mean

(a) Mean value of three measurements at +6.1 m, +1.8 m, and -5.8 m.

(b) Factor = 2.70 P/T; P = kPa, T = avg containment temp, °K.

(c) Smoothed data from plot of mass fraction determined by weighing filter paper and analyzing for Na.

(d) Only one sample taken.

TABLE 16

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC10

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
2.2	1.14	(d)	0.803	0.915	0.38	2.41
7.3	9.80	18.8	0.802	7.86	0.43	18.3
12.2	16.6	11.9	0.800	13.3	0.47	28.3
16	19.4	(d)	0.797	15.5	0.51	30.3
20	16.8	(d)	0.797	13.4	0.56	23.9
25	17.2	9.45	0.798	13.7	0.56	24.5
30	17.1	14.9	0.842	14.4	0.555	25.9
35	16.4	9.17	0.884	14.5	0.55	26.4
40	17.4	24.7	0.922	16.0	0.54	29.7
45	15.1	(d)	0.966	14.6	0.537	27.7
50	14.7	15.4	1.100	16.2	0.53	30.5
60	12.1	21.1	1.104	13.4	0.526	25.4
80	11.6	24.6	1.215	14.1	0.514	27.4
100	10.6	20.5	1.209	12.8	0.507	25.3
155	11.7	15.2	1.196	14.0	0.504	27.8
172	9.82	4.1	1.191	11.7	0.507	23.1
225	17.8	14.8	0.655	11.7	0.519	22.4
285	18.6	12.3	0.642	11.9	0.528	22.6
348	17.2	22.4	0.639	11.0	0.53	20.7
400	15.8	15.7	0.632	9.99	0.536	18.6
520	11.7	23.5	0.621	7.27	0.53	13.7
580	15.4	8.98	0.617	9.50	0.524	18.1
640	16.8	5.9	0.611	10.3	0.52	19.7
700	15.2	0.5	0.612	9.30	0.515	18.1
762	16.0	13.4	0.608	9.73	0.51	19.1

TABLE 16 (Cont'd)

AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE FOR TEST AC10

Sample Time (min)	g Na[a] per Std m^3	Std Deviation (%)	Factor[b] Std m^3 per Actual m^3	g Na per Actual m^3	Na[c] Mass Fraction	g Total per Actual m^3
880	15.8	10.9	0.606	9.57	0.503	19.0
940	15.5	(d)	0.609	9.44	0.499	18.9
980	13.2	(d)	0.610	8.05	0.496	16.2
1007	15.1	16.4	0.611	9.23	0.494	18.7
1062	14.1	18.5	0.612	8.63	0.49	17.6
1120	12.5	9.1	0.614	7.68	0.486	15.8
1184	14.3	17.3	0.611	8.74	0.482	18.1
1240	12.6	5.1	0.615	7.75	0.47	16.2
1300	13.7	16.1	0.613	8.40	0.474	17.7
1360	15.7	14.3	0.605	9.50	0.47	20.2
1425	16.5	17.2	0.603	9.95	0.462	21.5
1490	11.1	9.4	0.621	6.89	0.454	15.2
1540	2.25	23.6	0.654	1.47	0.446	3.30
1560	1.25	7.6	0.661	0.826	0.44	1.88
1590	0.505	20.8	0.671	0.339	0.435	0.779
1632	0.218	20.0	0.681	0.148	0.427	0.348
1700	0.0798	21.0	0.694	0.0554	0.412	0.134
1800	0.0138	26.2	0.718	0.0991	0.388	0.0255
1844	0.00439	22.3	0.732	0.0032	0.377	0.0085
1950	0.00130	11.4	0.751	0.00098	0.356	0.0027
2130	0.00073	42.0	0.771	0.00056	0.343	0.0016
210-1520	15.0 mean			9.26 mean		18.5 mean

(a) Mean value of three measurements at +6.1 m, +1.8 m, and -5.8 m.

(b) Factor = 2.70 P/T; P = kPa, T = avg containment temp, °K.

(c) Smoothed data from plot of mass fraction determined by weighing filter paper and analyzing for Na.

(d) Only one sample taken.

before and after sampling to obtain total mass of aerosol on the paper, then analyzing for Na. The sodium mass fractions are listed in column 6 of Tables 13 through 16, and, from these, the concentration expressed as grams total aerosol per actual m^3 was calculated and listed in column 7.

Each manner of expressing the concentration has merit for certain applications. For instance, those listed in column 2 as g Na per standard m^3 are useful in calculating decontamination factors in the air cleaning system because it relates the sodium mass to a constant mass of carrier gas. However, for determining the aerosol behavior in the containment atmosphere, the true aerosol concentration expressed as gram total aerosol per actual m^3 is important. The latter concentrations are plotted against time in Figures 15 through 18 for tests AC7 through AC10, respectively.

Figures 15 through 18 show that, in each test, the suspended total aerosol concentration reached a maximum value at approximately 15 minutes after initiating sodium flow, after which it decreased slightly. Addition of compressed air, steam and carbon dioxide at various times following the time of maximum concentration caused slight variations in the concentration from test to test. The figures show that, with the exception of test AC9, the concentrations were reasonably constant throughout the containment venting and purging periods. In test AC9, a small leak in the sodium delivery pipe caused a portion of the sodium to burn as a pool fire, thereby reducing the spray rate and the aerosol source term.

5.2.2 Aerosol Chemical Composition

Samples of aerosol were collected on nonreacting membrane* filters, protected from exposure to ambient atmosphere, and analyzed in an inert atmosphere glove box by x-ray diffraction and wet chemistry. The average compositions for each of the tests are listed in Table 17.

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*Mitex™ membrane, manufactured by the Gelman Co.

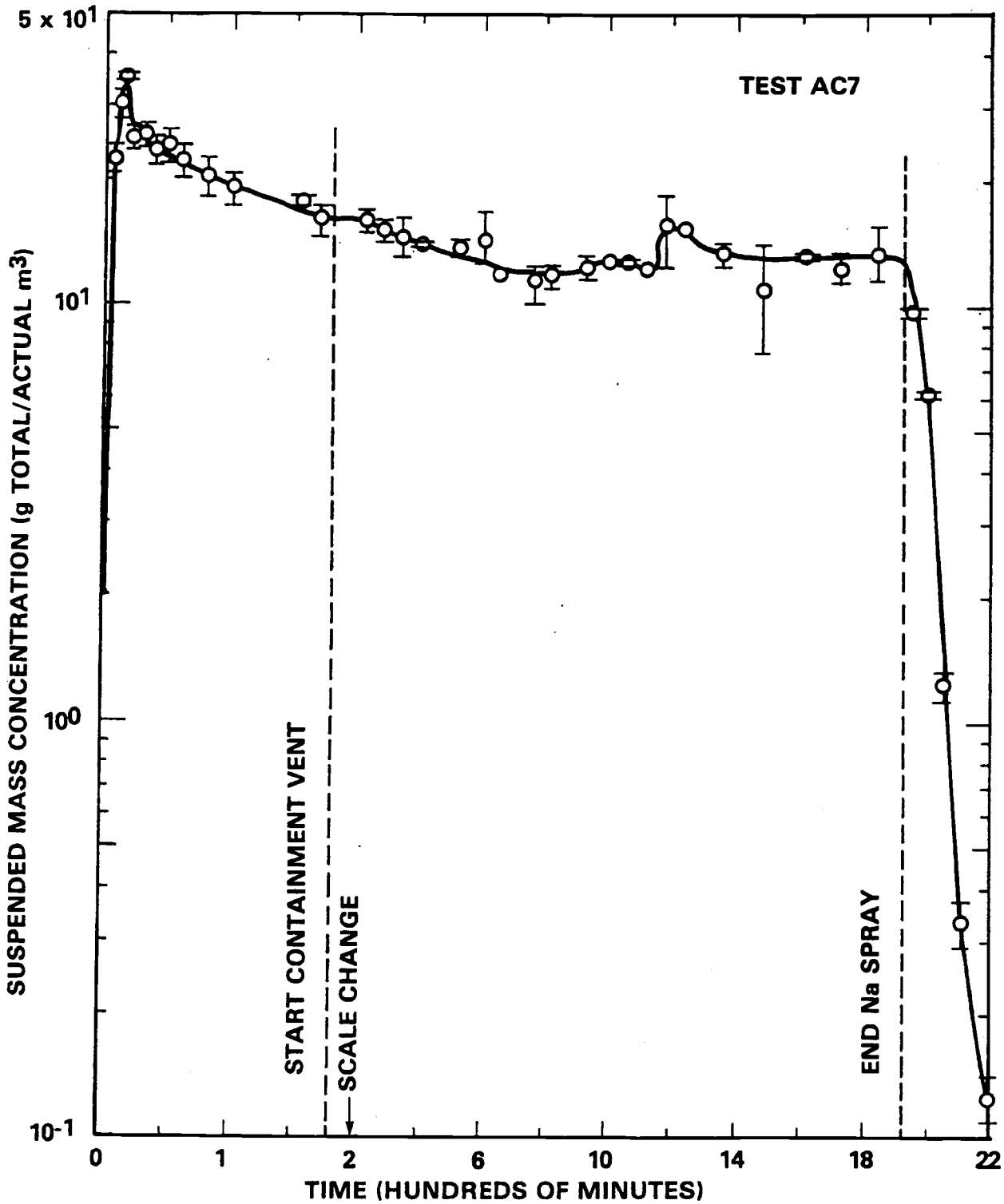

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FIGURE 15. Suspended Aerosol Concentration in the Containment Atmosphere During Test AC7.

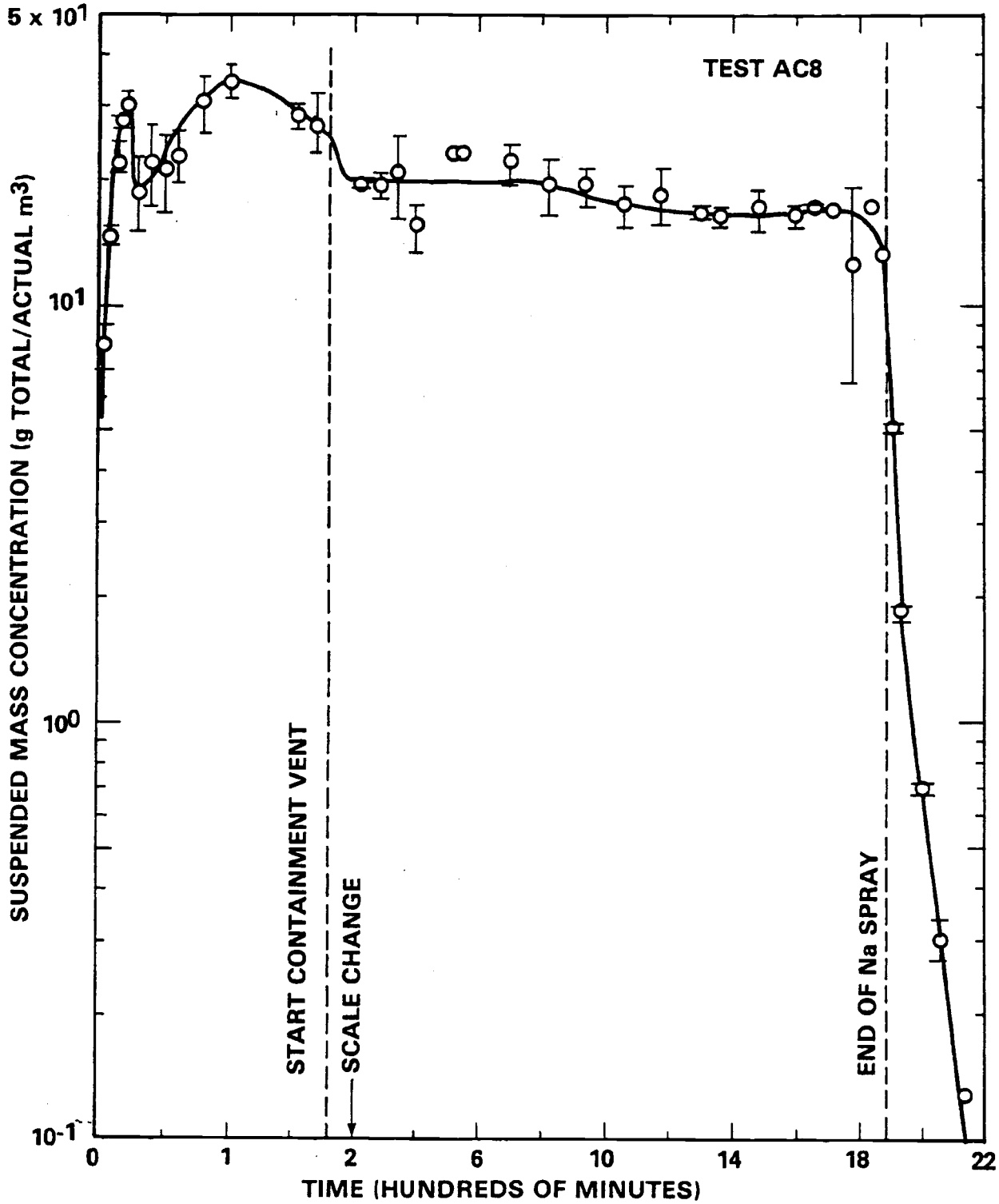

FIGURE 16. Suspended Aerosol Concentration in the Containment Atmosphere During Test AC8.

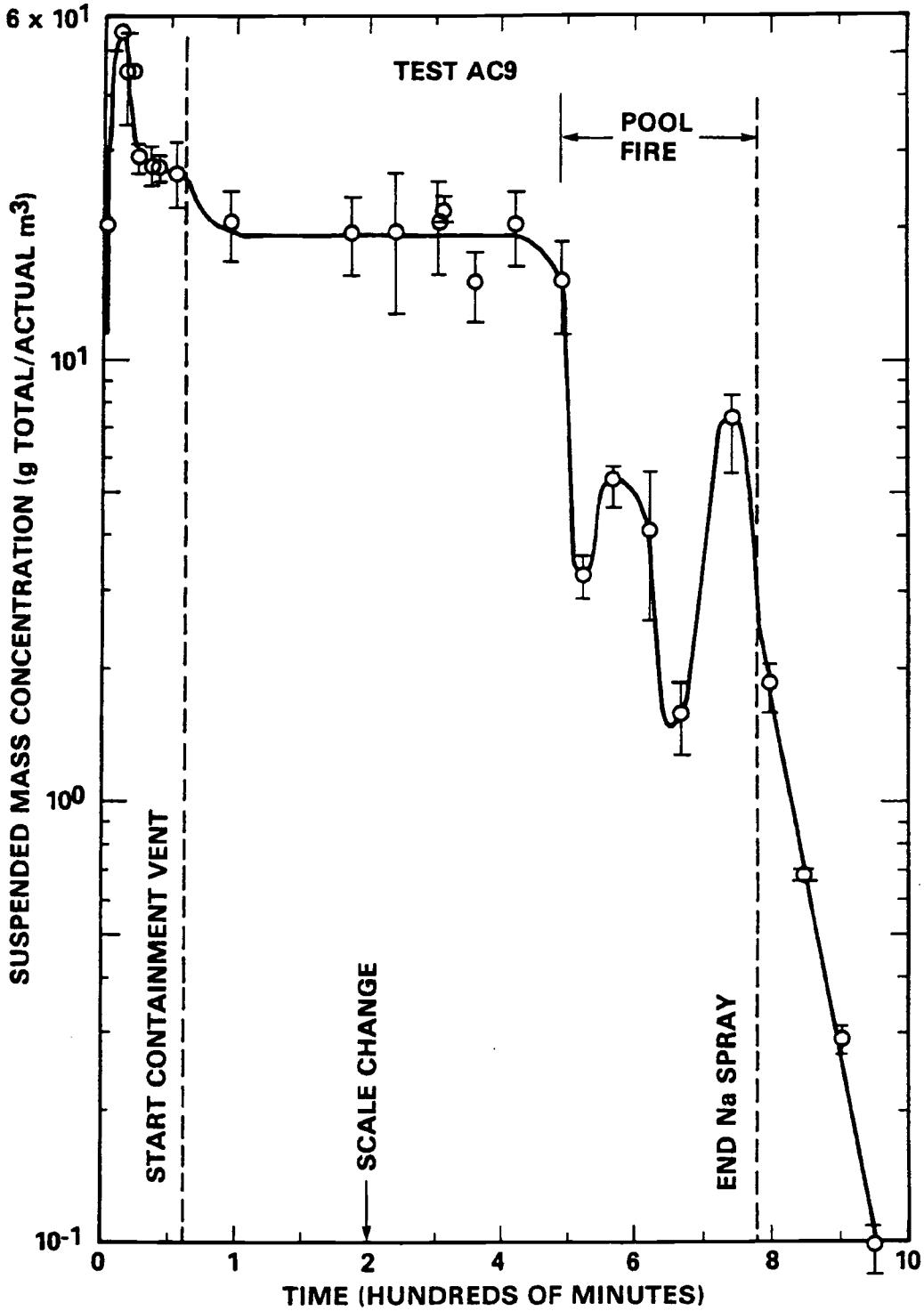

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FIGURE 17. Suspended Aerosol Concentration in the Containment Atmosphere During Test AC9.

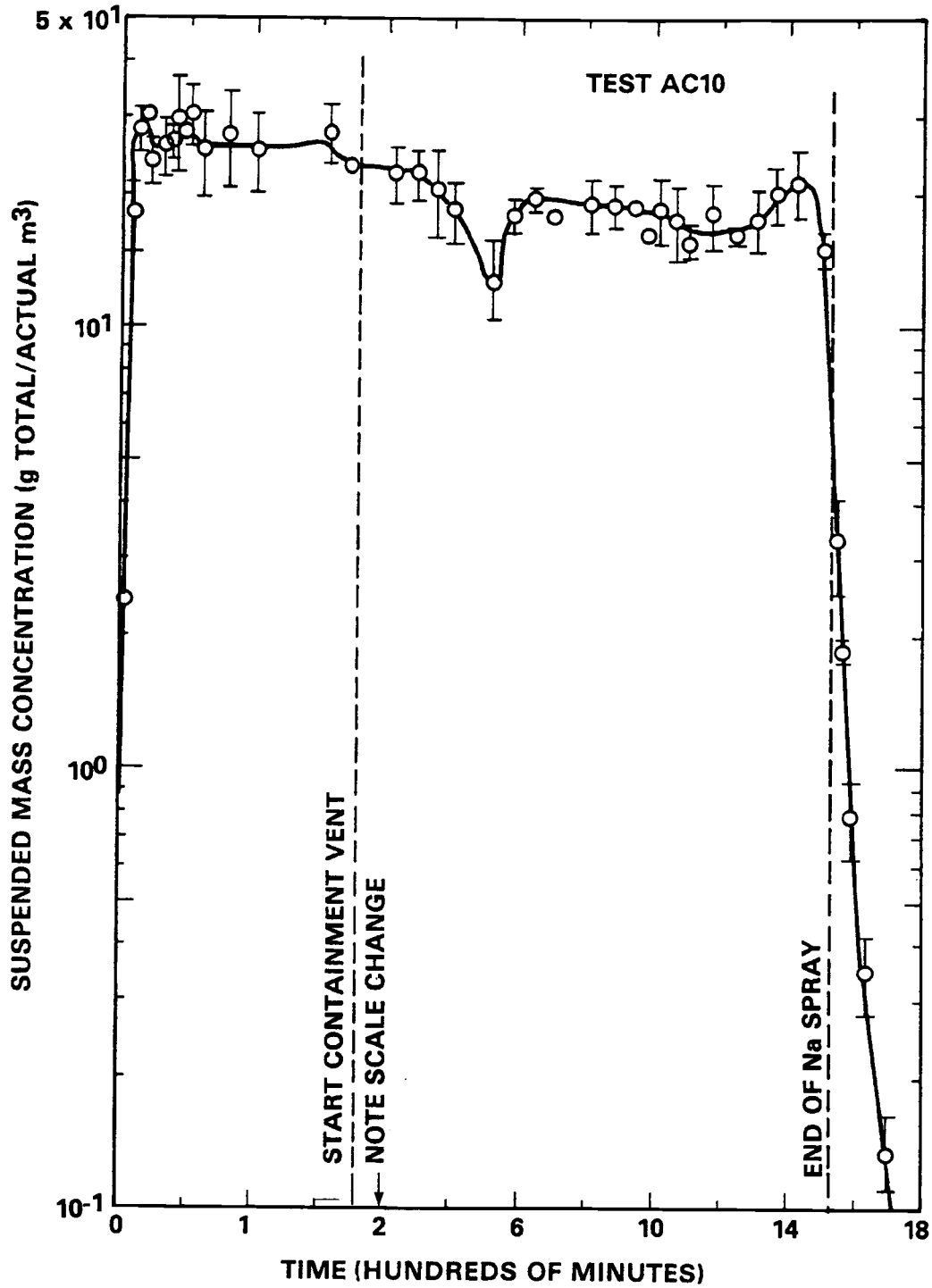

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FIGURE 18. Suspended Aerosol Concentration in the Containment Atmosphere During Test AC10.

TABLE 17

CHEMICAL COMPOSITION OF SUSPENDED AEROSOL

Compound	Weight Percent[a]			
	AC7	AC8	AC9	AC1C
Na_2O_2	12.2	n.d.[b]	0.5	6.3
Na_2O	n.d.	n.d.	n.d.	n.d.
Na_2CO_3	1.6	1.5	96.1	1.5
NaOH	73.6	75.1	n.d.	82.3
H_2O	12.6	23.4	3.4	9.9
Total	100.0	100.0	100.0	100.0
Total Na	50.2	43.9	42.0	51.7

(a) Time average for period when containment purged.

(b) Not detected.

The aerosol in test AC7 was a dry, pale yellow colored material that analyzed 74% NaOH, 12% Na_2O_2 and the balance chiefly water of hydration. Since no steam was added in this test, the water for conversion to the hydroxide and water of hydration came from ambient humidity in the purge air.

Steam was added in tests AC8 and AC1O. Complete conversion to NaOH with excess water was accomplished in test AC8. The ratio of steam to sodium was lower in test AC1O, and 6% of the aerosol remained as peroxide. The aerosol in test AC8 was white and sticky. The aerosol in test AC1O was also white, but was not as sticky as in AC8.

The aerosol in test AC9 was essentially all Na_2CO_3, with a small fraction of $Na_2CO_3 \cdot H_2O$. At 30 minutes after start of sodium spray, addition of CO_2 was started at 0.024 std m^3/s. A sample of suspended aerosol taken immediately prior to the start of CO_2 addition showed that no Na_2CO_3 was present. A sample taken 7 minutes after the start of CO_2 addition showed complete conversion to the carbonate, even though the concentration of CO_2 in the containment atmosphere averaged $< 0.1\%$ during that period. This shows that conversion of NaOH aerosol to Na_2CO_3 occurred very rapidly under these test conditions.

Specific tests performed on aerosol from all four tests showed that there was no metallic sodium or NaH present in the aerosol particles.

5.2.3 Aerosol Particle Size

Information about the size of suspended aerosol particles was obtained by several methods. In two methods, measurements were made directly on the aerosol, while two methods inferred a mean settling diameter from deposition rate, suspended mass concentration and source term measurements.

5.2.3.1 Cascade Impactor Data

The chief particle size measurement technique used in the present tests employed cascade impactors. The impactors were inserted directly into the containment atmosphere at three elevations, into the flowing gas stream in the ducts leading to the submerged gravel scrubber, in the plenum between the submerged gravel scrubber and the fiber demister, and in the duct downstream of the demister. Two types of multi-jet impactors were used, an Andersen Mark III* circular jet sampler and a Sierra Model 226** rectangular slit sampler. Precut fiberglass paper furnished by the manufacturers was

*Manufactured by Andersen 2000, Inc., Atlanta, GA.
**Manufactured by Sierra Instrument Co., Carmel Valley, CA.

used as the stage collection surface. The samplers were used in a horizontal position, and the aerosol which deposited in the inlet portion of the impactor body was analyzed and the mass was added to that collected on the stage collection papers to give the total mass sampled. The particle size of the mass deposited in the inlet portion was considered to be greater than the cut size of the first stage. A description of the technique and discussion of errors has been provided.[11]

The cascade impactor data showed that the aerosol generally had a log-normal distribution, but that significant deviations from log-normal occurred from time to time. One data set that typifies the cascade impactor results is shown in Figure 19. The aerodynamic mass median diameter (AMMD) and geometric standard deviation, σ_g, obtained from plots similar to Figure 19 are listed in Tables 18 through 21 for test AC7 through AC10, respectively. The data are presented in tabular form in Appendix A.

The cascade impactor data show that the particle size remained reasonably constant throughout tests AC7, AC8, and AC10. In test AC9, the leak in the sodium spray line and resultant pool fire reduced the aerosol source and the particle size for the latter half of the test.

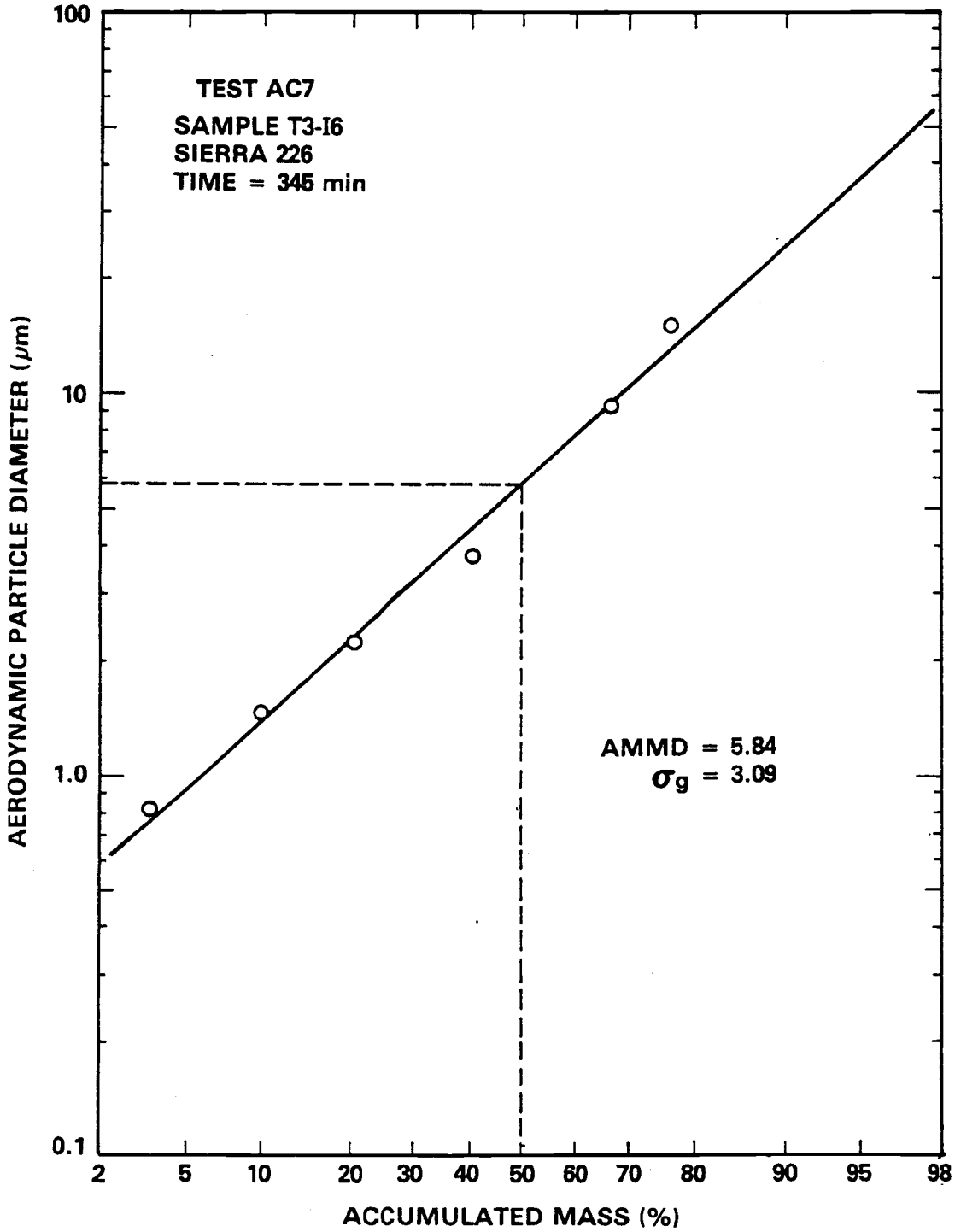

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FIGURE 19. Typical Cascade Impactor Data Plotted on Log-Probability Paper.

TABLE 18

CASCADE IMPACTOR MEASUREMENTS - TEST AC7

Time (min)	Sample No.	Containment Atmosphere AMMD (μm)	Containment Atmosphere σ_g	Inlet to Demister AMMD (μm)	Inlet to Demister σ_g	Outlet of Demister AMMD (μm)	Outlet of Demister σ_g
7	T3-I1	2.30	1.61				
30	T4-I1	4.30	2.67				
105	T3-I2	6.50	2.71				
160	T3-I3	6.00	2.72				
280	T3-I5	6.88	3.01				
345	T3-I6	5.84	3.09				
525	T6-I1			0.90	1.7		
529	T1-I1	4.93	2.94				
645	T3-I7	4.65	3.22				
720	T7-I2					0.7	1.8
815	T3-I8	5.00	3.10				
937	T1-I2	4.91	3.14				
1125	T6-I2			0.77	1.7		
1368	T1-I3	3.90	2.56				
1574	T7-I3					0.46	1.6
1606	T6-I3			0.88	1.6		
1691	T6-I4			0.75	1.4		
1725	T1-I4	4.00	2.70				
Mean[a]		5.01	2.97	0.82	1.6	0.62	1.7
σ		0.97	0.23	0.076	0.14	0.22	0.14

(a) For 180 < t < 1930 minutes.

TABLE 19

CASCADE IMPACTOR MEASUREMENTS - TEST AC8

		Containment Atmosphere		Inlet to Demister		Outlet of Demister	
Time (min)	Sample No.	AMMD (μm)	σ_g	AMMD (μm)	σ_g	AMMD (μm)	σ_g
2	T3-I1	1.85	2.81				
7	Te-I2	2.40	2.50				
34	T3-I3	4.85	3.09				
160	T3-I4	6.40	3.28				
225	T3-I5	4.15	3.45				
285	T3-I6	4.09	3.54				
345	T3-I7	5.20	3.23				
520	T1-I1	4.67	3.34				
704	T1-I2	4.01	3.59				
721	T7-I2					0.35	6.6
771	T6-I2			0.88	1.76		
795	T1-I3	3.94	3.48				
1010	T6-I3			0.84	2.40		
1064	T1-I4	3.75	3.65				
1365	T1-I5	4.63	3.29				
1485	T1-I6	4.71	3.34				
1575	T7-I3					0.62	1.08
1605	T1-I7	5.42	2.85				
1620	T6-I4			0.80	1.80		
1722	T1-I8	4.95	3.05				
1843	T3-I8	5.35	2.38				
Mean[a]		4.57	3.35	0.84	1.99	0.49	3.8
σ		0.58	0.228	0.040	0.36	0.19	3.9

(a) For 180 < t < 1890 minutes.

TABLE 20

CASCADE IMPACTOR MEASUREMENTS - TEST AC9

Time (min)	Sample No.	Containment Atmosphere AMMD (μm)	Containment Atmosphere σ_g	Inlet To Demister AMMD (μm)	Inlet To Demister σ_g	Outlet of Demister AMMD (μm)	Outlet of Demister σ_g
2	T3-I1	1.73	1.54				
7	T3-I2	3.87	2.25				
21	T1-I1	7.86	3.39				
31	T1-I2	7.45	2.99				
55	T1-I4	5.30	3.30				
130	T6-I1			0.78	1.50		
186	T1-I5	5.63	3.38				
206	T7-I1					0.67	6.4
304	T1-I6	5.85	2.38				
307	T1-I6A	6.49	3.16				
423	T6-I2			1.68	1.57		
496	T1-I8	4.55	4.69				
593	T7-I2					1.02	1.83
675	T3-I3	3.40	3.59				
Mean[a]		5.20	3.41	1.23	1.53	0.84	4.11
σ		1.09	0.75	0.64	0.05	0.25	3.23

(a) For 50 < t < 780 minutes.

TABLE 21

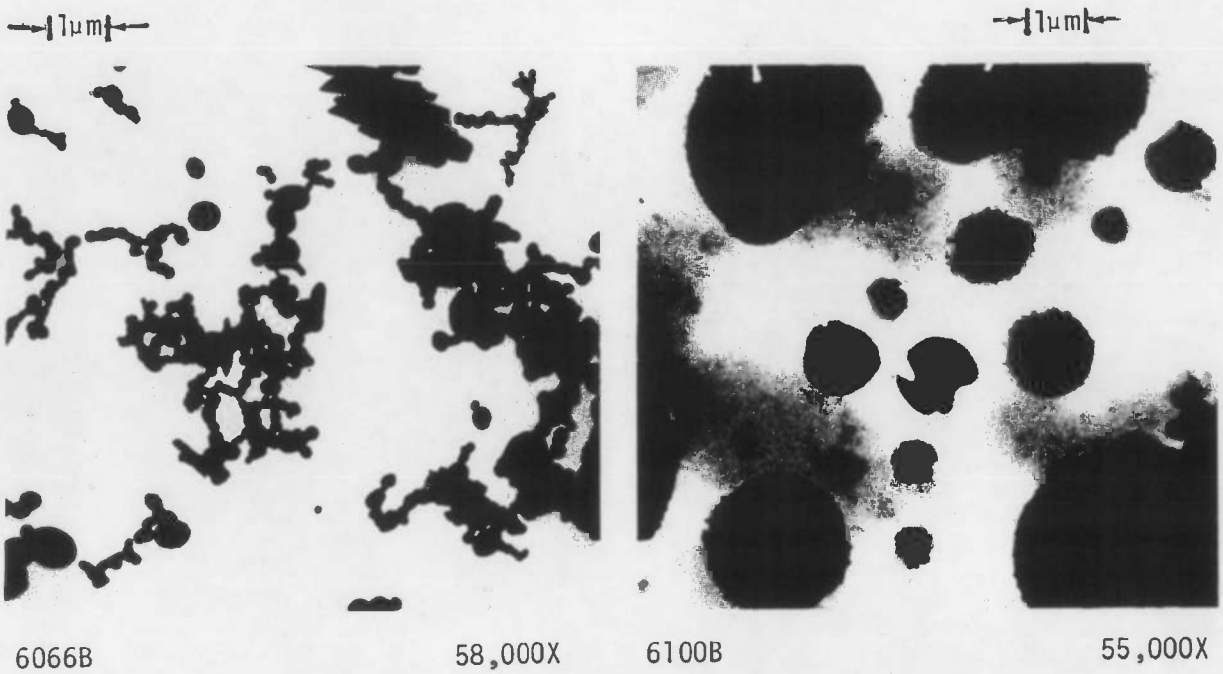
CASCADE IMPACTOR MEASUREMENTS - TEST AC10

Time (min)	Sample No.	Containment Atmosphere AMMD (μm)	Containment Atmosphere σ_g	Inlet To Demister AMMD (μm)	Inlet To Demister σ_g	Outlet of Demister AMMD (μm)	Outlet of Demister σ_g
2	T3-I1	0.98	1.65				
7	T3-I2	2.90	2.08				
20	T3-I3	8.08	2.84				
65	T3-I4	8.63	2.90				
160	T3-I5	5.29	2.62				
229	T3-I6	5.44	2.98				
290	T3-I7	4.70	3.55				
350	T3-I8	7.56	2.81				
415	T6-I1			1.15	3.1		
525	T1-I1	5.79	3.06				
525	T4-I1	7.01	3.17				
645	T4-I2	7.30	3.41				
657	T6-I2			1.04	2.67		
890	T3-I9	8.42	2.60				
1010	T4-I3	5.86	2.87				
1080	T6-I3			0.49	1.57		
1221	T7-I3					0.78	1.30
1245	T4-I4	6.21	2.96				
1428	T1-I3	4.95	3.40				
Mean[a]		6.23	3.10	0.89	2.45	0.78	1.30
σ		1.19	0.30	0.35	0.79	- -	- -

(a) For 180 < t < 1520 minutes.

5.2.3.2 Electron Microscopy

Information on aerosol shape and size was obtained by electron microscopy. Figure 20 shows some typical transmission electron microscope photographs of grids exposed to gravity settling in the containment atmosphere. Figure 20a shows the Na_2CO_3 aerosol in test AC9, while Figure 20b shows the NaOH aerosol in test AC10. The carbonate aerosol consisted of branched, chain-like agglomerates, while the hydroxide particles were nearly spherical and had a dense, consolidated appearance.



(a) Na_2CO_3 in Test AC9, t = 247 min

(b) NaOH in Test AC10, t = 1078 min

Figure 20. Electron Microscope Photographs.

5.2.3.3 Deposition Coupons

Differential deposition rates were obtained by inserting stainless steel coupons (19.3 cm^2 upward horizontal surface) into the containment atmosphere for short periods of time. The aerosol deposited on the upper surface was washed off and analyzed for sodium. Based on exposure time and suspended mass concentration, a deposition velocity, u_t, was calculated from Equation (1).

$$u_t = \frac{\text{Na deposition flux}}{\text{Na suspended mass concentration}} \tag{1}$$

Assuming that gravity settling greatly exceeds plate-out by diffusion (see Section 5.2.5), the settling mean diameter was calculated from Stokes law:

$$d_s = \left(\frac{18\mu_f \, u_t}{g \, \rho_p}\right)^{0.5} \tag{2}$$

where:

d_s = settling mean diameter (cm)
μ_f = fluid viscosity (g/cm s)
g = acceleration due to gravity (cm/s^2)
ρ_p = effective particle density (g/cm^3)

In order to compare the data with the aerodynamic data obtained with the cascade impactors, the particle density was assigned a value of unity. The values for the settling mean diameter calculated from deposition coupons are listed in Table 22.

5.2.3.4 Size Calculated from Mass Balance on Containment Atmosphere

For periods when the aerosol source term and suspended mass concentration are constant, a mass balance on the containment atmosphere gives:

$$I = u_t \, A_s \, C_g + G \, C_g \tag{3}$$

TABLE 22

SETTLING MEAN DIAMETERS CALCULATED FROM DEPOSITION COUPON DATA

Test AC7			Test AC8			Test AC9			Test AC10		
Sample No.	Time (min)	d_s(a) (μm)	Sample No.	Time (min)	d_s(a) (μm)	Sample No.	Time (min)	d_s(a) (μm)	Sample No.	Time (min)	d_s(a) (μm)
T1 D1	35	17.3	T1 D1	35	8.2	T3 D1	190	18.8	T4 D1	12	15.0
T3 D1	35	19.0	T4 D1	35	13.3	T1 D1	365	19.5	T4 D2	20	28.9
T1 D2	106	13.6	T1 D2	106	13.4	T3 D2	365	16.9	T4 D4	25	38.8
T4 D1	106	29.7	T3 D1	106	18.7	T4 D1	405	15.4	T4 D5	30	24.5
T4 D2	1375	15.0	T4 D2	106	23.0	T3 D3	425	19.0	T4 D6	40	17.5
T3 D2	1381	24.7	T3 D2	796	21.6	T3 D4	800	13.3	T4 D7	65	19.8
T3D2A	1388	12.1				T4 D2	800	19.5	T1D1A	84	14.4
									T1 D1	104	12.8
									T3 D1	105	19.2
									T4 D8	105	19.1
									T1 D2	230	20.3
									T4D9A	240	27.5
									T1 D3	290	18.4
									T4D10	290	22.8
									T1 D4	356	17.2
									T3 D2	525	21.7
									T4D13	1015	19.4
									T4D14	1185	28.7
									T4D15	1305	23.1
									T1 D5	1495	12.3
									T3 D3	1495	15.0
Mean		18.8			16.4			17.5			20.8
σ		6.35			5.69			2.39			6.34

(a) Calculated by Equations (1) and (2)

where:

I = aerosol generation rate (g/s)
A_s = settling area (cm^2)
C_g = suspended mass concentration (g/cm^3)
G = rate of purging containment (cm^3/s)

Equation (3) assumes a well mixed containment atmosphere and negligible plateout by diffusion. The validity of both of these assumptions has been verified for the present test conditions. (See Sections 5.2.1 and 5.2.5). Rearranging Equation (3) and substituting the Stokes law definition of settling velocity [Equation (2)], gives:

$$d_s = \left[\frac{18\mu_f \, (I - G\, C_g)}{g\, \rho_p\, A_s\, C_g} \right] 0.5 \qquad (4)$$

The settling mean diameters calculated from Equation (4) are listed in Table 23 for various times during the four tests. The accuracy of the calculation is limited by the error in measurement of the source term, I, which was assumed to be constant throughout the test. (See Table 12.)

5.2.3.5 Comparison of Particle Size Measurements

If the particle size distribution is log-normal, the aerodynamic settling mean diameter can be calculated from the cascade impactor data by Equation (5):

$$d_s = \text{AMMD} \exp(\ell n^2\, \sigma_g) \qquad (5)$$

The settling mean diameters calculated from cascade impactor data, deposition coupon data, and from a mass balance on the containment atmosphere are listed in Tables 24 through 27 for tests AC7 through AC10, respectively. Tables 24 through 27 show that the settling mean diameters calculated by the three methods agree very well for each test. The comparison is shown more

TABLE 23

SETTLING MEAN DIAMETERS CALCULATED FROM MASS BALANCE ON CONTAINMENT ATMOSPHERE

Time (min)	d_s (μm) [a] AC7	AC8	AC9	AC10
30	16.2	19.1	20.6	19.6
40	16.5	18.0	21.7	18.6
55	16.7	17.3	23.5	18.6
65	17.3	16.6	--	20.1
84	18.1	15.1	25.4	20.5
105	18.6	14.5	26.2	20.9
160	19.3	15.7	23.8	21.0
190	--	--	24.6	--
225	19.9	17.6	24.6	21.3
240	20.2	18.0	23.7	21.6
285	18.7	16.2	24.1	20.7
300	17.0	16.2	23.7	20.4
345	16.4	12.2	27.0	18.6
365	17.1	11.8	29.0	18.9
385	17.2	11.5	26.2	19.1
405	17.4	10.9	24.5	19.0
495	17.8	10.4	26.6	19.1
525	17.3	10.3		19.8
550	17.2	9.55		20.1
640	18.6	11.5		20.9
700	19.2	10.0		20.3
800	19.4	10.5		20.5
900	19.0	10.9		20.9
1000	18.6	11.5		21.5
1100	18.4	11.5		22.2
1200	14.3	12.1		22.4
1300	16.4	13.0		23.2
1400	17.4	13.2		25.0
1500	19.5	13.0		25.6
1600	17.2	14.9		
1700	18.5	16.2		
1800	17.3	17.2		
Mean	17.82	13.76	24.60	20.90
σ	1.29	2.89	1.99	2.19

(a) Calculated by Equation (4)

TABLE 24

COMPARISON OF AEROSOL SIZE IN CONTAINMENT ATMOSPHERE
MEASURED BY VARIOUS METHODS - TEST AC7

Time (min)	d_s, Settling Mean Diam (μm)			Ratio of d_s Measured		
	Cascade Imp. (a)	Dep. (b) Coupon	Mass (c) Balance	Coupon To Imp.	Mass Bal. To Imp.	Mass Bal. To Coupon
7	2.9					
30	11.3					
35		18.1 (d)	16.3			0.900
105	17.6	21.7 (d)	18.6	1.23	1.06	0.857
160	16.3		19.3		1.18	
280	23.2		18.7		0.81	
345	20.8		16.4		0.79	
529	15.7		17.3		1.10	
542			17.2			
645	18.3		18.6		1.02	
815	18.0		19.3		1.07	
937	18.2		18.9		1.04	
1134			17.7			
1368	9.43		17.0		1.80	
1380		17.3 (d)	17.0			0.999
1625			17.5			
1725	10.7		18.3		1.75	
Mean (e)	16.8	19.5	18.0	1.16	1.07	0.923
σ	4.17	3.1	0.94	--	--	---

(a) Calculated by Equation (5) using data of Table 18.
(b) From Table 22.
(c) From Table 23.
(d) Average of multiple measurements
(e) For t >100 minutes.

TABLE 25

COMPARISON OF AEROSOL SIZE IN CONTAINMENT ATMOSPHERE
MEASURED BY VARIOUS METHODS - TEST AC8

Time (min)	d_s, Settling Mean Diam (μm)			Ratio of d_s Measured		
	Cascade Imp. (a)	Dep. (b) Coupon	Mass (c) Balance	Coupon To Imp.	Mass Bal. To Imp.	Mass Bal. To Coupon
2	5.4					
7	5.5					
35	17.3	10.8(d)	18.5	0.62	1.07	1.71
106		18.4	14.5			
160	26.2		15.7		0.60	0.79
225	19.2		17.6		0.92	
285	20.2		16.2		0.80	
345	20.6		12.2		0.59	
520	20.0		10.3		0.52	
704	20.5		10.0		0.49	
795	18.6	21.6	10.5	1.16	0.56	0.49
1064	20.0		11.5		0.58	
1365	19.1		13.1		0.69	
1485	20.2		13.0		0.64	
1605	16.2		14.9		0.92	
1722	17.2		16.2		0.94	
1843	23.6		17.2		0.73	
Mean(e)	20.1	20.0	14.0	0.99	0.70	0.70
σ	2.4	2.26	2.27	--	--	--

(a) Calculated by Equation (5) using data of Table 19.
(b) From Table 22.
(c) From Table 23.
(d) Average of multiple measurements.
(e) For t >100 minutes.

TABLE 26

COMPARISON OF AEROSOL SIZE IN CONTAINMENT ATMOSPHERE
MEASURED BY VARIOUS METHODS - TEST AC9

Time (min)	d_s, Settling Mean Diam (μm)			Ratio of d_s Measured		
	Cascade Imp. (a)	Dep. (b) Coupon	Mass (c) Balance	Coupon To Imp.	Mass Bal. To Imp.	Mass Bal. To Coupon
2	2.08					
7	7.46					
21	34.9					
31	24.7		20.8		0.84	
42			22.0			
55	22.0		23.5		1.07	
186	24.9		24.6		0.99	
190		18.8	24.6	0.76		1.31
305	18.4[d]		23.9		1.30	
365		18.2[d]	29.0			1.59
405		15.4	24.5			1.59
425		19.0	25.0			1.32
496			26.6			
675	17.4					
Mean[e]	21.5	17.9	24.4	0.833	1.13	1.36
σ	3.48	1.67	2.27	--	--	--

(a) Calculated by Equation (5) using data of Table 20.
(b) From Table 22.
(c) From Table 23.
(d) Average of multiple measurements.
(e) For t >30 minutes.

TABLE 27

COMPARISON OF AEROSOL SIZE IN CONTAINMENT ATMOSPHERE MEASURED BY VARIOUS METHODS – TEST AC10

Time (min)	d_s, Settling Mean Diam (μm)			Ratio of d_s Measured		
	Cascade Imp. (a)	Dep. (b) Coupon	Mass (c) Balance	Coupon To Imp.	Mass Bal. To Imp.	Mass Bal. To Coupon
2	1.26					
7	4.94					
12		15.0				
20	24.0	28.9		1.20		
25		38.8				
30		24.5	19.6			0.80
40		17.5	18.6			1.06
65	26.7	19.8	20.1	0.74	0.75	1.02
84		14.4	20.5			1.42
105		17.0(d)	20.9			1.23
160	13.4		21.0		1.57	1.06
230	17.9	20.3	21.5	1.13	1.20	
240		27.5	21.6			0.79
290	23.4	20.6(d)	20.6	0.88	0.88	1.00
350	22.0	17.2	18.6	0.78	0.85	1.08
525	23.3(d)	21.7	19.8	0.93	0.85	0.91
645	32.8		20.9		0.64	
890	20.9		20.9		1.00	
1010	17.8	19.4	21.6	1.09	1.21	1.11
1185		28.7	22.4			0.78
1245	20.1					
1305		23.1	23.2			1.01
1365	22.8		24.3		1.07	
1428	22.1		25.1		1.14	
1495		13.7	25.5			1.86
Mean(e)	21.9	20.4	21.4	0.932	0.977	1.05
σ	4.83	4.45	1.95	--	--	--

(a) Calculated by Equation (5) using data of Table 21.
(b) From Table 22.
(c) From Table 23.
(d) Average of multiple measurements.
(e) For t >30 minutes.

clearly by Table 28, where the mean values of d_s (averaged over the time period when the containment was being vented and purged) are listed. The maximum deviation from the average was 22%, with most agreeing within 10%. Although the methods of calculating the mean settling diameter by deposition coupon and mass balance do not yield information regarding the size distribution, the good agreement between all three methods provides confidence in the cascade impactor measurements, for which σ_g data are available.

Table 28 shows that the average values for the mean settling diameter were nearly identical in tests AC7 and AC8. Likewise, tests AC9 and AC10 had nearly identical values for d_s. The relationship between the aerosol generation rate, suspended mass concentration, and mean settling diameter are displayed in Table 29 for the two pairs of tests. Table 29 shows that the particle size was affected more strongly by the source rate than was the suspended concentration.

5.2.4 Bulk Density of Settled Aerosol

The density of aerosol deposited by settling onto horizontal surfaces was calculated from weight and volume measurements on samples from various locations. The results are listed in Table 30.

The bulk density increased with time. Samples taken during the sodium spray period had significantly lower density than samples standing for six days in the containment atmosphere. This was especially true for the low-density carbonate aerosol in test AC9. The three tests with NaOH aerosol showed fairly similar densities, averaging 0.28 g/cm^3. The Na_2CO_3 aerosol density was much lower--0.04 g/cm^3 when freshly settled and 0.12 g/cm^3 after six days. In other tests[5] where the moisture content was greater, the settled bulk density of NaOH aerosol approached unity.

5.2.5 Aerosol Deposition on Floor and Walls

Aerosol deposition on the containment vessel walls and ceiling was measured post-test by wiping a measured area of the painted wall with a series of

TABLE 28

SUMMARY COMPARISON OF AEROSOL SIZING METHODS

Measurement Method	Mean Settling Diameter (μm)[a]			
	AC7	AC8	AC9	AC10
Cascade Impactor	16.8	20.1	21.5	21.9
Deposition Coupon	19.5	20.0	17.9	20.4
Mass Balance	18.0	14.0	24.4	21.4
Average	18.1	18.0	21.3	21.2

(a) From Tables 24-27, for time period when containment was being vented or purged and sodium spray operating.

TABLE 29

RELATION BETWEEN AEROSOL SOURCE RATE, SETTLING DIAMETER AND SUSPENDED CONCENTRATION

	Test Pair A (AC7 & AC8)	Test Pair B (AC9 & AC10)	Ratio A/B
I, Aerosol Source (g Na/s)	7.2 ± 0.2	12.5 ± 0.3	1.74
d_s, Mean Settling Diam (μm)	18.0 ± 0.1	21.2 ± 0.1	1.18
C_g, Suspended Conc (g Na/m^3 STP)	11.8 ± 1.8	12.5 ± 2.4	1.06

TABLE 30

BULK DENSITY OF SETTLED AEROSOL
(g/cm^3)

Test No.	During Na Spray Period[a]	6 Days Later[b]	From 265-mm Duct
AC7		0.32 ± 0.15	
AC8		0.29 ± 0.043	
AC9	0.041	0.12 ± 0.028	
AC10	0.18	0.24 ± 0.072	0.28

(a) Average of 2 samples from platform at personnel entrance.
(b) Mean of 10 samples in cans exposed for entire test at various locations.

damp cloths and analyzing the cloths for sodium. The results of sampling in this manner at seven different locations are listed in Table 31. The results are scattered, with approximately a ±50 % standard deviation. One of the seven samples was taken from the ceiling. Table 32 shows that the plateout on the ceiling was the same as on the vertical walls, within the range of experimental error.

The distribution of settled mass within the containment vessel was determined from analyses of settling trays located at ten different locations and exposed throughout each test. The results are presented in Table 33. Considerable scatter can be seen among the various locations. The scatter is fairly random except for the sample located near the top of the vessel (D 59), which collected only ~33 % of the average deposition. This may be due to a lower suspended mass concentration at that elevation, a smaller particle size, or a combination of these effects. Mass concentration measurements made at +6.1 m and -5.8 m elevations showed no significant

TABLE 31

WALL DECONTAMINATION SAMPLE DATA

Sample No.	Wall Elevation (m)	Surface Concentration (g Na/m^2) AC7	AC9	AC10
W1	Ceiling	16.2	10.9	23.6
W2	+6.1	8.3	39.4	115.
W3	+3.0	19.1	6.97	54.7
W4	+1.5	9.2	7.73	76.2
W5	-1.5	5.8	14.7	133.
W6	-3.0	14.5	4.08	98.7
W7	-6.1	25.2	8.69	73.0
Mean		14.0	13.21	82.0
σ		6.84	12.0	37.1
		(±49%)	(±91%)	(±45%)

TABLE 32

COMPARISON OF PLATEOUT ON CONTAINMENT CEILING AND VERTICAL WALLS

Test No.	Surface Concentration (g Na/m^2) Ceiling[a]	Vertical Wall[b]	Ratio Ceiling To Wall
AC7	16.2	13.7	1.18
AC9	10.9	13.6	0.80
AC10	23.6	91.8	0.26
Mean			0.747

(a) Sample W1, Table 31.

(b) Average of 6 samples, Table 31, excluding W1.

TABLE 33

INTEGRAL SETTLED MASS MEASURED BY DEPOSITION TRAYS

Sample No. (a)	Elevation In Containment (m)	Settled Mass Concentration (g Na/cm^2)			
		AC7	AC8	AC9	AC10
D50	0	(b)	0.198	0.456	0.608
D51	-1.7	0.281	0.817	0.289	0.418
D52	-1.7	1.087	0.490	0.821	1.992
D53	-1.7	0.852	0.757	0.479	1.141
D54	-8.5	2.357	0.593	1.019	0.973
D55	-8.5	0.563	0.449	0.821	1.072
D56	-8.5	0.483	0.367	0.570	0.745
D57	-8.5	0.361	1.141	0.494	0.593
D58	-8.5	0.958	0.278	(b)	2.342
D59	+8.8	0.228	0.130	0.259	0.361
Mean		0.798	0.521	0.578	1.025
σ		0.660	0.306	0.262	0.661
		(+83%)	(+59%)	(+45%)	(+64%)

(a) 263 cm^2 of upward facing surface.

(b) Not measured.

differences due to elevation. Cascade impactor and deposition coupon measurement indicated that the particle size was slightly smaller at higher elevations, but not enough to explain the 33% settling rate of sample D 59. A plausible explanation is that some resuspension of previously deposited material occurred. The effective particle size of the resuspended material was very large and settled chiefly into trays located at lower elevations.

A comparison of the aerosol plateout on the containment walls and ceiling with settling on horizontal surfaces is given in Table 34. The average

TABLE 34

COMPARISON OF AEROSOL DEPOSITION ON CONTAINMENT WALLS AND HORIZONTAL SURFACES

Test	Surface Deposit (g Na/cm²)		Deposited Mass (g Na)			Wt % Deposited		Flux Ratio Horiz to Vertical	Mass Recovered Post-Test Wash (g Na)	Ratio, Calc'd from Samples to Post-Test Wash
	Vertical Walls and Ceiling[a]	Horiz Surfaces[b]	Vertical Walls and Ceiling[c]	Horiz Surfaces[c]	Total	Walls and Ceiling	Horiz			
AC7	1.40(-3)[d]	7.98(-1)	1.28(4)	7.02(5)	7.15(5)	1.8	98.2	570	6.18(5)[e]	1.16
AC8	(f)	5.21(-1)	(f)	4.58(5)	4.67(5)[g]	(f)	(f)	(f)	4.61(5)	1.01
AC9	1.32(-3)	5.78(-1)	1.20(4)	5.09(5)	5.21(5)	2.3	97.7	438	5.13(5)	1.02
AC10	8.20(-3)	1.02(0)	7.48(4)	8.98(5)	9.72(5)	7.7	92.3	124	8.16(5)	1.19
Mean						3.84	96.2	377		1.09

(a) Mean of 7 wipe samples at various locations.

(b) Mean of 10 deposition can samples at various locations.

(c) Total vertical and ceiling surface area = 9.12(6) cm²; horizontal surface = 8.8(5) cm².

(d) Numbers in parenthesis are exponents of 10.

(e) Containment vessel washes, excluding non-aerosolized material in catch pan.

(f) Not measured.

(g) Estimated.

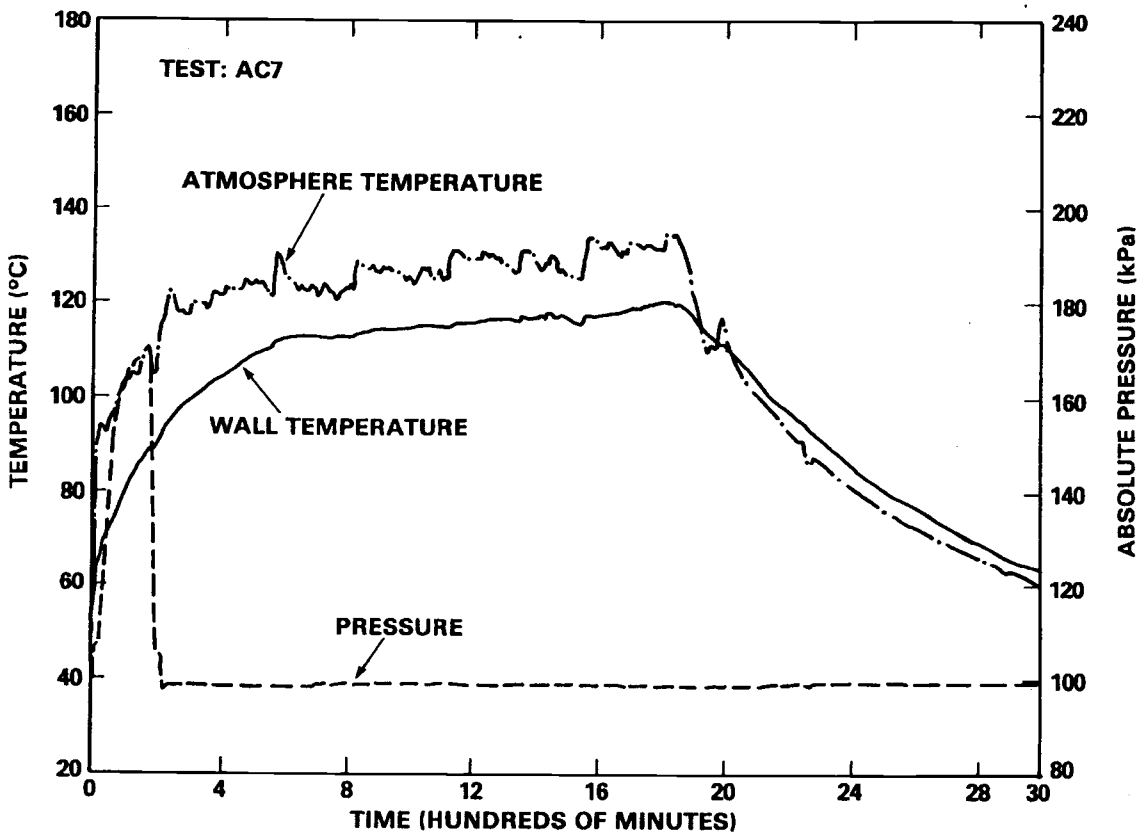
plateout flux to vertical and downward facing horizontal surfaces was approximately 1/400 that of settling flux to upward facing horizontal surfaces. The plating surface area was ~10 times greater than the settling surface area, giving an overall result of ~2.5% of the aerosol plated onto vertical and downward facing surfaces; 97.5% settled onto upward facing horizontal surfaces. Table 34 also shows a good agreement between the total aerosol accounted for by the settling trays and wall wipe method and the mass recovered by post-test water washes of the containment vessel. The good agreement (9%) is fortuitous, considering the scatter in the samples of the former method.

5.2.6 Containment Atmosphere Properties

5.2.6.1 Temperature and Pressure

The temperature of the containment atmosphere was measured by 10 thermocouples located at representative heights and radial positions. Table B1 in Appendix B gives the coordinates of each thermocouple. Likewise, 15 thermocouples were attached to the inner surface of the painted steel shell of the containment vessel at various elevations and angular positions. The average gas and wall temperatures are plotted as a function of time in Figures 21 through 24 for tests AC7 through AC10, respectively. Also shown on these plots is the absolute pressure within the containment vessel. Gas temperatures increased following initiation of sodium spray. An equilibrium temperature was reached when the energy given off by the chemical reactions was balanced by heat loss to the vessel walls and the sensible heat of ambient temperature purge air. Variations in the equilibrium temperature were due to changes in the air purge rate and the sodium burning rate. The temperature of the containment atmosphere was fairly uniform, with an average standard deviation among the ten thermocouple readings of only ~6°C.

The pressure in the containment atmosphere increased by 14 kPa to 20 kPa (2 psi to 3 psi) immediately after start of sodium spray due to chemical heat. To demonstrate venting from a higher pressure, compressed air was added in three of the tests until the pressure reached ~70 kPa gauge



HEDL 8110-072.32

FIGURE 21. Containment Temperature and Pressure in Test AC7.

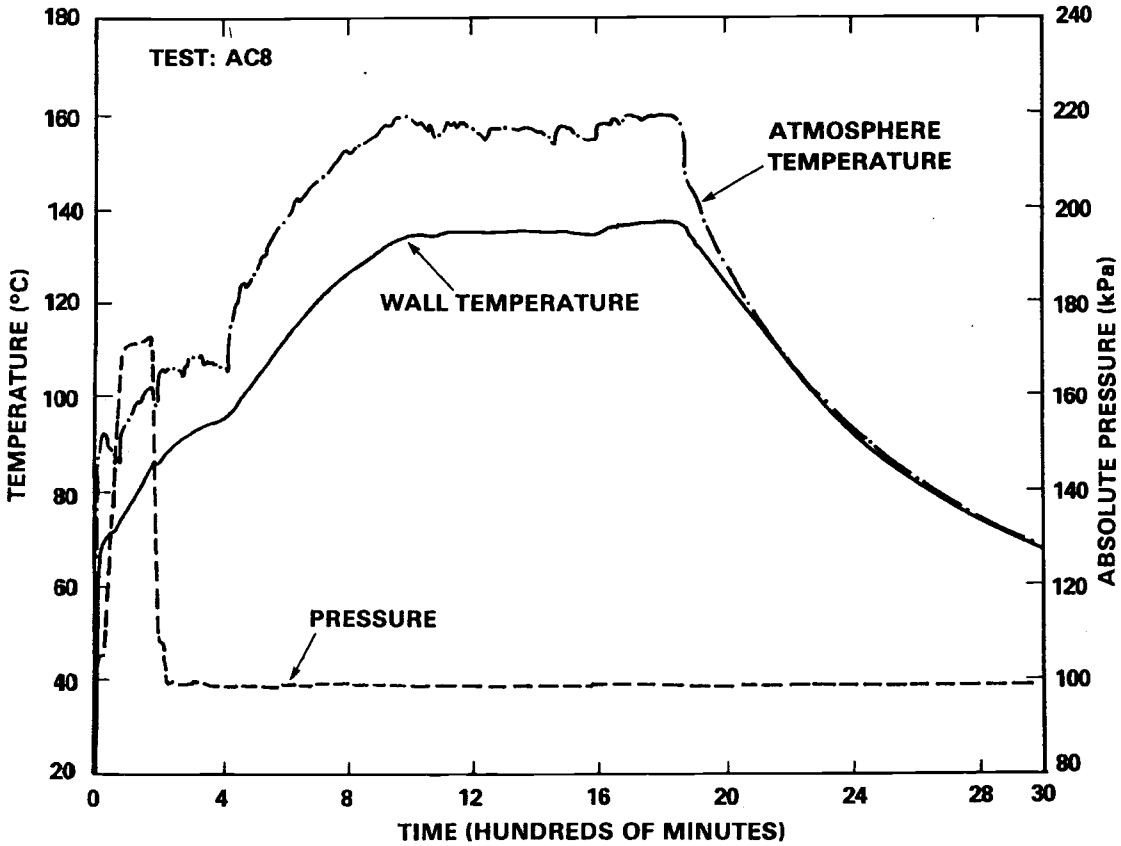


FIGURE 22. Containment Temperature and Pressure in Test AC8.

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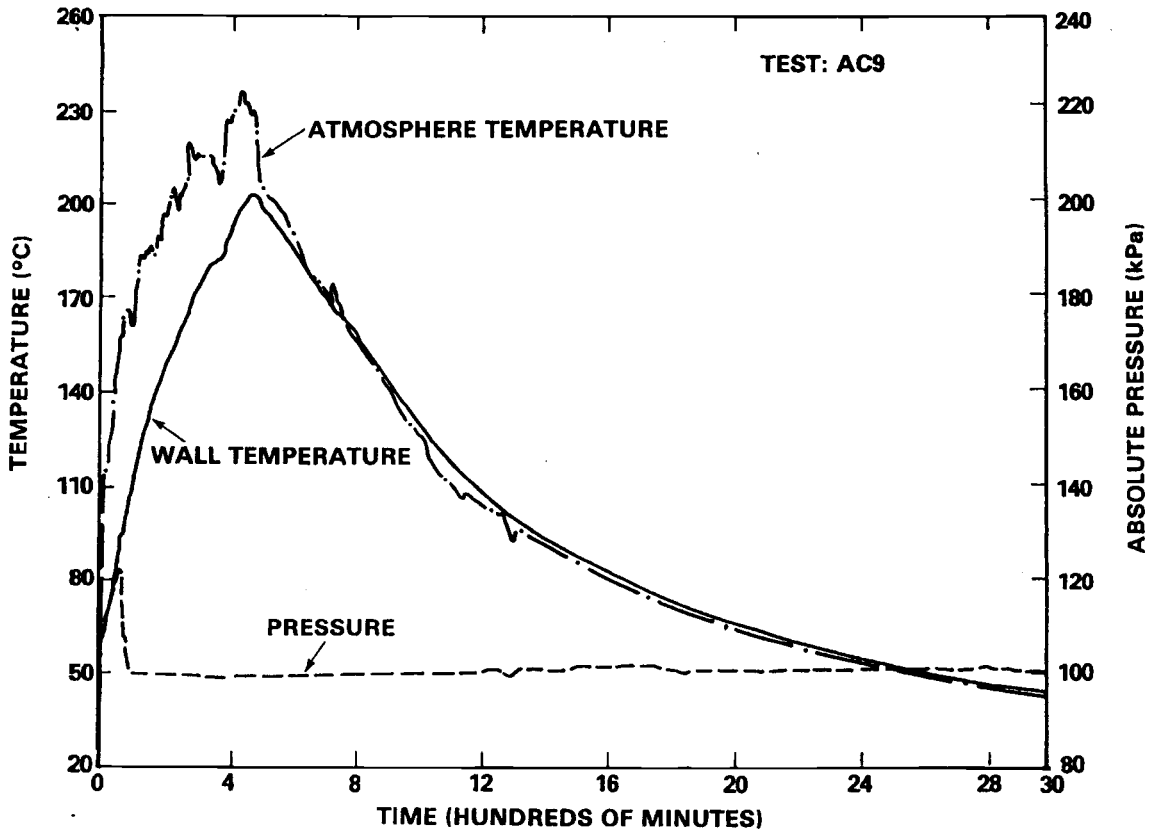

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FIGURE 23. Containment Temperature and Pressure in Test AC9.

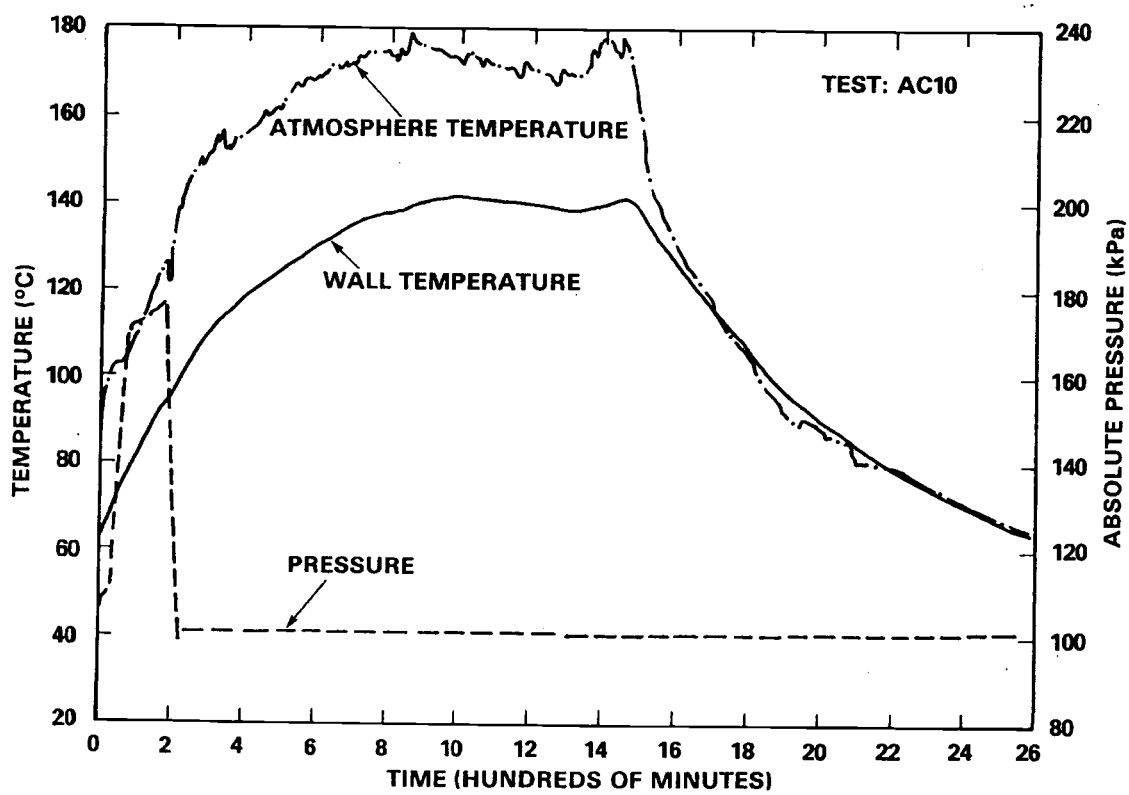

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FIGURE 24. Containment Temperature and Pressure in Test AC10.

(10 psig) prior to the vent phase. After venting to atmospheric pressure, the exhaust blower was started, and the containment pressure varied from -100 Pa to -500 Pa (-0.4 in. to -2 in. H_2O) during the purge phase. Additional details of containment temperature and pressure are presented in Appendix B.

Figures 21 through 24 show that a significant temperature difference existed between the vessel wall and the gas phase. A thermocouple array was installed to measure the temperature gradient near the wall at the vessel mid-elevation. Details of this measurement are presented in Appendix C, showing that the wall temperature was as much as 40°C lower than the gas and that most of this difference occurred within ~2 cm of the wall. The chief significance of the temperature gradient is that it induces natural convection currents that mix the containment atmosphere. Figures 21 through 24 show that after the end of sodium burning, the atmosphere temperature decreased more rapidly than the steel wall temperature until the gas was cooler than the wall. This was possible in the present tests because purging with cold air was continued for several hours after the end of sodium spraying.

The volumes of containment atmosphere withdrawn for aerosol measurements were measured by rotometers calibrated for standard conditions (0°C and 101 kPa absolute). Aerosol concentrations expressed in terms of acutal containment volume were computed from the measured volumes using the ratio of actual to standard volume. Numerical values of this ratio are presented in Appendix D.

5.2.6.2 Humidity

Moisture content of the containment atmosphere was measured continuously by dew point meters* located in the control room and periodically by samples withdrawn through a filter and desiccant trap. The desiccant, magnesium

*Model 1100A Dew Point Hygrometer, manufactured by General Eastern Instrument Corp., Watertown, MA.

perchlorate, trapped all water vapor passing through the bed in a measured volume of air. The gain in weight of the desiccant represented the mass of water vapor contained within the volume of sampled gas. Results of humidity measurements for the four tests are shown in Figures 25 through 28. Water contents are presented in terms of dew point. The solid curve represents the average value of dew point meter readings made on gas samples withdrawn from high and from low elevations in the vessel. The two methods generally agreed within 10°C, although in test AC10, the dew point meter is thought to have malfunctioned. The desiccant trap method is believed to be more accurate, especially at high humidity conditions, as in test AC9, where condensation occurred in the gas sample line leading to the dew point meter.

Test AC7 was a fairly dry test in that the only source of moisture was normal humidity brought in with purge air. As evident from Figure 25, the initial dew point of 16°C was rapidly lowered by water vapor sorption onto the aerosol particles, and averaged ~0°C throughout the test.

The humidity of the containment atmosphere depended not only on the total quantity of water present in the containment vessel, but on the temperature. As the temperature increased, the equilibrium partition of water between the aerosol particles and vapor in the containment atmosphere shifted in favor of the gas phase.

When CO_2 was added in test AC9, most of the water existed as vapor in the containment atmosphere, with very little associated with the sodium carbonate aerosol.

5.2.6.3 Gas Composition

The composition of the containment atmosphere was determined by continuously monitoring flowing samples withdrawn from two different points, one located high in the vessel (+6.1 m) and one located low in the vessel (-6.7 m). An

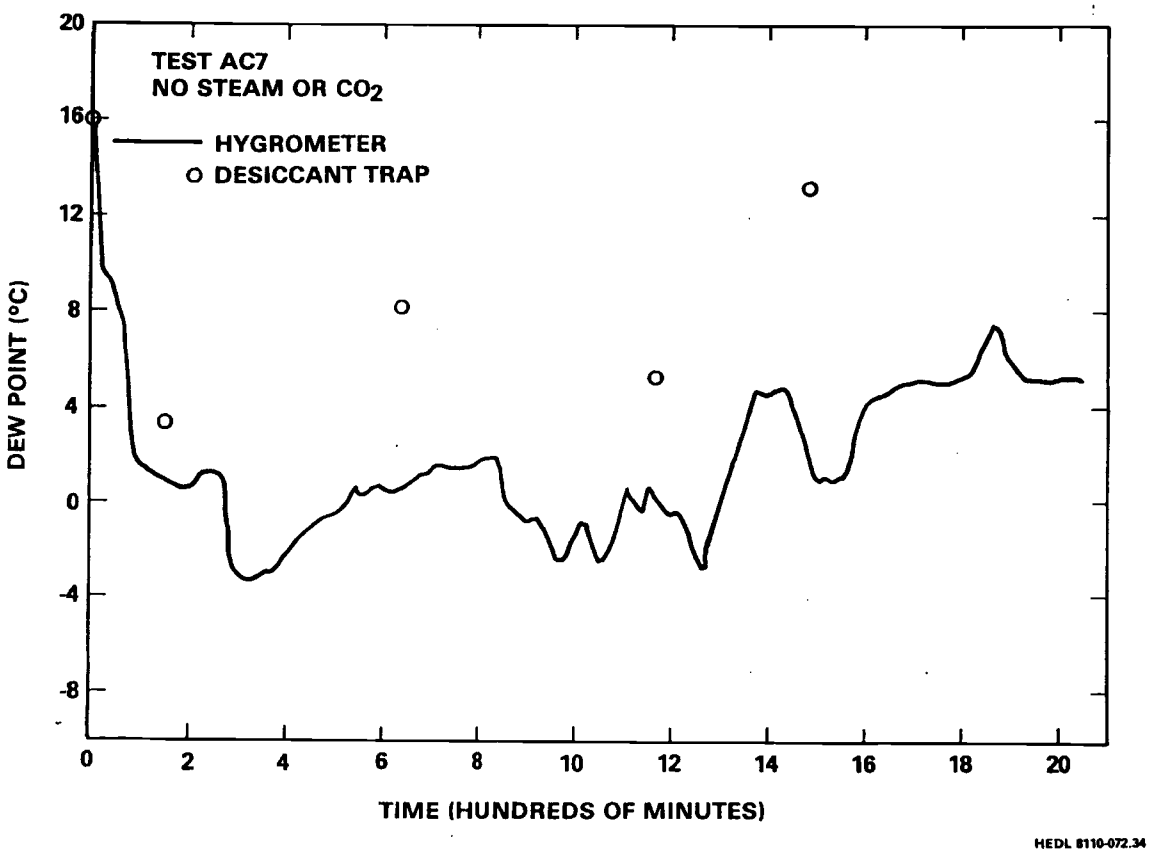

FIGURE 25. Containment Atmosphere Humidity in Test AC7.

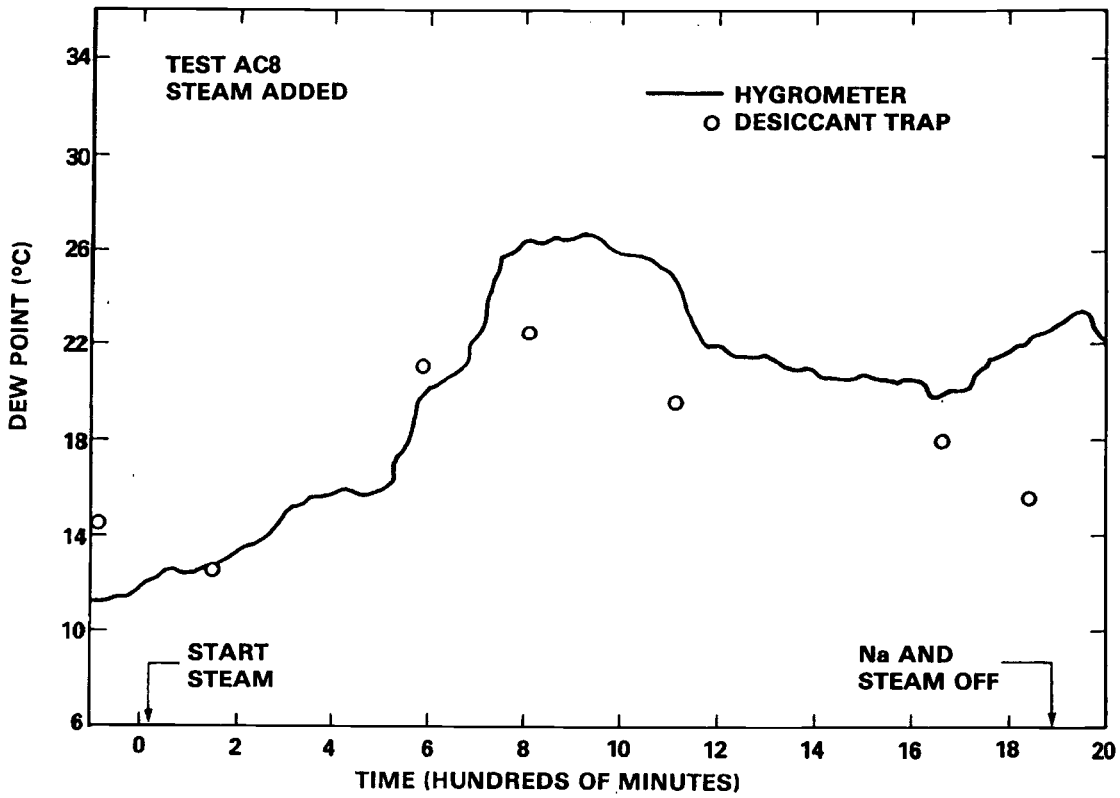

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FIGURE 26. Containment Atmosphere Humidity in Test AC8.

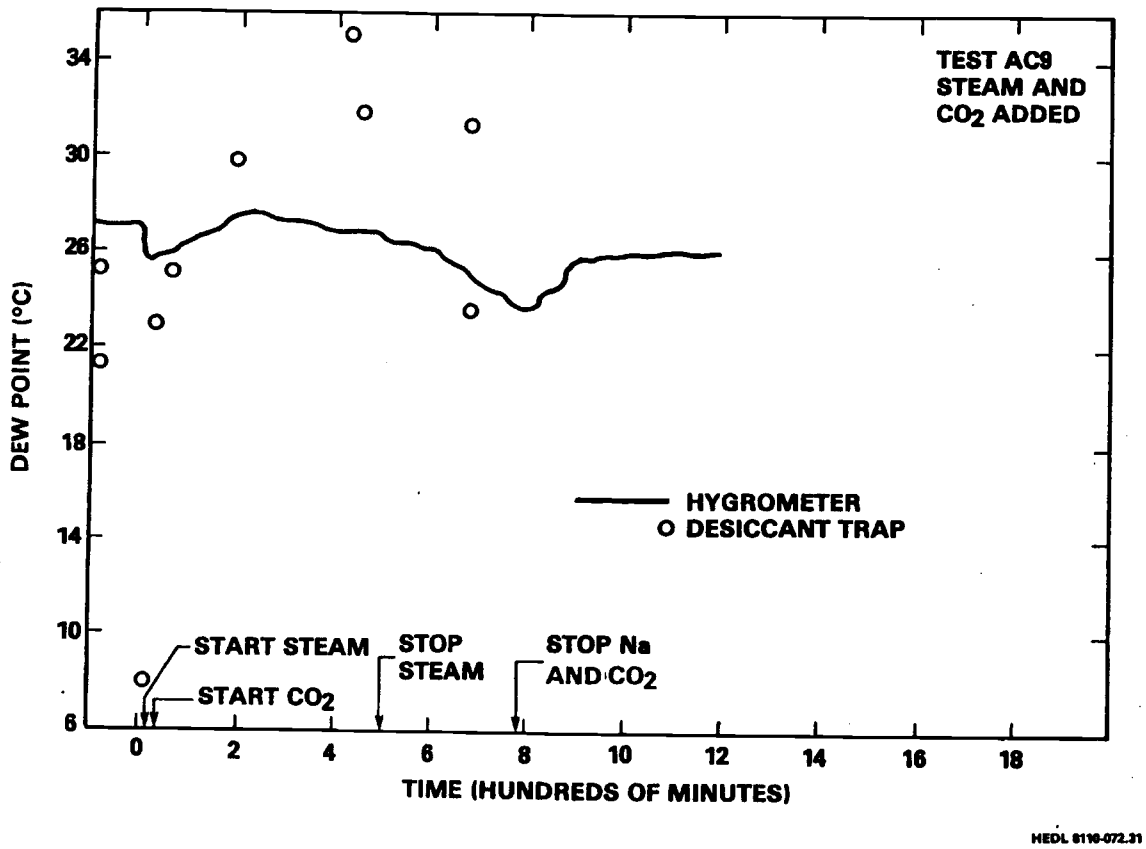

FIGURE 27. Containment Atmosphere Humidity in Test AC9.

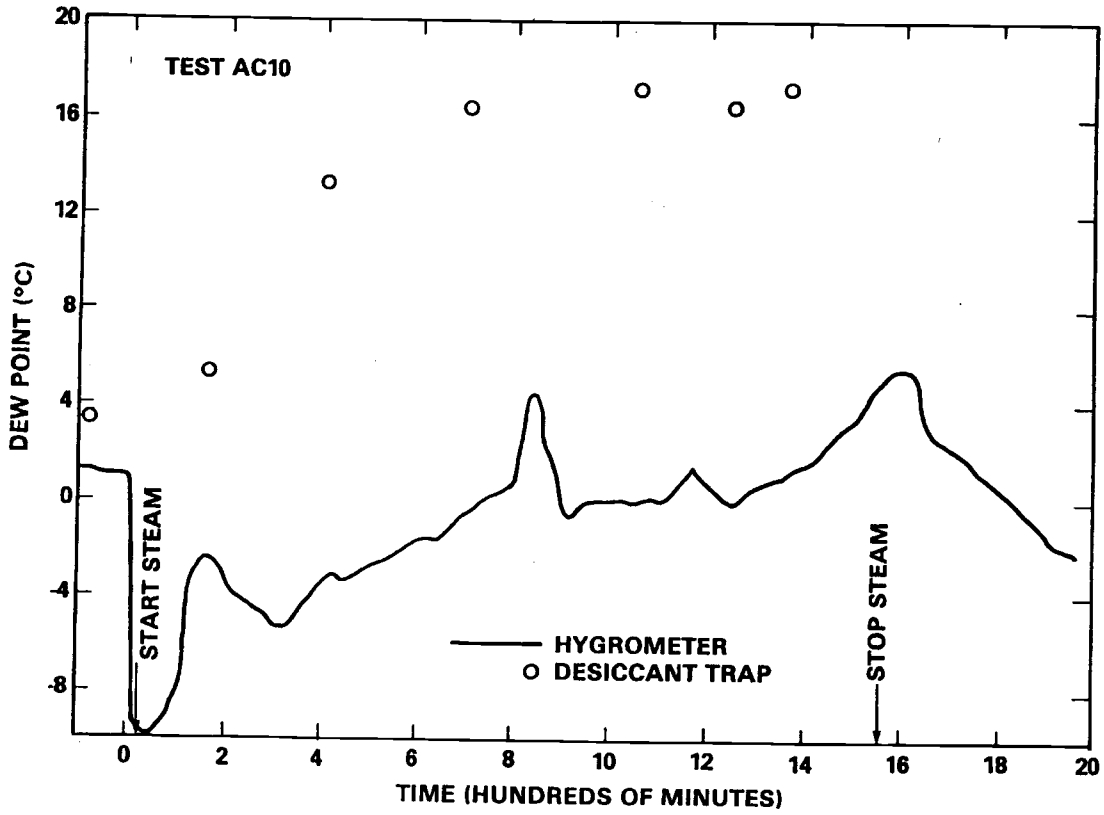

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FIGURE 28. Containment Atmosphere Humidity in Test AC10.

oxygen analyzer,* hydrogen analyzer,** and CO_2 analyzer*** were used in each sample line; and, in addition, periodic grab samples were analyzed by mass spectrometry. The mass spectrometric data are presented in Tables 35 through 37 for tests AC7, AC9 and AC10, respectively. No spectrometric analyses were performed for test AC8. Tables of the on-line gas analysis results are presented in Appendix F.

In test AC9, carbon dioxide gas was injected during the time period starting at 30 minutes and ending 782 minutes after start of sodium spray. Indications were that the suspended NaOH aerosol reacted very rapidly with the CO_2 to form anhydrous Na_2CO_3. The aerosol which had settled and plated prior to the start of CO_2 injection reacted more slowly. An excess of CO_2 was fed to the containment vessel, with the surplus accumulating in the containment atmosphere and eventually being purged from the vessel. Of the 25 kg-moles of CO_2 injected, approximately 15 kg-moles reacted with sodium hydroxide and 10 kg-moles were purged from the containment vessel. The time-averaged CO_2 concentration in the containment atmosphere during the sodium spray period was 2.3Δ, as determined by the on-line infrared analyzer.***

The CO_2 concentration is plotted as a function of time in Figure 29. The continuous curve is the output of the on-line infrared analyzer. Periodic grab samples were analyzed by two different techniques to confirm the infrared analysis. One involved pulling a known volume of gas through a three-component sampling train consisting of a filter to remove aerosol, a desiccant bed to remove water vapor, and bed of ascarite (sodium hydroxide distributed on asbestos fibers) to remove CO_2. The ascarite bed was weighed to determine the mass of CO_2 sorbed. The third analytical technique was a mass spectrometric analysis of periodic grab samples. The three methods agreed reasonably well, as shown in Figure 29.

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*Beckman Instruments, Inc., Fullerton, CA, Model 7003.
**Teledyne Analytical Instruments, San Gabriel, CA, Model 102.
***Horiba Instruments, Inc., Irvine, CA, Model PIR-2000.

TABLE 35

MASS SPECTROMETRIC ANALYSES OF CONTAINMENT ATMOSPHERE FOR TEST AC7

	Mole% On Dry Basis at Specified Time and Location[a]					
	-50 min	160 min	160 min	540 min	540 min	1440
Gas	Low [a]	Low	High	Low	High	High
O_2	20.9	17.0	21.0	20.9	21.1	21.4
N_2	78.1	82.0	77.9	78.1	77.8	77.6
CO_2	0.09	0.05	0.08	0.07	0.08	0.06
Ar	0.94	0.98	0.94	0.94	0.93	0.95
H_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CH_4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

(a) Withdrawal point was located high or low in containment vessel, as indicated.

TABLE 36

MASS SPECTROMETRIC ANALYSES OF CONTAINMENT ATMOSPHERE FOR TEST AC9

	Mole% on Dry Basis at Specified Time and Location[a]						
	-60 min	25 min	25 min	50 min	50 min	305	470
Gas	Low [a]	Low	High	Low	High	Low	Low
O_2	21.1	19.6	19.3	17.9	17.9	19.1	18.7
N_2	77.9	79.4	79.6	81.0	80.9	77.5	78.0
CO_2	0.13	0.06	0.05	0.15	0.06	2.43	2.32
Ar	0.95	0.97	0.96	0.97	0.98	0.94	0.95
H_2	<0.01	<0.01	0.01	<0.01	0.07	<0.01	0.04
CH_4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

(a) Withdrawal point was located high or low in containment vessel, as indicated.

TABLE 37

MASS SPECTROMETRIC ANALYSES OF CONTAINMENT ATMOSPHERE FOR TEST AC10

	Mole% on Dry Basis at Specified Time and Location[a]					
	-50 min	170 min	170 min	540 min	540 min	1440 min
Gas	Low[a]	Low	High	Low	High	High
O_2	20.8	17.3	20.3	20.1	21.0	20.4
N_2	78.0	79.8	78.5	78.7	77.8	78.4
CO_2	0.29	0.21	0.25	0.24	0.24	0.20
Ar	0.93	0.98	0.92	0.94	0.93	0.95
H_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CH_4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

(a) Withdrawal point high or low in containment vessel, as indicated.

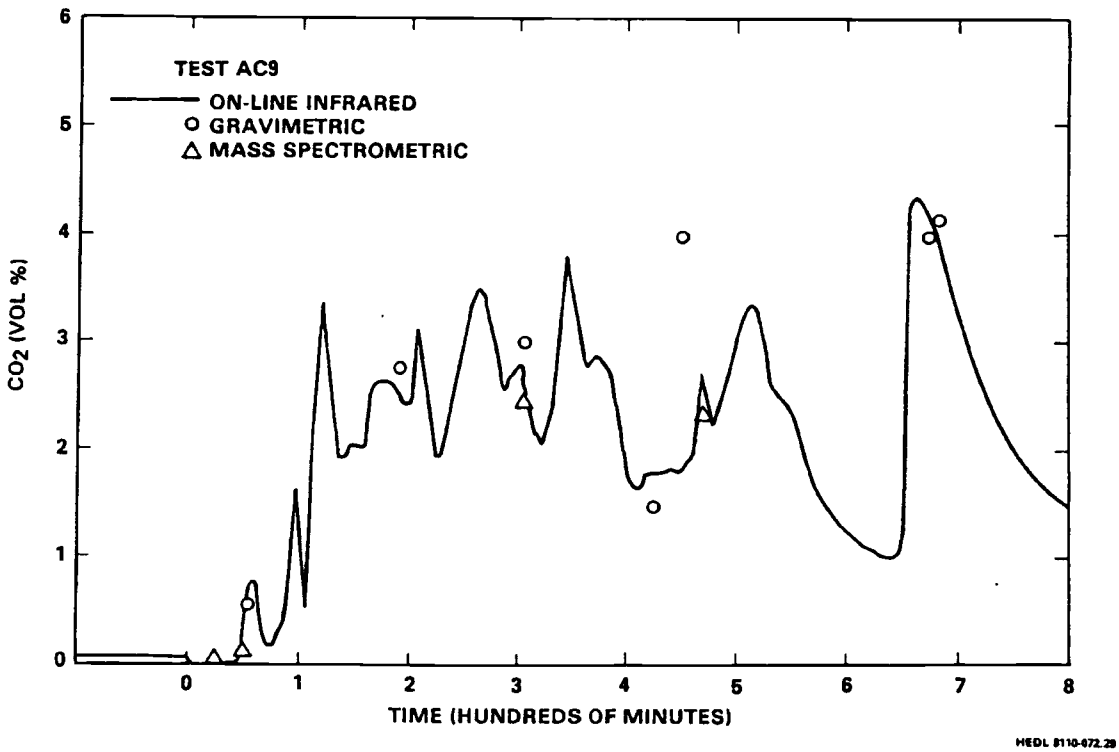

FIGURE 29. Carbon Dioxide Concentration in Containment Atmosphere During Test AC9.

5.3 THERMAL-HYDRAULIC BEHAVIOR IN THE TEST ARTICLE

5.3.1 Gas and Liquid Temperatures

The gas and liquid temperatures in the submerged gravel scrubber-fiber demister test article are listed in Tables E1 through E4 in Appendix E for tests AC7 through AC10, respectively. The values in the tables are arithmetic averages of readings made at 5-minute intervals throughout each operating period. The average and maximum temperatures at several locations in the test article are listed in Table 38.

TABLE 38

TEMPERATURES IN TEST ARTICLE

	Temperature (°C)[a]			
	AC7	AC8	AC9	AC10
Gas Inlet to SGS, avg	133	126	196	166
Gas Inlet to SGS, max	143	159	238	182
Gas Outlet of SGS, avg	36.0	44.8	43.7	41.1
Gas Outlet of SGS, max	40.5	61.2[b]	50.8	45.8
Gas Outlet of Demister, avg	36.8	45.1	48.3	42.4
Gas Outlet of Demister, max	40.0	60.2[b]	56.4	45.9
SGS Liquid Pool, avg	37.1	45.9	44.5	42.2
SGS Liquid Pool, max	41.6	62.9[b]	52.0	47.0

(a) For SGS operation period until end of Na spray.

(b) Supplemental heat provided by steam coil in SGS pool, 200 <t<360 minutes.

The hot gas entering the SGS was cooled to essentially the same temperature as the pool liquid. Accurate temperature measurements of the gas as a function of distance into the gravel bed was not possible because of the cyclic pulsing of pool liquid through the bed at a frequency of 30 cycles per minute. However, a thermocouple located within the gravel at a distance of 50 mm above the gravel support screen read the same as thermocouples located at greater distances into the bed, suggesting that equilibrium between gas and liquid occurred very rapidly.

5.3.2 Pressure Differentials

The pressure drops across the gravel bed and the demister were measured before charging the test article with water. Figure 30 is a plot of the pressure drop across the dry components as a function of gas flow rate. The pressure drop across the dry gravel bed increased in a nonlinear manner with gas velocity. Equation (6) is an empirical fit of the data in Figure 30.

$$(\Delta P)_{gravel} = 2400\ G^{1.72} \tag{6}$$

where:

$(\Delta P)_{gravel}$ = pressure drop across dry gravel (Pa)
G = gas flow rate (actual m^3/s)

The pressure drop across the dry fiber bed demister increased linearly with gas flow rate and can be expressed empirically by Equation (7).

$$(\Delta P)_{dry\ demister} = 9.6 \times 10^6\ G \tag{7}$$

where:

$(\Delta P)_{dry\ demister}$ = Pa
G = actual m^3/s
μ = gas viscosity (poise)

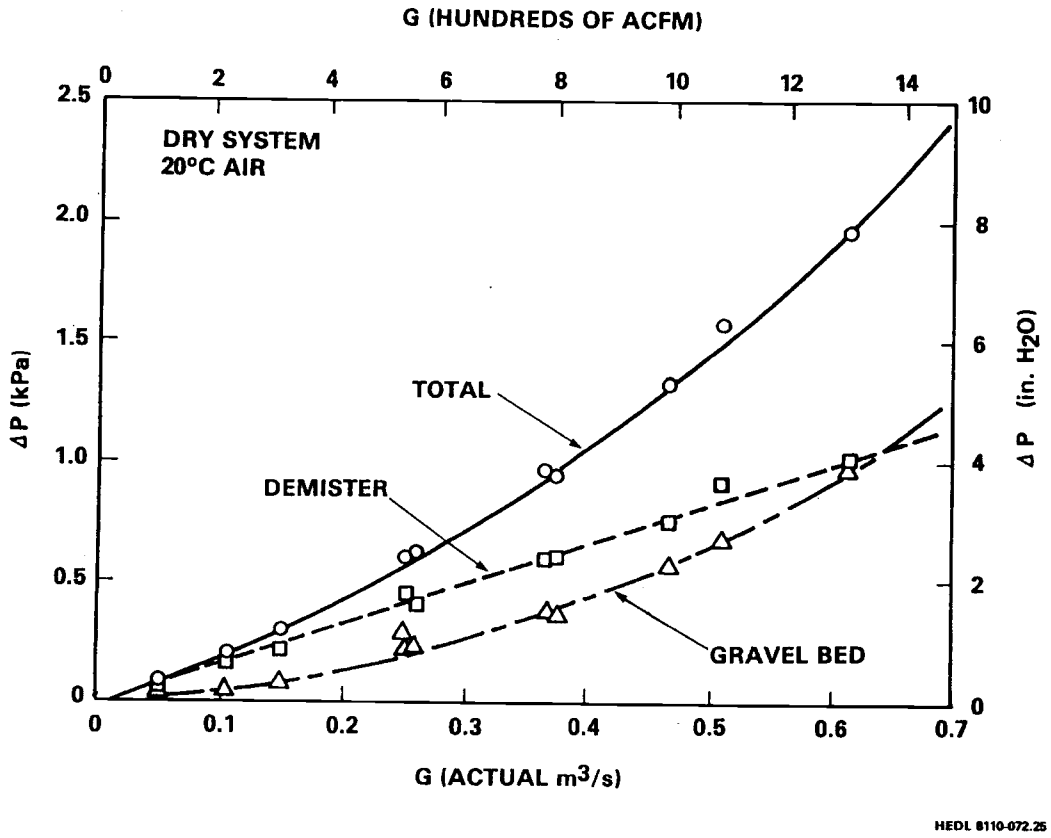

FIGURE 30. Pressure Drop Across Dry Test Article Components.

After water was charged to the SGS pool, the pressure drop was measured across the submerged gravel as a function of gas flow rate. The results are shown in Figure 31 for three different levels of the pool liquid. Of course, at zero flow, the ΔP was exactly equal to the depth of submergence of the gas inlet. The pressure drop increased linearly with gas flow rate, with the same slope of 2750 Pa per m^3/s for all three depths of submergence. This shows a greater dependence on gas velocity than for the case of the dry gravel bed, which is expected, because water partially fills the voids in the gravel bed. It should be pointed out that the data of Figure 31 were obtained with room temperature air and water. The ΔP across the SGS is also dependent upon the density of the pool solution, which normally increases with accumulation of aerosol. At the maximum concentration of

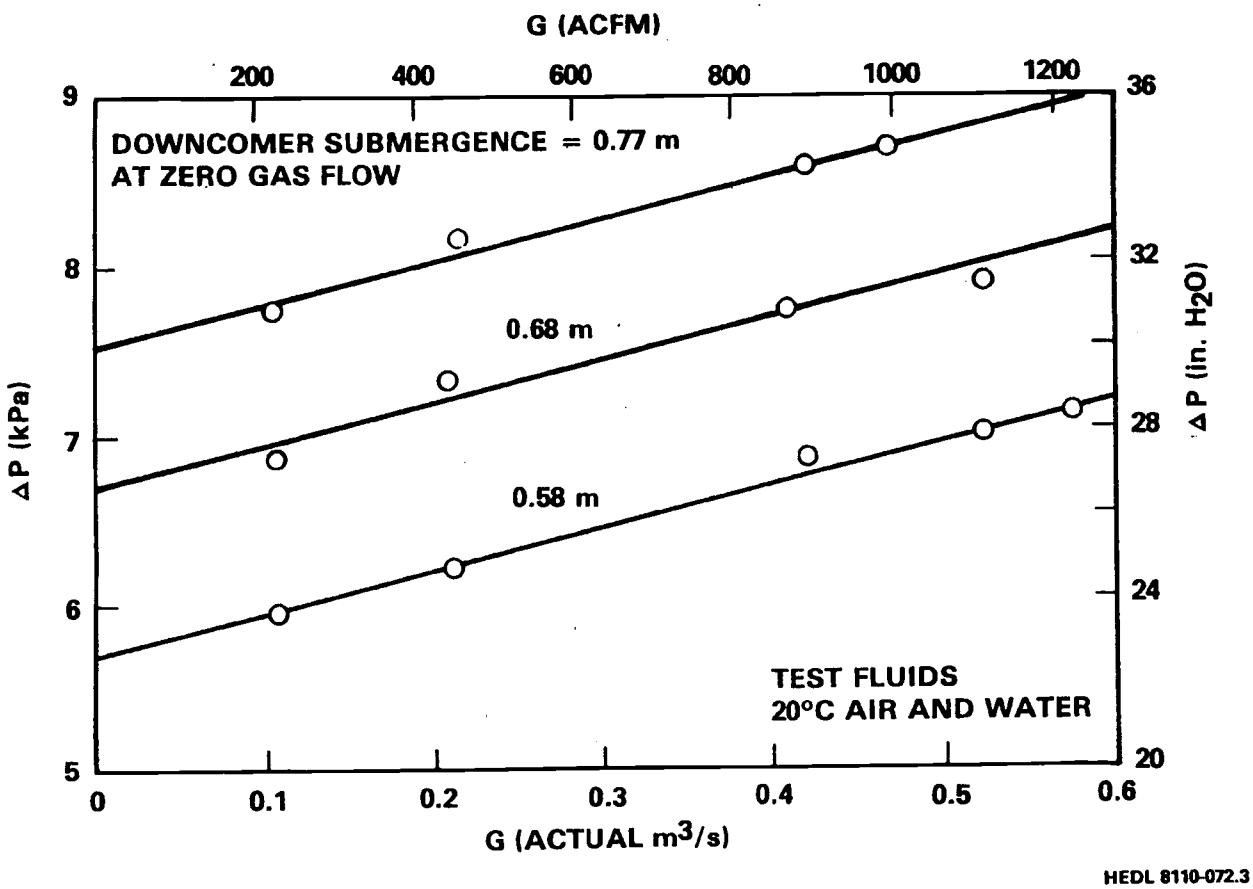

FIGURE 31. Pressure Drop Across SGS Pool at Several Liquid Levels.

NaOH expected during plant operation (5N), the density, and thus the ΔP, would be ~20% greater than for a water pool.

The pressure drop across the fiber bed demister is plotted as a function of gas flow rate in Figure 32. Three curves are shown, representing three states of liquid entrainment. All three cases showed that the pressure drop was linear with gas velocity, as expected from earlier work with a similar demister[5] and a study by Davies[12] with a packed bed of fibers. The empirical equation for the dry demister (Curve A) is given as Equation (7). The pressure drop through the demister with normal entrainment of water droplets from the SGS (Curve B) can be represented by Equation (8).

$$(\Delta P)_{\text{Curve B}} = 1.2 \times 10^7 \text{ G} \tag{8}$$

When water spray nozzles at the inlet to each demister were operated at 34 mℓ/s (Curve C) the pressure drop across the demisters increased, as expected due to reduction of void volume in the bed by entrained water. The empirical equation for this case is:

$$(\Delta P)_{\text{Curve C}} = 1.45 \times 10^7 \text{ G} \tag{9}$$

The pressure drops across the demister and the total pressure drops across the combined SGS/demister during each operating period are listed for tests AC7 through AC10 in Appendix E. The maximum pressure drops measured during the four tests were 1.46 kPa across the demister and 9.41 kPa total. These values are consistent with the room air tests discussed in the preceding paragraphs when allowance is made for changes in pool liquid density and pool level, and thus demonstrate that aerosol loading had no significant effect on pressure drop for these tests.

5.3.3 Gas Velocity and Liquid Pumping

The design superficial gas velocity through the gravel section of the SGS was 0.51 m/s (100 ft/min). Visual observations showed that as gas flowed

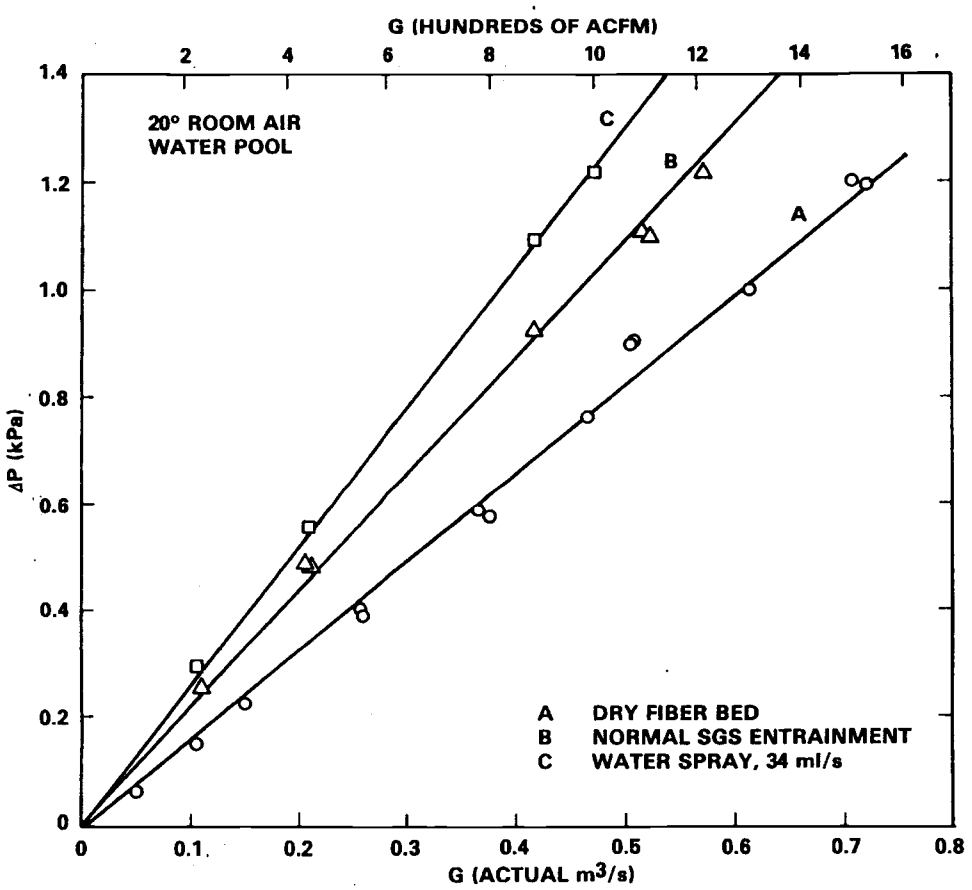

FIGURE 32. Pressure Drop Across the Demister.

upward through the liquid-filled gravel bed, liquid was pumped upward through the bed in much the same manner as that of an air lift pump.[13] However, due to the presence of packing material in the SGS, fluid flow was impeded andand the liquid phase did not flow at a steady rate. Rather, the liquid surged through the bed in pulses and overflowed the top rim of the gravel support barrel in waves. The gas flow rate did not vary in magnitude during a pulse cycle to the same extent that the liquid did, as evidenced by visual observations of the inlet aerosol/gas stream flowing in a uniform manner and the continuation of vigorous gas bubbling during the entire cycle.

Gas flow variation at the SGS duct inlet was measured by recording the pressure drop across the isolation valve, which was partially closed for the purpose of this measurement. The pressure drop across the valve oscillated at the same frequency as the liquid pulsing in the SGS, as shown in Figure 33. The pressure drop was related to gas flow rate by assuming that the valve acted as an orifice restriction and calibrating it by comparison with the downstream orifice meter. The results are presented in Table 39 and show that the gas velocity varied approximately $\pm 10\%$ from the mean during each cycle.

The water pumping rate was not measured with the present test article, but was measured by Owen and Postma[7] with a model having a cross-sectional gravel bed area of 0.062 m^2. The gravel type, grain size and bed depth was the same as used in the present large-scale tests. The data of Owen and Postma are presented in Figure 34 as a plot of the ratio of volumetric liquid to gas flow rate versus superficial gas velocity through the bed.

The level of the SGS pool surface increased with increasing gas flow rate due to the expulsion of water from the downcomer and gravel bed and the formation of a gas layer below the gravel bed support. The pool surface level was measured at various gas flow rates with a constant volume of water, and the data are presented in Figure 35. Figure 35 shows that the pool surface is elevated by ~100 mm at the design gas flow rate over the level at zero flow rate.

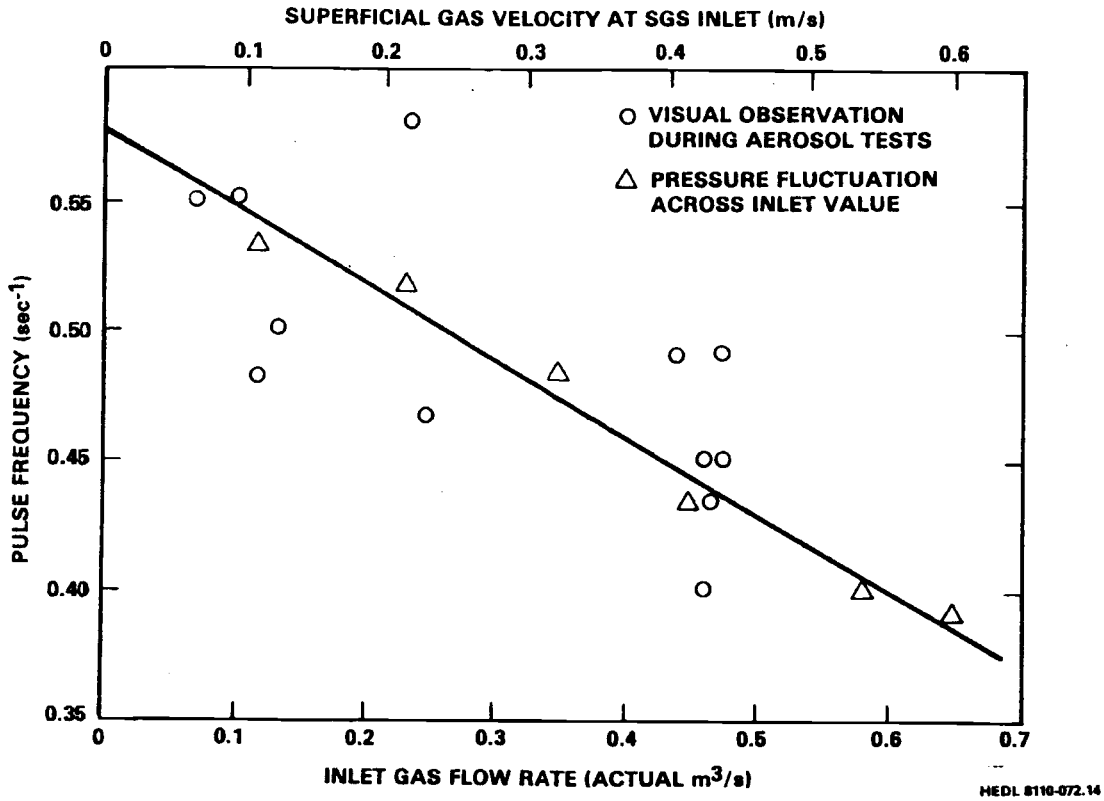

FIGURE 33. SGS Liquid Pulse Frequency as a Function of Gas Flow Rate.

TABLE 39

AMPLITUDE AND FREQUENCY OF SGS GAS FLOW PULSATION*

Downstream Average Gas Flow Rate (std m^3/s)	Inlet Gas Flow Rate During Pulse Cycle (std m^3/s)		Pulse Frequency (cycles/s)
	Maximum	Minimum	
0.097	0.106	0.083	0.533
0.191	0.203	0.179	0.517
0.288	0.300	0.276	0.483
0.368	0.394	0.340	0.433
0.477	0.528	0.418	0.400
0.528	0.574	0.482	0.390

*Measured by ΔP oscillation across inlet valve with SGS pool at normal level.

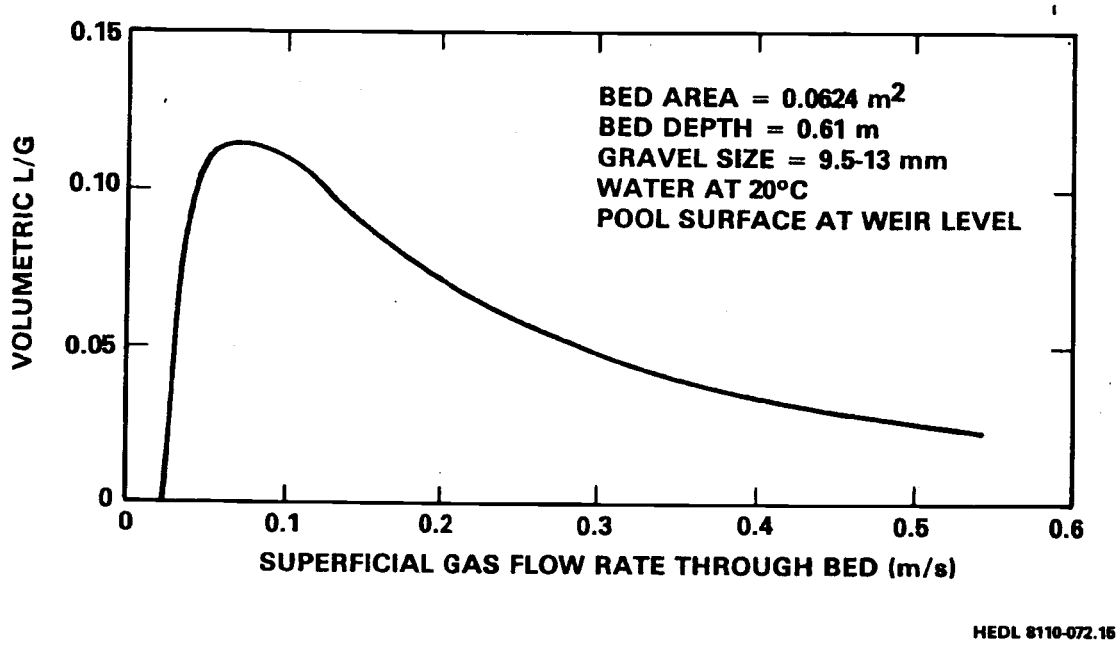

FIGURE 34. SGS Water Pumping Rate as a Function of Gas Flow Rate.

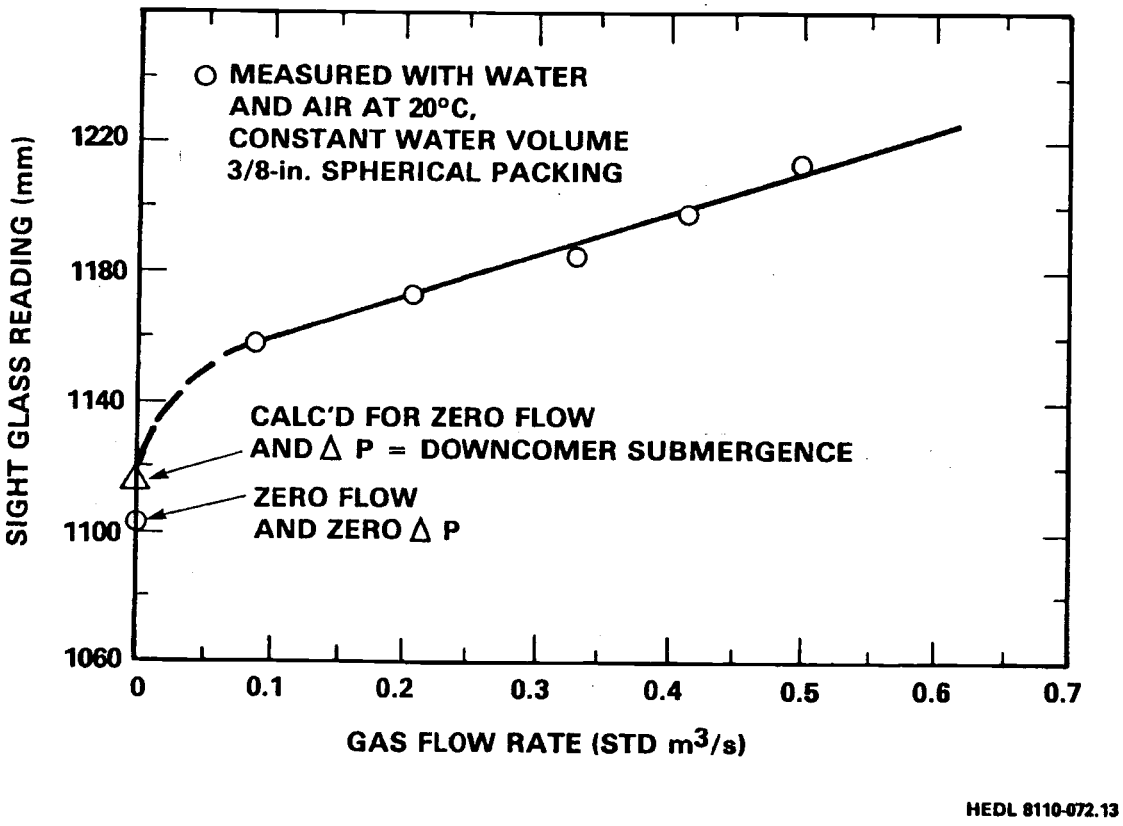

FIGURE 35. SGS Water Level as a Function of Gas Flow Rate for Constant Water Volume.

A series of measurements was made to determine the minimum level of the SGS pool surface at which water was circulated through the gravel bed. This was done by filling the SGS pool with water to the normal level and then slowly draining the liquid from the pool while observing the water overflowing the gravel basket weir. The gas flow rate was kept at a constant value during this time. As the level was lowered, the rate of water overflow decreased until a level was reached where no water overflowed the weir. This was defined as the "minimum water pumping level," and the results of measurements at five gas flow rates are listed in Table 40. The measurement is believed to be accurate to ±15 mm. The data are plotted as a function of gas flow rate in Figure 36.

5.4 LIQUID INVENTORIES

5.4.1 Sodium and NaI Inventories in Air Cleaning System

The sodium aerosol was deposited in various quantities throughout the air cleaning system. Figure 37 is a schematic flow diagram showing the flow paths and locations where aerosol collection occurred. The numerical figures in Figure 37 represent the average values of the mass fraction of sodium aerosol found at the various locations during post-test mass balances. Two conspicuous observations are clearly shown by the figure. The first is that by far the bulk of the aerosol mass is collected in the SGS pool (~99%). The second observation is that only a very small fraction (~0.0001) penetrated the test article.

The volume and sodium concentration in the SGS pool were measured at hourly intervals by withdrawing samples from near the top and near the bottom. The analyses from top and bottom agreed within ±3% of the mean, showing that the pool was well mixed. The pool volume and sodium concentration is given for each operating period in Tables G-1 through G-4 in Appendix G for tests AC7 through AC10, respectively. The calculated sodium inventory in the pool and incremental mass gain during each period is also shown for each operating period.

TABLE 40

MINIMUM POOL LEVEL REQUIRED FOR WATER PUMPING [a]

Inlet Gas Flow Rate (std m^3/s)	Inlet Gas Flow Rate (Actual m^3/s)	Pool Level, Distance Below Basket Weir (mm)[b]
0.0401	0.0463	10
0.0862	0.0992	60
0.212	0.244	91
0.415	0.476	205
0.531	0.612	215

(a) Water and air at 24°C, 3/8-in. ceramic spheres.

(b) Level below which water overflow ceased.

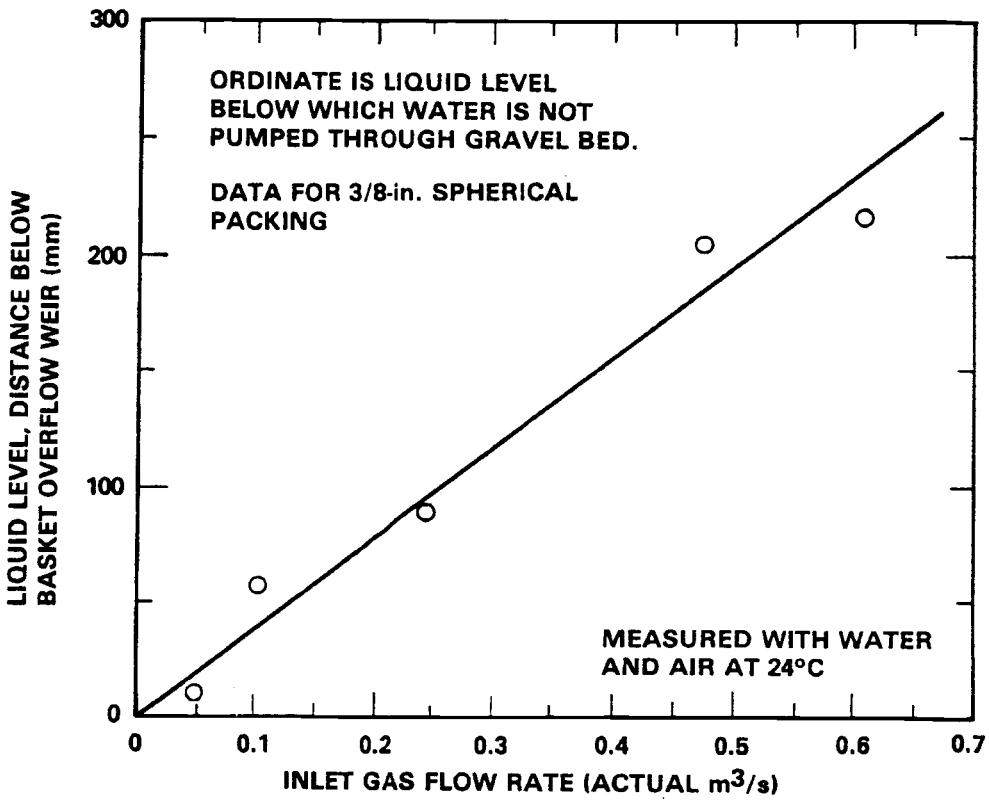

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FIGURE 36. Minimum Liquid Level for Water Pumping in the SGS.

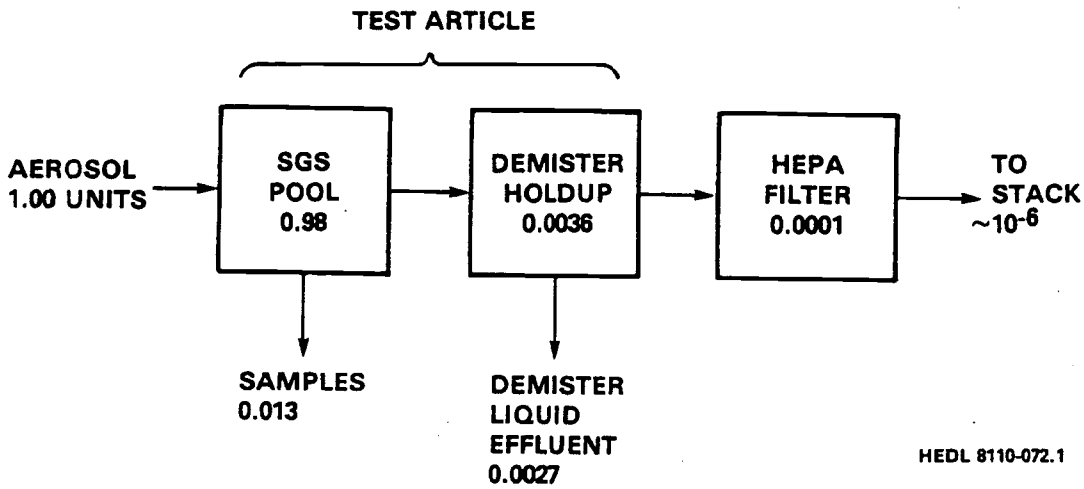

FIGURE 37. Schematic Flow Diagram of Aerosol Collection Locations.

Liquid entrainment from the SGS pool was carried by the gas stream to the demister, where a portion of it accumulated in the interstitial voids of the fiber bed and a portion flowed through the bed and was collected in the demister liquid effluent receiver. This receiver was emptied at hourly intervals and the contents measured for volume and sodium concentration. These measurements are listed in Tables G-5 through G-8 in Appendix G for tests AC7 through AC10, respectively. The effluent drainage rate varied significantly during each test, due to variations in gas flow rate, temperature, and initial state of demister bed liquid holdup saturation.

After each test, the demisters were washed by operating water spray nozzles at the inlet to the demisters while air was flowing through the demisters at the design rate. Several wash cycles were performed to ascertain when washing was sufficiently complete. The results for the four tests are presented in Table G-9 in Appendix G.

A significant volume of SGS pool solution was flushed through the sample line and discarded prior to taking each sample for analysis. These line washes were accumulated in a drum and analyzed for total quantity of sodium

at the end of each test. Other post-test material balance operations were the washing of ducts and the leaching of sodium aerosol from the backup HEPA filter. The duct deposition measurements are discussed in Section 5.6. The HEPA wash data are presented in Table G-10 in Appendix G.

The post-test aerosol mass accountability measurements on the air cleaning system are summarized in Table 41. NaI was added in test AC10, and the last column gives the mass of iodine (expressed as NaI) deposited in each location.

5.4.2 SGS Water Makeup

The liquid level in the SGS pool was monitored by visual readings of a sight glass. Water was added periodically by a manual valve to maintain the SGS pool liquid level at a constant value. The nominal liquid level throughout most of the operating time was 15 $\pm$ 30 mm above the gravel basket overflow weir. (See Figure 6). In three tests (AC7, AC8, AC10), the level was intentionally decreased to ~50 mm below the weir for a two-hour period, then increased to ~120 mm above the weir for a two-hour period to demonstrate the effect of pool level variation on operational behavior.

The times and quantities of water addition to the SGS pool are listed in Table G-11 in Appendix G. The times and quantities of pool drainage are also listed in Table G-11. The average rates of loss of SGS pool liquid are calculated in Table 42. The rates varied from 65 to 82 ml per standard m^3 of gas, with the average for the 4-test series being 69 ml per standard m^3. Most of this loss was due to evaporation by the hot, dry gas, with <10% being due to liquid drop entrainment loss.

5.4.3 Entrainment from the SGS Pool

The rate of liquid carryover from the SGS to the demister by entrainment in the gas stream was measured as a function of gas flow rate. The measurements were made with room temperature air and weak NaOH solution (0.2N) in the SGS

TABLE 41

POST-TEST AEROSOL MASS ACCOUNTED FOR IN AIR CLEANING SYSTEM

	Sodium Accounted For (kg Na)					Na Mass Fraction 4 Tests	NaI (g) AC 10
	AC7	AC8	AC9	AC10	4 Tests		
SGS Pool	240.49	249.24	78.87	249.18	817.78	0.9805	29.19
SGS Liquid Samples	3.553	3.965	0.877	2.566	10.961	0.0131	0.389
Demister Liquid Effluent	0.241	0.560	0.573	0.845	2.219	0.00266	32.85
Post-Test Demister Wash	0.723	1.007	0.512	0.771	3.013	0.00361	22.91
HEPA Filter Wash	0.0297	0.0414	0.0057	0.0166	0.0934	0.00011	0.599
Total	245.0367	254.8134	80.8377	253.3786	834.0664	0.99998	85.938

TABLE 42

RATE OF LOSS OF SGS POOL LIQUID

Parameter	AC7	AC8	AC9	AC10	All 4 Tests
Water Added to Pool[a] (ℓ)	2330	2110	600	1750	6790
Solution Drained From Pool (ℓ)	310	260	0	270	840
Net Water Added to Maintain Level (ℓ)	2020	1850	600	1480	5950
Gas Volume Handled (std m^3)[b]	30,990	28,300	8550	18,100	85,940
Average Liquid Loss Rate (ℓ/1000 std m^3)	65.2	65.4	70.2	81.8	69.2

(a) From Table G-11.

(b) For operation until end of Na Spray.

pool. Air was passed through the SGS/Demister test article at a constant flow rate while periodically draining off the effluent from the demisters. The volumetric entrainment rate, ξ, was measured by two methods. First, the volume of liquid flowing from the demisters over a known period of time was measured. Division of volume by time gave the average entrainment rate for that period. This method is subject to error if condensation or evaporation occurred in the test article downstream of the SGS pool. The measurements were continued until steady-state entrainment was attained. This required ~6 h at the design gas flow rate (0.47 m^3/s) and ~24 h at 20% of the design flow rate. A second method was also used by analyzing for sodium ion in the collected demister effluent. By relating the Na mass carryover to the sodium concentration in the SGS pool, the volumetric entrainment rate was calculated. The two methods agreed very closely, as shown by Table 43, indicating that heat transfer was negligible in these room temperature tests.

Measurements of the entrainment rate during aerosol tests AC7 through AC10 was attempted by using the same methods described in the preceding paragraph. The results are given in Table 43. Several complicating factors caused large errors in the measurements, however. First, the gas flow rate was not constant, so that time intervals were too short for equilibrium to be attained. Secondly, the gas exiting the SGS pool was at an elevated temperature and cooled slightly during transit through downstream sections of the test article. This caused condensation, with erroneously high results for the measurement based on liquid volume collected. Finally, the Na tracer method was affected by the changing sodium concentration in the SGS pool and the holdup in the demister.

The data of Table 43 are plotted in Figure 38. Two observations are apparent from the shape of the curve. First, the entrainment rate is strongly affected by gas flow rate. Second, there appears to be a break point at a gas flow rate of 0.2 to 0.3 m^3/s, below which the entrainment rate falls very rapidly with decreasing gas rate. This may be due to settling of entrainment drops in the plenum above the SGS pool. If the entrained liquid

TABLE 43

ENTRAINMENT FROM SGS POOL

Test No.	Gas Flow Rate[a] (m^3/s)	Steady State Volumetric Entrainment Rate (ml/s)	
		Based On Liquid Volume Collected	Based On Na Tracer
Room Temp 7-81	0.082	5.0 (-5)[b]	4.6 (-5)
	0.205	7.0 (-4)	5.8 (-4)
	0.328	9.5 (-2)	9.1 (-1)
	0.411	1.9 (-1)	1.8 (-1)
	0.533	4.1 (-1)	4.1 (-1)
AC7 [c]	0.36	4.0 (-1)	9.6 (-2)
AC8 [d]	0.36	7.8 (-1)	2.1 (-1)
AC10[e]	0.34	7.1 (-1)	1.5 (-1)

(a) At SGS Outlet conditions.
(b) Numbers in parenthesis are exponents of 10.
(c) For operating periods 13 through 18.
(d) For operating periods 9 through 18.
(e) For operating periods 10 through 15.

drops leaving the pool surface were in the range of 50 to 100 μm diameter, most of the entrained mass would settle back to the pool surface at gas flow rates of 0.2 to 0.3 m^3/s. This effect is design dependent, of course, and the curve of Figure 38 applies only to the present test article.

5.5 EFFICIENCY FOR SODIUM AEROSOL REMOVAL

Determination of the aerosol removal efficiency was one of the prime test objectives. The efficiency is defined as the fraction of the entering mass retained by the component or system of interest. Since chemical change in

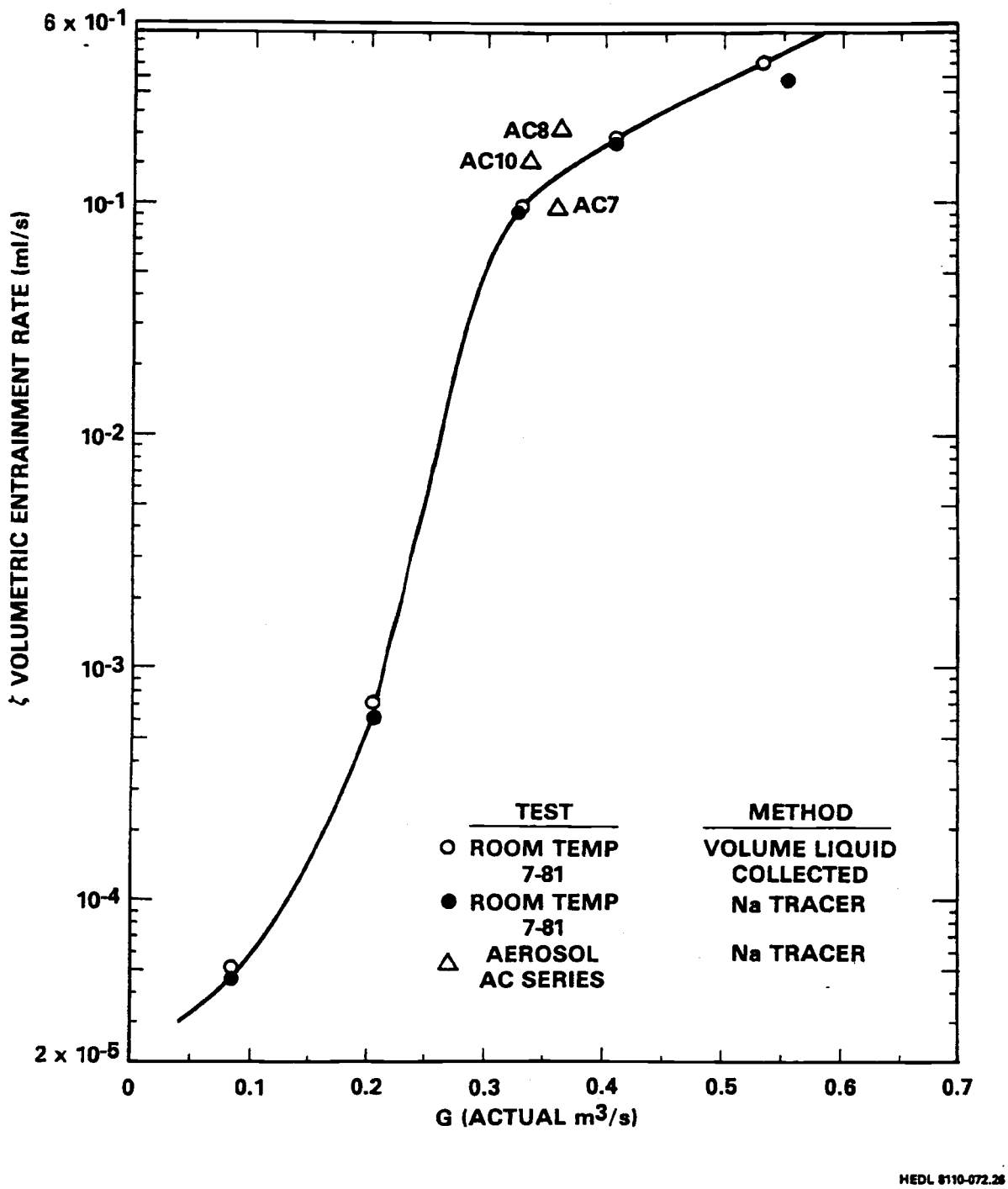

FIGURE 38. Volumetric Entrainment Rate from the SGS.

the aerosol may occur during transit through the scrubber system, it is convenient to express the efficiency in terms of the sodium content of the aerosol, rather than by total aerosol mass. Since radioactive aerosol materials should maintain a constant mass ratio relative to sodium this method of calculation gives an equivalent efficiency for coagglomerated, radioactive aerosol removal. The assumption that aerosol species of different materials (e.g., sodium oxide/hydroxide, fuel, fission products) coagglomerate continuously, yielding agglomerates of uniform composition has not been fully confirmed.[14] However, recent experiments[15,16] have shown that this assumption is valid for fuel-sodium mixtures.

Efficiencies were determined by two methods in the present work: 1) aerosol sampling of the gas upstream and downstream from each air cleaning component; and 2) by liquid sampling for sodium content in the recirculated scrubber solution for each component.

5.5.1 Sodium Removal Efficiency Based on Aerosol Sampling

The aerosol removal efficiency, E, was calculated from aerosol concentration measurements using:

$$E_i = 1 - \frac{C_{g_{out}}}{C_{g_{in}}} \tag{10}$$

where:

$C_{g_{out}}$ = Mass concentration in the gas outlet (g Na/m^3 STP)

$C_{g_{in}}$ = Mass concentration in the gas inlet (g Na/m^3 STP)

i = Air cleaning component of interest

An alternative expression for the effectiveness of an air cleaning device is the penetration, P, which is the fraction of the incident mass that

penetrates the component of interest. P is the complement of E and is defined by:

$$P_i = 1 - E_i = \frac{C_{g_{out}}}{C_{g_{in}}} \tag{11}$$

The penetration is more useful for correlating data on systems of very high efficiency, where E approaches unity.

Aerosol samples were withdrawn from the inlet gas stream, from the intermediate gas (the gas plenum between the SGS pool and the inlet to the demisters) and from the gas effluent from the demister section of the test article. The samples were analyzed for suspended sodium mass concentration and particle size by methods described in Section 3.5.1.

Several limitations on the accuracy of efficiencies obtained from these samples are worth noting. First, the filters were analyzed for sodium mass, rather than total aerosol mass, and for this reason, the results apply to sodium rather than total aerosol mass. This kind of efficiency is thought to be valid when related to the radioactive content of an accident-generated aerosol. On the other hand, the sodium efficiency measurement would not account for change in the mass of sorbed water, which could make up a significant fraction of total aerosol mass downstream of the SGS. A second limitation of efficiencies derived from aerosol samples is that the upstream sample duration was typically only 20 seconds as compared to 50 minutes for the downstream sample. Thus, if the aerosol concentration changed appreciably during the sampling period, error would be introduced.

A third source of sampling error was the variable quantity of entrained liquid drops collected from the gas plenum over the SGS pool. The breaking of bubbles at the surface of the SGS pool generated liquid droplets containing sodium at the same concentration as the SGS pool. The collection of entrained drops caused the indicated aerosol removal efficiency to be low,

particularly late in the test, when the sodium concentration in the pool was high. At very low values of inlet aerosol concentration, after the end of sodium spray, the SGS efficiency could easily be negative. However, in this case, the absolute value of the penetrating sodium mass would be very small, and furthermore, the demister would have a high efficiency for removing the relatively large entrained drops.

Finally, the upstream sample was affected by reentrainment of aerosol material previously deposited on the walls of the delivery duct. When one of these very large agglomerates was collected in the inlet duct sampler, the corresponding sample showed an unusually high sodium airborne concentration. This problem was circumvented by comparing the inlet duct aerosol concentration with the concentration in the containment vessel atmosphere. The suspended concentration measured in the containment atmosphere was used in place of the inlet duct concentration whenever the duct sample was obviously incorrect.

Sodium aerosol removal efficiencies based on aerosol sampling are presented in Tables 44 through 47 for tests AC7 through AC10, respectively. In addition to the efficiencies, the airborne concentration at the SGS inlet, SGS outlet and demister outlet are also listed. When only one set of aerosol samples was taken during an operating period, they are assumed to be representative of the entire period. When more than one set of samples was taken, the measurements were averaged to represent the operating period. The average efficiencies for the entire test during the time when sodium aerosol was being generated are also listed at the bottom of each table. Efficiencies are listed for the SGS (E_{SGS}), the demister (E_{Dem}) and for the combined SGS/Demister test article ($E_{overall}$).

Tables 44 through 47 show that the SGS typically achieved an efficiency of 0.99, the demister efficiency exceeded 0.97, and the overall efficiency for the SGS/Demister test article exceed 0.9997. A discussion of sodium aerosol removal efficiency and the effect of various operating parameters is given in Section 6.3.

TABLE 44

SODIUM AEROSOL REMOVAL EFFICIENCIES MEASURED BY AEROSOL SAMPLING IN TEST AC7

Time[a] (min)	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
187	1	8.38 (0)[e]	7.00 (-2)	3.91 (-4)	0.9916	0.9944	0.999953
243	2	1.27 (1)	1.84 (-2)	6.35 (-4)	0.9986	0.9655	0.999950
303	3	1.42 (1)	2.34 (-2)	9.57 (-5)	0.9984	0.9959	0.999993
364	4	1.06 (1)	1.87 (-2)	1.87 (-4)	0.9982	0.9900	0.999982
423	5	1.02 (1)	2.61 (-2)	2.71 (-4)	0.9975	0.9896	0.999974
500	6	1.05 (1)	2.62 (-2)	2.95 (-4)	0.9975	0.9887	0.999972
538	7	8.74 (0)	2.15 (-2)	4.57 (-4)	0.9975	0.9787	0.999948
613	8	1.08 (1)	4.98 (-2)	5.70 (-4)	0.9954	0.9886	0.999947
663	9	9.26 (0)	6.23 (-2)	8.47 (-4)	0.9933	0.9864	0.999909
726	10	1.09 (1)	4.29 (-2)	6.84 (-4)	0.9960	0.9841	0.999937
784	11	8.65 (0)	4.01 (-2)	7.82 (-4)	0.9954	0.9805	0.999910
843	11	9.70 (0)	4.45 (-2)	1.17 (-3)	0.9954	0.9737	0.999879
Avg.	11	--	--	--	0.9954	0.9771	0.999895
893	12	1.02 (1)	6.37 (-2)	1.47 (-3)	0.9938	0.9769	0.999856
968	12	1.17 (1)	6.90 (-2)	1.47 (-3)	0.9941	0.9787	0.999874
Avg	12	---	---	---	0.9940	0.9778	0.999865

TABLE 44 (Cont'd)

Time (min)	Operating Period No.	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency E_{SGS}	E_{Dem}	$E_{Overall}$
1023	13	9.43 (0)	9.43 (-2)	1.75 (-3)	0.9900	0.9814	0.999814
1073	13	9.41 (0)	5.13 (-2)	1.86 (-3)	0.9945	0.9637	0.999802
Avg	13	---	---	---	0.9923	0.9726	0.999808
1130	14	1.30 (1)	9.23 (-2)	2.59 (-3)	0.9929	0.9719	0.999801
1203	14	1.36 (1)	1.13 (-1)	3.30 (-3)	0.9913	0.9723	0.999757
Avg	14	---	---	---	0.9921	0.9721	0.999779
1263	15	1.22 (1)	9.45 (-2)	3.61 (-3)	0.9923	0.9618	0.999704
1333	15	9.85 (0)	7.39 (-2)	3.22 (-3)	0.9925	0.9564	0.999673
Avg	15	---	---	---	0.9924	0.9591	0.999689
1386	16	1.13 (1)	6.96 (-2)	3.75 (-3)	0.9938	0.9461	0.999668
1443	16	1.08 (1)	9.62 (-2)	3.80 (-3)	0.9911	0.9605	0.999648
Avg	16	---	---	---	0.9925	0.9533	0.999658
1503	17	7.74 (0)	7.65 (-2)	3.31 (-3)	0.9901	0.9567	0.999572
1558	17	9.20 (0)	1.60 (-1)	4.64 (-3)	0.9826	0.9710	0.999496
Avg	17	---	---	---	0.9863	0.9639	0.999534
1620	18	1.20 (1)	1.47 (-1)	4.80 (-3)	0.9877	0.9673	0.999598
1683	18	9.77 (0)	1.04 (-1)	4.64 (-3)	0.9894	0.9554	0.999525
Avg	18	---	---	---	0.9886	0.9614	0.999562
1743	19	1.12 (1)	1.14 (-1)	6.11 (-3)	0.9898	0.9464	0.999454
1863	20	1.13 (1)	1.05 (-1)	9.97 (3)	0.9907	0.9050	0.999118

TABLE 44 (Cont'd)

Time (min)[a]	Operating Period No.[b]	Aerosol Concentration (g Na/m³ STP)[c]			Removal Efficiency[d]		
		SGS Inlet	SGS Outlet	Demister Outlet	E_{SGS}	E_{Dem}	$E_{Overall}$
1985	21	5.00 (0)	1.28 (-1)	8.84 (-4)	0.9744	0.9931	0.999823
2089	22	4.10 (-1)	3.81 (-3)	4.29 (-5)	0.9907	0.9887	0.999895
	1 - 20				0.9939[f]	0.9725[f]	0.999771[f]

(a) Midpoint of sampling period.

(b) See Table 7 for time interval and test conditions.

(c) STP refers to standard temperature and pressure (0°C, 101.4 kPa).

(d) Fraction of incident aerosol sodium mass captured by identified component.

(e) Numbers in parenthesis are exponents of 10.

(f) Arithmetic average for period when Na spray operated.

TABLE 45

SODIUM AEROSOL REMOVAL EFFICIENCIES MEASURED BY AEROSOL SAMPLING IN TEST AC8

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c]			Removal Efficiency[d]		
		SGS Inlet	SGS Outlet	Demister Outlet	E_{SGS}	E_{Dem}	$E_{Overall}$
181	1	1.20 (1)[e]	1.21 (-2)	2.55 (-4)	0.9990	0.9789	0.999979
238	2	1.10 (1)	2.06 (-2)	1.19 (-4)	0.9981	0.9942	0.999989
258	2	1.04 (1)	1.55 (-2)	1.19 (-4)	0.9985	0.9923	0.999989
Avg	2	---	---	---	0.9983	0.9932	0.999989
298	3	1.15 (1)	1.92 (-2)	2.82 (-3)	0.9983	0.8531	0.999756
318	3	9.86 (0)	2.85 (-2)	2.82 (-3)	0.9971	0.9011	0.999714
Avg	3	---	---	---	0.9977	0.8771	0.999735
363	4	1.08 (1)	3.32 (-2)	5.05 (-4)	0.9969	0.9848	0.999953
423	5	1.38 (1)	4.97 (-2)	2.30 (-4)	0.9964	0.9954	0.999983
498	6	1.48 (1)	7.70 (-2)	5.18 (-4)	0.9948	0.9933	0.999965
551	7	1.46 (1)	9.91 (-2)	9.10 (-4)	0.9932	0.9908	0.999937
608	8	1.56 (1)	1.11 (-1)	8.98 (-4)	0.9929	0.9919	0.999942
654	9	1.38 (1)	8.62 (-2)	7.33 (-4)	0.9938	0.9915	0.999947
650	9	1.35 (1)	1.18 (-1)	7.33 (-4)	0.9913	0.9938	0.999946
Avg	9	---	---	---	0.9925	0.9926	0.999946
723	10	1.58 (1)	1.01 (-1)	9.67 (-4)	0.9936	0.9904	0.999939

TABLE 45 (Cont'd)

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
780	11	1.59 (1)[e]	(f)	1.40 (-3)	(f)	(f)	0.999912
833	12	1.46 (1)	1.32 (-1)	1.62 (-3)	0.9910	0.9877	0.999889
913	12	1.39 (1)	1.71 (-1)	2.02 (-3)	0.9877	0.9882	0.999854
Avg	12	---	---	---	0.9894	0.9880	0.999873
963	13	1.23 (1)	7.26 (-2)	1.82 (-3)	0.9941	0.9749	0.999853
1020	13	1.26 (1)	1.46 (-1)	2.29 (-3)	0.9884	0.9843	0.999818
Avg	13	---	----	---	0.9912	0.9796	0.999836
1083	14	1.29 (1)	1.61 (-1)	1.63 (-3)	0.9875	0.9899	0.999874
1138	14	1.48 (1)	1.46 (-1)	2.13 (-3)	0.9901	0.9854	0.999856
Avg	14	---	---	---	0.9888	0.9876	0.999865
1203	15	1.16 (1)	2.39 (-1)	2.60 (-3)	0.9795	0.9891	0.999776
1260	15	1.41 (1)	2.23 (-1)	3.31 (-3)	0.9842	0.9852	0.999765
Avg	15	---	---	---	0.9818	0.9871	0.999770
1328	16	1.00 (1)	2.72 (-1)	5.13 (-3)	0.9729	0.9811	0.999490
1383	16	9.65 (0)	2.70 (-1)	6.47 (-3)	0.9720	0.9760	0.999330
Avg	16	---	---	---	0.9725	0.9785	0.999410
1443	17	9.42 (0)	2.81 (-1)	4.56 (-3)	0.9702	0.9838	0.999516
1502	17	1.06 (1)	2.77 (-1)	3.18 (-3)	0.9740	0.9885	0.999701
Avg	17	---	---	---	0.9721	0.9862	0.999608

TABLE 45 (Cont'd)

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
1546	18	9.80 (0)[e]	2.45 (-1)	4.58 (-3)	0.9750	0.9813	0.999533
1629	18	1.02 (1)	2.26 (-1)	7.61 (-3)	0.9778	0.9663	0.999252
Avg	18	---	---	---	0.9764	0.9738	0.999392
1685	19	9.69 (0)	1.71 (-1)	6.92 (-3)	0.9824	0.9595	0.999286
1745	19	1.29 (1)	2.56 (-1)	6.34 (-3)	0.9801	0.9752	0.999507
Avg	19	---	---	---	0.9812	0.9673	0.999396
1803	20	9.17 (0)	1.94 (-1)	5.92 (-3)	0.9788	0.9695	0.999354
1870	20	7.45 (0)	2.37 (-1)	4.33 (-3)	0.9682	0.9817	0.999419
Avg	20	---	---	---	0.9735	0.9756	0.999353
1946	21	9.40 (-1)	5.69 (-2)	6.87 (-5)	0.9395	0.9988	0.999927
2030	22	3.54 (-1)	6.05 (-2)	1.99 (-5)	0.8291	0.9997	0.999944
	1 - 20	---	---	---	0.9885[g]	0.9796[g]	0.999765[g]

(a) Midpoint of sampling period.

(b) See Table 8 for time interval and test conditions.

(c) STP refers to standard temperature and pressure (0°C, 101.4 kPa).

(d) Fraction of incident aerosol sodium mass captured by identified component.

(e) Numbers in parenthesis are exponents of 10.

(f) Not sampled.

(g) Arithmetic average for period when Na spray operated.

TABLE 46

SODIUM AEROSOL REMOVAL EFFICIENCIES MEASURED BY AEROSOL SAMPLING IN TEST AC9

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c]			Removal Efficiency[d]		
		SGS Inlet	SGS Outlet	Demister Outlet	E_{SGS}	E_{Dem}	$E_{Overall}$
62	1	(e)	(e)	(e)	(e)	(e)	(e)
87	2	1.58 (1)[f]	8.29 (-2)	1.17 (-4)	0.9948	0.9984	0.999993
107	2	1.62 (1)	8.46 (-2)	1.17 (-4)	0.9948	0.9986	0.999993
Avg	2	---	---	---	0.9948	0.9985	0.999993
142	3	1.44 (1)	(e)	2.23 (-4)	(e)	(e)	0.999984
162	4	1.60 (1)	5.75 (-2)	(e)	0.9964	(e)	(e)
200	4	1.55 (1)	6.81 (-2)	3.20 (-4)	0.9956	0.9953	0.999979
Avg	4	---	---	---	0.9960	0.9953	0.999979
270	5	1.63 (1)	9.11 (-2)	3.00 (-4)	0.9944	0.9967	0.999981
280	5	1.64 (1)	9.35 (-2)	3.00 (-4)	0.9943	0.9968	0.999982
Avg	5	---	---	---	0.9943	0.9968	0.999981
322	6	1.71 (1)	9.71 (-2)	2.54 (-4)	0.9943	0.9974	0.999985
327	6	1.80 (1)	8.94 (-2)	2.54 (-4)	0.9951	0.9972	0.999986
Avg	6	---	---	---	0.9947	0.9973	0.999985
377	7	1.33 (1)	1.07 (-1)	2.50 (-4)	0.9920	0.9977	0.999981
437	8	1.93 (1)	1.25 (-1)	2.85 (-4)	0.9935	0.9977	0.999985
510	9	8.85 (0)	2.19 (-2)	1.00 (-4)	0.9975	0.9954	0.999989

TABLE 46 (Cont'd)

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
558	10	4.53 (0)[f]	1.62 (-2)	4.0 (-5)	0.9964	0.9975	0.999999
632	11	2.82 (0)	8.73 (-3)	1.0 (-5)	0.9969	0.9989	0.999999
692	12	2.57 (0)	2.22 (-2)	4.5 (-5)	0.9914	0.9980	0.999982
702	13	4.50 (0)	2.42 (-2)	4.8 (-5)	0.9946	0.9980	0.999989
747	13	5.06 (0)	2.61 (-2)	4.8 (-5)	0.9948	0.9982	0.999991
Avg	13	---	---	---	0.9947	0.9981	0.999990
812	14	1.11 (0)	∿1.0 (-3)	∿1.0 (-5)	0.9991	0.9900	0.999991
865	15	3.13 (-1)	1.44 (-3)	∿1.0 (-5)	0.9954	0.9931	0.999968
917	16	7.64 (-2)	(e)	∿1.0 (-5)	(e)	(e)	0.999870
938	16	5.22 (-2)	1.96 (-3)	∿1.0 (-5)	0.9625	0.9949	0.999808
Avg	16	---	---	---	0.9625	0.9949	0.999839
985	17	4.21 (-2)	2.42 (-3)	(e)	0.9425	(e)	(e)
1042	18	1.92 (-2)	∿2.0 (-4)	<1.0 (-5)	0.9896	>0.9500	>0.999479
1054	18	1.12 (-2)	∿2.0 (-3)	<1.0 (-5)	0.8214	>0.9950	>0.999107
Avg	18	---	---	---	0.9055	>0.9725	>0.999293

TABLE 46 (Cont'd)

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
1153	19	2.05 (-3)	(e)	<1.0 (-5)	(e)	(e)	>0.995122
1170	19	1.82 (-3)	1.17 (-3)	<1.0 (-5)	0.3571	0.9915	>0.994505
Avg	19	---	---	---	0.3571	0.9915	>0.994814
	1 - 13	---	---	---	0.9947[g]	0.9974[g]	0.999986[g]

(a) Midpoint of sampling period.

(b) See Table 9 for time interval and test conditions.

(c) STP refers to standard temperature and pressure (0°C, 101.4 kPa).

(d) Fraction of incident aerosol sodium mass captured by identified component.

(e) Not measured.

(f) Numbers in parenthesis are exponents of 10.

(g) Arithmetic average during period when Na spray operated.

TABLE 47

SODIUM AEROSOL REMOVAL EFFICIENCIES MEASURED BY AEROSOL SAMPLING IN TEST AC10

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c]			Removal Efficiency[d]		
		SGS Inlet	SGS Outlet	Demister Outlet	E_{SGS}	E_{Dem}	$E_{Overall}$
187	1	1.03 (1)[e]	4.18 (-2)	6.08 (-4)	0.9959	0.9855	0.999941
238	2	1.78 (1)	3.79 (-2)	1.17 (-4)	0.9979	0.9969	0.999993
258	2	1.79 (1)	3.91 (-2)	1.17 (-4)	0.9979	0.9970	0.999993
Avg	2	---	---	---	0.9979	0.9970	0.999993
303	3	1.79 (1)	3.78 (-2)	2.82 (-4)	0.9979	0.9925	0.999984
318	3	1.79 (1)	3.77 (-2)	2.82 (-4)	0.9979	0.9925	0.999984
Avg	3	---	---	---	0.9979	0.9925	0.999984
363	4	1.60 (1)	4.22 (-2)	8.46 (-4)	0.9974	0.9800	0.999947
423	5	1.78 (1)	5.97 (-2)	8.89 (-4)	0.9966	0.9851	0.999950
498	6	1.79 (1)	6.58 (-2)	1.10 (-3)	0.9963	0.9833	0.999938
538	7	1.89 (1)	1.05 (-1)	1.86 (-3)	0.9942	0.9823	0.999902
548	7	1.63 (1)	8.92 (-2)	1.86 (-3)	0.9945	0.9791	0.999886
Avg	7	---	---	---	0.9944	0.9807	0.999894
608	8	1.79 (1)	1.39 (-1)	2.14 (-3)	0.9922	0.9846	0.999880
663	9	1.60 (1)	8.35 (-2)	1.75 (-3)	0.9948	0.9790	0.999891

TABLE 47 (Cont'd)

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
723	10	1.59 (1)	1.02 (-1)	2.37 (-3)	0.9936	0.9768	0.999851
783	11	1.58 (1)	1.18 (-1)	3.01 (-3)	0.9925	0.9745	0.999809
853	11	1.55 (1)	1.79 (-1)	3.81 (-3)	0.9884	0.9787	0.999754
Avg	11	---	---	---	0.9904	0.9766	0.999781
908	12	1.54 (1)	1.52 (-1)	3.14 (-3)	0.9901	0.9793	0.999796
997	13	1.49 (1)	1.60 (-1)	(f)	0.9893	(f)	(f)
1027	13	1.22 (1)	1.72 (-1)	3.50 (-3)	0.9859	0.9797	0.999713
1088	13	1.69 (1)	1.88 (-1)	5.01 (-3)	0.9888	0.9734	0.999703
Avg	13	---	---	---	0.9880	0.9765	0.999708
1153	14	1.41 (1)	2.00 (-1)	5.04 (-3)	0.9858	0.9748	0.999642
1196	14	1.69 (1)	8.86 (-2)	6.55 (-3)	0.9948	0.9261	0.999612
1208	14	1.33 (1)	2.21 (-1)	(f)	0.9834	(f)	(f)
Avg	14	---	---	---	0.9903	0.9615	0.999627
1263	15	1.35 (1)	1.72 (-1)	6.56 (-3)	0.9873	0.9619	0.999514
1273	15	1.48 (1)	2.21 (-1)	6.56 (-3)	0.9851	0.9703	0.999557
1333	15	1.23 (1)	2.01 (-1)	6.10 (-3)	0.9837	0.9697	0.999504
Avg	15	---	---	---	0.9854	0.9673	0.999525
1378	16	1.42 (1)	1.68 (-1)	2.93 (-3)	0.9881	0.9826	0.999794
1388	16	1.44 (1)	1.69 (-1)	2.93 (-3)	0.9883	0.9827	0.999797
1398	16	1.45 (1)	2.05 (-1)	2.93 (-3)	0.9859	0.9857	0.999798
Avg	16	---	---	---	0.9874	0.9837	0.999796

TABLE 47 (Cont'd)

Time (min)[a]	Operating Period No. (b)	Aerosol Concentration (g Na/m³ STP)[c] SGS Inlet	SGS Outlet	Demister Outlet	Removal Efficiency[d] E_{SGS}	E_{Dem}	$E_{Overall}$
1438	17	1.64 (1)	1.51 (-1)	4.23 (-3)	0.9908	0.9720	0.999742
1448	17	1.42 (1)	1.88 (-1)	4.23 (-3)	0.9868	0.9775	0.999702
1458	17	1.45 (1)	8.52 (-2)	4.23 (-3)	0.9941	0.9504	0.999708
Avg	17	---	---	---	0.9906	0.9696	0.999714
1508	18	7.76 (0)	7.81 (-2)[g]	4.09 (-3)	0.9899	0.9476	0.999473
1518	18	6.23 (0)	1.61 (0)	4.09 (-3)	0.7416[g]	0.9975[g]	0.999343
Avg	18	---	---	---	0.9899	0.9478	0.999473
1575	19	6.90 (-1)	9.83 (-3)	3.50 (-5)	0.9858	0.9964	0.999949
1632	20	2.18 (-1)	(f)	(f)	(f)	(f)	(f)
1650	21	1.40 (-1)	1.17 (-2)[g]	1.44 (-5)	0.9164	0.9988	0.999897
1676	21	9.11 (-2)	2.30 (-2)	1.44 (-5)	0.7475[g]	0.9994	0.999842
Avg	21	---	---	---	0.9164	0.9988	0.999870
1770	23	1.73 (-2)	5.63 (-3)	1.58 (-5)	0.6746	0.9972	0.999087
1875	24	1.09 (-2)	8.23 (-3)	1.14 (-5)	0.2450	0.9987	0.998954
	1 - 18	---	---	---	0.9926	0.9774	0.999833

(a) Midpoint of sampling period.
(b) See Table 10 for time interval and test conditions.
(c) STP refers to standard temperature and pressure (0°C, 101.4 kPa).
(d) Fraction of incident aerosol sodium mass captured by identified component.
(e) Numbers in parenthesis are exponents of 10.
(f) Not measured.
(g) Special sample taken close to pool surface to catch entrainment.
(h) Arithmetic average for period when Na spray operated.

5.5.2 Sodium Removal Efficiency Based on Liquid Sampling

Samples of the SGS pool solution were withdrawn at hourly intervals, as discussed in Section 5.4.1. The inventory of sodium in the SGS pool and the incremental gain during each operating period are given in Tables G1 through G4 in Appendix G for tests AC7 through AC10, respectively. The liquid stream which penetrated the demister and flowed to the tube sheet was also drained at hourly intervals. The volume and sodium mass inventories in the demister drain are presented in Tables G5 through G8 in Appendix G.

In principle, the sodium removal efficiency of the SGS should be determinable from the material balance, based on incremental sodium mass accumulated in the SGS pool and demister drain during each operating period. However, the liquid holdup within the fiber bed of the demister was significant, and a reliable material balance could be obtained only after the demister was washed. This was done only at the end of each test. The sodium mass held within the fiber bed and recovered by post-test washing is reported in Table G9 in Appendix G.

The backup HEPA filters were destructively analyzed for sodium at the end of each test. The sodium inventories on the HEPA filters are listed in Table G9 in Appendix G.

The post-test accountability for sodium mass collected in the various components of the air cleaning system is listed in Table 41. From the data in Table 41, overall sodium removal efficiencies were calculated and are presented in Tables 48 through 51 for tests AC7 through AC10, respectively.

The liquid-based efficiency measurement method is thought to be reliable, particularly for the two-stage SGS/Demister system, because all of the effluent gas passed through a backup HEPA filter. HEPA filters are known to be highly efficient for particles of all sizes, so there is little question that all of the aerosol which penetrated the scrubber was accounted for. The uncertainty in the background sodium content of the HEPA filters limits the accuracy of this method.

TABLE 48

SODIUM AEROSOL REMOVAL EFFICIENCY BASED ON LIQUID SAMPLING FOR TEST AC7

Component(s)	Na Mass Collected[a] (kg Na)	Na Mass Fraction Collected	Efficiency[b]
SGS	244.043	0.99595	0.9959
Demister	0.964	0.00393	0.9701
SGS/Demister System	245.007	0.99988	0.999879
HEPA Filters	0.0297	0.00012	1.0000[c]
Total	245.0367	1.00000	- - -

(a) Mass accummulated during entire test.

(b) Fraction of incident Na mass collected by identified component.

(c) Not measured. Assumed for calculational purposes.

TABLE 49

SODIUM AEROSOL REMOVAL EFFICIENCY BASED ON LIQUID SAMPLING FOR TEST AC8

Component(s)	Na Mass Collected[a] (kg Na)	Na Mass Fraction Collected	Efficiency[b]
SGS	253.205	0.99369	0.9937
Demister	1.567	0.00615	0.9743
SGS/Demister System	254.772	0.99984	0.999838
HEPA Filters	0.0414	0.00016	1.0000[c]
Total	254.8134	1.00000	- - -

(a) Mass accumulated during entire test.

(b) Fraction of incident Na mass collected by identified component.

(c) Not measured. Assumed for calculational purposes.

TABLE 50

SODIUM AEROSOL REMOVAL EFFICIENCY BASED ON LIQUID SAMPLING FOR TEST AC9

Component(s)	Na Mass Collected[a] (kg Na)	Na Mass Fraction Collected	Efficiency[b]
SGS	79.747	0.98651	0.9865
Demister	1.085	0.01342	0.9948
SGS/Demister System	80.832	0.99993	0.999929
HEPA Filters	0.0057	0.00007	1.0000[c]
Total	80.8377	1.00000	- - -

(a) Mass accumulated during entire test.

(b) Fraction of incident Na mass collected on identified component.

(c) Not measured. Assumed for calculational purposes.

TABLE 51

SODIUM AEROSOL REMOVAL EFFICIENCY BASED ON LIQUID SAMPLING FOR TEST AC10

Component(s)	Na Mass Collected[a] (kg Na)	Na Mass Fraction Collected	Efficiency[b]
SGS	251.746	0.99356	0.9936
Demister	1.616	0.00638	0.9898
SGS/Demister System	253.362	0.99993	0.999934
HEPA Filters	0.0166	0.00007	1.0000[c]
Total	253.3786	1.00000	- - -

(a) Mass accumulated during entire test.

(b) Fraction of incident Na mass collected on identified component.

(c) Not measured. Assumed for calculational purposes.

5.5.3 Comparison of Sodium Removal Efficiencies Measured by Aerosol and Liquid Sampling

Average removal efficiencies based on aerosol and liquid sampling methods are compared in Table 52. Two observations drawn from the data of Table 52 are that: a) the two methods agree closely; and b) the liquid sampling method gives slightly higher efficiencies in general. The good agreement between the two methods supports the validity of both methods. The average value of measurements by the two methods is considered to be the best answer.

5.6 EFFICIENCY FOR NaI REMOVAL

5.6.1 NaI Removal Efficiency Based on Aerosol Sampling

Sodium iodide vapor was injected into the inlet duct during test AC10, using the method described in Section 3.2.2. Airborne concentrations were measured by withdrawing filter samples from the inlet duct immediately upstream of the SGS, from the plenum between SGS and demisters, and from the demister outlet duct. The filter papers were leached with water, which was analyzed for iodide ion by the ion selective electrode method. The concentrations of NaI aerosol measured at these three locations are listed in Table 53.

The accuracy of the data reported in Table 53 for SGS and the total system is limited by how well the SGS inlet sample represented the total inlet gas concentration. The sample filter inlet was located 11 pipe diameters downstream of the location where the hot NaI vapor was injected, and complete mixing of the freshly nucleated NaI particles may not have been attained.

5.6.2 NaI Removal Efficiency Based on Liquid Sampling

The mass of NaI recovered from the liquid phase in each component and the back-up HEPA filter was determined from concentration and liquid volume, as discussed in Section 5.4.1. These post-test measurements allowed the removal

TABLE 52

COMPARISON OF SODIUM REMOVAL EFFICIENCIES
MEASURED BY AEROSOL AND LIQUID SAMPLING

Component(s)	Method	Efficiency[a] Test AC7	Test AC8	Test AC9	Test AC10	4-Test Average[d]
SGS	Aerosol[b]	0.9939	0.9885	0.9947	0.9926	0.9924
SGS	Liquid[c]	0.9959	0.9937	0.9865	0.9936	0.9924
SGS	Average[d]	0.9949	0.9911	0.9906	0.9931	0.9924
Demister	Aerosol[b]	0.9725	0.9796	0.9974	0.9774	0.9817
Demister	Liquid[c]	0.9701	0.9743	0.9948	0.9898	0.9822
Demister	Average[d]	0.9713	0.9770	0.9961	0.9836	0.9820
SGS/Demister	Aerosol[b]	0.99977	0.99976	0.99999	0.99983	0.99984
SGS/Demister	Liquid[c]	0.99988	0.99984	0.99993	0.99993	0.99989
SGS/Demister	Average[c]	0.99983	0.99980	0.99996	0.99988	0.99987

(a) Average for entire test.
(b) From Tables 44-47.
(c) From Tables 48-51.
(d) Arithmetic average.

TABLE 53

NaI REMOVAL EFFICIENCIES MEASURED BY AEROSOL SAMPLING IN TEST AC10

Operating Period No.[a]	Aerosol Concentration (g I/m³ STP)[b]			NaI Removal Efficiency[c]		
	SGS Inlet	SGS Outlet	Demister Outlet	E_{SGS}	E_{Dem}	$E_{Overall}$
1 - 3	(d)	(d)	(d)	(d)	(d)	(d)
4	6.31(-3)[e]	2.68(-3)	7.48(-6)	0.575	0.997	0.9988
5	7.06(-3)	2.59(-3)	8.78(-6)	0.619	0.987	0.9988
6	4.70(-3)	2.96(-3)	1.48(-5)	0.370	0.995	0.9969
7	1.07(-2)	3.08(-3)	2.4(-5)	0.712	0.993	0.9980
8	2.52(-2)	3.51(-3)	2.43(-5)	0.861	0.993	0.9990
9	1.02(-2)	(f)	2.03(-5)	(f)	(f)	0.9980
10	1.37(-2)	2.97(-3)	2.52(-5)	0.783	0.991	0.9982
11	1.36(-2)	3.38(-3)	2.63(-5)	0.751	0.992	0.9981
12	2.08(-2)	2.90(-3)	2.35(-5)	0.861	0.992	0.9989
13	8.87(-3)	2.80(-3)	2.87(-5)	0.684	0.990	0.9968
14	1.14(-2)	2.18(-3)	3.41(-5)	0.809	0.984	0.9970
15	1.30(-2)	2.83(-3)	3.56(-5)	0.782	0.987	0.9973
16	1.40(-2)	6.55(-3)	5.35(-5)	0.532	0.992	0.9962
17	1.57(-2)	4.57(-3)	4.36(-5)	0.709	0.990	0.9972

TABLE 53 (Cont'd)

Operating Period No.[a]	Aerosol Concentration (g I/m³ STP)[b]			NaI Removal Efficiency[c]		
	SGS Inlet	SGS Outlet	Demister Outlet	E_{SGS}	E_{Dem}	$E_{Overall}$
18	1.68(-2)	3.52(-3)	3.86(-5)	0.789	0.989	0.9977
19	(f)	(f)	(f)	(f)	(f)	(f)
20	1.95(-2)	7.20(-3)	2.09(-5)	0.631	0.997	0.9989
21	(f)	(f)	(f)	(f)	(f)	(f)
22	(f)	(f)	(f)	(f)	(f)	(f)
23	1.67(-2)	7.90 (-3)	3.52(-5)	0.527	0.996	0.9979
24	6.00(-3)	3.27(-3)	(f)	0.455	(f)	(f)
25	3.62(-3)	2.49(-3)	3.78(-5)	0.312	0.985	0.9896
26	1.29(-2)	8.07(-3)	3.78(-5)	0.374	0.995	0.9971
4 - 26				0.639[g]	0.991[g]	0.9968[g]

(a) See Table 10 for time interval and test conditions.
(b) STP refers to standard temperature and pressure (0°C, 101.4 kPa). Values are for iodine. Multiply by 1.181 to obtain g NaI/m³ STP.
(c) Fraction of incident NaI mass captured by identified component.
(d) Insufficient NaI generated for reliable analyses.
(e) Numbers in parenthesis are exponents of 10.
(f) No sample.
(g) Arithmetic average.

efficiency to be calculated for the entire period when there was a NaI source. The results are listed in Table 54. The data of Table 54 show that the SGS exhibited a low efficiency for NaI, and most of the overall removal occurred in the demister.

5.6.3 Comparison of NaI Removal Efficiencies Measured by Aerosol and Liquid Sampling Methods

The NaI removal efficiencies measured by aerosol and by liquid sampling methods are summarized in Table 55. In order to compare the two methods, the efficiency data were converted to penetration by use of Eq. (11). The data of Table 55 show that the liquid sampling method yielded NaI penetrations approximately twice that of aerosol sampling for the SGS and for the SGS/Demister system. The demister penetrations were essentially the same by both methods. The liquid sampling method is thought to be more accurate than the aerosol method for the entire test period, but does not give the hourly fluctuations as does the aerosol method. The liquid sampling results in Table 54 should be used when assessing the overall efficiencies for NaI removal. A discussion of NaI removal results is given in Section 6.4.

5.7 PERFORMANCE WITH WATER-INSOLUBLE PARTICLES

Approximately 2000 kg of aerosol mass were removed from 100,000 m^3 of gas during the four tests. The demonstrated ability to handle this large mass of aerosol without plugging the air cleaning system accomplishes one of the key test objectives. However, the aerosol used in the tests was essentially completely soluble in the scrubber liquid. In some beyond-the-design base accidents postulated for large breeder reactors, a small fraction (<1%) of the aerosol mass may consist of water-insoluble materials, e.g., fuel, steel and concrete.[14,17] A test (PT-1) was performed in the 0.5 m^3/s model SGS/Demister to determine the effect of insoluble particles on aerosol removal efficiency and pressure drop across the air cleaning components.

TABLE 54

NaI REMOVAL EFFICIENCY BASED
ON LIQUID SAMPLING FOR TEST AC10

Component(s)	NaI Mass Collected (g NaI)[a]	NaI Mass Fraction Collected	Efficiency[b]
SGS	29.58	0.3442	0.3442
Demister	55.76	0.6488	0.9894
SGS/Demister System	85.34	0.9930	0.99303
HEPA Filters	0.599	0.0070	1.0000[c]
Total	85.939	1.0000	- - -

(a) Mass accumulated during entire test. See Table 41.

(b) Fraction of incident Na mass collected on identified component.

(c) Not measured. Assumed for calculational purposes.

TABLE 55

COMPARISON OF NaI REMOVAL EFFICIENCY MEASUREMENTS
MADE BY AEROSOL AND LIQUID SAMPLING METHODS

Component(s)	Efficiency[a]		Penetration[a]		Penetration Ratio (L/A)
	Aerosol	Liquid	Aerosol	Liquid	
SGS	0.639	0.314	0.361	0.656	1.82
Demister	0.991	0.9894	0.009	0.0106	1.18
SGS/Demister System	0.9968	0.9930	0.0032	0.0070	2.19

(a) Average for entire period when NaI was released.

The test aerosol was generated by dispersing hydrated alumina* with a powder feeder and air jet. The manufacturer's specifications state that the true density is 2.42 g/cm^3 and the loose bulk density is 0.13 to 0.22 g/cm^3. A cascade impactor sample of the dispersed aerosol gave a log-normal distribution with an aerodynamic mass median diameter of 1.8 μm and a σ_g of 1.67. The aerosol was injected into the 10-in. gas downcomer at the top of the SGS.

Aerosol filter samples were taken from the plenum between the SGS pool and the demister and at the outlet of the demister. The filter papers were analyzed for aerosol mass by desiccating and weighing the preweighed papers. The average value of five efficiency measurements was 97.1 for the SGS and 99.7 for the demister and a system efficiency of 99.99%. The SGS efficiency for the alumina aerosol was lower than for the sodium fire aerosol, as expected because of its smaller size distribution. The combined efficiency of the SGS/Demister was the same as for the sodium fire aerosol.

The alumina particles that penetrated the SGS had an AMMD of 0.5 μm and a σ_g of 3.0, as determined by cascade impactor measurements. As the particles deposited in the demister fiber bed, they caused the pressure drop across the demister to increase with time. The mass of aerosol deposited on the demister was calculated by multiplying the generation rate by the measured penetration of the SGS. A plot of the demister pressure drop as a function of mass of alumina aerosol collected on the demister is given in Figure 39.

Figure 39 shows that the pressure drop increased slowly with demister loading until an incremental increase of 0.6 kPa had been attained with 1.5 kg loading, after which the pressure drop increased more rapidly. A demister loading of only ~0.1 kg per standard demister unit (0.47 m^3/s capacity) would be expected in a large breeder, based on 1000 kg of insoluble aerosol released to containment, 80% retention in containment, and an air cleaning system consisting of a 99% efficient SGS and 20 standard demister units.

*Hydral 710, manufactured by the Aluminum Company of America, Pittsburgh, PA.

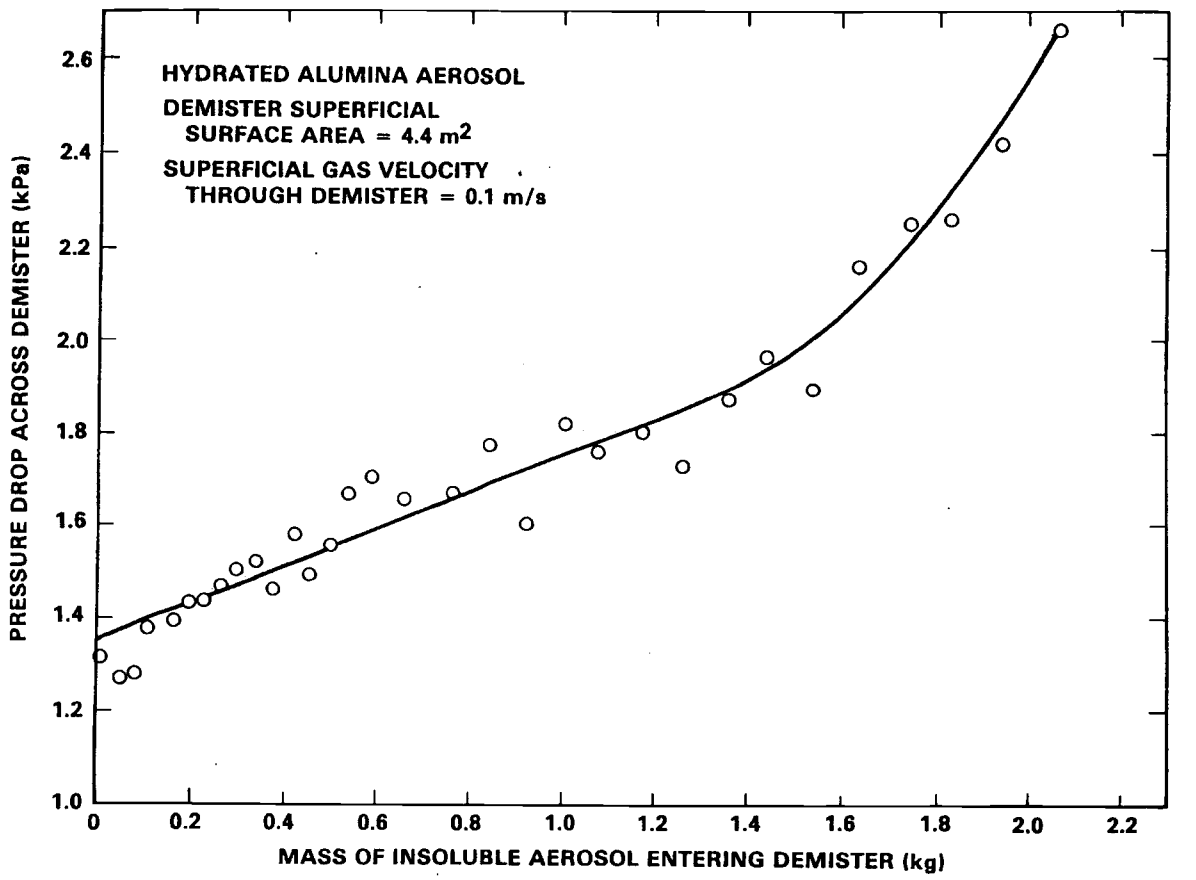

FIGURE 39. Pressure Drop Across Demister as a Function of Insoluble Aerosol Loading.

Figure 39 shows that the increase in pressure drop would be negligible for the assumed accident conditions.

A total of 67 kg of alumina aerosol was fed to the SGS during test PT-1, giving a suspended slurry of scrubber water containing 28 g/ℓ. The performance of the SGS was not impaired by the very high concentration of insoluble particles. When the gas flow was terminated, the particles settled to the floor of the SGS pool, but were quickly resuspended when gas flow was started again.

The conclusion is made that the performance of the SGS/Demister system was not adversely affected by the presence of insoluble particles in amounts postulated for beyond the design-basis accidents.

5.8 AEROSOL DEPOSITION IN DUCTS

In earlier tests,[5,6] small diameter ducts were used in parallel with the main 10-in. duct to determine the relationship between duct diameter and mass of aerosol required to cause plugging. Tubes with internal diameters ranging from 22 mm to 110 mm were plugged by the NaOH aerosol,[6] but insufficient aerosol was generated to plug the main 265-mm ID duct. The following empirical equation was found to fit the data within the range of ducts plugged:

$$m = 4 \times 10^4 \, d^3 \qquad (12)$$

where:

m = mass of aerosol entering duct (kg)
d = duct internal diameter (m)

In the present test series, no small ducts were tested, but the main, 265-mm ID duct was decontaminated after each test to determine the mass of aerosol deposited. The results are given in Table 56. In the two tests

TABLE 56

AEROSOL DEPOSITION IN INLET DUCT

Parameter	AC7	AC8	AC9	AC10
Aerosol mass recovered from duct[a][b] (kg)	7.75	108.2	(c)	71.6
Aerosol mass penetrating duct (kg)[b]	488.13	580.4	192.4[d]	489.9
Total aerosol mass entering duct (kg)[b]	495.88	688.6	192.4	561.5
Fraction of entering mass deposited in duct	0.016	0.157	(e)	0.127
Maximum ΔP across duct (Pa)	<50	1500	50	475
Gas flow rate at max. ΔP, % of design rate	100	50	100	100
Duct plugged	No	Yes[f]	No	No

(a) Refer to Table 4 for dimensions.

(b) Determined by analyzing for Na and dividing by Na mass fraction from Table 17.

(c) Not measured. Estimated <4 kg.

(d) Combined deposit in duct and air cleaning system.

(e) Not measured. Estimated <0.021.

(f) Continued flow possible but complete plugging imminent.

with dry aerosol (AC7 and AC9), duct deposition was very slight. It is thought that most of the aerosol that did deposit was reentrained by the gas stream and swept into the SGS. In the two tests that used an NaOH aerosol (AC8 and AC10), considerably more deposit was found in the duct during post-test cleanup, and the ΔP across the duct also increased significantly. It is thought that the deposited NaOH material had sufficient adhesiveness and strength to resist reentrainment. It is doubtful whether higher gas velocity and pressure differential than was possible in the present tests would have cleared the ducts. Although the ducts were not completely plugged, their flow resistances indicated that plugging was imminent. This was especially true for test AC8, where the maximum flow possible was only 50% of the design rate.

The duct deposition data from the four tests are plotted in Figure 40. The curve is Equation (12), derived from previous test data. Figure 40 shows that the current data are consistent with the earlier data and extend the validity of Equation (10) to a duct diameter of 0.265 m (10.4 in.) It should be noted, however, that non-sticky aerosols may not plug ducts even at much higher loading than indicated by Equation (12).

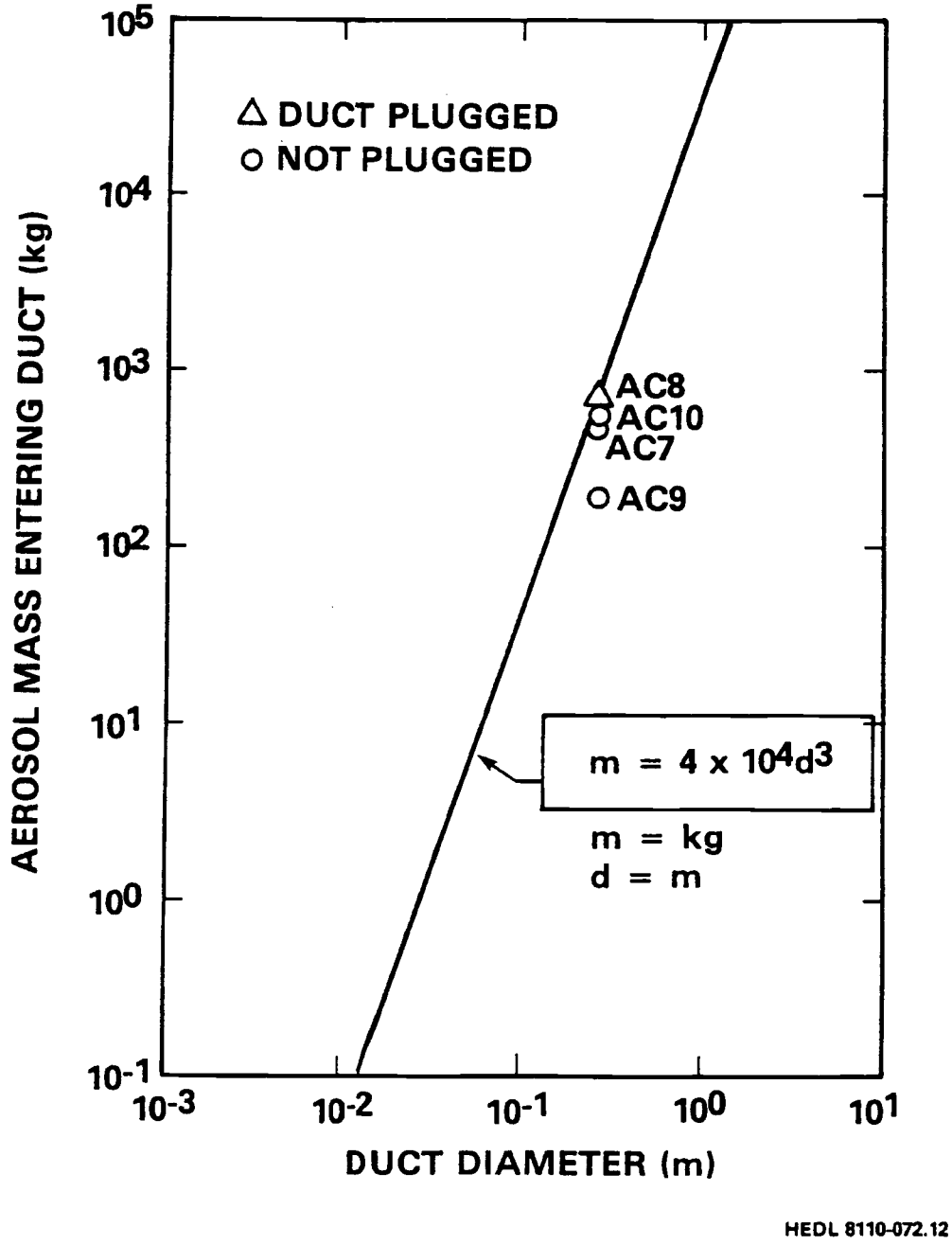

FIGURE 40. Duct Plugging as a Function of Duct Diameter.

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6.0 DISCUSSION OF RESULTS

6.1 GAS COOLING IN THE SGS

Hot gas which enters the gravel bed flows through channels between grains. These flow channels are of relatively small dimension, and the exposed area for heat transfer to grains is large. For these reasons, one anticipates that the gas would be quickly cooled to the liquid temperature. The pulsing nature of flow through the bed causes the surfaces of each stone to be re-wet by liquid after each gas pulse flow upward through the bed. Thus, the surfaces of the grains are expected to remain at a temperature very close to the liquid temperature.

Gas cooling in the gravel bed was analyzed as a heat transfer process wherein sensible heat of the flowing gas was transferred to a constant temperature sink with a constant heat transfer coefficient. Based on these assumptions, the temperature profile through a one-dimensional bed was derived to be:

$$\frac{T_x - T_s}{T_i - T_s} = \exp - \left(\frac{hax}{wC_p}\right) \tag{13}$$

where:

T_x = temperature of gas at distance x (°C)
T_s = temperature of heat sink surface (°C)
T_i = temperature of inlet gas (°C)
h = heat transfer coefficient (watt/m^2°C)
a = interfacial area for heat transfer per unit volume of bed (m^{-1})
x = distance into gravel bed (m)
w = gas mass flow rate (kg/m^2h)
C_p = gas heat capacity (watt h/kg°C)

The interfacial area, a, was evaluated by assuming the bed to consist of spheres packed in a bed with a void volume of ε. For spheres, a is found to be:

$$a = \frac{6\ (1 - \varepsilon)}{d_c} \tag{14}$$

where:

ε = void volume fraction of bed

d_c = diameter of spherical packing grains (m)

The heat transfer coefficient, h, was related to flow parameters using a mass transfer correlation developed for a packed bed.[18] The heat transfer coefficient, based on the Colburn analogy[18] was derived to be:

$$h = 0.687\ \frac{k}{d_c}\ Re^{0.673}\ Pr^{0.33} \tag{15}$$

where:

k = thermal conductivity of gas (watt/m°C)

Re = Reynolds number for flow around grains, based on superficial gas velocity

Pr = Prandtl number of gas

The temperature can be computed as a function of distance, x, by substituting Equations (14) and (15) into Equation (13). A numerical evaluation of Equation (13) was made for a test period in which the gas entering the scrubber was near the maximum value achieved in the test series. At 430 min in test AC9, the following conditions existed:

Inlet gas temperature = 239°C

Liquid temperature = 51°C

Gas flow rate = 0.514 m^3/s

These conditions, along with the SGS construction parameters noted in Section 3.3, permitted Equation (13) to be evaluated. The instantaneous gas flow rate, w, was assigned a value corresponding to a gas velocity of 1 m/s, the value estimated from visual observations. Results of this evaluation are shown graphically in Figure 41.

As indicated by the temperature curve of Figure 41, most of the heat is transferred in the first 5 cm of the packed bed. At 30 cm, it was predicted that the gas and liquid temperatures would differ by only 0.01°C. Because the bed was 61 cm in length, it is predicted that the gas leaving the bed would be in thermal equilibrium with the liquid.

An examination of the temperature data indicates that the gas entering the demisters was in thermal equilibrium with the liquid in the gravel bed. Any measured differences (generally less than 0.5°C) are thought to be indicative of measurement error, rather than real differences. The temperature measurements support the theoretical predictions in that the temperature of the gas leaving the bed was equal to the liquid temperature. However, the temperature versus depth profile was not obtainable from thermocouple measurements, and a direct comparison with predictions was not possible.

Detailed instantaneous temperature data for fluid streams in the SGS are provided in Tables E5 through E8 in Appendix E.

6.2 PRESSURE DIFFERENTIAL ACROSS TEST ARTICLE COMPONENTS

6.2.1 Pressure Differential Across SGS

The pressure difference required to induce gas flow through the SGS depends mainly on the submergence of the downcomer. Hydraulic aspects of the gas flow distribution geometry are shown in Figure 42. With reference to Figure 42, one can visualize that flow proceeds as follows. At very low flow rates, gas is able to bubble out of the downcomer with a very small gas

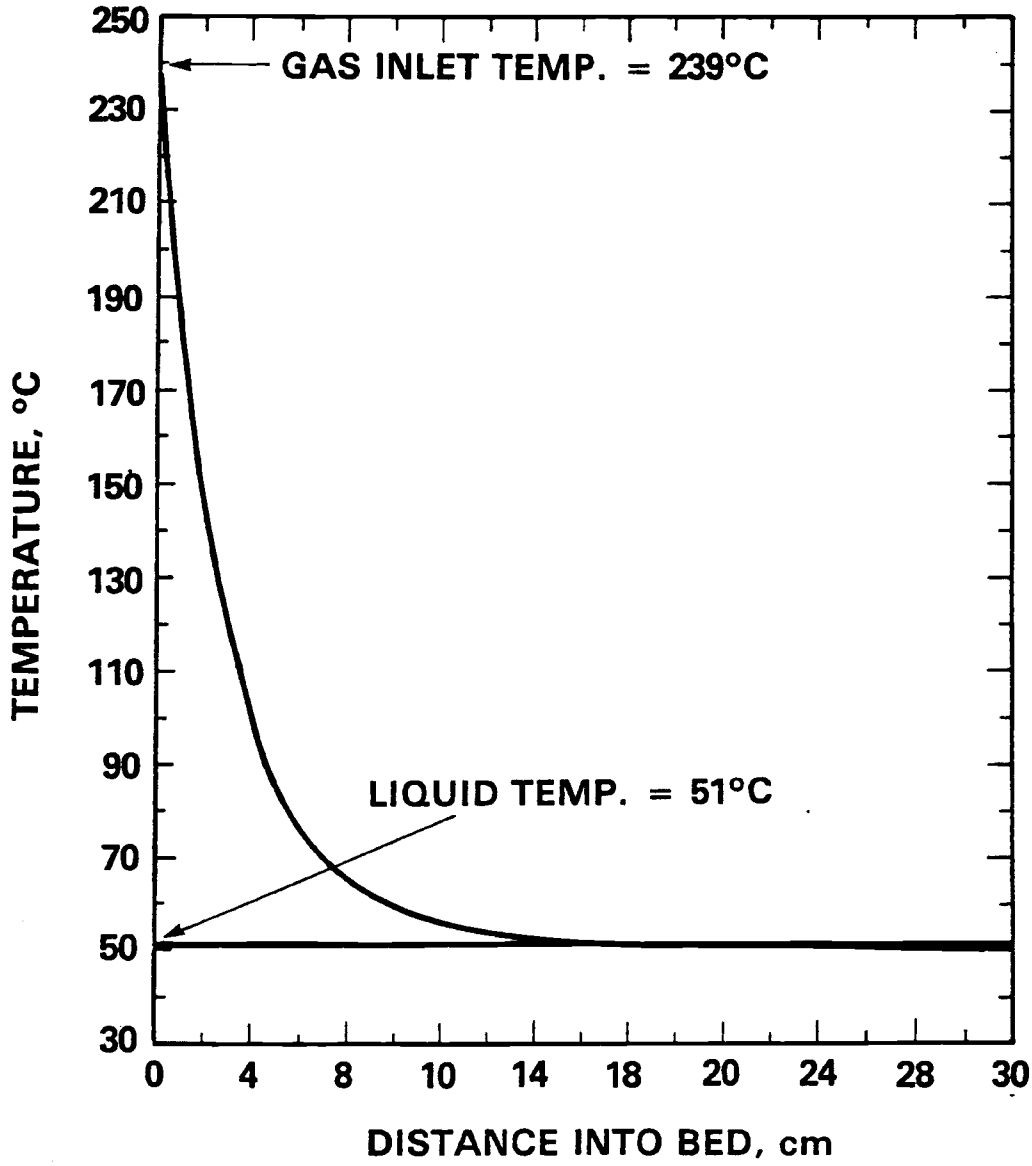

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FIGURE 41. Predicted Gas Temperature in Gravel Bed.

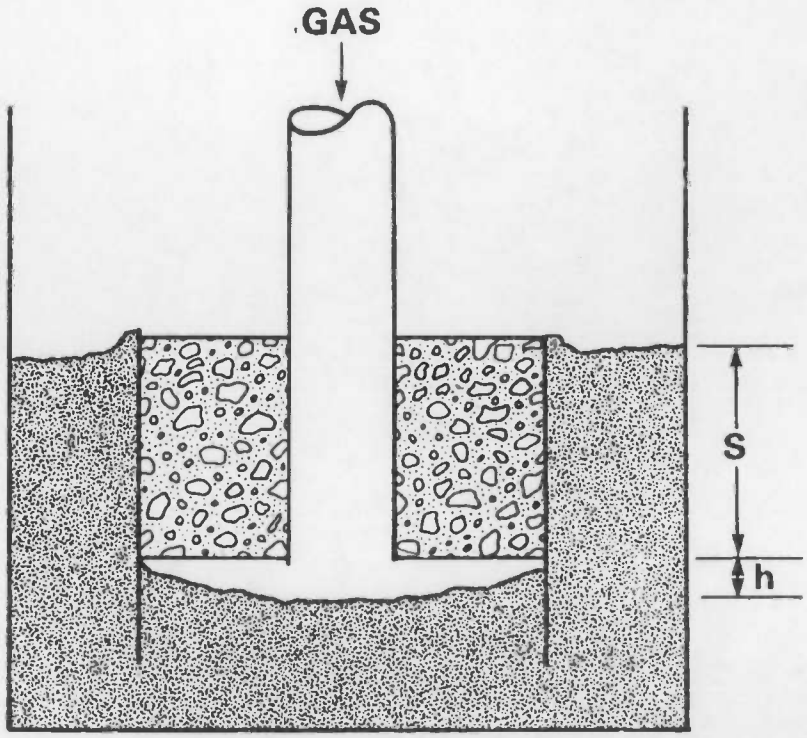

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FIGURE 42. Gas Flow Distribution Near Outlet of Downcomer.

space, and the pressure drop would be very nearly equal to the submergence of the downcomer. As the gas flow rate is increased, the pool surface directly beneath the downcomer moves downward to provide an adequate flow opening for the gas to escape radially. The magnitude of the pool depression below the end of the downcomer will vary with flow rate, because hydrostatic pressure of the liquid must be overcome to provide the opening.

The pressure drop required to depress the liquid surface can be estimated by modeling the outlet area as an orifice. For an orifice, the pressure drop may be expressed as

$$\Delta P = \frac{\rho_g V_g^2}{2C^2} \tag{16}$$

where:

ΔP = pressure drop

ρ_g = density of escaping gas

V_g = radial velocity of gas

C = orifice coefficient, assumed = 0.6

The gas velocity can be related to gas flow rate and exit area:

$$V_g = \frac{G}{A} \tag{17}$$

where:

G = gas volumetric flow rate

A = flow area of radial escape path

The flow area, A, is equal to the perimeter of the downcomer pipe multiplied by the pool depression:

$$A = \pi D h \tag{18}$$

where:

D = diameter of downcomer

h = height of space for gas flow, termed the pool depression

The height of the gas space, h, is directly related to the liquid density and the pressure loss required to create the opening:

$$\Delta P = \rho_\ell h \tag{19}$$

where: ρ_ℓ = density of liquid

The pressure drop due to the pool depression, expressed as head of liquid, can be obtained by combining Equations (16) through (19) to give:

$$h = \left(\frac{\rho_g \, G^2}{2 \, \rho_\ell \, C^2 \, \pi^2 D^2} \right)^{1/3} \tag{20}$$

The total pressure drop expressed in terms of height of liquid in the SGS pool is thus

$$\Delta P_{SGS} = h + S \tag{21}$$

where:

ΔP_{SGS} = overall pressure drop across SGS
h = liquid depression from Eq. 20
S = submergence of downcomer

Experimental measurements of pressure drop across the SGS are compared with predictions based on Equation (21) in Table 57.

The data of Table 57 are shown graphically in Figure 43. Measured and predicted pressure drops are in good agreement, indicating that the theoretical expression is adequate for the conditions encountered in the tests.

Interestingly, the pressure drop across the SGS is not dependent on the nature of the gravel bed itself. Gravel bed parameters would, however, determine the quantity of water entrained and the maximum allowable gas velocities that can be used prior to bed dryout.

TABLE 57

COMPARISON OF MEASURED AND PREDICTED PRESSURE DROP ACROSS SGS

Gas Flow Rate (m^3/sec)	Downcomer Submergence (m)	Measured Pressure Drop, (kPa)[a]	Predicted Pressure Drop, (kPa)[b]
0.094	0.606	5.95	6.07
0.189	0.621	6.21	6.30
0.378	0.665	6.85	6.86
0.472	0.673	6.97	6.99
0.567	0.681	7.10	7.12
0.094	0.696	6.87	6.96
0.189	0.716	7.32	7.24
0.382	0.742	7.72	7.61
0.477	0.749	7.87	7.74
0.095	0.779	7.74	7.77
0.194	0.798	8.14	8.04
0.381	0.823	8.59	8.41
0.425	0.826	8.69	8.46
0.207	0.724	7.37	7.40
0.331	0.734	7.58	7.58
0.414	0.748	7.80	7.77
0.500	0.756	8.05	7.89

(a) From Tables E1 through E4 in Appendix E.

(b) By Equations (20) and (21).

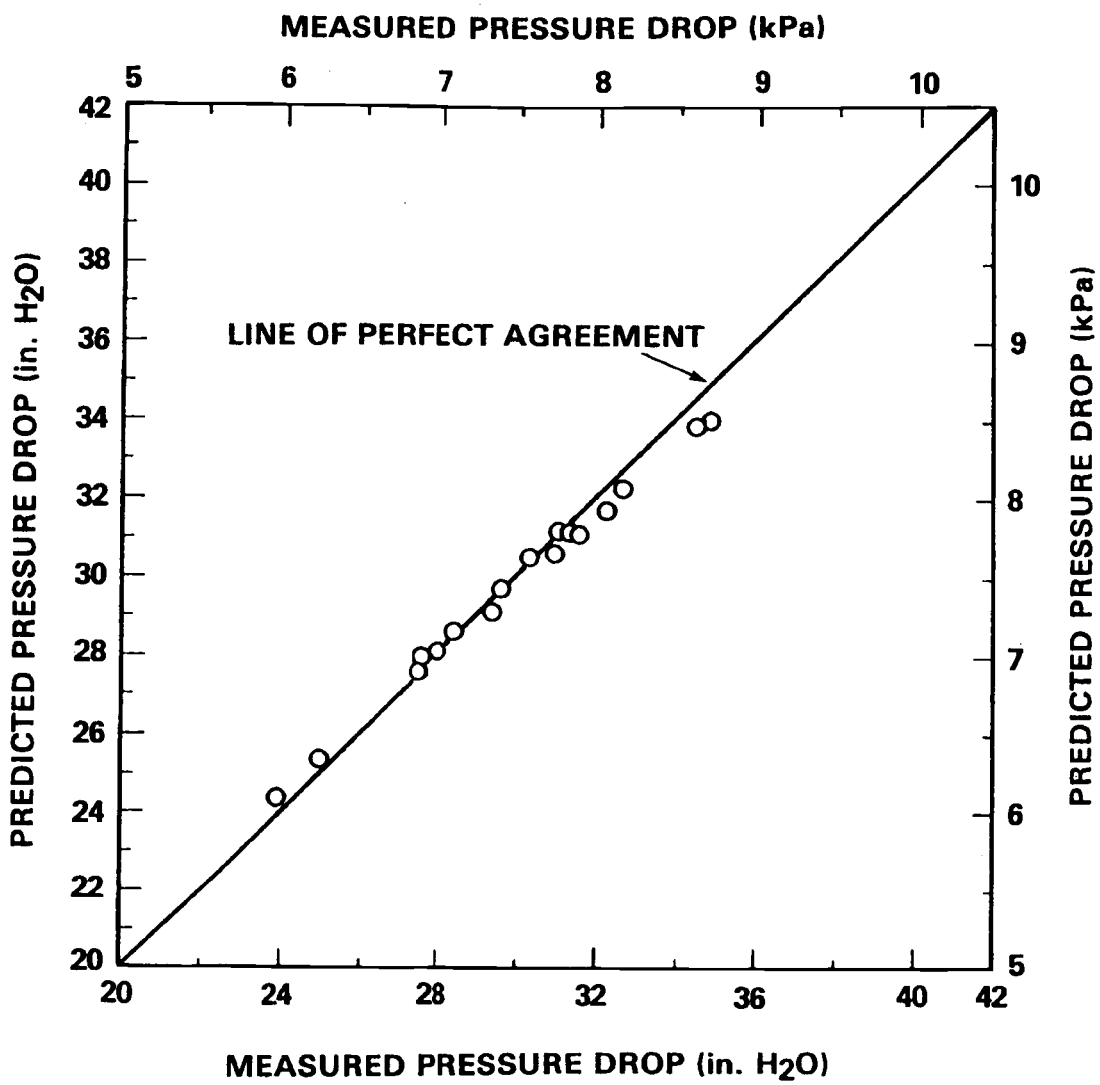

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FIGURE 43. Comparison of Measured and Predicted Pressure Drop Across the SGS.

Pressure drop through the downcomer pipe was neglected in Equation (12) because it was negligible in the unit tested. However, pressure loss in the inlet line might not be totally negligible for systems of different design.

6.2.2 Pressure Differential Across Fiber Demister

The pressure drop across the demister is due predominantly to that incurred for fluid flow through the fiber bed. The other pressure losses, due to expansion and contraction, directional changes and friction on walls, are relatively low and are ignored in this treatment. The pressure drop for fluid passing through a packed bed of fibers was studied by Davies,[12] who found the following correlation:

$$\Delta P = \frac{16\ \mu h G f^{1.5}\ (1 + 56^3)}{A r^2} \tag{22}$$

where:

ΔP = pressure drop (dyne/cm^2)
A = flow area (cm^2)
r = radius of fiber (cm)
μ = fluid viscosity (poise)
G = actual gas flow rate (cm^3/s)
h = bed thickness (cm)
f = fraction of volume filled with nongaseous media

Two demisters were used in the present tests (see Section 3.2.6). The following geometrical parameters apply:

A = 5.12 m^2 (mean of inner and outer bed surfaces for both units)
h = 76.2 mm
r = 10 μm

The parameter f was not measured directly but was derived by inserting empirical measurements in Equation (22) and solving for f. From a previous study,[5] the value for f is 0.131 for a new, clean fiber bed unsaturated with liquid. Inserting this value for f and the measured values for A, h and r into Equation (22) gives a simplified expression that is applicable for the fiber bed used in the present tests:

$$\Delta P = 1.27 \times 10^7 \, G\mu \tag{23}$$

where the dimensions have been changed to SI units:

ΔP = Pa
G = actual m^3/s
μ = Pa·s = poise

Equation (23) applies for a bed that is not saturated with liquid, since the void fraction, f, was calculated from data taken for this case. During the present work, the liquid entrainment from the SGS pool has sufficient operating time to saturate the bed at the design gas flow rate. The effect of a two-phase mixture of gas and liquid flowing through the bed can be estimated using data published by Brown[19] for permeabilities for oil and gas flowing through sand. For a bed saturated with liquid at low liquid rates, the pressure drop is calculated to increase by 18% due to the liquid. Therefore, Equation (23) is modified by multiplying the constant by a factor of 1.18. The resulting predictor equation for the present test article saturated with liquid is:

$$\Delta P = 1.50 \times 10^7 \, G\mu \tag{24}$$

The pressure drops across the demister were measured during each test and are reported in Tables E1 through E4. In addition, a series of measurements was made with room temperature water and clean air after test AC10 was completed. Typical test measurements are listed in Table 58 for test AC7 through AC10 and for the final clean air test.

TABLE 58

COMPARISON OF MEASURED AND PREDICTED
PRESSURE DROP ACROSS THE DEMISTERS

Test and Op. Period	Gas Flow (Actual m^3/s)	ΔP Across Demister (kPa)	
		Predicted (a)	Measured (b)
7 - 5	0.355	1.00	1.08
7 - 11	0.370	1.04	1.00
7 - 20	0.359	1.01	1.02
7 - 21	0.109	0.307	0.37
8 - 2	0.084	0.237	0.24
8 - 3	0.214	0.603	0.59
8 - 4	0.411	1.16	1.10
8 - 10	0.362	1.02	1.03
8 - 15	0.364	1.03	0.99
8 - 19	0.313	0.883	0.76
8 - 20	0.242	0.682	0.61
8 - 21	0.092	0.259	0.22
9 - 1	0.347	0.979	0.92
9 - 2	0.083	0.234	0.25
9 - 3	0.169	0.477	0.52
9 - 4	0.308	0.869	1.01
9 - 9	0.409	1.15	1.46
9 - 10	0.178	0.502	0.56
9 - 18	0.370	1.04	1.17
10 - 1	0.527	1.49	1.01
10 - 2	0.087	0.245	0.33
10 - 3	0.172	0.485	0.54
10 - 4	0.346	0.976	0.99
10 - 15	0.335	0.945	0.97
10 - 16	0.049	0.138	0.35
10 - 17	0.167	0.471	0.60
10 - 18	0.330	0.931	0.98
Post-test (c)	0.100	0.267	0.336
Post-test (c)	0.250	0.668	0.826
Post-test (c)	0.400	1.06	1.125
Post-test (c)	0.500	1.33	1.332
Post-test (c)	0.612	1.63	1.733

(a) Equation [24].
(b) From Tables E1 - E4 in Appendix E.
(c) Room Temperature Water and Clean Air, 7-20-81.

The data of Table 58 are shown graphically in Figure 44. Measured and predicted pressure drops agree to within ~±15%, indicating that aerosol and NaOH in the SGS pool had very little effect on the pressure drop and that Equation (24) is valid for the conditions of these tests.

It should be noted that the aerosol used in Tests AC7 through AC10 was essentially completely soluble in the scrubber liquid. Aerosol particles which penetrated the SGS and were deposited on the demister fibers were dissolved and washed out of the demister bed by liquid entrainment from the SGS pool or by condensation of water vapor. The behavior of water-insoluble particles is discussed in Section 5.7.

6.3 SODIUM AEROSOL REMOVAL EFFICIENCY

6.3.1 Aerosol Removal in the SGS

6.3.1.1 Removal Mechanisms

Particles entering the gravel bed of the SGS are subject to collection by a number of mechanisms. The following mechanisms can be identified as being potentially important.

- Inertial impaction
- Interception
- Diffusional deposition
- Gravitational settling
- Thermophoretic deposition
- Diffusiophoretic deposition
- Particle growth due to water vapor condensation
- Electrical attraction

Preliminary calculations indicate that several of these mechanisms are not very important, and can be neglected. Electrical collection mechanisms can be dismissed because the particles are not charged to a significant extent.

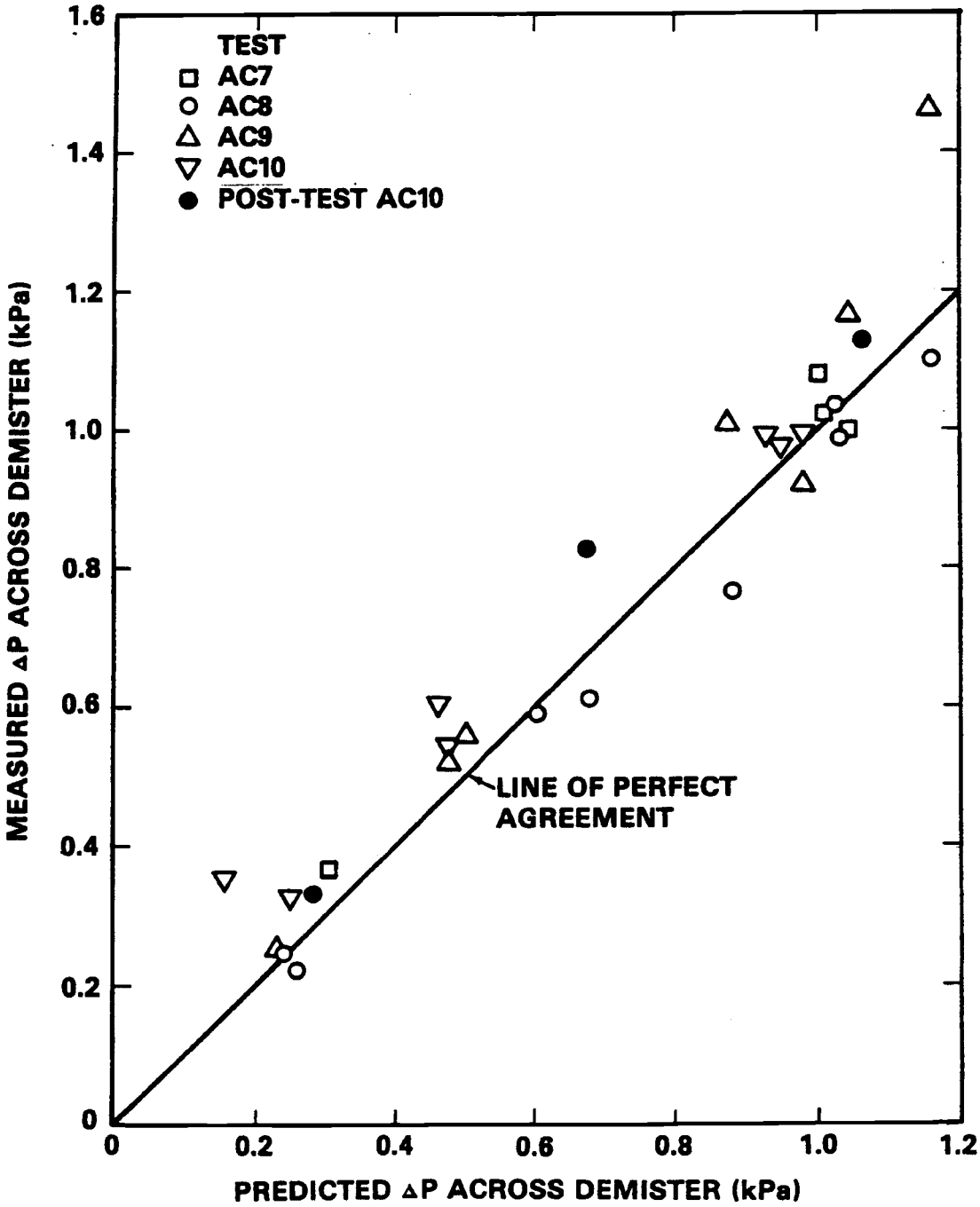


FIGURE 44. Comparison of Measured and Predicted Pressure Drop Across Demister.

Gravity settling would not be expected to be significant because the gas velocity is orders of magnitude higher than particle settling velocities. For example, the settling velocity of a 5-μm diameter particle of unit density in air is approximately 0.08 cm/s, compared to a superficial gas velocity of approximately 100 cm/s. Because the target collection efficiency is roughly equal to the ratio of settling and flow velocities, a first estimate of the gravity target efficiency of 0.08/100 = 0.0008, a value too small to be of much effect in the SGS. Similar arguments indicate that interception, thermophoresis, diffusiophoresis, and diffusion would play a minor role in particle removal in the SGS for aerosol with the size distribution in the present tests. Thus, one is left with inertial impaction, possibly augmented by particle growth, as the dominant collection mechanism.

Several theories on inertial collection of particles in packed beds were considered. First, the bed can be modeled as an assemblage of isolated collectors. Preliminary calculations with this theory showed that the predicted collection efficiency was much lower than the measured efficiencies, and also lower than the efficiencies based on two other models.

The second model considered was one presented by Tien,[20] wherein the flow paths through a granular bed are modeled as a series of constricted tubes. Constants in this model were selected on the basis of experimental measurements of particle collection in dry granular beds. The presence of water in the SGS makes the model of Tien of questionable validity when applied to the SGS.

The third model, and the one thought to be most applicable to the SGS, is the model of Calvert et al.[21] This model applies to particle collection in a packed bed, wet by a small quantity of liquid. Particle collection is envisioned to result from centrifugal forces generated as the gas flows around each piece of packing. A mathematical expression of the model is as follows:

$$P = \exp - \left[\frac{\pi z}{2 (j + j^2) (\varepsilon - H) d_c} (Stk) \right] \tag{25}$$

where:

P = fractional penetration of aerosol
j = a parameter relating channel width to packing size
ε = void volume in packed bed
H = liquid holdup in bed, expressed as volume fraction of bed
z = bed height (m)
d_c = diameter of packing element (m)
Stk = Stokes number

The inertia parameter, commonly called the Stokes number, is defined as follows:

$$Stk = \frac{V_g \, d_p^2}{9 \mu \, d_c} \tag{26}$$

where:

V_g = superficial gas velocity (cm/s)
d_p = aerodynamic particle diameter (cm)
μ = gas viscosity (g/cm·s)

In order to establish whether Equation (25) would explain particle capture in the SGS, calculations were performed for two representative operating periods in Test AC7. Case A was at the design gas flow rate and Case B was at ~50% design flow rate. The particle size spectrum was broken into a number of increments, and Equation (25) applied to each increment. The predicted penetration versus particle size curve for the two cases is shown in Figure 45.

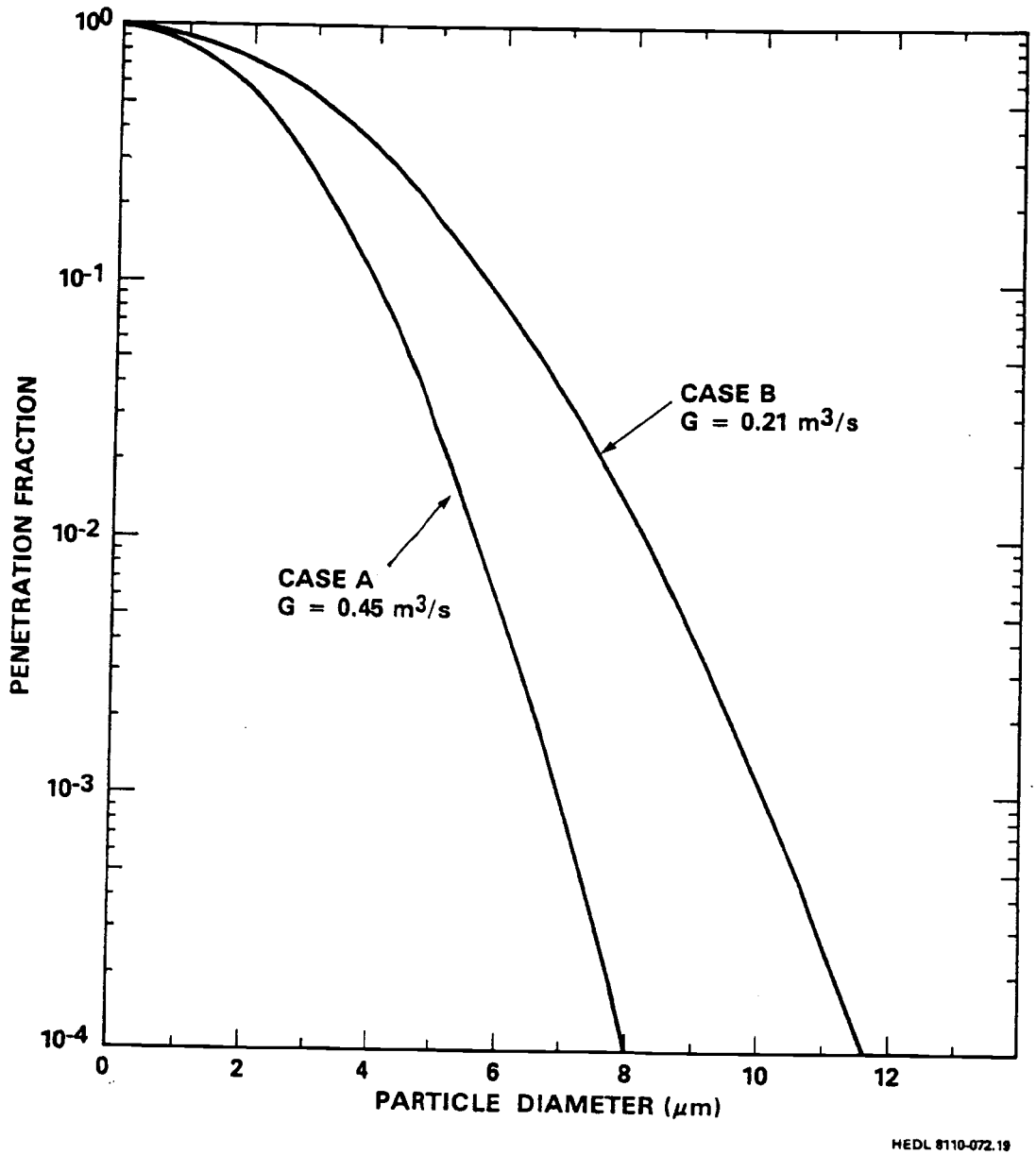


FIGURE 45. Predicted Penetration of SGS Based on Reference (21). (Refer to Table 59 for Operating Conditions.)

Measured aerosol removal efficiency data presented in Section 5.5 were converted to penetration and are listed in Tables 59 through 62. Overall penetrations for the inlet particle size distribution are compared with the measured penetration in Table 63.

Table 63 shows that the predicted penetrations are one to two orders of magnitude higher than measured. A cursory examination of SGS efficiencies for all four tests indicates that this discrepancy is general. The under prediction of removal efficiency by Equation (25) is thought to result from the following factors, which are not explicitly accounted for in the model:

- Particle growth due to water vapor condensation
- Capture by exposed liquid surfaces
- Enhancement due to turbulence caused by energy dissipation

An alternative, nonmechanistic way to correlate removal efficiency is to compare performance with other devices which expend the same amount of energy per unit volume of the gas. Calvert[22] presented a correlation of "cut size" versus pressure drop for several types of scrubbers, and data from his correlation are reported in Figure 46. The cut diameter is defined as the size at which 50% of inlet particles are removed by the scrubber. As a rough guide, one can approximate the collection efficiency of a device by assuming that all particles larger than the cut diameter are collected, and that particles smaller than the cut size penetrate the scrubber. As shown in Figure 46, the cut diameter for the SGS is approximately that found for gas-atomized venturi scrubbers and fiber beds containing 0.005-cm diameter fibers.

As shown in Figure 46, the SGS is generally more efficient than a gas-atomized venturi, as evidenced by a smaller cut diameter for a given pressure drop, and this enhancement may be due to growth of the soluble sodium compound aerosol particles.

TABLE 59

SODIUM AEROSOL PENETRATION AT VARIOUS OPERATING CONDITIONS FOR TEST AC7[a]

Oper. Periods	G[b] (Actual m^3/s)	Aerosol[c] Conc. (g Na/ Std m^3	Aerosol Size[c] AMMD (μm)	σ_g	C_L[d] (g Na/l)	Pool[e] Level (mm)	Pool Temp (°C)	Penetration x 10^4[f] P_{SGS}	P_{Dem}	$P_{Overall}$
1	0.509	8.38	5.9	2.7	0.5	0	22.7	84	56	0.47
2	0.081	12.7	6.0	2.9	1.6	63	25.5	14	345	0.50
3	0.242	14.2	6.0	3.1	3.3	35	28.3	16	41	0.07
4	0.461	10.5	5.7	3.1	6.5	53	32.5	18	100	0.18
5-6	0.466	10.3	5.1	3.1	12.7	58	36.7	25	108	0.27
7-8	0.482	10.1	4.7	3.1	21.0	50	39.2	35	164	0.52
9	0.510	9.3	4.7	3.1	27.7	-50	39.9	67	136	0.91
10	0.481	10.8	4.8	3.1	29.6	130	37.9	40	159	0.63
11-14	0.477	10.7	4.8	3.0	44.8	45	39.2	65	251	1.63
15-17	0.476	10.2	4.0	2.7	69.2	45	40.6	96	412	3.73
18-20	0.473	11.1	4.0	2.7	86.3	57	41.5	104	624	6.22
21	0.133	5.0	4.0	2.7	92.7	70	39.3	256	69	1.77
22	0.097	0.41	2.5	2.5	90.8	75	37.8	93	113	1.05

(a) Average values for specified operating periods.
(b) Gas flow rate at SGS inlet conditions.
(c) At SGS inlet.
(d) Concentration of sodium in SGS pool.
(e) Distance above top of gravel packing.
(f) Fraction of incident sodium aerosol mass penetrating indicated component, based on aerosol sampling.

TABLE 60

SODIUM AEROSOL PENETRATION AT VARIOUS OPERATING CONDITIONS FOR TEST AC8[a]

Oper. Periods	G[b] (Actual m^3/s)	Aerosol[c] Conc. (g Na/ Std m^3)	Aerosol Size[c] AMMD (μm)	σ_g	C_L[d] (g Na/l)	Pool[e] Level (mm)	Pool Temp (°C)	Penetration x 10^4[f] P_{SGS}	P_{Dem}	$P_{Overall}$
1	0.544	12.0	5.3	3.3	0.2	92	27.8	10	211	0.21
2	0.098	11.0	4.2	3.4	0.9	57	45.5	17	68	0.11
3	0.242	10.8	4.4	3.4	1.8	62	62.9	23	229	2.65
4	0.470	10.7	5.2	3.2	3.5	62	60.1	31	152	0.47
5-6	0.479	14.3	5.0	3.2	7.9	43	44.3	44	56	0.25
7-8	0.509	15.0	4.4	3.3	16.4	-21	42.5	70	89	0.62
9-10	0.479	14.8	4.1	3.5	25.1	120	42.9	70	85	0.59
11-14	0.492	14.1	3.9	3.5	44.8	48	45.4	102	149	1.52
15-17	0.469	10.8	4.4	3.2	72.5	50	46.4	245	161	3.95
18-19	0.351	10.6	5.1	3.0	88.2	44	46.6	212	295	6.25
20	0.242	8.3	5.2	3.1	94.0	55	47.2	265	244	6.47
21	0.092	2.6	5.1	3.1	95.8	55	45.5	605	12	0.73
22	0.095	0.2	(g)	(g)	97.0	60	43.2	1709	3	0.56

(a) Average values for specified operating periods.
(b) Gas flow rate at SGS inlet conditions.
(c) At SGS inlet.
(d) Concentration of sodium in SGS pool.
(e) Distance above top of gravel packing.
(f) Fraction of incident sodium aerosol mass penetrating indicating component, based on aerosol sampling.

TABLE 61

SODIUM AEROSOL PENETRATION AT VARIOUS OPERATING CONDITIONS FOR TEST AC9[a]

Oper. Periods	$G^{(b)}$ (Actual m^3/s)	Aerosol[c] Conc. (g Na/ Std m^3)	Aerosol Size[c] AMMD (μm)	σ_g	$C_L^{(d)}$ (g Na/l)	Pool[e] Level (mm)	Pool Temp (°C)	Penetration x 10^4[f] P_{SGS}	P_{Dem}	$P_{Overall}$
2	0.119	16.0	5.3	3.4	1.1	50	23.5	52	15	0.08
3	0.258	14.4	5.4	3.4	2.8	95	31.3	(g)	(g)	0.16
4	0.465	15.7	5.5	3.4	6.2	95	41.3	40	47	0.19
5-6	0.465	16.9	6.0	2.9	12.8	78	49.0	55	30	0.17
7-8	0.501	16.3	5.4	2.9	22.0	45	51.7	72	23	0.17
9	0.622	8.85	4.6	3.3	27.7	55	51.8	25	46	0.12
10-11	0.255	3.68	3.8	3.4	29.7	43	47.6	33	18	0.39
12-13	0.242	3.67	3.6	3.4	31.8	10	45.0	70	20	0.14
14	0.100	1.11	3.9	3.0	31.6	0	44.4	9	10	0.01
15	0.099	0.31	3.6	2.8	30.5	60	40.8	46	69	0.32
16-17	0.247	0.053	3.3	2.5	30.9	60	39.1	475	51	2.42

(a) Average values for specified operating periods.
(b) Gas flow rate at SGS inlet conditions.
(c) At SGS inlet.
(d) Concentration of sodium in SGS pool.
(e) Distance above top of gravel packing.
(f) Fraction of incident sodium aerosol mass penetrating indicated components, based on aerosol sampling.
(g) Not measured.

TABLE 62

SODIUM AEROSOL PENETRATION AT VARIOUS OPERATING CONDITIONS FOR TEST AC10[a]

Oper. Periods	G[b] (Actual m^3/s	Aerosol[c] Conc. (g Na/ Std m^3)	Aerosol Size[c] AMMD (μm)	σ_g	C_L[d] (g Na/l)	Pool[e] Level (mm)	Pool Temp (°C)	Penetration x 10^4[f] P_{SGS}	P_{Dem}	$P_{Overall}$
1	0.686	10.3	5.3	2.6	0.5	0	26.4	41	145	0.59
2	0.116	17.8	5.0	3.2	1.9	50	29.0	21	30	0.06
3	0.242	17.9	4.8	3.4	4.2	25	32.9	21	75	0.16
4	0.481	16.1	7.5	3.0	8.7	10	37.9	26	200	0.52
5-6	0.483	17.7	7.1	3.0	17.2	20	42.4	36	158	0.57
7-8	0.481	17.7	6.9	3.1	29.4	-45	44.2	67	174	1.16
9-10	0.472	16.0	7.6	3.2	39.0	125	44.4	59	221	1.30
11-13	0.477	15.2	7.4	2.8	56.8	40	46.4	105	225	2.36
14-15	0.466	14.1	6.1	3.0	80.8	33	46.7	97	385	3.73
16	0.069	14.4	5.0	3.3	87.2	65	45.8	126	163	2.04
17	0.238	14.5	4.4	3.3	85.5	80	45.6	94	304	2.86
18	0.439	7.0	4.1	3.2	88.0	75	47.0	101	521	5.27
19	0.119	0.69	3.6	2.9	90.2	50	45.9	142	36	0.51
21	0.101	0.11	2.7	2.5	93.0	40	53.4	836	12	1.00

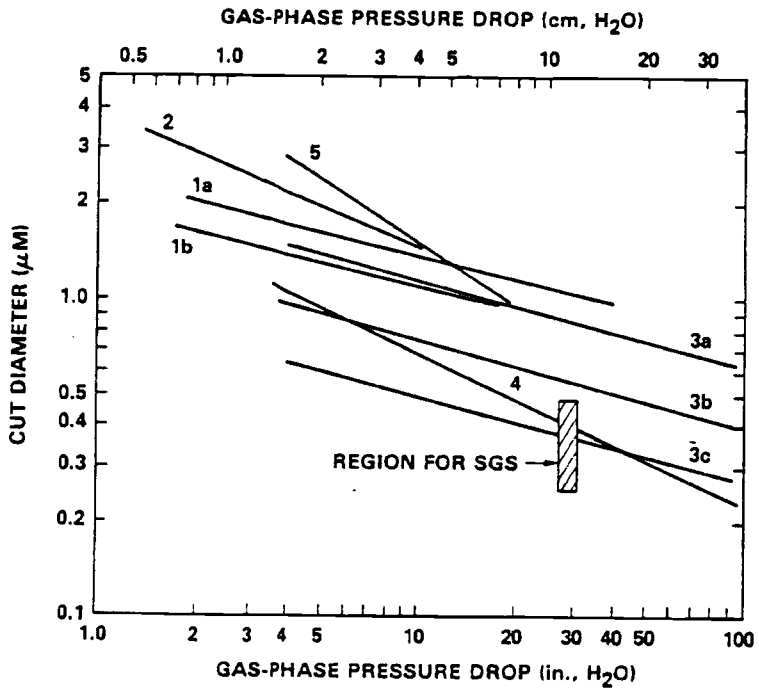
(a) Average values for specified operating periods.
(b) Gas flow rate at SGS inlet conditions.
(c) At SGS inlet.
(d) Concentration of sodium in SGS pool.
(e) Distance above top of packing material.
(f) Fraction of incident sodium aerosol mass penetrating indicated component, based on aerosol sampling.

TABLE 63

COMPARISON OF PREDICTED AND MEASURED AEROSOL PENETRATIONS OF THE SGS FOR TWO REPRESENTATIVE CASES

Case	Test No.	Oper. Period	Gas Flow Rate (m^3/s)(a)	Particle Size AMMD (μm)	Particle Size σ_g	Aerosol Penetration Predicted(b)	Aerosol Penetration Measured
A	AC 7	9	0.45	4.7	3.1	0.256	0.0067
B	AC 7	3	0.21	6.0	3.1	0.287	0.0016

(a) Average of inlet and outlet SGS conditions. (b) By Equation (25).



1a. SIEVE-PLATE COLUMN, 0.2-in. HOLE DIAMETER
1b. SIEVE-PLATE COLUMN, 0.125-in. HOLE DIAMETER
2 PACKED COLUMN, 1-in. RINGS OR SADDLES
3a. FIBROUS PACKED BED, 0.012-in. DIAMETER FIBERS
3b. FIBROUS PACKED BED, 0.004-in. DIAMETER FIBERS
3c. FIBROUS PACKED BED, 0.002-in. DIAMETER FIBERS
4 GAS-ATOMIZED SPRAY
5 MOBILE BED, 1 TO 3 STAGES, HOLLOW SPHERES

FIGURE 46. Scrubber Performance Correlation Based on Energy Dissipation Per Reference (22).

In summary, the particle removal efficiency of the submerged gravel bed correlates reasonably well with that of a gas-atomized spray scrubber which uses the same energy dissipation per unit volume of gas. On the other hand, the SGS is far more efficient than predicted by a simple impaction model developed for packed beds operating at low pressure drops with low liquid flow rates. The overall removal efficiency for a specified aerosol can be approximated using a cut diameter of approximately 0.4 μm.

6.3.1.2 Effect of Operating Parameters on SGS Efficiency

A large number of parameters can affect the aerosol removal efficiency of the SGS. The parameters measured and varied in the present work were:

- Aerosol chemical form
- SGS packing type and size
- Aerosol particle size
- Aerosol concentration in SGS pool
- Aerosol concentration in inlet gas
- Gas velocity
- SGS pool level
- Temperature of inlet gas
- Temperature of SGS pool
- Method of inducing gas flow

The large-scale tests described in the present work were designed to demonstrate the performance of the SGS/Demister system when challenged by aerosols and operating conditions typical of those expected in severe breeder accidents. The effect of most of the individual parameters listed above was confounded by the integral nature of the tests. Nevertheless, some trends and conclusions can be drawn from the test data.

Effect of Aerosol Chemical Form -- The aerosol in all four tests was comprised of mixtures of partially hydrated Na_2O_2, NaOH, and Na_2CO_3, which are the dominant mass contributors in postulated breeder accidents. No effort

was made to study other aerosol materials which may also be of interest, e.g., fuel and concrete. A simulated fission product compound, NaI, was used in one test, but it was purposely released in a manner to form submicron sized particles and thus was not typical of containment-agglomerated aerosols.

The dominant sodium chemical form was different in each of the four tests. Table 64 shows that average penetration of the SGS for all four tests was 0.0076 and that none of the tests varied more than 0.0025 from the average, a variation attributable to measurement error and effects of other parameters. It is concluded that the SGS and SGS/Demister system were equally effective for all sodium compound aerosols used in the test series.

TABLE 64

EFFECT OF AEROSOL CHEMICAL TYPE ON PENETRATION

Test	Aerosol Dominant Chemical Form (a)	Penetration x 10^4 (b) SGS	Demister	Overall
AC 7	Na_2O_2 and NaOH	51	287	1.7
AC 8	$NaOH \cdot H_2O$	89	230	2.0
AC 9	Na_2CO_3	94	39	0.4
AC10	NaOH	69	164	1.2
Avg		76	180	1.3

(a) From Table 17.

(b) From Table 52.

SGS Packing Type and Size -- Two types of packing material were used in the tests. In tests AC7, AC8 and AC9, the packing was crushed Hanford basalt gravel, which was described in Section 3.3.4. Commercially available ceramic packing of spherical shape was used in Test AC10. The mean sizes of the packing elements were approximately the same for each type. Table 65 shows that the penetrations were essentially equal for both types of packing.

TABLE 65

EFFECT OF SGS PACKING TYPE ON PENETRATION

Test	SGS Packing Type[a]	Penetration x 10^{-4} (b) SGS	Demister	Overall
AC 7	Gravel	51	287	1.7
AC 8	Gravel	89	230	2.0
AC 9	Gravel	94	39	0.4
Avg, AC 7, AC 8, AC 9	Gravel	78	185	1.4
AC10	Ceramic Spheres	69	164	1.2

(a) Refer to section 3.3.4 for description.

(b) From Table 52.

Effect of Aerosol Particle Size -- Because particle capture in the SGS is thought to be due chiefly to inertial forces, penetration is expected to vary with particle size. As indicated in Section 6.3.1, the cut size of the SGS is ~0.4 μm diameter, and thus the penetration would be controlled by the fraction of particles smaller than ~0.4 μm diameter. An examination of data on penetration and aerosol particle size (Tables 59 through 62) showed that particle size did not have a strong influence on penetration for these tests, and any trend was obscured by variations in other parameters, most notably the concentration of sodium in the SGS pool. An attempt was made to filter out the effect of C_L and the resulting data are presented in Table 66. No strong trend is seen, but there was a slight increase in penetration for smaller particles, as expected. This lack of a notable effect of particle size in the present tests is not surprising, because particle size did not change greatly during the tests.

In a separate test, the penetration of dioctylphthalate (DOP) aerosol was measured by means of a portable air aspirated generator and a photometer. The DOP mean particle diameter measured by light scattering was ~0.7 μm.

TABLE 66

EFFECT OF AEROSOL PARTICLE SIZE ON SGS PENETRATION

Aerosol Size Range, AMMD (μm)	Penetration x 10^4 (a) AC7	AC8	AC9	AC10
C_L = Low (b)				
4 - 5	25			
5 - 6	18		46	41
6 - 7			55	36
7 - 8				26
C_L = High (c)				
4 - 5	100		245	101
5 - 6	65		212	97
6 - 7				67
7 - 8				100

(a) At inlet gas flow rate of 0.47 m^3/s from Tables 59-62.
(b) C_L < 10 g Na/ℓ.
(c) C_L = 50 to 100 g Na/ℓ.

The SGS removed approximately 50 of the DOP particles, which approximates the cut size range of 0.3 to 0.6 μm derived from the sodium aerosol scrubbing tests.

Additional tests to characterize the efficiency of the SGS as a function of particle size are warranted.

Effect of Sodium Concentration in SGS Pool -- The collected aerosol caused the dissolved sodium concentration to increase with time, as shown in Tables 59 through 62. The dissolved NaOH or Na_2CO_3 changed the density and viscosity of the pool liquid slightly, which caused a slight increase in pressure drop across the SGS. However, the chief effect of the dissolved

sodium was to increase penetration by carryover of entrained liquid drops from the SGS pool. The effect of entrainment is shown by Equation 27, where the total penetration is equated to the sum of the fraction of aerosol penetrating the SGS without being captured and the entrained sodium expressed as a fraction of entering sodium aerosol mass.

$$P = P_A + \frac{\xi C_L}{G\, C_g} \tag{27}$$

P = total fractional penetration
P_A = fraction of aerosol mass escaping capture
ξ = volumetric entrainment rate (m^3/s)
C_L = concentration of Na ion in SGS pool (g Na/m^3)
G = gas flow rate at SGS inlet conditions (m^3/s)
C_g = concentration of Na in the inlet gas (g Na/m^3) at inlet conditions

As indicated in Tables 59 through 62, penetration generally increased with time in each test, in parallel with the liquid concentration. This observation is explainable in terms of entrainment of liquid drops. At the beginning of each test, when the liquid concentration is low, the entrained drops carry little sodium compared to the aerosol. However, near the end of a test, entrained drops dominated.

The data of Tables 59 through 62 were condensed to show the effect of C_L, and the result is given in Table 67. Only data for a nominal inlet gas flow rate of 0.47 m^3/s are listed in Table 67. Insufficient variation of C_L was obtained in Test AC9, so the data from that test are omitted.

The data of Table 67 for tests AC7 and AC10 are plotted in Figure 47 as total SGS penetration versus C_L. Although there is scatter due to the effect of other parameters, a strong influence of C_L on P_{SGS} is evident. The solid curve in Figure 47 is described by Equation (28), which is valid only for an inlet gas flow rate of 0.47 m^3/s.

$$P_{SGS} = 0.0025 + 1.0 \times 10^{-7}\, C_L \tag{28}$$

TABLE 67

EFFECT OF SODIUM CONCENTRATION IN THE POOL LIQUID ON SGS PENETRATION

C_L Range (g Na/ℓ)	C_L Midpoint (g Na/m^3)	Penetration x 10^4 (a) AC7	AC8	AC10
0-10	0.005	18	28	33
10-30	0.02	30	70	51
30-50	0.04	57	102	59
50-70	0.06	96		105
70-80	0.075	104	245	97
80-100	0.09			101

(a) For inlet gas flow rate of 0.47 m^3/s, from Tables 58 - 61.

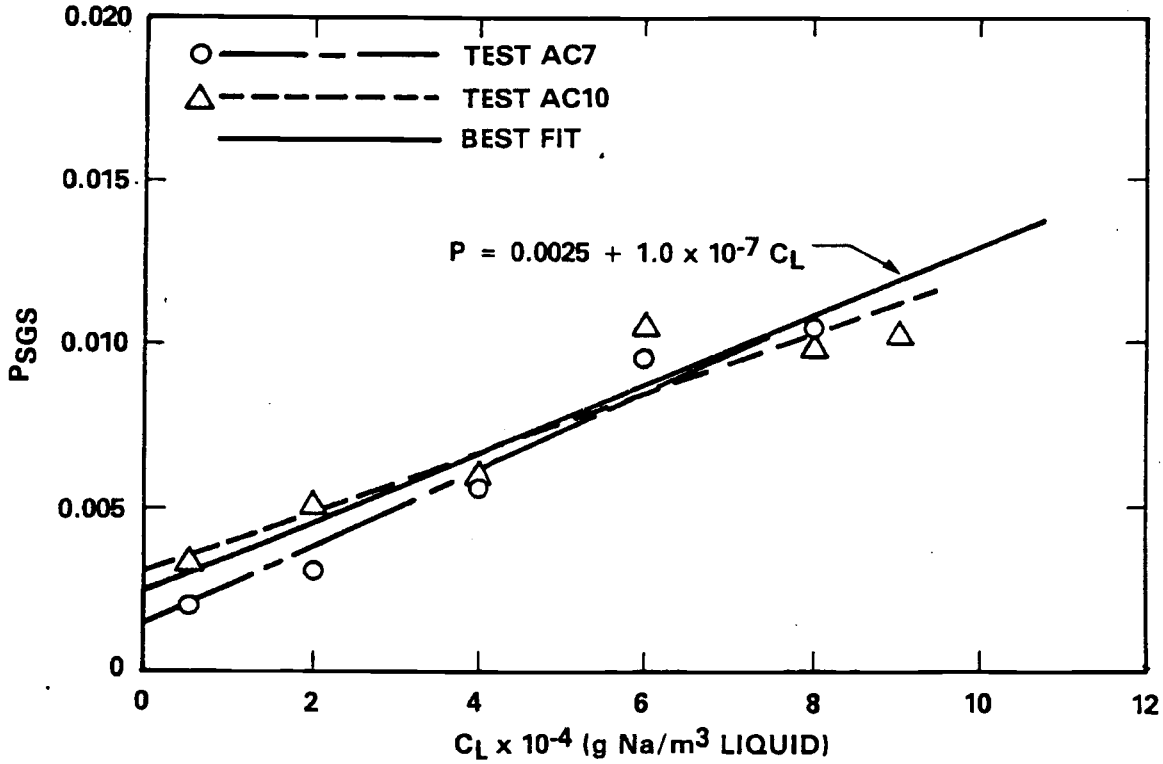


FIGURE 47. Effect of C_L on SGS Penetration.

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Relating the empirical Equation (28) with Equation (27) indicates that P_A, the true aerosol penetration in these tests was 0.0025; and the volumetric entrainment rate, ξ, has a numerical value of 0.5 mℓ/s. This value of ξ has a large uncertainty, but agrees reasonably well with the value of 0.28 mℓ/s obtained from room temperature air tests shown in Figure 38. Considering the complexity of parameter interactions in the aerosol tests, the agreement is considered good. Total liquid carryover during the aerosol tests is thought to be higher than during the room temperature air tests because the penetrating aerosol created a fog in the saturated gas downstream.

As discussed in earlier work,[5,6] the performance of the fiber bed demister can be affected by the concentration of dissolved aerosol in the entrained liquid from prescrubbers. Most of the aerosol which penetrates the SGS without being captured will be deposited in the demister fiber bed. The aerosol which penetrates the SGS pool will consist of NaOH (or Na_2CO_3) with water of hydration and solution in equilibrium with the water vapor concentration in the exit gas. The gas leaving the SGS is extremely close to being saturated with water, as discussed in Section 6.1. In severe accidents where the SGS pool temperature is elevated significantly above ambient, additional cooling of the gas probably would occur in the plenum above the pool and the gas may become supersaturated. Thus, the aerosol deposited on the demister bed would probably be a solution droplet which would flow by gravity from the demister. Evidence that this was the case in the present tests included visual observation of fog drops in the plenum above the SGS pool and lack of pressure buildup across the fiber bed demister.

Cooling in the demister bed and conversion of NaOH to Na_2CO_3 may decrease the solubility of the liquid held up in the demister. Thus, it is prudent to limit the concentration of sodium ion in the SGS pool well below saturation at the demister bed conditions. A maximum of 115 g Na/ℓ (5 normal) is recommended as a value to be used for design purposes.

Aerosol Inlet Concentration -- Much evidence exists that aerosol particle size increases with increased aerosol concentration.[14] Thus, aerosol concentration indirectly affects removal efficiency by affecting particle size. Very high concentration of suspended aerosol in the containment atmosphere would cause agglomeration to relatively large particles which would be removed in the SGS with high efficiency. Conversely, a very low aerosol concentration in containment would not be conducive to particle growth and the SGS efficiency would be lower. In the present test series, the suspended aerosol concentration ranged from 1.6 to 23 g/m^3 at containment conditions (1.2 to 18 g Na/m^3 STP). Higher concentrations can be postulated for severe accidents,[14] with maximum concentration on the order of 50 g/m^3 (~25 g Na/m^3 STP). Thus, the present tests are conservative for the particle size influence of aerosol concentration.

Another effect of inlet aerosol concentration is that due to mass loading in the gravel bed. Aerosol deposited in the bed is dissolved in the SGS pool liquid circulating through the bed. From a sodium mass balance,

$$\Delta C_L = \frac{C_g \, E_{SGS} \, G}{L} \tag{29}$$

where:

ΔC_L = increase in liquid conc for single pass through bed (g Na/m^3)
C_g = inlet gas aerosol concentration (g Na/m^3)
E_{SGS} = removal efficiency of SGS (dimensionless)
G = inlet gas flow rate (m^3/s)
L = liquid volumetric flow rate through bed (m^3/s)

The ratio of volumetric liquid to gas flow rates, L/G, is obtained from Figure 34 as 0.028 for the design gas flow rate of 0.47 m^3/s. The efficiency, E_{SGS}, is taken as 0.9975 from Figure 47. Solving Equation (29) with these input values and assuming an upper limit of ~50 g/m^3 aerosol

concentration (25 g Na/m^3) gives ΔC_L = 0.89 g Na/ℓ. Since the solubility of NaOH and Na_2CO_3 at 60°C is 600 and 185 g Na/ℓ, respectively,[6] the sodium concentration in the liquid at the gravel bed overflow weir would be far below saturation if the concentration in the main SGS pool is limited to ~115 g/ℓ (5 normal). Momentary values higher than this could occur if large chunks of deposited aerosol break off from the inlet duct walls, but the high liquid pumping rate would rapidly dissolve and dilute the material.

It is concluded that inlet aerosol concentration per se has very little effect on the SGS performance.

Gas Velocity -- If impaction is the dominant particle removal mechanism, as assumed in the model of Calvert et al.[21] and expressed in Equation (24), the penetration should decrease exponentially with increasing gas velocity. However, the validity of Equation (24) was shown to be questionable in Section 6.3.1.1, where predictions based on this equation greatly overpredicted particle penetration compared with measurements made in the present work. It was concluded that mechanisms other than impaction were also important, possibly particle growth due to water absorption and turbulence not accounted for in the impaction model. Thus, the effect of velocity is not readily predictable from present theory.

In the present work, superficial inlet gas velocities were varied from 0.088 m/s to 0.744 m/s (inlet gas flow rates of 0.081 to 0.686 m^3/s). This range includes velocities well above and below the nominal design velocity of 0.5 m/s. Sodium aerosol penetrations are listed for each operating period in Tables 59 through 62, along with the respective gas flow rates. An examination of Tables 59 through 62 indicates that the SGS removal efficiency is not sensitive to gas velocity. Data from Tables 59 through 62 that show the effect of gas velocity are summarized in Table 68, where typical penetrations are listed for three nominal gas flow rates. No effect of gas velocity is evident.

TABLE 68

EFFECT OF GAS FLOW RATE ON SGS PENETRATION[a]

V_g (m/s)	G (m^3/s)	C_L (g Na/ℓ)	Na Penetration x 10^4			
			AC7	AC8	AC9	AC10
0.055	0.05	∿5	14	17	52	21
0.26	0.24	∿5	16	23	--	21
0.51	0.47	∿5	18	31	40	26
0.11	0.1	∿80	--	--	--	126
0.26	0.24	∿80	--	265	--	94
0.51	0.47	∿80	100	245	--	101

(a) Data taken from Tables 59 through 62.

SGS Pool Level -- Slight lowering of the SGS pool surface level below the gravel basket weir should not affect the particle removal because the aerosol, gas and entrained water must still traverse the same fixed geometry gravel bed. However, if the level is lowered below the minimum water pumping level, shown in Figure 36, sufficient liquid may not be entrained to clean the gravel of deposited aerosol and the bed could conceivably plug. It is doubtful that this would really happen because small amounts of water are observed to be entrained as a mist even at levels below the minimum bulk pumping level. The pressure drop decreases as the level is decreased, in accordance with Equation (21).

Raising the pool level above the basket overflow weir should increase the particle removal efficiency slightly, since some removal may occur in the incremental pool volume above the gravel bed. This effect is thought to be minor. Increasing the pool level increases the pressure drop, in accordance with Equation (21).

In three of the present tests, the effect of small variations in pool level was demonstrated by lowering the level ~40 mm below the basket weir for two hours and then raising it to ~125 mm above the weir for two hours. The extreme range covered in this manner was -50 to +130 mm (-2.0 in. to +5.1 in.). No effect on aerosol penetration was seen, as indicated by Table 69. Pressure drop varied, as expected.

TABLE 69

EFFECT OF SGS POOL LEVEL ON PENETRATION AND PRESSURE DROP

Pool Level (mm)[a]	Penetration x 10^4[a]			ΔP_{SGS} (kPa)[b]		
	AC7	AC8	AC10	AC7	AC8	AC10
-50	67			6.37		
+130	40			7.99		
-21		70			6.50	
+120		70			8.08	
-45			67			6.30
+125			59			7.74

(a) From Tables 59 - 62.

(b) From Tables E1 - E4, Appendix E.

These tests demonstrated that pool level variation of approximately ±90 mm (±3.5 in.) from the design level have no significant effect on the operation and efficiency of the SGS.

Gas Temperature -- The temperature of the inlet gas is expected to have a minor effect on the aerosol removal efficiency of the SGS. Some possible effects are as follows:

- An increased efficiency due to thermophoretic forces
- A decreased efficiency due to evaporation of water

- Uncertain effect due to reduced gas velocity caused by cooling

- In designs where the gas downcomer pipe is exposed to the gas in the plenum between SGS pool and demister, some heat transfer to the downstream gas may occur, possibly evaporating some of the penetrating aerosol-fog drops and causing dry or partially dry aerosol to deposit on the demister. Although this would have no effect on the SGS, it may cause an increase in ΔP across the demister. It would be prudent to insulate the downcomer or to design the SGS with the gas entering from the side.

No effect of inlet gas temperature can be seen in the present tests.

SGS Pool Temperature -- Pool liquid temperature increased from ~20°C to 50°C as the tests progressed. Because the evaporating water flux increases with pool temperature, any effect of Stephan flow on particle collection would increase with water temperature. A comparison of aerosol penetrations for operating periods where water temperature varied (see Tables 59 through 62) indicates that pool temperature does not significantly affect scrubbing efficiency. This finding is as expected because: 1) diffusiophoretic effects are usually of minor importance in scrubbers; and 2) the scrubbing energy, which controls the removal efficiency, did not vary significantly with temperature.

6.3.2 Aerosol Removal in Fiber Demister

The fiber bed captures particles by three mechanisms:

- Diffusion
- Impaction
- Interception

The overall collection of particles due to these three mechanisms was modeled by picturing the fiber bed to consist of a mat of fibers aligned perpendicularly to the direction of air flow. A material balance on a differential element of the bed gives:

$$P_F = \exp(-\beta Z) \tag{30}$$

where:

P_F = Mass fraction of inlet particles penetrating the fiber bed

β = Removal constant (cm^{-1})

Z = Bed thickness (cm)

The removal constant, β, can be expressed as:

$$\beta = \frac{4fE_f}{d_f(1-f)} \tag{31}$$

where:

f = Fraction of bed filled by fibers

E_f = Single fiber collection efficiency

d_f = Diameter of fiber (cm)

Combining Equations (30) and (31) gives:

$$P_F = \exp - \left[\frac{4fE_f Z}{d_f(1 - f)} \right] \tag{32}$$

This is the equation used to predict particle capture by the fiber demister in this study. All of the right-hand terms in Equation (32) are fixed by the fiber bed geometry, except E_f.

The efficiency for diffusional capture of particles was accounted for by using an equation based on the analogy between heat and mass transfer:[23]

$$E_D = \frac{1}{Pe} + 1.727 \frac{Re^{1/6}}{Pe^{2/3}} \tag{33}$$

where:

E_D = Single fiber collection efficiency due to diffusion
Pe = Peclet number = $d_f\ u/D$
Re = Reynolds number = $d_f\ u\rho/\mu$
u = Gas velocity far from the fiber bed (cm/s)
D = Particle diffusivity (cm^2/s)
ρ = Gas density (g/cm^3)
μ = Gas viscosity (g/cm·s)

The gas velocity, μ, was computed as the bulk average gas velocity flowing through the free volume of the bed:

$$\mu = \frac{G}{A_F\ (1 - f)} \tag{34}$$

where:

G = Gas flow rate (actual cm^3/s)
A_F = Mean bed area (cm^2)
f = Bed packing fraction

The particle diffusivity, D, was computed from Equation (35), which was derived from Fuchs.[24]

$$D = \frac{kT}{6\pi\mu r_p} \left[1 + \frac{1.246\lambda}{r_p} + \frac{0.034\lambda}{r_p} \exp\left(\frac{-0.87\ r_p}{\lambda} \right) \right] \tag{35}$$

where:

k = Boltzmann's constant (dyne cm/K)

T = Absolute temperature (K)

r_p = Particle radius (cm)

λ = Gas molecule mean free path (assumed constant at 7.1×10^{-6} cm for these test conditions)

D = Particle diffusion coefficient (cm^2/s)

μ = Gas viscosity (dyne s/cm^2)

Particle collection by interception and impaction was accounted for by using numerical computations of particle capture by fibers as tabulated by Davies.[25] The single fiber efficiencies due to impaction plus interception, E_{imp} and E_{int}, were calculated using the Spielman-Goren flow field as computed by Dawson and reported by Davies.[25] The data presented by Davies[25] were plotted to facilitate interpolation for specific Stokes numbers and ratio of particle diameter to fiber diameter. The total single fiber collection efficiency, E_f, was taken to be the sum of the efficiencies for the three mechanisms:

$$E_f = E_D + (E_{imp} + E_{int}) \tag{36}$$

where E_f is used in Equation (31) for computation of the particle penetration of the fiber bed.

The values of the parameters used to characterize the physical properties of the fiber bed test article are summarized in Table 70.

The particle size distribution of the aerosol entering the fibrous scrubber was determined by cascade impactor samples taken from the gas inlet duct. Extrapolation of the size distribution into the smaller size range was required to obtain estimates for the small particle sizes (0.05 to 1.0 μm) that give the maximum penetration of the fiber bed. The extrapolation was done by assuming that the log-normal distribution was applicable for the entire size spectrum.

TABLE 70

PHYSICAL PARAMETERS FOR FIBER BED

Parameter	Value
Bed thickness (Z)	7.62 cm
Fiber diameter (d_f)	0.0020 cm
Superficial mean bed area (A_f)	5.12×10^4 cm^2
Fraction of bed filled by non-gaseous media (f)	0.15

Comparisons of measured and predicted penetrations are given in Table 71 and Figure 48. The calculations tabulated in Table 71 were made for test periods when cascade impactor size data were available.

TABLE 71

COMPARISON OF PREDICTED AND MEASURED SODIUM PENETRATION OF THE DEMISTER

Test No.	Time (min)	Measured Particle Size AMMD (μm)	σ_g	Gas Flow Rate (a) (m^3/sec)	Na Penetration x 10^2 Predicted	Measured
AC 7	525	0.9	1.7	0.37	1.3	1.64
AC 7	1125	0.77	1.7	0.37	1.87	2.81
AC 7	1606	0.88	1.6	0.36	1.20	3.27
AC 8	771	0.88	1.76	0.37	1.41	1.1
AC 8	1010	0.84	2.4	0.37	1.76	1.57
AC 9	130	0.78	1.5	0.17	0.80	(b)
AC 9	423	1.68	1.57	0.34	0.10	0.23
AC 10	415	1.15	3.1	0.35	1.21	1.49
AC 10	657	1.04	2.67	0.32	1.24	2.10
AC 10	1080	0.49	1.57	0.34	3.28	2.35

(a) At demister conditions.

(b) Not available.

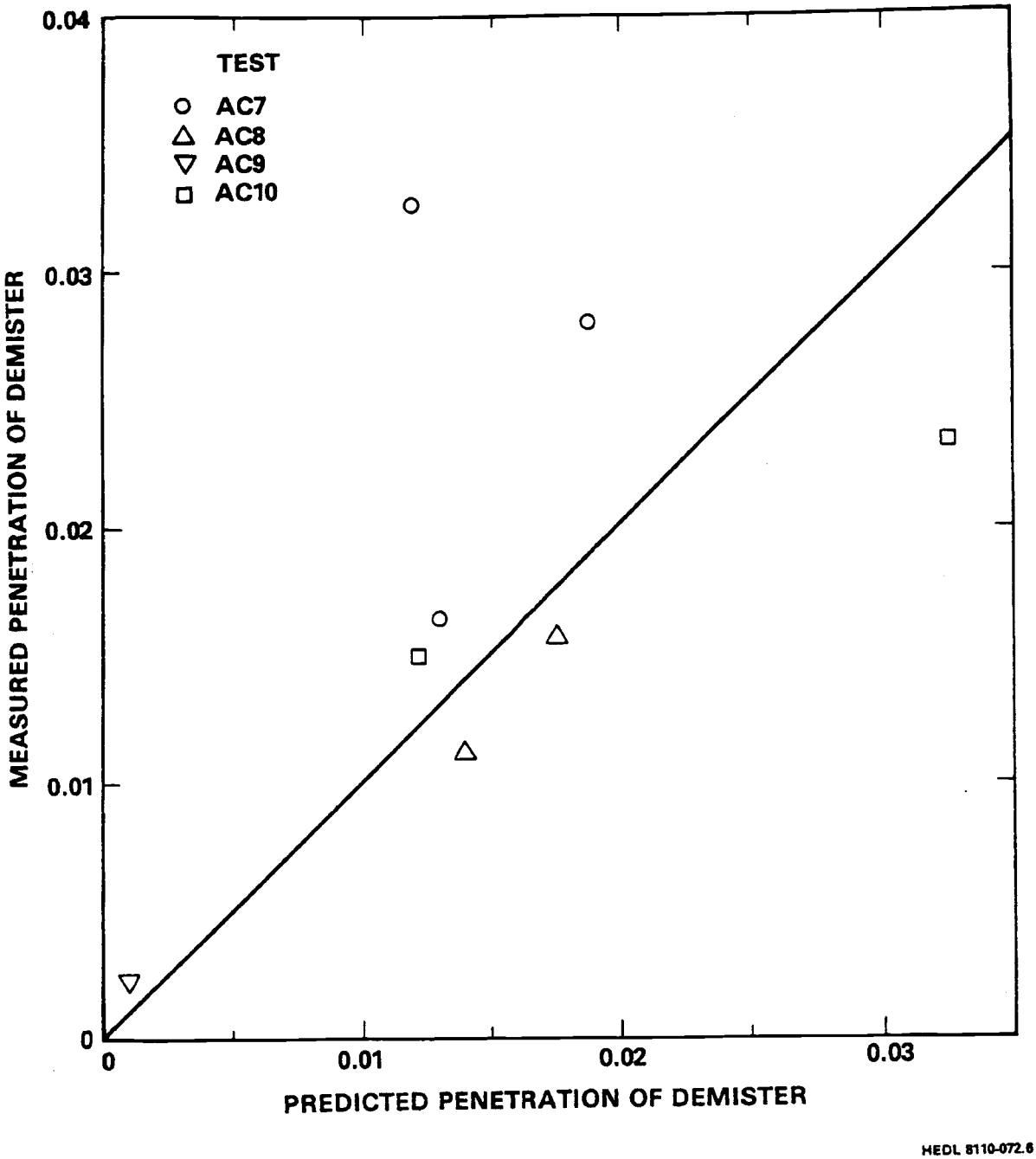

FIGURE 48. Comparison of Predicted and Measured Sodium Aerosol Penetration of the Demister.

Several important conclusions which may be drawn from the comparison of predicted and measured removal efficiencies are noted as follows. First, the predicted and measured efficiencies agree reasonably well. This numerical agreement supports the validity of the model and the substantial correctness of critical input parameters, such as particle size, fiber size, and packing density. The degree of agreement between predicted and measured removal efficiencies indicated in Table 71 is comparable to or somewhat better than reported for earlier tests[5] which used a fiber bed of similar design.

Second, it was observed that the measured penetration generally increased with time. This trend is attributed to entrainment of solution drops from the fiber bed. The sodium concentration in the SGS pool increased with time, and this would cause the sodium concentration in entrained liquid to increase with time. Thus, although the entrainment rate was very low when measured in terms of mass per unit time, the entrainment can be comparable to penetration of aerosol from a highly efficient scrubber system.

Third, the penetration of the demister appears to decrease when the gas flow rate is decreased. This effect is illustrated by the predicted penetration for the first calculational period for test AC9 listed in Table 71. Although a measured penetration was not available for this time period, measurements reported in earlier work[5] indicated the inverse relationship between efficiency and flow rate. This effect apparently arises because Brownian diffusion is the dominant capture process for the particles which penetrate the fiber bed; and, as indicated by Equation (33), the collection efficiency decreases with Pe and, therefore, with increasing gas velocity.

6.3.3 Aerosol Removal in Total System

One of the reasons that the SGS/Demister system was developed was that its particle capture efficiency was thought to be fairly independent of particle size. Particle capture was visualized as a series process, where particles

in a particular size range were subject to two removal processes. For a narrow particle size range, the overall penetration is the product of the two individual penetrations:

$$P_T = P_{SGS} P_{DEM} \tag{37}$$

where:

P_T = Total fractional penetration for the system
P_{SGS} = Fractional penetration of SGS
P_{DEM} = Fractional penetration of demister

Each of the terms in Equation (37) is based on the mass of aerosol entering that particular component.

The mass of aerosol in a given size range was determined from log-normal size distribution parameters reported in Tables 7 through 10 for particles entering the SGS.

The removal efficiency of the SGS was predicted using the cut-size approach noted in Section 6.3.1, assigning a value of 0.4 μm as the cut diameter. Removal of particles in the demister was modeled using the equations listed in Section 6.3.2. This approach for modeling introduces several approximations, the more important of which are:

- The mass of aerosol present in the size ranges which penetrate the system (0.05 to 0.5 μm diameter) must be obtained by extrapolation of cascade impactor data. The validity of the log-normal approximation is questionable at the extreme particle sizes.
- The cut diameter method of predicting efficiency of the SGS is not highly accurate, nor is the cut diameter known precisely for the SGS.
- Particle growth within the system is ignored.
- Entrainment of scrubbing liquid is not accounted for.

The predicted and measured sodium aerosol penetrations for typical operating conditions are listed in Table 72. An examination of Table 72 shows that the predicted and measured penetrations agree within an order of magnitude, with the predicted penetration generally being the larger. The discrepancy is believed due mainly to particle growth due to water absorption and errors in particle size measurements for the small end of the size spectrum. Although there is much room for improvement of the models discussed in Section 6.3, the models do provide a reasonable method for predicting aerosol removal efficiencies for various operating conditions during postulated breeder accidents.

6.4 EFFICIENCY FOR NaI REMOVAL

NaI was introduced as a vapor carried in nitrogen sweep gas. When this hot gas stream mixed with the cooler aerosol stream, very rapid cooling occured, and NaI vapor condensed. Earlier studies of this process[5,26] indicated that NaI would nucleate to form very small particles which would rapidly agglomerate to form particles a few tenths of a micrometer in diameter. The agglomerated particles would then attach to neighboring NaOH aerosol particles to an extent depending on the aerosol concentration and time available. Predicted characteristics of NaI aerosol in earlier tests[5] with aerosols similar to those used in the present work are listed in Table 73.

The main feature of the results presented in Table 72 is that the NaI particles are predicted to be much smaller in size than the aerosol produced by the sodium spray fire. Because an appreciable fraction of the NaI aerosol is present in the most penetrating size range, the removal efficiency is expected to be appreciably lower for NaI than for the sodium fire aerosol. Measured removal efficiencies for the two aerosol populations are compared in Table 74.

TABLE 72

COMPARISON OF PREDICTED AND MEASURED SODIUM PENETRATIONS IN THE SGS/DEMISTER SYSTEM

Test No.	Time (min)	Particle Size[a] AMMD (μm)	Particle Size[a] σ_g	Gas Flow Rate (b) (m^3/s)	Na Penetration x 10^4 Predicted	Na Penetration x 10^4 Measured[c]
AC7	280	6.88	3.01	0.182	1.11	0.07
AC7	645	4.65	3.22	0.392	10.6	0.91
AC7	1368	3.90	2.56	0.363	4.25	3.73
AC8	285	4.09	3.54	0.214	7.89	2.65
AC8	704	4.01	3.59	0.362	11.3	0.59
AC8	1365	4.63	3.29	0.364	9.63	3.95
AC9	186	5.63	3.38	0.308	6.38	0.19
AC9	675	3.40	3.59	0.175	7.93	0.14
AC10	229	5.44	2.98	0.087	0.47	0.06
AC10	1245	6.21	2.96	0.335	3.14	3.75

(a) From Tables 18 through 21.

(b) At SGS inlet conditions.

(c) From Tables 59 through 62.

TABLE 73

NaI AEROSOL PARAMETERS[a]

Test	Mass Injected (g NaI)	NaI Conc (g NaI/cm³)	Fraction Attached to NaOH	AMMD, μm	
				Unattached Particles	Attached Particles
AC3	582	3.84×10^{-8}	0.0764	0.22	0.67
AC4	368	1.38×10^{-8}	0.0769	0.13	0.87

(a) From Reference (5).

TABLE 74

COMPARISON OF MEASURED REMOVAL EFFICIENCIES
FOR NaI AND NaOH AEROSOLS IN TEST AC10

Component(s)	Penetration Based on Liquid Sampling	
	NaOH Aerosol	NaI Aerosol
SGS	0.0064	0.656
Demister	0.0102	0.0106
SGS/Demister System	0.000066	0.0070

As expected, the SGS was much more efficient for the NaOH aerosol than for NaI aerosol. Interestingly, the demister was equally efficient for NaOH and NaI. Only the submicron fraction of the aerosol (NaOH and NaI) penetrates the SGS, and therefore the sizes of the two types of aerosol which enter the demister would not be greatly different. Thus, the observed similar removal efficiencies by the demister are as expected.

6.5 SCALEUP CONSIDERATIONS

The major questions regarding scaleup of the SGS/Demister system deal with the SGS. Scaleup of the demister is readily accomplished by using multiple commercial units of the size tested in the present work. Scaleup of the SGS unit is less certain. The chief uncertainty in scaling the SGS is the effect of increasing bed diameter on gas distribution. Aerosol collection efficiency and pressure drop across the gravel bed are not expected to depend on radial scale. For a bed of the same height (0.61 m) and gravel grain size as used in the present tests, the pressure drop and particle collection efficiency would be essentially the same as measured in tests AC7 through AC10. However, scaling the bed radially may introduce variations in gas and liquid distribution within the bed.

Visual observations of the flow patterns that develop in the SGS were made with models fabricated from transparent plastic. At very low flow rates, incoming gas rises through the bed in bubbles with most of the bubbles rising near the gas downcomer. As the gas velocity is increased, a layer of gas spreads across the entire cross-section of the gravel support basket. Waves form on the depressed liquid surface and reflect off the restraining walls beneath the gravel basket. Crests of waves also intercept the gravel support grid and liquid is swept into the gravel at various radii. The gas continues to flow at nearly a steady velocity, as discussed in Section 5.3.3. Liquid flows through the bed in pulses with a frequency of ~0.5 cycles per second. For the test article studied in the present tests, the slug-type of flow existed for flow rates ranging from approximately 10% of the design velocity to the maximum attainable, 1.3 times the design flow rate of 0.47 m^3 per second.

As gas velocity is increased still further, a point is reached where the pressure drop across the bed exceeds the water head, pulsing ceases, and no water flows through the bed. This "dry-out" state was found to occur at a superficial velocity greater than 1 m/s in a small-scale model.

A series of tests was performed with the small-scale model shown in Figure 49.[7] The gravel bed in this model has a cross-sectional area of 0.070 m^2. Hydraulic and aerosol collection tests were performed with beds of various heights, gravel grain size, and packing type. The particle collection efficiency for a bed of the same height and grain size as used in tests AC7 through AC10 was 0.998 for sodium fire aerosols.[7] This is significantly better efficiency than measured in tests AC7 through AC10 (0.9924 average), but it is thought to be an artifact of sampling and inlet line clogging in the small-scale tests, rather than true effect of size scale.

In order to determine the effect of bed diameter on flow distribution within the gravel bed, hydraulic tests were performed with a bed in which gas was distributed across a radial distance of 1.07 m. Because a high capacity exhaust blower was not available, the test atricle was constructed as a 50° sector of a 3.1-m diameter bed (Figure 50). The model had transparent sides and gravel of the same grain size and bed depth used in tests AC7 through AC9. The grating visible in Figure 50 was added as a restraint to keep the top screen in place. Figures 51 and 52 are photographs taken while gas was flowing through the bed at 0.152 m/s and 0.51 m/s, respectively. On the basis of visual observations, the gas was essentially uniformly distributed across the complete breadth of the gravel bed.

Table 75 lists the radial distance from edge of gas downcomer to outer gravel basket rim in the three SGS models tested to date. The radial distance required for plant scale prototypes handling 4.7 m^3/s to 18.9 m^3/s (10,000 ft^3/ min to 40,000 ft^3/min) are also listed, assuming a cylindrical bed and a superficial gas velocity of 0.5 m/s. Table 75 shows that the 50° sector test was at ~78 of the scale required for a 4.7 m^3/s unit and ~35 of that required for a 19 m^3/s unit. Although extrapolation to the

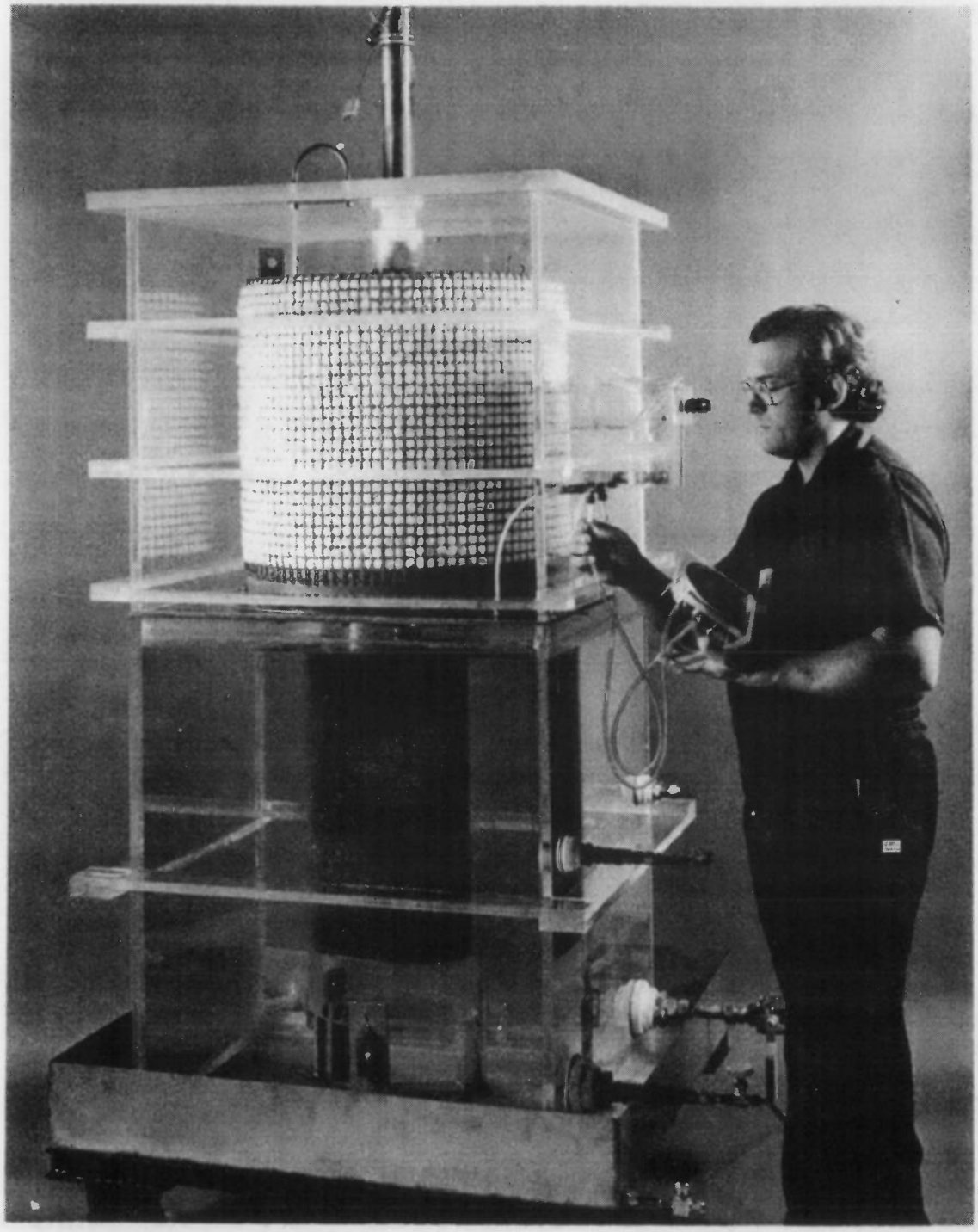

FIGURE 49. Photograph of Small-Scale Model of SGS. Neg 7908846-1cn

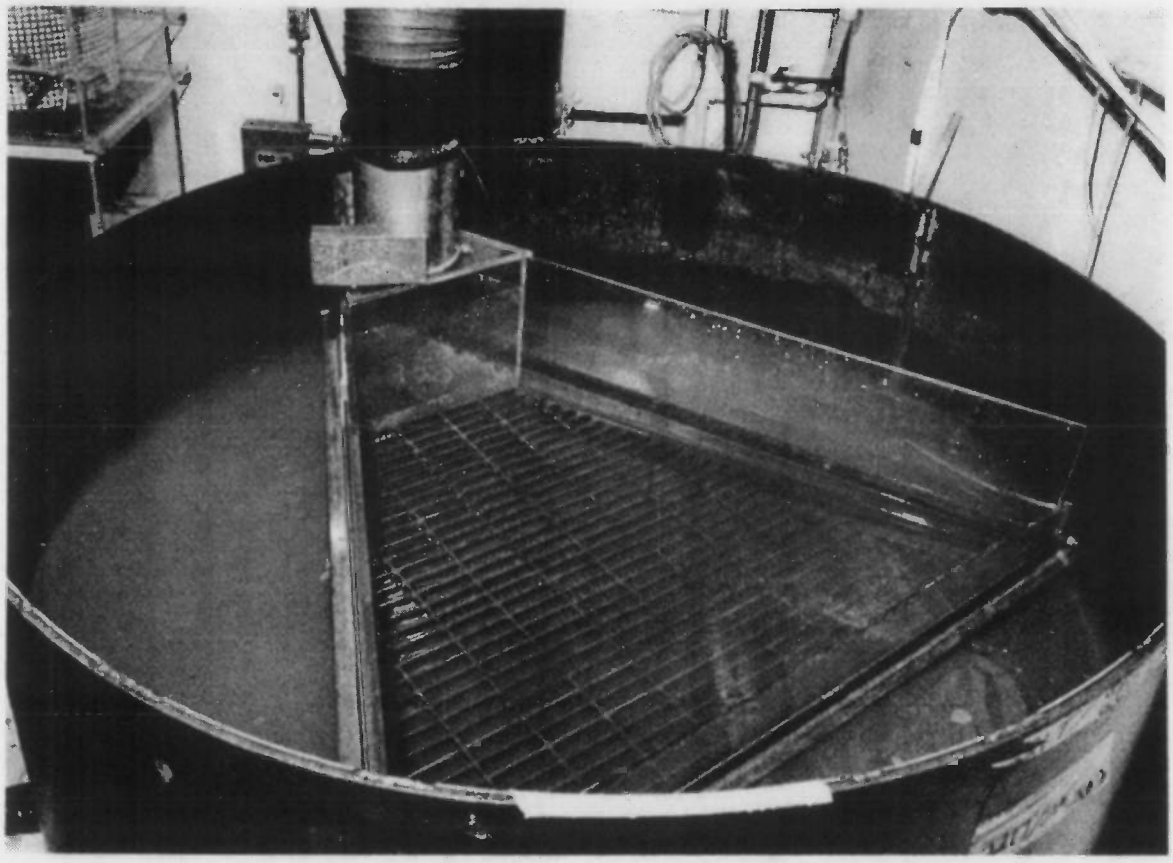

FIGURE 50. Photograph of 50° Sector Test Article. Neg 7912779-9cn

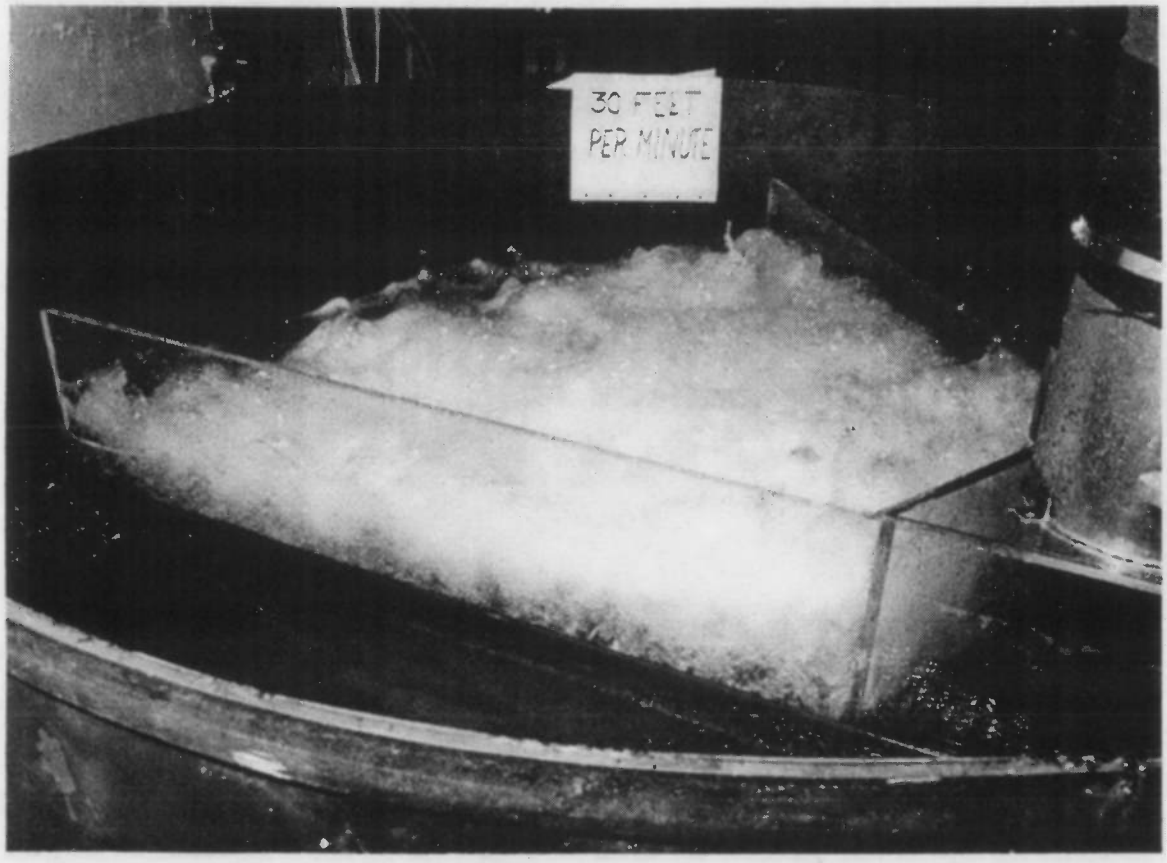

FIGURE 51. Photograph Showing Gas Distribution in 50° Sector Test at One-Third Design Flow Rate.
Neg 7912779-5cn

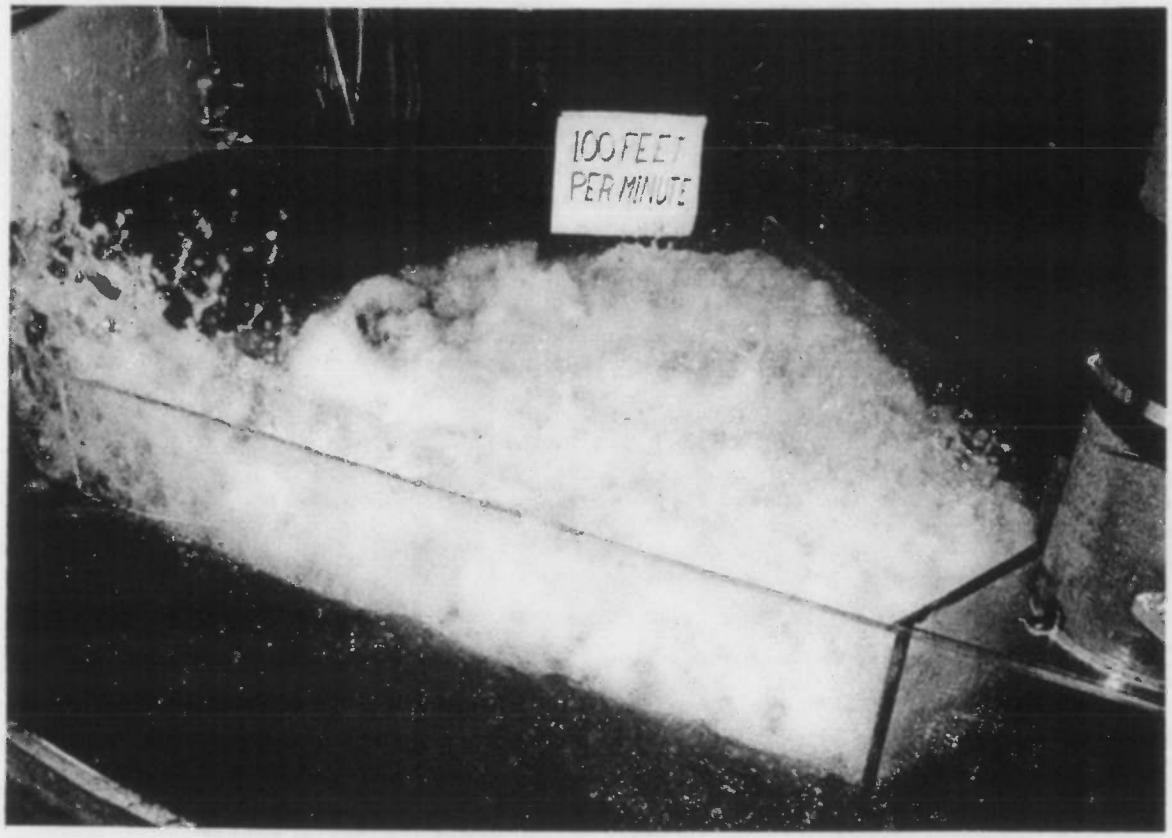

FIGURE 52. Photograph Showing Gas Distribution in 50° Sector Test At Design Flow Rate.
Neg 7912779-6cn

TABLE 75

RADIAL DIMENSION OF VARIOUS SGS UNITS

Unit	Design Gas Flow Rate (m^3/s)	Gravel Bed Radial Dimension (m) [a][b]
Small-Scale Test Article[c]	0.035	0.15
Present Test Article	0.472	0.43
50° Sector Test Article	0.472	1.07
Plant Prototype	4.7	1.38
Plant Prototype	9.4	2.09
Plant Prototype	18.9	3.00

(a) Outer edge of downcomer to basket rim.

(b) Design superficial gas velocity = 0.5 m/s.

(c) Reference 7 .

plant scale appears warranted, a hydraulic test with the full-scale radial dimension is warranted.

If radial dimension should prove to be a problem, scaleup could be accomplished by using a rectangular bed with the narrow dimension set at the maximum length shown by testing to give acceptable gas distribution. Alternatively, multiple units of cylindrical baskets could be installed in a common tank of water.

7.0 NOMENCLATURE

Variables

a	Interfacial area per unit volume (m^{-1})
A	Area (cm^2)
C	Concentration (g/cm^3 or g/m^3) or orifice coefficient
C_p	Heat capacity (watt h/kg °C)
d	Diameter (m or cm)
d_c	Diameter of spherical packing grain
d_f	Diameter of fiber (cm)
d_p	Diameter of particle (cm or μm)
D	Diameter (m) or diffusion coefficient (cm^2/s)
E	Aerosol removal efficiency
f	Fraction of bed volume filled with nongaseous media
g	Gravitational acceleration (cm/s^2)
G	Gas volumetric flow rate (m^3/s)
h	Heat transfer coefficient (watt/m^2 °C) or height of SGS pool depression (m) or bed thickness (cm)
H	Liquid holdup in bed (fraction of bed volume)
I	Source rate (g/s)
j	Parameter relating channel width to packing size
k	Thermal conductivity (watt/m °C)
L	Liquid volumetric flow rate (m^3/s)
m	Mass (kg)
P	Pressure (Pa) or aerosol penetration (dimensionless)
ΔP	Differential pressure (Pa)
Pe	Peclet number
Pr	Prandtl number
r	Radius (cm or m)
Re	Reynolds number
S	Submergence of gas downcomer (m)
Stk	Stokes number
T	Temperature
u	Gas velocity (m/s)

V_g	Gas velocity (m/s)
w	Mass flow rate of gas ($kg/m^2 \cdot h$)
x	Distance (m)
z	Bed height (m)
Z	Bed thickness (cm or m)

Subscripts

A	Aerosol
D	Diffusion
DEM	Demister
f	Fluid or fiber
F	Fiber bed
g	Gas
i	Individual component or inlet
imp	Impaction
imt	Interception
ℓ	Liquid
p	Particle
s	Settling mean or heat sink surface
SGS	Submerged Gravel Scrubber
t	Terminal
T	Total
x	Distance

Greek Symbols

β	Removal constant (cm^{-1})
ε	Void volume fraction
ξ	Volumetric entrainment rate (m^3/s)
λ	Gas molecule mean free path (cm)
μ	Viscosity ($g/cm \cdot s$)
π	Constant = 3.1416
ρ	Density (g/cm^3)
σ_g	Geometric standard deviation

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APPENDIX A

CASCADE IMPACTOR DATA

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CASCADE IMPACTOR DATA

Data for individual cascade impactor measurements and the calculational procedures used to extract size data from the stage deposits are presented in this appendix. The collection characteristics of each impactor stage were assumed to be controlled by the dimensionless impaction parameter:

$$\Psi = \frac{\rho u d^2 C}{18 \mu D} \tag{A-1}$$

where:

Ψ = Impaction parameter (dimensionless)
u = Gas velocity (cm/s)
ρ = Particle density (g/cm^3)
d = Particle diameter (cm)
μ = Gas viscosity (g/cm·s)
D = Impactor jet diameter (cm)
C = Cunningham slip factor (dimensionless)

At the point of the impaction curve where 50% of the particles are collected, the impaction parameter Ψ takes the value Ψ_{50}. The 50% size is:

$$d_{50} = \left(\frac{18 \mu D \Psi_{50}}{uC} \right)^{0.5} \tag{A-2}$$

where:

d_{50} = Particle diameter at the 50% point on efficiency vs size curve

Ψ_{50} = Impaction parameter for the jet at the 50% efficiency point

Equation A-2 was used to determine d_{50} values at flow conditions different from those used to calibrate the impactor; it can also be used to relate the d_{50} to the value under calibration conditions. If C is assumed to be constant, then d_{50} can be expressed as:

$$d_{50} = (d_{50})_{ref} \left(\frac{\mu}{\mu_{ref}} \times \frac{Q_{ref}}{Q} \right)^{0.5} \qquad \text{(A-3)}$$

where:

d_{50} = Aerodynamic diameter at sampling conditions
μ = Viscosity of gas at sampling conditions
Q = Gas flow rate at sampling conditions
ref = Subscript indicating value of parameter under calibration or reference conditions

Cascade impactors of two designs (Andersen Mark III circular jet impactor* and Sierra rectangular jet impactor**) were used for particle size analysis. Stage cut-size diameters used to interpret data obtained from the circular jet impactor are recommended by the manufacturer[A-1] and listed in Table A-1. These values are in good agreement with calibrations reported by Cushing et al.[A-2]

Stage cut-off diameters for the rectangular jet impactor are listed in Table A-2, and the data were obtained from the work of Cushing et al.[A-2] Cut diameters listed in Tables A-1 and A-2 were adjusted for sampling conditions using Equation A-3.

Particle size distributions were constructed from cascade impactor data using the cut-off diameter approach described by Mercer.[A-3] Table A-3 presents an example of the calculation method.

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*Manufactured by Andersen 2000, Inc., Atlanta, GA.
**Model 226, Stack Sampler, Manufactured by Sierra Instrument Co., Inc., Carmel Valley, CA.

TABLE A-1

STAGE CUT DIAMETERS FOR CIRCULAR JET IMPACTOR USED IN AIR CLEANING TESTS

Stage No.	d_{50}* (μm)
0	13.2
1	8.3
2	5.64
3	3.8
4	2.45
5	1.25
6	0.77
7	0.52

*Size of unit density spheres removed with 50% efficiency at 21°C, 1 atm pressure, and 0.50-ACFM flow rate.

TABLE A-2

STAGE CUT DIAMETERS FOR RECTANGULAR JET IMPACTOR USED IN AIR CLEANING TESTS

Stage No.	d_{50}* (μm)
1	18.0
2	11.0
3	4.4
4	2.65
5	1.70
6	0.95

*Size of unit density spheres removed with 50% efficiency at 28°C, 29.5-in. Hg pressure, and 0.25-ACFM flow rate.

The stage accumulations of sodium were obtained by washing each stage collection paper with water and analyzing the water by flame emission spectometry. Losses to the interstage impactor walls were ignored. The inlet walls were washed and analyzed for sodium, and the recovered sodium was assumed to be associated with aerosol particles larger than the first-stage cut-off diameter.

The particle size distribution was obtained by plotting the two right-hand columns in Table A-3 on log-probability paper as shown in Figure 19. The mass median diameter and geometric standard deviation can be obtained from the line drawn through the data points. The geometric standard deviation was obtained from:

$$\sigma_g = \frac{\text{Particle Diameter at 50\%}}{\text{Particle Diameter at 15.84\%}} \qquad \text{(A-4)}$$

Mass median diameters and standard deviations are summarized in Tables 18 through 21 for Tests AC7, AC8, AC9, and AC10, respectively. Mass distributions of sodium found on the cascade impactor stages are presented in Tables A-4 through A-7 for the four tests.

TABLE A-3

EXAMPLE TREATMENT OF CASCADE IMPACTOR DATA*

Stage No.	Sodium Mass** (mg)	Mass Fraction	Cumulative Fraction	One Minus Cumulative Fraction	d_{50} (μm)
Inlet	3.55	0.1762	0.1762	0.924	--
1	1.23	0.0610	0.2372	0.763	15.12
2	1.90	0.0942	0.3314	0.669	9.24
3	5.38	0.2671	0.5985	0.402	3.70
4	3.97	0.1971	0.7956	0.204	2.23
5	2.10	0.1042	0.8998	0.100	1.43
6	1.33	0.0660	0.9658	0.034	0.80
7 (filter)	0.69	0.342	1.000	0.000	--
	20.15	1.0000			

*Sample Number - AC7-T3-I6, taken at time 345 min
Impactor - Sierra Model 226
Flow Rate - 0.134 std ℓ/s
Temperature - 120°C
Pressure - 98.6 kPa absolute

**Net mass after correction for stage collection paper background

TABLE A-4

SODIUM DISTRIBUTION ON CASCADE IMPACTOR STAGES FOR TEST AC7

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
529	T1	14.97	0.786
		9.15	0.680
		3.66	0.501
		2.20	0.309
		1.41	0.125
		0.79	0.029
937	T1	15.01	0.804
		9.17	0.682
		3.67	0.465
		2.21	0.295
		1.42	0.140
		0.79	0.041
1386	T1	11.97	0.854
		7.53	0.780
		5.12	0.614
		3.45	0.472
		2.22	0.287
		1.13	0.089
		0.70	0.022
		0.47	0.005
1725	T1	12.07	0.819
		7.59	0.767
		5.16	0.621
		3.48	0.480
		2.24	0.326
		1.14	0.105
		0.70	0.027
		0.48	0.010

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-4 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
2005	T1	15.08	0.881
		9.22	0.763
		3.69	0.492
		2.22	0.252
		1.42	0.109
		0.80	0.041
2055	T1	15.13	0.732
		9.24	0.569
		3.70	0.338
		2.23	0.136
		1.43	0.042
		0.80	0.009
2198	T1	12.08	0.956
		7.60	0.903
		5.16	0.782
		3.48	0.650
		2.24	0.340
		1.14	0.126
		0.71	0.087
		0.48	0.078
7	T3	12.60	0.983
		7.93	0.976
		5.39	0.954
		3.63	0.883
		2.34	0.512
		1.19	0.096
		0.74	0.008
		0.50	0.002

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-4 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
105	T3	19.52	0.694
		11.93	0.614
		4.77	0.424
		2.87	0.209
		1.84	0.085
		1.03	0.032
160	T3	19.76	0.701
		12.08	0.632
		4.83	0.471
		2.91	0.244
		1.87	0.106
		1.04	0.039
280	T3	15.20	0.707
		9.29	0.602
		3.72	0.372
		2.24	0.175
		1.44	0.075
		0.80	0.020
345	T3	15.12	0.763
		9.24	0.669
		3.70	0.402
		2.23	0.204
		1.43	0.100
		0.80	0.034

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-4 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
645	T3	11.91	0.734
		7.49	0.658
		5.09	0.551
		3.43	0.409
		2.21	0.267
		1.13	0.119
		0.70	0.028
		0.47	0.003
815	T3	12.12	0.720
		7.62	0.630
		5.18	0.520
		3.49	0.408
		2.25	0.271
		1.15	0.100
		0.71	0.025
		0.48	0.008
30	T4	26.47	0.936
		16.64	0.914
		11.31	0.867
		7.62	0.801
		4.91	0.598
		2.51	0.245
		1.54	0.130
		1.04	0.083
525	T6	15.75	0.975
	SGS Outlet	9.62	0.969
		3.85	0.948
		2.32	0.932
		1.49	0.845
		0.83	0.400

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-4 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1125	T6	15.74	0.996
	SGS Outlet	9.62	0.991
		3.85	0.978
		2.32	0.967
		1.49	0.882
		0.83	0.561
1606	T6	15.37	0.991
	SGS Outlet	9.39	0.984
		3.76	0.970
		2.26	0.954
		1.45	0.850
		0.81	0.427
1691	T6	15.88	0.989
	SGS Outlet	9.70	0.980
		3.88	0.960
		2.34	0.949
		1.50	0.904
		0.84	0.477
720	T7	15.78	0.967
	Demister	9.64	0.959
	Outlet	3.86	0.952
		2.32	0.931
		1.49	0.875
		0.83	0.605

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-4 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1574	T7	12.52	0.986
	Demister	7.87	0.980
	Outlet	5.35	0.970
		3.60	0.965
		2.32	0.955
		1.19	0.941
		0.73	0.836
		0.49	0.566

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-5

SODIUM DISTRIBUTION ON CASCADE IMPACTOR STAGES FOR TEST AC8

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
520	T1	16.71	0.791
		10.21	0.708
		4.08	0.538
		2.46	0.383
		1.58	0.231
		0.88	0.050
704	T1	12.03	0.769
		7.56	0.691
		5.14	0.593
		3.46	0.482
		2.23	0.340
		1.14	0.184
		0.70	0.075
		0.47	0.044
795	T1	11.87	0.777
		7.46	0.702
		5.07	0.584
		3.42	0.481
		2.20	0.346
		1.12	0.176
		0.69	0.068
		0.47	0.041
1064	T1	17.05	0.809
		10.72	0.756
		7.28	0.693
		4.91	0.598
		3.16	0.471
		1.61	0.310
		0.99	0.164
		0.67	0.072

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°.
All at 80 mm from containment vessel wall.

TABLE A-5 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1365	T1	16.32	0.802
		9.98	0.701
		3.99	0.528
		2.40	0.374
		1.54	0.221
		0.86	0.048
1485	T1	16.32	0.801
		9.97	0.701
		3.99	0.526
		2.40	0.369
		1.54	0.190
		0.86	0.054
1605	T1	23.16	0.816
		14.15	0.717
		5.66	0.534
		3.41	0.385
		2.19	0.207
		1.22	0.065
1722	T1	16.37	0.773
		10.00	0.691
		4.00	0.558
		2.41	0.362
		1.55	0.162
		0.86	0.036

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°. All at 80 mm from containment vessel wall.

TABLE A-5 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1960	T1	16.46	0.747
		10.06	0.609
		4.02	0.385
		2.42	0.174
		1.55	0.079
		0.87	0.047
2065	T1	11.96	0.852
		7.52	0.794
		5.11	0.685
		3.44	0.550
		2.22	0.365
		1.13	0.180
		0.70	0.101
		0.47	0.071
2	T3	12.34	0.904
		7.76	0.865
		5.27	0.820
		3.55	0.775
		2.29	0.715
		1.17	0.531
		0.72	0.209
		0.49	0.086
7	T3	12.49	0.925
		7.85	0.893
		5.34	0.850
		3.60	0.780
		2.32	0.529
		1.18	0.179
		0.73	0.080
		0.49	0.049

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°.
All at 80 mm from containment vessel wall.

TABLE A-5 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
34	T3	17.55	0.841
		10.72	0.746
		4.29	0.549
		2.58	0.316
		1.66	0.159
		0.93	0.061
160	T3	19.99	0.707
		12.22	0.595
		4.89	0.436
		2.94	0.290
		1.89	0.157
		1.06	0.066
225	T3	11.86	0.805
		7.46	0.588
		5.07	0.560
		3.41	0.440
		2.20	0.300
		1.12	0.150
		0.69	0.074
		0.47	0.046
285	T3	11.86	0.788
		7.46	0.701
		5.07	0.568
		3.42	0.453
		2.20	0.299
		1.12	0.154
		0.69	0.075
		0.47	0.046

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°. All at 80 mm from containment vessel wall.

TABLE A-5 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
345	T3	16.40	0.769
		10.02	0.663
		4.01	0.468
		2.41	0.320
		1.55	0.169
		0.87	0.051
1843	T3	16.39	0.761
		10.02	0.672
		4.01	0.488
		2.41	0.327
		1.55	0.174
		0.87	0.045
771	T6	15.73	0.966
	SGS Outlet	9.61	0.934
		3.85	0.900
		2.32	0.869
		1.49	0.816
		0.83	0.452
1010	T6	15.74	0.946
	SGS Outlet	9.62	0.899
		3.85	0.844
		2.32	0.798
		1.49	0.729
		0.83	0.495

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°. All at 80 mm from containment vessel wall.

TABLE A-5 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1620	T6	15.85	0.971
	SGS Outlet	9.69	0.944
		3.88	0.915
		2.33	0.889
		1.50	0.850
		0.84	0.538
721	T7	11.77	0.972
	Demister	7.19	0.943
	Outlet	2.88	0.860
		1.73	0.771
		1.11	0.729
		0.62	0.633
1575	T7	18.17	0.987
	Demister	11.10	0.973
	Outlet	4.44	0.959
		2.68	0.941
		1.72	0.910
		0.96	0.720

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°. All at 80 mm from containment vessel wall.

TABLE A-6

SODIUM DISTRIBUTION ON CASCADE IMPACTOR STAGES FOR TEST AC9

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
2	T1	17.74	0.688
		10.84	0.583
		4.34	0.371
		2.61	0.236
		1.68	0.119
		0.94	0.026
31	T1	17.77	0.716
		10.86	0.613
		4.35	0.351
		2.62	0.174
		1.68	0.091
		0.94	0.027
55	T1	18.21	0.712
		11.13	0.642
		4.45	0.472
		2.68	0.304
		1.72	0.178
		0.96	0.055
186	T1	16.89	0.725
		10.32	0.662
		4.13	0.535
		2.49	0.321
		1.60	0.154
		0.89	0.046

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-6 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
304	T1	18.25	0.709
		11.15	0.681
		4.46	0.593
		2.69	0.453
		1.72	0.041
		0.96	0.020
307	T1	16.43	0.665
		10.04	0.597
		4.02	0.476
		2.42	0.291
		1.55	0.128
		0.87	0.023
496	T1	16.11	0.717
		9.85	0.647
		3.94	0.523
		2.37	0.432
		1.52	0.308
		0.85	0.092
800	T1	16.44	0.859
		10.04	0.773
		4.02	0.607
		2.42	0.411
		1.55	0.215
		0.87	0.055

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-6 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
957	T1	16.55	0.927
		10.11	0.880
		4.04	0.743
		2.44	0.497
		1.56	0.178
		0.87	0.052
2	T3	16.89	0.971
		10.32	0.966
		4.13	0.951
		2.49	0.887
		1.60	0.417
		0.89	0.063
7	T3	17.31	0.927
		10.58	0.904
		4.23	0.688
		2.55	0.381
		1.63	0.112
		0.91	0.030
675	T3	16.41	0.777
		10.03	0.713
		4.01	0.599
		2.42	0.449
		1.55	0.267
		0.87	0.113

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-6 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
130	T6	12.30	0.976
	SGS Outlet	7.73	0.948
		5.25	0.920
		3.54	0.900
		2.28	0.866
		1.16	0.752
		0.72	0.431
		0.48	0.113
423	T6	12.15	0.985
	SGS Outlet	7.64	0.970
		5.19	0.959
		3.50	0.938
		2.26	0.753
		1.15	0.091
		0.71	0.027
		0.48	0.018
206	T7	12.99	0.951
	Demister	8.17	0.909
	Outlet	5.55	0.847
		3.74	0.805
		2.41	0.743
		1.23	0.694
		0.76	0.549
		0.51	0.392
593	T7	11.71	0.936
	Demister	7.16	0.906
	Outlet	2.86	0.876
		1.72	0.801
		1.11	0.537
		0.62	0.205

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-7

SODIUM DISTRIBUTION ON CASCADE IMPACTOR STAGES FOR TEST AC10

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
525	T1	16.49	0.798
		10.08	0.688
		4.03	0.429
		2.43	0.241
		1.56	0.108
		0.87	0.040
1365	T1	16.39	0.775
		10.02	0.684
		4.01	0.484
		2.41	0.314
		1.55	0.157
		0.87	0.048
1428	T1	16.40	0.773
		10.02	0.686
		4.01	0.504
		2.41	0.331
		1.55	0.128
		0.87	0.010
1802	T1	17.55	0.912
		10.72	0.912
		4.29	0.912
		2.58	0.736
		1.66	0.531
		0.93	0.003
		0.52	0.003
		0.29	0.003

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-7 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
2	T3	12.32	0.975
		7.74	0.975
		5.26	0.975
		3.55	0.975
		2.29	0.947
		1.17	0.672
		0.72	0.259
		0.49	0.000
7	T3	12.25	0.917
		7.70	0.910
		5.23	0.881
		3.53	0.742
		2.27	0.358
		1.16	0.075
		0.72	0.022
		0.48	0.011
20	T3	17.31	0.720
		10.58	0.606
		4.23	0.332
		2.55	0.159
		1.64	0.050
		0.91	0.017
65	T3	19.26	0.723
		11.77	0.615
		4.71	0.374
		2.84	0.159
		1.82	0.060
		1.02	0.020

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-7 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
160	T3	19.98	0.929
		12.21	0.780
		4.88	0.453
		2.94	0.277
		1.89	0.133
		1.05	0.053
229	T3	16.60	0.835
		10.15	0.708
		4.06	0.446
		2.44	0.234
		1.57	0.113
		0.88	0.047
290	T3	16.65	0.776
		10.17	0.701
		4.07	0.493
		2.45	0.261
		1.57	0.183
		0.88	0.139
350	T3	16.64	0.763
		10.17	0.617
		4.07	0.291
		2.45	0.149
		1.57	0.061
		0.88	0.017

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-7 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
890	T3	16.97	0.601
		10.37	0.527
		4.15	0.367
		2.50	0.196
		1.60	0.053
		0.90	0.004
525	T4	15.97	0.699
		9.76	0.557
		3.90	0.437
		2.35	0.217
		1.51	0.081
		0.84	0.026
645	T4	15.92	0.711
		9.73	0.559
		3.89	0.369
		2.34	0.205
		1.50	0.095
		0.84	0.032
1010	T4	16.05	0.789
		9.81	0.672
		3.92	0.439
		2.36	0.224
		1.52	0.099
		0.85	0.025

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-7 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1245	T4	15.71	0.717
		9.60	0.627
		3.84	0.436
		2.31	0.255
		1.48	0.103
		0.83	0.019
415	T6	11.48	0.923
	SGS Outlet	7.01	0.879
		2.80	0.853
		1.69	0.824
		1.08	0.659
		0.61	0.172
		0.34	0.079
		0.19	0.043
657	T6	16.15	0.984
	SGS Outlet	9.87	0.966
		3.95	0.949
		2.38	0.927
		1.53	0.785
		0.85	0.429
		0.48	0.185
		0.27	0.050
1080	T6	16.43	1.000
	SGS Outlet	10.04	1.000
		4.01	0.999
		2.41	0.998
		1.55	0.992
		0.86	0.878
		0.48	0.531
		0.27	0.117

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

TABLE A-7 (Cont'd)

Time (min)	Location*	Cut Diameter (μm)	Fraction Smaller Than Cut Size
1221	T7	12.25	0.997
	Demister	7.70	0.997
	Outlet	5.24	0.997
		3.53	0.997
		2.27	0.993
		1.16	0.935
		0.72	0.405
		0.48	0.031

*T1 at +9.1 m, 255°C; T3 at +2.1 m, 135°C; T4 at -8.6 m, 85°C. All at 80 mm from containment vessel wall.

REFERENCES

A-1. Operating Manual for Andersen 2000, Inc., Mark II and Mark III Particle Sizing Stack Samplers, TR 76-900023, Andersen 2000 Inc., Atlanta, GA, January 1976.

A-2. K. M. Cushing et al., Particle Sizing Techniques for Control Device Evaluation: Cascade Impactor Calibrations, EPA-600/2-76-280, Southern Research Institute, Birmingham, AL, October 1976.

A-3. T. T. Mercer, "The Interpretation of Cascade Impactor Data," Industrial Hygiene Journal 26, pp. 236-241, 1965.

A P P E N D I X B

TEMPERATURES AND PRESSURES IN THE CONTAINMENT ATMOSPHERE

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TEMPERATURES AND PRESSURES IN THE CONTAINMENT ATMOSPHERE

Temperatures of the atmosphere and the vessel wall were measured at numerous locations by stainless steel sheathed, Type K Chromel-Alumel thermocouples. Locations of thermocouples are defined in Table B-1 and Figure B-1. Coordinates used to define the thermocouple locations cited in Table B-1 are illustrated in Figure B-1.

Wall temperatures, averaged over each operating period, are listed in Tables B-2, B-3, B-4, and B-5 for Tests AC1, AC2, AC3, and AC4, respectively. Containment temperatures and pressures, averaged over each operating period, are listed in Tables B-6, B-7, B-8, and B-9 for Tests AC1, AC2, AC3, and AC4, respectively.

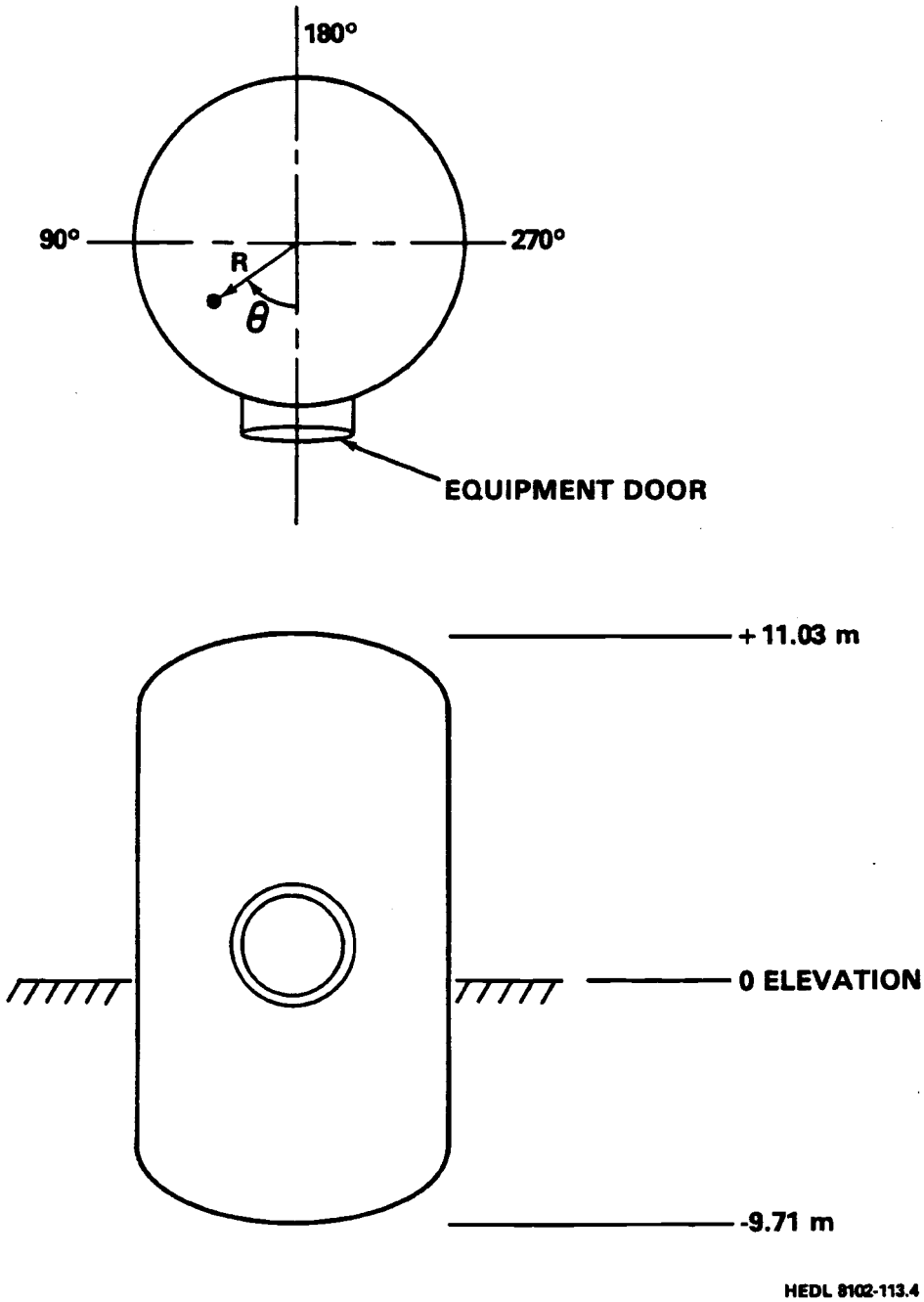

FIGURE B-1. Spatial Coordinates Used to Define Thermocouple Locations in Table B-1.

TABLE B-1

THERMOCOUPLE LOCATIONS FOR TESTS AC1 THROUGH AC4

Thermocouple Number	Wall or Atmosphere	Location
1	wall	Inside CV surface, top head center, +11.0 m
2	atmosphere	1.22-m radius, 285°, +10.7 m
3	wall	Outside steel surface, top head center, +11.0 m
4	wall	Outside steel surface, 180°, +6.10 m
5	wall	Outside steel surface, 180°, +1.22 m
6	wall	Outside steel surface, 180°, -3.05 m
7	wall	Inside CV surface, 170°, +7.32 m
8	atmosphere	0.61 m from wall, 236°, +2.14 m
9	wall	Inside CV surface, 180°, +1.22 m
10	atmosphere	0.61 m from wall, 85°, +1.22 m
11	wall	Inside CV surface, 345°, +1.22 m
12	wall	Inside CV surface, 30°, -5.80 m
13	atmosphere	0.31 m from wall, 95°, -5.80 m
14	wall	Inside CV surface, 225°, -5.80 m
15	atmosphere	0.31 m from wall, 315°, -5.80 m
16	wall	Inside CV surface, bottom head, 300°, -5.80 m
17	wall	Inside CV surface, bottom head near center
18	atmosphere	2.75 m from center, 180°, +7.32 m
19	atmosphere	2.75 m from center, 330°, -3.66 m
20	wall	Inside CV surface, 100°, +1.53 m
21	wall	Inside CV surface, 345°, +7.32 m
22	atmosphere	1.8 m from center, 260°, +7.32 m
23	atmosphere	2.75 m from center, 270°, +3.66 m
24	atmosphere	centerline, 0.41 m above burn pan

TABLE B-2. CONTAINMENT WALL TEMPERATURE DATA FOR AC-7

OPERATING PERIOD	TIME INTERVAL MINUTES	AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C)														
		TC 1	TC 3	TC 4	TC 5	TC 6	TC 7	TC 9	TC 11	TC 12	TC 14	TC 16	TC 17	TC 20	TC 21	AVERAGE 14 TC'S
1	180- 200	104.4	98.0	97.6	94.3	68.3	99.2	83.4	92.7	96.7	92.5	68.7	62.2	90.2	102.8	89.4
2	210- 270	110.6	102.8	102.8	99.4	73.8	104.5	87.9	98.0	105.3	98.9	71.4	68.0	96.2	108.2	94.8
3	270- 330	114.6	107.1	108.1	105.2	80.6	109.1	91.9	102.8	109.9	104.4	74.0	72.4	101.7	112.8	99.6
4	330- 390	116.0	108.7	111.1	108.6	86.1	111.7	94.0	106.2	113.5	108.2	76.7	75.7	104.6	115.0	102.6
5	390- 450	117.7	110.1	113.5	111.5	91.0	114.1	95.8	109.3	118.9	112.5	81.9	79.6	107.4	116.7	105.7
6	450- 510	119.5	111.8	115.2	113.6	95.3	115.8	97.3	111.6	124.3	116.0	87.1	84.0	110.0	118.0	108.5
7	510- 570	119.8	112.5	116.0	115.0	99.0	116.6	98.1	112.8	128.8	119.5	92.2	87.0	111.0	118.4	110.5
8	570- 630	122.0	114.0	117.1	116.7	102.4	118.0	99.2	115.0	128.4	122.3	95.9	91.7	112.6	119.9	112.5
9	630- 690	121.2	113.7	117.1	116.7	105.0	118.0	98.6	115.3	127.1	121.7	98.7	93.1	112.0	119.6	112.7
10	690- 750	120.6	113.1	116.7	116.3	106.6	117.7	97.9	115.4	127.2	121.2	102.8	92.9	111.7	119.1	112.8
11	750- 870	120.6	112.7	115.9	115.7	108.1	117.2	97.3	114.9	129.1	121.6	107.5	92.2	111.9	118.5	113.1
12	870- 990	123.3	115.1	116.7	116.8	109.9	116.4	97.8	116.2	130.8	123.4	109.0	94.7	113.6	119.7	114.7
13	990-1110	122.5	114.5	115.9	116.4	111.1	117.9	97.0	116.1	133.3	123.9	110.9	95.9	112.5	118.8	114.8
14	1110-1230	124.5	115.9	115.8	116.9	112.0	118.3	96.9	117.2	134.9	125.4	112.6	97.8	113.2	119.0	115.7
15	1230-1350	125.4	117.2	115.8	117.3	112.8	118.7	96.9	117.8	136.7	125.9	114.5	99.9	113.6	119.3	116.6
16	1350-1470	124.7	116.5	115.1	117.5	113.6	118.3	97.2	118.0	143.8	127.0	114.8	101.5	113.7	118.4	117.1
17	1470-1590	122.7	114.8	113.9	116.5	114.2	117.2	96.8	116.8	147.6	127.8	114.8	103.9	112.4	116.8	116.9
18	1590-1710	125.8	117.2	114.6	117.7	114.9	118.3	98.0	118.5	145.8	128.7	114.8	106.9	113.9	117.8	118.0
19	1710-1830	127.0	118.5	115.2	118.4	115.4	119.0	98.5	119.5	158.1	128.8	114.4	109.7	115.0	118.3	119.7
20	1830-1930	125.4	117.9	114.8	117.8	115.8	118.5	97.3	118.1	139.6	127.6	113.0	112.5	114.2	117.4	117.6
21	1930-2050	114.3	108.7	109.2	110.2	113.3	113.0	91.5	110.4	120.8	117.6	110.2	111.7	105.4	111.6	110.6
22	2050-2220	103.5	98.7	101.1	100.2	107.3	104.7	84.9	101.1	103.4	104.9	105.9	105.3	94.6	103.1	101.3

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-3. CONTAINMENT WALL TEMPERATURE DATA FOR AC-8

OPERATING PERIOD	TIME INTERVAL MINUTES	AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C)														
		TC 1	TC 3	TC 4	TC 5	TC 6	TC 7	TC 9	TC 11	TC 12	TC 14	TC 16	TC 17	TC 20	TC 21	AVERAGE 14 TC'S
1	180- 200	97.9	93.5	94.5	91.8	67.7	96.6	83.9	88.2	92.2	86.3	63.9	54.6	89.9	97.2	85.6
2	210- 270	101.6	97.0	98.5	95.7	72.8	99.8	87.1	91.3	96.5	89.9	64.9	58.2	93.2	101.3	89.1
3	270- 330	104.0	99.3	101.6	98.8	78.3	102.2	89.5	94.3	99.9	93.4	67.9	62.3	95.7	103.8	92.2
4	330- 390	104.7	100.2	103.7	100.9	82.7	103.6	91.1	96.4	100.0	96.1	73.1	67.4	97.0	105.3	94.4
5	390- 450	105.8	100.8	105.0	102.4	86.3	104.6	92.2	98.3	103.1	98.6	77.6	69.5	99.0	106.2	96.4
6	450- 510	114.4	107.3	112.1	109.7	90.4	110.1	98.2	103.4	109.0	105.1	84.6	73.0	105.8	113.2	102.6
7	510- 570	121.3	112.8	118.4	116.5	95.3	115.6	102.5	109.0	114.2	111.1	91.4	77.6	111.2	119.1	108.3
8	570- 630	127.1	117.6	123.4	122.6	100.4	120.6	105.9	114.5	119.3	116.8	96.5	81.9	116.7	124.4	113.4
9	630- 690	132.4	122.3	127.6	128.2	105.3	124.9	109.6	119.8	124.6	122.0	100.1	85.9	121.3	128.9	118.1
10	690- 750	137.1	126.4	131.0	132.8	109.9	128.8	112.7	124.5	130.0	126.3	102.6	89.8	125.0	132.7	122.1
11	750- 810	141.2	130.3	133.8	136.5	114.1	132.2	114.8	128.6	134.5	130.2	104.8	93.6	128.0	136.0	125.6
12	810- 930	145.7	134.6	137.0	140.9	119.8	136.6	117.2	133.8	139.2	135.2	108.0	98.5	131.6	139.8	129.9
13	930-1050	149.8	138.7	139.8	144.8	126.1	140.4	119.3	138.8	143.4	140.4	111.7	104.4	134.8	143.0	134.0
14	1050-1170	148.5	138.0	139.3	143.8	129.8	140.8	117.9	140.0	144.2	141.3	116.1	108.6	134.1	142.9	134.7
15	1170-1290	147.9	137.4	138.4	143.2	131.6	140.3	117.5	140.2	144.6	142.3	118.6	111.4	133.8	142.5	135.0
16	1290-1410	147.9	137.3	137.4	142.6	132.5	140.0	117.2	140.0	145.9	142.8	118.2	113.3	133.9	142.8	135.1
17	1410-1530	147.1	136.7	136.9	141.9	133.0	138.9	116.8	139.7	146.2	142.7	117.4	115.3	133.8	143.5	135.0
18	1530-1650	146.3	136.1	136.9	141.3	133.1	137.8	116.7	139.2	148.3	143.0	117.0	118.0	133.5	144.3	135.1
19	1650-1770	148.1	137.4	140.9	143.0	133.7	137.9	117.9	140.0	152.0	144.8	117.2	119.9	134.4	146.2	136.7
20	1770-1890	147.7	137.6	143.8	143.4	134.2	138.2	117.6	140.3	148.2	145.0	117.9	121.4	133.6	146.3	136.8
21	1890-2010	133.9	126.6	133.5	131.2	131.0	132.6	108.6	131.0	130.4	131.7	117.7	121.1	121.0	135.7	127.6
22	2010-2220	117.6	111.8	116.7	113.1	119.9	120.0	95.9	116.4	112.5	113.2	112.9	115.2	104.8	119.7	113.5

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-4. CONTAINMENT WALL TEMPERATURE DATA FOR AC-9

AVERAGE TEMPERATURE OVER TIME INTERVAL
FOR IDENTIFIED THERMOCOUPLES, (DEG C)

OPERATING PERIOD	TIME INTERVAL MINUTES	TC 1	TC 3	TC 4	TC 5	TC 6	TC 7	TC 9	TC 11	TC 12	TC 14	TC 16	TC 17	TC 20	TC 21	AVERAGE 14 TC'S
1	60- 64	118.3	105.3	103.5	98.8	51.3	107.2	93.1	100.1	127.5	89.6	70.2	46.4	102.5	112.0	94.7
2	70- 120	137.2	122.9	122.2	119.4	61.7	122.2	107.8	111.4	137.4	107.5	81.4	59.7	120.9	129.2	110.1
3	120- 160	161.2	145.5	143.6	144.4	78.1	140.2	128.2	126.8	151.6	132.4	95.5	88.0	145.2	147.9	130.6
4	160- 220	171.8	156.6	156.7	160.5	94.1	151.6	141.4	140.2	167.8	151.1	102.9	115.6	160.6	159.0	145.0
5	220- 280	183.5	167.8	170.9	176.7	113.1	163.1	153.4	156.0	184.0	169.7	106.7	155.3	175.5	171.4	160.5
6	280- 340	194.7	177.6	183.3	190.5	130.9	174.0	163.7	170.7	198.4	185.5	112.3	192.7	188.7	182.0	174.7
7	340- 400	198.8	182.3	191.0	197.0	146.2	181.6	167.1	179.6	200.3	193.5	117.3	225.9	192.0	188.0	182.9
8	400- 460	211.6	192.4	201.9	207.3	158.9	192.6	177.1	191.4	214.0	205.2	123.3	268.6	203.6	196.9	196.0
9	460- 520	210.1	194.0	206.6	210.3	170.6	198.9	176.1	196.1	208.9	207.4	127.3	308.8	201.8	200.9	201.3
10	520- 580	194.0	180.5	196.1	196.3	175.2	193.1	163.2	189.5	194.9	195.9	129.0	313.7	184.9	193.5	192.8
11	580- 640	181.9	169.5	185.6	184.8	174.8	185.4	153.4	182.3	185.1	186.3	131.1	295.0	173.2	184.9	183.8
12	640- 700	171.1	159.8	174.8	173.2	171.3	176.8	143.5	173.6	174.4	175.3	132.2	273.4	161.8	175.7	174.1
13	700- 780	161.0	150.8	164.4	162.9	165.0	167.0	134.7	164.5	165.9	166.4	133.4	252.6	152.4	166.0	164.8
14	780- 840	151.5	142.1	154.5	152.6	158.1	157.6	125.8	154.9	154.0	155.9	133.5	232.4	142.2	156.5	155.1
15	840- 900	144.0	135.2	146.7	144.4	152.1	150.2	119.4	147.5	145.3	147.5	133.0	216.6	134.4	149.0	147.5
16	900- 960	136.1	127.9	138.2	135.5	145.3	142.4	112.5	139.4	135.6	138.3	131.8	199.7	125.5	140.8	139.2
17	960-1020	128.7	121.3	130.2	127.2	138.5	135.1	106.0	131.6	127.4	129.9	130.1	185.1	117.6	133.2	131.6
18	1020-1140	117.6	111.4	118.5	115.0	128.2	123.4	96.6	119.2	113.7	117.6	126.5	164.4	106.0	121.9	120.0
19	1140-1250	105.8	100.5	106.0	102.8	115.7	110.7	87.1	107.4	104.5	105.6	121.0	149.6	95.4	109.2	108.7

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-5. CONTAINMENT WALL TEMPERATURE DATA FOR AC-10

OPERATING PERIOD	TIME INTERVAL MINUTES	AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C)														
		TC 1	TC 3	TC 4	TC 5	TC 6	TC 7	TC 9	TC 11	TC 12	TC 14	TC 16	TC 17	TC 20	TC 21	AVERAGE 14 TC'S
1	180- 195	110.6	100.4	103.7	100.4	70.2	106.8	87.9	96.7	103.2	96.7	71.0	59.1	95.7	107.1	93.5
2	210- 270	119.9	107.6	110.9	107.9	77.1	114.0	93.3	104.2	114.7	105.4	76.0	66.6	102.7	115.5	101.1
3	270- 330	131.5	118.5	120.7	118.4	87.1	123.6	99.8	112.4	123.0	115.9	82.6	75.7	109.8	125.4	110.3
4	330- 390	136.6	124.0	126.1	124.5	94.6	128.5	103.1	117.6	126.6	122.1	87.0	83.0	113.1	130.3	115.5
5	390- 450	140.2	127.4	129.9	128.8	101.0	132.4	105.4	122.2	131.4	127.0	90.9	90.1	116.0	133.8	119.7
6	450- 510	143.6	130.4	132.8	132.4	106.5	135.6	107.6	126.1	135.3	131.2	94.4	96.6	118.7	136.7	123.4
7	510- 570	147.3	133.5	135.5	135.6	111.3	138.7	110.9	129.8	138.9	135.0	97.4	102.5	121.3	139.8	127.0
8	570- 630	150.6	136.7	137.8	138.5	115.3	141.2	112.8	133.0	144.1	137.8	99.8	107.6	123.5	143.0	130.1
9	630- 690	154.1	140.0	140.1	141.4	119.4	143.8	114.6	136.6	151.0	140.7	102.2	112.7	125.8	145.8	133.4
10	690- 750	156.9	142.6	142.0	143.6	122.8	146.0	116.1	139.2	153.8	142.9	104.1	117.3	127.3	148.0	135.9
11	750- 870	158.5	144.6	143.7	145.4	127.0	148.2	116.8	141.8	155.9	145.9	107.0	124.1	128.2	150.0	138.4
12	870- 990	159.4	145.7	144.5	146.2	130.5	150.8	116.8	144.1	156.4	148.3	109.3	131.7	137.3	151.1	140.9
13	990-1110	158.1	144.9	143.6	145.2	132.6	150.8	115.3	144.6	155.3	147.6	110.8	137.3	135.9	150.0	140.9
14	1110-1230	156.0	143.1	141.8	143.3	133.2	149.1	114.0	143.4	158.7	146.2	111.7	140.6	133.8	148.2	140.2
15	1230-1350	154.3	141.5	139.9	141.1	132.8	147.7	111.8	142.1	157.2	144.6	112.1	142.8	131.7	146.2	139.0
16	1350-1410	156.6	142.6	139.1	140.9	132.6	147.9	112.6	142.8	160.6	144.7	112.3	144.3	133.4	146.0	139.8
17	1410-1470	158.9	145.2	139.8	142.1	132.9	148.9	113.6	144.0	160.6	145.5	112.7	145.4	134.5	146.8	140.8
18	1470-1520	154.8	143.4	139.0	140.9	133.1	147.4	111.8	141.3	149.2	143.1	112.8	145.7	129.4	145.0	138.4
19	1520-1580	144.9	134.9	134.4	134.2	131.8	142.5	106.3	133.5	131.3	135.1	112.2	142.9	120.0	139.5	131.7
20	1580-1640	135.2	125.9	128.4	126.1	128.5	136.6	101.7	126.1	122.0	126.4	111.3	138.1	112.8	133.0	125.1
21	1640-1700	126.8	118.1	122.1	118.5	124.3	130.5	96.7	119.8	115.4	118.7	109.8	133.5	106.7	126.5	119.1
22	1700-1760	119.3	111.5	115.9	111.6	119.8	124.2	91.7	113.5	108.2	111.6	107.9	128.6	100.7	119.9	113.2
23	1760-1820	112.6	105.4	110.0	105.1	114.9	118.0	87.0	107.7	102.3	105.3	105.8	123.5	95.1	113.5	107.6
24	1820-1880	106.2	99.6	104.3	99.0	110.3	111.6	82.5	101.6	96.2	99.3	103.5	117.6	89.7	107.2	102.1
25	1880-1940	100.0	94.0	98.7	93.2	105.5	105.4	78.0	95.8	90.9	93.7	101.0	112.2	84.6	101.1	96.7
26	1940-2000	94.8	89.1	93.7	88.2	100.9	100.1	74.3	91.6	88.0	89.1	98.4	108.4	80.8	96.0	92.4
27	2000-2060	90.5	85.2	89.5	84.2	96.7	95.4	71.5	87.8	84.4	85.1	95.8	104.4	77.6	91.8	88.6

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-6. CONTAINMENT ATMOSPHERE TEMPERATURES AND PRESSURE IN AC-7

OPERATING PERIOD	TIME INTERVAL MINUTES	AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C) TC 2	TC 8	TC 10	TC 13	TC 15	TC 18	TC 19	TC 22	TC 25	AVERAGE 9 TC'S	CONTAINMENT PRESSURE K PASCAL ABSOLUTE
1	180- 200	116.7	113.0	112.3	107.8	109.0	115.8	109.3	119.6	122.4	114.0	131.9
2	210- 270	132.4	127.4	121.8	118.0	118.0	130.9	119.3	129.2	136.9	126.0	99.3
3	270- 330	129.4	125.7	125.0	121.1	119.5	131.3	121.7	127.9	132.8	126.1	98.7
4	330- 390	128.9	126.4	125.8	123.7	123.9	131.4	126.7	130.0	132.0	127.6	98.3
5	390- 450	128.7	127.6	128.3	127.0	129.1	132.2	132.6	131.0	133.3	129.9	98.3
6	450- 510	128.8	128.7	131.1	129.1	130.5	133.6	134.3	132.3	135.3	131.5	98.2
7	510- 570	126.4	126.0	130.4	131.4	133.0	131.5	136.3	130.3	131.3	130.7	98.1
8	570- 630	131.6	130.7	134.5	133.3	134.5	137.0	136.8	135.7	137.6	134.6	98.1
9	630- 690	127.2	126.3	131.2	129.9	131.1	132.7	133.6	131.7	130.7	130.5	98.2
10	690- 750	126.8	126.0	130.8	129.7	131.0	132.3	133.7	131.4	131.2	130.3	98.6
11	750- 870	128.0	127.4	132.3	131.8	133.1	134.0	136.2	132.8	133.6	132.1	98.7
12	870- 990	130.5	129.2	134.5	134.3	134.8	136.6	138.1	135.4	135.9	134.4	98.9
13	990-1110	128.8	127.5	133.3	135.9	135.7	135.0	138.8	133.9	134.1	133.7	99.0
14	1110-1230	132.7	131.3	137.2	139.3	139.0	139.0	142.2	138.0	138.7	137.5	98.8
15	1230-1350	130.0	129.6	136.4	138.1	139.2	138.0	142.2	136.8	136.8	137.0	98.7
16	1350-1470	133.3	129.6	137.6	140.3	140.6	137.9	143.2	136.7	136.0	137.2	98.8
17	1470-1590	130.5	127.9	136.6	141.3	141.4	135.6	143.1	134.6	134.0	136.1	98.8
18	1590-1710	134.9	131.8	141.2	142.3	142.7	140.7	145.1	139.6	139.6	139.8	98.8
19	1710-1830	135.0	131.7	143.0	142.5	143.7	141.6	146.2	140.2	140.4	140.5	98.6
20	1830-1950	127.4	124.9	132.5	133.8	135.7	134.9	138.5	133.2	130.2	132.5	98.4
21	1950-2050	114.1	112.1	115.7	117.1	119.0	119.2	119.6	117.8	117.8	116.9	98.4
22	2050-2220	103.2	100.4	101.1	102.0	103.9	107.2	104.3	104.5	104.8	103.5	98.7

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-7. CONTAINMENT ATMOSPHERE TEMPERATURES AND PRESSURE IN AC-8

		AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C)										CONTAINMENT PRESSURE	
OBSERVATION PERIOD	TIME INTERVAL MINUTES	TC 2	TC 8	TC 10	TC 13	TC 15	TC 18	TC 19	TC 22	TC 23	TC 24	AVERAGE 10 TC'S	N PASCAL ABSOLUTE
1	150- 200	103.5	102.4	100.4	96.6	95.1	105.7	98.0	103.6	105.6	84.6	99.5	134.1
2	210- 270	108.5	107.5	104.8	100.6	99.6	111.6	102.5	109.0	111.3	95.0	105.0	100.3
3	270- 330	109.4	108.8	106.7	102.6	102.4	112.7	104.9	110.5	112.6	99.3	107.0	97.3
4	330- 390	108.3	108.6	106.6	103.2	103.3	111.3	106.4	110.0	111.6	97.6	106.7	99.0
5	390- 450	112.9	113.8	111.4	107.5	107.8	116.8	111.7	115.2	117.1	105.4	112.0	98.7
6	450- 510	125.8	126.3	122.3	118.1	117.6	130.6	123.7	128.2	130.9	117.6	124.1	98.6
7	510- 570	132.7	131.4	128.7	124.6	123.4	137.8	130.4	135.0	132.9	126.4	130.8	98.6
8	570- 630	139.1	136.4	134.6	129.9	128.9	144.1	137.0	141.6	144.5	137.2	137.3	98.9
9	630- 690	143.9	140.9	140.2	134.8	133.9	149.8	141.8	146.9	150.0	138.6	142.1	98.9
10	690- 750	148.3	145.2	144.4	138.4	147.4	154.4	145.6	151.3	154.5	141.4	146.1	99.1
11	750- 810	152.2	149.8	148.4	144.1	141.4	158.4	149.5	155.1	158.7	146.1	150.3	99.0
12	810- 930	155.2	152.1	152.3	148.6	146.0	161.9	154.2	158.8	162.4	150.2	154.2	98.9
13	930-1050	156.4	154.5	155.3	152.2	150.1	165.1	157.5	162.2	165.6	154.8	157.6	98.7
14	1050-1170	155.1	152.1	155.1	151.5	150.2	161.7	161.7	159.6	162.2	154.4	156.4	98.6
15	1170-1290	154.8	151.6	155.3	151.5	150.4	161.8	157.1	159.4	162.1	157.2	156.1	98.5
16	1290-1410	155.1	150.9	155.6	151.8	151.2	162.0	156.4	159.7	162.4	156.8	156.2	98.5
17	1410-1530	154.2	149.2	155.1	151.6	152.0	161.0	155.5	158.9	161.5	157.1	155.6	98.6
18	1530-1650	153.4	148.3	155.3	151.4	151.8	160.7	155.5	158.5	161.2	159.5	155.6	98.8
19	1650-1770	156.6	150.0	157.0	154.0	154.3	164.7	159.1	161.2	164.5	160.8	158.2	99.0
20	1770-1890	157.6	148.0	154.2	152.5	152.5	161.4	159.9	159.4	163.0	163.4	157.3	98.7
21	1890-2010	133.3	129.0	129.8	129.4	130.2	137.4	130.9	133.4	134.9	143.2	133.1	98.5
22	2010-2220	117.9	112.2	111.7	111.1	111.8	120.7	112.4	116.5	117.3	117.8	114.9	98.8

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-8. CONTAINMENT ATMOSPHERE TEMPERATURES AND PRESSURE IN AC-9

OPERATING PERIOD	TIME INTERVAL MINUTES	AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C) TC 2	TC 8	TC 10	TC 13	TC 15	TC 18	TC 19	TC 22	TC 23	TC 24	AVERAGE 10 TC'S	CONTAINMENT PRESSURE N PASCAL ABSOLUTE
1	60- 64	163.7	162.7	154.3	140.2	139.3	174.4	149.8	163.4	172.5	140.9	156.1	121.3
2	70- 120	170.3	165.2	157.8	155.8	149.0	179.3	158.4	170.6	178.3	183.5	167.0	101.4
3	120- 160	177.5	175.1	173.1	173.5	168.2	190.4	180.2	183.7	190.5	212.2	182.4	99.7
4	160- 220	180.4	177.1	188.6	186.3	181.6	195.0	191.9	189.5	195.5	241.9	192.8	99.6
5	220- 280	189.7	184.2	201.3	198.1	174.5	204.7	205.2	190.9	205.2	260.0	204.2	99.6
6	280- 340	199.8	193.3	213.1	209.4	207.4	216.7	218.7	211.0	217.1	258.5	214.5	99.3
7	340- 400	200.8	192.5	212.6	209.5	208.7	216.5	216.8	212.6	216.9	246.4	213.3	99.0
8	400- 460	218.2	208.6	229.0	227.1	226.0	235.5	232.8	230.3	236.0	261.3	230.5	99.5
9	460- 520	206.5	201.6	214.4	213.8	217.1	220.6	218.4	214.9	220.6	246.5	217.4	99.4
10	520 580	187.7	186.1	195.0	196.5	200.1	200.5	199.9	197.3	200.7	216.1	198.2	99.6
11	580- 640	177.3	177.3	183.9	186.2	189.0	189.3	189.0	186.9	190.0	203.8	187.3	99.8
12	640- 700	166.9	167.5	172.0	174.4	176.9	177.3	177.1	175.9	178.5	187.3	175.4	99.7
13	700- 780	159.5	159.1	163.5	166.4	168.4	168.2	168.8	167.3	169.3	180.3	167.1	99.9
14	780- 840	151.3	147.4	151.9	153.8	155.8	156.9	156.2	156.5	158.0	163.5	155.3	99.8
15	840- 900	143.5	141.7	143.3	144.8	146.8	148.8	147.0	148.1	149.9	153.4	146.7	99.8
16	900- 960	135.3	132.9	132.6	133.6	136.2	139.2	135.6	137.5	138.0	141.5	136.2	99.7
17	960-1020	127.9	125.0	124.2	125.2	127.7	131.2	126.9	129.0	129.6	131.9	127.9	99.8
18	1020-1140	115.7	111.7	109.9	111.1	114.4	117.3	112.9	114.7	115.2	116.5	113.9	99.7
19	1140-1250	105.3	102.2	102.1	103.1	104.7	107.5	104.7	106.0	106.8	107.3	105.0	100.1

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

TABLE B-9. CONTAINMENT ATMOSPHERE TEMPERATURES AND PRESSURE IN AC-10

OPERATING PERIOD	TIME INTERVAL MINUTES	AVERAGE TEMPERATURE OVER TIME INTERVAL FOR IDENTIFIED THERMOCOUPLES, (DEG C) TC 2	TC 8	TC 10	TC 13	TC 15	TC 18	TC 19	TC 22	TC 23	TC 24	AVERAGE 10 TC'S	CONTAINMENT PRESSURE K PASCAL ABSOLUTE
1	180- 195	122.4	123.9	124.0	114.4	111.6	128.3	116.8	124.7	128.8	119.3	121.4	148.9
2	210- 270	142.7	146.1	145.1	137.7	132.0	153.9	140.9	145.3	153.3	134.0	143.1	102.8
3	270- 330	153.0	153.8	152.9	144.2	143.5	161.8	150.6	156.5	159.6	148.9	152.5	101.1
4	330- 390	155.0	154.2	151.8	145.7	147.8	160.6	151.5	157.8	159.5	155.1	153.9	100.9
5	390- 450	155.9	157.4	155.2	153.7	151.2	164.8	155.4	160.8	164.0	163.5	158.2	101.0
6	450- 510	159.0	161.6	158.5	157.0	155.1	167.4	158.8	164.2	167.1	169.3	161.8	101.3
7	510- 570	165.6	167.8	163.6	162.7	161.1	171.2	165.1	169.0	171.5	172.1	167.0	101.2
8	570- 630	167.1	170.2	168.8	163.1	162.1	173.6	166.6	171.7	173.6	172.3	168.9	101.1
9	630- 690	170.2	173.2	170.6	167.4	165.0	177.0	169.5	175.5	177.3	172.0	171.8	101.1
10	690- 750	172.2	174.4	172.1	167.8	167.5	179.2	171.6	178.0	179.5	174.5	173.7	101.2
11	750- 870	170.4	173.9	172.7	170.6	170.0	178.6	172.7	177.8	179.1	185.8	175.2	101.1
12	870- 990	170.4	174.1	174.4	170.7	169.7	179.2	174.3	178.1	179.7	180.9	175.2	101.2
13	990-1110	167.2	170.9	172.0	170.2	168.7	176.5	171.5	175.3	176.8	180.5	173.0	101.2
14	1110-1230	164.6	168.8	169.2	166.5	167.6	173.8	169.7	172.9	174.2	.181.8	170.9	101.2
15	1230-1350	163.3	166.9	168.5	165.1	165.7	172.1	169.5	171.1	174.0	181.0	169.7	100.9
16	1350-1410	171.2	173.8	175.5	171.4	171.8	179.0	174.3	177.8	180.9	183.1	175.9	100.7
17	1410-1470	172.8	174.0	174.2	172.1	170.5	180.1	173.6	178.4	180.6	185.2	176.2	100.7
18	1470-1520	158.1	157.3	155.5	155.5	155.4	165.4	158.0	163.2	162.2	171.3	160.2	100.7
19	1520-1580	144.0	136.4	133.9	133.1	134.4	148.7	135.6	144.2	145.0	143.3	139.9	101.0
20	1580-1640	134.3	126.3	123.5	122.1	123.7	139.2	124.8	133.7	134.8	129.6	129.2	101.1
21	1640-1700	126.4	118.8	116.1	114.8	116.3	131.3	117.7	125.8	126.9	121.4	121.5	101.1
22	1700-1760	119.1	110.3	107.9	106.1	107.8	122.9	109.1	116.2	117.3	112.3	112.9	100.9
23	1760-1820	112.5	104.0	101.7	100.0	101.6	115.8	102.9	109.3	110.4	105.4	106.4	100.9
24	1820-1880	105.6	94.3	93.5	92.4	94.4	106.5	95.9	100.6	101.2	98.5	98.3	100.9
25	1880-1940	99.4	87.7	87.6	86.7	88.7	99.7	87.9	94.0	94.8	92.6	91.9	101.2
26	1940-2000	95.0	88.2	86.7	85.9	86.9	97.4	86.9	92.7	93.8	90.2	90.4	101.3
27	2000-2060	91.4	85.1	83.7	82.5	83.3	94.0	83.4	90.0	90.8	86.6	87.1	101.3

NOTE: SEE TABLE B-1. FOR THERMOCOUPLE LOCATIONS

APPENDIX C

TEMPERATURE GRADIENT NEAR CONTAINMENT VESSEL WALL AT +1.52-m ELEVATION

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TABLE C-1. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-7

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
0	60.3	63.6	64.1	64.3	64.1
5	63.5	88.1	89.9	91.9	94.0
10	65.4	88.6	89.5	90.9	94.1
20	68.7	91.9	94.3	96.7	100.4
25	70.1	91.7	94.3	97.2	100.1
30	71.2	89.7	92.6	96.2	99.6
35	72.7	91.6	94.8	97.4	101.3
45	74.3	92.1	96.2	97.9	100.4
50	75.1	91.2	95.3	98.1	101.1
55	75.9	91.7	97.0	102.1	101.4
60	76.7	91.7	96.9	101.8	100.9
95	81.2	97.0	103.1	108.4	104.2
125	84.6	100.5	107.2	112.9	103.5
155	87.3	102.9	109.9	114.3	116.8
185	89.8	102.5	107.8	107.3	107.5
220	93.4	112.4	120.7	125.3	115.3
250	97.8	116.8	124.6	125.6	123.1
280	100.3	115.8	122.5	123.4	121.1
310	102.2	117.7	123.7	127.2	122.5
345	103.7	117.2	121.9	123.2	123.8
375	105.2	119.4	124.3	126.5	126.8
405	106.7	121.2	125.2	128.2	130.7
435	107.8	121.4	125.2	128.3	131.9
465	109.2	123.7	127.5	130.2	134.6
500	110.8	124.9	129.2	131.9	136.6
530	111.2	124.0	127.8	131.6	138.1
560	110.7	122.8	126.4	129.8	139.2
590	112.7	126.2	130.6	135.5	143.4
625	112.6	125.4	128.3	132.4	141.8
655	112.1	124.0	127.7	131.8	141.3
685	111.8	124.2	128.0	132.1	139.9
715	111.3	122.8	126.7	131.1	137.5
750	112.0	122.9	126.7	130.9	135.7
780	111.6	122.1	126.0	130.3	133.8
810	111.2	121.5	125.6	130.3	132.8
840	112.6	123.4	128.5	135.0	137.5
875	113.6	124.6	129.1	134.7	137.1
905	113.6	123.8	128.4	134.1	136.4
935	113.6	123.3	127.6	133.6	136.6
965	113.7	123.1	127.3	133.1	135.8
1000	113.3	122.9	127.2	132.9	135.1
1030	112.3	121.7	125.9	131.9	134.3
1060	112.7	122.4	126.7	132.9	135.4
1090	112.5	123.3	127.8	133.2	135.1
1125	111.8	122.3	126.7	132.9	135.4
1155	113.6	124.9	130.2	138.2	140.5
1185	113.3	123.9	128.9	136.3	138.9
1215	113.2	123.5	128.3	135.8	138.2
1250	113.6	125.2	130.2	136.5	138.7
1280	113.9	124.6	129.4	135.7	137.9
1310	113.7	124.3	129.1	135.4	137.6
1340	112.9	123.2	127.5	133.7	136.2
1375	113.7	124.8	130.0	137.7	140.4
1405	113.6	123.9	128.4	135.3	139.0
1435	113.6	124.4	129.3	135.7	137.4
1465	113.2	123.4	127.9	134.3	137.6
1500	112.4	122.9	127.6	133.7	135.7
1530	111.6	122.0	126.3	132.4	134.7
1565	112.4	125.2	130.8	138.9	139.1
1595	113.3	125.3	130.8	139.9	142.9

TABLE C-1. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-7

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
1625	113.7	125.3	130.5	138.7	141.7
1655	114.1	125.2	130.4	138.6	141.7
1690	113.8	125.2	130.3	138.0	140.4
1720	114.3	126.3	131.8	140.2	142.9
1750	115.1	126.6	132.1	140.2	142.4
1780	115.2	126.2	131.4	139.6	142.2
1815	115.4	127.2	133.1	141.8	142.8
1845	116.2	127.6	133.4	142.3	144.9
1875	115.4	125.3	130.0	137.9	141.6
1905	112.9	120.7	123.8	128.6	132.9
1945	108.7	114.1	116.1	118.6	121.2
1975	106.2	111.6	113.9	117.1	117.6
2005	105.7	112.1	114.6	119.2	121.7
2035	102.6	107.8	110.2	113.7	114.7
2070	99.6	104.3	106.5	109.7	110.2
2100	97.2	101.8	103.8	106.6	107.1
2130	94.9	99.5	101.3	103.9	104.4
2160	92.7	97.2	98.9	101.2	101.7
2195	90.4	94.6	96.3	98.2	98.6
2225	88.4	92.4	94.1	95.8	96.3
2255	86.8	90.2	91.9	93.4	94.1
2300	84.2	87.5	88.8	90.1	90.4
2340	82.2	85.4	86.4	87.5	87.9
2380	80.3	83.5	84.3	85.1	85.5
2440	77.3	80.9	81.2	81.8	82.2
2480	75.4	79.0	79.2	79.8	80.1
2540	72.8	76.6	76.6	77.2	77.6
2580	71.2	74.9	74.9	75.6	75.9
2640	69.1	73.3	72.9	73.5	74.0
2680	67.7	71.4	71.3	72.0	72.6
2740	65.8	69.2	69.3	69.9	70.4
2780	64.5	68.1	68.1	68.7	69.1
2840	62.8	65.9	66.0	66.6	67.2
2880	61.6	64.8	64.9	65.4	65.9
2940	59.9	63.0	63.1	63.6	64.1
2980	58.9	61.6	61.9	62.6	63.1

TABLE C-2. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-8

	TEMPERATURE, (DEG C)				
TIME MINUTES	WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
0	63.2	66.2	66.5	66.8	66.8
5	66.2	83.8	85.1	86.4	88.0
10	67.9	86.0	87.3	89.2	91.5
15	69.4	88.8	89.9	91.8	94.2
20	70.1	86.9	88.7	90.7	93.7
25	70.9	86.4	88.2	89.7	92.8
30	71.7	86.9	88.2	89.8	91.3
35	72.3	86.4	87.5	89.0	90.5
40	73.2	86.9	87.6	88.8	90.6
45	73.7	86.6	87.2	88.4	90.1
50	74.2	86.5	86.8	87.8	89.8
55	74.4	87.2	87.4	88.4	89.8
65	74.8	86.6	86.8	87.8	89.5
95	79.0	93.6	94.3	95.2	96.9
125	83.5	95.8	96.3	97.4	99.1
155	87.3	97.7	98.4	99.9	101.9
185	89.6	96.9	97.4	98.4	99.9
215	91.9	100.1	101.5	102.8	105.7
245	93.4	100.4	101.9	103.3	105.7
275	94.3	100.4	101.6	102.8	104.7
305	96.1	102.7	104.6	106.4	108.6
335	96.7	103.0	104.6	106.1	108.1
365	97.0	102.6	104.1	105.3	107.5
395	97.2	102.9	104.2	105.7	107.5
425	99.2	106.7	109.7	112.6	115.5
455	102.8	111.8	115.3	118.9	122.7
485	106.3	114.7	118.1	122.0	124.9
515	109.2	117.5	121.1	125.0	129.1
545	111.1	120.6	124.7	129.4	132.4
575	114.7	123.4	127.4	132.7	135.6
605	116.9	125.6	129.6	134.8	137.8
635	119.4	128.8	133.3	139.2	141.9
665	121.7	130.8	135.4	140.9	143.6
695	123.4	132.7	137.1	142.2	145.4
725	125.2	134.5	139.3	145.3	147.7
755	126.8	136.7	141.4	146.6	149.7
785	128.1	138.7	143.7	149.0	151.9
815	129.8	139.8	144.3	149.7	153.3
845	130.7	141.5	146.7	152.0	155.6
875	131.7	142.3	147.3	152.7	156.4
905	132.8	143.4	148.3	153.8	158.2
935	133.9	144.7	150.0	155.6	160.0
965	134.8	145.5	150.6	156.2	160.9
995	135.2	145.3	149.7	156.3	158.3
1025	135.1	145.2	149.8	156.4	158.2
1055	134.6	144.1	148.4	154.8	156.8
1085	133.8	143.7	147.3	152.2	154.0
1115	134.1	145.5	150.1	156.2	158.0
1145	134.6	145.9	150.6	156.7	159.6
1175	134.3	145.7	150.3	156.2	158.6
1205	134.3	144.9	149.1	154.8	157.2
1235	133.4	143.7	147.7	153.1	155.1
1265	133.7	144.6	149.1	155.2	157.9
1295	133.6	144.6	149.2	155.2	157.1
1325	133.6	144.6	149.0	154.8	157.3
1355	134.0	144.8	149.2	155.2	157.6
1385	134.0	144.9	148.4	153.2	155.8
1415	133.9	145.7	149.5	153.6	156.4
1445	133.9	145.3	148.7	152.8	155.9
1475	133.6	145.7	149.7	154.6	157.3

TABLE C-2. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-8

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
1505	133.8	145.0	148.8	153.4	156.8
1535	134.1	146.1	150.6	154.4	157.5
1565	133.6	144.8	148.5	152.9	155.9
1595	132.8	144.7	148.9	153.4	157.4
1625	133.9	146.4	150.6	155.4	159.3
1655	134.1	146.4	150.5	155.4	158.8
1685	134.3	147.2	151.3	156.0	158.7
1715	134.4	147.3	151.6	156.0	158.8
1745	134.4	146.4	150.2	154.7	157.4
1775	134.2	146.7	150.6	155.2	158.0
1805	134.1	146.2	150.1	154.7	157.6
1835	133.9	145.6	149.2	153.8	156.9
1865	133.2	144.1	147.4	151.9	154.2
1910	127.2	134.2	135.7	137.6	138.7
1940	123.5	129.8	131.1	132.9	133.7
1970	119.7	125.7	126.9	128.3	129.1
2000	116.1	121.7	122.9	124.4	125.2
2030	112.9	118.1	119.3	120.8	121.6
2060	109.8	114.8	116.0	117.4	118.2
2090	106.9	111.8	112.9	114.3	114.1
2120	104.1	108.9	110.0	111.2	111.1
2150	101.6	106.3	107.3	108.5	108.3
2180	99.3	103.8	104.7	105.9	105.8
2210	97.3	101.4	102.2	103.4	103.9
2243	95.0	98.6	99.2	100.2	100.1
2275	92.7	96.3	97.1	98.0	97.9
2320	89.6	93.2	94.0	94.8	94.9
2360	87.4	90.5	91.4	92.0	91.9
2400	85.1	87.9	88.8	89.3	89.3
2440	82.9	85.6	86.3	86.7	86.7
2480	80.7	83.4	84.2	84.4	84.6
2520	78.9	81.7	82.8	83.4	83.7
2560	77.4	80.1	81.0	81.8	81.9
2600	75.6	78.4	79.3	80.1	80.3
2640	74.1	76.7	77.6	78.5	78.6
2680	72.5	75.2	76.0	76.7	76.9
2720	71.0	73.6	74.4	75.2	75.3
2760	69.4	72.0	72.9	73.7	73.8
2800	67.9	70.6	71.3	72.2	72.3
2840	66.7	69.1	69.8	71.2	70.9
2880	65.4	67.8	68.6	69.7	69.6
2920	64.4	66.6	67.2	68.3	68.4
2960	63.3	65.4	66.0	66.9	67.2
3000	62.2	64.3	64.9	65.8	66.0

TABLE C-3. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-9

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
0	55.7	58.6	59.1	59.3	59.6
5	62.9	103.8	106.1	108.6	112.6
10	67.3	106.7	108.1	110.4	114.1
15	71.2	108.7	110.1	111.9	117.3
20	75.1	112.0	113.8	117.5	125.2
25	77.8	108.1	111.7	116.7	125.7
30	79.9	104.4	109.0	116.3	126.1
35	84.8	108.9	115.8	130.3	135.5
40	87.8	116.5	122.9	138.6	141.5
45	91.6	119.6	127.5	144.3	147.9
50	95.0	126.7	134.7	147.7	150.7
55	99.4	131.6	140.9	150.3	155.8
60	102.5	137.2	144.0	150.7	161.1
65	104.1	135.4	141.4	146.8	159.7
95	120.1	150.2	155.3	159.0	171.1
125	137.5	170.8	177.1	181.2	179.4
155	149.7	172.6	177.0	182.9	179.9
185	157.2	175.3	180.0	184.1	182.5
215	168.7	193.2	199.3	203.4	195.2
245	173.2	190.4	196.3	200.6	196.6
275	180.3	197.4	204.9	210.6	203.0
305	189.0	205.9	212.8	215.3	213.7
335	191.9	205.1	210.2	214.3	214.3
365	190.1	201.3	203.6	204.5	212.0
395	195.2	211.1	217.7	224.2	227.3
425	202.5	217.7	224.8	232.1	232.2
455	208.6	225.4	229.9	236.6	236.1
485	207.7	220.0	223.9	229.3	229.7
515	193.5	199.8	200.3	200.3	203.8
545	186.4	194.4	196.3	198.4	199.4
575	180.5	188.7	190.9	193.4	193.9
605	174.8	182.7	184.7	186.6	187.1
635	168.7	176.3	178.0	179.7	180.0
665	162.4	169.4	170.3	170.7	172.1
695	158.7	167.8	169.6	172.3	172.1
725	154.1	162.2	163.6	165.8	165.8
755	151.2	159.6	161.4	163.6	164.0
785	146.2	153.4	154.8	155.9	156.6
815	141.9	149.2	150.7	152.2	152.7
845	137.7	144.8	146.4	148.1	148.4
875	133.7	140.2	141.4	142.3	143.2
905	129.5	135.9	137.1	137.9	138.8
935	125.2	131.1	132.2	132.6	133.4
965	121.1	126.8	127.8	128.4	129.3
995	117.2	122.8	123.8	124.3	125.2
1025	113.6	119.0	119.8	120.2	121.3
1055	109.2	113.3	113.4	112.9	114.6
1085	105.5	109.4	109.6	108.9	110.8
1115	102.1	105.9	106.1	105.6	107.2
1145	98.9	103.8	104.9	105.6	105.6
1175	97.0	102.3	103.5	104.7	104.8
1205	94.9	99.8	100.9	101.9	102.2
1235	92.8	97.7	98.8	99.6	99.9
1265	90.8	96.0	97.6	99.4	99.0
1313	86.9	91.4	92.8	94.5	93.9
1360	84.5	89.4	90.9	92.8	92.3
1400	82.4	86.9	88.2	90.1	89.8
1440	80.4	84.8	86.1	87.9	87.6
1480	78.4	82.6	83.8	85.5	85.4
1520	76.6	80.7	81.8	83.6	83.3

TABLE C-3. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-9

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
1560	74.7	78.7	79.9	81.4	81.3
1600	72.9	76.9	78.0	79.4	79.4
1640	71.3	75.1	76.3	77.8	77.6
1680	69.8	73.3	74.3	75.6	75.8
1720	68.2	71.6	72.6	74.0	73.9
1760	66.7	69.9	71.0	72.3	72.3
1800	65.2	68.4	69.3	70.6	70.7
1840	63.8	66.9	67.9	69.2	69.2
1880	62.6	65.6	66.6	67.8	67.8
1920	61.2	64.1	65.0	66.0	66.3
1960	59.9	62.9	63.7	64.9	65.0
2000	58.7	61.5	62.4	63.3	63.4
2040	57.6	60.3	61.1	62.1	62.1
2080	56.6	59.1	59.8	60.8	60.8
2120	55.5	57.9	58.7	59.7	59.7
2160	54.4	56.7	57.4	58.4	58.4
2200	53.5	55.8	56.4	57.4	57.4
2240	52.5	54.6	55.3	56.2	56.2
2280	51.6	53.8	54.4	55.3	55.3
2320	50.7	52.8	53.5	54.3	54.3
2360	49.9	51.8	52.4	53.3	53.3
2400	49.1	50.9	51.5	52.3	52.4
2440	48.3	50.1	50.7	51.4	51.5
2480	47.5	49.2	49.7	50.4	50.6
2520	46.8	48.4	49.1	49.8	49.8
2560	46.1	47.7	48.3	49.0	49.0
2600	45.4	46.9	47.3	48.1	48.1
2640	44.7	46.2	46.7	47.4	47.4
2680	44.0	45.6	46.1	46.8	46.7
2720	43.4	44.8	45.3	46.0	45.9
2760	42.8	44.1	44.6	45.2	45.2
2800	42.2	43.6	44.0	44.6	44.6
2840	41.6	42.9	43.4	43.8	44.0
2880	41.1	42.3	42.7	43.4	43.4
2920	40.6	41.8	42.3	42.8	42.8
2960	40.1	41.2	41.6	42.2	42.3
3000	39.7	40.8	41.2	41.7	41.7

TABLE C-4. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-10

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
10	65.6	92.3	94.1	95.9	98.7
15	66.9	90.8	92.8	95.1	98.8
20	68.3	95.4	97.1	96.3	99.2
25	69.8	95.5	96.9	100.3	101.4
30	71.4	96.2	96.6	101.1	103.1
35	73.1	96.1	96.6	101.4	104.4
40	74.5	95.8	97.2	103.4	106.4
45	76.1	96.9	98.3	104.9	108.7
60	79.8	99.1	100.8	104.3	108.7
65	80.6	97.8	100.3	104.1	108.2
95	85.7	100.7	103.9	108.5	111.9
125	89.4	104.5	107.8	113.0	117.1
155	93.4	110.4	114.3	120.1	124.1
185	95.7	109.7	114.0	120.6	123.4
216	100.6	119.1	125.6	134.4	139.7
250	104.8	124.3	131.4	141.6	145.9
280	107.9	126.7	134.3	145.2	149.3
310	110.3	128.6	136.5	147.9	151.9
340	111.9	128.8	136.2	146.9	151.6
370	113.4	131.3	139.2	150.2	154.3
400	114.9	132.8	140.7	151.7	155.9
430	116.5	135.7	142.8	153.2	157.7
460	117.7	135.7	143.8	155.3	159.4
490	119.0	137.0	145.0	156.9	161.7
520	120.3	139.1	147.3	159.2	163.7
550	121.7	140.6	149.1	161.5	167.3
580	122.9	141.2	149.8	162.6	168.7
625	124.4	143.6	152.1	164.6	171.1
655	125.6	145.2	153.9	166.6	173.4
685	126.3	145.4	154.0	167.4	174.4
715	127.2	146.8	155.4	168.7	174.7
745	128.0	148.1	157.0	170.6	176.6
775	128.3	148.0	156.4	169.7	176.1
805	128.4	148.1	155.8	168.9	175.6
835	128.3	151.2	157.9	169.8	175.5
865	127.7	156.0	161.9	171.5	178.3
895	137.3	163.5	171.7	175.0	177.4
930	137.6	163.7	172.7	177.9	175.6
960	137.7	164.6	172.2	175.2	175.5
990	137.1	160.2	169.8	173.3	173.0
1020	136.9	159.3	171.3	174.9	174.7
1050	136.1	157.7	168.0	172.1	173.6
1080	135.3	156.7	167.7	171.6	172.4
1110	135.2	156.1	167.6	171.0	171.7
1140	134.5	155.3	166.8	170.6	171.2
1170	133.4	153.8	164.8	167.3	169.6
1200	133.5	154.7	167.4	172.4	171.2
1230	133.1	154.3	166.1	170.3	170.8
1260	131.9	151.6	162.3	166.3	168.8
1290	131.6	152.3	163.1	168.0	169.3
1320	131.3	152.1	161.7	166.8	169.1
1350	131.7	153.5	164.5	169.6	172.2
1385	133.8	156.1	167.9	174.3	179.2
1415	134.3	156.0	168.1	174.9	176.4
1445	134.4	154.2	164.7	172.1	176.2
1475	133.3	152.5	161.5	169.3	171.3
1505	128.2	141.9	147.4	152.1	152.4
1535	122.4	132.6	135.8	138.7	138.7
1565	118.3	128.0	130.4	131.2	131.3
1595	114.7	123.4	125.4	125.4	125.6

TABLE C-4. TEMPERATURE GRADIENT IN CONTAINMENT ATMOSPHERE

NEAR VESSEL WALL AT MID-HEIGHT IN TEST AC-10

TIME MINUTES	TEMPERATURE, (DEG C) WALL SURFACE	0.95 CM FROM WALL	1.9 CM FROM WALL	5.08 CM FROM WALL	30.5 CM FROM WALL
1625	111.4	119.6	121.6	121.9	121.9
1655	108.4	115.8	117.8	117.8	117.9
1685	105.5	112.6	114.5	114.5	114.5
1715	102.4	108.4	109.5	109.1	109.4
1745	99.5	104.9	105.9	105.6	105.8
1775	96.7	102.1	103.3	103.1	103.3
1805	94.0	99.1	100.0	99.3	99.9
1835	91.3	95.2	95.2	94.4	94.3
1865	88.6	92.2	92.2	91.3	91.6
1895	86.0	89.4	89.4	88.4	88.5
1925	83.4	86.6	86.3	85.1	85.4
1955	81.7	86.1	87.1	86.8	86.9
1985	80.2	84.8	86.0	86.0	86.2
2015	78.6	83.3	84.7	85.1	85.2
2045	76.9	81.5	82.7	82.6	82.7
2079	75.5	80.3	81.5	81.7	81.9
2201	70.2	75.1	76.8	77.9	78.1
2241	68.9	73.4	74.9	76.1	76.4
2281	67.6	71.9	73.4	74.6	74.8
2321	65.9	70.2	71.8	72.9	73.0
2361	64.7	68.7	70.0	71.2	71.3
2401	63.4	67.3	68.7	69.7	69.8
2441	62.2	65.9	67.1	68.0	68.4
2521	60.0	63.9	64.7	65.3	65.6
2561	58.7	62.6	63.6	63.9	64.2

APPENDIX D

RATIO OF STANDARD TO ACTUAL GAS VOLUME IN THE CONTAINMENT ATMOSPHERE

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RATIO OF STANDARD TO ACTUAL GAS VOLUME IN THE CONTAINMENT ATMOSPHERE

The volume occupied by a given molar quantity of gas in the containment atmosphere varied throughout the tests as the gas temperature and pressure varied. Assuming that the containment atmosphere behaved as an ideal gas, the following relationship holds for relating standard volume to actual volume:

$$\frac{V_{STP}}{V_{ACTUAL}} = \frac{(273)\ P}{T\ (101)}$$

where:

STP = 0°C, 101 kPa abs (32°F, 14.7 psia)

V_{STP} = Volume at standard temperature and pressure

V_{ACTUAL} = Volume at actual temperature and pressure

P = Actual pressure (kPa abs)

T = Actual temperature (K)

The ratio of standard to actual volumes in the containment atmosphere are listed in Table D-1 for Tests AC7 through AC10.

TABLE D-1

RATIO OF STANDARD TO ACTUAL GAS VOLUME IN THE CONTAINMENT ATMOSPHERE

TIME (min)	RATIO (Std m3 per Actual m3)			
	AC7	AC8	AC9	AC10
0	0.799	0.797	0.821	(a)
5	0.798	0.789	0.794	(a)
10	0.797	0.784	0.783	0.802
15	0.795	0.781	0.782	0.798
20	0.792	0.777	0.775	0.797
30	0.879	0.815	0.773	0.842
40	0.954	0.903	0.778	0.922
50	1.031	0.988	0.776	(a)
60	1.095	1.075	0.759	1.105
70	1.127	1.171	0.678	1.193
80	1.149	1.254	0.621	1.215
100	1.167	1.252	0.614	1.209
120	1.186	1.251	0.589	1.202
140	1.195	1.245	0.587	1.200
160	1.190	1.245	0.584	1.193
180	1.172	1.235	0.583	1.190
200	0.741	0.776	0.574	0.725
220	0.675	0.717	0.564	0.650
240	0.674	0.706	0.572	0.650
270	0.681	0.704	0.558	0.641
300	0.680	0.705	0.551	0.640
330	0.676	0.701	0.546	0.632
360	0.674	0.700	0.551	0.637
390	0.670	0.702	0.539	0.634
420	0.669	0.683	0.533	0.631
450	0.670	0.677	0.527	0.627
480	0.665	0.669	0.533	0.628
510	0.666	0.663	0.561	0.623
540	0.667	0.658	0.567	0.618
570	0.661	0.651	0.573	0.617
600	0.662	0.649	0.579	0.617
630	0.667	0.644	0.588	0.615
660	0.668	0.641	0.598	0.613
690	0.669	0.638	0.601	0.611
720	0.671	0.636	0.610	0.610

(a) Data not available

TABLE D-1 (Cont)

RATIO OF STANDARD TO ACTUAL GAS VOLUME IN THE CONTAINMENT ATMOSPHERE

TIME (min)	RATIO (Std m3 per Actual m3)			
	AC7	AC8	AC9	AC10
750	0.672	0.633	0.610	0.608
780	0.672	0.629	0.622	0.608
810	0.671	0.627	0.628	0.608
840	0.663	0.624	0.634	0.609
870	0.666	0.623	0.641	0.605
900	0.668	0.620	0.647	0.607
930	0.666	0.618	0.656	0.608
960	0.667	0.616	0.663	0.609
990	0.670	0.614	0.670	0.610
1020	0.670	0.616	0.676	0.608
1050	0.670	0.618	0.687	0.610
1080	0.670	0.620	0.695	0.612
1110	0.669	0.620	0.701	0.613
1140	0.659	0.616	0.710	0.613
1170	0.660	0.616	0.709	0.615
1200	0.662	0.618	0.714	0.614
1230	0.661	0.619	0.719	0.615
1260	0.660	0.616	0.721	0.617
1290	0.659	0.617	0.731	0.612
1320	0.664	0.617	0.735	0.614
1350	0.659	0.618	0.737	0.612
1380	0.659	0.617	0.741	0.606
1410	0.666	0.618	0.744	0.600
1440	0.661	0.621	0.748	0.606
1470	0.665	0.619	0.751	0.605
1500	0.667	0.618	0.759	0.626
1530	0.669	0.619	0.763	0.651
1560	0.655	0.621	0.766	0.661
1590	0.655	0.624	0.769	0.671
1620	0.658	0.619	0.773	0.679
1650	0.657	0.618	0.776	0.685
1680	0.659	0.619	0.778	0.692
1710	0.655	0.618	0.782	0.699
1740	0.657	0.618	0.785	0.707
1770	0.657	0.617	0.787	0.713

(a) Data not available

TABLE D-1 (Cont)
RATIO OF STANDARD TO ACTUAL GAS
VOLUME IN THE CONTAINMENT ATMOSPHERE

TIME (min)	RATIO (Std m3 per Actual m3)			
	AC7	AC8	AC9	AC10
1800	0.656	0.615	0.786	0.718
1830	0.651	0.616	0.785	0.727
1860	0.654	0.617	0.789	0.734
1890	0.666	0.632	0.792	0.743
1920	0.683	0.642	0.794	0.751
1950	0.691	0.652	0.797	0.751
1980	0.690	0.658	0.800	0.750
2010	0.690	0.664	0.801	0.754
2040	0.699	0.672	0.804	0.758
2070	0.704	0.678	0.806	0.760
2100	0.709	0.683	0.808	0.770
2130	0.716	0.688	0.810	0.771
2160	0.722	0.695	0.814	0.773
2190	0.726	0.699	0.816	0.775
2220	0.731	0.705	0.819	0.776
2250	0.734	0.709	0.820	0.778
2280	0.740	0.712	0.822	0.781
2310	0.744	0.717	0.824	0.785
2340	0.747	0.721	0.825	0.788
2370	0.751	0.725	0.828	0.791
2400	0.755	0.728	0.830	0.794
2430	0.757	0.732	0.831	0.797
2460	0.761	0.735	0.833	0.800
2490	0.764	0.738	0.835	0.802
2520	0.767	0.741	0.837	0.805
2550	0.769	0.744	0.838	0.807
2580	0.772	0.747	0.840	(a)
2610	0.773	0.751	0.842	(a)

(a) Data not available

APPENDIX E

TEMPERATURES, PRESSURE DROPS, AND FLOW RATES IN THE AIR CLEANING SYSTEM

TABLE E1
TEMPERATURES, FLOW RATES AND PRESSURE DROPS
IN AIR CLEANING SYSTEM - TEST AC7

		GAS FLOW, CU.m/s			GAS TEMP, DEG C			AVE TEMP, DEG C		PRESS. DROP, KPa	
OPERATING PERIOD	TIME INTERVAL MINUTES	STD. DAS 97	ACTUAL SGS INLET DAS 19	ACTUAL SGS OUTLET DAS 53	SGS INLET DAS 19	SGS OUTLET DAS 53	DEMIST. OUTLET DAS 54	SGS LIQUID (a)	GRAVEL (b)	DEMIST. DAS 103	TOTAL DAS 102
1	180- 200	0.3495	0.5092	0.3981	105.1	22.6	23.7	22.7	22.0	0.64	8.57
2	210- 270	0.0539	0.0806	0.0618	116.2	25.3	34.8	25.5	24.6	0.41	6.80
3	270- 330	0.1582	0.2425	0.1818	128.1	27.7	32.0	28.3	27.5	0.83	7.42
4	330- 390	0.2987	0.4605	0.3467	131.6	31.5	32.9	32.5	31.7	1.22	8.26
5	390- 450	0.3027	0.4687	0.3546	134.3	35.0	36.2	36.1	35.1	1.08	8.11
6	450- 510	0.2988	0.4635	0.3514	134.9	36.2	36.8	37.3	36.3	1.03	8.72
7	510- 570	0.3079	0.4741	0.3630	132.8	37.7	37.9	38.7	37.7	1.06	8.46
8	570- 630	0.3138	0.4912	0.3713	139.5	38.7	38.7	39.7	38.7	1.04	8.29
9	630- 690	0.3310	0.5102	0.3918	133.2	38.8	38.8	39.9	38.9	1.07	7.44
10	690- 750	0.3118	0.4809	0.3663	133.4	36.4	37.1	37.9	36.9	1.04	9.03
11	750- 870	0.3145	0.4685	0.3704	118.8	36.7	36.7	37.7	36.9	1.00	8.24
12	870- 990	0.3076	0.4810	0.3630	139.1	38.0	37.9	39.0	38.0	1.00	8.38
13	990-1110	0.3025	0.4701	0.3579	136.5	38.7	38.3	39.8	38.8	0.99	8.30
14	1110-1230	0.3105	0.4889	0.3681	141.9	39.3	38.7	40.4	39.5	1.03	8.40
15	1230-1350	0.3009	0.4715	0.3568	140.0	39.4	38.8	40.7	39.8	1.00	8.50
16	1350-1470	0.3067	0.4795	0.3632	139.1	39.0	38.7	40.5	39.6	1.01	8.98
17	1470-1590	0.3083	0.4768	0.3655	134.5	39.4	38.8	40.5	39.6	1.02	8.95
18	1590-1710	0.3031	0.4782	0.3597	142.8	39.7	39.7	41.2	40.3	1.00	9.09
19	1710-1830	0.3015	0.4755	0.3585	142.7	40.3	40.0	41.6	40.7	1.01	9.09
20	1830-1930	0.3017	0.4657	0.3590	133.8	40.5	40.0	41.6	40.5	1.02	9.33
21	1930-2050	0.0923	0.1332	0.1090	107.4	38.2	40.7	39.3	38.3	0.37	8.29
22	2050-2220	0.0696	0.0971	0.0822	93.1	36.9	39.1	37.8	36.6	0.30	8.34

(a) - AVERAGE OF FOUR THERMOCOUPLES

(b) - AVERAGE OF THREE THERMOCOUPLES

TABLE E2
TEMPERATURES, FLOW RATES AND PRESSURE DROPS
IN AIR CLEANING SYSTEM - TEST ACB

OPERATING PERIOD	TIME INTERVAL MINUTES	GAS FLOW, CU.m/s			GAS TEMP, DEG C			AVE TEMP, DEG C		PRESS. DROP, KPa	
		STD. DAS 97	ACTUAL SGS INLET DAS 19	ACTUAL SGS OUTLET DAS 53	SGS INLET DAS 19	SGS OUTLET DAS 53	DEMIST. OUTLET DAS 54	SGS LIQUID (a)	GRAVEL (b)	DEMIST. DAS 103	TOTAL DAS 102
1	180- 200	0.4033	0.5442	0.4662	78.6	28.1	28.8	27.8	27.1	1.10	8.73
2	210- 270	0.0695	0.0975	0.0838	95.1	43.3	42.0	45.5	44.6	0.24	7.11
3	270- 330	0.1699	0.2416	0.2143	103.8	61.2	60.2	62.9	61.9	0.59	7.68
4	330- 390	0.3277	0.4702	0.4107	107.0	58.8	59.0	60.1	58.7	1.10	8.22
5	390- 450	0.3288	0.4765	0.3966	109.7	45.4	46.6	46.6	45.5	1.08	8.09
6	450- 510	0.3288	0.4822	0.3919	113.4	41.0	42.4	42.0	41.0	1.08	8.05
7	510- 570	0.3325	0.5119	0.3976	131.9	41.4	42.5	42.1	41.2	1.09	7.66
8	570- 630	0.3242	0.5054	0.3878	137.8	42.1	42.8	42.9	42.0	1.07	7.71
9	630- 690	0.3014	0.4761	0.3600	142.4	41.1	42.0	42.1	41.2	1.01	9.07
10	690- 750	0.3023	0.4813	0.3623	146.5	42.7	43.3	43.7	42.7	1.03	9.12
11	750- 810	0.3054	0.4915	0.3672	151.1	43.8	44.1	44.7	43.7	0.99	8.26
12	810- 930	0.3030	0.4920	0.3648	154.9	44.1	44.2	45.1	44.2	1.00	8.28
13	930-1050	0.3027	0.4960	0.3652	158.8	44.9	44.5	45.9	44.9	0.99	8.52
14	1050-1170	0.3013	0.4904	0.3637	155.9	45.0	44.6	46.0	45.1	0.98	8.57
15	1170-1290	0.3013	0.4859	0.3640	152.0	45.3	44.7	46.3	45.3	0.99	8.61
16	1290-1410	0.3021	0.4746	0.3642	141.8	45.2	44.9	46.4	45.4	0.99	8.81
17	1410-1530	0.3029	0.4459	0.3653	115.7	45.4	44.9	46.5	45.5	1.00	9.12
18	1530-1650	0.2794	0.3895	0.3373	95.0	45.7	45.5	46.7	45.8	0.96	9.04
19	1650-1770	0.2215	0.3134	0.2666	101.3	45.4	46.6	46.5	45.6	0.76	9.02
20	1770-1890	0.1728	0.2418	0.2085	97.1	46.1	47.6	47.2	46.2	0.61	8.61
21	1890-2010	0.0636	0.0921	0.0763	110.4	44.6	48.4	45.5	44.5	0.22	8.60
22	2010-2220	0.0686	0.0953	0.0820	93.6	42.3	45.5	43.2	42.2	0.24	8.42

(a) - AVERAGE OF FOUR THERMOCOUPLES

(b) - AVERAGE OF THREE THERMOCOUPLES

TABLE E3
TEMPERATURES, FLOW RATES AND PRESSURE DROPS
IN AIR CLEANING SYSTEM - TEST AC9

OPERATING PERIOD	TIME INTERVAL MINUTES	GAS FLOW, CU.m/s			GAS TEMP, DEG C			AVE TEMP, DEG C		PRESS. DROP, KPa	
		STD. DAS 97	ACTUAL SGS INLET DAS 19	ACTUAL SGS OUTLET DAS 53	SGS INLET DAS 19	SGS OUTLET DAS 53	DEMIST. OUTLET DAS 54	SGS LIQUID (a)	GRAVEL (b)	DEMIST. DAS 103	TOTAL DAS 102
1	60- 64	0.3067	0.4008	0.3472	66.2	20.7	28.1	19.6	18.3	0.92	8.26
2	70- 120	0.0727	0.1186	0.0831	150.3	23.6	29.4	23.5	22.7	0.25	7.08
3	120- 160	0.1455	0.2584	0.1694	190.0	30.4	35.2	31.3	30.5	0.52	7.87
4	160- 220	0.2590	0.4653	0.3083	199.6	40.0	44.8	41.3	40.3	1.01	8.80
5	220- 280	0.2544	0.4639	0.3087	208.6	47.4	52.5	48.6	47.5	1.05	8.76
6	280- 340	0.2511	0.4668	0.3066	219.0	50.1	55.4	51.2	50.1	1.09	8.63
7	340- 400	0.2558	0.4736	0.3127	217.0	50.4	55.9	51.5	50.5	1.14	8.53
8	400- 460	0.2736	0.5278	0.3350	237.5	50.8	56.4	52.0	51.0	1.26	8.87
9	460- 520	0.3338	0.6224	0.4085	220.5	50.8	55.6	51.8	50.8	1.46	9.17
10	520- 580	0.1468	0.2585	0.1777	193.0	47.1	51.6	48.2	47.2	0.56	8.13
11	580- 640	0.1456	0.2509	0.1759	182.1	46.0	49.0	47.0	45.9	0.62	8.08
12	640- 700	0.1455	0.2446	0.1751	170.9	44.7	47.6	45.7	44.7	0.57	7.86
13	700- 780	0.1438	0.2376	0.1726	162.4	43.3	45.7	44.4	43.3	0.57	7.57
14	780- 840	0.0626	0.0996	0.0749	145.2	41.4	44.1	42.7	41.7	0.25	6.99
15	840- 900	0.0634	0.0989	0.0756	136.2	39.7	41.7	40.8	39.8	0.24	7.72
16	900- 960	0.1600	0.2467	0.1901	131.7	38.8	40.7	39.7	38.7	0.60	8.37
17	960-1020	0.1631	0.2467	0.1930	124.0	37.6	39.8	38.5	37.5	0.61	8.21
18	1020-1140	0.3144	0.4605	0.3702	110.2	35.1	36.3	36.0	35.0	1.17	8.95
19	1140-1250	0.0661	0.0944	0.0773	100.7	33.2	35.1	34.0	33.0	0.27	6.86

(a) - AVERAGE OF FOUR THERMOCOUPLES

(b) - AVERAGE OF THREE THERMOCOUPLES

TABLE E4
TEMPERATURES, FLOW RATES AND PRESSURE DROPS
IN AIR CLEANING SYSTEM - TEST AC10

OPERATING PERIOD	TIME INTERVAL MINUTES	GAS FLOW, CU.m/s STD. DAS 97	GAS FLOW, CU.m/s ACTUAL SGS INLET DAS 19	GAS FLOW, CU.m/s ACTUAL SGS OUTLET DAS 53	GAS TEMP, DEG C SGS INLET DAS 19	GAS TEMP, DEG C SGS OUTLET DAS 53	GAS TEMP, DEG C DEMIST. OUTLET DAS 54	AVE TEMP, DEG C SGS LIQUID (a)	AVE TEMP, DEG C GRAVEL (b)	PRESS. DROP, KPa DEMIST. DAS 103	PRESS. DROP, KPa TOTAL DAS 102
1	180- 195	0.4567	0.6858	0.5267	116.8	26.3	27.3	26.4	25.8	1.01	8.29
2	210- 270	0.0754	0.1165	0.0874	129.5	28.8	33.9	29.0	28.2	0.33	6.41
3	270- 330	0.1474	0.2423	0.1726	155.4	32.0	35.5	32.9	32.0	0.54	7.66
4	330- 390	0.2929	0.4812	0.3460	158.1	36.9	39.7	37.9	37.2	0.99	8.33
5	390- 450	0.2897	0.4824	0.3457	164.9	40.7	42.8	41.7	40.9	1.02	8.13
6	450- 510	0.2891	0.4836	0.3451	167.8	41.5	43.8	43.1	42.3	1.02	7.98
7	510- 570	0.2818	0.4755	0.3379	171.7	42.9	44.1	43.6	42.8	1.01	7.38
8	570- 630	0.2872	0.4873	0.3456	174.2	44.1	44.9	44.9	44.0	1.01	7.25
9	630- 690	0.2689	0.4600	0.3210	177.8	41.5	43.7	43.5	42.7	0.96	8.63
10	690- 750	0.2813	0.4840	0.3386	180.4	44.2	44.9	45.3	44.4	0.98	8.88
11	750- 870	0.2801	0.4793	0.3381	179.0	45.7	45.9	46.6	45.7	0.97	7.91
12	870- 990	0.2765	0.4755	0.3340	180.2	45.3	45.1	46.2	45.3	0.96	8.21
13	990-1110	0.2799	0.4768	0.3379	175.9	45.0	45.0	46.4	45.6	0.96	8.26
14	1110-1230	0.2751	0.4662	0.3329	173.5	45.8	44.9	46.8	45.8	0.96	8.18
15	1230-1350	0.2769	0.4662	0.3348	170.6	45.5	44.6	46.6	45.6	0.97	8.48
16	1350-1410	0.0409	0.0692	0.0492	172.8	43.6	45.1	45.8	45.0	0.35	7.63
17	1410-1470	0.1388	0.2375	0.1672	177.9	44.5	45.2	45.6	44.6	0.60	8.93
18	1470-1520	0.2730	0.4394	0.3301	151.2	45.6	46.1	47.0	45.8	0.98	9.41
19	1520-1580	0.0783	0.1186	0.0944	126.4	44.7	45.8	45.9	44.9	0.44	8.08
20	1580-1640	0.0641	0.0944	0.0782	114.9	48.5	47.9	50.5	49.5	0.40	8.25
21	1640-1700	0.0700	0.1009	0.0858	108.5	51.2	50.9	53.4	52.3	0.40	8.05
22	1700-1760	0.1682	0.2392	0.2063	103.3	51.5	51.6	53.3	52.4	0.69	8.38
23	1760-1820	0.1693	0.2376	0.2089	98.3	53.4	52.6	56.7	55.8	0.66	8.07
24	1820-1880	0.3418	0.4720	0.4216	92.4	53.4	52.3	57.0	55.7	1.16	8.85
25	1880-1940	0.3622	0.4916	0.4446	86.1	51.7	50.0	54.0	52.7	1.25	9.02
26	1940-2000	0.0966	0.1312	0.1198	86.3	55.2	53.5	59.3	58.4	0.47	7.53
27	2000-2060	0.0803	0.1085	0.1020	84.8	63.5	60.5	67.8	66.6	0.43	7.26

(a) - AVERAGE OF FOUR THERMOCOUPLES

(b) - AVERAGE OF THREE THERMOCOUPLES

TABLE E5. SCRUBBER TEMPERATURES AT SELECTED TIMES FOR TEST AC7

	GAS TEMPERATURE DEG C				LIQUID TEMP DEG C				GRAVEL TEMP DEG C				
TIME MIN	CV DUCT IN DAS37(a)	SGS IN DAS19	DEMIST IN DAS 53	DEMIST OUT DAS 54	16in.(b) 45DEG DAS57	18 in. 230DEG DAS 61	36 in 230DEG DAS 58	36 in 120DEG DAS 63	20in. 45DEG DAS50	30in. 45DEG DAS51	40in. 45DEG DAS52	AVG. LIQUID 4 TC'S	AVG. GRAVEL 3 TC'S
120	112.3	28.6	26.9	31.6	20.7	22.8	21.9	24.1	20.4	21.1	23.2	22.4	21.6
180	118.6	29.6	26.7	33.8	21.9	22.7	22.6	23.9	18.9	20.8	21.7	22.8	20.4
245	137.7	118.2	25.4	31.3	24.9	26.7	24.9	26.7	24.9	24.9	24.9	25.8	24.9
300	135.3	127.8	27.9	32.4	27.8	29.3	27.8	29.3	27.8	27.9	27.8	28.6	27.8
360	135.1	131.3	31.7	32.9	31.8	33.4	31.6	33.6	31.8	31.7	31.6	32.6	31.7
425	137.8	134.2	35.3	36.8	35.6	37.2	35.3	37.2	35.3	35.3	35.2	36.3	35.3
480	141.6	137.7	36.5	37.5	36.6	38.3	36.5	38.4	36.5	36.5	36.4	37.5	36.5
540	134.0	131.1	37.7	38.0	37.9	39.8	37.9	39.7	38.0	37.7	37.8	38.8	37.9
600	142.3	139.3	38.8	38.8	39.0	40.8	38.9	40.7	38.9	38.7	38.8	39.8	38.8
660	136.2	132.7	38.8	38.6	39.0	40.8	38.9	40.8	39.0	38.9	38.9	39.9	38.9
725	137.7	134.9	36.8	37.0	37.0	38.6	36.8	38.6	37.0	36.7	36.7	37.7	36.8
780	135.3	132.8	37.4	37.4	37.7	39.3	37.5	39.4	37.7	37.4	37.5	38.5	37.6
840	145.4	105.7	35.9	36.1	36.2	37.9	36.2	37.9	36.1	36.1	36.1	37.1	36.1
900	141.2	138.7	37.6	37.7	37.7	39.5	37.7	39.6	37.6	37.6	37.7	38.6	37.6
960	141.2	138.8	38.3	38.1	38.6	40.2	38.5	40.3	38.6	38.3	38.3	39.4	38.4
1025	138.8	136.0	38.8	38.4	39.1	40.8	38.9	40.8	38.9	38.8	38.8	39.9	38.9
1080	136.8	134.4	38.8	38.3	39.1	40.8	38.9	40.8	38.9	38.8	38.8	39.9	38.8
1140	148.1	145.4	38.3	38.3	39.1	40.8	39.0	40.8	39.1	38.9	38.9	39.9	39.0
1200	144.0	141.8	39.8	38.9	40.4	41.9	40.0	41.8	40.4	39.8	39.8	41.0	40.0
1260	145.6	143.1	39.8	39.1	40.1	41.8	39.9	41.8	40.1	39.8	39.8	40.9	39.9
1325	137.8	135.7	36.9	37.4	40.0	41.6	37.7	39.7	39.9	39.9	38.9	39.7	39.6
1380	143.2	141.3	39.8	38.9	40.0	41.7	39.9	41.7	39.9	39.8	39.8	40.8	39.8
1440	141.9	140.4	39.4	38.6	39.7	41.4	39.6	41.4	39.8	39.5	39.6	40.5	39.6
1500	135.5	114.4	39.7	38.8	40.4	41.6	39.8	41.6	42.5	39.8	39.7	40.9	40.7
1565	147.7	144.2	39.4	39.1	39.7	41.3	39.6	41.4	39.6	39.4	39.4	40.5	39.5
1620	144.1	141.4	40.4	39.8	40.7	42.4	40.6	42.4	40.6	40.4	40.5	41.5	40.5
1680	141.7	139.7	40.2	39.7	40.4	42.2	40.3	42.1	40.4	40.2	40.2	41.3	40.3
1740	143.7	141.6	40.8	40.1	41.0	42.7	40.9	42.7	41.0	40.8	40.8	41.8	40.9
1800	143.9	141.3	39.9	39.7	40.2	42.0	40.2	41.9	40.2	40.1	40.1	41.1	40.1
1865	142.5	139.9	40.8	40.3	41.0	42.8	41.0	42.8	40.9	40.8	40.8	41.9	40.9
1920	120.4	119.3	39.9	39.6	40.1	41.9	40.1	41.9	40.1	39.9	40.0	41.0	40.0
1980	120.2	107.5	37.9	41.0	38.0	39.9	38.0	39.8	37.9	37.9	37.9	38.9	37.9
2045	112.5	99.6	37.7	40.1	37.7	39.5	37.7	39.5	37.7	37.6	37.6	38.6	37.6
2100	106.6	94.6	37.2	39.3	37.1	38.9	37.1	38.9	37.1	37.0	37.1	38.0	37.1
2160	101.3	92.0	36.7	38.8	36.7	38.4	36.7	38.4	36.6	36.5	36.6	37.6	36.6

(a) DAS 37 MEANS DATA AQUISITION SYSTEM CHANNEL NUMBER 37

(b) DISTANCES ARE MEASURED FROM THE BOTTOM OF THE POOL

TABLE E6. SCRUBBER TEMPERATURES AT SELECTED TIMES FOR TEST AC8

	GAS TEMPERATURE DEG C				LIQUID TEMP DEG C				GRAVEL TEMP DEG C				
TIME MIN	CV DUCT IN DAS37(a)	SGS IN DAS19	DEMIST IN DAS 53	DEMIST OUT DAS 54	16in.(b) 45DEG DAS57	18 in. 230DEG DAS 61	36 in 230DEG DAS 58	36 in 120DEG DAS 63	20in. 45DEG DAS50	30in. 45DEG DAS51	40in. 45DEG DAS52	AVG. LIQUID 4 TC'S	AVG. GRAVEL 3 TC'S
120	95.2	30.8	30.1	30.6	25.5	27.6	26.7	28.7	25.6	26.3	27.9	27.1	26.6
180	102.1	30.9	30.2	30.9	25.6	27.5	26.6	28.3	25.6	26.4	28.0	27.0	26.7
240	112.1	97.3	44.6	42.4	46.2	47.5	45.6	47.9	46.1	45.9	46.5	46.8	46.2
300	116.6	104.4	62.2	61.4	63.6	64.9	62.9	65.3	63.7	62.6	63.4	64.2	63.2
360	114.7	107.5	60.4	60.3	61.6	63.2	61.4	63.5	61.1	60.3	61.9	62.4	61.1
420	116.8	107.2	44.6	45.9	44.1	46.6	44.7	46.4	44.6	44.3	44.5	45.5	44.5
480	136.9	119.8	40.9	42.4	40.9	42.5	40.8	42.6	40.8	40.6	40.7	41.7	40.7
540	145.1	132.2	41.1	41.5	41.3	42.8	40.8	41.6	41.3	41.3	41.2	41.6	41.3
600	151.3	137.1	42.2	42.6	42.2	43.9	42.1	43.8	42.3	41.9	41.9	43.0	42.1
660	156.9	143.1	41.2	42.2	41.8	42.9	41.1	43.1	41.6	41.1	41.1	42.2	41.2
720	161.3	147.3	42.8	43.4	43.6	44.6	42.8	44.6	43.0	42.7	42.7	43.9	42.8
780	164.6	150.9	43.8	44.0	44.5	45.7	43.8	45.6	44.1	43.8	43.8	44.9	43.9
840	165.8	152.8	43.7	44.1	43.8	45.4	43.6	45.6	43.6	43.5	43.6	44.6	43.6
900	170.1	156.0	44.6	44.4	44.6	46.5	44.6	46.5	44.7	44.4	44.6	45.6	44.6
965	170.4	159.9	45.1	44.8	45.2	46.8	45.1	46.9	45.4	45.0	44.9	46.0	45.1
1020	168.8	159.6	45.0	44.6	45.0	46.9	45.1	46.8	45.1	45.0	45.0	45.9	45.0
1080	163.1	153.8	45.1	44.6	45.3	46.9	45.1	46.9	45.2	45.1	45.1	46.0	45.1
1140	168.6	154.5	45.2	44.6	45.3	47.0	45.1	46.8	45.1	44.9	45.1	46.0	45.0
1200	166.5	157.3	45.3	44.6	45.4	47.2	45.3	47.2	45.4	45.3	45.3	46.3	45.3
1260	168.5	133.9	45.5	44.8	45.6	47.3	45.4	47.2	45.4	45.3	45.4	46.4	45.4
1320	166.7	149.0	45.3	45.0	45.4	47.2	45.3	47.3	45.4	45.4	45.3	46.3	45.4
1380	167.1	133.3	45.0	44.6	45.2	46.8	45.0	46.9	45.1	45.2	45.0	46.0	45.1
1440	164.4	122.7	45.8	45.3	45.9	47.6	45.7	47.7	45.9	45.7	45.7	46.7	45.8
1500	167.8	105.2	45.7	44.9	45.7	47.4	45.6	47.4	45.7	45.4	45.6	46.5	45.6
1560	162.9	89.9	44.9	45.2	45.6	47.2	45.4	47.3	45.4	45.3	45.4	46.3	45.4
1620	165.7	100.8	46.1	45.8	46.1	47.8	46.0	47.9	46.0	45.9	46.1	47.0	46.0
1680	169.7	113.2	44.6	46.3	44.8	46.6	44.9	46.6	44.8	44.7	44.7	45.7	44.7
1740	166.1	95.3	45.9	47.0	45.8	47.6	45.8	47.7	46.1	45.7	45.8	46.7	45.9
1800	168.2	92.8	46.4	47.7	46.5	48.4	46.5	48.3	46.4	46.3	46.4	47.4	46.4
1860	163.7	95.1	46.3	47.7	46.3	48.1	46.3	48.2	46.3	46.2	46.4	47.2	46.3
1920	141.1	112.0	44.9	48.6	45.0	46.8	44.9	46.8	45.0	44.8	44.9	45.9	44.9
1980	130.7	108.9	44.3	47.7	44.3	46.2	44.3	46.2	44.2	44.2	44.3	45.2	44.2
2040	122.9	103.9	43.4	47.4	43.4	45.2	43.3	45.2	43.3	43.2	43.3	44.3	43.3
2100	116.1	100.0	42.3	46.5	42.4	44.2	42.3	44.2	42.3	42.3	42.3	43.3	42.3
2160	110.1	96.4	41.4	45.1	41.4	43.2	41.3	43.1	41.3	41.2	41.3	42.3	41.2

(a) DAS 37 MEANS DATA AQUISITION SYSTEM CHANNEL NUMBER 37

(b) DISTANCES ARE MEASURED FROM THE BOTTOM OF THE POOL

TABLE E7. SCRUBBER TEMPERATURES AT SELECTED TIMES FOR TEST AC9

	GAS TEMPERATURE DEG C				LIQUID TEMP DEG C				GRAVEL TEMP DEG C				
TIME MIN	CV DUCT IN DAS37(a)	SGS IN DAS19	DEMIST IN DAS 53	DEMIST OUT DAS 54	16in.(b) 45DEG DAS57	18 in. 230DEG DAS 61	36 in 230DEG DAS 58	36 in 120DEG DAS 63	20in. 45DEG DAS50	30in. 45DEG DAS51	40in. 45DEG DAS52	AVG. LIQUID 4 TC'S	AVG. GRAVEL 3 TC'S
120	200.8	181.3	26.3	31.9	29.2	27.7	25.9	27.8	26.4	26.6	26.1	27.7	26.4
180	198.4	192.2	38.9	43.5	39.9	40.7	39.1	40.9	39.2	39.3	39.0	40.2	39.2
240	212.1	205.4	47.2	51.7	47.7	48.8	47.1	48.9	47.2	47.1	47.1	48.1	47.1
300	231.2	221.8	50.0	55.3	50.3	51.8	50.0	51.9	50.1	49.9	49.9	51.0	50.0
360	217.7	210.9	50.6	56.4	50.8	52.6	50.7	52.5	50.8	50.5	50.6	51.7	50.6
420	243.8	233.4	51.1	56.9	51.9	52.8	51.1	52.8	51.5	50.9	50.9	52.1	51.1
480	241.9	236.6	51.4	55.7	51.8	53.3	51.5	53.3	51.8	51.3	51.0	52.5	51.4
540	203.0	194.3	47.3	51.9	47.4	49.2	47.4	49.2	47.3	47.2	47.3	48.3	47.3
600	193.2	184.3	46.2	49.9	46.2	48.1	46.2	48.1	46.2	46.0	46.1	47.1	46.1
660	177.6	170.8	44.8	47.4	45.0	46.7	44.9	46.7	44.9	44.7	44.8	45.8	44.8
720	170.4	163.7	43.7	47.3	43.8	45.6	43.8	45.6	43.7	43.6	43.6	44.7	43.6
780	160.3	154.6	42.3	44.3	42.6	44.4	42.6	44.4	42.4	42.3	42.4	43.5	42.4
840	153.4	137.5	40.0	42.2	40.3	42.0	40.2	42.0	40.1	40.1	40.2	41.1	40.1
905	140.9	135.3	39.3	41.0	39.3	41.1	39.3	41.1	39.3	39.2	39.3	40.2	39.2
960	131.4	127.9	38.1	40.5	38.2	39.9	38.2	40.0	38.1	38.1	38.1	39.1	38.1
1020	122.9	119.9	37.0	39.8	37.0	38.7	37.0	38.8	36.9	36.8	36.8	37.9	36.9
1080	110.7	109.4	34.9	36.4	35.0	36.8	35.1	36.8	34.9	34.8	34.9	35.9	34.9
1140	103.3	102.2	33.5	35.4	33.6	35.3	33.5	35.3	33.4	33.4	33.4	34.4	33.4
1200	105.1	100.3	33.2	35.2	33.2	34.8	33.2	34.8	33.1	33.0	33.0	34.0	33.0
1260	102.0	71.7	33.4	36.9	32.7	34.4	32.7	34.4	32.6	32.6	32.4	33.5	32.5
1333	96.2	61.6	32.2	32.9	31.8	33.4	31.7	33.5	31.6	31.6	31.4	32.6	31.5
1380	93.5	51.2	31.9	31.2	31.7	33.3	31.6	33.4	31.5	31.6	31.1	32.5	31.4
1440	90.2	43.3	31.6	29.7	31.7	33.3	31.6	33.3	31.6	31.6	30.9	32.5	31.4
1500	86.7	38.9	31.1	28.9	31.7	33.2	31.6	33.2	31.6	31.6	30.6	32.4	31.2
1560	83.4	35.9	30.6	28.3	31.7	33.0	31.4	33.1	31.6	31.6	30.3	32.3	31.2
1620	80.3	33.7	30.2	27.9	31.6	32.8	31.3	33.1	31.5	31.6	30.1	32.2	31.0
1680	77.4	32.3	29.9	27.8	31.5	32.8	31.2	32.9	31.4	31.6	29.9	32.1	31.0
1740	74.8	31.2	29.6	27.4	31.3	32.6	31.0	32.8	31.3	31.6	29.7	31.9	30.8
1800	72.2	30.3	29.5	27.2	31.3	32.5	30.9	32.6	31.3	31.4	29.4	31.8	30.7
1860	69.8	29.5	29.1	26.9	31.1	32.4	30.8	32.6	31.1	31.4	29.3	31.7	30.6
1920	67.4	28.9	29.2	26.7	31.1	32.3	30.7	32.4	30.9	31.3	29.2	31.6	30.5
1980	65.3	28.2	28.9	26.4	30.9	32.1	30.5	32.3	30.8	31.2	28.9	31.4	30.3
2040	63.3	27.9	28.6	26.3	30.7	32.0	30.4	32.1	30.6	31.1	28.8	31.3	30.2
2100	61.3	27.4	28.7	26.1	30.6	31.8	30.2	32.0	30.5	30.9	28.7	31.2	30.0
2160	59.5	27.2	28.4	25.9	30.5	31.7	30.2	31.9	30.4	30.8	28.6	31.1	29.9

(a) DAS 37 MEANS DATA AQUISITION SYSTEM CHANNEL NUMBER 37

(b) DISTANCES ARE MEASURED FROM THE BOTTOM OF THE POOL

TABLE E8. SCRUBBER TEMPERATURES AT SELECTED TIMES FOR TEST AC10

	GAS TEMPERATURE DEG C				LIQUID TEMP DEG C				GRAVEL TEMP DEG C				
TIME MIN	CV DUCT IN DAS37(a)	SGS IN DAS19	DEMIST IN DAS 53	DEMIST OUT DAS 54	16in.(b) 45DEG DAS57	18 in. 230DEG DAS 61	36 in 230DEG DAS 58	36 in 120DEG DAS 63	20in. 45DEG DAS50	30in. 45DEG DAS51	40in. 45DEG DAS52	AVG. LIQUID 4 TC'S	AVG. GRAVEL 3 TC'S
120	123.8	28.1	26.4	26.1	24.4	26.4	25.3	27.3	24.4	24.7	25.3	25.9	24.8
180	135.3	28.3	26.5	40.9	24.5	26.4	25.4	27.3	24.4	24.8	25.4	25.9	24.9
240	156.9	138.4	27.9	33.9	28.2	29.8	28.1	29.8	28.3	27.9	28.0	29.0	28.1
300	161.7	157.6	32.3	35.8	32.4	33.9	32.2	33.9	32.2	32.2	32.2	33.1	32.2
360	161.5	162.7	37.3	39.9	37.4	38.9	37.3	39.1	37.4	37.3	37.3	38.2	37.3
420	166.8	166.5	40.8	43.1	41.1	42.7	40.9	42.7	41.1	40.8	40.9	41.8	40.9
480	168.8	168.3	42.7	43.8	42.7	44.5	42.7	44.4	43.1	42.4	42.7	43.6	42.7
540	173.6	173.9	42.2	44.5	43.1	44.6	41.2	42.4	43.6	43.0	43.1	42.8	43.2
600	174.8	173.8	44.2	45.0	44.2	45.9	44.2	45.9	44.2	44.1	44.2	45.1	44.2
660	176.8	176.4	42.0	43.6	42.3	43.9	42.1	43.9	43.1	41.9	42.1	43.1	42.4
720	182.0	180.7	44.2	44.7	44.6	46.2	44.3	46.2	45.1	44.2	44.3	45.3	44.5
780	178.9	178.3	45.6	45.9	45.7	47.4	45.5	47.4	45.6	45.4	45.6	46.5	45.5
840	178.2	176.9	45.8	45.7	45.9	47.8	45.9	47.7	45.9	45.8	45.9	46.8	45.9
905	182.2	181.3	44.5	45.0	44.6	46.4	44.6	46.4	44.8	44.3	44.6	45.5	44.6
960	179.0	178.2	45.2	44.7	45.6	47.2	45.4	47.2	45.6	45.1	45.4	46.3	45.4
1020	180.0	177.6	38.9	45.3	45.9	47.6	43.3	43.2	46.1	45.7	46.0	45.0	45.9
1080	179.9	176.7	45.7	45.0	45.7	47.6	45.7	47.4	45.7	45.4	45.7	46.6	45.6
1140	175.9	173.7	45.8	45.1	45.9	47.7	45.9	47.6	45.9	45.6	45.8	46.8	45.8
1200	173.3	172.8	46.3	45.2	46.5	48.3	46.4	48.2	46.6	46.2	46.3	47.3	46.4
1260	169.9	165.3	45.7	44.6	45.8	47.4	45.7	47.6	45.9	45.4	45.6	46.6	45.6
1320	171.1	169.3	45.1	44.7	45.7	47.4	45.4	47.3	45.5	45.3	45.4	46.5	45.4
1380	178.1	172.1	34.6	45.6	45.9	47.7	39.7	40.3	45.8	45.7	45.9	43.4	45.8
1440	177.3	177.6	44.6	45.6	44.6	46.6	44.8	46.6	44.8	44.4	44.6	45.7	44.6
1500	161.5	152.3	45.7	46.9	45.9	47.8	46.1	47.7	46.1	45.7	45.8	46.9	45.9
1560	146.5	122.9	44.6	45.7	44.9	46.7	45.0	46.5	44.8	44.6	44.7	45.8	44.7
1620	137.2	113.3	49.3	48.5	50.3	51.9	49.8	51.6	50.4	50.1	50.2	50.9	50.2
1680	129.8	107.7	51.4	50.6	52.6	54.4	52.4	54.2	52.4	52.3	52.4	53.4	52.4
1740	121.4	102.0	51.1	51.5	52.5	53.8	51.9	53.8	52.5	52.1	52.3	53.0	52.3
1800	114.7	97.8	54.3	53.6	57.7	59.2	56.8	59.8	57.6	56.9	57.2	58.4	57.2
1860	104.0	91.0	53.4	51.5	54.8	56.9	54.6	56.6	54.6	54.6	55.2	55.7	54.8
1920	97.2	86.6	51.4	49.4	51.2	55.1	52.8	54.8	49.4	52.7	53.1	53.5	51.8
1980	97.3	86.4	57.9	55.6	61.1	62.6	60.9	63.0	61.3	60.7	60.9	61.9	61.0
2040	93.2	83.9	64.9	61.5	67.8	69.8	67.8	70.7	68.3	67.3	67.7	69.0	67.8
2098	85.4	78.0	63.6	60.0	64.8	69.4	66.6	69.8	55.5	65.1	65.7	67.7	62.1
2201	84.4	66.2	69.1	50.8	82.8	72.7	70.4	71.9	84.4	86.7	77.0	74.4	82.7

(a) DAS 37 MEANS DATA AQUISITION SYSTEM CHANNEL NUMBER 37

(b) DISTANCES ARE MEASURED FROM THE BOTTOM OF THE POOL

APPENDIX F

ON-LINE GAS ANALYSES OF CONTAINMENT ATMOSPHERE

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TABLE F1
ON-LINE GAS ANALYSIS OF CONTAINMENT
ATMOSPHERE FOR TEST AC7

OPERATING PERIOD	TIME INTERVAL	VOLUME PERCENT			
		OXYGEN		HYDROGEN	
		HIGH (a)	LOW (b)	HIGH	LOW
1	180- 200	(c)	16.7	0.02	-0.06
2	210- 270	(c)	17.2	0.02	-0.01
3	270- 330	(c)	17.8	0.02	-0.01
4	330- 390	19.9	19.3	-0.02	-0.03
5	390- 450	20.5	20.0	-0.01	-0.03
6	450- 510	20.6	20.1	-0.01	-0.02
7	510- 570	20.8	20.4	0.00	-0.02
8	570- 630	20.9	20.5	0.00	-0.01
9	630- 690	20.9	20.6	0.00	-0.01
10	690- 750	20.9	20.6	0.00	-0.01
11	750- 870	20.9	20.6	0.01	-0.01
12	870- 990	20.7	20.3	0.02	-0.03
13	990-1110	20.9	20.5	0.02	-0.01
14	1110-1230	21.0	20.5	0.02	-0.01
15	1230-1350	21.1	20.7	0.05	-0.01
16	1350-1470	20.8	20.5	0.05	0.00
17	1470-1590	20.5	20.6	0.08	0.00
18	1590-1710	20.8	20.5	0.04	0.00
19	1710-1830	20.8	20.5	0.03	0.00
20	1830-1930	20.8	20.5	0.04	0.00
21	1930-2050	20.7	20.6	0.08	0.02
22	2050-2220	20.8	20.6	0.08	0.03

(a) Sampled from +6.1 meters elevation.
(b) Sampled from -6.7 meters elevation.
(c) Data not available.

TABLE F2
ON-LINE GAS ANALYSIS OF CONTAINMENT
ATMOSPHERE FOR TEST AC8
(Invalid data from time zero-675 minutes)

OPERATING PERIOD	TIME INTERVAL	VOLUME PERCENT			
		OXYGEN		HYDROGEN	
		HIGH (a)	LOW (b)	HIGH	LOW
10	690- 750	19.8	20.0	-0.04	0.06
11	750- 810	19.8	20.4	-0.04	0.06
12	810- 930	19.8	20.5	-0.04	0.06
13	930-1050	20.0	20.5	-0.03	0.06
14	1050-1170	20.2	20.4	-0.01	0.08
15	1170-1290	20.2	20.4	-0.01	0.08
16	1290-1410	20.3	20.4	0.01	0.09
17	1410-1530	20.2	20.3	0.00	0.09
18	1530-1650	20.4	20.3	0.00	0.09
19	1650-1770	20.3	20.2	0.02	0.10
20	1770-1890	20.2	20.1	0.05	0.12
21	1890-2010	20.6	20.2	0.08	0.15
22	2010-2220	20.8	20.4	0.06	0.14

(a) Sampled from +6.1 meters elevation.
(b) Sampled from -6.7 meters elevation.

TABLE F3
ON-LINE GAS ANALYSIS OF CONTAINMENT
ATMOSPHERE FOR TEST AC9

OPERATING PERIOD	TIME INTERVAL	VOLUME PERCENT				
		OXYGEN		HYDROGEN		CARBON DIOXIDE
		HIGH (a)	LOW (b)	HIGH	LOW	
1	60- 64	17.5	17.5	0.06	0.12	0.74
2	70- 120	16.1	17.5	0.13	0.13	0.87
3	120- 170	15.2	16.3	0.09	0.15	2.30
4	170- 220	17.1	17.6	0.08	0.14	2.60
5	220- 280	17.5	18.2	0.05	0.11	2.84
6	280- 340	17.7	18.4	0.06	0.04	2.19
7	340- 400	19.4	18.9	0.05	0.11	2.87
8	400- 460	18.3	19.0	0.13	0.16	1.62
9	460- 520	18.8	19.4	0.07	0.06	2.64
10	520- 580	19.1	19.9	0.06	0.06	2.37
11	580- 640	18.9	20.6	0.06	0.05	1.26
12	640- 700	19.0	20.3	0.05	0.06	2.97
13	700- 780	19.7	20.2	0.04	0.05	2.30
14	780- 840	20.4	21.1	0.03	0.05	1.34
15	840- 900	20.7	21.5	0.03	0.04	0.81
16	900- 960	21.1	21.7	0.02	0.02	0.40
17	960-1020	21.4	21.9	0.00	0.01	0.17
18	1020-1140	21.7	22.2	-0.02	-0.01	0.04
19	1140-1250	21.8	22.2	-0.03	0.00	0.02

(a) Sampled from +6.1 meters elevation.
(b) Sampled from -6.7 meters elevation.

TABLE F4
ON-LINE GAS ANALYSIS OF CONTAINMENT
ATMOSPHERE FOR TEST AC10

OPERATING PERIOD	TIME INTERVAL	VOLUME PERCENT OXYGEN HIGH (a)	VOLUME PERCENT OXYGEN LOW (b)	VOLUME PERCENT HYDROGEN HIGH	VOLUME PERCENT HYDROGEN LOW
1	180- 200	20.3	17.0	0.00	0.00
2	210- 270	19.0	16.4	-0.01	-0.01
3	270- 330	19.7	17.7	-0.03	0.00
4	330- 390	20.8	19.2	-0.03	0.00
5	390- 450	20.8	19.8	-0.02	0.01
6	450- 510	20.8	19.9	-0.02	0.00
7	510- 570	20.8	20.0	-0.02	0.00
8	570- 630	20.8	20.0	-0.02	0.00
9	630- 690	20.8	20.1	-0.01	0.01
10	690- 750	20.6	20.2	0.03	-0.04
11	750- 870	20.6	20.3	0.01	-0.04
12	870- 990	20.5	20.4	0.02	-0.04
13	990-1110	20.6	20.4	0.01	-0.04
14	1110-1230	20.5	20.4	0.00	-0.03
15	1230-1350	20.6	20.4	0.00	-0.03
16	1350-1410	20.6	20.1	0.02	-0.02
17	1410-1470	20.5	19.8	0.02	0.01
18	1470-1520	20.6	20.1	0.03	0.00
19	1520-1580	20.7	20.5	0.04	0.01
20	1580-1640	20.8	20.6	0.06	0.03
21	1640-1700	20.8	20.7	0.06	0.02
22	1700-1760	20.8	20.8	0.05	0.00
23	1760-1820	20.8	20.9	0.02	-0.02
24	1820-1880	20.8	21.0	0.01	-0.03
25	1880-1940	20.8	21.1	0.02	-0.04
26	1940-2000	20.9	21.1	0.00	-0.04
27	2000-2060	21.1	21.0	0.03	-0.04

(a) Sampled from +6.1 meters elevation.
(b) Sampled from -6.7 meters elevation.

APPENDIX G

SCRUBBER LIQUID VOLUMES AND AEROSOL CONTENT

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TABLE G1

SGS POOL SODIUM INVENTORY - TEST AC7

Oper. Period No.	Conditions At End Of Operating Period				Incremental Gain During Op. Period (kg Na)
	Time (min)	Volume (liters)	C_L (g Na/ℓ)	Na In Pool (kg Na)	
1	200	2470	1.03	2.544	2.54
2	270	2440	2.18	5.319	2.77
3	330	2400	4.43	10.632	5.31
4	390	2400	8.55	20.520	9.89
5	450	2350	13.43	31.560	11.04
6	510	2410	16.9	40.729	9.17
7	570	2380	20.3	48.314	7.59
8	630	2330	25.1	58.483	10.17
9	690	2160	30.3	65.448	10.22[b]
10	750	2550	28.8	73.440	7.99
11	870	2400	33.7	80.880	12.62[c]
12	990	2400	43.5	104.400	23.52
13	1110	2350	52.3	122.905	18.50
14	1230	2330	60.8	141.664	18.76
15	1350	2380	65.5	155.890	14.23
16	1470	2360	70.5	166.380	10.49
17	1590	2360	77.6	183.136	16.76
18	1710	2380	83.0	197.540	14.40
19	1830	2430	85.4	207.522	9.98
20	1930[a]	2370	95.0	225.150	17.63
21	2050	2560	90.5	231.680	6.53
22	2220	2550	91.0	232.050	0.37
Total					240.490[d]

(a) End of Na spray at 1930 minutes.
(b) Includes 3.26 kg Na drained from pool at t = 635 minutes.
(c) Includes 5.18 kg Na drained from pool at t = 751 minutes.
(d) Includes 8.44 kg Na drained from pool.

TABLE G2

SGS POOL SODIUM INVENTORY - TEST AC8

Oper. Period No.	Conditions At End Of Operating Period				Incremental Gain During Op. Period (kg Na)
	Time (min)	Volume (liters)	C_L (g Na/ℓ)	Na In Pool (kg Na)	
1	200	2500	0.41	1.025	1.03
2	270	2490	1.35	3.361	2.34
3	330	2420	2.25	5.445	2.08
4	390	2350	4.7	11.045	5.60
5	450	2330	6.65	15.495	4.45
6	510	2350	11.1	26.085	10.59
7	570	2270	15.6	35.412	10.11[b]
8	630	2270	21.7	49.259	13.85
9	690	2580	23.6	60.888	11.63
10	750	2580	28.5	73.530	12.64
11	810	2360	34.0	80.240	12.13[c]
12	930	2420	43.5	105.270	25.03
13	1050	2400	53.0	127.200	21.93
14	1170	2410	61.0	147.010	19.81
15	1290	2400	71.5	171.600	24.58
16	1410	2420	76.0	183.92	12.32
17	1530	2430	84.0	204.12	20.20
18	1650	2400	92.5	222.00	17.88
19	1770	2460	92.5	227.55	5.55
20	1890[a]	2410	95.5	230.15	2.60
21	2010	2450	96.0	235.20	5.05
22	2220	2480	98.0	243.04	7.84
Total					249.24[d]

(a) End of Na spray at 1890 minutes.
(b) Includes 0.78 kg Na drained from pool at t = 510 minutes.
(c) Includes 5.42 kg Na drained from pool at t = 751 minutes.
(d) Includes 6.20 kg Na drained from pool.

TABLE G3

SGS POOL SODIUM INVENTORY - TEST AC9

Oper. Period No.	Conditions At End Of Operating Period				Incremental Gain During Op. Period (kg Na)
	Time (min)	Volume (liters)	C_L (g Na/ℓ)	Na In Pool (kg Na)	
1	64	2420	0.47	1.137	1.14
2	120	2530	1.68	4.250	3.11
3	160	2530	4.00	10.120	5.87
4	220	2480	8.30	20.584	10.46
5	280	2450	12.6	30.870	10.29
6	340	2390	17.2	41.108	10.24
7	400	2390	21.1	50.429	9.32
8	460	2400	26.8	64.320	13.90
9	520	2400	28.5	68.400	4.08
10	580	2380	30.0	71.400	3.00
11	640	2360	30.9	72.924	1.52
12	700	2340	31.4	73.476	0.55
13	780[a]	2330	32.7	76.191	2.71
14	840	2510	30.5	76.555	0.36
15	900	2510	30.6	76.806	0.25
16	960	2480	30.9	76.632	(-)0.17
17	1020	2450	31.2	76.440	(-)0.19
18	1140	2400	32.7	78.480	2.04
19	1250	2390	33.0	78.870	0.39
Total					78.87

(a) End of Na spray at 780 minutes.

TABLE G4

SGS POOL SODIUM INVENTORY - TEST AC10

Oper. Period No.	Conditions At End Of Operating Period				Incremental Gain During Op. Period (kg Na)
	Time (min)	Volume (liters)	C_L (g Na/ℓ)	Na In Pool (kg Na)	
1	195	2330	0.99	2.307	2.31
2	270	2500	2.71	6.775	4.47
3	330	2450	5.76	14.112	7.34
4	390	2410	11.6	27.956	13.84
5	450	2360	17.6	41.536	13.58
6	510	2310	22.7	52.437	13.33[b]
7	570	2300	28.5	65.550	13.11
8	630	2220	36.0	79.920	14.37
9	690	2580	36.0	92.880	12.96
10	750	2550	42.0	107.100	14.22
11	870	2290	55.0	125.950	23.57[c]
12	990	2380	62.0	147.560	21.61
13	1110	2400	71.5	171.600	24.03
14	1230	2430	81.0	196.830	25.22
15	1350	2400	90.0	216.000	19.17
16	1410	2500	84.5	211.250	(-) 4.75
17	1470	2480	86.5	214.520	3.27
18	1520[a]	2440	89.5	218.38	3.86
19	1580	2430	90.8	220.644	2.26
20	1640	2440	92.5	226.188	5.54
21	1700	2425	93.5	226.738	0.550
22	1760	2365	(d)	- - -	- - -
23	1820	2330	101.5	236.495	9.76
24	1880	2400	(d)	- - -	- - -
25	1940	2370	102.0	241.740	5.25
26	2000	2360	(d)	- - -	- - -
27	2060	2350	103.0	242.05	0.31
Total					249.18[e]

(a) End of Na spray period.
(b) Includes 2.43 kg Na drained from pool at t = 504 minutes.
(c) Includes 4.70 kg Na drained from pool at t = 750 minutes.
(d) Not analyzed.
(e) Includes 7.13 kg Na drained from pool.

TABLE G5

DEMISTER DRAIN VOLUME AND SODIUM CONTENT - TEST AC7

Operating Period No.	Conditions At End Of Operating Period				Cumulative Volume Collected (ℓ)
	Time (min)	Volume Collected (ℓ)	C_L (g Na/ℓ)	Na Mass Collected (g Na)	
1	200	0	(a)	0	0
2	270	0	(a)	0	0
3	330	0.018	0.02	0	0.02
4	390	0.005	0.02	0	0.02
5	450	0.005	0.02	0	0.03
6	510	0.395	0.02	0.01	0.42
7	570	0.158	0.02	0.01	0.58
8	630	0.513	0.02	0.01	1.09
9	690	0.018	0.03	0	1.11
10	750	0.281	0.02	0.01	1.39
11	870	1.788	0.05	0.08	3.18
12	990	2.856	1.92	5.49	6.04
13	1110	3.550	5.28	18.75	9.59
14	1230	3.352	8.65	28.99	12.94
15	1350	2.859	10.57	30.21	15.80
16	1470	3.000	11.40	34.20	18.80
17	1590	2.408	12.39	29.83	21.21
18	1710	1.984	14.17	28.12	23.19
19	1830	1.859	17.77	33.04	25.05
20	1930(b)	1.228	22.21	27.28	26.28
21	2050	0.217	24.4	5.30	26.49
22	2220	0.004	30.1	0.13	26.50
Total		26.50		241.46	

(a) No analysis due to zero sample flow.
(b) End of Na spray at 1930 minutes.

TABLE G6

DEMISTER DRAIN VOLUME AND SODIUM CONTENT - TEST AC8

Operating Period No.	Conditions At End Of Operating Period				Cumulative Volume Collected (ℓ)
	Time (min)	Volume Collected (ℓ)	C_L (g Na/ℓ)	Na Mass Collected (g Na)	
1	200	2.56	0.16	0.40	2.56
2	270	0.41	0.25	0.10	2.97
3	330	4.78	0.12	0.57	7.75
4	390	6.88	0.091	0.63	14.63
5	450	0.050	0.10	0.01	14.68
6	510	0.032	0.10	0.01	14.72
7	570	0.023	0.10	0.00	14.79
8	630	1.22	0.12	0.15	15.96
9	690	3.18	0.43	1.38	19.14
10	750	4.05	1.63	6.60	23.19
11	810	3.68	4.40	16.19	26.87
12	930	7.165	8.35	59.83	34.03
13	1050	4.295	11.50	49.40	38.33
14	1170	7.645	11.91	91,09	45.97
15	1290	6.50	14.27	92.78	52.47
16	1410	4.52	15.54	70.25	56.99
17	1530	3.77	17.40	65.60	60.76
18	1650	2.63	20.82	54.75	63.39
19	1770	0.823	24.4	20.05	64.22
20	1890[a]	0.217	26.0	5.65	64.43
21	2010	0	- -	0	64.43
22	2220	0.760	31.8	24.17	65.19
Total		65.19		559.61	

(a) End of Na spray at 1890 minutes.

TABLE G7

DEMISTER DRAIN VOLUME AND SODIUM CONTENT - TEST AC9

Operating Period No.	Conditions At End Of Operating Period				Cumulative Volume Collected (ℓ)
	Time (min)	Volume Collected (ℓ)	C_L (g Na/ℓ)	Na Mass Collected (g Na)	
1	64	0.13	39.6	4.99	0.13
2	120	0	(a)	0	0.13
3	160	0	(a)	0	0.13
4	220	1.53	51.0	77.83	1.66
5	280	2.91	28.0	81.42	4.57
6	340	3.09	22.0	67.91	7.66
7	400	3.11	21.7	67.70	10.77
8	460	6.33	22.0	139.26	17.10
9	520	1.83	23.0	42.07	18.93
10	580	1.10	22.0	24.16	20.03
11	640	0.36	14.0	5.04	20.39
12	700	0	(a)	0	20.39
13	780(b)	0.44	7.9	3.44	20.83
14	840	0.03	8.8	0.24	20.86
15	900	0.02	8.7	0.16	20.88
16	960	0	(a)	0	20.88
17	1020	0.02	10.6	0.19	20.90
18	1140	1.84	8.6	15.85	22.74
19	1250	0.23	18.9	4.27	22.97
20	2984	1.44	26.5	38.08	24.41
Total		24.41		572.62	

(a) No analysis due to zero sample flow.
(b) End of Na spray at 780 minutes.

TABLE G8

DEMISTER DRAIN VOLUME AND SODIUM CONTENT - TEST AC10

Operating Period No.	Conditions At End Of Operating Period: Time (min)	Volume Collected (ℓ)	C_L (g Na/ℓ)	Na Mass Collected (g Na)	Cumulative Volume Collected (ℓ)
1	195	0	(a)	0	0
2	270	0	(a)	0	0
3	330	0	(a)	0	0
4	390	0	(a)	0	0
5	450	0	(a)	0	0
6	510	0.054	2.2	0.12	0.05
7	570	0.239	2.45	0.59	0.29
8	630	1.364	4.00	5.46	1.66
9	690	2.108	9.9	20.87	3.77
10	750	2.612	14.7	38.40	6.38
11	870	4.237	16.9	71.76	10.61
12	990	6.351	20.45	129.90	16.97
13	1110	5.480	23.5	128.78	22.44
14	1230	4.933	26.0	128.29	27.38
15	1350	4.673	28.75	134.43	32.05
16	1410	0.476	26.0	12.38	32.53
17	1470	0.01	27.5	0.25	32.54
18	1520(b)	2.152	24.0	51.65	34.69
19	1580	(c)	(c)	(c)	- -
20	1640	0.499	16.0	7.98	35.19
21	1700	1.728	2.44	4.22	36.92
22	1760	(c)	(c)	(c)	- -
23	1820	2.741	0.44	1.21	39.66
24	1880	(c)	(c)	(c)	- -
25	1940	5.04	18.8	94.75	44.70
26	2000	(c)	(c)	(c)	- -
27	2060	5.768	2.5	14.42	50.46
Total		50.465		845.46	

(a) No analysis due to zero sample flow.
(b) End of Na spray at 1520 minutes.
(c) No analysis. Sample combined with following period.

TABLE G9

SODIUM AND NaI RECOVERED BY POST-TEST DEMISTER WASHES

Wash No.	Mass of Na Recovered (g Na)				NaI Recovered (g NaI)
	AC7	AC8	AC9	AC10	AC10
1	39	394	336	175	3.83
2	232	259	43	264	7.15
3	196	256	21	40	1.14
4	183	98	64	95	3.17
5	47		35	74	2.65
6	26		9	55	2.06
7			4	30	1.17
8				19	0.72
9				10	0.56
10				9	0.46
Total	723	1007	512	771	22.91

TABLE G10

SODIUM AND NaI RECOVERED BY POST-TEST
WASH OF BACKUP HEPA FILTERS

Measurement	Sodium AC7	Sodium AC8	Sodium AC9	Sodium AC10	NaI AC10
HEPA Filter A					
Recovered During Leach, g	16.59	27.76	6.45	75.1	0.3044
Blank, g	2.67	2.67	2.67	67.3	0.0094
Net mass, g	13.82	25.09	3.78	7.8	0.2950
HEPA Filter B					
Recovered During Leach, g	18.55	19.00	4.60	73.8	0.3134
Blank, g	2.67	2.67	2.67	65.0	0.0094
Net Mass, g	15.88	16.33	1.93	8.8	0.3040
Total Net Mass From Both Filters, g	29.70	41.42	5.71	16.6	0.599

TABLE G11

NaI INVENTORY IN SGS POOL - TEST AC10

Operating Period No.	Conditions At End Of Operating Period				Incremental Gain During Op. Period (g NaI)
	Time (min)	Pool Volume (liters)	C_L (g NaI/ℓ)	NaI In Pool (g NaI)	
1	195	2330	5.7(-4)[b]	1.32	1.32
2	270	2500	7.5(-4)	1.87	0.55
3	330	2450	5.8(-4)	1.42	-0.45
4	390	2410	2.36(-3)	5.69	4.27
5	450	2360	3.61(-3)	8.52	2.83
6	510	2310	4.42(-3)	10.21	2.47[c]
7	570	2300	5.19(-3)	11.94	1.73
8	630	2220	5.90(-3)	13.10	1.16
9	690	2580	6.14(-3)	15.84	2.74
10	750	2550	6.76(-3)	17.24	2.01[d]
11	870	2290	7.59(-3)	17.38	0.14
12	990	2380	8.03(-3)	19.11	1.73
13	1110	2400	8.39(-3)	20.14	1.03
14	1230	2430	8.66(-3)	21.04	0.90
15	1350	2400	8.79(-3)	21.10	0.06
16	1410	2500	9.14(-3)	22.85	1.75
17	1470	2480	9.56(-3)	23.71	0.86
18	1520[a]	2440	9.84(-3)	24.01	0.30
19	1580	2430	1.00(-2)	24.30	0.29
20	1640	2440	1.04(-2)	25.38	1.08
21	1700	2425	1.07(-2)	25.95	0.57
22	1760	2365	1.10(-2)	26.02	0.07
23	1820	2330	1.12(-2)	26.10	0.08
24	1880	2400	1.11(-2)	26.64	0.54
25	1940	2370	1.12(-2)	26.54	-0.10
26	2000	2360	1.14(-2)	26.90	0.36
27	2060	2350	1.15(-2)	27.03	0.13
Total					28.42[e]

(a) End of Na spray period.
(b) Numbers in parenthesis are exponents of ten.
(c) Includes 0.78 g NaI drained from pool at t = 509 minutes.
(d) Includes 0.61 g NaI drained from pool at t = 750 minutes.
(e) Includes 1.39 g NaI drained from pool.

TABLE G12

NaI CONTENT IN DEMISTER LIQUID EFFLUENT - TEST AC10

Operating Period No.	Conditions At End of Operating Period			NaI Mass Collected (g NaI)
	Time (min)	Volume Collected (ℓ)	C_L (g NaI/ℓ)	
1	195	0		
2	270	0		
3	330	0		
4	390	0		
5	450	0		
6	510	0.054	0.052	0.0028
7	570	0.239	0.068	0.0163
8	630	1.364	0.211	0.2878
9	690	2.108	0.705	1.486
10	750	2.612	0.959	2.505
11	870	4.237	1.032	4.373
12	990	6.351	0.966	6.135
13	1110	5.480	0.952	5.217
14	1230	4.933	0.944	4.657
15	1350	4.673	0.966	4.514
16	1410	0.476	0.912	0.434
17	1470	0.01	0.915	0.0092
18	1520[a]	2.152	0.856	1.811
19	1580	(b)	(b)	
20	1640	0.494	0.420	0.210
21	1700	1.728	0.072	0.124
22	1760	(b)	(b)	
23	1820	2.741	0.013	0.0356
24	1880	(b)	(b)	
25	1940	5.04	0.441	2.223
26	2000	(b)	(b)	
27	2060	5.768	0.066	0.381
Total		50.465		34.42

(a) End of Na spray.
(b) No sample.