

**DEVELOPMENT OF A DRAFT METHOD OF TEST FOR DETERMINING
GREASE REMOVAL EFFICIENCIES**

**Final Report
ASHRAE 1151-RP**

**Phase I
Design and Demonstration of a Commercial Cooking Effluent Generator**

for:

**AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-
CONDITIONING ENGINEERS, INC.**

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EXECUTIVE SUMMARY

Ventilation systems are integral components of commercial cooking operations. They are primarily used to exhaust heat, smoke, and odors from commercial kitchens in order to provide a comfortable environment for workers and patrons in commercial food service establishments. Most ventilation systems are equipped with grease filters that are used to prevent fires from occurring in ventilation ducts. Recently, manufacturers of grease filters have designed units to remove particles and condensed vapors prior to discharging of the effluent.

There is considerable discrepancy in the industry as to the effectiveness of these devices in removing grease from cooking effluents. Test results show a wide range of removal efficiencies, depending mainly on the method of test (MOT) used for measurement.

To provide an accurate and repeatable assessment of grease removal efficiencies, a standardized test method must be developed and demonstrated. Once approved, the method will establish a nationally recognized measurement tool for evaluating competing grease removal technologies.

As an initial step in this process, the University of California, Riverside, Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) with assistance from the University of Minnesota (U of M), developed a grease generator technology that can simulate actual cooking emissions, including particulate matter and condensable grease vapors. The combined team evaluated possible approaches, designed and developed a prototype, and evaluated the prototype with regard to effectiveness in simulating cooking effluent. This successful first step is expected to lead to a second phase of work, where the grease generator will be used in inter-laboratory comparisons and in evaluation of several different types of grease removal systems.

This work was conducted under contract with the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. The development and demonstration of the grease generator was conducted at CE-CERT's laboratory facilities in Riverside, Ca.

1.0 INTRODUCTION

Historically, restaurateurs have conducted business subject to numerous building and ventilation codes designed to ensure the safe and unobtrusive cooking operations. Recently, commercial cooking operations were identified as significant contributors to ambient air pollution in many non-attainment areas in the United States. Over the past few years, manufacturers of ventilation systems have been developing hood systems designed to capture and remove grease emitted from a variety of cooking processes. To properly evaluate these systems, development of a standard test protocol is necessary. The first step of the process is the development of a grease generator that can simulate the effluent of typical commercial cooking processes.

Several air quality agencies in the United States, including the South Coast Air Quality Management District (SCAQMD), have identified the need to reduce PM_{10} and/or $PM_{2.5}$ and VOC emissions from restaurant operations. PM_{10} refers to particulate matter with an aerodynamic diameter of 10 microns or less. $PM_{2.5}$ refers to particulate matter with an aerodynamic diameter of 2.5 microns or less. VOC refers to volatile organic compounds, precursors to the oxidant that leads to ambient ozone and secondary aerosols. As part of a strategy to achieve National and State ambient air quality standards for these pollutants, these agencies and the restaurant industry are interested in developing and demonstrating cost-effective grease emissions reduction strategies for cooking operations. To this end, SCAQMD has conducted a series of research projects to specify standardized emissions measurement methods and to test alternative control technologies.

Concurrent with air quality agency research, manufacturers of commercial cooking ventilation systems have designed "in-the-hood" grease removal devices as a primary strategy for reducing emissions from cooking processes upstream of exhaust ductwork. Some manufacturers claim grease removal efficiencies of 95% or better. Recent research, however,

has determined that actual removal efficiencies of 30% - 60% are to be expected from current systems. It is apparent that a standard method of test (MOT) is necessary to resolve differences between results.

A previous research program conducted at American Gas Association Research (AGAR) and sponsored by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) investigated the fundamental elements of grease removal determinations.¹ The primary purpose of the program (ASHRAE 851-RP) was to design a testing protocol that could repeatably determine the collection efficiency of in-line grease removal devices. The program developed several key recommendations that are consistent with other research in cooking emissions: 1) proportional sampling of effluent rather than total capture, 2) use of a reference hood to test with and without grease removal devices, and 3) to quantify the particle size distribution of effluents. While the basic test protocol developed in this program was technically sound, results showed a high degree of variability. Previous research at CE-CERT² suggests that some of the variability in results may have resulted from the type of grease generator used in the AGAR program (a chain-driven charbroiler cooking hamburger meat). Furthermore, emissions from the chain-driven charbroiler processes are substantially different in mass, particle to vapor ratio, and composition than other types of cooking processes. Chain-driven charbroiling processes also represent only a small segment of commercial operations. As a result of these factors, CE-CERT concluded that the chain-driven charbroiler is not appropriate to use as a standard grease generator.

It was apparent that a standard method of test (MOT) for determining grease removal efficiencies must begin with a grease generator that is highly repeatable and representative of a wide variety of cooking effluents (e.g. underfired charbroilers, griddles, and deep fat fryers). Once developed and verified, the remaining elements of the MOT can be specified,

including ventilation flow parameters, effluent temperatures, sampling techniques, and analytical procedures.

The Phase I design and development of a grease generator relied on the combined efforts of CE-CERT and the University of Minnesota, both of which have been involved with numerous research projects related to cooking emissions characterization and protocol development.

Two previous studies conducted at CE-CERT under contract with the SCAQMD have included development of standardized procedures, demonstration of the validity of those procedures for evaluating emissions from commercial cooking operations, and the development of emission factors from various commercial cooking operations.

Under contract with the SCAQMD, CE-CERT adapted an SCAQMD Interim Field Protocol for use in a test chamber with controlled process and environmental conditions to reduce variables associated with individual restaurant processes. The program involved the formation of a technical advisory committee, development of a test plan, preparation of the test chamber facility, operational checkout, and emissions testing using one common restaurant cooking process.

The main objective of CE-CERT's effort was the initial development of standardized procedures as well as the demonstration of the validity of those procedures for evaluating emissions from commercial cooking operations. A second objective was the investigation of alternative (surrogate) methods for determination of emission factors for several subset pollutants, including particulate matter with an aerodynamic diameter less than 10 microns (PM_{10}), speciated organic gases, VOC from a modified reference method, and total gaseous hydrocarbons using a continuous flame ionization detector (FID). The investigation focused

on refining traditional methods to reduce variability in sample results. Finally, CE-CERT investigated discrepancies found in the VOC measurement method through performance of several diagnostic test runs.

Under a subsequent contract with the SCAQMD, CE-CERT refined methods for sampling and analysis of volatile organic compound (VOC) and particulate matter (PM) emissions from commercial cooking operations. The methods are adaptations of the reference methods detailed in the Interim Protocol. CE-CERT verified that the surrogate VOC emissions measurement method was more consistent and precise than the accepted reference method.

CE-CERT used the refined procedures to determine emission factors for eleven uncontrolled cooking processes and three processes with emission control technology.² CE-CERT demonstrated the effectiveness of catalytic incineration units in reducing PM and VOC emissions from chain-driven charbroilers. Emissions reductions were successfully demonstrated for two catalytic control technologies with the automated (commercial, chain-driver) charbroiler process, and for the double-sided flat griddle process. At an estimated cost of \$5,000 for a seven-year life, the technology has been demonstrated as cost-effective according to SCAQMD guidelines. As of November 14, 1999, chain-driven charbroilers in the Los Angeles area processing more than 125 pounds of meat per day are required to have approved catalysts installed.

The July 1997 report also recognized the difficulty in finding cost-effective emission reduction technologies for the underfired charbroiler and flat griddle cooking processes. Since October 1997, other options for the underfired charbroiler process have been investigated. Based on SCAQMD estimates, open underfired charbroilers are responsible for the largest portion of the total inventory of PM and VOC emissions from commercial cooking operations.

The first task of CE-CERT's most recent study³ was to review commercially available, prototype, and experimental technologies to reduce PM and VOC emissions from commercial charbroiling operations. CE-CERT examined and evaluated the following control strategies:

- specialized hood grease extraction;
- ceramic filtration/incineration;
- dedicated hood/catalytic incineration;
- filtration/absorption;
- electrostatic precipitation;
- scrubbers; and
- process design.

The evaluation identified three technologies to be tested by CE-CERT in the final phase of the study. The three technologies chosen represented a cross-section of control options, including a rooftop ventilation system design, a dedicated hood design, and a process design, respectively.

The University of Minnesota recently completed an ASHRAE-sponsored research project (745-RP) to characterize the emissions from ten different commercial cooking processes under a canopy hood. Appliances included griddles, fryers, broilers, ovens and range tops. An electric and gas version of each type was tested. Typical food products were used for each appliance including hamburger, potatoes, chicken, pizza and a spaghetti meal. The results included particle size and concentration data, grease vapor concentration, and plume velocity, temperature and volumetric flow rate information.

The particle measurements in the plume were obtained with a modified personal cascade impactor that was designed in their laboratory. The impactor was positioned in the plume and allowed to reach an equilibrium temperature before sampling began. This procedure enabled the correct particle size distribution to be obtained in the plume with a minimum of particle losses in sampling lines and changes caused by evaporation or condensation. Particle sampling in the exhaust duct was accomplished using a micro-orifice uniform deposit impactor (MOUDI) that was also designed at the University of Minnesota laboratory. This required a sampling probe that was designed and constructed to ensure isokinetic sampling and a minimum of impaction losses in the probe. An electrical low pressure impactor (ELPI) also was used for some of the measurements with the same sampling probe to obtain real time particle concentration and size distribution data.

The cooking plume information from this previous study was used as a basis in determining the design requirements for the artificial effluent generator designed and built in Phase I of the current project. Some of the same sampling procedures were used for characterizing the generator performance.

This report describes the design and development of a prototype grease generator, and presents the results of validation test runs conducted at CE-CERT.

2.0 TEST CHAMBER AND EQUIPMENT SPECIFICATIONS

2.1 Test Chamber

An enclosed chamber equipped with natural gas, electricity, ventilation and fire suppression utilities was used to conduct the testing program. A schematic of the chamber is shown in Figure 1. The dimensions of the chamber are 25 x 25 x 10 feet. Natural gas is provided inside the chamber through 1 1/4" pipe at 5 psig. 115 V single phase, 230 V single phase, 230 V three phase, and 480 V three phase electrical utilities are available inside the chamber. Exhaust ventilation is provided by a hood that is ducted to a centrifugal-type upblast blower located on the roof of the chamber. Make-up air is supplied by an evaporative cooler and blower through four penetrations and eight diffuser panels in the test chamber ceiling. Access to the sampling locations is provided by a stairway on the west end of the chamber.

Emissions generated during the cooking process were captured by a 4 x 4-foot Captive-Aire stainless steel wall canopy hood. Emissions captured by the hood were ducted horizontally across the roof of the test chamber to the upblast blower. The exhaust blower, equipped with a variable speed drive and controller, was adjusted to ensure velocity and flow rate parameters met Uniform Mechanical Code (UMC) and National Fire Protection Association (NFPA) guidelines regarding exhaust velocities and flow rates. Emissions samples were drawn from the horizontal section of the duct through access ports. The cooking and ventilation equipment configuration is shown in Figure 2.

DESIGN AND DEMONSTRATION OF A COMMERCIAL COOKING EFFLUENT GENERATOR

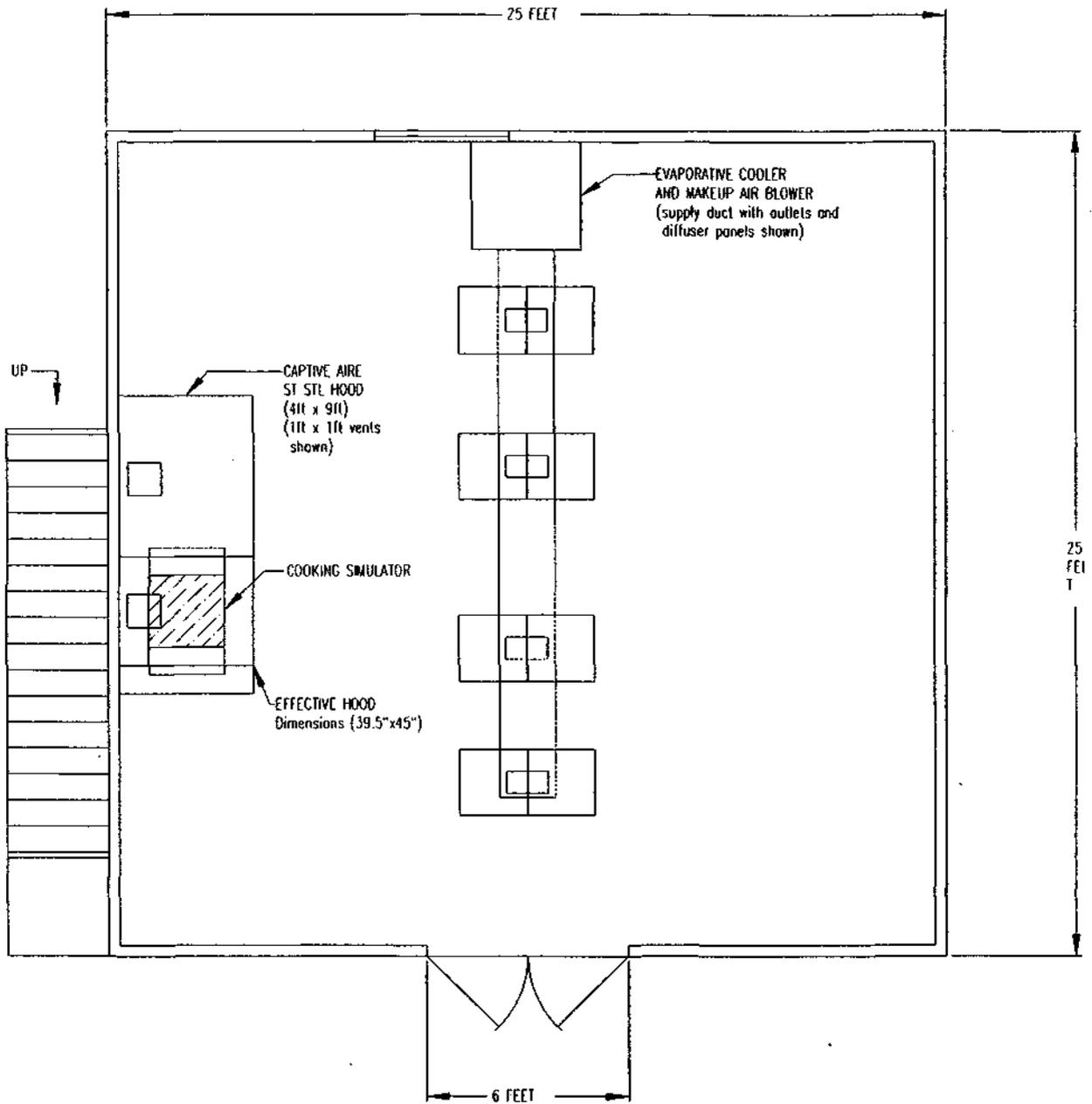


Figure 1
Test Chamber Schematic

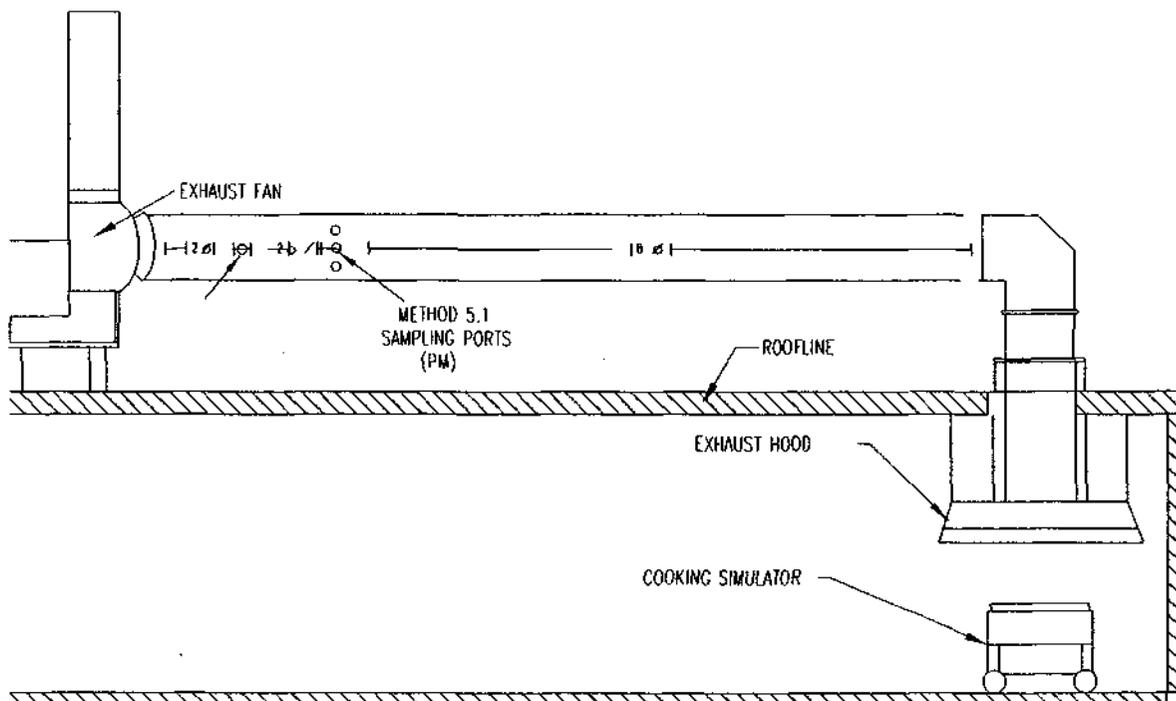


Figure 2
Cooking Equipment and Ventilation Configuration

2.2 Grease Generator Design

The objectives of the grease generator design were threefold: 1) to generate grease emissions representative (in chemical composition, mass quantity, and particle size) of common commercial cooking processes, 2) to introduce the grease emissions into an effluent that is representative of common cooking processes, and 3) to produce a device that could be used to evaluate performance of ventilation hoods (with grease extractors) under representative operating conditions (including flow rates and geometric orientations).

The second and third criteria were addressed by a basic design of a three-foot charbroiler set under a four-foot wall canopy hood. The natural gas combustion in the charbroiler provides representative heat input, as well as combustion products (e.g. carbon dioxide and water).

The fuel input to the charbroiler can be adjusted (at the main as well as with individual burner controls) to simulate a gas-fired griddle or deep fat fryer. The combustion effluent is then exhausted into a four-foot wall canopy hood, which can be fitted with a variety of typical grease extractors placed in a normal orientation with regard to height above the cooking device and angle with respect to effluent flow.

The most difficult aspect of the design was the first criteria – generating grease emissions that are representative of common commercial cooking processes.

The following table summarizes the particle distributions measured in the plume in ASHRAE 745-RP for three common cooking processes; a griddle cooking hamburger, an open underfired charbroiler cooking hamburger, and a deep-fat fryer cooking potatoes.

Table 1
Estimated grease particle mass flow rates versus size
for the effluent plume measurements taken in ASHRAE 745-RP
(normalized to CE-CERT 2/3 loading scenario)

	Griddle	Broiler	Fryer
Total particle mass, mg/min	4000	11000	1400
dp > 10 μm, mg/min	3400	7300	1290
2.5 < dp < 10 μm, mg/min	300	900	30
dp < 2.5 μm, mg/min	300	2800	80
smallest mode (μm)	0.2	0.2 - 0.5	0.5 - 0.8
Geom. Std. Dev.	1.8 - 2	1.8 - 2	1.8 - 2

The design challenges were to generate a representative material in sufficient mass flow rates to meet the criteria above, meet the respective particle size criteria (both mass median diameter and standard deviation), and provide stable output over long time periods. The generator had to be flexible enough to simulate other cooking processes, be easily obtainable, and be supported by the manufacturer if problems in operation develop.

The mass median aerodynamic diameter (MMAD) for the particle mode greater than 10 microns is not precisely known, as inertial sampling techniques are only effective for smaller diameter particles. ASHRAE 745-RP indicates it is above 15 μm (the approximate cut point the 90 degree sampling inlet), and below 100 μm (estimated based on gravitational settling, plume velocity, and the height at which measurements were made). Using an MMAD value at the lower end of this 15 μm – 100 μm range would provide an aerosol that is more difficult to remove by the filter, and would represent a “worse case” scenario when testing the removal efficiency of grease filters.

Our first discussions revolved around some sort of paint sprayer, as these can produce large enough mass flow rates of aerosol to approximate commercial cooking emissions. However, extensive literature searches and discussions with colleagues did not result in much detailed information regarding the performance of these devices. Although relatively inexpensive, they are not very flexible or controllable. The particle size they produce is thought to be in excess of 20 microns, perhaps as much as 200 microns for some units. Although the final particle size could be reduced by aerosolizing a mixture with a solvent that would be smaller in diameter when the solvent has evaporated, it was determined that the lack of control was a problem.

Members of an aerosol list serve group were asked for recommendations for this application. Representatives from NIOSH and TSI recommended the use of the Sono-Tek ultrasonic nebulizing system. The system consists of a broadband ultrasonic generator, a conical-tip atomizing nozzle, and a liquid feed system. NIOSH uses this device to generate liquid aerosols, and has experienced that the droplet distribution has a MMAD at about 30 microns with a geometric standard deviation of about 1.3, with a tail to smaller sizes. Using this device, NIOSH found the size distribution was relatively independent of liquid feed rate and reasonably stable. TSI indicated that this device should be able to cover a wide range in

mean particle diameter and geometric standard deviation by choosing appropriate combinations of nozzle inlet pressure, flow rate, nozzle diameter and frequency. The following table presents the general technical specifications of the ultrasonic nebulizing systems from Sono-Tek.

Table 2
Sono-Tek Ultrasonic Nebulizing System Technical Specifications

Module dimensions:	12"W x 13"D x 10"H
Spray width range:	0.25" - 12" per module
Flow rate range:	1 - 200 ml/min
Spray uniformity:	+/- 15%
Median droplet size range:	18 - 68 μ m
Droplet velocity:	3 - 5 inches/sec (15 - 25 fpm)
Transducer power:	< 15 Watts
Flow rate range (turn down ratio):	5:1
Maximum temperature:	150 °C
Maximum liquid viscosity at full flow rate:	10 cps

Various types of liquid feed pumps or pressurized liquid feeds can be used with the system. The spray particle diameter is inversely proportional to the piezoelectric transducer frequency raised to the 2/3 power. The width of the spray jet and its velocity can be altered by supplying air jets to either focus or spread the spray to the desired configuration.

By comparison, the aerosol generator used in ASHRAE 1033-RP had a liquid feed rate between about 0.5 and 3 ml/min. The Sono-Tek unit has a volumetric flow rate nearly two orders of magnitude larger. The Sono-Tek unit can produce aerosol indefinitely as the liquid is fed to the atomizer head through a liquid pump or pressurized system, not from a syringe as in the system used previously. Both devices use air jets to shape and convey the spray from the nozzle.

The mass median aerodynamic diameter (MMAD) of the particles produced with the aerosol generator used in ASHRAE 1033-RP was about 5.5 microns. Smaller sizes were produced by diluting the nonvolatile liquid (oleic acid) with a solvent (isopropyl alcohol). When the solvent evaporated, the remaining nonvolatile liquid particles could be considerably smaller than the original droplets generated. This allowed the researchers to generate oleic acid particles with a wide range of MMAD.

Unfortunately, the design criteria for the current program were not compatible with the use of a volatile solvent (such as isopropyl alcohol) for several reasons. First, in order to simulate the heat input and combustion gases from cooking processes, an open underfired charbroiler was employed. The presence of an open flame precluded the use of a solvent for safety reasons. Secondly, it is expected in Phase II of the program to design and develop a system for simulating gaseous hydrocarbon emissions common to charbroiling operations. The presence of an organic solvent used in particle generation would contaminate the effluent and artificially bias the gaseous hydrocarbon measurements. It was necessary, then, to specify the nozzle for a single MMAD using pure oleic acid (without a solvent) as the feedstock. Results from Table 1 indicate between 66% and 92% of the total particulate mass from each of the three processes studied fall in the largest mode. Using the DISTFIT model, the University of Minnesota characterized the largest particle mode in the 28 – 40 μm MMAD range from all three cooking processes (see Appendix C). Consequently, a nozzle with a 35 μm MMAD was specified for the Sono-Tek system to simulate the largest particle mode.

After a number of discussions with various researchers, it was decided that particles in the 0.2 to 0.8 micron size range should be generated from the condensation of grease vapor; and in particular, oleic acid vapor. The natural process of homogeneous nucleation produces a large quantity of particles in this small size range. This is the particle generation mechanism that creates these small particles in the actual cooking process. Oleic acid was chosen as it is

a major component of beef fat, and is consistent with the material used in previous University of Minnesota studies. In the design, oleic acid is dripped at a constant rate onto a heated metal plate placed on the grate of the charbroiler. The surface temperature of the plate is adjusted using spacers between the grate and the metal plate. The goal of the design was to reach a plate surface temperature hot enough to vaporize the oleic acid without combusting it.

A pressurized reservoir was chosen as the basis for the feed system. The reservoir can hold up to 10 kg of material, enabling uninterrupted operation for hours at a time. The lid provides an airtight seal with a gasket, and is equipped with fittings for connection to liquid feed lines and a constant-pressure air line. The two liquid feed lines (one for large particle generation and one for submicron particle generation) are each equipped with a flow control valve for individual feed rate adjustment. As oleic acid is viscous at room temperature, both the reservoir and feed lines are heated to approximately 185 °F to allow for smooth even flow of liquid through the lines. A schematic of the complete system is shown in Figure 3.

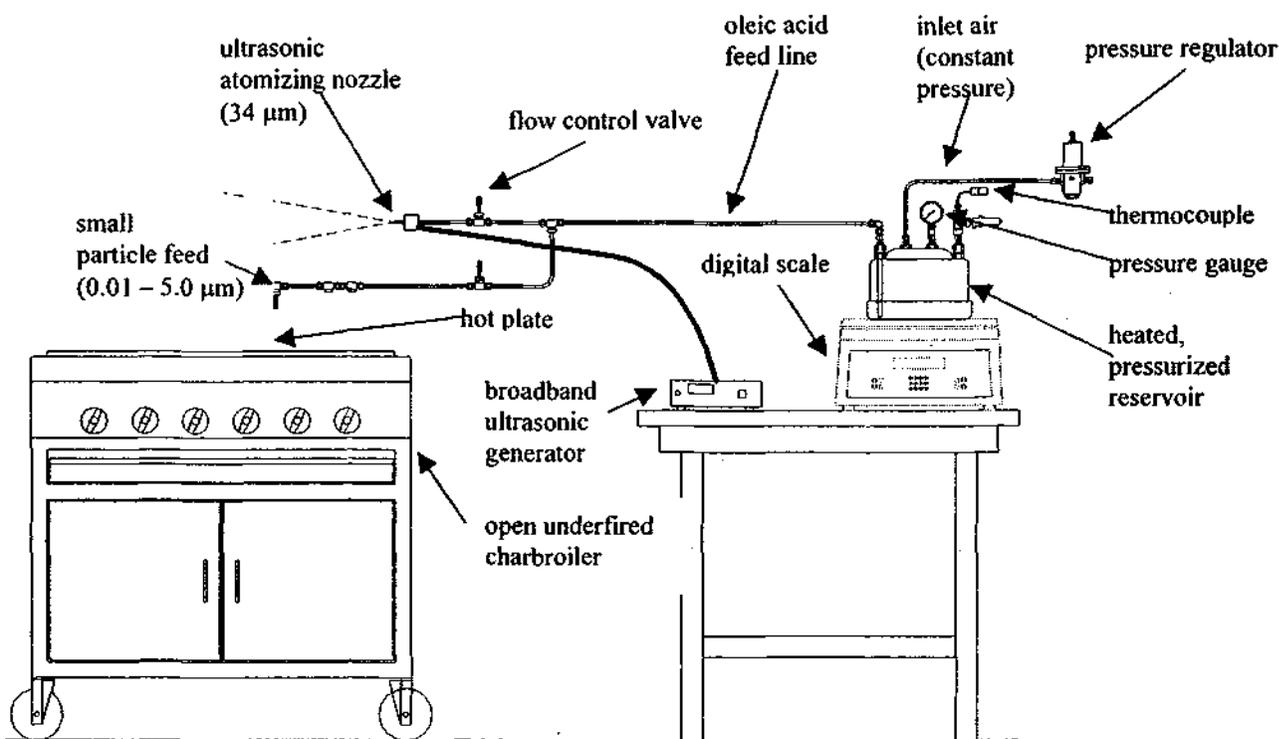


Figure 3
Prototype Grease Generator Schematic

In summary, the specification of the Sono-Tek ultrasonic spray system for the grease generator design was made to satisfy the requirement to generate a relatively high mass flow rate of grease particles with a mass median diameter above $10\ \mu\text{m}$ in size (specifically to obtain an MMAD of $\sim 35\ \mu\text{m}$, characteristic of all cooking processes). The particle production can be continuous for long periods of time, the initial temperature can be up to $150\ ^\circ\text{C}$, and the width of the aerosol spray can be controlled with auxiliary air jets. Particle size and flow rate can be easily controlled to simulate a wide variety of cooking effluent. If desired, more than one spray nozzle could be used to generate particles of different mean sizes. This is an off-the-shelf device that can readily be incorporated into replicates of the initial test setup. The particles less than 1 micron in size should be generated by the natural formation of particles from grease vapor by homogeneous nucleation. This is the same

particle formation mechanism that occurs in actual cooking and will occur naturally with the introduction of hot grease vapor into the test system effluent.

3.0 SAMPLING AND ANALYTICAL PROCEDURES

3.1 Particle Size Distribution

For determination of the particle size distribution by aerodynamic diameter, the exhaust stream (in the ventilation hood) was sampled isokinetically using a micro-orifice uniform deposit cascade impaction (MOUDI) system. An integrated sample for each test was acquired over a minimum of 30 minutes. Each sample was extracted from the thermal plume of the grease generator at a single point located in the middle of the hood, approximately 16" vertically below the bottom of the grease extractors (see Figure 4). The sample was acquired through a stainless steel nozzle and probe, ten-stage cascade impactor, and 0.45 μm quartz fiber afterfilter located downstream of the last impactor substrate (Figure 5). The entire system was contained in an insulated box and heated to the effluent temperature for each test. The mass of material collected on each stage was determined gravimetrically after a conditioning period of at least 24 hours in a temperature and humidity controlled environment (77 °F (25 °C) and 40% relative humidity).

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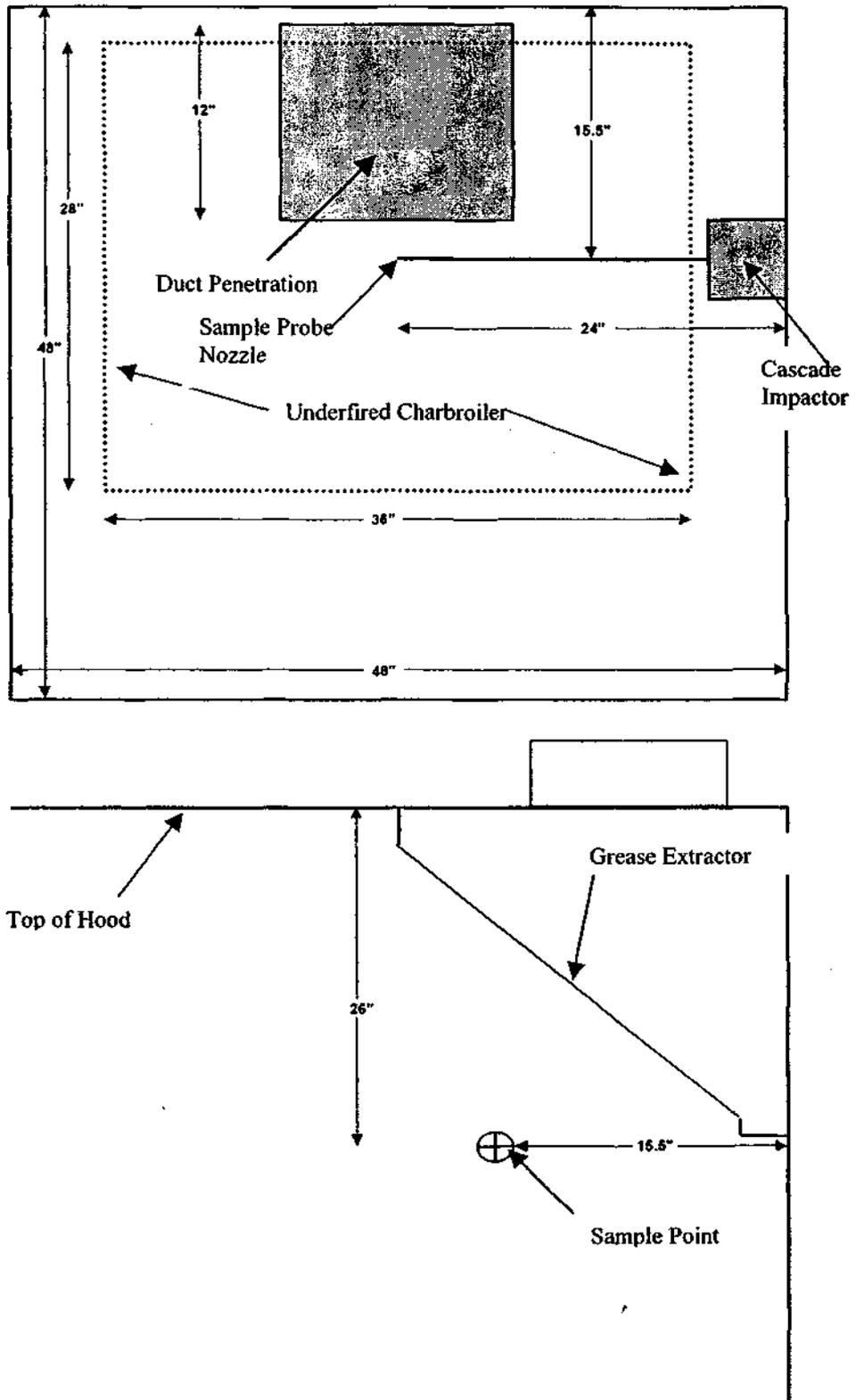


Figure 4
Sample Point Location

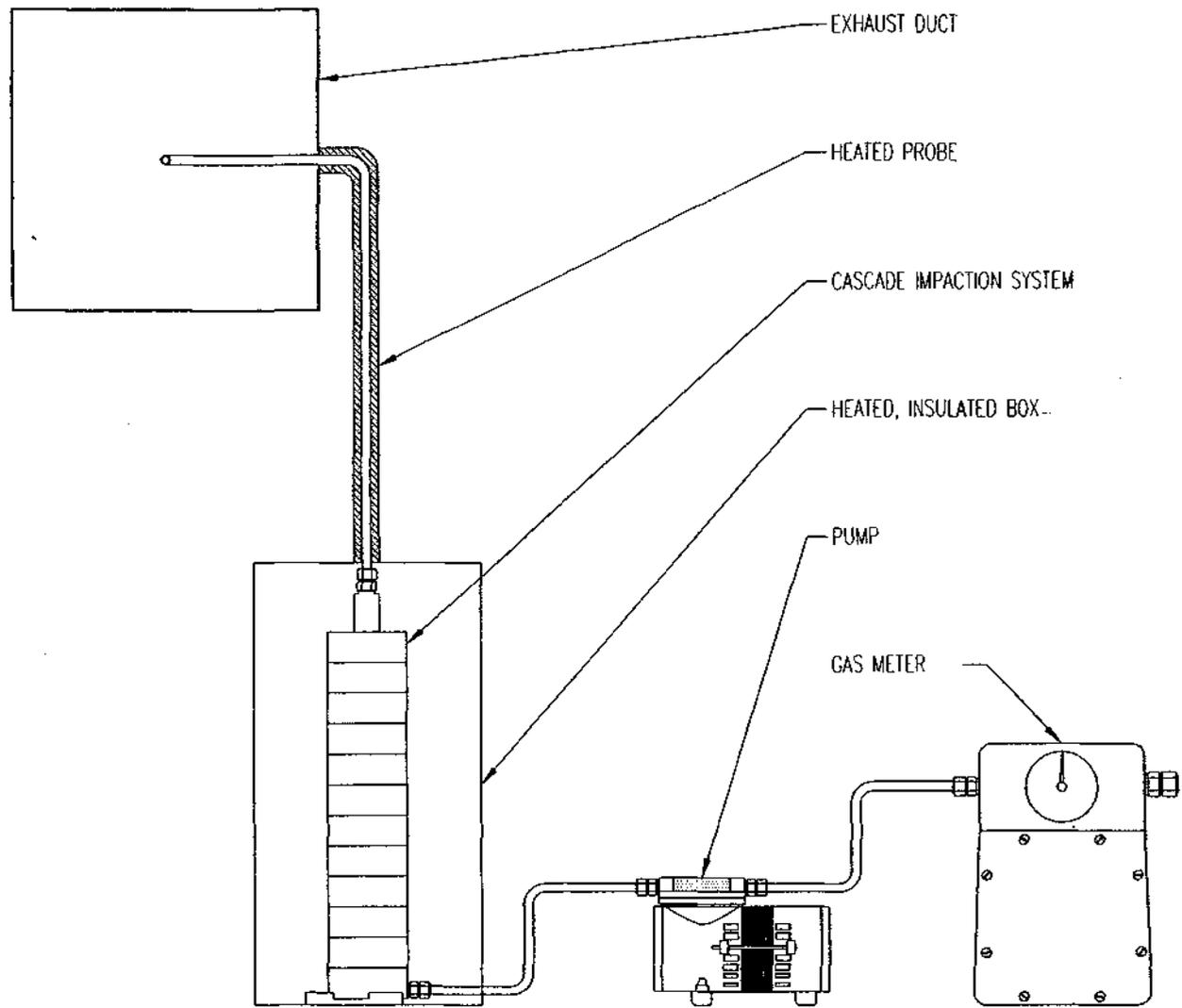


Figure 5
Particle Size Distribution Sampling System

3.2 Particulate Matter Method

For determination of total PM, the exhaust stream was sampled isokinetically following SCAQMD Method 5.1. An integrated sample for each test was acquired over a minimum of 30 minutes. Each sample was extracted from the exhaust duct through a stainless steel nozzle and probe, impingers immersed in an ice bath, and a tared 0.45 micron Gelman quartz fiber filter located downstream of the last impinger. An additional straight tube impinger (empty bubbler) was placed at the front of each sampling train (see Figure 6). The sample train was analyzed according to a modified SCAQMD Method 5.1. After sampling, the filter was removed and placed in a dessicator until completely dry. Following drying, the filter was weighed to determine the fraction of sample acquired on the filter. The probe, nozzle, sampling lines, and impingers were washed with deionized water and methylene chloride, and the washing solutions were combined with the impinger solutions. The combined solution was extracted with methylene chloride. The aqueous fraction was heated to boil off water, and the organic fraction was allowed to evaporate at room temperature. Residues from both fractions were weighed and combined with the sample weight from the filter to determine the total particulate sample weight. Samples not analyzed within a 48-hour period after acquisition were stored at 4 °C until analyses.

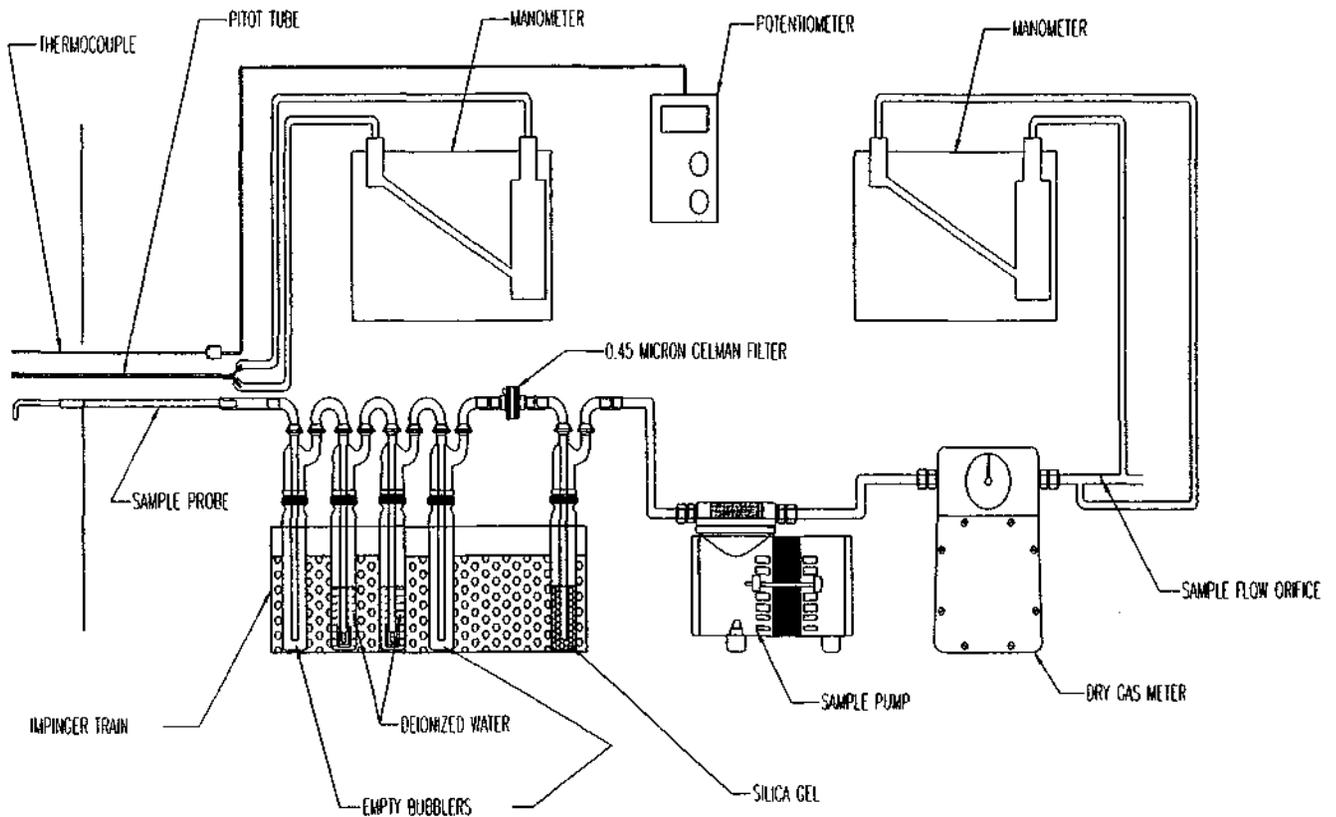


Figure 6
Total Particulate Matter Sampling System

3.3 Fixed Gases, Moisture, and Flow Determination

Carbon monoxide and carbon dioxide concentrations were continuously monitored and recorded using a non-dispersive infrared detector. The sampling, conditioning, and analyses of CO and CO₂ followed SCAQMD Method 100.1. Flow rate in the exhaust duct was determined using differential pressure and temperature measurements according to SCAQMD Methods 1, 2 and 3. Moisture content in the effluent was determined gravimetrically using SCAQMD Method 4.

4.0 PROCESS DESCRIPTION

The device used to simulate heat and combustion products was a 36" Wolf underfired charbroiler, fired with natural gas. The natural gas flow rate was measured with a calibrated dry gas meter. The heating value of the gas was measured with a Cutler-Hammer calorimeter. The firing rate was set to operate within 5% of the manufacturer's specified input rate. In addition, the gas supply pressure was adjusted to within +/- 2.5% of the manufacturer's specified operating pressure. The broiler controls were set such that the broiling area achieved an average temperature of 600 ° F, as measured by a plate thermocouple. The grill surface temperature was measured at the center of each of location where hamburger patties would be placed in a typical cooking operation.

4.1 Process Conditions

The broiler grate was conditioned in accordance with the manufacturer's instructions. The underfired broiler controls were set to achieve maximum input (not exceeding 600 ° F grate temperature), and allowed to warm up for a minimum of one hour.

Analytical-grade oleic acid was added to the reservoir, sealed, and heated to approximately 185 °F. An initial time and weight was recorded prior to the start of testing. Air pressure was applied to the sealed reservoir container at 25 psi.

A 1/2" thick stainless steel plate (6" x 6") was placed on the broiler grate and centered under the drip nozzle for the submicron particle generator feed line. Small stainless steel spacers were placed between the charbroiler grate and stainless steel plate until the surface temperature of the plate (as measured by a surface thermocouple) was between 475 °F and 500 °F. The flow control valve on the submicron particle generator feed line was set to provide a constant flow rate of approximately 2800 mg/min of oleic acid.

The feed line and ultrasonic nozzle for the large particle generator were positioned approximately two feet above the broiler grate, in an orientation to allow the conical spray to spread evenly across the thermal plume (see Figure 3). The flow control valve on the large particle feed line was set to provide a constant flow rate of approximately 11000 mg/min of oleic acid.

Clean grease baffles were installed in the hood prior to testing. The velocity in the duct was set at 1600 fpm (with the charbroiler on). This velocity corresponds to a hood flow rate of 400 cfm for each linear foot of hood length. Testing was conducted for a minimum of 30 minutes.

5.0 RESULTS

5.1 Hamburger/Charbroiler Simulation

Three identical test runs were performed using the process described in Section 4.0. The product loading rate, exhaust gas concentrations, PM mass emissions and size distribution results were calculated from the data collected during each run.

Exhaust duct conditions were first compared between the simulated grease emission runs and runs conducted using an actual charbroiler process. The comparative results are presented in Table 3.

Table 3
Exhaust Duct Comparison of Grease Generator to Actual Charbroiling Process

(values normalized to 1600 dscfm)				
Test	Temp (°F)	CO ₂ (%)	H ₂ O (%)	TPM (lb/hr)
grease generator run #1	117.2	0.16	1.24	0.957
grease generator run #2	116.5	0.16	1.67	0.642
grease generator run #3	120.6	0.16	1.29	0.731
AVG	118	0.16	1.4	0.78
21% fat hamburger/ underfired charbroiler	108	0.14	1.2	0.73

The following figures illustrate the small diameter (< 10 µm) particle size distributions measured with the cascade impactor for the three test runs using the particle generator.

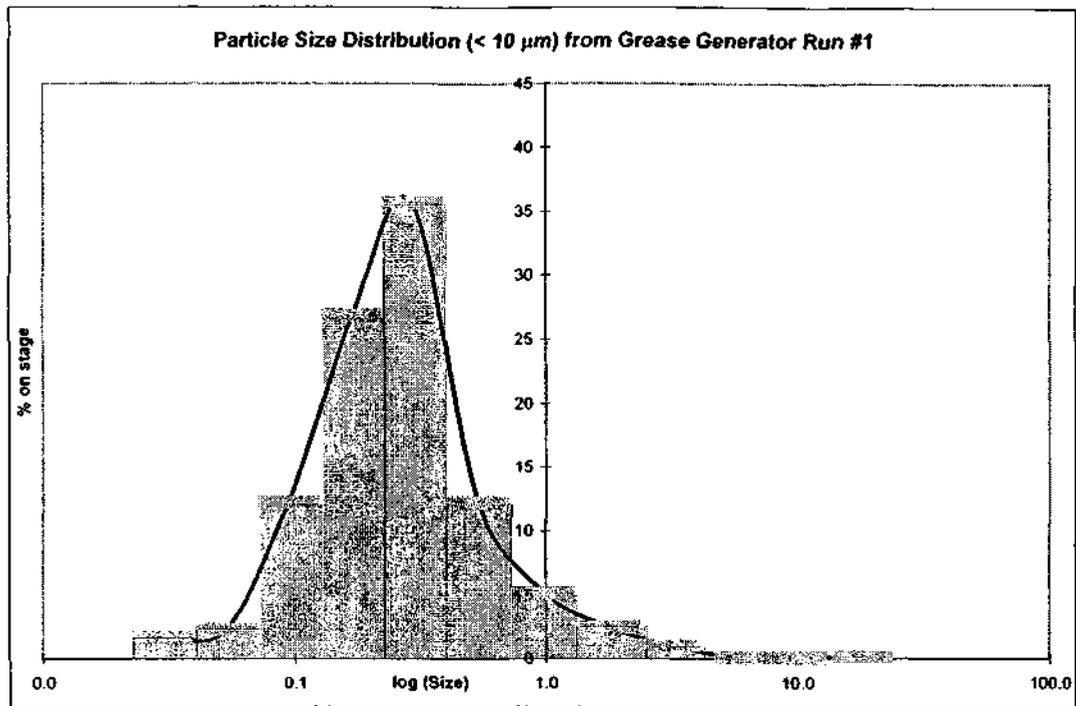


Figure 7 (a) – Small Particle (<10 μm) Size Distribution from Grease Generator Run #1

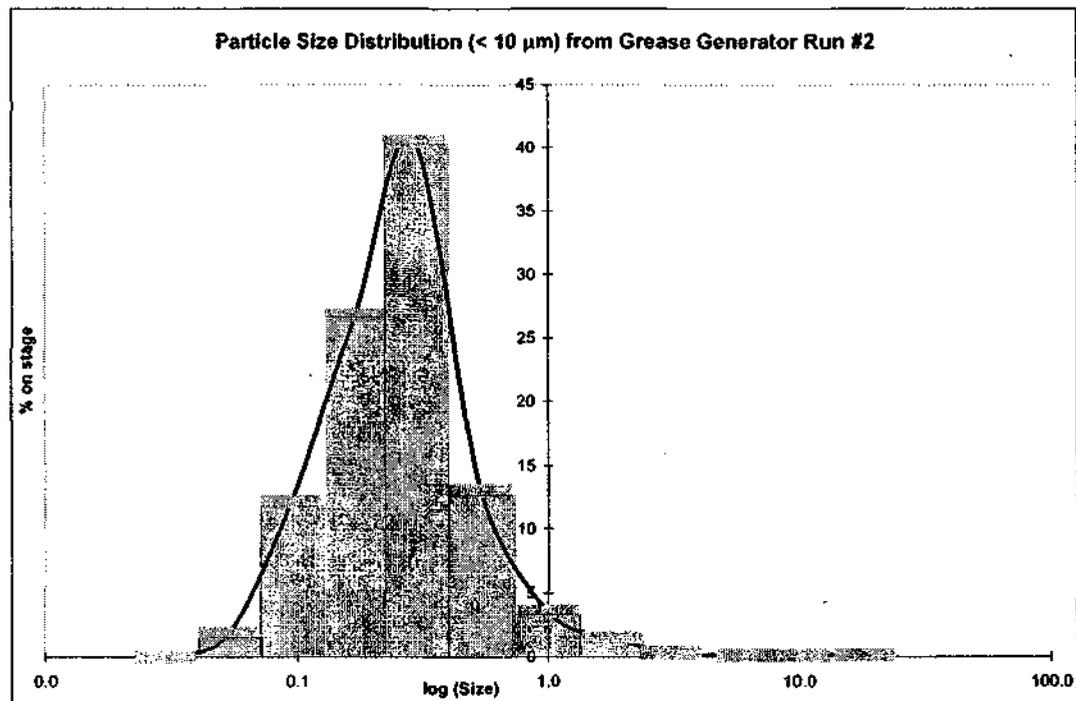


Figure 7 (b) – Small Particle (<10 μm) Size Distribution from Grease Generator Run #2

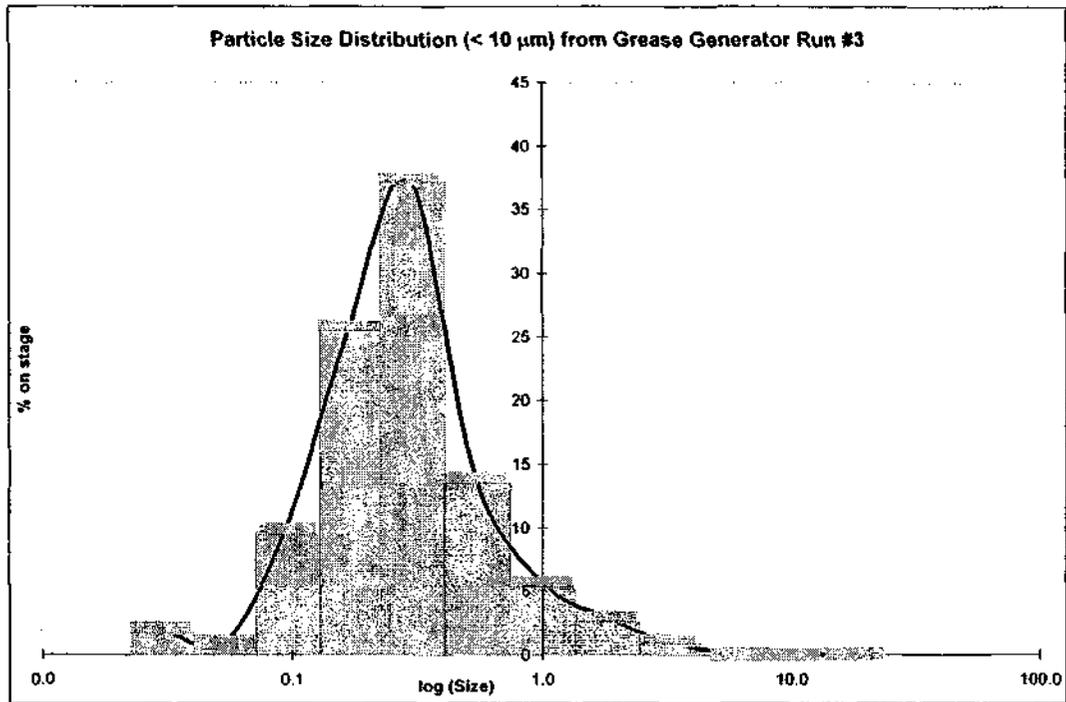


Figure 7 (c) – Small Particle (<10 μm) Size Distribution from Grease Generator Run #3

In order to illustrate repeatability, the particle size distribution results from all three test runs are plotted in Figure 8.

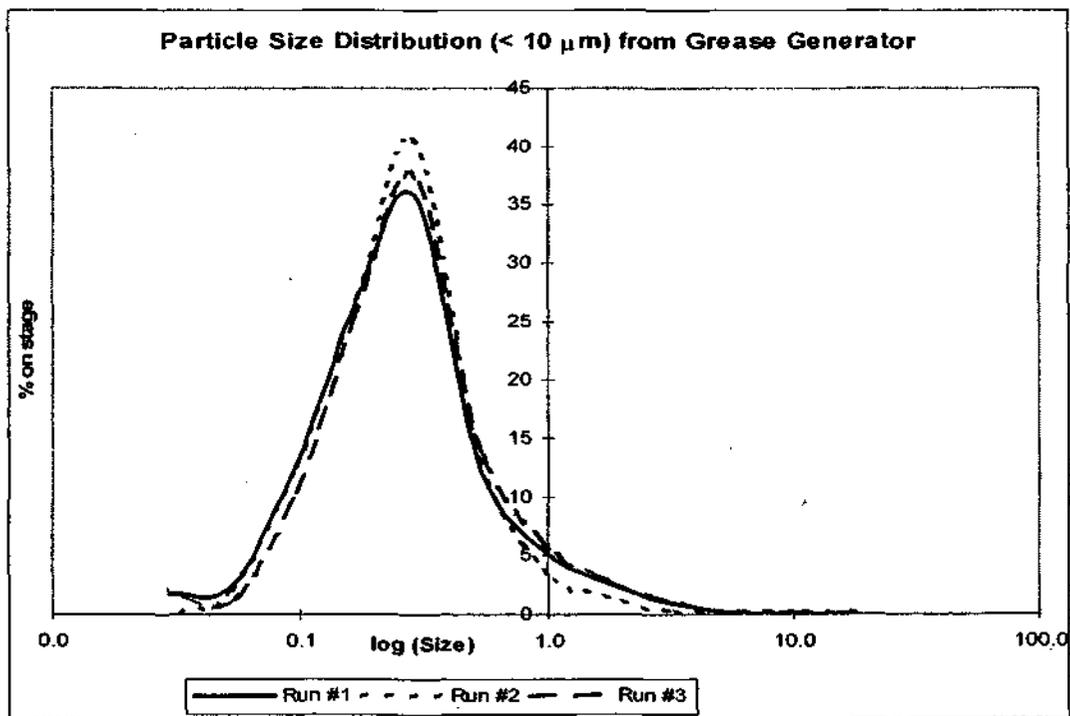


Figure 8 - Small Particle (< 10 μm) Size Distributions from Grease Generator Runs

The following Figure illustrates the average total particle size distributions using the grease generator compared with the average total particle size distribution from an actual charbroiling process (in the thermal plume) conducted by University of Minnesota in ASHRAE 1033-RP.

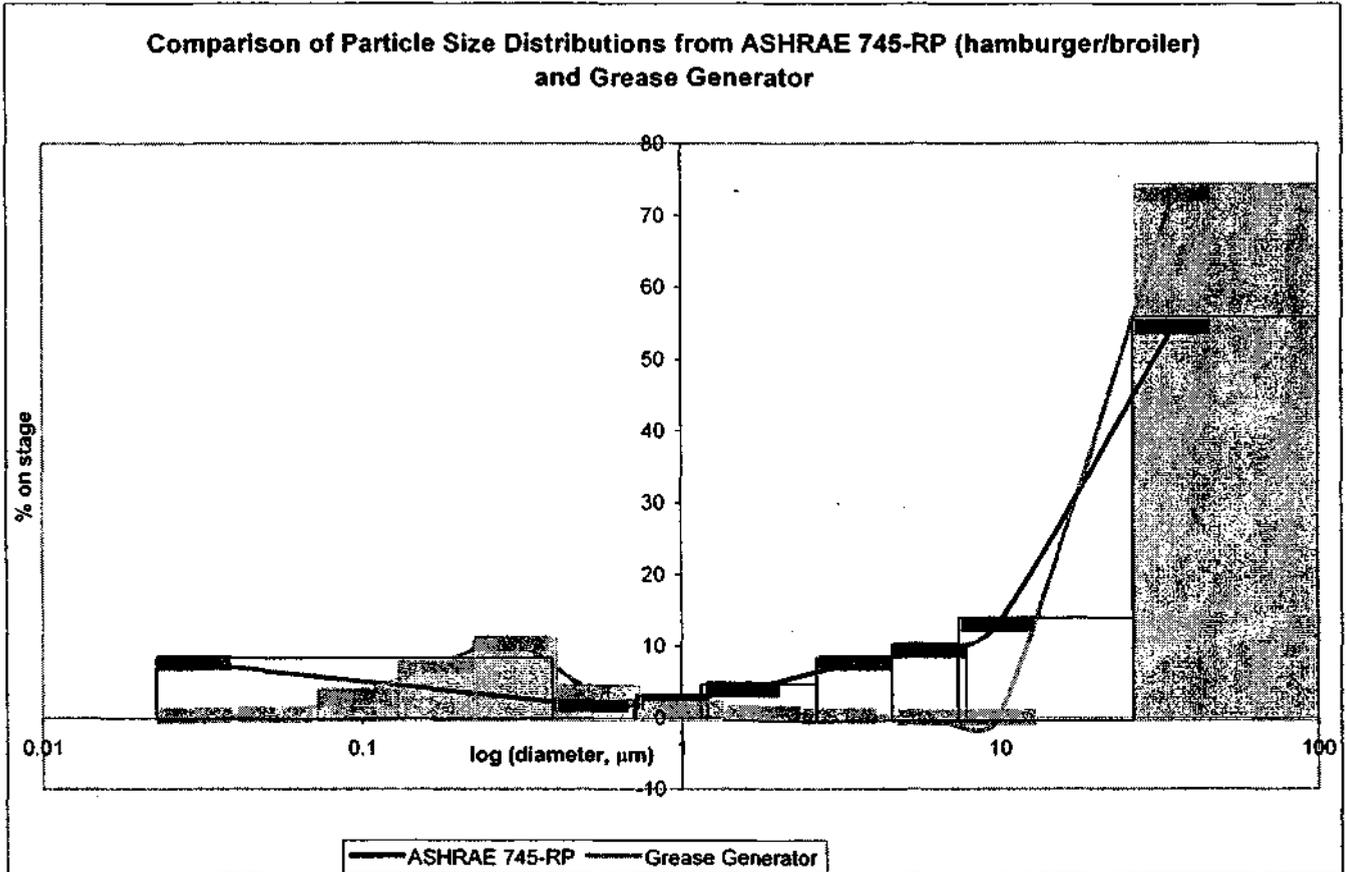


Figure 9
Particle Size Distribution Comparison Between
Grease Generator and Charbroiling Process

For particles less than 1 μm and greater than 10 μm in aerodynamic diameter, the grease generator size distribution closely matches that of the 745-RP actual charbroiling process. The generator did not produce significant mass rates of particles in the 1 μm to 10 μm size range, as were found in the 745-RP study. The difference between the two studies may relate

to differences in ventilation configuration. In AHSRAE 745-RP, a broiler with an input rate of 105,000 Btu/hr was used under a hood with an effective capture area of 27 ft². In the current study, a broiler with an input rate of 87,000 Btu/hr was used under a hood with an effective capture area of 16 ft². Both studies conformed to the standard ventilation flow rate of 400 cfm/ft. of hood length. As a result, the heat loading in the current study was 40% higher than that in 745-RP (91 Btu/ft²/min vs. 65 Btu/ft²/min). It is suspected that the higher heat loading in the current study (corresponding to higher temperatures at the sampling point) prevented the condensation/nucleation mechanism for producing particles in the 1 μm to 10 μm diameter range.

Table 4 presents a comparison of the designed particle mass flow criteria versus the average measured emissions for the three test runs using the grease generator.

Table 4
Comparison of Measured Particle Emissions
Using Grease Generator vs. Design Criteria

	Gen. #1	Gen. #2	Gen. #3	Avg. Gen.	Broiler
Total particle mass, mg/min	14213	11816	11333	12454	11000
dp > 10 μm, mg/min	10442	8530	8261	9078	7300
2.5 < dp < 10 μm, mg/min	44.5	17	38.7	33	900
dp < 2.5 μm, mg/min	3726	3034	3034	3265	2800

5.2 Deep Fat Fryer Simulation

Results from the test runs described in Section 5.1 were used to compare between the simulated grease emission runs and runs conducted using an actual deep fat frying process. Figure 10 illustrates the average total particle size distributions using the grease generator compared with the average total particle size distribution from an actual deep fat frying process (in the thermal plume) conducted by University of Minnesota in ASHRAE 1033-RP.

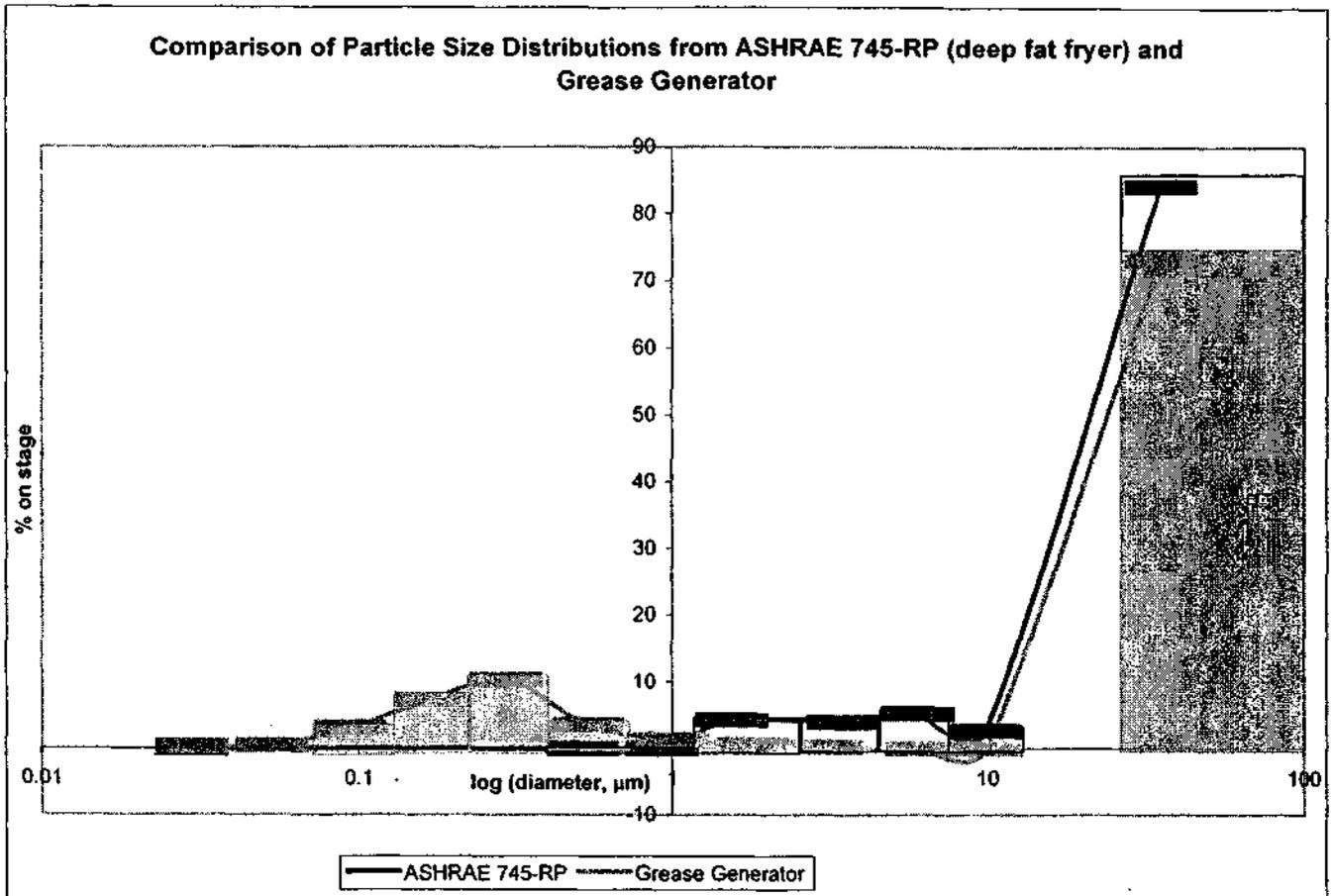


Figure 10
Particle Size Distribution Comparison Between
Grease Generator and Deep Fat Frying Process

For particles greater than 10 μm in aerodynamic diameter, the grease generator size distribution closely matches that of the 745-RP actual deep fat frying process. In order to simulate a deep fat frying process, the particles less than 1 μm in diameter from the grease generator are eliminated by simply turning off the small particle generating portion of the system. The 745-RP study shows small mass rates of particles in the 1 μm to 10 μm size range. The authors contend, however that “the particle concentrations shown below 15 μm in the figure are all within the measurement noise range. Therefore, we conclude that the gas fryer emits an undetectable amount of small grease particulates.”⁴

Simulating a deep fat fryer process, then, becomes a matter of reducing the burner input rate and setting the oleic acid flow rate to the ultrasonic nozzle to reflect the heat loading and emissions of a deep fat fryer. In the case of 745-RP, the input rate was 80,000 Btu/hr, and the mass emission rate of large particles (as estimated by DISTFIT) is 1290 mg/min.

5.3 Hamburger/Griddle Simulation

Additional tests were performed to see if the particle size distributions from hamburgers cooked on a griddle could be simulated with a modified grease generator. For these tests, several mixtures of oleic acid and ice were used to simulate the frying of frozen hamburger patties on a hot, flat surface. A number of variables were explored, including crushed vs. cube ice, deionized water ice vs. tap water ice, ice/oil mixtures placed on a hot plate vs. ice added to hot oil. In all but one case, a mixture of 70% ice to 20% oleic acid (by mass) was used, representative of an average water to fat content in raw hamburger. In one case, an ice/oleic acid mass ratio of 14:2 was used.

A flat stainless steel plate (8" x 16" x 1/2") was placed above the charbroiler surface, supported on each side with stainless steel risers. The height of the risers was adjusted to achieve an average surface temperature (as measured by a surface thermocouple) of 375 °F +/- 25 °F. Ice (crushed or cubed) and oleic acid were premixed in batches of 180 grams in tared containers, and placed in a freezer set at 0 °C +/- 4 °C. For each test run, the mixture was added to the hot plate at a rate of 18 grams every three minutes, for a total of 30 minutes. In the case of ice added to hot oil, the oil was placed in a sheet pan prior to the start of testing. The sheet pan was placed on the hot plate, and allowed to achieve temperature equilibrium. Ice cubes were then added to the oil at a rate of 14 grams every three minutes.

Figure 11 shows the particle size distributions of the various test runs. It is clear from this figure that there is a large degree of variability due to geometry (crushed vs. cubed ice),

composition (deionized vs. tap water), and process (ice/oleic acid mixture on hot plate vs. ice added to hot oleic acid).

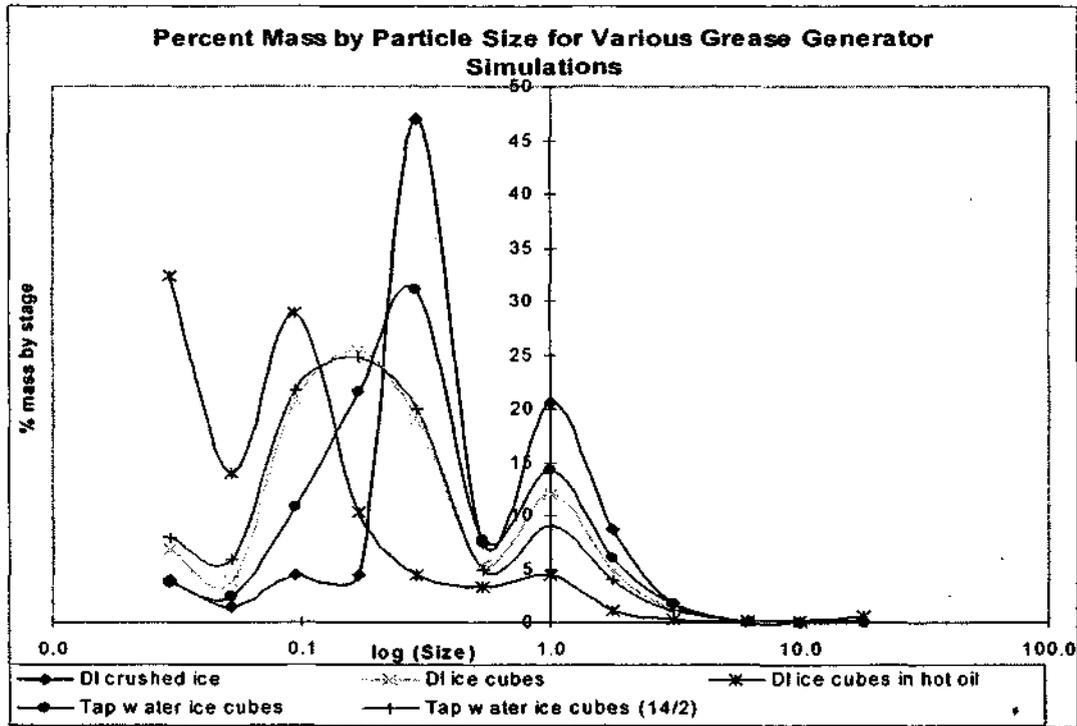


Figure 11

Experimental Griddle Simulations

The size distribution from the DI crushed ice/oil mixture was chosen to best represent the size distribution measured in 745-RP for hamburgers cooked on a flat griddle. Figure 12 compares the DI crushed ice/oil + large particle simulation distribution to the average measured distribution from 745-RP.

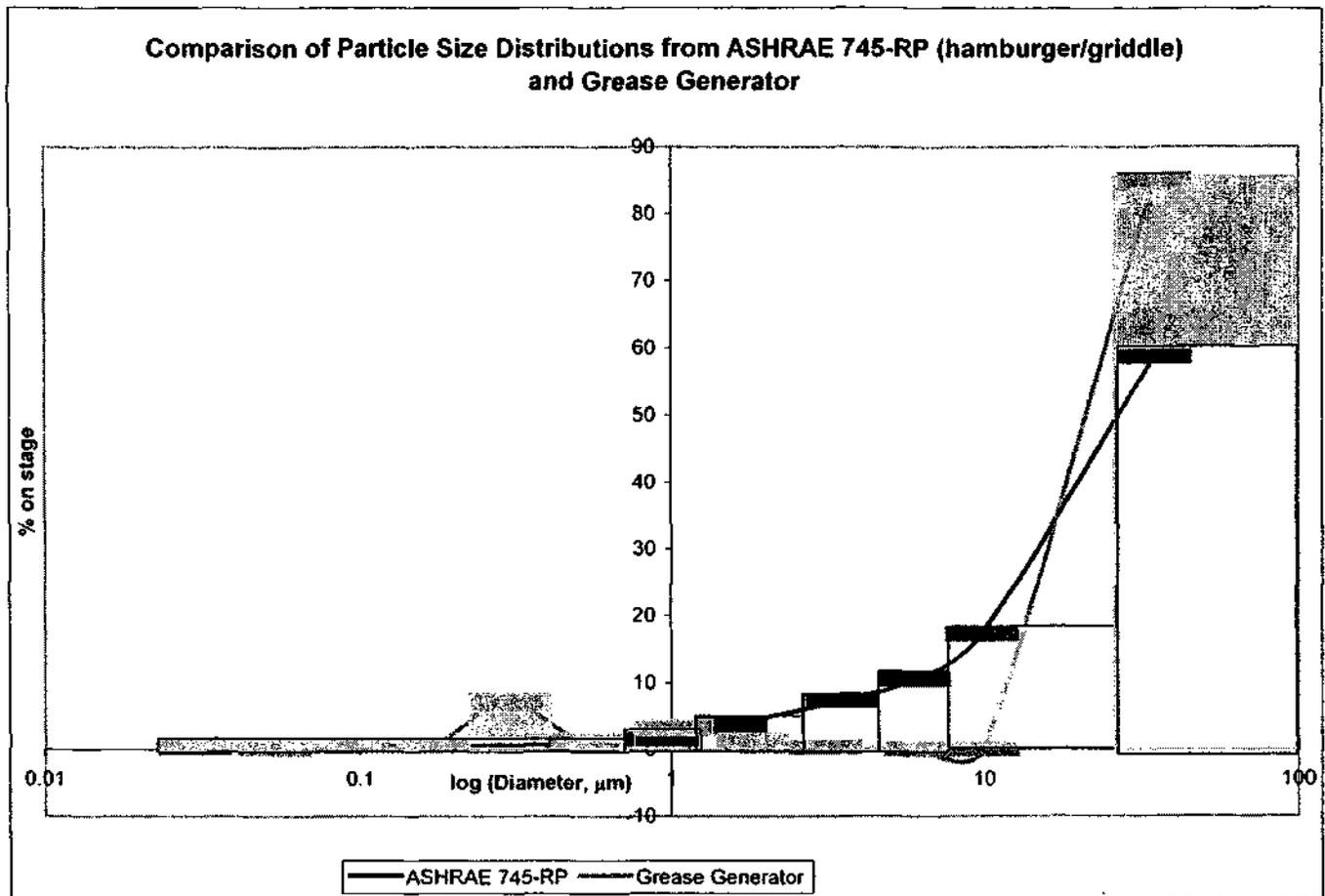


Figure 12

**Particle Size Distribution Comparison Between
Grease Generator and Flat Griddle Process**

For particles less than 2 μm and greater than 10 μm in aerodynamic diameter, the grease generator size distribution closely matches that of the 745-RP actual flat griddle process. The generator did not produce significant mass rates of particles in the 2 μm to 10 μm size range, as were found in the 745-RP study. The grease generator distribution did, however, show a shift of particles from the submicron range to larger diameters. The generator produced a significant mass rate of particles in the 0.5 μm to 3 μm range, characteristic of the hamburger/griddle process. As was the case in the charbroiler simulation, the difference between the two studies may relate to differences in heat load and subsequent higher hood temperatures in the CE-CERT scenario. The fact that this shift is seen when mixing oleic

acid with crushed ice lends support for the argument that further particle growth (through condensation/nucleation) can be achieved by lowering the hood temperature.

The size distribution from the DI ice cubes added to hot oil was chosen to best represent the size distribution measured in a previous program for whole, butterflied chicken cooked on a flat griddle. Figure 13 compares the DI ice cubes added to oil simulation distribution to the average cooking distribution for this process. Note that the cooking emissions distribution was obtained in the ventilation duct, downstream of the hood and grease filters.

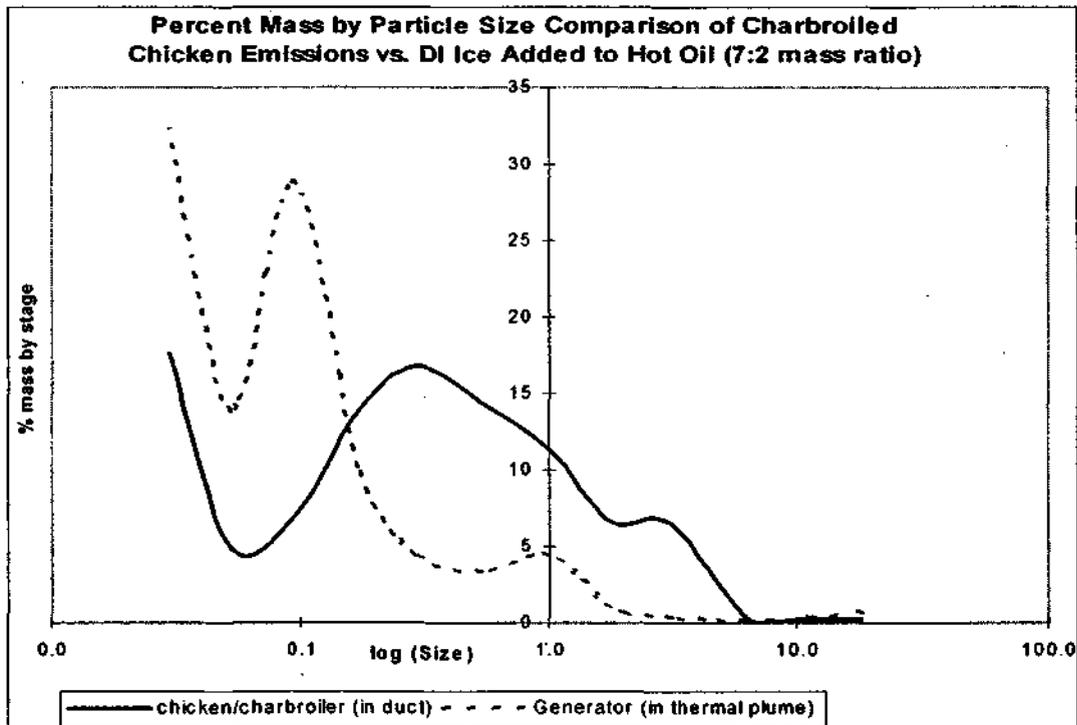


Figure 13

Comparison of Chicken/Charbroiler Process to Grease Generator

As is evident in the figure, the grease generator exhibits a sharp peak at 0.094 μm , while the chicken/charbroiler process does not. The grease generator was, however, able to produce a significant mass of particles less than 0.053 μm , characteristic of the chicken/charbroiler

process. Once again, it is possible that the differences between the two processes may be attributable to particle nucleation phenomena, as the chicken/charbroiler samples were acquired in the downstream duct.

5.4 Repeatability

Results from the SCAQMD Method 5.1 total PM sampling train were used to assess the repeatability of the grease generating process. These measurements were obtained in the ventilation duct, downstream of the hood and grease extractors. Table 5 shows a comparison of Method 5.1 results using an actual charbroiling process with results using the grease generator.

Table 5
SCAQMD Method 5.1 PM Emission Factors

Process	Commercial Chain-Driven Charbroiler (lb./1000 lb. Meat cooked)	Grease Generator (lb./10 lb. Generated)
Run #1	10.95	2.42
Run #2	7.22	2.56
Run #3	6.51	2.68
Average	8.23	2.55
Std. Dev.	2.39	0.13
Error % (SD/AVG)	29.0%	5.1%

Results show that the repeatability of the grease generator is significantly better than that of an actual cooking process. Error coefficients from 3-run tests of a variety of different cooking processes range from 15 – 30%.²

Results indicate that an average of 74.5% of the particles produced using the grease generator were removed by the ventilation system (hood area, hood, grease extractors, and ductwork) upstream of the sampling point.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Results from the current study indicate that emissions from commercial cooking processes can be successfully emulated (without actually cooking food) using commercially available equipment and relatively simple process techniques. Refinements to the prototype design, however, are necessary to emulate particle size fractions and corresponding mass flow rates found in cooking processes that are most likely to be removed by common grease extraction systems. In addition, a non-condensable vapor generator component should be added to the design to reflect hydrocarbon gases typically found in charbroiler processes.

The test results using the prototype grease generator demonstrate that representative, multi-modal grease particle distributions can be generated in the quantities and composition characteristics of charbroiler, griddle, and deep-fat frying processes. Furthermore, the prototype design can generate these emissions in a much more repeatable manner than actual cooking of hamburgers. The ratio and total mass quantities of large and submicron particles can be adjusted on the prototype system to emulate many processes, such as griddle or deep fat fryer cooking operations. Emulating the exact aerodynamic size distribution and mass emissions of commercial cooking emissions, however, requires further study. Specifically, the mechanism of particle formation and interaction with ventilation systems needs to be fully understood in order to effectively apply the grease generator to a Method of Test (MOT) for determining the effectiveness of grease filters and emission control technologies. While the current study lends insight to cooking emissions, research to date has yet to fully explain how particles are formed in different cooking processes, and what physical and/or chemical processes occur as the effluent travels through a hood, grease extractor, ventilation duct, and into the atmosphere.

The volumetric flow rates for the particle generator feeds were adjusted using needle valves plumbed into the feed lines downstream of the heated, pressurized container. While this

arrangement provided a consistent flow rate during the course of a test run, the flow rate would change between test runs (after depressurizing the container, adding oleic acid, and repressurizing). This phenomenon occurred in spite of the needle valves set at the exact same position for each run. For the testing in Phase I, this was not a problem, as the ratio of mass flow rates generated during each run (measured weight loss) correlated with ratio of total mass flow recovered in the total particulate sample trains in the ventilation duct for the same runs. For Phase II application, however, it will be important for the generator to produce mass flow rates in each desired particle size range that are both accurate and repeatable. It is recommended that a more repeatable flow control method (e.g. critical flow orifice, peristaltic pump) be employed in the grease generator for the final MOT.

Emissions from griddle cooking operations exhibit a characteristic particle size distribution peak between 0.9 μm and 5 μm . While these emissions represent a only a small fraction of the total PM generated from charbroiling processes, they also represent the size range of particles that would be most likely removed by traditional inertial grease extraction devices. Figure 14 illustrates a typical mechanical grease extractor challenged by a range of particle sizes.⁵ As evident from the graph, virtually no small particles are removed, and virtually all of the large particles ($> 10 \mu\text{m}$) are removed. It is clear from these results that differentiating inertial-type grease extractors will require repeatable generation of particles in the 2 – 10 μm diameter range.

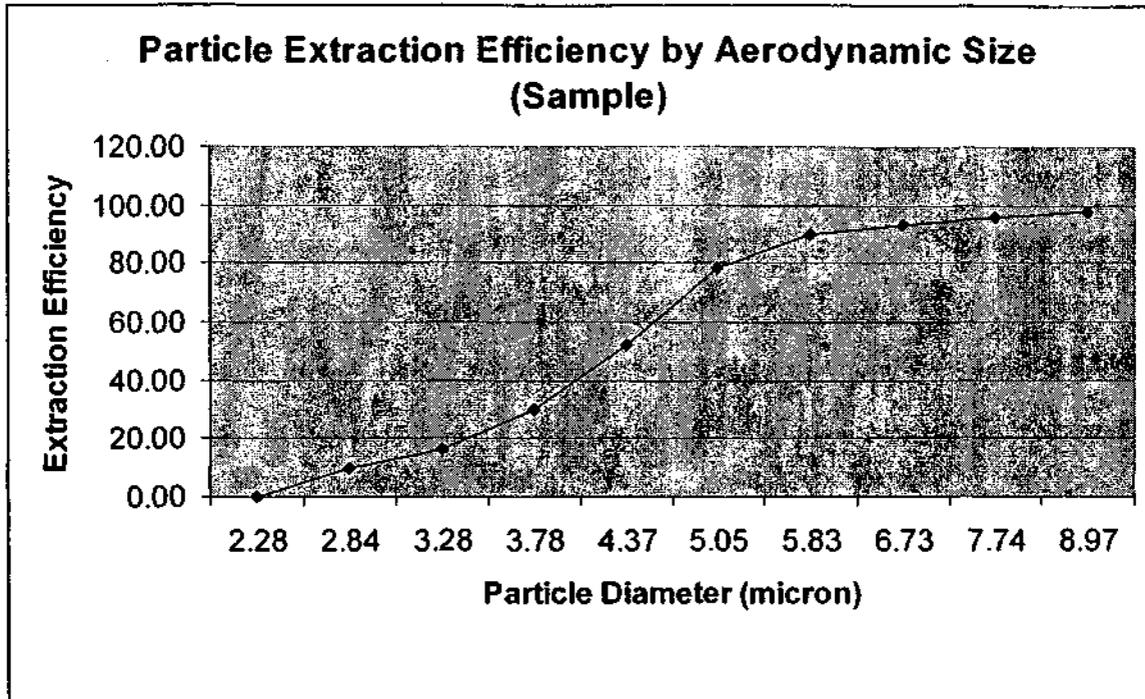


Figure 14 – Typical Inertial Grease Extractor Efficiency

The results illustrated above raise the question whether large particles (> 30 μm) need to be produced in the grease generator, as effectively 100% of particles in this aerodynamic size range and larger are removed by even the most rudimentary grease extractor design. This is an important point, as the equipment needed to generate the large particles is expensive, and the large particles tend to fall out of the ventilation stream, or deposit on the surfaces of the walls and hood. This fact makes it difficult to generate a repeatable mass flow rate of large particles that can be passed across a grease extractor. Another concern relates to the adaptation of the grease generator processes to an MOT that provides a “grease removal efficiency” rating for removal technologies. All of the particle size distribution measurements in Phase I were taken in the thermal plumes of the generating process. An accurate emission mass flow rate determination requires a proportional sample concentration that is representative of the average concentration in the bulk stream. This is difficult to do in the thermal plume, as local velocities and particle concentrations vary widely across the hood

face. There is also the potential for some material to deposit or condense on surfaces downstream of the sample point (but upstream of the grease extractors), leading to errors in efficiency calculations. It is recommended that the MOT incorporate a definitive uniform flow rate to challenge the potential grease extractors. This can be accomplished by acquiring samples in the exhaust duct, downstream of any tested filter; providing for a minimum of two (2) duct diameters length prior to the sampling point. Furthermore, it is recommended that a "baseline" set of grease filters be developed to serve as a standard to compare grease extraction efficiencies. The baseline filters should be flat plates, having "face opening" cross sections equivalent to common grease extractors. The plates would not have any inertial removal designs (such as 180° turns, or mesh). Used in this way, the method could determine baseline emissions in the downstream duct, allowing for complete mixing and uniform flow development of the effluent from the grease generator. It would also provide a representative extractor face velocity, characteristic of actual ventilation parameters.

Recommendations for Phase II of this work include further development of the "mid-micron" particle generation technique, development of a "standard" grease filter (one without any inertial impaction designs, addition of a non-condensable hydrocarbon gas component, development of simpler sampling/analytical techniques, and incorporating the knowledge gained into an official Method of Test (MOT). The MOT could then be used to demonstrate the cooking emissions generator using a variety of grease extractors, and could ultimately replace current regulatory emissions test protocols for commercial cooking emissions.

7.0 REFERENCES

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SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT

METHOD 5.1

**DETERMINATION OF PARTICULATE MATTER EMISSIONS FROM
STATIONARY SOURCES USING A WET IMPINGEMENT TRAIN**

**OFFICE OF OPERATIONS
TECHNICAL SERVICES DIVISION
MARCH 1989**

METHOD 5.1

DETERMINATION OF PARTICULATE MATTER EMISSIONS FROM STATIONARY SOURCES USING A WET IMPINGEMENT TRAIN

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APPENDIX A
Equipment List

EQUIPMENT LIST

Basic Process

<u>Qty</u>	<u>Item</u>	<u>Vendor</u>
1	36" Underfired Charbroiler	Wolf
1	flat stainless steel plate (8" x 16" x 1/2")	-

Particle Generators

<u>Qty</u>	<u>Item</u>	<u>Vendor</u>
1	ultrasonic atomizing nozzle Model No. 8700-60 w/ conical tip (nozzle #Q060-2-26-17-303-052)	Sono-Tek
1	broadband ultrasonic frequency generator, free-standing unit (part #06-05108)	Sono-Tek
1	pressure gauge, 2 1/2" diameter, 0-15 PSI, 1/4" NPT (part #1X680)	Grainger
2	pressure relief valves, adjustable (part #6D915)	Grainger
1	portable stainless steel ASME-Code pressure tank (part #41665K18)	McMaster-Carr
1	silicon rubber extruded heat tape, 1" wide x 8' long (part #11-463-55D)	Fisher Scientific
1	inline filter (part #SS-2F-60)	San Diego Valve & Fitting
1	inline filter (part #SS-6F-7)	San Diego Valve & Fitting
2	1/8" stainless steel tubing, 4' lengths	Grainger
2	1/8" needle valves	Grainger
1	analytical-grade oleic acid, 4 liter container (part #36,452-5)	Sigma-Aldrich

EQUIPMENT LIST (cont.)**Sampling/Analytical Equipment**

<u>Qty</u>	<u>Item</u>	<u>Vendor</u>
1	10-stage Multi Orifice Uniform Deposit Impactor (MOUDI)	MSP Corp.
1	Method 5-style particulate matter sampling train	NuTech
2	velocity measurement and sample flow control systems	NuTech
1	sample conditioner/moisture removal system	Universal
1	pressure gauge, 2 1/2" diameter, 0-15 PSI, 1/4" NPT	Grainger

APPENDIX B
Construction and Assembly of Grease Generator

CONSTRUCTION AND ASSEMBLY OF GREASE GENERATOR

- 1) Gather all parts listed in the equipment list for the grease generator (Appendix A).
- 2) The portable stainless steel pressure tank is pre-fabricated with four (4) taps in the lid to accommodate all of the connections required for operation and process monitoring.
- 3) Install a Type-K thermocouple through one of the pre-fabricated taps on the outer diameter of the pressure reservoir lid. The thermocouple should be placed so that the tip is approximately $\frac{1}{4}$ " above the bottom of the reservoir (when the lid is in place). Wrap Teflon tape on the male end of the fitting to ensure an airtight seal.
- 4) Install the pressure gauge on one of the pre-fabricated taps on the inner diameter of the pressure reservoir lid. Wrap Teflon tape on the male end of the fitting to ensure an airtight seal.
- 5) Install the $\frac{1}{8}$ " stainless steel feed line through the remaining pre-fabricated tap on the outer diameter of the pressure reservoir lid. The end of the feed line should be placed so that the tip is approximately $\frac{1}{4}$ " above the bottom of the reservoir (when the lid is in place). Wrap Teflon tape on the male end of the fitting to ensure an airtight seal. Attach a 90° Swagelok elbow at the top of the line coming out of the reservoir, and run a 3 ft. horizontal section of $\frac{1}{8}$ " tubing from the other side of the elbow (see Figure 3).
- 6) Attach an $\frac{1}{8}$ " stainless steel "T" to the other end of the 3 ft. tubing section. To each of the remaining connections of the "T" attach small lengths (1 - 2 ft.) of $\frac{1}{8}$ " tubing, each equipped with a flow control valve.
- 7) Attach the ultrasonic atomizing nozzle to the end of one section of tubing, downstream of the flow control valve. To the other section of tubing, attach a 90° elbow. To the

CONSTRUCTION AND ASSEMBLY OF GREASE GENERATOR (cont.)

other side of this elbow, attach a very small section of $1/8$ " tubing to serve as a nozzle.

The orientation of the ultrasonic nozzle should be such that the flow pattern occurs across the horizontal plane. The orientation of the other "nozzle" should be such that the liquid flows vertically down (Figure 3).

- 8) Attach a compressed air line (equipped with a pressure regulator) to the remaining pre-fabricated tap on the inner diameter of the pressurized reservoir lid. The compressed air system and regulator should be capable of providing a constant uninterruptable pressure of 25 psi. Wrap Teflon tape on the male end of the fitting to ensure an airtight seal.
- 9) Wrap the outside of the pressure reservoir with heating tape. Care should be taken to ensure that the tape does not overlap at any point. A small space between adjacent wraps is acceptable.
- 10) Connect the Type-K thermocouple to a potentiometer equipped with a digital readout.
- 11) Connect heating tape elements to an adjustable voltage regulator.
- 12) Connect the output wire from the frequency generator to the ultrasonic nozzle.
- 13) Place pressurized reservoir on a digital scale with a minimum range of 0 – 5000 g.

APPENDIX C
Operation and Verification of Grease Generator

OPERATION AND VERIFICATION OF GREASE GENERATOR

- 1) Set the firing rate of the charbroiler to within 5% of the manufacturer's specified input rate. Allow broiler to warm up for a minimum of one hour.
- 2) Set burner controls such that the average broiler cooking surface temperature (as measured by a plate thermocouple) is $600\text{ }^{\circ}\text{F} \pm 50\text{ }^{\circ}\text{F}$.
- 3) Obtain a tare weight of the empty pressurized reservoir (without lid).
- 4) Add analytical-grade oleic acid to the reservoir, and re-weigh reservoir with oleic acid to obtain a final weight.
- 5) Attach and seal lid to top of reservoir. Attach all connections to lid (thermocouple wire, compressed air inlet).
- 6) Heat the reservoir by turning on the variable voltage controller attached to the heat tape around the container. Initially, set the voltage controller to 50% maximum, and allow to warm up for approximately 45 minutes. Monitor the temperature with the digital readout from the thermocouple potentiometer. Increase or decrease voltage as necessary to obtain a final operating temperature of $185\text{ }^{\circ}\text{F} \pm 5\text{ }^{\circ}\text{F}$.
- 7) Turn on the compressed air, and adjust the pressure regulator to obtain a pressure of 25 psi in the pressurized reservoir.
- 8) Open the flow control valve leading to the ultrasonic nozzle (large particle generator) approximately $\frac{1}{2}$ of full, and mark the initial time. After a period of at least 15 minutes, close the valve and mark the final time. Re-weigh the pressurized reservoir (without the lid) to obtain a final weight. Calculate the mass flow rate of oleic acid (initial weight minus final weight divided by time). Alternatively, the oleic acid mass can be obtained by

OPERATION AND VERIFICATION OF GREASE GENERATOR (cont.)

collecting the nozzle output in a tared container, such as a glass beaker. This alternative eliminates the need to disconnect and remove the lid on the pressurized reservoir.

- 9) Calculate the oleic acid flow rate in mg/min based on the results from step #8. Repeat step #8 with a different setting on the flow control valve, increasing or decreasing the flow rate as necessary to achieve the target flow rates for particles $> 10 \mu\text{m}$ specified in Table 1 for the process desired (charbroiler, griddle, deep fat fryer). For example, the target flow rate for particles $> 10\mu\text{m}$ in simulating charbroiler exhaust is 7300 mg/min. Mark the setting of the flow control valve corresponding to the verified target flow rate. Then close the flow control valve.

- 10) Open the flow control valve leading to the tubing nozzle (small particle generator) approximately $\frac{1}{2}$ of full, and mark the initial time. After a period of at least 30 minutes, close the valve and mark the final time. Re-weigh the pressurized reservoir (without the lid) to obtain a final weight. Calculate the mass flow rate of oleic acid (initial weight minus final weight divided by time). Alternatively, the oleic acid mass can be obtained by collecting the nozzle output in a tared container, such as a glass beaker. This alternative eliminates the need to disconnect and remove the lid on the pressurized reservoir.

- 11) Calculate the oleic acid flow rate in mg/min based on the results from step #8. Repeat step #8 with a different setting on the flow control valve, increasing or decreasing the flow rate as necessary to achieve the target flow rates for particles $< 2.5 \mu\text{m}$ specified in Table 1 for the process desired (charbroiler, griddle, deep fat fryer). For example, the target flow rate for particles $< 2.5 \mu\text{m}$ in simulating charbroiler exhaust is 2800 mg/min. Mark the setting of the flow control valve corresponding to the verified target flow rate. Then close the flow control valve.

OPERATION AND VERIFICATION OF GREASE GENERATOR (cont.)

- 12) Once the flow control settings are established, obtain an initial weight of the oleic acid in the pressurized reservoir (without the lid) immediately prior to the start of testing.
Replace the lid, and pressurize the container.
- 13) Place a ½" thick stainless steel plate (6" x 6") on the broiler grate, and center under the drip nozzle for the submicron particle generator feed nozzle. Adjust the height of the plate using stainless steel spacers (e.g. washers) between the charbroiler grate and the plate. The plate height should be adjusted until the surface temperature (as measured by a surface thermocouple) is between 475 °F and 500 °F.
- 14) Turn on the frequency generator (attached to the ultrasonic nozzle), and adjust the setpoint to 60 Hz.
- 15) Position the outlet of the ultrasonic nozzle to spray horizontally across the thermal plume of the charbroiler, approximately 1 ft. above the charbroiler grate.
- 16) Position the outlet of the drip nozzle to flow vertically down to the centerpoint of the 6" x 6" stainless steel plate on the charbroiler grate.
- 17) At the start of the test run, open the two flow control valves to the preset marks, and record the time.
- 18) At the end of the test run, close the two flow control valves and record the time. Turn off the frequency generator.
- 19) Obtain a final weight of the remaining oleic acid in the pressurized reservoir (without the lid). The difference between the initial and final weights is the total mass of particles generated during the test run.

APPENDIX D
South Coast Air Quality Management District Method 5.1

1/20/03 FINAL REPORT

METHOD 5.1

DETERMINATION OF PARTICULATE MATTER EMISSIONS FROM STATIONARY SOURCES USING A WET IMPINGEMENT TRAIN

Section 1 of 4

1. Overview

1.1 Principle

A sample of stack gases is withdrawn isokinetically from the source through a sample train. Particulate matter is collected in impingers containing deionized water and on a backup filter. The impingers are contained in an ice bath to maintain a sampled gas temperature of approximately 15°C (60°F). The filter is not heated.

Total particulate matter mass is defined as the sum of the mass collected in the impingers and probe, and on the filter after removal of combined water, plus extractable organic matter. Solid particulate matter mass is defined as the total particulate matter mass minus extractable organic matter and sulfuric acid. An adjustment to the total particulate matter mass is allowed for sulfuric acid formed from reactions between

SO₂ and SO₃ with the sample train components. When ammonia is injected to enhance the efficiency of a control device, a second adjustment is allowed for neutral sulfates. This adjustment is allowed for fluid catalytic cracking units only.

Because of the complexity of this method, personnel involved in both the collection and analysis of samples must be trained and experienced in the test procedures.

1.2 Applicability

This method is used to measure particulate emissions from stationary sources, except when determining compliance with New Source Performances Standards. When the particulate matter is hygroscopic, SO_x is present in concentrations greater than 10 ppm, or ammonia is injected to enhance control device efficiency, an in-stack filter or a heated filter before the impingers is recommended.

METHOD 5.1

DETERMINATION OF PARTICULATE MATTER EMISSIONS FROM STATIONARY SOURCES USING A WET IMPINGEMENT TRAIN

Section 2 of 4

2. Field Procedures

2.1 Sampling Apparatus

2.1.1 Sampling Train

A schematic of the sampling train used in this method is shown in Figure 5.1-1.

The sampling train consists of the following components:

a. Probe Nozzle

The nozzle material should be 316 stainless steel or glass, with a sharp, tapered leading edge. The taper angle should be $\leq 30^\circ$ and on the outside, to preserve a constant internal diameter. The stainless

steel nozzle should be constructed from seamless tubing. Other materials which will not be corroded by the sampled gases or interfere with sample recovery may be used.

A range of nozzle sizes suitable for isokinetic sampling should be available in increments of 0.16 cm (1/16 in.), e.g. from 0.32 to 1.27 cm (1/8 to 1/2 in.) or larger if higher volume sampling trains are used.

Each nozzle must be calibrated before its use in the field. Measure the inside diameter of the nozzle with a micrometer to the nearest 0.025 mm (0.001 in.). Make three separate measurements using different diameters each time, and obtain the average. The difference between the high and low numbers shall not exceed 0.1 mm (0.004 in.). Nicked, dented, or corroded nozzles must be reshaped, sharpened, and recalibrated before use.

Connect the nozzle to the liner with a leak-free fitting resistant to heat and chemicals.

b. Probe Liner

Use borosilicate or quartz probe liners for stack temperatures up to about 480°C (900°F); use quartz liners for temperatures between 480 and 900°C (900 and 1,650°F). If high temperatures are encountered see Chapter X section on Sampling High Temperature Sources.

Whenever practical, use borosilicate or quartz glass probe liners. Otherwise, use metal liners made of seamless tubing (e.g. 316 stainless steel, Inconel 825, or other corrosion resistant metals) when acid particulates are present in concentrations less than 1 mg/m³ at probe conditions or SO₂ is less than 20 ppm.

When assembling the probe and nozzle, verify that all components, including ferrules and other connectors, are heat-resistant, leak-free and non-contaminating for the sample.

The liner may be connected to the impingers rigidly with glass, or flexibly with inert vacuum tubing.

c. Pitot Tube

Use an S-type Pitot tube as described in Section 1.1 of Method 2.1, or other device approved by the Executive Officer. Attach the Pitot tube to the probe, as shown in Figure 5.1-1, to allow constant monitoring of the stack gas velocity. If this is not practical see Chapter X, section on Flue Factor.

The impact (high pressure) opening plane of the Pitot tube must be even with or above the nozzle entry plane (see Method 2.1) during sampling. The S-type Pitot tube assembly must have a

known coefficient, as determined in Method 2.1.

d. Differential Pressure Gauge

Use an inclined manometer or equivalent device, as described in Method 2.1, for stack velocity head readings, and a separate manometer for orifice differential pressure readings.

e. Filter Holder

Use a borosilicate glass filter holder, with a glass frit filter support and a silicone rubber gasket. Other materials such as stainless steel, Teflon, or Viton may be used if they do not react with the particulate matter or sample gases. (Reactions normally are not a problem after the impingers.) The holder design provides a positive seal against leakage from the outside or around the filter. Attach the holder after the dry impinger in the impinger train.

f. Impinger Train

The train consists of four Greenburg-Smith design impingers connected in series with leak-free ground glass fittings, or any similar leak-free non-contaminating fittings. The first and second impingers must be of the Greenburg-Smith design with the standard tip. The third and fourth impingers must be of the Greenburg-Smith design, modified by replacing the tip with 1.3 cm (1/2 in.) ID glass tube extending to about 1.3 cm (1/2 in.) from the bottom of the flask. Acceptable modifications include the following: using non-reactive flexible connections between the impingers, using materials other than glass, or using flexible vacuum lines to connect the filter holder to the impinger train.

The first and second impingers contain 100 ml of deionized water (run blanks prior to field use), the third is

empty, and the fourth contains a known weight of 6 to 16 mesh indicating-type silica gel or equivalent. Place a thermometer capable of measuring temperature to within 1°C (2°F) at the outlet of the fourth impinger to monitor outlet gas temperature. In certain applications an extra dry impinger with a shortened straight stem may be placed before the wet impinger to act as a drop out for particulates that cause excessive foaming, or when there is excessive moisture.

Instead of using silica gel the moisture leaving the third impinger may be measured by monitoring the temperature and pressure at the exit of the impinger train and using Dalton's law of partial pressures.

Even if means other than silica gel are used to determine the amount of moisture leaving the impinger train, silica gel, or equivalent should be used between the impinger system and

pump to prevent moisture condensation in the pump and metering devices.

g. Metering System

The metering system includes vacuum gauge, leak-free pump, thermometers capable of measuring temperature to within 3°C (5.4°F), dry gas meter capable of measuring volume to within 2 percent, and related equipment, as shown in Figure 5.1-1. An alternative to the thermometer and dry gas meter is an equivalent temperature-compensated dry gas meter. When the metering system is used in conjunction with a Pitot tube, the system should allow for checks of isokinetic rates.

2.1.2 Barometer

A mercury, aneroid, or other barometer capable of measuring atmospheric pressure to within 2.5 mm (0.1 in.) Hg is used. The barometric pressure may be obtained from a nearby National Weather Service (NWS) station. Request the station value

(which is the absolute barometric pressure) and adjust for elevation difference between the NWS station and the sampling point at the rate of minus 2.5 mm (0.1 in.) Hg per 30 m (100 ft) elevation increase or plus the same adjustment for elevation decrease.

2.1.3 Temperature Determination Equipment

Use the temperature sensor described in Method 2.1. Preferably, the temperature sensor should be permanently attached to the Pitot tube or sampling probe so that the tip of the sensor extends beyond the leading edge of the probe sheath and touches no metal. Alternatively the sensor may be attached just prior to use in the field. If the temperature sensor is attached in the field, place it in an interference-free arrangement with respect to the S-type Pitot tube openings (see Method 2.1).

As another alternative, if a difference of not more than 1 percent in the average measurement and resulting stack flow rate

calculation would be introduced, the temperature gauge need not be attached to the probe or Pitot tube.

2.1.4 Gas Molecular Weight - Determination Equipment

Same as Method 3.1. Concurrent determination is not required when the process is steady state and molecular weight varies less than 2 percent.

2.2 Sampling Reagents

a. Filters

Glass fiber filters, without organic binder.

The filters should be at least 99.95 percent efficient (≤ 0.05 percent penetration) on 0.3 micron dioctyl phthalate smoke particles.

Conduct the filter efficiency test in accordance with ASTM Standard Method D2986-71, or use test data from the supplier's quality control program. Low sodium filters are recommended when SO_2 is present.

b. Silica Gel

Indicating-type silica gel, 6 to 16 mesh.

Use new silica gel as received. If previously used, dry at 175°C (350°F) for 2 hours.

Other types of desiccants may be used subject to the approval of the Executive Officer.

c. Water

Deionized, distilled water to conform to ASTM specification D1193-77 Type 3.

At the option of the chemist, the KMnO_4 test for oxidizable matter may be eliminated when high concentrations of organic matter are not expected to be present. Reference to water throughout this method implies deionized, distilled water.

Run blanks prior to field use to eliminate a high blank on test samples.

d. Crushed Ice or Dry Ice Pellets

e. Stopcock Grease

Stopcock grease is not recommended and not necessary if screw-on connectors with Teflon sleeves or similar are used. Acetone-insoluble, heat-stable silicone grease may be used. Other types of grease may be used, subject to the approval of the Executive Officer.

2.3 Pretest Determinations

Select the sampling site and the minimum number of sampling points according to Method 1.1. If it is not possible to follow Method 1.1, or more than one sample site must be tested, see Chapter X. Determine the stack pressure, temperature, and the range of velocity heads using Method 2.1.

Determine the moisture content, using Method 4.1 or its alternative, to make sampling rate settings.

Determine the stack gas dry molecular weight as described in Method 3.1. If integrated sampling (Method 3.1) is used for molecular weight determination, take the integrated bag sample

used to calculate $\Delta H\theta$ at these three flow rates,
where $\Delta H\theta$ is calculated as follows:

$$\Delta H\theta = 0.0319 \Delta H \frac{T_m \theta^2}{P_{\text{bar}} (Y^2 V_m^2 A^2)}$$

where:

$\Delta H\theta$ = Average pressure differential across the
orifice meter, in. H₂O at 0.75 scfm
(528°F, 29.92 in. Hg)

T_m = Absolute average dry gas meter
temperature, °R

P_{bar} = Barometric pressure, in. Hg

θ = Total sampling time, min

Y = Dry gas meter calibration factor,
dimensionless, obtained from percent
Chapter III

ΔH = Pressure differential across the
orifice, in. H₂O

V_m = Volume of gas sample as measured by
dry gas meter, dcf

$$0.0319 = (0.0567 \text{ in. Hg/}^{\circ}\text{R}) \times (0.75 \text{ cfm})^2$$

A = 1, if meter is not temperature compensated

$$= \frac{T_m}{\text{Compensated Temp. (}^{\circ}\text{R)'}}$$

if temperature compensated.

If the measured $\Delta H\theta$ differs by more than ± 3 percent of the actual $\Delta H\theta$ obtained in Chapter III, the results of the tests are voided.

An alternative procedure (e.g. using an orifice meter with a known K-Factor) may be used, subject to the approval of the Executive Officer.

2.5 Pretest Preparation

Set up the train as in Figure 5.1-1.

Mark the probe with heat resistant tape or by some other method to denote the proper distance to insert the probe into the stack or duct for each sampling point.

Place crushed ice or dry ice pellets around the impingers.

2.6 Leak Checks

2.6.1 Pretest Leak Check

If a Viton A O-ring or other leak-free connection is used in assembling the probe nozzle to the probe liner, leak check the train at the sampling site by plugging the nozzle and drawing a 380 mm (15 in.) Hg vacuum.

A lesser vacuum may be used if it is not exceeded during the test. The probe may be leak checked separately at a pressure equal to the stack pressure minus 25 mm (1 in.) Hg. Alternatively, the probe may be leak checked with the rest of the sampling train, at 380 mm (15 in.) Hg vacuum.

A leakage rate in excess of either 4 percent of the average sampling rate or $0.00057 \text{ m}^3/\text{min}$ (0.02 cfm), is unacceptable.

Start the pump with the bypass valve fully open and the coarse adjust valve completely closed. Partially open the coarse adjust valve and slowly close the bypass valve until the desired vacuum is reached. Do not reverse direction of bypass valve; this will cause water to back up into the probe. If the desired vacuum is exceeded, either leak check at this higher vacuum or end the leak check as shown below and start over.

When the leak check is completed, slowly remove the plug from the inlet to the probe, and then turn off the vacuum pump. This prevents the water in the impingers from being forced backward into the filter holder and silica gel from being entrained into the third impinger.

Perform a leak check of the Pitot lines.
(See Method 2.1).

2.6.2 Leak Check During Sampling Run

If a component change (e.g. filter assembly or impinger) becomes necessary

during the sampling run, conduct a leak check immediately before the change is made. Use the pretest leak check procedure, but use a vacuum equal to or greater than the maximum value recorded up to that point in the test.

If the leakage rate is not greater than either $0.00057 \text{ m}^3/\text{min}$ (0.02 cfm) or 4 percent of the average sampling rate, the results are acceptable and no correction has to be applied to the total volume of dry gas metered. However, if the leakage rate exceeds either of these limits, the tester must either record the leakage rate and correct the sample volume as shown in Chapter X, Section 7, or void the sampling run immediately after component change.

2.6.3 Post Test Leak Check

A leak check is mandatory at the conclusion of each sampling run. Follow the procedures outlined in Section 2.6.1 at a vacuum equal to or greater than the maximum value reached during the sampling run.

Compare the leakage rate to the limits indicated in Section 2.6.2 and follow the procedure described there.

2.7 Sampling Train Operation

During the sample run, maintain an isokinetic sampling rate within 10 percent of true isokinetic.

For each run, record the data required on the data sheet shown in Figure 5.1-4. Be sure to record the initial dry gas meter reading. Record the dry gas meter readings at the beginning and end of each sampling time increment, when changes in flow rates are made, before and after each leak check, and when sampling is halted.

Record other data required by the sheet in Figure 5.1-4 at least once for each sample point during each time increment. Take additional readings when significant changes (20 percent variation in velocity head readings) require adjustments in flow rate.

Level and zero the manometer and make periodic checks during the traverse because the manometer level and zero may drift due to vibrations and temperature changes.

Clean the portholes prior to the test run to minimize the chance of contamination. To begin sampling, remove the nozzle cap and verify that the Pitot tube and probe are properly positioned.

During the period before sampling, the nozzle can be pointed downstream. Position the nozzle at the first traverse point and rotate the nozzle until the tip is pointing directly into the gas stream before turning on the sampling pump. Immediately start the pump and adjust the flow to isokinetic conditions.

Use calculators or nomographs to determine correct adjustment of the isokinetic sampling rate.

When the stack is under significant negative pressure (height of water in impinger stem), take care to close the coarse adjust valve before inserting the probe into the stack to prevent water from backing into the probe. If necessary,

the pump may be turned on with the coarse adjust valve closed.

When the probe is in position, block off the openings around the probe and porthole to prevent flow disturbance and dilution of the gas stream.

Traverse the stack cross section, as required by Method 1.1. Be careful to avoid bumping the probe nozzle into the stack walls when sampling near the walls or when removing or inserting the probe through the portholes. This minimizes the chance of extracting stack deposits.

During the test run, periodically add ice to maintain a temperature less than 15°C (60°F) at the condenser/silica gel outlet. Also, periodically check the level and zero of the manometer. Note and investigate any changes in stack temperature or velocity pressure over those measured during previous tests or traverses. Changes can mean failure of sampling equipment or a change in process.

If the pressure drop of the filter becomes too high, making isokinetic sampling difficult to maintain, the filter may be replaced during a

sample run. Use another complete filter assembly rather than attempting to change the filter itself. Before a new filter assembly is installed, conduct a leak check (see Section 2.6.2).

The total particulate weight includes the summation of all filter assembly catches. Use a single train for the entire sample run, except when sampling is required in two or more ducts or at two or more locations within the same duct, or when equipment failure necessitates a change of trains. When two or more trains are used, separate analyses of each train must be performed.

At the end of the sample run, turn off the coarse adjust valve, remove the probe and nozzle from the stack, turn off the pump, record the final dry gas meter reading, and conduct a post test leak check, as outlined in 2.6.3. Also, leak check Pitot lines as described in Method 2.1. The lines must pass this leak check to validate the velocity head data. Perform a gas volume meter check as described in Section 2.4.

2.8 Calculation of Percent Isokinetic

Calculate percent isokinetic, using the equation shown in Figure 5.1-6, to determine whether the run was valid or another test run should be made.

2.9 Sample Handling

Proper clean-up procedure begins as soon as the probe is removed from the stack at the end of the sampling period.

Allow the probe to cool. When the probe can be safely handled, wipe off all external particulate matter near the tip of the probe nozzle and place a cap over it to prevent losing or gaining particulate matter. Do not cap off the probe tip tightly while the sampling train is cooling down. This would create a vacuum in the probe, drawing water from the impingers into the probe.

Before moving the sample train to the clean-up site, remove the probe from the sample train, wipe off any stopcock grease, and cap the open outlets of the probe. Be careful not to lose any condensate that might be present. Wipe any

stopcock grease off of the impinger train inlet where the probe was fastened and cap it. Remove the umbilical cord from the last impinger and cap the impinger. If a flexible line is used between the first impinger and the probe, disconnect the line at the probe and let any condensed water or liquid drain into the impingers. After wiping off any stopcock grease, cap off the open inlet of the flexible line opening. Either ground glass stoppers, plastic caps, or serum caps may be used to close these openings.

Transfer the probe and filter-impinger assembly to the clean-up area. This area should be clean and protected from the wind to reduce chances of contaminating or losing the sample. It is recommended that sample recovery be performed in a controlled laboratory environment.

2.10 Calibration

See Chapter III.

METHOD 5.1

DETERMINATION OF PARTICULATE MATTER EMISSIONS FROM STATIONARY SOURCES USING A WET IMPINGEMENT TRAIN

Section 3 of 4

3. Laboratory Procedures

3.1 Apparatus

3.1.1 Sampling Train

See Section 2.1.1.

3.1.2 Sample Recovery

a. Balance

The balance must be accurate to the nearest 0.5 g.

b. Nylon Bristle Brushes with Stainless Wire Handles.

The probe brush must have extensions at least as long as the probe, and

made of stainless steel, Nylon, or Teflon, or similarly inert material. The brushes must be properly sized and shaped to brush out the probe liner and nozzle.

c. Wash Bottles

Glass wash bottles are recommended; polyethylene wash bottles may be used at the option of the tester.

d. Glass Sample Storage Containers

Use 500 ml or 1000 ml chemically-resistant, borosilicate glass bottles. Screw cap liners must be rubber-backed Teflon or constructed to be leak-free and resistant to chemical attack. Narrow mouth glass bottles are less prone to leakage. Alternatively, polyethylene bottles may be used.

e. Petri Dishes

For filter samples, use glass or polyethylene dishes, unless otherwise specified by the Executive Officer.

f. Plastic Storage Containers

Air-tight containers to store silica gel.

g. Funnel and Rubber Policeman

To aid in transfer of silica gel to container; not necessary if silica gel is weighed in the field.

h. Funnel

Glass or polyethylene, to aid in sample recovery.

3.1.3 Analysis of Particulate Matter

a. Glass Weighing Dishes

b. Desiccator

Containing indicating-type calcium sulfate or indicating-type silica gel desiccant.

c. Analytical Balance

To measure to 0.1 mg.

d. Beakers

600 to 1000 ml, 150 ml.

e. Hygrometer

To measure the relative humidity of the laboratory environment.

f. Temperature Gauge

To measure the temperature of the laboratory environment.

g. Drying Oven

$105^{\circ}\text{C} \pm 2^{\circ}\text{C}$ ($221 \pm 3.6^{\circ}\text{F}$).

h. Separatory Funnel

1000 ml.

i. Hot Plate

Heavy duty.

j. Ribbed Watch Glasses

k. Filtration Apparatus

Includes suction flask, filter holder
and vacuum pump.

l. Rubber Policeman

To aid in quantitative sample
transfer.

3.1.4 Acid and Sulfate Analysis

a. Beakers

400 or 600 ml.

b. Buret

10 ml or 50 ml (0.02 divisions), or autotitrator.

c. Hot Plate

Heavy duty.

d. Furnace

800-900°C (1470-1650°F).

e. Crucibles

Gooch, 20-40 ml. Prepared with asbestos mat and tared after 900°C (1650°F) and 6 hours desiccation.

f. Crucible tongs.

g. Analytical Balance

To measure to 0.1 mg.

h. Desiccator

Containing indicating-type calcium sulfate or indicating-type silica gel desiccant.

i. Hygrometer

To measure relative humidity.

j. Temperature Gauge

To measure the temperature of the laboratory environment.

k. Pipet

Graduated 25 ml, in 1 ml increments.

l. Sample Containers

To hold filter and impinger residue.

m. Stirring Rods

Glass.

n. Watch Glass

Ribbed, to cover beakers.

o. Filtration Apparatus

Includes suction flask, filter holder
and vacuum pump.

p. Steam Bath.

3.2 Reagents

3.2.1 Sample Collection Train Preparation

a. Filters

Same as Section 2.2 a.

b. Silica Gel

Same as Section 2.2.b.

c. Water

Same as Section 2.2 c.

d. Crushed Ice or Dry Ice Pellets

e. Stopcock Grease

Same as Section 2.2 e.

3.2.2 Sample Recovery

a. Water

Same as Section 3.2.1 c.

3.2.3 Analysis of Particulate Matter

a. Water

Same as Section 3.2.1 c.

b. Desiccant

Indicating-type anhydrous calcium sulfate, or silica gel (see Section 3.2.1 b.

c. Organic Solvent

Reagent grade dichloromethane with
 ≤ 0.001 percent residue.

3.2.4 Reagents for Analysis of Sulfuric Acid and
Sulfates

a. Water

Same as 2.2 c.

b. Sodium Hydroxide 0.1N

Dissolve 4.00 grams of sodium
hydroxide in 200 ml of carbon-dioxide
free water. Dilute to 1 liter with
carbon dioxide free water.

Standardize and protect from exposure
to air.

c. Methyl Orange Indicator

Aqueous.

d. Barium Chloride Solution, 10 Percent

Dissolve 100 grams of barium chloride dihydrate with 900 ml of water.

e. Hydrochloric Acid (HCl)

Concentrated.

f. Hydrochloric Acid (HCl) 0.1N
(Approximately)

Dilute 8.3 ml concentrated HCl to 1 liter water.

g. Silver Nitrate Test Solution

3.3 Pretest Preparation

All equipment, including balances, oven temperature, glassware, and safety equipment should be checked for readiness before proceeding. Weigh several 200 to 300 g portions of silica gel in air-tight containers to the nearest 0.5 g. Record the total weight of the silica gel plus container, on each container. As

an alternative, the silica gel may be weighed directly in its impinger or sampling holder just prior to train assembly.

Check filters visually against light for irregularities, flaws, or pinhole leaks. Label filters of the proper diameter on the back side near the edge using numbering machine ink. As an alternative, label the shipping containers (glass or plastic petri dishes), and keep the filters in these containers at all times except during sampling and weighing.

Desiccate the filter at $15 \pm 5.6^{\circ}\text{C}$ ($60 \pm 10^{\circ}\text{F}$) and ambient pressure for at least 24 hours. Weigh at intervals of at least 6 hours to a constant weight (i.e. 0.5 mg change from previous weighing); record each weight to the nearest 0.1 mg. During each weighing the filter must not be exposed to the laboratory atmosphere for a period greater than 2 minutes and a relative humidity above 50 percent. Alternatively, the filters may be oven dried at 105°C (220°F) for 2 to 3 hours, desiccated for 2 hours, and weighed.

During preparation and assembly of the sampling train, cover all openings wherever contamination can occur until just prior to assembly. Assemble the impingers in the tray as shown in Figure 5.1-1. Load each of the first two impingers with exactly 100 ml of water. Leave the third impinger empty. Place approximately 200 to 300 g of silica gel in the fourth impinger and record its weight to the nearest 0.5 g. More silica gel may be used, but ensure that it is not entrained and carried out of the impinger during sampling.

If moisture content is to be determined gravimetrically, weigh each impinger plus its contents to the nearest 0.5 g and record the weights.

Using a tweezer or clean disposable surgical gloves, place a weighed and identified filter in the filter holder. Be sure that the filter is properly centered and the gasket properly placed to prevent the sample gas stream from circumventing the filter. Check the filter for tears after assembly is completed.

circumventing the filter. Check the filter for tears after assembly is completed.

When using a glass liner, install the selected nozzle using a Viton A O-ring when stack temperatures are less than 260°C (500°F), and an asbestos string gasket when temperatures are higher (consult with source testers). Teflon ferrules may also be used for temperatures less than 350°F. With metal liners, install the nozzle as above or by a leak-free direct mechanical connection. Set up the train as in Figure 5.1-1 using a very light coat of stopcock grease on ground glass joints, greasing only the outer portion to avoid the possibility of contamination by the stopcock grease. Use of stopcock grease is not recommended unless it is absolutely necessary. Connect the impingers, and seal the train or its components for transport to the sampling site.

3.5 Sample Collection Train Leak Check

The sample collection train may be leak checked in the laboratory after assembly using the procedure in Section 2.5.

3.6 Sample Recovery

In most cases the intact and secured train is delivered to the laboratory for subsequent recovery. Occasionally, conditions demand that recovery be made by source testers in the field, but this is not recommended as a standard procedure. The following discussion is directed to source test or laboratory personnel. The latter should determine when laboratory recovery methods should be used. If the train is recovered in the field, collect the sample in leak-free containers, which are subsequently recovered in the laboratory (Section 3.6.5). If the train is recovered in the laboratory, collect the sample in analytical glassware, and delete container recovery.

Inspect the train for general condition. Note if the silica gel is completely expended, and if the train or its components are sealed. Note any unusual conditions that may affect results, including torn filters, cloudiness in the impinger liquids, etc.

3.6.1 Filter

Working in an area that is protected from the wind and free from dust, disconnect the filter holder from the rest of the train. Carefully remove the filter from the filter holder and place it in its identified petri dish container. Use a pair of tweezers and/or clean disposable surgical gloves to handle the filter. If it is necessary to fold the filter, fold the particulate cake to the inside. Carefully transfer to the petri dish any particulate matter and/or filter fibers which adhere to the filter holder gasket by using a dry nylon bristle brush and/or a sharp-edged blade. Seal the container.

3.6.2 Probe and Nozzle

Wipe the connection of the probe and train, and disconnect the probe from the train. During the probe and nozzle recovery, keep the remainder of the train sealed to prevent any contamination from occurring. Wipe down the outside of the probe and nozzle. Taking care to see that

dust on the outside of the probe or other exterior surfaces does not get into the sample, quantitatively recover particulate matter or any condensate from the probe nozzle, probe fitting, and probe liner by washing these components with water and placing the wash in a sample container.

Carefully remove the probe nozzle and clean the inside surface by rinsing with water from a wash bottle and brushing with a Nylon bristle brush. Brush until the rinse shows no visible particles, then make a final rinse of the inside surface with water. Similarly, brush and rinse the inside parts of the Swagelok fitting with water until no visible particles remain.

Rinse the probe liner with water by tilting and rotating the probe while squirting water into its upper end so that all inside surfaces are wetted. Let the water drain from the lower end into the sample container. A glass or polyethylene funnel may be used to transfer liquid washes to the container.

Follow the water rinse with a probe brush. Hold the probe in an inclined position and squirt water into the upper end as the probe brush is being pushed with a twisting action through the probe. Hold a sample container underneath the lower end of the probe and catch any water and particulate matter which is brushed from the probe. Run the brush through the probe three or more times until no visible particulate matter is carried out with the water or until none remains in the probe liner on visual inspection.

With stainless steel or other metal probes, run the brush through in the above prescribed manner at least six times, since metal probes have small crevices in which particulate matter can be entrapped. Rinse the brush and quantitatively collect these washings in the sample container. After the brushing, make a final rinse of the probe.

To reduce sample losses, it is recommend that two people clean the probe. Between

sampling runs, keep brushes clean and protected from contamination.

If the sample is recovered in the field, tighten the sample container lid and mark the fluid level to indicate if leakage has occurred during transport. Label the container to clearly identify its contents.

3.6.3 Impinger Catch

Wipe any dust or grit or water from the outside of the impingers, especially near the impinger joint. Carefully disconnect the impingers. Weigh the impingers plus content to the nearest 0.5 g and record the weights. Transfer the catch to a sample container. Clean all surfaces by rubbing them with a Nylon bristle brush and rinsing with water three times or more if necessary to remove visible particulates. Make a final rinse of each component and the brush.

If this recovery is performed in the field, tighten the sample container lid and mark the fluid level to indicate if

leakage has occurred during transport. Label the container to clearly identify its contents.

3.6.4 Silica Gel

Transfer the silica gel to its container and tighten the lid. Alternatively, weigh the impinger plus content to the nearest 0.5 g and record this weight, or seal the impinger for return to the laboratory.

3.6.5 Container Recovery

If the sample has been recovered in the field, check all the sample containers to ensure that no sample was contaminated or lost during transport.

For a liquid catch, note the liquid level in the container and determine if noticeable leakage has occurred. If so, void the entire sample. Wipe the cap area and transfer the sample to a beaker. Carefully rinse the cap and container into the beaker, tilting the container and using a brush if necessary to dislodge

throughout the total time of the particulate sample run, unless the effect on the velocity measurement and resulting stack flow rate calculation is less than 1 percent. In that case take the integrated sample immediately before, after, or for a shorter time during the particulate sample run.

Select a nozzle size based on the range of velocity heads encountered, so that it is not necessary to change the nozzle size to maintain isokinetic sampling rates. Do not change the nozzle size during the run. Choose the differential pressure gauge appropriate for the range of velocity heads encountered (see Method 2.1).

Select a probe length suitable for sampling all traverse points. Consider sampling large stacks from opposite sides (four sampling port holes) to reduce probe lengths.

Select a total sampling time equal to or greater than the minimum total sampling time specified in test procedures for the specific industry. The sampling time per point must not be less than 2 minutes and the total sample volume taken

(corrected to standard conditions) must not be less than 30 ft³.

To avoid timekeeping errors, it is recommended that the number of minutes sampled at each point should be an integer or an integer plus one-half minute. The sampling time should be the same at each point. In some circumstances, e.g. batch cycles, it may be necessary to sample for shorter times at the traverse points, resulting in smaller gas sample volumes. In these cases, test two or more cycles.

2.4 Gas Volume Meter Checks

Check the meter against the $\Delta H\theta$ orifice calibration obtained in Chapter III without the probe, filter and train connected. A pretest check is recommended. A post test check is mandatory.

Check the calibration of the metering system by performing calibration runs at three different flow rates. Set the flow rates at 0.4 cfm \pm 10 percent, 0.7 cfm \pm 10 percent, and 1.0 cfm \pm 10 percent. The calibration will be

particulate matter. Record the total volume to the nearest 10 ml, and proceed with the analysis.

Combine the probe and impinger catches. Note whether the silica gel, impinger, or container was properly sealed; weigh and record to the nearest 0.5 g.

3.7 Analysis

The South Coast Air Quality Management District has separate rules regulating the emissions of total and solid particulate matter and therefore it is necessary to analyze for both solid and liquid particulates from a single particulate sample. The only liquid particulates routinely analyzed are organics and sulfuric acid.

While the complete analysis for solid and liquid particulates is described in sequence in the following sections, not all steps are necessarily applied to every sample.

Where organics are not expected to be a significant portion of the combined probe and impinger catch (greater than 5 mg or 5 percent),

the organic extraction procedure found in Sections 3.7.2 and 3.7.3 may be eliminated, and the probe and impinger catch analysis begun directly with Section 3.7.4.

If the sampled gases contained SO_2 in concentrations less than 5 ppm, the analyses of combined probe and impinger catch for acid and sulfate found in Sections 3.7.6, 3.7.7, and 3.7.8 may be eliminated.

Finally, if the filter has collected more than 10 mg, it must be analyzed for acid and sulfate. Filter preparation for subsequent analysis is found in Section 3.7.5.

3.7.1 Filter Catch

Leave the contents in the shipping container or transfer the filter and any loose particulate from the sample container to a tared glass weighing dish. Desiccate for 24 hours in a desiccator containing anhydrous calcium sulfate. Weigh to a constant weight and report the results to the nearest 0.1 mg. For this method, the term "constant weight" means a

difference of no more than 0.5 mg or 1 percent of total weight less tare weight, whichever is greater, between two consecutive weighings, with no less than 6 hours of desiccation time between weighings.

Alternatively, the sample may be oven-dried at 105°C (220°F) for 2 to 3 hours, cooled in a desiccator, and weighed to a constant weight.

3.7.2 Probe and Impinger Catch - Insoluble Particulates

If organic extraction is to be performed, first filter the sample through a tared fiberglass filter dried at 105°C. This prevents any insolubles from interfering with the organic extraction. Rinse the filter and insoluble catch using dichloromethane and combine this rinse with the dichloromethane extract described in the next section. Dry the fiberglass filter at 105°C (220°F) and report as "Insoluble Particulate".

3.7.3 Probe and Impinger Catch - Organic Extraction

Transfer the aqueous filtrate from Section 3.7.2 to a separatory funnel.

Extract the aqueous catch five times with 25 ml portions of dichloromethane. Each time, extract for 30 seconds with vigorous shaking, then allow the layers to separate. This may take up to 15 minutes due to emulsion formation. When using dichloromethane, use gloves and work in a hood.

Drain the dichloromethane layers into a tared 150 ml beaker. Save the aqueous layer for use in Section 3.7.4. Evaporate the organic extract under a stream of clean filtered air at room temperature in a hood. Place in a desiccator overnight. Weigh the extract residue to the nearest 0.1 mg. Record the gross and tared weights and report the net weight as "Solvent Extract".

3.7.4 Probe and Impinger Catch - Soluble Residue

Quantitatively transfer the aqueous catch to a beaker. If solvent extraction has been performed, warm the sample on a hot plate, being careful to prevent any residual solvent from causing the sample to "bump". Use a ribbed watch glass to cover the beaker. This will allow scrubbing of the beaker walls and protect the sample from contamination. Concentrate the sample to about 50 ml.

Quantitatively transfer the aqueous concentrate to a tared 150 ml beaker and evaporate in an oven at 105°C (220°F) to dryness.

Weigh the residue to constant weight, to the nearest 0.1 mg, and record the weight. Desiccate the sample for 6 hours and reweigh the sample. Repeat until the weight changes less than 0.5 mg between weighings.

Add the insoluble and soluble weights from Sections 3.7.2 and 3.7.4 and report as

"Impinger Catch". Do not include the solvent extract.

3.7.5 Filter Catch - Preparation for Acid and Sulfate Analysis

Filters are analyzed for acid and sulfate if the filter catch is greater than 10 mg. The whole filter is processed. Cut the filter into pieces into a 400 ml beaker, being careful not to lose any sample. Submerge it in distilled water. Add 5.0 ml of approximately 0.1N HCl and soak the filter at least four hours, with occasional stirring. Recover the liquid quantitatively by vacuum filtration using a 0.45 micron cellulose ester paper and rinsing the sample filter at least three times with water. Process a blank filter at the same time following the same procedure.

3.7.6 Probe and Impinger Catch - Preparation for Acid and Sulfate Analysis

Add distilled water to the 150 ml beaker containing the residue from Section 3.7.4

until the beaker is three-fourths full.
Cover the beaker and allow it to soak at
least four hours.

3.7.7 Acid Analysis

Add several drops of methyle orange to
each extraction solution from Sections
3.7.5 and 3.7.6, including the blank
filter extract.

Titrate each solution with standardized
0.1N sodium hydroxide solution to a straw
yellow colored end point (pH 4.2). Record
the volumes to the nearest 0.02 ml.
Alternately, use an automatic titrator
known to be accurate.

Filter the aqueous catch through a 0.45
micron cellulose ester paper to remove any
insolubles, and quantitatively recover
this extract using at least three rinsings
with water.

3.7.8 Sulfate Analysis

Adjust each titrated solution from Section 3.7.7, to approximately pH 7 and add 2 ml of concentrated HCl. Place each beaker on the hot plate, add a stirring rod, and cover with a ribbed watch glass. Heat until the solution is nearly boiling. While stirring, slowly add 15 ml of 10 percent barium chloride solution. Let the precipitate settle. Add a ml of BaCl_2 ; if more precipitate forms, keep adding BaCl_2 until no more precipitate is produced. Allow the precipitate to digest several hours on the steam bath.

Quantitatively filter through a properly prepared Gooch crucible (see Section 3.1.4 e; use safety precaution while handling the asbestos for the mat). Rinse the mat thoroughly with hot distilled water and test for chloride in the rinse, using silver nitrate solution. If chloride is absent, place the crucible in the furnace and heat at 900°C (1650°F) for one hour. Cool and place the crucible in a

desiccator for at least 6 hours. Weigh until constant weight is reached (6 hours desiccation between weighings). Record to the nearest 0.1 mg.

3.8 Calculations and Reporting

Carry out calculations, retaining at least one decimal figure more than that of the acquired data. Round off figures after the final calculation. Summarize the data to be reported to source testers using the following listing:

Total Impinger Volume, ml (g)
Impinger Gain, ml (g)
Total Impinger Volume Incl. Washings, ml (g)
Silica Gel Gain, g
Organic Extract, mg
Insoluble Residue, mg
Soluble, or Total, Residue, mg
Acid, as $H_2SO_4 \cdot 2H_2O$, mg
Sulfate, as $H_2SO_4 \cdot 2H_2O$, mg
Filter Catch, mg
Acid, as $H_2SO_4 \cdot 2H_2O$, mg
Sulfate, as $H_2SO_4 \cdot 2H_2O$, mg

Calculate the above measurements as follows:

$$W_f - W_t$$

where:

W_f = Constant weight measurement of the
the sample plus container, to 0.1
mg

W_t = Tare weight of the sample
container, to 0.1 mg

Acid, as

$$\text{H}_2\text{SO}_4 \cdot 2\text{H}_2\text{O} = V \times N \times \frac{134.11}{2} \times \text{AF}$$

where:

V = Volume of sample titration (minus
blank, where required), ml

N = Normality of NaOH used

$\frac{134.11}{2}$ = Equivalent weight of $\text{H}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$

AF = Aliquot factor (sample volume/
analysis volume), normally 1

Sulfate,

as,

$$\text{H}_2\text{SO}_4 \cdot 2\text{H}_2\text{O} = (W_f - W_t) \times \frac{134.11}{233.43} \times \text{AF}$$

Where:

W_f = Constant weight of barium sulfate
precipitate plus crucible to 0.1
mg

W_t = Tare weight of crucible, to 0.1 mg

$$\frac{134.11}{233.43} = \text{Molecular weight of } \frac{\text{H}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}}{\text{BaSO}_4}$$

3.9 Calibrations

3.9.1 Balance Calibration

Calibrate the analytical balance using NBS traceable weights. Retain calibration records for each balance. These records are usually furnished yearly by a professional service providing the

calibrations. Check at least monthly for balance accuracy, using NBS traceable weights.

3.9.2 Furnace Check

Check the furnace and oven operating temperatures in accordance with the manufacturer's instruction manuals.

3.9.3 Sodium Hydroxide Standardization

Standardize the sodium hydroxide using the following procedure:

Dry crushed primary grade potassium acid phthalate (KHP) in an oven at 105°C (220°F) for two hours. Cool to room temperature in a desiccator. Weigh 0.95 g ± 0.05 g of KHP, to the nearest 0.1 mg, into an Erlenmeyer flask. Dissolve in 70 ml of water and add 2-4 drops of phenolphthalein indicator. Titrate quickly to a faint pink end point using 0.1N NaOH. Repeat this titration using another portion of KHP. Titrate duplicate 70 ml blanks of water using the above

procedure, and average the results. Replicate blanks must agree within 0.05 ml. Calculate the normality for each KHP aliquot as follows:

$$N = \frac{\text{mg KHP}/203.44}{(\text{ml std-avg. blank})}$$

Values must agree within 0.5 percent. Average the results and report to four significant figures. Label the sodium hydroxide with the normality, date of standardization, and reference to the data.

3.9.4 Autotitrator

Calibrate the pH meter of the autotitrator using pH 4 and pH 7 buffers and following the manufacturer's instructions.

METHOD 5.1

DETERMINATION OF PARTICULATE MATTER EMISSIONS FROM STATIONARY SOURCES USING A WET IMPINGEMENT TRAIN

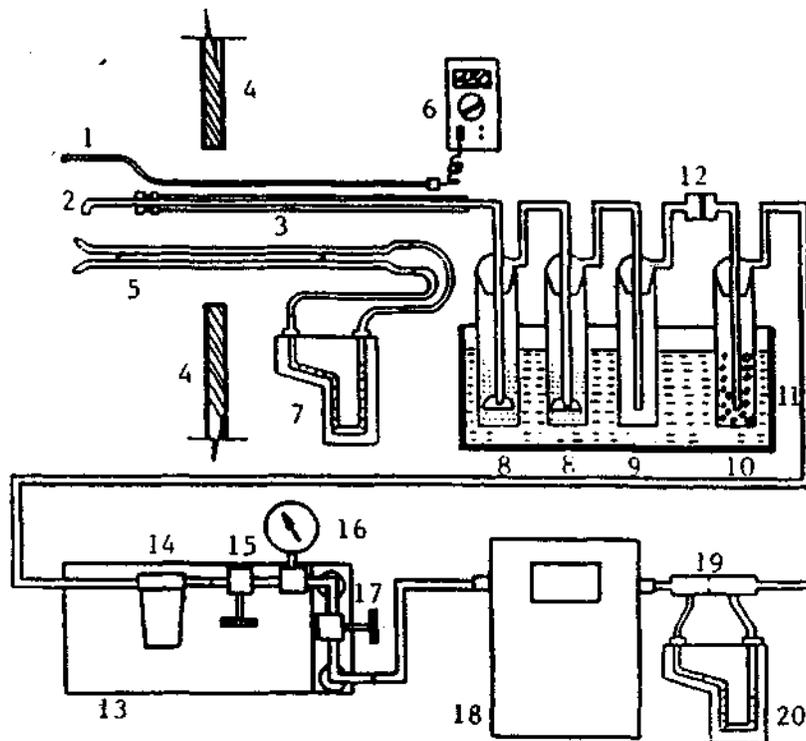
Section 4 of 4

4. Engineering Calculations and Reporting

4.1 Calculations

Carry out calculations, retaining at least one extra decimal figure beyond that of the acquired data. Round off figures after the final calculation. Other forms of the equations may be used as long as they give equivalent results.

See Figure 5.1-4, 5.1-5 and 5.1-6.



- | | |
|--|--|
| 1. Temperature Sensor | 11. Ice Bath |
| 2. Nozzle | 12. Filter |
| 3. Glass Lined Stainless Steel Probe | 13. Sealed Pump (Leak Free) |
| 4. S-type Pitot Tube | 14. Filter for Pump |
| 5. Stack Wall | 15. Metering Valve |
| 6. Temperature Sensor Meter | 16. Vacuum Gauge |
| 7. Pitot Tube Inclined Manometer | 17. By-pass Valve |
| 8. Impinger with 100 ml H ₂ O | 18. Temperature Compensated
Dry Gas Meter |
| 9. Empty Bubbler | 19. Orifice |
| 10. Bubbler with Silica Gel | 20. Orifice Inclined Manometer |

Figure 5.1-1

Particulate Sampling Train Setup-Wet Impingement Method

Nozzle Calibration

Date _____

Calibrated by _____

Nozzle identification number	D_1 mm (in.)	D_2 mm (in.)	D_3 mm (in.)	ΔD mm (in.)	D_{avg}

where

$D_{1,2,3}$ = nozzle diameter measured on a different diameter, mm (in.). Tolerance = measure within 0.25 mm (0.001.)

Δ = maximum difference in any two measurements, mm (in.). Tolerance = 0.1 mm (0.004 in.)

D_{avg} = average of D_1 , D_2 , D_3 .

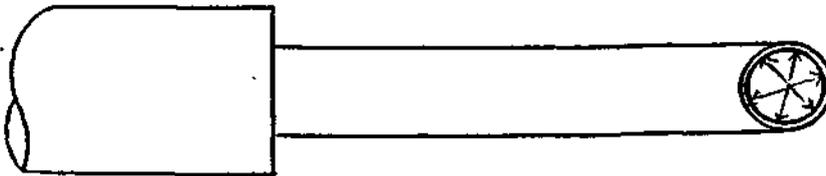


Figure 5.1-2
Nozzle Calibration Sheet

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT

Test No. _____

METER/PUMP SAMPLING SYSTEM CHECK

Pretest: _____ Date _____ Time _____

Meter # _____
 Pump # _____
 Orifice # _____

A - Orifice ΔH (in H ₂ O)	B - Metered Volume (ft ³)	C - Time (seconds)	K*
0.40			
0.75			
1.6			

Average _____

Performed by _____
 Senior _____

Post Test: _____ Date _____ Time _____

A - Orifice ΔH (in H ₂ O)	B - Metered Volume (ft ³)	C - Time (seconds)	K*
0.40			
0.75			
1.6			

Average _____

Performed by _____
 Senior _____

$$*K = \frac{60 \times B}{C \times \sqrt{A}}$$

*Maximum allowable difference in any two measurements of K is 0.02.

Figure 5.1-3
 Meter Calibration Sheet

CALCULATION SHEET

PAGES	PAGE
TEST NO.	DATE
PROCESSED BY	CHECKED BY

LAB ANALYSIS

A. Filter Catch	_____	mg
B. (1) Filter Acid	_____	mg
(2) Filter Total Sulfate	_____	mg
C. Probe Catch	_____	mg
D. (1) Probe Acid	_____	mg
(2) Probe Total Sulfate	_____	mg
E. Impinger Catch	_____	mg
F. (1) Impinger Acid	_____	mg
(2) Impinger Total Sulfate	_____	mg
G. Organic Extract	_____	mg
H. H ₂ SO ₄ .2H ₂ O from SO _x Train Thimble	_____	mg
I. Particulate Train Corrected Gas Volume Metered	_____	dscf
J. SO _x Train Corrected Gas Volume Metered	_____	dscf
K. Prorated H ₂ SO ₄ .2H ₂ O Mass ($\frac{H \times I}{J}$)	_____	mg

FILTER (PARTICULATE) TEMPERATURE GREATER THAN 200°F

L. Total Particulate (A-B*+C-D*+E-F*+G+K)	_____	mg
M. Solid Particulate (L-G-K)	_____	mg
N. Total Particulate (Corrected for Ammonium Sulfate) (A-B*+C-D*+E-F(1)+G+K-[F(2)-(1)] $\cdot \frac{132}{134}$)	_____	mg
O. Solid Particulate (Corrected for Ammonium Sulfate) (N-G-J)	_____	mg

FILTER TEMPERATURE LESS THAN 200°F

P. Total Particulate (A+C+E-F*+G)	_____	mg
Q. Solid Particulate (P-B*-D*-C)	_____	mg
R. Total Particulate (Corrected for Ammonium Sulfate) (A+C+E-F(1)+G-[F(2)-F(1)] $\cdot \frac{132}{134}$)	_____	mg
S. Solid Particulate (Corrected for Ammonium Sulfate) (R-B*-D*-C)	_____	mg

* USE LOWER OF (1) AND (2)

Figure 5.1-5
Calculation Data Sheet for Particulate Matter

Test No. _____ Sampling Train _____ Date _____
 Calculated By _____ Checked By _____

SOURCE TEST CALCULATIONS

SUMMARY

- A. Average Traverse Velocity (Pre-Test) _____ fps
- B. Average Reference Point Velocity (Pre-Test) _____ fps
- C. Average Traverse Velocity (During Test) _____ fps
- D. Gas Meter Temperature (Use 60°F, for Temp. Comp. Meters) _____ °F
- E. Gas Meter Correction Factor _____
- F. Average Stack Temp. ... _____ °F
- G. Stack Cross-Sect. Area _____ ft²
- H. Barometric Pressure ... _____ "HgA
- I. Gas Meter Pressure _____ "HgA
- J. Total Stack Pressure .. _____ "HgA
- K. Pitot Correction Factor _____
- L. Sampling Time _____ min
- M. Nozzle Cross-Sect. Area _____ ft²
- N. Net Sample Collection .. _____ mg
- O. Net Solid Collection .. _____ mg
- P. Water Vapor Condensed .. _____ ml
- Q. Gas Volume Metered _____ dcf
- R. Corrected Gas Volume Metered $\left[(C \times I / 29.92) \times \frac{520}{(460 + D)} \times E \right]$ _____ dscf

PERCENT MOISTURE / GAS DENSITY

- S. Percent Water Vapor in Gas Sample $\left[\frac{4.64 \times P}{(0.0464 \times P) + R} \right]$ _____ %
- T. Average Molecular Weight (Wet):

(Component)	(Volume % / 100) x (1 - S/100) x (Molec. Wt.) = (Wt./Mole)		
Water		1.00	18.0
Carbon Dioxide	Dry Basis		44.0
Carbon Monoxide	Dry Basis		28.0
Oxygen	Dry Basis		32.0
Nitrogen/Inerts	Dry Basis		28.2
		(Sum)	

FLOW RATE

- U. Gas Density Correction Factor ($\sqrt{29.95/T}$) _____
- V. Flue Correction Factor (A/B) _____
- W. Velocity Pressure Correction Factor ($\sqrt{29.92/J}$) ... _____
- X. Corrected Velocity (C x K x U x V x W) _____ fps
- Y. Flow Rate (X x G x 60) _____ cfm
- Z. Flow Rate $\left[Y \times \frac{J}{29.92} \times \frac{520}{(460 + F)} \right]$ _____ scfm
- AA. Flow Rate $\left[Z \times (1 - S/100) \right]$ _____ dscfm

SAMPLE CONCENTRATION/EMISSION RATE

- BB. Sample Concentration (0.01543 x N/R) _____ gr/dscf
- CC. Sample Concentration (54,143 x BB/ _____ Molec. Wt.) ... _____ ppm (dry)
- DD. Sample Emission Rate (0.00857 x AA x BB) _____ lb/hr
- EE. Solid Emission Rate $\left(\frac{0.0001322 \times O. \times AA}{R} \right)$ _____ lb/hr
- FF. Isokinetic Sampling Rate $\left(\frac{G \times R \times V \times 100}{L \times M \times AA} \right)$ _____ %

Figure 5.1-6
 Calculation Sheet

APPENDIX E
Particle Size Distribution Determination

2. Principle of Operation

The principle of operation of the MOUDI™ is the same as any inertial cascade impactor with multiple nozzles. At each stage jets of particle laden air impinge upon an impaction plate, particles larger than the cut-size of that stage cross the air streamlines and are collected upon the impaction plate. The smaller particles with less inertia do not cross the streamlines and proceed on to the next stage where the nozzles are smaller, the air velocity through the nozzles is higher and finer particles are collected. This continues on through the cascade impactor until the smallest particles are collected at the after-filter.

Figure 1 shows a schematic diagram of one stage of the MOUDI™, say the Nth stage. Each stage contains the impaction plate for the proceeding (N-1) stage and the nozzle plate for itself (the Nth stage). By rotating this stage relative to those above and below, the impaction plate for the N-1 stage will be rotating relative to the N-1 stage nozzle plate and the Nth stage nozzle plate will be rotated relative to the stationary Nth stage impaction plate below. Simply by rotating every other stage of the impactor and holding the others stationary, every nozzle plate/impaction plate combination will have relative rotation. This is what allows the MOUDI™ to achieve a near uniform particle deposit.

Rotation of every other stage is achieved by attaching a ring gear to the odd numbered stages that will mesh with drive gears on the shaft in the rotator cabinet. The even numbered, non rotating stages are held stationary by hooks that engage bearings on the same drive shaft.

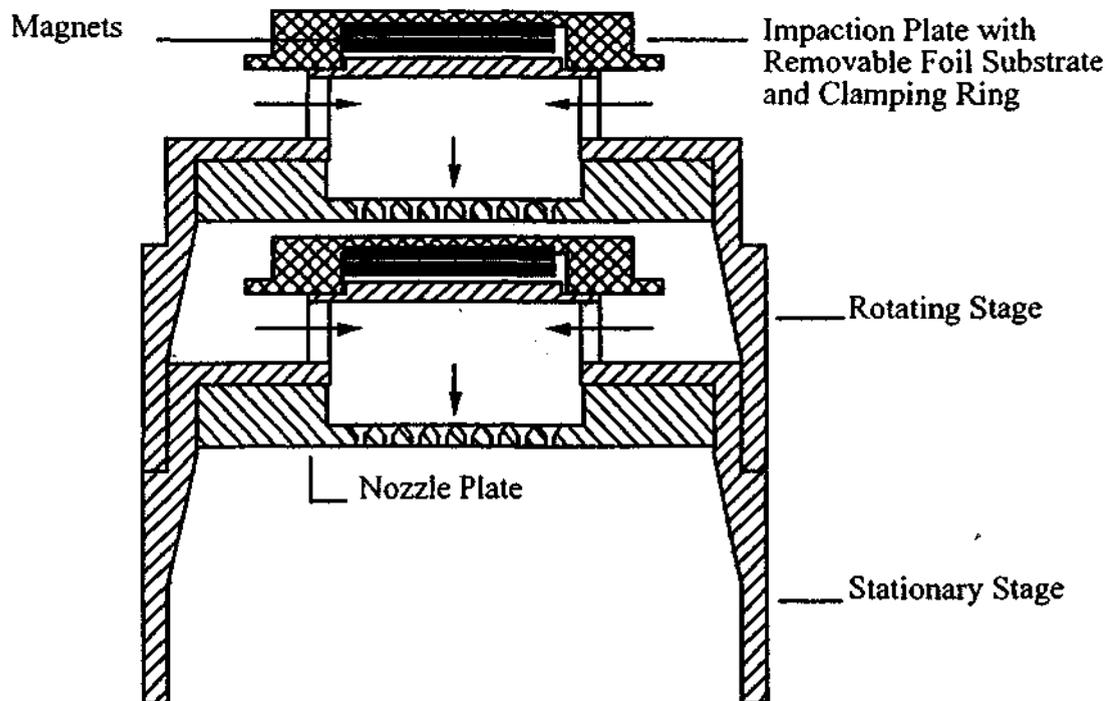


Figure 1. Schematic diagram of a typical MOUDI™ stage.

3. Description of MOUDI™

The MOUDI™ consists of two basic assemblies. One is a cascade impactor and the other is the rotator cabinet. The impactor can be used without the rotator cabinet, however, without rotation the material collected on the impaction plates will not be uniformly distributed over the plate.

Figure 2 shows the impactor in its simplest form. This is a non-rotating version and consists of 8 stages plus an after-filter located in the base.

In order to rotate every other stage of the impactor, it must be equipped with gears and hooks as shown in Figure 3. This assembly is inserted into the rotator cabinet, Figure 4, to complete the final assembly as shown in Figure 5.

Figure 6 is a picture of a partially disassembled MOUDI™ showing the inlet, the impactor stages, the filter base and filter base cover. Figure 7 shows the impaction plate, the substrate hold-down ring and the nozzle plate.

Technical Note: Although this is considered an 8 stage cascade impactor, an impaction plate can also be placed on top of the first stage. This impaction plate along with the inlet tube can constitute a 0th stage. By removing particles at this point (the cut size of which is 18µm), an upper size limit for particles collected on the first stage is obtained.

The primary purpose of the rotator, shown in Figure 4, is to provide a drive shaft which rotates every other stage in the MOUDI™. The rotator also houses the pressure gauges and a valve for controlling the flow of air through the MOUDI™. The upper pressure gauge monitors the pressure drop across the upper stages, to provide information on the flow rate through the impactor. The lower pressure gauge monitors the pressure drop across the final stages.

Service Note: If the pressure drop across the final stages begins to rise while the flow remains constant, it indicates that the nozzles in the final stages are becoming dirty and it is time for them to be cleaned. The micro-orifice nozzles used in the final stages are quite small (50 to 100µm in diameter) and can become partially clogged due to particle deposition by impaction or diffusion (Brownian and turbulent). When this occurs the pressure drop across the nozzle plates will rise.

Caution: Do not clean any part of the MOUDI™ in an ultra-sonic bath. The proper cleaning procedure is to soak the stage bodies in water containing a mild detergent or another cleaning solvent followed by rinsing the bodies in distilled water and then with alcohol.

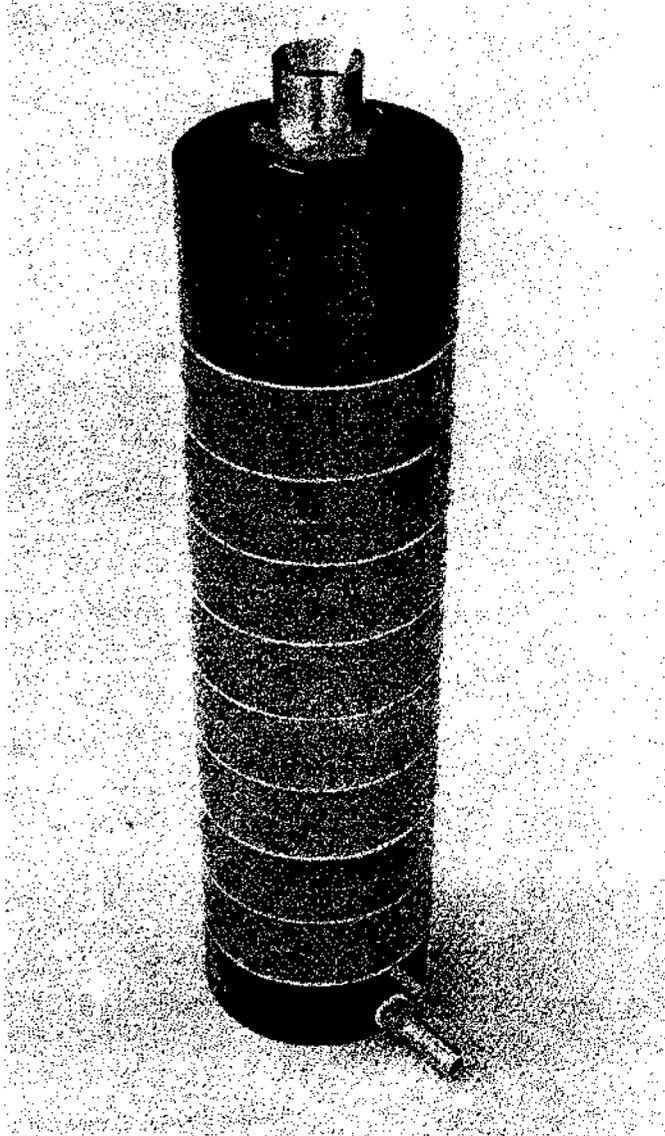


Figure 2. Non-rotating version of impactor

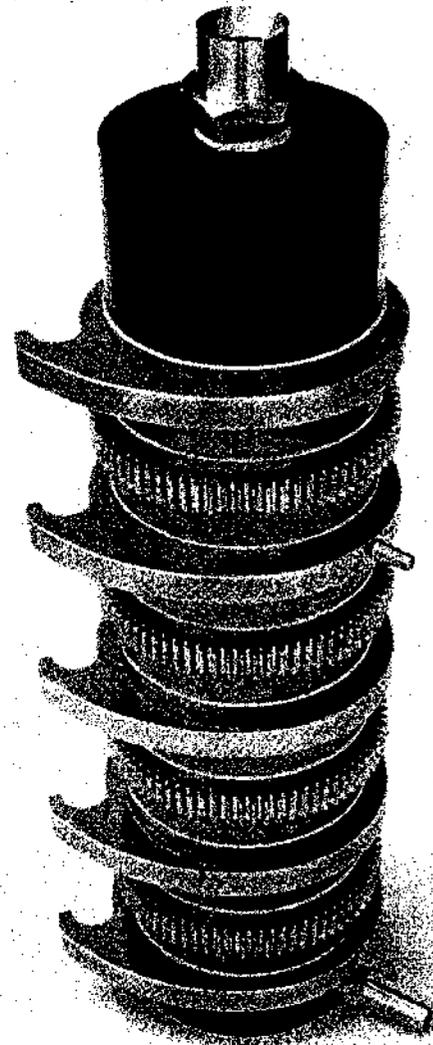


Figure 3. Rotating version of impactor

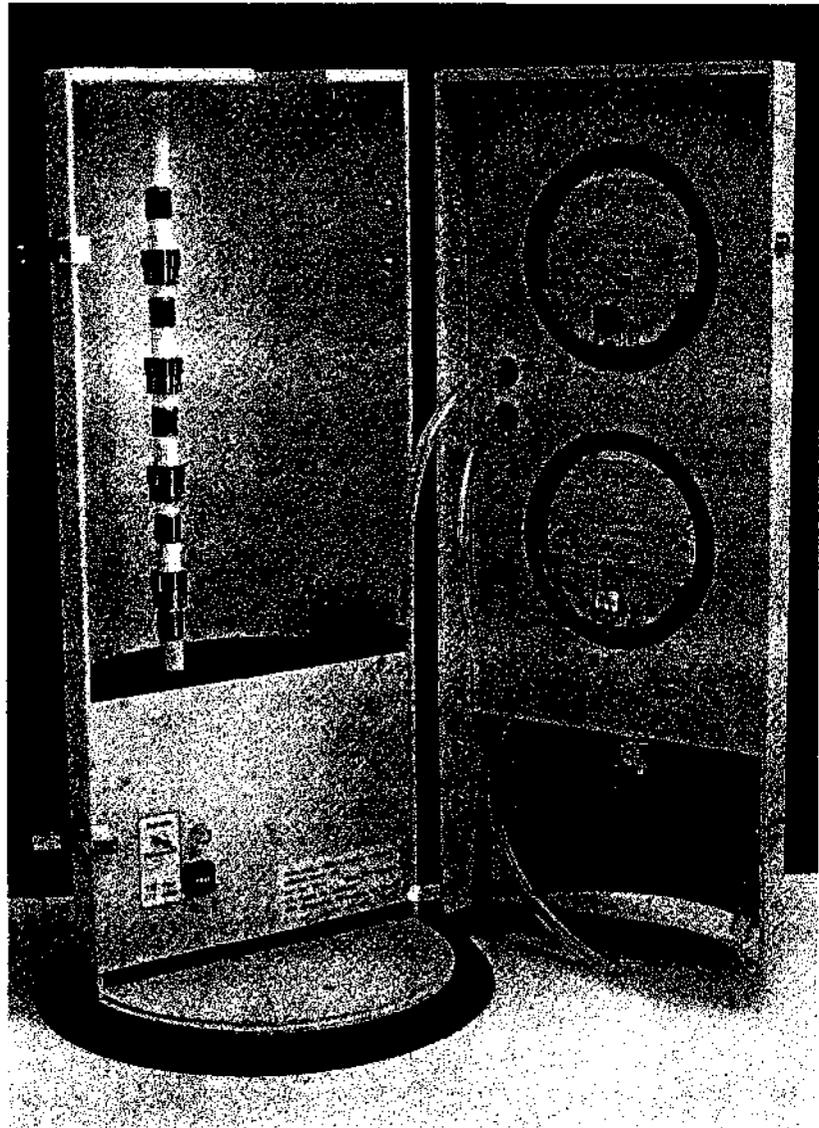


Figure 4. Rotator unit

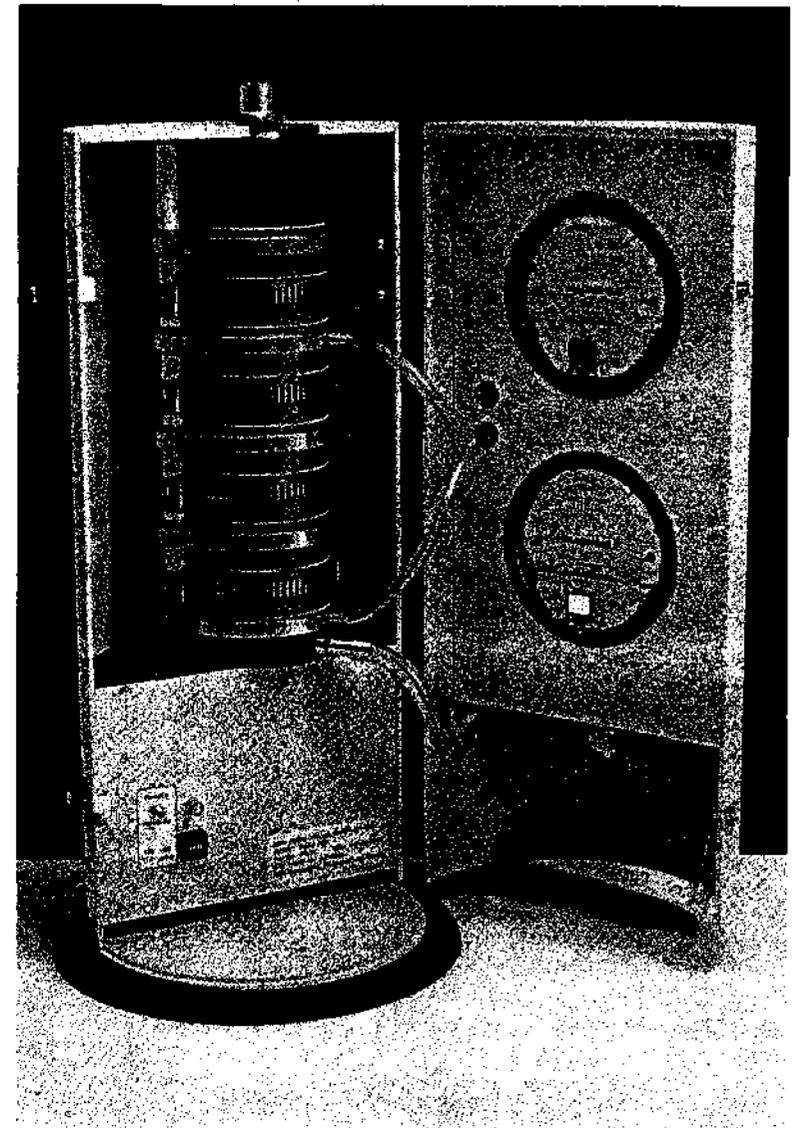


Figure 5. Fully assembled unit, rotator and impactor

3.1. Cut Sizes and Efficiency Curves

The nominal cut-size of each impactor stage is shown in Table I, and the particle collection efficiency curves are shown in Figure 8. The calibrations were performed with the Berglund-Liu Vibrating Orifice Monodisperse Aerosol Generator for particle sizes larger than 1.0 μm and with the electrostatic classifier technique for sub-micrometer particles. For more detailed information on aerosol generation see Berglund and Liu (1973) and Liu and Pui (1974)

Table I
Cut Size and Number of Nozzles

Stage	Cut Size μm	Number of Nozzles
Inlet	18	1
1	10	1
2	5.6	10
3	3.2	10
4	1.8	20
5	1.0	40
6	0.56	80
7	0.32	900
8	0.18	900
9	0.10	2000
10	0.056	2000
Filter	0	--

Note: Only eight of the ten stages can be used at one time in an 8 stage MOUDI™ rotator cabinet. For the non-rotating version, any number of stages can be used. See the data sheet supplied with each unit for the calibrated cut points for that particular impactor.

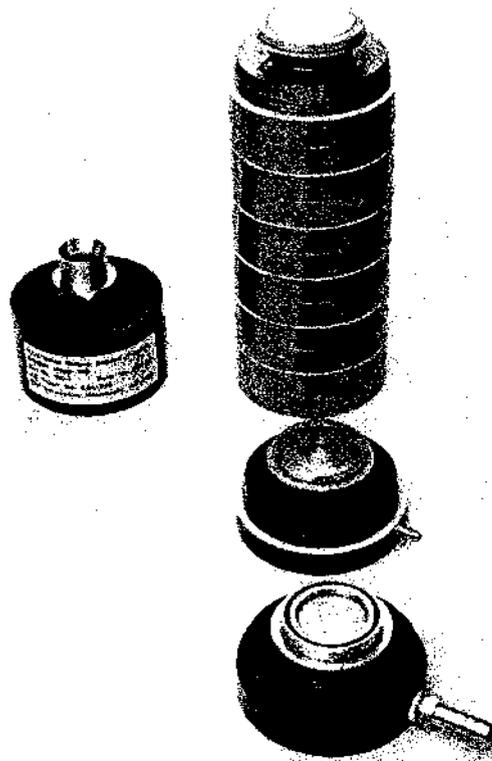


Figure 6. Partially disassembled impactor unit

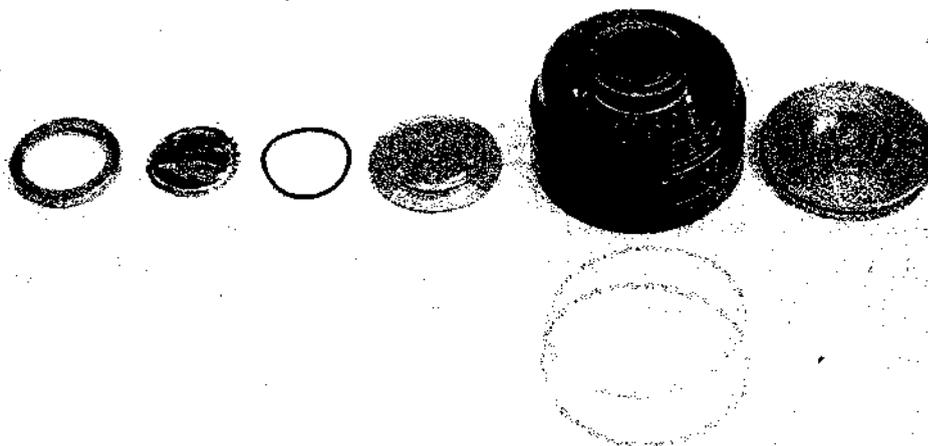


Figure 7. Parts of an individual MOUDI™ stage

4. Operation

4.1 Disassembly and Substrate Removal

*Disassemble the MOUDI™ prior to each use to verify proper interstage o-ring grease.

To remove the impactor from the rotator cabinet, plug the cabinet into a 110 VAC outlet and hold the switch in the reverse position. The drive shaft will rotate clockwise and the impactor will disengage from the shaft.

Each impactor stage consists of a body, the impaction plate for the stage above and the nozzle plate for the stage below. The impactor is disassembled by first removing the inlet and then each stage of the impactor from the top down to the base. The impaction plates need to be removed so that the impaction substrates can be replaced. Removal of the impaction plate substrates and the after-filter can be performed at the test site or laboratory. If necessary, the nozzle plates can be taken out by removing the three screws and pushing down on the nozzle plate through the screw holes.

Caution: Never push directly on the center of the nozzle plate. This part of the plate is quite thin and easily damaged.

The final step in disassembling the MOUDI™ is to remove the after-filter. This is accomplished by unscrewing the filter base cover from the filter base. Remove the filter holder from the base by lifting upward. Take off the hold down ring and remove the filter. The filter holder has a pin on the hold down ring so that the ring must be lifted straight up.

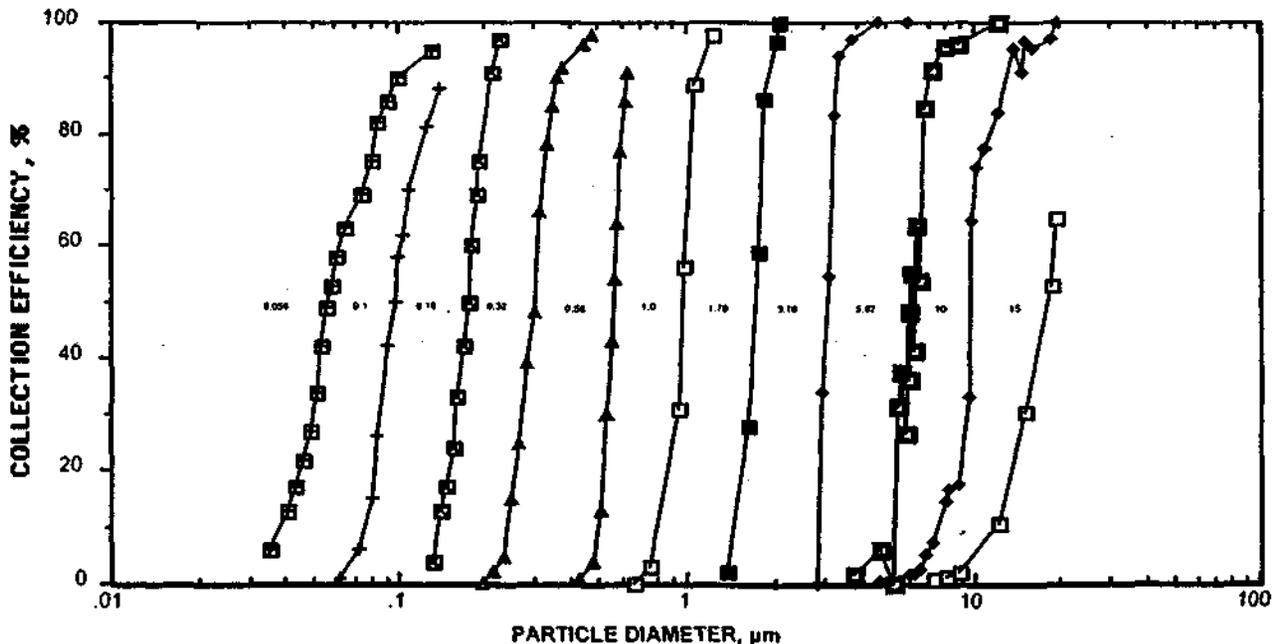


Figure 8: Nominal Collection Efficiency Curves

4.2 Assembly and Substrate Installation

Assembly of the MOUDI™ is the reverse of disassembly. First, substrates are placed into the impaction plate holders by removing the ring, inserting a substrate, and then pressing the ring back onto the holder. A filter is inserted into the after-filter holder in the same fashion. Care must be taken to align the pin on the hold-down ring with the hole in the filter holder.

The filter holder is then placed onto the base and the filter base cover is screwed into place. Next, place an impaction plate on the pedestals of the filter base cover and each stage. Assemble the stages in reverse order with the smallest cut-size at the bottom and the largest at the top. The impactor cut-sizes are etched into the nozzle plates and can be read from underneath the stage. The stages are also numbered on the outside of each stage body. Lastly, place the cap on top of the MOUDI™. Rotate the cap, stage 5 and the filter base cover so that the three small hose fittings are parallel.

Place the impactor in the rotator cabinet and turn on the drive motor for a few seconds (if you are using a voltage changer supplied by MSP Corporation see Appendix B for proper hookup of MOUDI™ rotator cabinet to voltage changer). This will pull the MOUDI™ into the rotator cabinet and fully engage the hooks and gears. Connect the pressure gauges to the MOUDI, the upper tube to the upper small hose fitting, the middle to the middle and the lower to the lower. Finally connect the tube from the flow control valve to the large fitting in the base of the MOUDI™ and connect the tube from the other side of the valve to a pump or other vacuum source.

Caution: Periodically apply a moderate amount of grease to the double O-Rings between stages when reassembling the MOUDI™. If these O-Rings become dry, the torque required to rotate the MOUDI™ may cause damage to the motor.

Caution Labels are used on the MOUDI™ rotator cabinet to indicate points of possible danger. Places of danger from high voltages, inside the cabinet, are indicated by a label showing a lightning bolt centered in a yellow triangle. Places that pose a danger of finger pinch are indicated by a label showing black silhouettes of gears and a hand on a white background, all surrounded by the universal "no" symbol of red circle with red diameter.

APPENDIX F
Sample Calculations

UNIVERSITY OF CALIFORNIA, RIVERSIDE

CE-CERT

Test No. : 010925-1
 Sampling Location : On roof of chamber
 Sampling Train : Mod. PM5.1 TR#2A

Test Date : 09/25/01
 Input by : Bill Welch

SOURCE TEST CALCULATIONS (VELOCITY)

Pre-test Velocity Leak Check: OK

Post-Test Velocity Leak Check: OK

Stack Diameter: 12.0 in
 Nozzle Diameter: 0.2995 in
 Nozzle Cross Area: 0.000489 ft²
 Barometric Pressure: 28.82 in-Hg
 Static Pressure in Stack: -0.92 in-water

Gas Meter Correction Factor: 0.9843
 Pitot Factor: 0.840
 K Factor: 0.5784
 % of Moisture: 2.00
 Sampling Time: 30 min

Time (min)	Traverse Point	Gas Meter Reading	Vel Head (" water)	Temp (°F)	Calc. Vel (fps)	Sampling Rate (cfm)	Theo. Orif P (" water)	Act. Orif P (" water)	Meter Temp		
									In (°F)	Out (°F)	
		491.393									
2.5	1	493.35	0.30	119	38.22	0.828	2.29	2.05	90	90	
5	2	495.45	0.30	119	38.22	0.828	2.29	2.34	90	89	
7.5	3	497.65	0.29	120	37.61	0.813	2.21	2.59	91	90	
10	4	499.692	0.25	119	34.89	0.755	1.91	2.24	92	90	
12.5	5	502.15	0.39	122	43.69	0.941	2.99	3.26	94	91	
15	6	504.5	0.39	122	43.69	0.941	2.99	2.98	94	91	
17.5	7	507.1	0.33	121	40.16	0.866	2.53	3.64	94	90	
20	8	509.974	0.22	118	32.70	0.709	1.70	4.46	95	90	
22.5	9	511.22	0.33	120	40.12	0.867	2.53	0.84	93	91	
25	10	513.65	0.37	122	42.56	0.917	2.83	3.19	95	90	
27.5	11	516.05	0.36	122	41.98	0.904	2.77	3.12	96	91	
30	12	518.227	0.28	123	37.05	0.797	2.15	2.57	96	91	
Net Volume		26.834									
Average			0.318	120.6	39.241	0.8472	2.433	2.773	93.3	90.3	
									Average		91.8 °F

UNIVERSITY OF CALIFORNIA, RIVERSIDE

CE-CERT

Test No. : 010925-1
 Sampling Location : On roof of chamber
 Sampling Train : Mod. PM5.1 TR#2A

Test Date : 09/25/01
 Input by : Bill Welch

SOURCE TEST CALCULATIONS (VELOCITY)

SUMMARY

Stack Diameter:	12.0 in	Nozzle Diameter:	0.2995 in
A. Average Traverse Velocity.....			39.241 fps
B. Gas Meter Temperature (Use 60 °F for Temp Comp. Meters).....			91.8 °F
C. Gas Meter Correction Factor.....			0.9843
D. Average Stack Temp. :	120.6 °F	J. Sampling Time :	30 min
E. Stack Cross Sect. Area :	1.00 ft ²	K. Nozzle Cross Sect. Area :	0.000489 ft ²
F. Barometric Pressure :	28.82 in HgA	L. Net Sample Collection :	66 mg
G. Gas Meter Pressure :	29.02 in HgA	M. Net Solid Collection :	43 mg
H. Total Stack Pressure :	28.75 in HgA	N. Water Vapor Condensed :	8.7 ml
I. Pitot Correction Factor :	0.84	O. Gas Volume Metered :	26.834 dcf
P. Corrected Gas Volume [(O x G/ 29.92) x 520/ (460 + B) x C].....			24.144 dscf

PERCENT MOISTURE DENSITY

Q. Percent Water Vapor in Gas Sample [(4.64 x N)/ ((0.0464 x N) + P)]..... 1.48 %

R. Average Molecular Weight (Wet):

Component	Vol. Fract.	x	Moisture fract.	x	Molecular Wt.	=	Wt/ Mole
Water	0.0148		1.00		18		0.267
Carbon Dioxide	0.002 (dry basis)		0.99		44		0.087
Carbon Monoxide	3.92E-05 (dry basis)		0.99		28		0.001
Oxygen	0.209 (dry basis)		0.99		32		6.589
Nitrogen & Inerts	0.774 (dry basis)		0.99		28.2		21.507
						SUM =	28.451

FLOW RATE

S. Gas Density Correction Factor [(28.95/ R)^5]..... 1.009
 T. Velocity Pressure Correction Factor [(29.92/ H)^5]..... 1.020
 U. Corrected Velocity [A x I x S x T]..... 33.92 fps
 V. Flow Rate [U x E x 60]..... 2035.11 cfm
 W. Flow Rate (Standard) [V x (H/ 29.92) x (520/ (460 + D))]..... 1751.62 scfm
 AA. Flow Rate (Dry Standard) [W x (1 - Q/ 100)]..... 1725.66 dscfm

SAMPLING CONCENTRATION/ EMISSION RATE

BB. Sample Concentration [0.01543 x (L/ P)]..... 0.042 gr/ dscf
 CC. Sample Concentration [54,143 x (BB/ NA (molecular Wt.))]..... 22.84 ppm (dry)
 DD. Sample Emission Rate [0.00857 x AA x BB]..... 0.624 lb/ hr
 EE. Solid Emission Rate [(0.0001322 x M x AA)/ P]..... 0.406 lb/ hr
 FF. Isokinetic Sampling Rate [(E x P x 100)/ (J x K x AA)]..... 95.3 %

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CE-CERT

Test No. : 010925-1
Sampling Location : On roof of chamber
Sampling Train : Mod. PM5.1 TR#2A

Test Date : 09/25/01

Input by : Bill Welch

PM 5.1 CALCULATIONS

LAB ANALYSIS

Moisture Gain:	<u>8.7 g</u>
Organic Extract:	<u>23 mg</u>
Insoluble:	<u>2 mg</u>
Soluble:	<u>11 mg</u>
Filter	<u>30 mg</u>

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Test No. : 010925-1
 Sampling Location : On roof of chamber
 Sampling Train : Mod. PM5.1 TR#2A

Test Date : 09/25/01
 Input by : Bill Welch

K* Determination

Pre-Test				
Orifice del-h (in-Hg)	Volume final (ft ³)	Volume initial (ft ³)	Time (s)	K*
2.6	481.400	480.400	61.47	0.6053
1.9	482.900	481.900	76.53	0.5688
1.0	484.300	483.300	102.43	0.5858
Average:				0.5866

Post-Test				
Orifice del-h (in-Hg)	Volume final (ft ³)	Volume initial (ft ³)	Time (s)	K*
2.6	560.400	559.400	65.65	0.5668
1.9	562.800	561.800	77.85	0.5591
1.0	563.700	562.700	102.60	0.5848
Average:				0.5702

Average K* for experiment: 0.5784

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Test No. : 010925-1
 Sampling Location : On roof of chamber
 Sampling Train : Moudi

Test Date : 09/25/01
 Input by : Bill Welch

Moudi-- K* Determination

Pre-Test				
Orifice del-h (in-Hg)	Volume final (ft ³)	Volume final (ft ³)	Time (s)	K*
2.6	856.000	855.000	68.21	0.5455
1.9	858.000	857.000	80.60	0.5401
1.0	861.000	860.000	107.19	0.5598
Average				0.5484

Post-Test				
Orifice del-h (in-Hg)	Volume final (ft ³)	Volume final (ft ³)	Time (s)	K*
2.6	541.500	540.500	65.19	0.5708
1.9	542.800	541.800	77.54	0.5614
1.0	544.100	543.100	104.67	0.5732
Average				0.5685

Average K* for experiment: 0.5585

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Test No. : 010925-1
 Sampling Location : On roof of chamber
 Sampling Train : Moudi

Test Date : 09/25/01
 Input by : Bill Welch

Moudi Catch Data

Initial Volume: 973.535 (ft³)
 Final Volume: 997.774 (ft³)
 net volume: 24.239 (ft³) probe: 116 4.785676

Filter #	Stage size (µm)	Tare weight (mg)	Final weight (mg)	Weight gain (mg)	% on stage (%)	mg/ft ³
1	18.0	78.198	78.233	0.035	0.08	0.00
2	9.9	77.35	77.371	0.021	0.05	0.00
3	6.2	78.393	78.42	0.027	0.06	0.00
4	3.1	77.463	77.958	0.495	1.15	0.02
5	1.8	77.47	78.726	1.256	2.91	0.05
6	1	78.02	80.475	2.455	5.68	0.10
7	0.54	77.5	83.5	6.000	13.89	0.25
8	0.295	77.5	93.661	16.161	37.42	0.67
9	0.17	77.162	88.314	11.152	25.82	0.46
10	0.094	77.545	81.816	4.271	9.89	0.18
11	0.053	77.493	77.918	0.425	0.98	0.02
After (<0.053)	0.0296	75.454	76.345	0.891	2.06	0.04
sum				43.189	100.00	

	mg/min	%	lb/hr
total	11816.208		1.5616134
D > 10	8529.9275	72.188366	1.1273032
10 > D > 2.5	16.658	0.1409759	0.0022015
D < 2.5	3033.6224	25.673401	0.4009193

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Moudi Size Distribution Graphs

