

**Development of a Standard Method of Test for  
Commercial Kitchen Effluent Grease Removal Systems**

**Draft Final Report**

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## 1. EXECUTIVE SUMMARY

The main objective of this project was to develop a reliable, repeatable, and practical method of test to determine the performance of devices intended to capture grease particles in commercial cooking effluent. Characterization of commercial cooking effluent by ASHRAE 745-RP documented the particulate and vapor phases that entered the exhaust hood, their concentrations and mass flow rates, particle size distributions, and how these varied widely by appliance and typical food product. Kitchen equipment manufacturers have subsequently been developing better grease capture devices.

To develop a standard method of test, several issues needed to be addressed. These included test facility design, construction and characterization, instrumentation requirements, effluent characterization, surrogate particle generation methods and a procedure to determine the collection efficiency characteristics of grease filters.

A test kitchen previously constructed within the Thermal Environmental Research Laboratory at the University of Minnesota for the ASHRAE 745-RP research program was modified for this study. An electric griddle was installed under a 4 ft. wide by 4 ft. deep by 2 ft. high Type 1 wall-mounted canopy exhaust hood which was connected to a 12 in. diameter 90 degree elbow. A 12 inch diameter exhaust duct was connected to the elbow which then ran horizontally to the exterior wall of the laboratory where it was connected to an exhaust fan with a 1 HP motor. Conditioned makeup air was supplied by an existing air handling system within the laboratory.

Because the test kitchen used in ASHRAE 745 RP was modified, the flow characteristics of the new system needed to be established. The sampling location in the exhaust duct was determined to be seven feet (seven duct diameters) downstream of the 90 degree elbow. Velocity profiles and exhaust airflow rates were determined at this sampling location using a hot-film anemometer to measure the time averaged velocity in the duct at radial velocity sampling points specified by the log-Tchebycheff method. Data were obtained at various fan speeds using this method. The test airflow rate of 1,000 CFM was chosen based upon the nominal filter design flow rate of 250 CFM per linear ft. of exhaust hood (250 CFM x 4 ft exhaust hood = 1,000 CFM).

Particle collection efficiency tests were conducted on two removable baffle-style grease filters that were commercially available. One was a standard baffle design and the other was an enhanced baffle design (GX Filter) to increase the centrifugal extraction. Tests were performed using the effluent generated while cooking hamburger and using oleic acid particles generated with an aerosol generator (griddle on and griddle off). Each test consisted of first having no filter in the exhaust hood and sampling the aerosol downstream in the exhaust duct with an optical particle counter (OPC) spectrometer to determine the “upstream” particle concentration as a function of particle size. Next, the filters were placed in the hood and the aerosol was sampled in the exhaust duct to determine the “downstream” concentrations. Samples were taken at the exhaust duct sampling location.

Sampling particles in the exhaust duct with and without filters installed in the exhaust hood requires that the aerosol challenge be time invariant and well mixed since a single sample point in the air stream must adequately represent the contaminant present. Therefore, spatial aerosol uniformity tests were conducted at the exhaust duct sampling location to ensure that the particle concentrations in the cross-section of the duct were uniform. EPA Standard 40

CFR 60 specifies that twelve horizontal and twelve vertical points are required. Tests were performed by placing the discharge from either a small particle aerosol generator or large particle aerosol generator at the center, and on each corner of a heated electric griddle with the exhaust flow set at 1,000 CFM. The aerosol was sampled through an isokinetic probe. The aerosol was sent to an aerosol diluter, with a 50:1 dilution ratio, and then to an optical particle counter (OPC) spectrometer. The results showed that the aerosol was uniformly distributed in the duct cross-section; with standard deviations of 5 % or less for particles in the size range of 0.32-0.42  $\mu\text{m}$  and 13 % or less for particles in the size range of 4.2-5.6  $\mu\text{m}$ .

The effluent generated when cooking hamburger on an electric griddle was characterized using a personal cascade impactor (PCI), Micro-Orifice Uniform Deposit Impactor (MOUDI) and an OPC to determine the mass size distribution and total mass of the particulate matter and an EPA Method 5 sampling train for the total grease vapor. The results show that the mass size distribution is bimodal with mass median aerodynamic sizes of 0.23  $\mu\text{m}$  using the MOUDI for the small mode and 6.2  $\mu\text{m}$  using the OPC for the large mode. Total particulate mass and grease vapor mass concentrations were found to be about 15  $\text{mg}/\text{m}^3$  and 141  $\text{mg}/\text{m}^3$ , respectively.

When particle collection efficiency tests were performed on grease baffles and grease filters, aerosol samples were drawn through an isokinetic probe that was placed in the center of the exhaust duct at the sampling location. The aerosol was first sent to an aerosol diluter, with a 50:1 dilution ratio, and then to an OPC. Several tests with and without the filters installed were performed sequentially to determine the filter collection efficiency. A method similar to that used by ASHRAE Standard 52.2 was used to determine the 95% confidence interval and data criteria for a successful test. When cooking hamburger, the criteria were not met for most of the OPC channels for both the grease baffles and filters. However, the criteria were met for all the oleic acid tests with the griddle off and for all but one channel for the oleic acid tests with the griddle on. The difficulty when cooking hamburger is that the number of tests that can be performed in a day is generally not sufficient to meet the criteria (approximately 1.5 hrs. per test), whereas, this is not a problem with the oleic acid tests (approximately 5 min. per test). The collection efficiency data for cooking hamburger, oleic acid with the griddle on and oleic acid with griddle off are plotted in Figure 1 for the grease baffles and Figure 2 for the grease filters. The error bars show the 95% confidence intervals. It can be seen that, while the data criteria are not met when cooking hamburger, there is good agreement between the cooking and oleic acid filter efficiency results.

Recommendations for a standard method of test include:

- 1) Writing a prescriptive instead of a guideline MOT. While it will be necessary to duplicate the test facility used in this study, little characterization will be required, whereas for a guideline MOT all of the characterization work would need to be repeated.
- 2) Use oleic acid particles as a good surrogate for hamburger particulate grease effluent since it is much easier to generate and filter collection efficiencies were found to be similar.
- 3) Use an OPC for collection efficiency tests because it is an efficient way to take data and the particle size range is in the size range needed to characterize current grease filters.
- 4) Use a heated griddle when testing because this provides similar thermal plume and temperature conditions as when cooking hamburger.

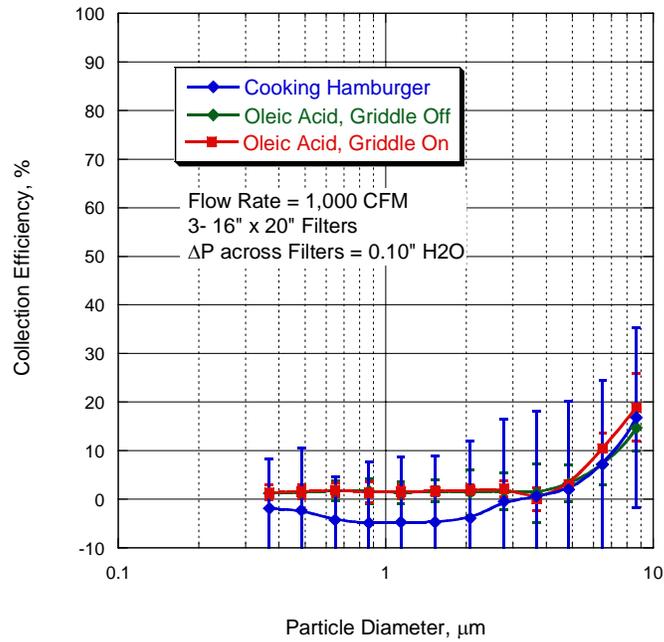


Figure 1.1. Baffle Collection Efficiency for Cooking Hamburger, Oleic Acid with Griddle Off, and Oleic Acid with Griddle On

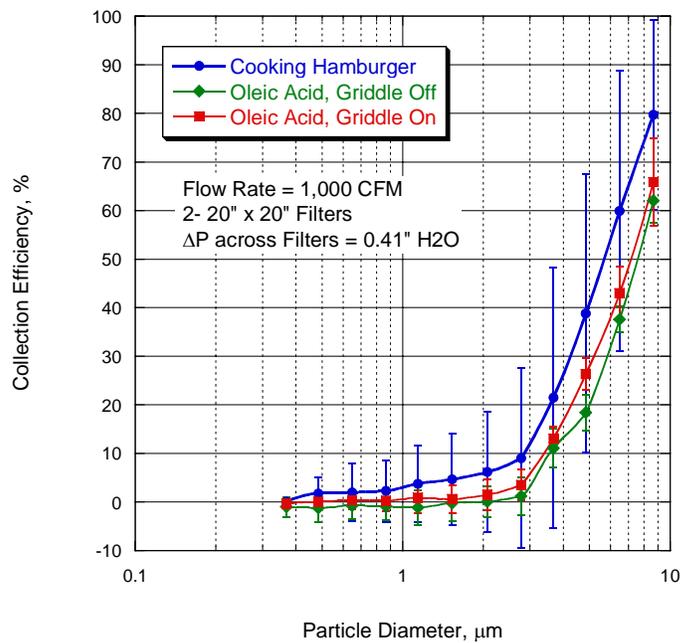


Figure 1.2. GX Filter Collection Efficiency for Cooking Hamburger, Oleic Acid with Griddle Off, and Oleic Acid with Griddle On

## 2. PURPOSE AND SCOPE

The need for an accurate and representative method of test for determining the grease removal efficiency of grease filters or extractors has been acknowledged by the commercial kitchen ventilation (CKV) industry for many years. Although it is often assumed (particularly by the specifying engineer) that UL 1046, Standard for Grease Filters for Exhaust Ducts, incorporates an efficiency test, this is not the case. While ULC-S649-93, the Canadian Standard for Grease Filters for Commercial and Institutional Kitchen Exhaust, specifies a mass-balance-based efficiency test using an atomized oil mist challenge, the results of this test are believed to overstate the real-world efficiency of grease filters.

In response to this industry need, the ASHRAE task group on kitchen ventilation (now a formal Technical Committee designated TC 5.10) solicited and secured ASHRAE research funding to develop a more effective test method. ASHRAE 851-RP, Grease Removal Efficiency from Hoods, was completed in 1999. However, the reported test method was not ratified as an industry standard due to technical issues identified towards the end of the project. ASHRAE TC 5.10 undertook a second research project, 1151-RP, to develop a Standard Test Method for Grease Filters and Emission Control Equipment. The primary goal of this project, which was completed in 2002, had been to develop a reliable cooking effluent simulator to relieve the variability and cost associated with challenging a filter using an actual cooking process. But the project vision was greater than the project budget, and a practical and cost-effective test method again eluded the industry.

The data generated by the two ASHRAE research projects, combined with a dramatically expanded understanding of the cooking effluent through ASHRAE 745-RP, suggested that one more concentrated research effort was needed to secure the goal. But soliciting funding for a third ASHRAE research project was not realistic. In response, an ad hoc group of TC 5.10 industry participants agreed to co-fund a new effort to leverage the ASHRAE research and provide the industry with a functional method of test. The industry sponsors unanimously selected the Department of Mechanical Engineering, University of Minnesota, as the contractor based on its exemplary performance under 745-RP, Characterization of Effluent from Various Cooking Appliances and Processes, and 1033-RP, Effects of Air Velocity on Grease Deposition in Exhaust Ductwork. The Principal Investigator on the project is Professor Thomas Kuehn. Fisher-Nickel, Inc. and manager of the Food Service Technology Center in San Ramon, California coordinated the initiative and administered the industry co-funding.

Characterization of commercial cooking effluent by ASHRAE 745-RP documented the particulate and vapor phases that enter the exhaust hood, their concentrations and mass flow rates, particle size distributions, and how these varied widely by appliance and typical food product. Kitchen equipment manufacturers have subsequently been developing better grease capture systems.

A draft standard method of test (MOT) has been developed to determine the performance of commercial kitchen grease removal systems on selected typical cooking effluent. This MOT is provided as a separate document.

The scope of this project consisted of designing, constructing and characterizing a test facility, characterizing the effluent generated while cooking hamburger, conducting tests to determine the particle collection efficiencies of grease baffles and filters using hamburger and artificial effluents as test aerosols, comparing results, and subsequently using this information to draft a MOT document.

### **3. APPROACH**

#### **3.1 APPARATUS**

##### **3.1.1 Test Facility**

The test facility was constructed within the Thermal Environmental Research Laboratory at the University of Minnesota. A test kitchen was previously constructed within the laboratory for the ASHRAE 745-RP research program. A schematic diagram of the test kitchen showing the location of the kitchen in the laboratory, the kitchen dimensions, griddle location, exhaust hood size and location, and exhaust duct dimensions are shown in Figures 3.1 and 3.2. A detailed description of the test kitchen is given in ASHRAE 745-RP Phase II Final Report [1].

The exhaust hood is 4 ft. wide by 4 ft. deep by 2 ft. high Type 1 wall-mounted canopy listed ventilation hood. The exhaust duct is connected to the exhaust hood using a stainless steel 12 in. collar. A 90° 12 in. elbow having 3 segments and a radius of 14 in. is connected to the collar. The 12 in. round duct connects to the elbow and runs horizontally to the exterior wall where there is a 12 in. to 16 in. expansion section. This section is connected to a 16 in. centrifugal roof fan with a 1 HP motor, modified by the manufacturer to operate in a horizontal position. This fan is controlled by an adjustable frequency AC motor controller mounted inside the test kitchen.

The griddle is a Wolf Range model TME-36A having a 36 in. wide by 28 in. deep cooking surface, 6 thermostatically controlled heating elements with 47.5 amperes, 208 V, 3 phase service. When positioned in the test kitchen, the back of the griddle was 10 in. away from the back of the kitchen wall. To prevent air from passing vertically upward between the back of the griddle and wall, a 10 in. by 36 in. sheet of stainless steel was mounted horizontally from the back edge of the griddle to the kitchen wall.

##### **3.1.2 Instrumentation**

The aerosol instrumentation used in this project consisted of a:

- 1) Climet Model Spectro 0.3 Airborne Optical Particle Counter (OPC),
- 2) TSI Model 3302 Aerosol Diluter,
- 3) MSP Model 100 Micro-Orifice Uniform Deposit Impactor (MOUDI),
- 4) Marple Model 290 Personal Cascade Impactor (PCI),
- 5) Graseby Andersen EPA Method 5 Sampling Train, and
- 6) Vapor Trap.

A detailed description of the aerosol instrumentation is given in Appendix A.

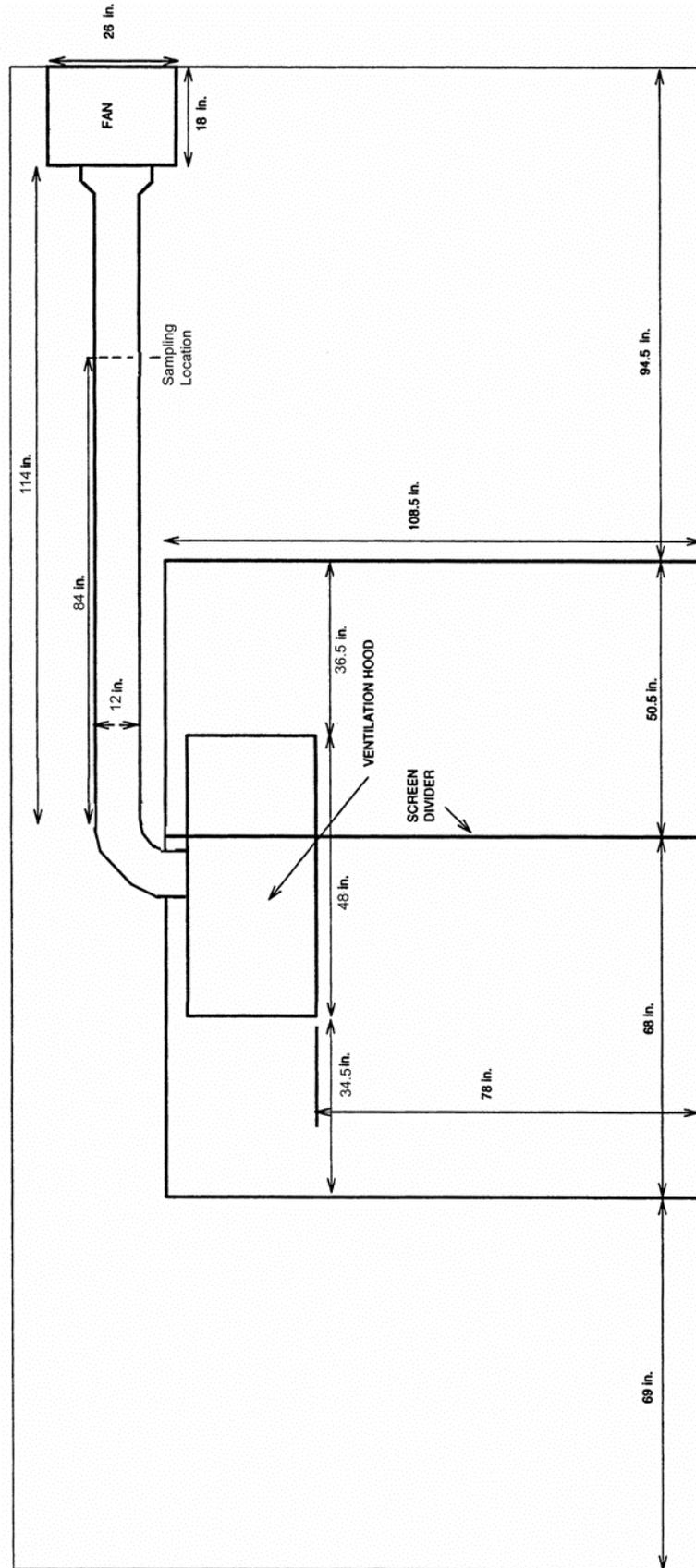


Figure 3.1. Schematic of the Test Kitchen and Exhaust Ventilation System

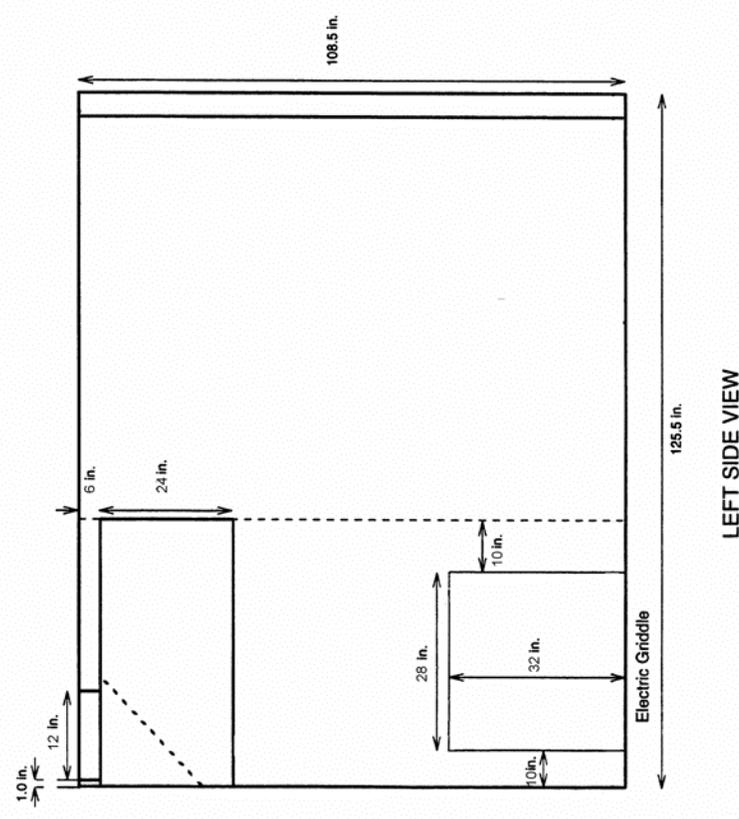
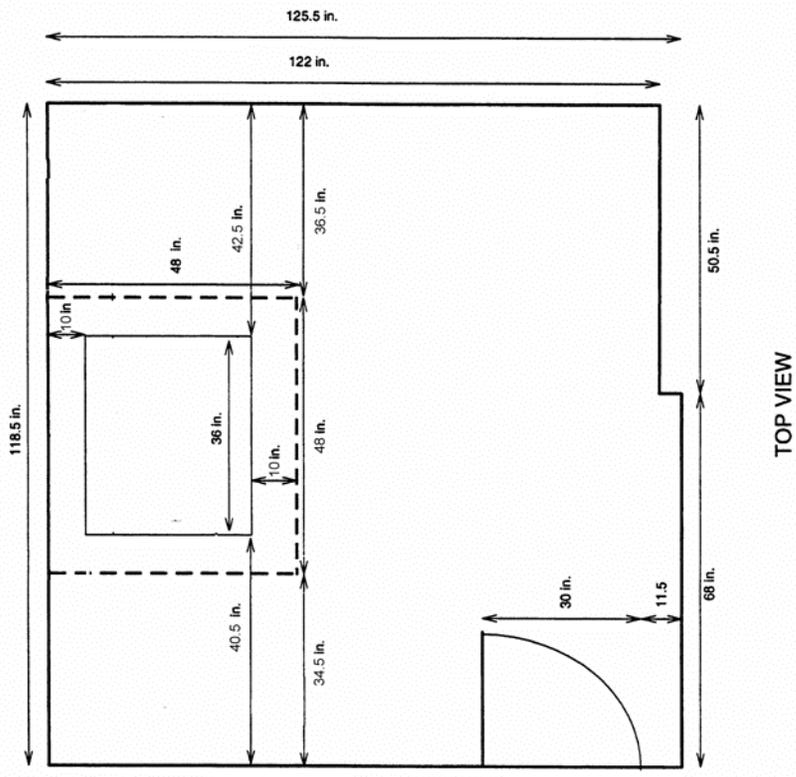


Figure 3.2. Schematic of the Test Kitchen

The optical particle counter (OPC) along with the diluter and cascade impactors were used to characterize the non-condensable particulate matter, and the EPA Method 5 sampling train was used to determine the total grease vapor of the effluent generated when cooking hamburger. It was found in initial testing when cooking hamburger that a dilution ratio of 50:1 was required to keep the total aerosol concentration below the maximum concentration limit specified by the manufacturer of  $10^7$  particles per ft<sup>3</sup>. The OPC, with 50:1 dilution, was also used to determine the collection efficiency of grease baffles and filters while cooking hamburger and when generating oleic acid particles using aerosol generators.

Two aerosol generators were used to measure the aerosol spatial uniformity in the exhaust duct. An ATI Model TDA-4B aerosol generator was used to generate small oleic acid particles with a mass mean size of approximately 0.3  $\mu\text{m}$  diameter and a modified TSI Model 3450 Vibrating Orifice Aerosol Generator (VOAG) was used to generate large oleic acid particles with a mass mean size of approximately 5  $\mu\text{m}$  diameter. The VOAG was modified by replacing the vibrating orifice with an Alltech nebulizer. The syringe pump liquid feed system was replaced with a constant liquid feed pressurized vessel. The modified VOAG was also used for the grease baffle and filter collection efficiency tests. A neutralization column, containing six NRD Model 2U500 Staticmaster Po210 (500  $\mu\text{Ci}$ ) radioactive sources, was used to bring the generated aerosols to a Boltzmann charge distribution [2].

Ancillary equipment was used to measure pressures, temperatures and relative humidity (RH). A Curtin Matheson Scientific Nova barometer was used to measure the barometric pressure. The room temperature was measured using a mercury thermometer. Griddle, hood, and in duct temperature measurements were made using Type K thermocouples (20 gage with glass braid insulation; 900 °F) connected to a Keithley 2700 Multimeter/Data Acquisition System. Magnehelic pressure gauges models 2000-00 (0-0.25 in. H<sub>2</sub>O) and 2001C (0-1.5 in. H<sub>2</sub>O) were used to measure the pressure drop across the grease baffles and filters, respectively. The RH was maintained and measured using a Vaporstream Model VLC-9-1 humidifier system.

Appendices E and F give a detailed description of the test and sampling procedures, and Appendices G and H detail the analytic procedures.

## 3.2 TEST FACILITY CHARACTERIZATION.

### 3.2.1 Calibration of Griddle

The griddle was calibrated in accordance with ASTM Standard F 1275-99 [3]. Six Type K thermocouples were welded to the surface, 3 in. from one side, 6 in. between and 5 in. from the back, of the griddle. The thermocouples were connected to a Keithley 2700 Multimeter/Data Acquisition System which converted the thermocouple emf voltages to temperatures and displayed the temperatures. The calibration procedure is given in Appendix D.

### 3.2.2 Calibration of Test Airflow Rate

To perform the test airflow rate calibration, three ½ in. diameter holes were drilled in the exhaust duct at the sampling location shown in Figure 3.1, one hole at the bottom of the duct, and at 60° on either side of the bottom of the duct. A support fixture was fabricated and attached to the duct using a large hose clamp so that it could be rotated to the three different access holes. The hot-film anemometer was used to measure the time averaged velocity in the duct. This device had been sent to the manufacturer for recalibration prior to the measurements. A cylindrical sleeve was designed and fabricated to slide through a hole in

the fixture mounted outside the duct and contain the body of the anemometer probe. The exterior of the sleeve was scribed so that the radial position of the velocity sensor inside the duct could be determined by matching a scribe mark on the sleeve with the outer surface of the support fixture.

The exhaust duct sampling location was 7 ft. (7 duct diameters) downstream of the 90°, 12 in. diameter elbow as specified by the EPA [4]. The radial velocity sampling points were determined following the log-Tchebycheff method described in Chapter 14 of the 2001 ASHRAE Handbook of Fundamentals [5]. Using this method, both the velocity profiles in the duct and the total volumetric flow rate through the duct could be obtained at various fan speeds. The test protocol is given in Appendix B.

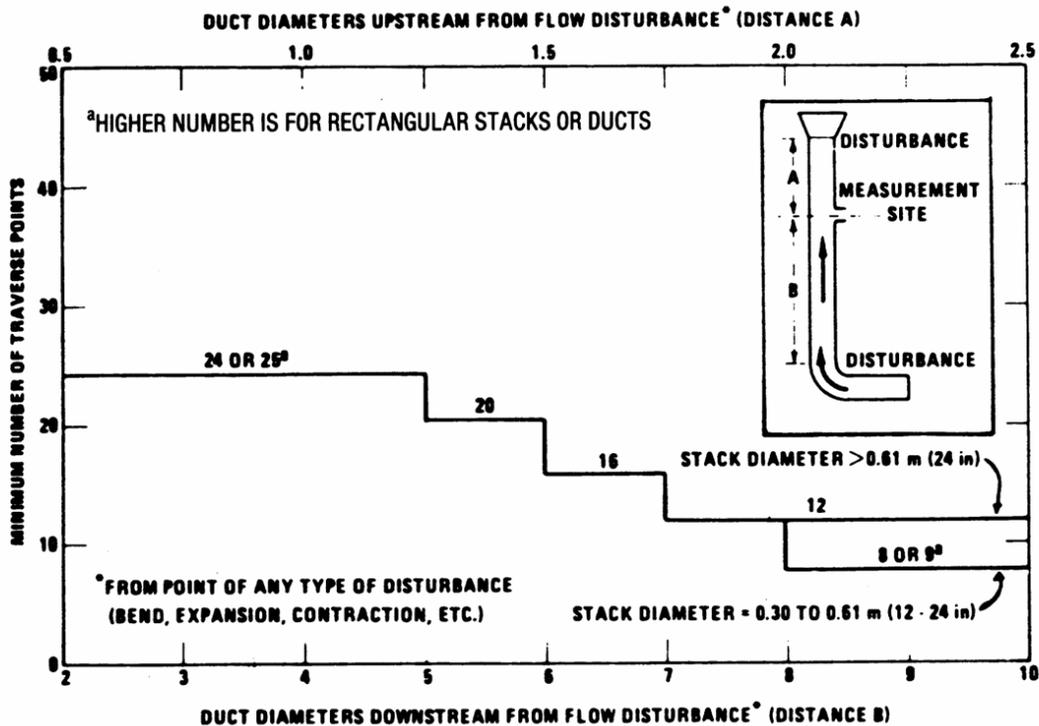
The makeup airflow rate handling system was required to provide the conditioned makeup air to the test kitchen. The makeup airflow rate handling system calibration is given in Appendix B.

### 3.2.3 Aerosol Spatial Uniformity Tests

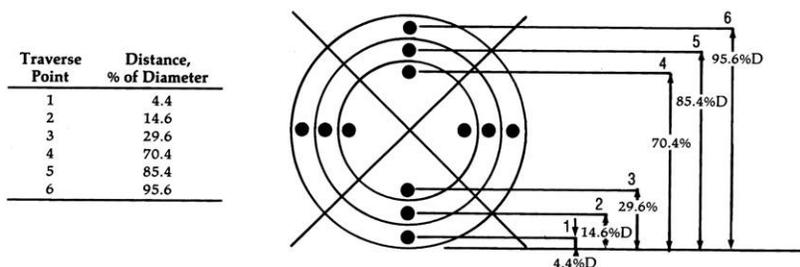
To determine the uniformity of the aerosol distribution in the exhaust duct, two series of measurements were made. One set used aerosol with a mass mean diameter near 0.3  $\mu\text{m}$  (small particles) produced by the ATI aerosol generator using 100% oleic acid. The second set used aerosol particles near 5  $\mu\text{m}$  in diameter produced by the Alltech aerosol generator using a 2:1 mixture of oleic acid and isopropyl alcohol. In each set of tests, data were obtained with and without a set of baffle filters installed in the hood. The aerosol source was located on top of the heated griddle to simulate cooking aerosol. The source was alternatively positioned at the center of the griddle surface and at each of the four corners. Using the small particles, all five source locations were used without the filters and three of the positions with the filters installed. With the large particles, all five positions were used with the filters and three positions with the filters removed.

EPA Standard 40 CFR 60 [4] specifies that 12 horizontal and 12 vertical traverse points need to be taken and specifies the locations of the points as shown in Figure 3.3a and Figure 3.3b, respectively. A ½ in. hole was drilled in the bottom of the duct and one 90° to the bottom for vertical and horizontal traverses, respectively.

A small isokinetic sampling probe was fabricated that could be inserted into the sleeve used for the velocity measurements. The end of the probe was connected to the diluter, having a 50:1 dilution factor, and then to the optical particle counter. The data from the particle counter were sent to a computer for storage and analysis.



(a)



Example showing circular stack cross section divided into 12 equal areas, with location of traverse points indicated (6 points on a diameter).

Traverse Point No. on a Diameter	Number of Traverse Points on a Diameter													
	2	4	6	8	10	12	14	16	18	20	22	24		
1	14.6	6.7	4.4	3.2	2.6	2.1	1.8	1.6	1.4	1.3	1.1	1.1		
2	85.4	25.0	14.6	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2		
3	—	75.0	29.6	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6.0	5.5		
4	—	93.3	70.4	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9		
5	—	—	85.4	67.7	34.2	25.0	20.1	16.9	14.6	12.9	11.6	10.5		
6	—	—	95.6	80.6	65.8	35.6	26.9	22.0	18.8	16.5	14.6	13.2		
7	—	—	—	89.5	77.4	64.4	36.6	28.3	23.6	20.4	18.0	16.1		
8	—	—	—	96.8	85.4	75.0	63.4	37.5	29.6	25.0	21.8	19.4		
9	—	—	—	—	91.8	82.3	73.1	62.5	38.2	30.6	26.2	23.0		
10	—	—	—	—	97.4	88.2	79.9	71.7	61.8	38.8	31.5	27.2		
11	—	—	—	—	—	93.3	85.4	78.0	70.4	61.2	39.3	32.3		
12	—	—	—	—	—	97.9	90.1	83.1	76.4	69.4	60.7	39.8		
13	—	—	—	—	—	—	94.3	87.5	81.2	75.0	68.5	60.2		
14	—	—	—	—	—	—	98.2	91.5	85.4	79.6	73.8	67.7		

(b)

Figure 3.3. EPA Standard 40 CFR 60 showing (a) number of traverse points required and (b) radial locations for the traverse points

### 3.3 A. PROCEDURES WITH HAMBURGER

The procedures for the hamburger cooking tests are given in Appendix E. The set up procedure for the instrumentation used in the test is given in Appendix F. These procedures assume that all calibration procedures for the griddle, the makeup air, and the exhaust flow rate have been performed (see Appendices B and D).

### 3.3 B. PROCEDURES WITH OLEIC ACID

Oleic acid was selected as the material for the simulated effluent tests because it is a major constituent of beef fat, readily available, easy to work with, not hazardous and has well known physical properties. The procedures for the oleic acid generation tests are given in Appendix E. The set up procedure for the instrumentation used in the test is given in Appendix F. These procedures assume that all calibration procedures for the griddle, the makeup air, and the exhaust flow rate have been performed (see Appendices B and D).

### 3.4 A. DATA ANALYSIS FOR HAMBURGER

The data analysis method follows closely that specified in ASHRAE Standard 52-2 [6]. However, because of differences in test facilities and test procedures some changes to methodology were needed. For example, since accurate upstream particle concentrations could not be taken in the plume upstream of the filter, the filter was removed and samples taken downstream in the duct at the same sampling location and this was considered the upstream particle concentration.

To determine particle collection efficiency, a batch of hamburger patties (24 per batch) was cooked without the filter in the hood. The OPC was used to determine the effluent particle number concentration as a function of particle size for each size channel of the instrument over a seven minute sample period. This was the amount of time needed to cook the hamburger to a 35% weight loss as specified in ASTM Standard F 1275-99 [3]. The filter was then installed and another batch of hamburger was cooked while the OPC sampled for a seven minute time period to determine the downstream concentration. The collection efficiency is defined as:

$$\text{Collection Efficiency, \%} = (1 - C_o/C_i) \times 100 \quad (1)$$

where:  $C_o$  = Particle Concentration of each OPC channel with Filters in Hood  
 $C_i$  = Particle Concentration of each OPC channel without Filters in Hood

This procedure was repeated to determine the average collection efficiency and uncertainty in collection efficiency. The test protocol is given in Appendices E and F, and the data analysis method is given in Appendices G and H.

### 3.4 B. DATA ANALYSIS FOR OLEIC ACID PARTICLES

As with the procedures for cooking hamburger, the data analysis method follows closely that that specified in ASHRAE Standard 52-2 [6]. However, because of differences in test facilities and test procedures some changes to the methodology were needed. As in the case of hamburger cooking, accurate upstream particle concentrations could not be taken upstream of the filter, so the filter was removed and samples taken downstream in the duct to determine the upstream particle concentration.

To determine particle collection efficiency, the large particle aerosol generator outlet was placed on the center of the griddle and 11 in. above the griddle (with the griddle off or on) without a filter in the hood. The OPC was used to determine the particle concentration as a function of size of the effluent for a two minute sample period. The filter was then installed and then the OPC sampled for another two minute sample period to determine the downstream concentration. The collection efficiency for each particle size range is defined in Equation 1.

This procedure was repeated to determine the average collection efficiency and uncertainty in collection efficiency. The test protocol is given in Appendix E and the data analysis method is given in Appendix G.

## 4. RESULTS

### 4.1 CHARACTERIZATION

#### 4.1.1 Calibration of Griddle

The results of the griddle calibration are given in Table 4.1. The average temperature measured for each location was found to be  $375 \pm 5$  °F and was, therefore, within the specification of the ASTM Standard F 1275-99 [3].

TABLE 4.1. GRIDDLE TEMPERATURES (°F) FROM LEFT TO RIGHT

Location 1	Location 2	Location 3	Location 4	Location 5	Location 6
376	378	380	379	380	380

#### 4.1.2 Calibration of Test Airflow Rate

The velocity profiles in the duct and the total volumetric flow rate through the duct were obtained for a total of four flow conditions. Approximately 63 data points were taken at each condition. As shown in Figure 4.1, the velocity profiles were found to agree well with published results for fully developed turbulent flow [7]. The remaining velocity profiles are given in Appendix B. The results were also used to determine the total exhaust volumetric flow rate at each condition so that the fan-system curve could be determined (see Figure 4.2). For a fan frequency of 24.5 Hz, the centerline velocity was found to be 1381 fpm with a total volumetric flow rate of 1,000 CFM through the 12 in. round exhaust duct (Figure 4.3).

To obtain the correct airflow rate (1,000 CFM) when the baffles or filters were installed, the hot-film anemometer was placed at the sampling location in the center of the duct and the fan speed was increased until a velocity of 1381 fpm was obtained. The electrical power frequency supplied to the fan when the baffles were used was found to be 28.0 Hz and that for the filters was found to be 38.2 Hz. In addition, the pressure drops across the baffles and filters were measured and found to be 0.10 in. H<sub>2</sub>O and 0.41 in. H<sub>2</sub>O, respectively.

#### 4.1.3 Aerosol Spatial Uniformity Tests

Before any spatial uniformity data were obtained, the aerosol concentration was measured at the centerline of the duct with the aerosol generator located in the center of the griddle for at least 30 minutes to check the stability of the aerosol generators. No discernable variation with time was measured with each aerosol generator when the fluid levels in the reservoirs were properly maintained (see Appendix C).

### Velocity Profile in Duct

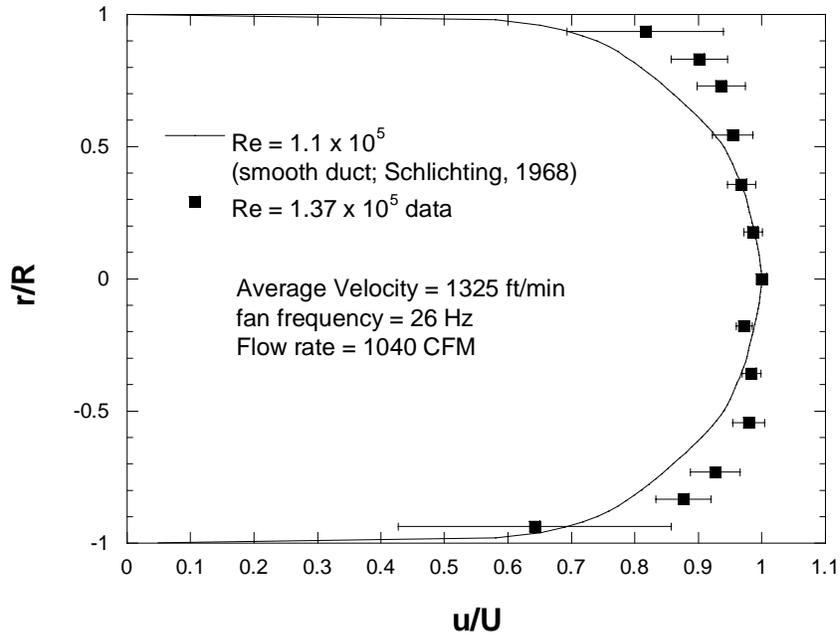


Figure 4.1. Comparison between measured velocity profile and theory [7]

### Flow Rate vs Fan Frequency

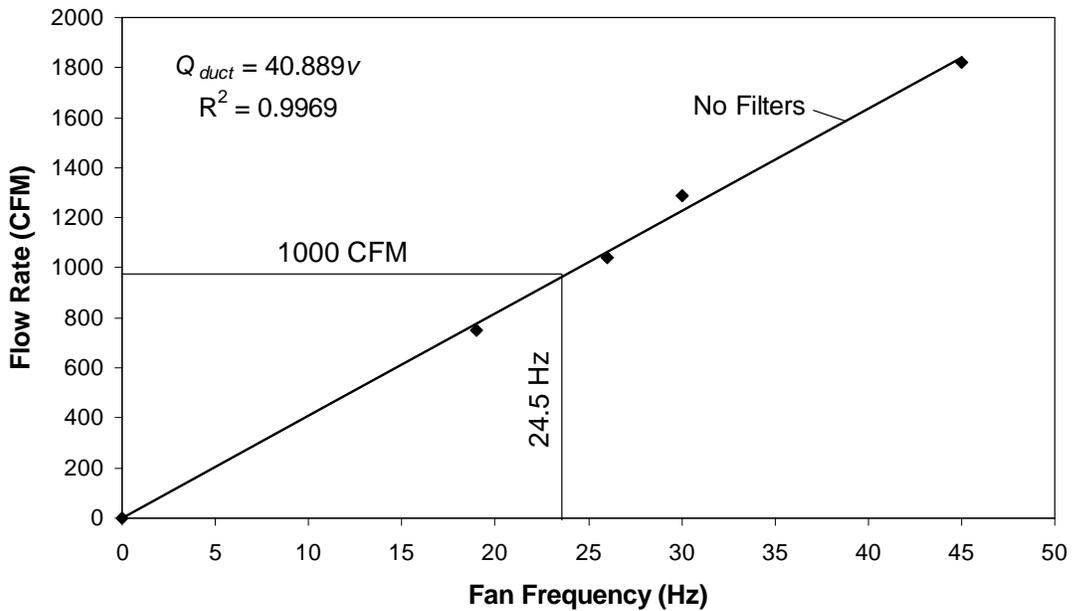


Figure 4.2. Flow Rate vs. Fan Frequency using hot-wire anemometer

### Centerline Velocity vs Flow Rate

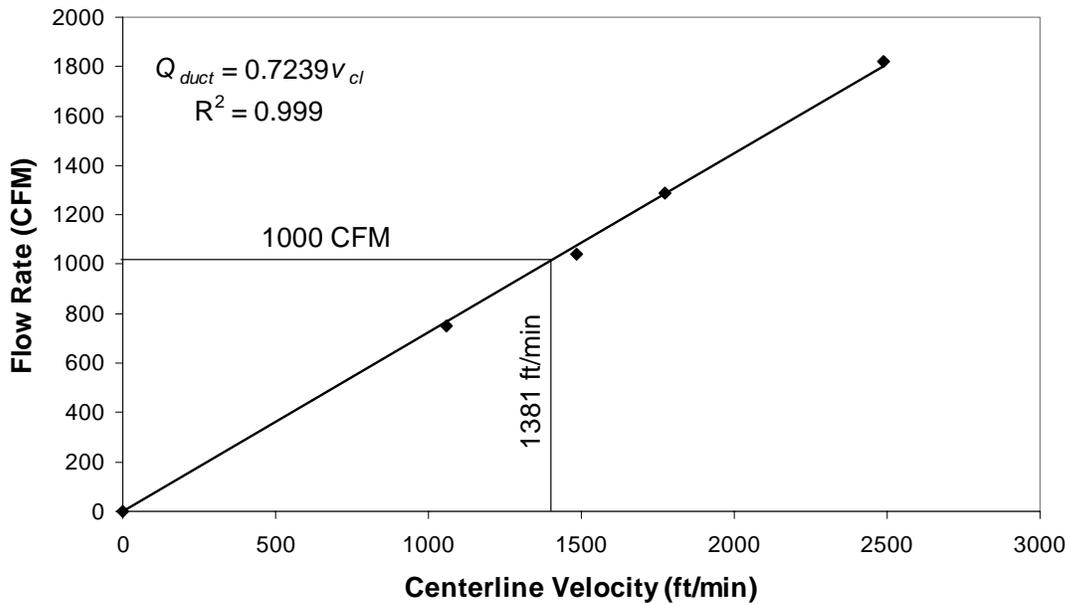


Figure 4.3. Flow Rate vs. Centerline Velocity using hot-wire anemometer

The results of the spatial uniformity tests showed that for the small particles, near  $0.3 \mu\text{m}$ , the concentration distribution within the exhaust duct is very uniform both with and without the filters installed, and regardless of the location of the aerosol source on the griddle. As shown in Table 4.2, the maximum standard deviation was found to be 5 % or less. For the particles near  $5 \mu\text{m}$  in size as shown in Table 4.3, the variation was larger but no observable trend was found, top to bottom or left to right. Slightly more variation was observed when the source was located at one of the corners rather than at the center. The maximum standard deviation for these tests was 13 % or less. Plots of particle number counts vs. duct sampling locations for each aerosol source position on the griddle are given in Appendix C.

The conclusions drawn from these spatial uniformity tests are that no mixing device is required in the exhaust duct to mix the aerosol, it is well mixed already, and the concentration distribution is insensitive to the position of the source on the griddle surface. Thus, a sample probe inlet located at the centerline of the exhaust duct will provide a representative sample of the effluent in the exhaust. Other quantities measured at the duct centerline, such as temperature and vapor concentration, will also be representative of the exhaust values as their diffusion is much higher than for the small aerosol particles that were found to be very well mixed.

TABLE 4.2. SUMMARY OF SPATIAL UNIFORMITY TESTS  
FOR SMALL PARTICLES

<b>0.32 - 0.42 <math>\mu\text{m}</math> PARTICLES, VERTICAL TRAVERSES</b>				
<b>POSITION ON GRIDDLE</b>	<b>MEAN PARTICLE COUNT</b>		<b>STDEV/MEAN X 100, %</b>	
	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>
Center	89000	76063	0.69	2.44
Back Right	87683	96143	0.74	3.51
Back Left	-	102624	-	2.88
Front Right	-	90106	-	1.18
Front Left	87919	99458	0.91	2.85

<b>0.32 - 0.42 <math>\mu\text{m}</math> PARTICLES, HORIZONTAL TRAVERSES</b>				
<b>POSITION ON GRIDDLE</b>	<b>MEAN PARTICLE COUNT</b>		<b>STDEV/MEAN X 100, %</b>	
	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>
Center	90973	79657	1.12	1.23
Back Right	87539	97523	0.52	5.03
Back Left	-	96129	-	2.41
Front Right	-	92126	-	3.68
Front Left	85928	96528	0.94	2.33

TABLE 4.3. SUMMARY OF SPATIAL UNIFORMITY TESTS  
FOR LARGE PARTICLES.

<b>4.2 - 5.6 <math>\mu\text{m}</math> PARTICLES, VERTICAL TRAVERSES</b>				
<b>POSITION ON GRIDDLE</b>	<b>MEAN PARTICLE COUNT</b>		<b>STDEV/MEAN X 100, %</b>	
	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>
Center	651	642	7.59	6.46
Back Right	679	739	7.27	8.24
Back Left	666	-	8.35	-
Front Right	1034	-	9.03	-
Front Left	394	685	13.16	6.25

TABLE 4.3. SUMMARY OF SPATIAL UNIFORMITY TESTS  
FOR LARGE PARTICLES (continued).

<b>4.2 - 5.6 <math>\mu\text{m}</math> PARTICLES, HORIZONTAL TRAVERSES</b>				
<b>POSITION ON GRIDDLE</b>	<b>MEAN PARTICLE COUNT</b>		<b>STDEV/MEAN X 100, %</b>	
	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>	<b>WITH BAFFLES</b>	<b>NO BAFFLES</b>
Center	787	598	5.47	5.81
Back Right	530	596	7.32	11.94
Back Left	579	-	5.69	-
Front Right	587	-	6.49	-
Front Left	470	549	8.66	6.36

#### 4.14 Effluent Characterization

To accurately determine the size distribution of the effluent in the exhaust duct, a new isokinetic aerosol sampling probe was developed and characterized. This probe was needed because the sampling probe used for the aerosol spatial uniformity tests did not allow particles larger than approximately  $10\ \mu\text{m}$  to travel through it, however, particles larger than  $10\ \mu\text{m}$  are present in the effluent. The particle penetration through the new probe as a function of particle size was determined by placing a Marple model 290 Personal Cascade Impactor at the sampling location in the exhaust duct and a second Personal Cascade Impactor connected downstream of the probe. An isokinetic sampling inlet was also made for the impactor used in the duct. The impactors were then run simultaneously while cooking hamburger. Two tests were performed with each one consisting of cooking three batches of hamburger patties (24 per batch). The impactor placed in the duct should provide an accurate representation of the particle mass size distribution of the effluent. Therefore, for each stage of the impactors, the mass collected in the impactor connected downstream of the probe divided by the mass collected in the impactor placed in the duct gives the penetration. The result of the probe characterization is shown in Figure 4.4. The penetrations of only four stages of the impactors are shown because the mass collected on the other stages were low and therefore excluded. Figure 4.4 shows a comparison between probe penetration data obtained using the impactors and that of theory by Pui et al. [8].

The effluent generated while cooking hamburger on an electric griddle was characterized by placing a Marple model 290 Personal Cascade Impactor (PCI) at the sampling location in the duct. An isokinetic probe was placed on the inlet of the impactor. Two tests were performed where each test consisted of cooking three batches of hamburger patties (24 per batch). The results are provided in Figure 4.5. Figure 4.5a shows the mass size distributions for the two tests conducted and Figure 4.5b shows the average size distribution along with a curve fit to the data using the software program DISTFIT. The results of the curve fit show a bi-model distribution with a mass median aerodynamic diameter (MMAD) of  $0.24\ \mu\text{m}$  and a geometric standard deviation (GSD) of  $3.6\ \mu\text{m}$  for the small mode and a MMAD of  $4.6\ \mu\text{m}$  and a GSD of  $1.8\ \mu\text{m}$  for the large mode.

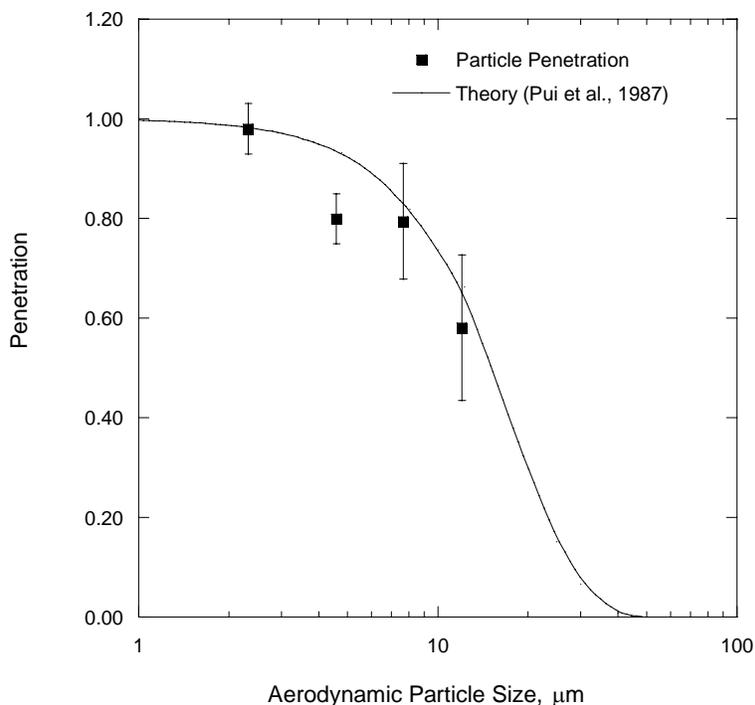
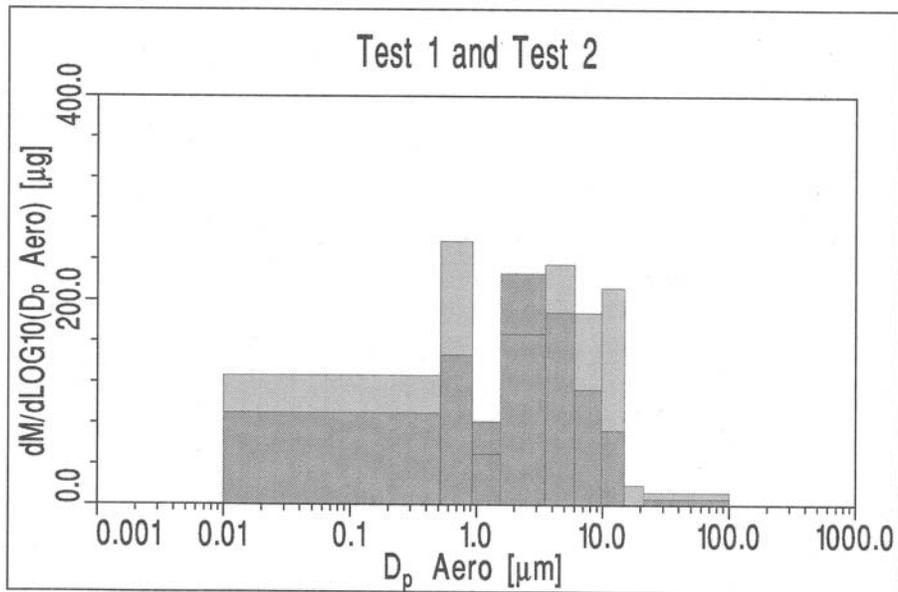


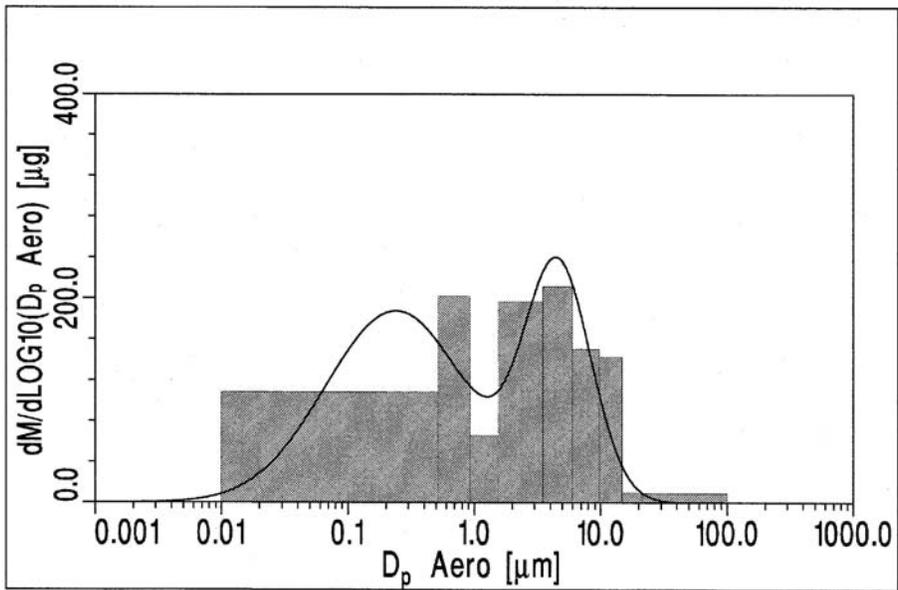
Figure 4.4. Particle Penetration Characteristics for Isokinetic Sampling Probe

The effluent was also characterized using the OPC and MOUDI. A size distribution comparison is shown in Figure 4.6. Both the MOUDI and OPC data were adjusted to take into account the losses in the isokinetic sampling probe. However, the MOUDI sampling line went through a 90° bend at the base of the sampling probe upstream of the MOUDI inlet. It can be assumed that some of the large particles would be lost in this bend. This is evident in the comparison plot where the MMAD of the MOUDI is smaller than that of the OPC. However, the MOUDI data does show a second mode that is below the detection limit of the OPC.

An overall comparison between the PCI, MOUDI, and OPC showing the MMAD's, GSD's for the large and small modes, total particulate mass concentrations and grease vapor concentrations are given in Table 4.4. The total particulate mass concentrations determined by the three samplers are very comparable. However, there is some variability in the MMAD's and GSD's for the large mode between the different instruments. For the small mode, the PCI and MOUDI MMAD's compare well. However, the PCI does not have sufficient resolution to accurately resolve the GSD while the MOUDI does. Finally, grease vapor was measured at the same time as the MOUDI and OPC data were taken using the EPA Method 5. The total mass concentration of grease vapor is approximately ten times that of the total particulate mass.



(a)



(b)

Figure 4.5. (a) Effluent particle size distributions for tests 1 and 2 using a Marple Model 290 Personal Cascade Impactor, (b) Average size distribution and curve fit using DISTFIT

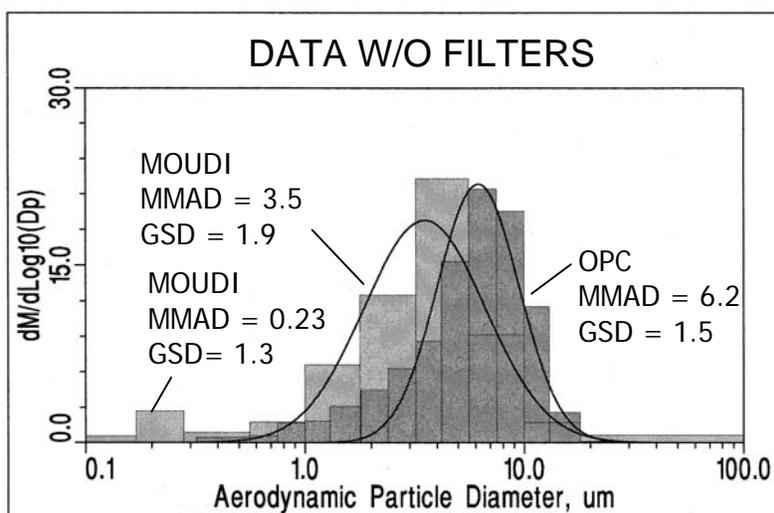


Figure 4.6. Comparison between MOUDI and OPC Data while Cooking Hamburger (no filters)

TABLE 4.4. EFFLUENT CHARACTERIZATION COMPARISON

Instrument	MMAD 1, μm	GSD 1	MMAD 2, μm	GSD 2	Total Particulate Mass Conc., mg/m <sup>3</sup>	Grease Vapor Mass Conc., mg/m <sup>3</sup>	Total Grease Mass Conc., mg/m <sup>3</sup>
PCI	4.6	1.8	0.24	3.6	12.9	-	-
OPC	6.2	1.5	-	-	12.8	141	153.8
MOUDI	3.5	1.9	0.23	1.3	15.4	141	156.4

#### 4.2 BAFFLE EFFICIENCY: HAMBURGER VS. OLEIC ACID (GRIDDLE ON AND OFF)

Table 4.5 gives the results of the baffle particle collection efficiency as a function of particle size for cooking hamburger, oleic acid with the griddle off and oleic acid with the griddle on. The error bars show the 95% confidence intervals. The table indicates that the criteria at the 95% confidence interval are not met for most OPC channels when cooking hamburger, while the criteria are met for all the oleic acid tests. The ASHRAE 52.2 criteria states that the 95% confidence interval shall be less than either  $0.05$  or  $0.07 \cdot \bar{P}_o$  for OPC size ranges 1 through 8,  $0.15 \cdot \bar{P}_o$  for OPC size ranges 9 and 10, and  $0.20 \cdot \bar{P}_o$  for OPC size ranges 11 and 12, whichever one is greater, where  $\bar{P}_o$  is the average observed penetration as described in Appendix G. The difficulty while cooking hamburger is the amount of time necessary to obtain a sample; while it only takes seven minutes to collect a sample, it takes approximately 1 hour to reduce the background levels low enough to start another sample and to reduce the griddle temperature to the correct cooking temperature. Therefore, it is difficult to obtain enough samples within a day to provide statistically significant results. In contrast, the sampling time and time between samples is very short for the oleic acid test method. Therefore, sufficient samples can be taken within a day to provide accurate results.

The baffle particle collection efficiencies are plotted for cooking hamburger, oleic acid with griddle off and oleic acid with griddle on are shown in Figure 4.7. While the 95% confidence

interval is not met for the cooking hamburger case, the overall collection efficiencies are in good agreement.

TABLE 4.5. BAFFLE PARTICLE COLLECTION EFFICIENCY AS A FUNCTION OF PARTICLE SIZE

OPC Channel, $\mu\text{m}$	Cooking			Oleic Acid - Griddle Off			Oleic Acid - Griddle On		
	Collection Efficiency, %	95% Confidence Interval	ASHRAE 52.2 Criteria	Collection Efficiency, %	95% Confidence Interval	ASHRAE 52.2 Criteria	Collection Efficiency, %	95% Confidence Interval	ASHRAE 52.2 Criteria
0.32-0.42	-1.9	0.10	< 0.07	1.2	0.01	< 0.07	1.4	0.01	< 0.07
0.42-0.56	-2.3	0.13	< 0.07	1.4	0.01	< 0.07	1.6	0.01	< 0.07
0.56-0.75	-4.3	0.09	< 0.07	1.8	0.02	< 0.07	1.9	0.01	< 0.07
0.75-1.0	-4.9	0.13	< 0.07	1.7	0.03	< 0.07	1.4	0.02	< 0.07
1.0-1.3	-4.7	0.13	< 0.07	1.3	0.02	< 0.07	1.6	0.01	< 0.07
1.3-1.8	-4.7	0.14	< 0.07	1.7	0.02	< 0.07	1.7	0.01	< 0.07
1.8-2.4	-3.9	0.16	< 0.07	1.4	0.05	< 0.07	1.9	0.01	< 0.07
2.4-3.2	-0.4	0.17	< 0.07	1.7	0.04	< 0.07	2.2	0.02	< 0.07
3.2-4.2	0.6	0.18	< 0.15	1.3	0.06	< 0.15	0.0	0.02	< 0.15
4.2-5.6	2.0	0.18	< 0.15	3.2	0.04	< 0.15	3.1	0.01	< 0.15
5.6-7.5	7.2	0.17	< 0.19	7.1	0.04	< 0.19	10.5	0.03	< 0.18
7.5-10.0	16.8	0.19	< 0.17	14.7	0.05	< 0.17	18.9	0.07	< 0.16

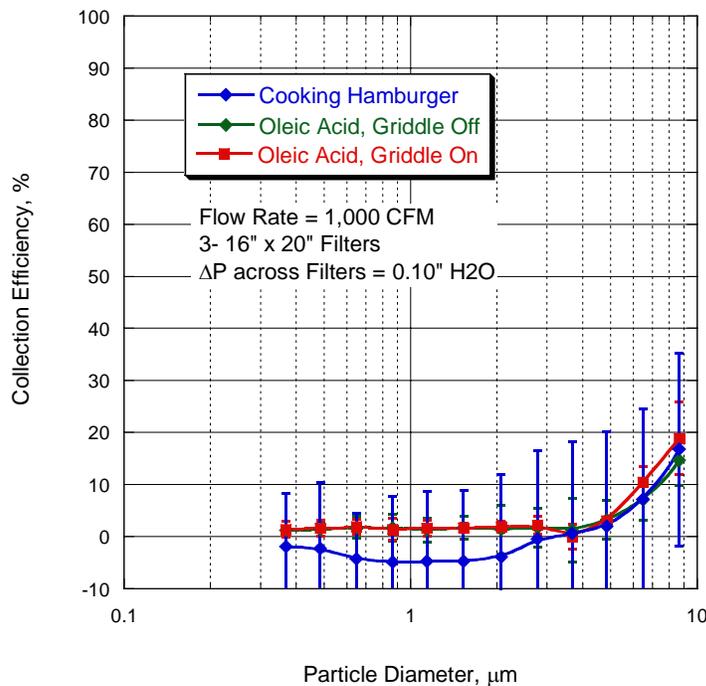


Figure 4.7. Baffle Particle Collection Efficiency for Cooking Hamburger, Oleic Acid with Griddle Off, and Oleic Acid with Griddle On

#### 4.3 GX FILTER EFFICIENCY: HAMBURGER VS. OLEIC ACID (GRIDDLE ON AND OFF)

Table 4.6 gives the results of the GX filter particle collection efficiency as a function of particle size for cooking hamburger, oleic acid with the griddle off and oleic acid with the griddle on. The error bars show the 95% confidence intervals. The table indicates that criteria at the 95% confidence interval are not met particles greater than 1  $\mu\text{m}$  when cooking hamburger, while the criteria are met for all the oleic acid tests with the griddle off and for all but one channel for the oleic acid tests with the griddle on. The difficulty while cooking hamburger as mentioned in section 4.2, is the amount of time necessary to run a test and bring the griddle and background aerosol concentrations back to their original conditions. Therefore, it is difficult to obtain enough tests within a day to provide statistically significant results. In contrast, the sampling time and time between tests is very short for the oleic acid test method. Therefore, sufficient tests can be made within a day to provide accurate results when oleic acid is used.

The filter particle collection efficiencies are plotted for cooking hamburger, oleic acid with the griddle off and oleic acid with the griddle on are shown in Figure 4.8. The cooking hamburger case shows slightly higher collection efficiency than the collection efficiencies for oleic acid with the griddle on and with the griddle off. However, overall collection efficiencies are in good agreement.

TABLE 4.6. GX FILTER PARTICLE COLLECTION EFFICIENCY AS A FUNCTION OF PARTICLE SIZE

OPC Channel, $\mu\text{m}$	Cooking			Oleic Acid - Griddle Off			Oleic Acid - Griddle On		
	Collection Efficiency, %	95% Confidence Interval	ASHRAE 52.2 Criteria	Collection Efficiency, %	95% Confidence Interval	ASHRAE 52.2 Criteria	Collection Efficiency, %	95% Confidence Interval	ASHRAE 52.2 Criteria
0.32-0.42	0.1	0.00	< 0.07	-1.0	0.02	< 0.07	-0.3	0.01	< 0.07
0.42-0.56	1.8	0.03	< 0.07	-1.2	0.03	< 0.07	0.1	0.02	< 0.07
0.56-0.75	2.0	0.06	< 0.07	-0.7	0.03	< 0.07	0.4	0.02	< 0.07
0.75-1.0	2.3	0.06	< 0.07	-0.9	0.03	< 0.07	0.3	0.02	< 0.07
1.0-1.3	3.8	0.08	< 0.07	-1.1	0.04	< 0.07	0.9	0.03	< 0.07
1.3-1.8	4.7	0.09	< 0.07	-0.2	0.04	< 0.07	0.6	0.03	< 0.07
1.8-2.4	6.2	0.12	< 0.07	0.1	0.03	< 0.07	1.5	0.03	< 0.07
2.4-3.2	9.0	0.18	< 0.06	1.2	0.04	< 0.07	3.5	0.03	< 0.07
3.2-4.2	21.5	0.27	< 0.12	11.1	0.04	< 0.13	13.1	0.02	< 0.13
4.2-5.6	38.8	0.29	< 0.09	18.4	0.04	< 0.12	26.4	0.03	< 0.11
5.6-7.5	59.9	0.29	< 0.08	37.6	0.03	< 0.12	43.0	0.05	< 0.11
7.5-10.0	79.7	0.20	< 0.04	62.0	0.05	< 0.08	65.9	0.09	< 0.07

#### 4.4 GREASE VAPOR

Using the EPA Method 5, the total mass concentration of grease vapor was found to be 141  $\text{mg}/\text{m}^3$ , approximately ten times that of the total particulate mass as shown in Table 4.4. This is in good agreement with the data from the ASHRAE 745-RP Phase II Final Report for cooking hamburger on an electric griddle.

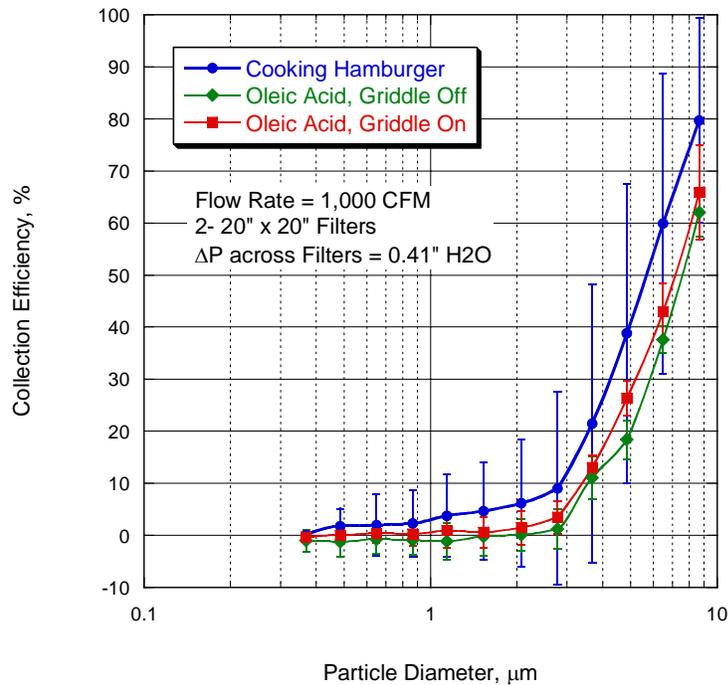


Figure 4.8. GX Filter Particle Collection Efficiency for Cooking Hamburger, Oleic Acid with Griddle Off, and Oleic Acid with Griddle On

## 5. DISCUSSION

### 5.1. Cooking Hamburger vs. Oleic Acid Challenge

There are several difficulties associated with using the effluent generated when cooking hamburger as the challenge aerosol for filter collection efficiency tests. The first is that of shipping and handling. The hamburger must be kept frozen in shipment and while being stored at or below  $0 \pm 5^\circ \text{F}$ . If the hamburger is stored for fairly long periods of time, freezer burn can occur or if the freezer malfunctions and the temperature increases the hamburger can be ruined. Another difficulty is that of variability in food product. Different batches of hamburger might have different fat and moisture contents that might lead to differences in collection efficiency, especially if different batches are used for the same test. Also, different cooks may have slightly different cooking procedures and this could influence the test as well. Another difficulty is the amount of time necessary to run a test. While a run might take only 7 to 10 minutes to complete, it takes a long time (approximately 1 hr) to reduce the aerosol background concentrations to initial levels and to bring the electric griddle back to correct cooking temperature since the griddle temperature increased while cooking. Therefore, it may not be possible to perform a sufficient number of runs in a given day to pass the collection efficiency data criteria. Finally, testing is expensive because of the cost of the hamburger, special shipping and handling procedures, labor costs for a cook and long test times.

All of these difficulties associated with cooking hamburger are eliminated when using oleic acid particles as the challenge aerosol: 1) there are no special handling requirements for oleic acid 2) the sample times are short (2-5 minutes), the time between samples is short; requiring just enough time to insert or remove the filter and allow the aerosol to stabilize, 3) the aerosol generator provides much better reproducibility than cooking hamburger, and 4) the aerosol is easy to generate.

### 5.2 Comparison between Cooking Hamburger and Oleic Acid Particle Collection Efficiencies

Comparisons between filter efficiency measurements using the effluent generated while cooking hamburger and using oleic acid particles are in good agreement despite neglecting the influence of grease vapor in the oleic acid tests. The reason for this might be because that the sampling location is downstream in the exhaust duct when sampling with and without filters. Therefore, even though condensation or evaporation may be taking place in the duct with hamburger effluent, the same phenomenon occurs during both sets of tests so the effect cancels out. This might not be the case if the sampling locations were upstream and downstream of the filter as performed in the ASHRAE 52.2 Standard. In this case, if vapor were changing the aerosol size distribution it would be expected that condensation would cause a decrease in collection efficiency and evaporation would cause an increase in collection efficiency. Another reason for the good agreement might be that the high amount of dilution air quenches the effluent and prevents condensation from occurring, however, evaporation could still take place.

For baffle collection efficiency tests, as shown in Figure 4.7, the data sets for cooking hamburger and for oleic acid challenge with the griddle on and off appear to be the same for particles greater than 3  $\mu\text{m}$ . For particles smaller than 3  $\mu\text{m}$ , the collection efficiency should be zero since it is physically impossible for the collection efficiency to be negative.

For the GX filter collection efficiency tests, as shown in Figure 4.8, the collection efficiency when cooking hamburger is slightly greater than when using oleic acid with the griddle on or off. In order to determine if the collection efficiencies are statistically the same, additional tests would need to be performed.

### 5.3 Comparison of Hamburger Effluent Data Obtained with Different Aerosol Instruments

Data were obtained in the exhaust duct while cooking hamburger using the OPC, MOUDI and the PCI and the results are compared in Table 4.4. It was found that the aerosol size distribution was bi-modal in nature. The OPC provides better resolution than the MOUDI and the PCI, above 0.3  $\mu\text{m}$ , having twice as many “channels” as the MOUDI. However because the OPC has a lower limit of 0.3  $\mu\text{m}$ , it cannot be used to detect the small particle mode (mode 1). For the PCI, the smallest particle size captured on a substrate is 0.5  $\mu\text{m}$  followed by an after filter so while it can be used to detect the small mode, there are no additional stages below 0.5  $\mu\text{m}$  to resolve it. For the grease filters currently being tested, the OPC provides a sufficient size range to determine the collection efficiency characteristics. However, when choosing an aerosol instrument for sampling, the size range of the aerosol being sampled should always be taken into account.

For the MOT, the OPC is the instrument of choice because it provides the data required, there is little labor involved with its operation, the data can be downloaded directly into a computer for analysis, and only short sampling times are necessary. Conversely, for the MOUDI and PCI, labor is intensive because substrates have to be conditioned, pre-weighted and then post-weighted to determine the amount of sample collected. In addition, the sampling time has to

be long enough to collect sufficient mass for accurate gravimetric analysis. When cooking hamburger, one batch (24 hamburger patties) was required for the MOUDI to collect sufficient mass for weighing using a microbalance and three batches were required for the PCI.

#### 5.4 Prescriptive vs. Guideline MOT

A prescriptive MOT requires that the test facility be built exactly to specification. Here all of the details of the test kitchen, hood, ventilation system, instrumentation, standards, etc., are laid out in the MOT. Once completed, only a minimum number of tests would be required to ensure that the test facility is operating properly since complete characterization has been performed previously. On the contrary, a guideline MOT would specify general guidelines for the test facility, ranges for equipment and instrumentation used and relevant standards where applicable. Once completed, the test facility would have to go through complete characterization.

#### 5.5 Continuation of work

Beyond the work that has been performed under this contract, additional work could be performed to look at grease vapor removal for filtration systems that are designed to remove both particulate matter and vapor. Analogous to oleic acid particles being used as a surrogate to particulate matter generated while cooking hamburger, after sufficient tests have been performed to characterize the grease vapor, a surrogate for grease vapor could be determined. This would require that the vapor have a high vapor pressure so it would not spontaneously nucleate. Instrumentation may include the EPA Method 5 and the vapor trap constructed under this contract.

In addition to investigating grease vapor removal, the particle size range should be extended down one decade from 0.3  $\mu\text{m}$  to approximately 0.03  $\mu\text{m}$  so that filtration systems designed to remove the particulate matter generated using woks, charbroilers and wood-fired equipment could be investigated. Instrumentation could include the Electrical Low Pressure Impactor to cover the size range from 0.03  $\mu\text{m}$  to 10  $\mu\text{m}$ , or a Scanning Mobility Particle Sizer could be used for particles below 0.3  $\mu\text{m}$  and an OPC could be used for particles from 0.3 $\mu\text{m}$  to 10  $\mu\text{m}$ .

## **6. RECOMMENDATIONS FOR MOT**

Recommendations for a standard method of test include:

- 1) Writing a prescriptive MOT following the protocol developed here and for ASHRAE Standard 52.2.
- 2) Using oleic acid particles as a good surrogate for hamburger particulate grease effluent.
- 3) Using a commercially available particle generator.
- 4) Using an OPC with a size range from 0.3  $\mu\text{m}$  to 10  $\mu\text{m}$  with 12 channels for the collection efficiency tests. The OPC should operate at 0.1 CFM so the isokinetic probe design developed in this study can be used.
- 5) Using a heated griddle when testing since this provides a similar thermal plume and temperature conditions as when cooking hamburger.

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