Ambient Measurements in Support of APEX2 and APEX3

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INTRODUCTION

Particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), and weather data were measured in the ambient air at the Oakland International Airport and the Cleveland Hopkins Airport. The two studies were call JETS/APEX2 and APEX3. The test dates were August 22 – 24, 2005 for the Oakland airport and October 31, 2005 to November 9, 2005, for the Cleveland Airport. The measurements were done in support of the on-going work of PM characterization from commercial jet aircraft engines. Ambient sampling is reported in this document while the actual characterization measurements using probes at multiple distances in the exhaust plume are reported by other members of the team.

The PM samples were analyzed gravimetrically and via X-Ray Fluorescence to determine the amount and elemental composition. Support for the probe measurements was accomplished in the immediate vicinity of the test aircraft. Upwind and downwind testing of the airfield was also accomplished, along with measured meteorology

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measurements, permitting the particulate and elemental quantities to be evaluated using a simple mass balance in an effort to quantify airport contributions to PM. The methodology and general results of the ambient measurements are reported in this document while complete data are tabulated in a companion spreadsheet (APEX2&3 Ambient Report.xls).

INSTRUMENTATION

At both airports $PM_{2.5}$ and CO_2 were measured with portable bag and filter sample units called Mini-Vols[2] (see Figure 1). Both short term and 24 hour measurements were accomplished for $PM_{2.5}$ while CO_2 measurements only occurred during the time of probe sampling. Weather information was continuously recorded except during data downloads. Different measurement locations were needed for each airport to match the configuration of each airport and to supply meaningful data.

The Mini-Vols employ particle size separators (impactors) and a 47 mm filter for collection of $PM_{2.5}$. A metered pump system fills 5 liter Tedlar bags during a defined period for the ambient gas sampling. The units were carefully calibrated and verified for correct flow through the sample filter (5 liters/minute) using a differential manometer before each measurement. Flow to the Tedlar bags was set using the electronic controls and experience to fill the bags during the various measurement periods at each location. Time of operation was 24 hours for airfield testing and dependent upon the probe sample times for probe ambient support measurement. All $PM_{2.5}$ and CO_2 measurements were collected at 6 feet above ground level.

Filters were sealed in cases until use. Each filter was installed in cassette filter holders during the unexposed gravimetric analysis at the Airmetrics laboratory so that direct contact to the filter was avoided during use. Blanks (filters removed from packaging and restored to cases without being used) were also used and sent back to the laboratory for testing as a quality control measure. The Tedlar bags were carefully evacuated and installed before each test so that no air was present in the bag when testing began. Batteries were changed each test to avoid any problems due to a low charge.

PM samples were sent to the Airmetrics certified laboratory for gravimetric analysis both before and after the sampling to determine the difference in mass due to $PM_{2.5}$ deposited on the filter. After the sampling, X-Ray Fluorescence (XRF) was also performed for 38 elements. A listing of these elements is shown in Table 1. CO_2 was analyzed on location by the U.S. EPA mobile laboratory. Quality control included the review of the laboratory measurements of the blanks, field notes, and laboratory notes.

Meteorological data, which included wind speed and wind direction, was measured using three-dimensional (u-v-w) sonic anemometers at an above ground elevation of 10 feet as shown in Figure 2. The average data were stored to a self-contained data logger unit

[2] Mini-vol is a trade name of Airmetrics Corporation.

Figure 1. Mini-Vol Sampler

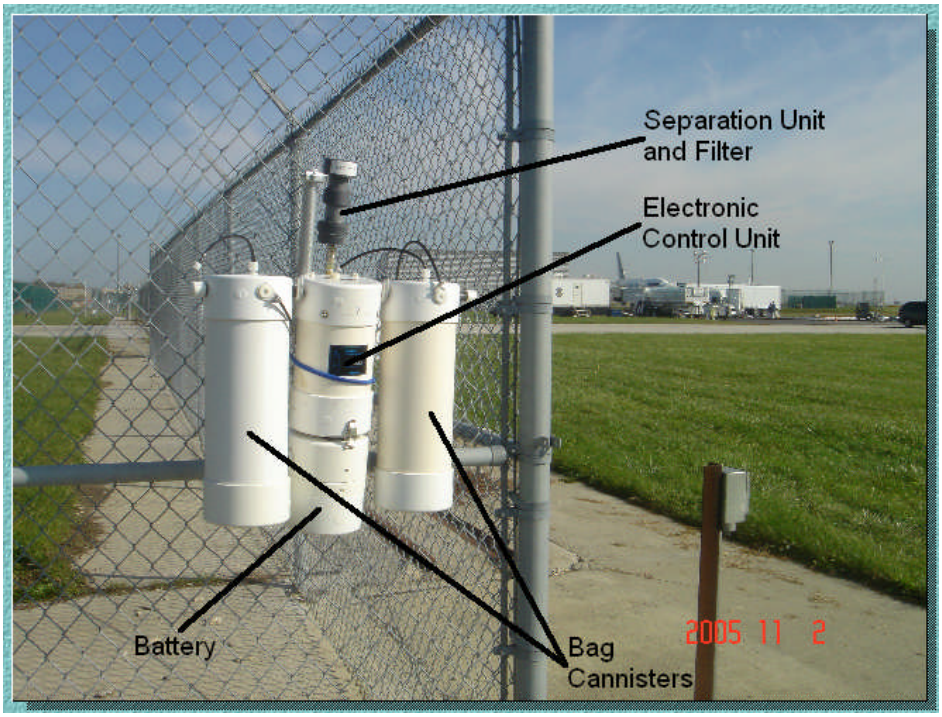


Table 1. Elements Analyzed

Ag	Cu	Mo	Si
Al	Fe	Na	Sn
As	Ga	Ni	Sr
Ba	Ge	P	Ti
Br	Hg	Pb	V
Ca	In	Pd	Y
Cd	K	Rb	Zn
Cl	La	S	Zr
Co	Mg	Sb	
Cr	Mn	Se	

Figure 2. U-V-W Sonic Anemometers

every 5 seconds during measurements. A portable computer on location on location was used for later data downloading. After collection, quality control steps were taken and the data analyzed.

AIRPORT DETAILS AND RESULTS

Each airport is unique and the probe measurement locations varied due to runway configurations and the probe measurement location at each airport. As such, even though the equipment was used as previously described, the measurement locations and measurement times were different for each airport. In this section, the details for each airport are described and important results presented. Complete data, too extensive to report in this document, are included in a companion spreadsheet (APEX2&3 Ambient Report.xls).

OAKLAND INTERNATIONAL AIRPORT

The sampling was conducted August 22 – 24, 2005, although considerable work occurred before and after to facilitate the measurements. The three-day sampling average ambient temperature was 61°F. The three-day high was 70°F with an average high during sampling of 69°F. The three-day low was 52°F with an average low sampling

temperature of 53°F. Sampling for $PM_{2.5}$ and CO_2 were accomplished for two specific purposes. In support of probe measurements in the Ground Run-up Enclosure (GRE), $PM_{2.5}$ and CO_2 ambient measurements were conducted. The measurements in the GRE were short-term to match the time of the probe sampling. Overlapping this sample period were upwind and downwind $PM_{2.5}$ and meteorology (wind speed and wind direction) measurements along the active runway. These measurements, were taken to provide data on the aircraft contribution to the local area and were 24 hours in duration.

Figure 3 shows a map of the Oakland International Airport with sample locations noted. Upwind/downwind sampling locations included R1, R2, and R3. The GRE location represents multiple locations and will be described later in this section. $PM_{2.5}$ was measured at all locations. Meteorological information was measured at Locations R1 and R3. CO_2 was only measured at the GRE.

R1/R2 and R3 were selected to provide upwind and downwind conditions along the active runway. Northwesterly winds dominated the three-day study period creating a very constant wind pattern along the runway (Runway 11/29) from the upwind Location R3 to the downwind Locations R1 and R2. Winds were measured to be from the northwest 74% of the time at R1 and 63% of the time at R3. The wind speeds were most often greater than 1 meter-per-second (m/s). The maximum hourly average wind speed was 7.3 m/s while the minimum hourly average was 0.4 m/s. Overall R1 typically had slightly higher wind speeds than R3. Wind roses were completed for all cases to provide a visual representation and Figure 4 shows a typical day. Overall typical trends are shown by Figure 5. Of note is that the winds were very consistent from one end of the runway to the other. Full data are shown in the accompanying spreadsheet.

The remaining 8 sampling locations were all located within the GRE to focus collection of information in the immediate vicinity of the test aircraft. The sample locations in the GRE are shown in Figure 6. Locations G1, G2 and G3 are on the northeast inside wall of the GRE while the remaining 5 sampling locations are located along the southwest wall with G4 and G5 located along the opening of the GRE. Location G8 is the closest to the back wall of the enclosure. All samplers were bolted to the pavement to avoid any possible problems due to the jet engine air movement.

The results of the total mass gravimetric analysis are shown in Table 2. It should be noted that R8, R9, and R10 were 24 hour samples while all G measurement locations were shorter term, lasting only as long at the probe sampling. Using the mass data, flow rates, and the time of measurements, ambient concentrations were calculated and are listed in Table 3. Of interest is that the downwind locations were greater on the first and third day of measurements but not the second even though wind patterns were similar. Also of note is that the airfield samples, very near active runways, are far below the National Ambient Air Quality Standard of 35 $\mu g/m^3$.

CO_2 concentrations were also measured to support the probe sampling. Results are shown in Table 4. All results were very near what would be expected for ambient

Figure 3. Sample Locations at Oakland International Airport

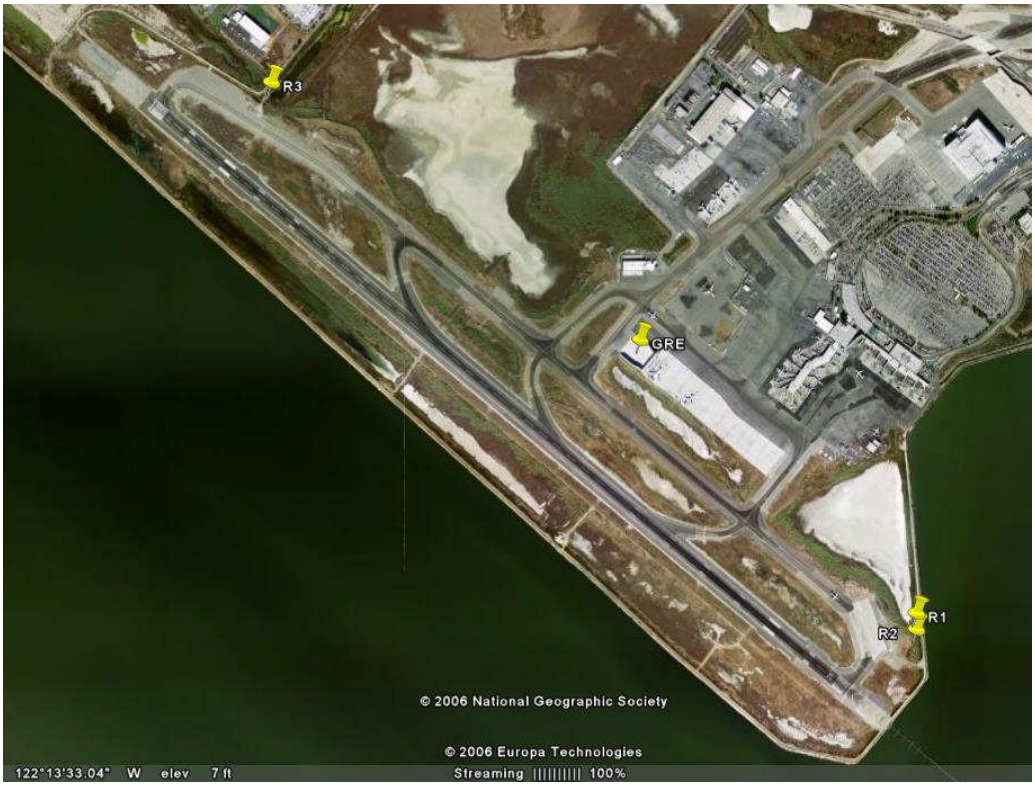


Figure 4. Typical Wind Rose Plots, Oakland International Airport

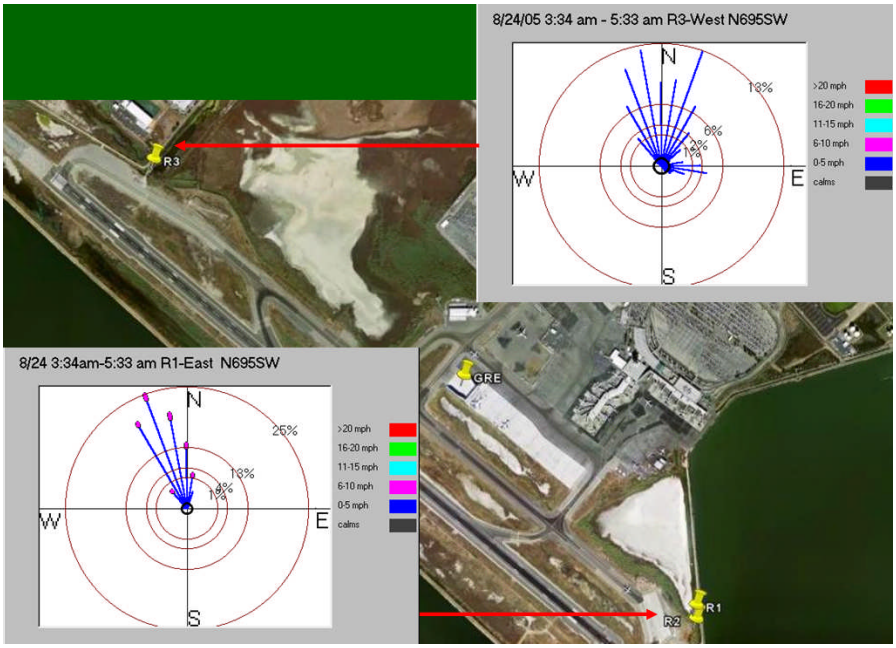


Figure 5. Overall Wind Patterns During Measurements, Oakland International Airport

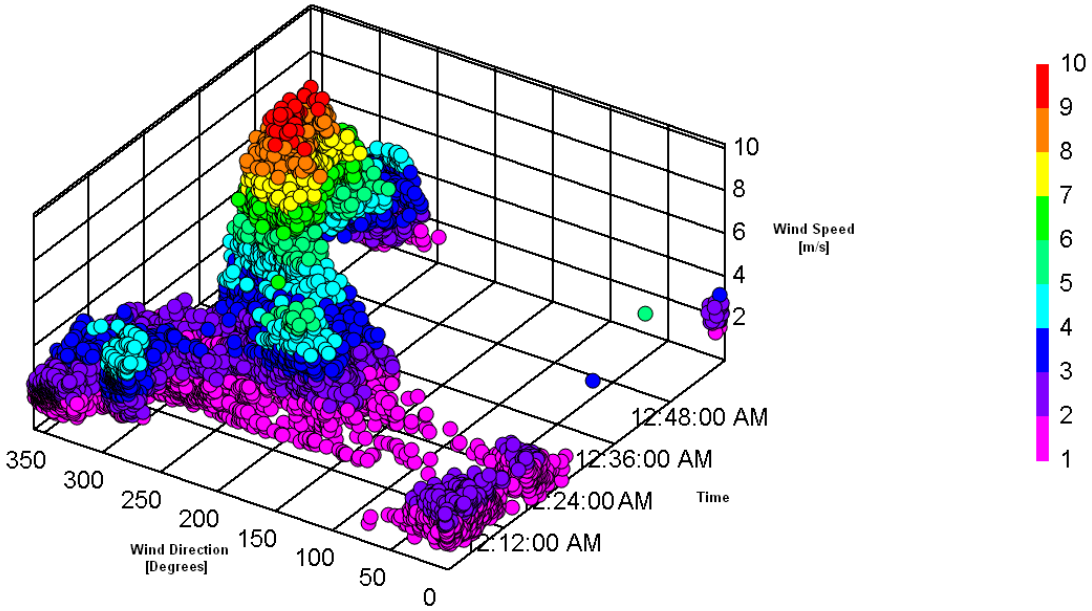


Figure 6. Measurement Location in the GRE

Table 2. Results for Total Mass, Oakland International Airport, $PM_{2.5}$

FilterID	*Julian Date*	*Location*	*Clean Mass*	*Exposed Mass*	*Diff (mg)*	*Comments*
UCF-0101	234	R1	143.435	143.563	0.128	Downwind
UCF-0102	234	R2	139.262	139.382	0.120	Downwind
UCF-0103	234	R3	140.884	141.028	0.144	Upwind
UCF-0104	234	G1	142.308	142.359	0.051	GRE Support
UCF-0105	234	G2	139.821	139.888	0.067	GRE Support
UCF-0106	234	G3	141.627	141.692	0.065	GRE Support
UCF-0107	234	G4	144.481	144.529	0.048	GRE Support
UCF-0108	234	G5	139.937	140.027	0.090	GRE Support
UCF-0109	234	G6	142.927	142.974	0.047	GRE Support
UCF-0110	234	G7	140.256	140.313	0.057	GRE Support
UCF-0111	234	G8	142.383	142.426	0.043	GRE Support
UCF-0112						Blank
UCF-0113	235	R1	141.084	141.221	0.137	Downwind
UCF-0114	235	R2	141.051	141.220	0.169	Downwind
UCF-0115	235	R3	148.989	149.117	0.128	Upwind
UCF-0116	235	G1	144.587	144.705	0.118	GRE Support
UCF-0117	235	G2	147.117	147.194	0.077	GRE Support
UCF-0118	235	G3	148.751	148.836	0.085	GRE Support
UCF-0119	235	G4	142.416	142.506	0.090	GRE Support
UCF-0120	235	G5	139.777	139.829	0.052	GRE Support
UCF-0121	235	G6	155.657	155.714	0.057	GRE Support
UCF-0122	235	G7	148.038	148.116	0.078	GRE Support
UCF-0123	235	G8	142.686	142.740	0.054	GRE Support
UCF-0124	235	G8	146.890	147.027	0.137	GRE Support
UCF-0125						Blank
UCF-0126	236	R1	146.418	146.500	0.082	Downwind
UCF-0127	236	R2	154.096	154.189	0.093	Downwind
UCF-0128	236	R3	146.210	146.299	0.089	Upwind
UCF-0129	236	G1	148.141	148.232	0.091	GRE Support
UCF-0130	236	G2	146.604	146.667	0.063	GRE Support
UCF-0131	236	G3	140.352	140.501	0.149	GRE Support
UCF-0132	236	G4	146.167	146.210	0.043	GRE Support
UCF-0133	236	G5	144.446	144.497	0.051	GRE Support
UCF-0134	236	G6	148.520	148.577	0.057	GRE Support
UCF-0135	236	G7	142.190	142.259	0.069	GRE Support

Table 3. Calculated Ambient $PM_{2.5}$ Concentrations, Oakland International Airport

Julian Date	*Date*	*Filter*	*Location*	*Mass [mg]*	*SOT [hours]*	*EOT [hours]*	*Volume [liters]*	*Conc. [μg/m³]*	*Comments*
234	8/22/2005	101	R1	0.128	41.1	64.5	7020	18.2	Airfield ambient sample
		102	R2	0.12	60.5	84	7050	17.0	Airfield ambient sample
		103	R3	0.144	33.8	57.4	7080	20.3	Airfield ambient sample
		104	G1	0.051	64.9	69	1230	41.5	In GRE
		105	G2	0.067	68.2	72.4	1260	53.2	In GRE
		106	G3	0.065	22.1	26.3	1260	51.6	In GRE
		107	G4	0.048	55.2	59.4	1260	38.1	In GRE
		108	G5	0.09	44.6	48.5	1170	76.9	In GRE
		109	G6	0.047	41.3	44.3	900	52.2	In GRE
		110	G7	0.057	97.1	99.8	810	70.4	In GRE
		111	G8	0.043	53.5	58.1	1380	31.2	In GRE
		112	BLANK						
235	8/23/2005	113	R1	0.137	64.5	88.4	7170	19.1	Airfield ambient sample
		114	R2	0.169	84	107.9	7170	23.6	Airfield ambient sample
		115	R3	0.128	57.4	80.9	7050	18.2	Airfield ambient sample
		116	G1	0.118	69	75.5	1950	60.5	In GRE
		117	G2	0.077	72.4	78.9	1950	39.5	In GRE
		118	G3	0.085	26.3	32.8	1950	43.6	In GRE
		119	G4	0.09	59.4	66	1980	45.5	In GRE
		120	G5	0.052	48.5	52.5	1200	43.3	In GRE
		121	G6	0.057	44.3	48.3	1200	47.5	In GRE
		122	G7	0.078	99.8	103.8	1200	65.0	In GRE
		123	G8	0.054	65	68.2	960	56.2	In GRE
		124	G8	0.137	58.1	65	2070	66.2	In GRE
		125	BLANK						
236	8/24/2005	126	R1	0.082	88.4	100.2	3540	23.2	Airfield ambient sample
		127	R2	0.093	107.9	119.8	3570	26.1	Airfield ambient sample
		128	R3	0.089	80.9	92.8	3570	24.9	Airfield ambient sample
		129	G1	0.091	75.5	78.6	930	97.8	In GRE
		130	G2	0.063	78.9	81.9	900	70.0	In GRE
		131	G3	0.149					Flagged for QC
		132	G4	0.043	66	69.1	930	46.2	In GRE
		133	G5	0.051	52.5	55	750	68.0	In GRE
		134	G6	0.057	48.3	50.8	750	76.0	In GRE
		135	G7	0.069	103.8	106.3	750	92.0	In GRE

Table 4. Measured CO_2 Concentrations, Oakland Airport

Julian Date	*Date*	*Location*	*Bag*	*CO_2 ppm_v*	*SOT**	*EOT***
234	8/22/2005	G7	L-1	368	1:41 AM	3:05 AM
		G5	R-1	374	12:30 AM	2:00 AM
		G5	L-1	387	2:01 AM	3:30 AM
		G6	L-1	378	1:46 AM	3:15 AM
		G7	R-1	377	12:15 AM	1:37 AM
		G6	R-1	378	12:15 AM	1:45 AM
235	8/23/2005	G7	L-3	366	4:01 AM	5:00 AM
		G6	R-2	359	12:00 AM	1:00 AM
		G7	R-3	354	3:00 AM	4:00 AM
		G6	L-2	356	1:01 AM	2:00 AM
		G5	R-2	362	12:00 AM	1:00 AM
		G5	L-2	356	1:01 AM	2:00 AM
		G5	L-3	358	4:01 AM	5:00 AM
		G7	R-2	358	12:00 AM	1:00 AM
		G5	R-3	358	3:00 AM	4:00 AM
		G7	L-2	361	1:01 AM	2:00 AM
		G6	L-3	360	4:01 AM	5:00 AM
		G6	R-3	356	3:00 AM	4:00 AM
236	8/24/2005	G6	L-4	367	1:16 AM	2:30 AM
		G7	R-4	370	12:00 AM	1:15 AM
		G5	L-4	369	1:16 AM	2:30 AM
		G7	L-4	361	1:16 AM	2:30 AM
		G5	R-4	--	12:00 AM	1:15 AM
		G6	R-4	367	12:00 AM	1:15 AM

*SOT = start of test
**EOT = end of test

concentrations even those these samples that were in the GRE. As with the $PM_{2.5}$ this is due to the measurement locations being situated out of the direct aircraft engine plume.

In addition to total mass measurements, an analysis was performed to evaluate which were the most important elements measured. Figure 7 shows the relative average contributions. Such graphs were prepared for all locations to help with analysis. A ranking of the average measured elements, based on measured mass, is shown in Table 5. In this table, the locations have been grouped to allow a further evaluation of overall trends. The measurement values for the blanks are also shown to allow a direct comparison to the measured values. The values for the top eight elements are greater than the values of the blanks and as such are thought to present meaningful measurement results.

The upwind data summary (Location R3) shows that sodium, chloride and sulfur dominate, accounting for 87.4% of the total mass collected. At the downwind locations these three elements were 80.6% of the total. The high levels of sodium and chlorine can be accounted for due to the close proximity of the ocean. The use of diesel fuel in the area and the nearby ocean may have contributed to the sulfur mass measured, but 3.2 micrograms (μg) of sulfur is still significantly lower than the downwind concentration of 5.6 μg. This difference of 2.4 μg was considered to approximate the airport's contribution to the sulfur levels in the ambient area. However, it also must be considered that the continued contribution of human activities (e.g., burning of fuels that contain sulfur) and from the nearby ocean has an influence that could not be measured. Regardless, the analysis shows the sulfur mass to be consistently higher at the downwind locations when compared to the upwind.

The amount of aluminum and iron were also reviewed since these are metals typically related to jet engine wear. Although present, these elements were in much smaller amounts. Of interest is that for both of these metals the downwind averages were greater than the upwind, but overall deposition was small. Chromium was not among the top 10 elements measured and in general was in very low amounts, very near the detection limit.

The GRE measurement averages show lower mass quantities of the three elements than the upwind or downwind locations, even though they were in very close proximity to the test aircraft. This is somewhat as expected since these locations were not measured for a full 24 hours, but only during the testing. Additionally, a measurement location could not be placed behind the aircraft, directly in the plume, due to the high wind velocities that occur. Sulfur was again among the top three measured elements. The difference in mass values among various locations was smaller and no clear trends occurred.

Taking the analysis a step further, it was desirable to perform a closer examination of sulfur, iron and chromium. Again, this is because these elements are directly related to emissions due to jet A fuel and from engine wear and any trends could help in estimating the aircraft contributions. For this analysis, the maximums by location were reviewed. Table 6, is a listing of the maximum mass per filter per day by location. Blank values are shown for comparison.

Table 5. Oakland Maximum Mass per Location per Day

Julian Date	*Location*	*Cr [ug/filter]*	*Julian Date*	*Location*	*S [ug/filter]*	*Julian Date*	*Location*	*Fe [ug/filter]*
234-235	R1	0.0316	234-235	R1	7.6910	234-235	R1	0.3797
	Blank	0.0226		R3	6.4870		R2	0.2599
	R2	0.0215		R2	4.6470		R3	0.2147
	G6	0.0102		G2	0.8927		G5	0.0384
	G8	0.0090		G8	0.8735		G2	0.0362
	G5	0.0079		G1	0.8667		G7	0.0328
	G7	0.0056		G5	0.8159		G4	0.0316
	G4	0.0045		G3	0.8068		G3	0.0305
	G1	0.0034		G4	0.7639		G8	0.0226
	G2	0.0011		G7	0.5492		Blank	0.0215
	R3	0.0000		G6	0.4802		G1	0.0158
	G3	0.0000		Blank	0.0215		G6	0.0023
235-236	G4	0.0294	235-236	R2	7.1590	235-236	R2	0.4486
	Blank	0.0282		R1	7.0050		R3	0.3627
	R3	0.0215		R3	5.8330		R1	0.2204
	G5	0.0192		G8	2.3940		G1	0.1243
	G1	0.0181		G3	2.0340		G6	0.1130
	G7	0.0170		G1	1.9780		Blank	0.1028
	G8	0.0158		G4	1.9530		G8	0.0848
	G3	0.0136		G2	1.7750		G3	0.0836
	G2	0.0136		G7	1.1850		G4	0.0667
	G8	0.0124		G5	1.0540		G2	0.0622
	R2	0.0102		G6	0.9481		G7	0.0497
	R1	0.0000		G8	0.9040		G5	0.0350
	G6	0.0000		Blank	0.0734		G8	0.0170
236-237	G2	0.0305	236-237	R2	3.1080	236-237	R2	0.0960
	R3	0.0282		R1	3.0770		G1	0.0734
	R1	0.0271		R3	2.9120		G4	0.0644
	R2	0.0237		G3	0.8102		R3	0.0554
	G4	0.0226		G4	0.7616		R1	0.0531
	G6	0.0215		G1	0.6961		G2	0.0316
	G5	0.0158		G2	0.6961		G5	0.0237
	G7	0.0124		G7	0.6339		G6	0.0215
	G3	0.0023		G6	0.5480		G3	0.0192
	G1	0.0000		G5	0.5379		G7	0.0068

Figure 7. Relative Contribution of Measured Elements, Oakland Airport

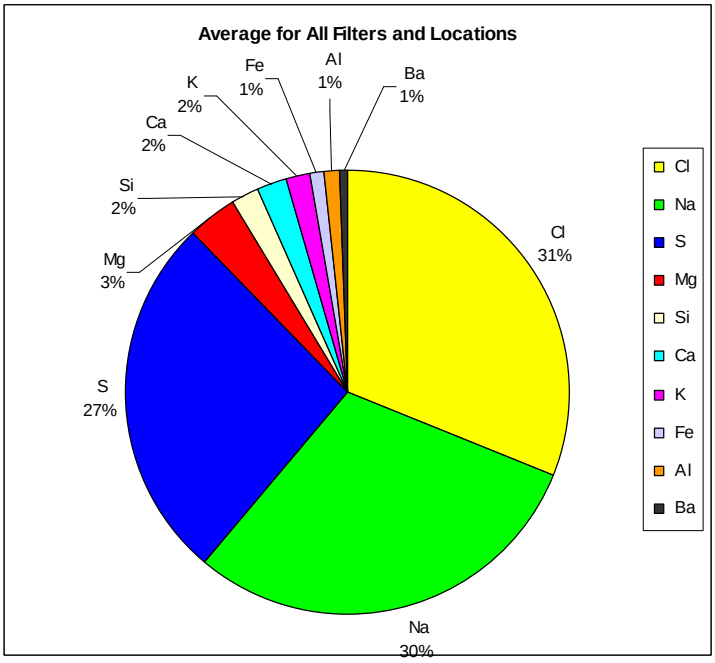


Table 6. Oakland Average Top 10 Elements by Mass at Grouped Locations

Rank	*Average All Sites*			*Downwind*			*Upwind*			*GRE*			*Blank*		
		µg	%		µg	%		µg	%		µg	%		µg	%
1	Cl	2.42	29.8	S	5.60	31.1	Cl	3.48	30.3	Cl	1.67	32.2	Na	0.24	19.9
2	Na	2.36	29.0	Na	5.25	29.2	Na	3.35	29.2	Na	1.49	28.9	Si	0.19	16.0
3	S	2.08	25.6	Cl	4.90	27.3	S	3.20	27.9	S	1.04	20.1	Mg	0.15	12.5
4	Mg	0.27	3.3	Mg	0.42	2.3	Ca	0.27	2.3	Mg	0.25	4.8	Al	0.10	8.3
5	SI	0.17	2.1	Si	0.35	2.0	Si	0.25	2.2	Ca	0.10	2.0	Ca	0.09	7.4
6	Ca	0.17	2.0	Ca	0.35	1.9	K	0.22	1.9	Si	0.10	1.9	Ba	0.07	5.7
7	K	0.13	1.6	K	0.33	1.8	Fe	0.14	1.3	Al	0.08	1.5	Fe	0.06	5.1
8	Fe	.09	1.2	Fe	0.24	1.3	Mg	0.12	1.0	K	0.06	1.2	Pb	0.06	4.8
9	Al	.08	0.9	AL	0.08	0.4	Ba	0.06	0.6	Fe	0.05	0.9	S	0.05	3.9
10	Ba	.05	0.6	La	0.07	0.4	Al	0.05	0.4	Ba	0.04	0.8	Ti	0.03	2.4

It can be seen that the sulfur measured was always much greater than the values for the maximum blank, and as such considered to be significant. For iron, some but not all, samples were significant. A review shows the greatest concentrations for iron occurred at R1 and R2 (the downwind locations for the airfield) indicating a possible trend to be explored. For chromium it cannot be established if values are truly significant since many are near or below the measured mass on the blank. Additionally, the chromium maximums exhibited no clear trend. In sum, sulfur may provide a key for future

measurement programs to determine the contribution of the jet engine activities. Iron may be a possibility. This can not be concluded from this study for chromium.

CLEVELAND HOPKINS INTERNATIONAL AIRPORT

The ambient measurement period extended from October 31, 2005 to November 9, 2005, although as before considerable time and effort were needed both before and after the testing. The ambient measurements were began before the probe measurements and extended to after completion of these measurements. The average ambient temperature was 57°F. The high was 69°F with an average six day high temperature of 64°F. The low was 40°F with an average six day low temperature of 49°F when probe sampling was accomplished.

As at Oakland, the purposes of the sampling had the same two goals: support of the probe measurements and examine the idea of upwind and downwind concentrations for the active runway. Locations were selected based on expected wind patterns. Figure 8 shows the airport locations. Locations R9 and R10 were selected to be downwind while R8 was to be the upwind location. Locations were also selected near the probe measurement location and included seven locations to surround the aircraft test area. The expected general wind pattern and the positioning of the aircraft led to R1- R4 being designated as the downwind locations to allow analysis of the aircraft exhaust while Locations R5 - R7 were upwind locations to allow measurement of ambient conditions. Figure 9 shows the ambient locations near the probe sampling area.

Meteorological stations as described in the equipment section were located at Locations R1 and R8. Location R1 had an average hourly wind from the southwest quadrant 98% of the time when sampling was not occurring. This is an important point because during sampling the wind speed and direction were heavily biased by the jet exhaust and a measure of plume velocity, not the ambient weather. Location R8 had an average hourly wind 87% of the sampling period from the southwest quadrant. However, it should be noted that even though the wind angles were typically between 180 and 270 degrees, there was considerable variance within this range. A typical wind rose showing the trends for the unbiased R8 Location is shown in Figure 10. Figure 11 shows a graphical representation of the variation as well. Because of this variation (as can be easily seen in Figures 10 and 11), the wind patterns were not as conducive to a defined upwind and downwind location as occurred at Oakland. Wind speeds were typically higher at R1 than upwind at R8 as expected because of the jet exhaust influence. The maximum wind speed at R8, more typical of the local area wind field, was 3.3 m/s with a minimum of 0.3 m/s. Again, complete data is shown in the companion spreadsheet.

Figure 8. Measurement Locations at Cleveland Hopkins Airport

Figure 9. Ambient Measurement Locations Near the Probe Sampling Area

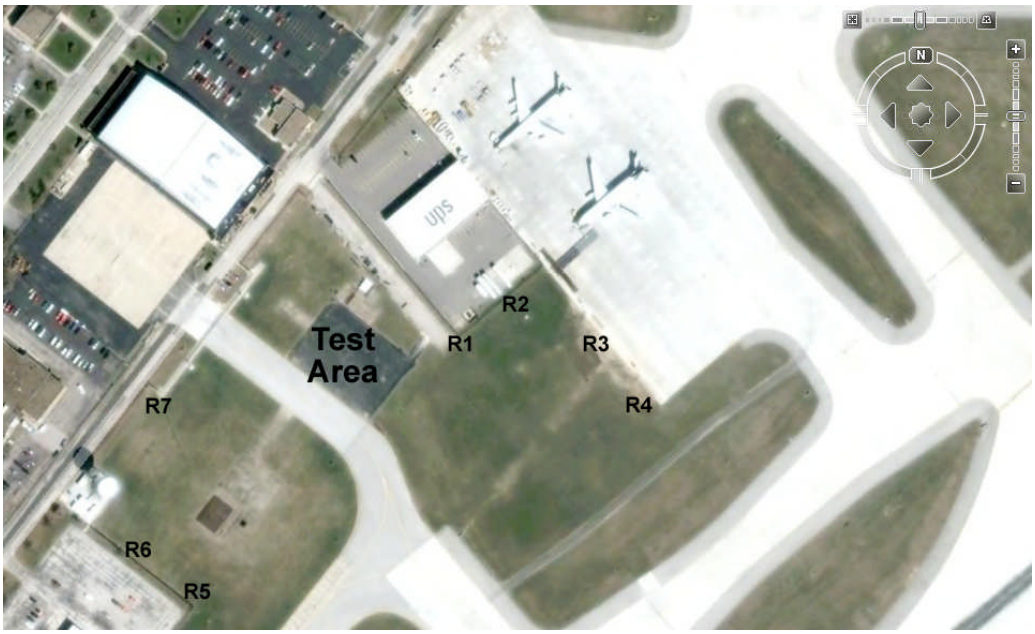


Figure 10. Typical Wind Rose Plot, Cleveland Hopkins Airport

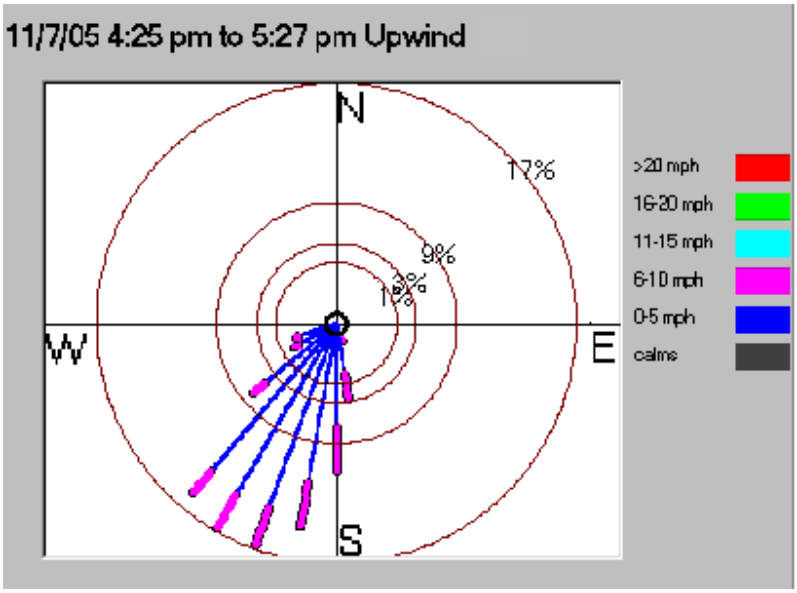
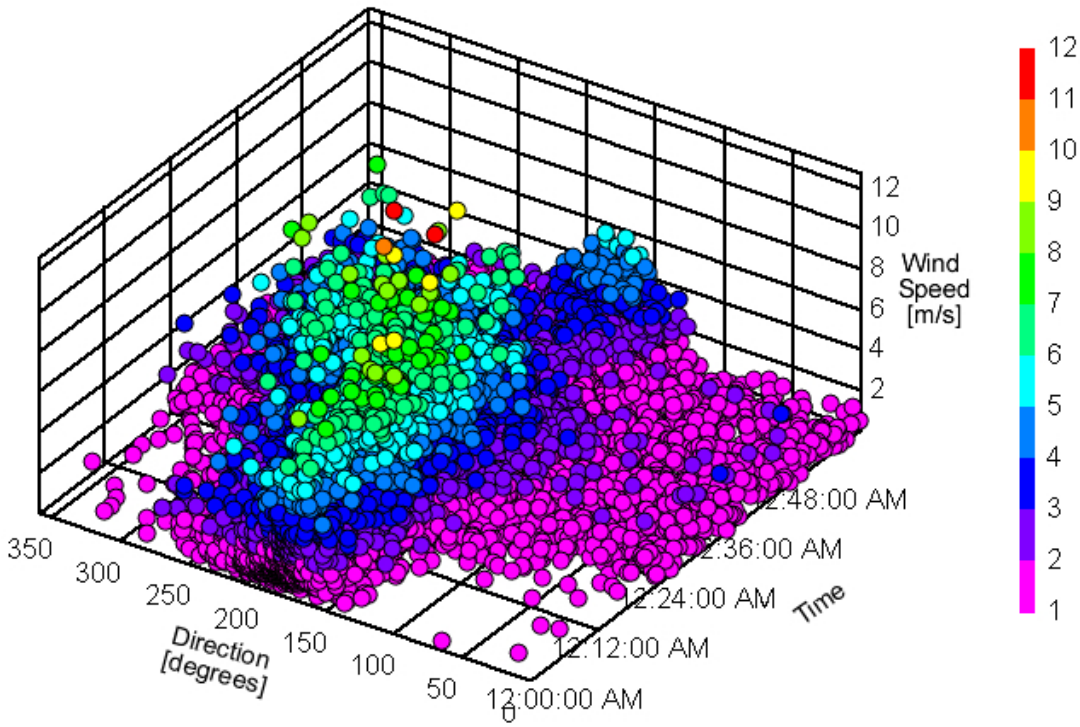


Figure 11. Typical Wind Patterns During Measurements, Cleveland Hopkins Airport



Analysis was performed in a similar manner for the Cleveland Airport as for the Oakland Airport for total mass. Table 7 shows the measured total $PM_{2.5}$ mass at the locations. Because of a crosswind condition with the active runways, the so called "upwind" and "downwind" locations exhibited an even split during sample days of which locations measured the largest amount of total $PM_{2.5}$ mass. This was most likely heavily influenced by alternate runway use, nearby automobile traffic, and industrial operations in the nearby area.

Table 7. Results for Total Mass, Oakland International Airport, $PM_{2.5}$

FilterID	*Julian Date*	*Location*	*Clean Mass*	*Exposed Mass*	*Diff (mg)*	*Comments*
UCF-0001	304	R8	141.248	141.290	0.042	24hour
UCF-0002	304	R9	143.907	144.084	0.177	24hour
UCF-0003	304	R10	143.734	143.972	0.238	24hour
UCF-0004	305	R8	142.642	144.476	1.834	24hour
UCF-0005	305	R9	142.306	143.647	1.341	24hour
UCF-0006	305	R10	144.143	145.161	1.018	24hour
UCF-0007	305	R1	142.777	143.968	1.191	During probe test
UCF-0008	305	R2	141.912	143.718	1.806	During probe test
UCF-0009	305	R3	144.955	146.389	1.434	During probe test
UCF-0010	305	R4	143.885	145.583	1.698	During probe test
UCF-0011	305	R5	142.662	144.160	1.498	During probe test
UCF-0012	305	R6	143.290	144.336	1.046	During probe test
UCF-0013	305	R7	142.318	144.775	2.457	During probe test
UCF-0014						Blank
UCF-0015	307	R1	142.612	143.590	0.978	Test suspended
UCF-0016	307	R2	142.201	143.625	1.424	Test suspended
UCF-0017	307	R3	142.012	142.441	0.429	Test suspended
UCF-0018	307	R4	141.873	142.389	0.516	Test suspended
UCF-0019	307	R7	142.633	143.290	0.657	Test suspended
UCF-0020	307	R6	140.458	141.397	0.939	Test suspended
UCF-0021	307	R5	145.987	147.172	1.185	Test suspended
UCF-0022	306	R9	141.084	141.210	0.126	24hour
UCF-0023	306	R8	142.668	142.809	0.141	24hour
UCF-0024	306	R10	143.367	143.486	0.119	24hour
UCF-0025	307	R9	144.832	145.778	0.946	24hour
UCF-0026	307	R8	143.745	144.389	0.644	24hour
UCF-0027	307	R10	142.488	142.815	0.327	24hour
UCF-0028	308	R1	143.404	143.465	0.061	During probe test
UCF-0029	308	R2	142.457	142.537	0.080	During probe test
UCF-0030	308	R3	140.615	141.106	0.491	During probe test
UCF-0031	308	R4	142.161	142.372	0.211	During probe test
UCF-0032	308	R5	142.730	142.961	0.231	During probe test
UCF-0033	308	R6	142.453	142.983	0.530	During probe test
UCF-0034	308	R7	142.460	142.958	0.498	During probe test
UCF-0035	308	R8	142.944	143.352	0.408	24hour
UCF-0036	308	R9	141.546	141.725	0.179	24hour
UCF-0037	308	R10	141.032	141.504	0.472	24hour

UCF-0038						Blank
UCF-0039	309	R1	143.005	143.160	0.155	During probe test
UCF-0040	309	R2	143.837	144.123	0.286	During probe test
UCF-0041	309	R3	142.877	143.255	0.378	During probe test
UCF-0042	309	R4	142.307	142.526	0.219	During probe test
UCF-0043	309	R5	145.740	146.084	0.344	During probe test
UCF-0044	309	R6	140.902	141.041	0.139	During probe test
UCF-0045	309	R7	142.740	143.098	0.358	During probe test
UCF-0046	309	R8	142.045	142.296	0.251	24hour
UCF-0047	309	R9	142.462	142.703	0.241	24hour
UCF-0048	309	R10	144.351	144.817	0.466	24hour
UCF-0049						Blank
UCF-0050	310	R9	142.678	142.856	0.178	24hour
UCF-0051	310	R10	141.223	141.398	0.175	24hour
UCF-0052	310	R8	144.407	144.482	0.075	24hour
UCF-0053	310	R1	142.752	142.916	0.164	During probe test
UCF-0054	310	R2	144.968	145.118	0.150	During probe test
UCF-0055	310	R3	144.060	144.162	0.102	During probe test
UCF-0056	310	R4	143.897	143.989	0.092	During probe test
UCF-0057	310	R5	142.926	143.073	0.147	During probe test
UCF-0058	310	R6	143.924	144.000	0.076	During probe test
UCF-0059	310	R7	145.063	145.158	0.095	During probe test
UCF-0060						Blank
UCF-0061	311	R10	143.264	143.418	0.154	24hour
UCF-0062	311	R9	143.765	143.903	0.138	24hour
UCF-0063	311	R8	144.533	144.645	0.112	24hour
UCF-0064	311	R1	144.458	144.550	0.092	During probe test
UCF-0065	311	R2	144.092	144.171	0.079	During probe test
UCF-0066	311	R3	145.333	145.406	0.073	During probe test
UCF-0067	311	R4	144.462	144.523	0.061	During probe test
UCF-0068	311	R5	144.882	144.927	0.045	During probe test
UCF-0069	311	R6	143.900	143.954	0.054	During probe test
UCF-0070	311	R7	145.918	146.006	0.088	During probe test
UCF-0071						Blank
UCF-0072	312	R10a	145.953	146.067		Runway study
UCF-0073	312	R10	145.372	145.482	0.110	Runway study
UCF-0074	312	R9	147.523	147.626	0.103	Runway study
UCF-0075	312	R8	144.503	144.626	0.123	Runway study
UCF-0076	312	R8a	145.660	145.797	0.137	Runway study

$PM_{2.5}$ ambient concentrations were also calculated and are listed in Table 8. The PM2.5 measured values for the locations away from the test area were below the National Ambient Air Quality Standard of 35 $\mu g/m^3$ even though sampling was done very close to aircraft operations. As can be seen from Table 8, ambient conditions caused multiple quality control problems due to rain and contamination of samples. Work is continuing with cooperation of the measurement laboratory and some of the data flagged for quality control may be useable at a later date. The results of the runway test are also not shown because the test was stopped prematurely due to weather.

Table 8. Calculated Ambient $PM_{2.5}$ Concentrations, Cleveland Hopkins Airport

Julian Date	*Date*	*Filter*	*Location*	*Mass [mg]*	*SOT [hours]*	*EOT [hours]*	*Volume [liters]*	*Conc. [μg/m³]*	*Comments*
304	10/31/2005	UCF-0001	R8	0.042					Rain.
304		UCF-0002	R9	0.177					Rain
304		UCF-0003	R10	0.238					Rain
305	11/1/2005	UCF-0004	R8	1.834					Flagged for QC
305		UCF-0005	R9	1.341					Flagged for QC
305		UCF-0006	R10	1.018					Flagged for QC
305		UCF-0007	R1	1.191					Flagged for QC
305		UCF-0008	R2	1.806					Flagged for QC
305		UCF-0009	R3	1.434					Flagged for QC
305		UCF-0010	R4	1.698					Flagged for QC
305		UCF-0011	R5	1.498					Flagged for QC
305		UCF-0012	R6	1.046					Flagged for QC
305		UCF-0013	R7	2.457					Flagged for QC
305		UCF-0014	blank						
307	11/3/2005	UCF-0015	R1	0.978	78.9	94	4530	215.9	At test location
307		UCF-0016	R2	1.424	72.5	89.7	5160	276.0	At test location
307		UCF-0017	R3	0.429	43.9	61	5130	83.6	At test location
307		UCF-0018	R4	0.516	74.9	90.4	4650	111.0	At test location
307		UCF-0019	R7	0.657	126.4	142.4	4800	136.9	At test location
307		UCF-0020	R6	0.939	59.9	77.9	5400	173.9	At test location
307		UCF-0021	R5	1.185	55.6	71.5	4770	248.4	At test location
306	11/4/2005	UCF-0022	R9	0.126	140.6	164.7	7230	17.4	Airfield
306		UCF-0023	R8	0.141	106.8	130.7	7170	19.7	Airfield
306		UCF-0024	R10	0.119	126.4	150.4	7200	16.5	Airfield
307	11/5/2005	UCF-0025	R9	0.946					Flagged for QC
307		UCF-0026	R8	0.644					Flagged for QC
307		UCF-0027	R10	0.327					Flagged for QC
308	11/6/2005	UCF-0028	R1	0.061	94	97	900	67.8	At test location
308		UCF-0029	R2	0.08	89.7	94.6	1470	54.4	At test location
308		UCF-0030	R3	0.491					Flagged for QC
308		UCF-0031	R4	0.211					Flagged for QC
308		UCF-0032	R5	0.231					Flagged for QC
308		UCF-0033	R6	0.53					Flagged for QC
308		UCF-0034	R7	0.498					Flagged for QC
308		UCF-0035	R8	0.408					Flagged for QC
308		UCF-0036	R9	0.179	188.3	212.7	7320	24.5	Airfield
308		UCF-0037	R10	0.472					Flagged for QC
308		UCF-0038	blank						
309	11/7/2005	UCF-0039	R1	0.155	94.6	105.6	3300	47.0	At test location
309		UCF-0040	R2	0.286	97	111.5	4350	65.7	At test location

309		UCF-0041	R3	0.378	65.7	80.2	4350	86.9	At test location
309		UCF-0042	R4	0.219	93.4	104.6	3360	65.2	At test location
309		UCF-0043	R5	0.344	76.1	91.1	4500	76.4	At test location
309		UCF-0044	R6	0.139	82.4	97.3	4470	31.1	At test location
309		UCF-0045	R7	0.358	146.7	161.6	4470	80.1	At test location
309		UCF-0046	R8	0.251					Flagged for QC
309		UCF-0047	R9	0.241	212.7	236.9	7260	33.2	Airfield
309		UCF-0048	R10	0.466					Flagged for QC
		UCF-0049	blank						
310	11/8/2005	UCF-0050	R9	0.178	236.9	260.4	7050	25.2	Airfield
310		UCF-0051	R10	0.175	222.7	246.2	7050	24.8	Airfield
310		UCF-0052	R8	0.075	202.3	226.3	7200	10.4	Airfield
310		UCF-0053	R1	0.164	105.6	110.4	1440	113.9	At test location
310		UCF-0054	R2	0.15	111.5	119.6	2430	61.7	At test location
310		UCF-0055	R3	0.102	80.2	88.2	2400	42.5	At test location
310		UCF-0056	R4	0.092	104.6	109.4	1440	63.9	At test location
310		UCF-0057	R5	0.147	91.1	98.8	2310	63.6	At test location
310		UCF-0058	R6	0.076	97.3	105.2	2370	32.1	At test location
310		UCF-0059	R7	0.095	161.6	169.6	2400	39.6	At test location
		UCF-0060	blank						
311	11/9/2005	UCF-0061	R10	0.154	246.2	266.7	6150	25.0	Airfield
311		UCF-0062	R9	0.138	260.4	283.6	6960	19.8	Airfield
311		UCF-0063	R8	0.112	226.3	249.5	6960	16.1	Airfield
311		UCF-0064	R1	0.092	110.4	112.1	510	180.4	At test location
311		UCF-0065	R2	0.079	119.6	124.3	1410	56.0	At test location
311		UCF-0066	R3	0.073	88.2	92.8	1380	52.9	At test location
311		UCF-0067	R4	0.061	109.4	111.2	540	113.0	At test location
311		UCF-0068	R5	0.045	98.8	104	1560	28.8	At test location
311		UCF-0069	R6	0.054	105.2	110.5	1590	34.0	At test location
311		UCF-0070	R7	0.088	169.6	174.9	1590	55.3	At test location
		UCF-0071	blank						
312		UCF-0072	R10a	0.114					Runway test, NA
312		UCF-0073	R10	0.11					Runway test, NA
312		UCF-0074	R9	0.103					Runway test, NA
312		UCF-0075	R8	0.123					Runway test, NA
312		UCF-0076	R8a	0.137					Runway test, NA

CO_2 was also sampled in support of the probe sampling in the vicinity of the test aircraft. Table 9 lists this data. The first day of measurements (Julian date 307) was accomplished upwind and downwind of the probe test area. As might be expected, the downwind measurements were greater with one exception.

Table 9. Measured CO_2 Concentrations, Cleveland Airport

Julian Date	*Date*	*Location*	*Bag*	*CO_2 ppm_v*	*SOT*	*EOT*
307	11/3/2005	R5	4L	355	10:00 AM	1:20 PM
		R7	1L	309	10:00 AM	1:20 PM
		R7	1R	300	2:00 PM	6:00 PM
		R5	13RB	312	2:00 PM	6:00 PM
		R1	12L	321	1:16 AM	3:14 AM
		R1	7R	--	10:30 PM	11:15 AM
		R4	11L	356	1:16 AM	3:20 AM
		R4	11R	335	10:30 PM	11:15 AM
308	11/4/2005	R1	1R	--		
		R1	1L	443	4:30 PM	6:00 PM
		R4	13RB	302	3:00 PM	4:30 PM
		R4	4L	305	4:30 PM	6:00 PM
309	11/5/2005	R1	12L	379	1:00 PM	4:00 PM
		R4	1L	327	1:00 PM	4:00 PM
		R1	13RB	296	10:00 AM	1:00 PM
		R4	1R	297	10:00 AM	1:00 PM
		R4	11L	296	9:30 PM	11:00 PM
		R1	7R	320	8:00 PM	9:30 PM
		R4	11R	312	8:00 PM	9:30 PM
		R1	4L	497	9:30 PM	11:00 PM
310	11/6/2005	R1	1R	305	7:36 PM	9:00 PM
		R1	1L	375	9:00 PM	10:15 PM
		R4	13RB	320	7:00 PM	9:00 PM
		R4	12L	499	9:00 PM	10:15 PM
311	11/7/2005	R1	7R	350	12:30 AM	1:15 AM
		R1	4L	331	1:16 AM	2:00 AM
		R4	11R	344	12:30 AM	1:15 AM
		R4	11L	322	1:16 AM	2:00 AM
		R1	1L	320	6:01 PM	7:30 PM
		R1	1R	384	4:30 PM	6:00 PM
		R4	11R	305	4:30 PM	6:00 PM
		R4	11L	302	6:01 PM	7:30 PM
312*	11/8/2005	R10	1R	328	9:30 AM	1:00 PM
		R10	1L	329	1:00 PM	5:00 PM
		R8	11R	322	9:55 AM	1:10 PM
		R8	11L	311	1:11 PM	5:00 PM

*runway study

The next four measurement days, CO_2 measurements were only made downwind of the test area. Again, the term downwind is slightly misleading because of the cross winds that occurred. However, as expected, there was a general falloff with distance with the further distance (R4) being about 11 percent lower in concentration on average than at the near location (R1). The last day was an airport study. As expected concentrations were

near what would be expected as ambient background. There was a very slight increase for the downwind locations (~ 7 - 18 ppm_v).

The overall mass amounts by element were reviewed as for Oakland. Figure 12 shows the overall results graphically. The graph and data summary in Table 10 show that sulfur again dominates both the upwind and downwind locations accounting for about 70% of the total mass collected. The elemental breakdown for Cleveland looks remarkable similar in the downwind case as it does in the upwind case with the exception being that the downwind mass amounts are generally greater. Of note is the large difference between the sulfur mass measurement results and the blank, indicating a small measurement error during analysis.

Figure 12. Relative Contribution of Measured Elements, Cleveland Airport

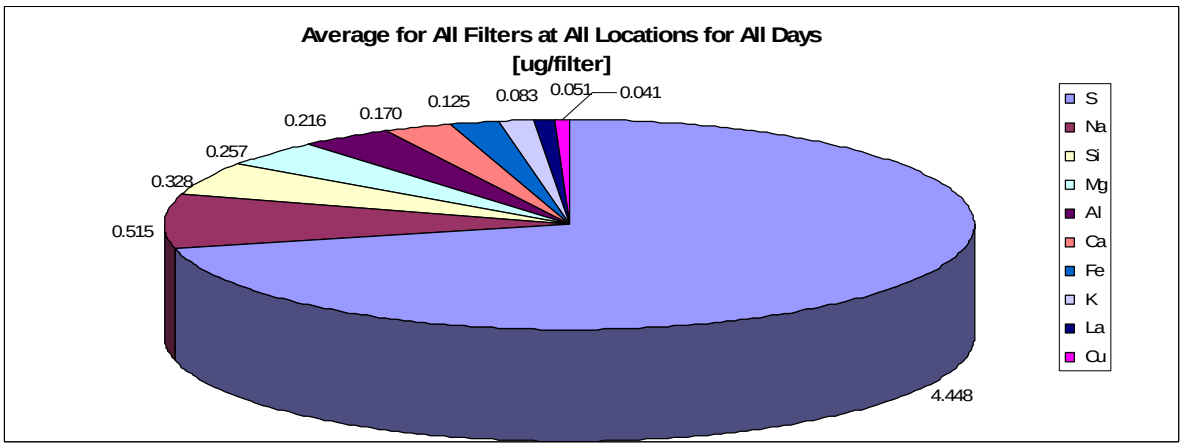


Table 10. Cleveland Average Top 10 Elements by Mass at Group Locations

	Downwind			*Upwind*			*Blank*		
Rank		*µg*	*%*		*µg*	*%*		*µg*	*%*
1	S	7.61	71	S	5.88	69	S	0.34	38
2	Na	0.77	7	Na	0.62	7	Na	0.16	18
3	Si	0.53	5	Si	0.46	5	Si	0.08	9
4	Mg	0.41	4	Mg	0.37	4	Mg	0.06	7
5	Al	0.35	3	Al	0.32	4	Al	0.04	5
6	Ca	0.27	2	Ca	0.25	3	Ca	0.04	4
7	Fe	0.20	2	Fe	0.16	2	Fe	0.03	3
8	K	0.12	1	K	0.11	1	K	0.02	3
9	La	0.07	1	La	0.06	1	La	0.02	2
10	Cu	0.06	1	Cu	0.05	1	Cu	0.02	2

A simple mass balance between the downwind and upwind locations shows an average 1.8 μg difference for the sulfur. To place in perspective, this value 75% of the difference that was measured at the Oakland Airport, albeit the total mass measured at Oakland was lower by more than 2 μg for both the upwind and downwind locations. Of extreme interest is that based the ratio for the differences of mass at the airports is very close to the same ratio (78%) of the number of operations compared at each airport.[3] While this may be coincidence, it does further suggest that deposited sulfur may be an indicator of the airport activity. Of course, sulfur alone does not provide a complete "picture" because of the possible influence of other sources.

Again, as expected, the filters analyzed for those locations close to the test area show lower overall mass quantities than the upwind or downwind airport locations for sulfur. This is primarily due once again to a much shorter sample time (only during the length of the probe measurements) and the greater distance from hub airport operations.

The large, frequent variation of wind direction from the centerline of the test aircraft presented more challenges during measurements than at Oakland. Still, meaningful results from Locations R1 to R4 (downwind of test aircraft) as compared to Locations R5 to R7 (upwind of the aircraft) were possible. Table 11 shows the averaged mass values of the top ten elements collected by each general location. Again, grouping permitted a broader overview for trends. Sulfur dominated once again and was over two-thirds of the total mass, similar to the airfield measurements. Of interest, is that even though these were short term samples, a difference of over 1μg still occurred with the downwind measurements being greater.

Table 11. Cleveland Average Top 10 Elements by Mass at Grouped Locations

	Average All			*Average R5-R7*			*Average R1-R4*		
Rank		*μg*	*%*		*μg*	*%*		*μg*	*%*
1	S	4.45	69	S	3.25	67	S	4.06	67
2	Na	0.52	8	Na	0.43	9	Na	0.48	9
3	Si	0.33	5	Si	0.23	5	Si	0.32	5
4	Mg	0.26	4	Mg	0.19	4	Mg	0.25	4
5	Al	0.22	3	Al	0.16	3	Al	0.21	3
6	Ca	0.170	3	Ca	0.130	3	Ca	0.165	3
7	Fe	0.125	2	Fe	0.104	2	Fe	0.113	2
8	K	0.083	1	K	0.073	2	K	0.078	1
9	La	0.051	1	La	0.047	1	La	0.050	1
10	Cu	0.041	1	Cu	0.039	1	Cu	0.038	1

[3] Data used from each airport home internet site.

A closer analysis was done of the three elements considered to be related to aircraft operations (sulfur, iron, and chromium). Table 5 shows the three highest mass per filter measured each day and their corresponding locations.

Table 12. Top Three Mass Results by Day and Location

Julian Date	*Location*	*Cr [ug/filter]*	*Julian Date*	*Location*	*S [ug/filter]*	*Julian Date*	*Location*	*Fe [ug/filter]*
305	R10	0.0486	305	R9	4.3480	305	R9	0.2994
	R9	0.0475		R10	3.9230		R1	0.1277
	R2	0.0294		R8	0.1074		R8	0.1074
306	R10	0.0384	306	R10	7.7810	306	R10	0.3548
	R8	0.0328		R9	7.5700		R8	0.2011
	R9	0.0316		R8	7.5460		R9	0.1040
307	R10	0.0373	307	R10	5.6480	307	R2	0.2350
	R4	0.0350		R8	5.5310		R7	0.2294
	R9	0.0339		R9	5.4420		R9	0.1921
308	R10	0.0520	308	R8	11.2600	308	R8	0.3209
	R8	0.0486		R10	11.2500		R9	0.3051
	R3	0.0316		R9	11.0600		R10	0.2136
309	R9	0.0429	309	R10	16.4100	309	R8	0.2893
	R2	0.0373		R8	15.6300		R1	0.2667
	R8	0.0373		R9	15.1500		R10	0.2531
310	R9	0.0282	310	R8	3.4260	310	R8	0.1379
	R7	0.0260		R10	3.3100		R9	0.1164
	R6	0.0249		R9	3.2440		R4	0.0960
311	R9	0.0633	311	R9	6.8930	311	R10	0.2090
	R8	0.0407		R8	6.2300		R9	0.1910
	R5	0.0282		R10	5.3060		R8	0.1074
312	R10	0.0384	312	R10a	3.1310	312	R10a	0.1842
	R10a	0.0373		R8	3.0100		R8	0.1548
	R8	0.0249		R9	2.9630		R8a	0.1232

For sulfur, the highest mass per filter always occurs at R8, R9, or R10. Again, this is the 24 hour sample locations and near the active runway. On Julian dates 308 to 310, the mass was much greater than on other days. A review of the meteorology shows similar patterns except on 310 when the wind angle was more oriented with the runway. However, no conclusive reason has yet been found for this larger measured mass.

The measured iron mass most often was the greatest at R8, R9, and R10, but not always. There was a slight trend for downwind concentrations being larger on some days, but not

consistently. Other locations also had higher values. Additionally, the large increase on days 308 to 310 did not occur as it did for sulfur.

The measurement results for chromium also showed that locations other than R8, R9, and R10 had high values and also did not show the large increase on days 308 to 310. Again, trends were not evident for chromium.

CONCLUSIONS

The report has presented the key data and presented preliminary results. Due to the large volume of data, a complete listing has not been included in this report but in a companion spreadsheet named APEX2&3 Ambient Report.xls. Analysis of the data is continuing and will be included in further work dealing with the probe data and comparisons as more upwind/downwind airport data become available.

Some conclusions can be drawn from this initial reporting.

- Total $PM_{2.5}$ would seem to be below the National Ambient Air Quality Standards, even in close proximity to the runway. No clear trend of greater total mass was found at the downwind locations.
- The sulfur mass measured was significantly above the blanks used and the measurement threshold levels indicating a measurement with a low error.
- Sulfur would seem to be an indicator of airport activity. This is confirmed by the upwind versus downwind simple mass balancing at different ends of the operating runway. It is also of note that the ratio of the upwind to downwind concentrations at the two airports was very similar to the ratio of reported operations. More work is needed but sulfur may be one possible indicator of the contribution of emissions from aircraft operations.
- Iron and chromium were found to be in very small mass quantities. Iron showed some trend to greater concentrations downwind but not conclusively. Chromium did not appear to exhibit any trends and was measured in low mass amounts, very near the detection limits.
- CO2 seemed to exhibit a slight trend of higher concentrations downwind and might also be used in conjunction with sulfur as an indicator of the aircraft contributions to local concentrations.
- Other metals were also found in small amounts and the results are continuing to be analyzed.
- A data base has been established and can be added to in the future to permit trends and total expected amounts of $PM_{2.5}$ to be further developed. More data are needed to establish a more robust data base. Some limited measurements have been done at a major U.S. airport since these projects have been completed and will be added to the data base as well.