PM Speciation Profiles for Commercial Aircraft—Jet Fuel (PM1411-1414)

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1 Introduction

The current CARB PM speciation profile assigned to aircraft—jet fuel combustion is PM141 [1]. Because an explicit jet fuel combustion profile was not available at the time, this profile, which is based on an industrial boiler source test that was conducted in 1979 [2], was assigned. The profile assignment implies that the $PM_{2.5}$ emitted from jet aircraft combustion consists of 25% sulfate and 15% elemental carbon (EC), and the species of the other 54% of the $PM_{2.5}$ are not identified. This does not represent the composition of actual aircraft exhaust because organic carbon (OC), an important PM component in fuel combustion exhaust, is missing. Therefore, a new PM speciation profile is needed to better describe the composition of aircraft-generated PM emissions.

To obtain direct PM emissions information from aircraft exhausts, NASA, EPA, FAA, CARB, and others sponsors organized an aircraft engine emission measurement program called APEX (Aircraft Particle Emissions eXperiment) in 2003 [3]. One of the objectives of the multi-agency study is to update and improve chemical source profiles for aircraft engines. During the three campaigns (APEX-1, -2, and -3), exhaust plume of $PM_{2.5}$ samples from several commercial turbofan engine models were collected on the ground at a distance of 30 meter behind the engine exit[4]. This distance is a widely accepted practice as it allows for the formation of volatile PM while still keeping plume integrity. Time integrated $PM_{2.5}$ sampling was conducted over the entire test period for selected engines operating at a series of steady-state power conditions.

Four speciation profiles are developed in this work:

- PM1411: Aircraft-Jet Fuel (1639 ppm S)
- PM1412: Aircraft-Jet Fuel (130-550 ppm S)
- PM1413: Aircraft-Jet Fuel (CFM56-3B)
- PM1414: Aircraft-Jet Fuel (RB211)

2 Methodology

Due to technical issues that occurred during the experiments, such as unrealistically high EC/OC background ratios and filter contamination, the data from some tests of engine/fuel combinations are not utilized in this work. Four aircraft engines were involved in the selected tests: CFM56-2C1, CFM56-7B24, CFM56-3B, and RB211-535E4-B. Although the test engines are limited relative to the entire fleet, the CFM56 engine family is the most prevalent engine type operating in the commercial aircraft fleet.

Jet-A fleet fuel was used in most of the tests, and the fuel sulfur content varied from 130 to 550 ppm. A 'spiked', unrealistically high sulfur fuel (1639 ppm) was used in one test to examine the impact of fuel sulfur on PM emissions.

The following steps are used to create the speciation profiles out of the reported data:

a. OC (organic carbon) was reported directly; thus, the corresponding OM (organic matter) can be estimated by multiplying the OM/OC conversion factor and the NCOM is calculated by subtracting OC from OM. The conversion factor of OM/OC is 1.15 for this profile, based on the identified organic aerosol species [4].

b. A species group named 'others' is created to capture the mass of oxygen associated with the five geological elements (i.e. Al, Si, Ca, Fe and Ti) using the following formula:

$$0.89 \times [Al] + 1.14 \times [Si] + 0.40 \times [Ca] + 0.43 \times [Fe] + 0.67 \times [Ti]$$

where [Al], [Si], [Ca], [Fe] and [Ti] are weight percentages of these five elements, respectively [5].

c. The species of chlorine and potassium are replaced by *insoluble chlorine* and *insoluble potassium*, respectively, to avoid double-counting of the chloride and potassium ions.

d. The weight percentages of all the species are added up as the total percentage of the $PM_{2.5}$ mass; and then this total percentage is used as the denominator in calculating the normalized speciation profile.

3 Results and Discussion

There are four $PM_{2.5}$ speciation profiles for jet aircraft created in this work (Table 1): PM1411 Aircraft-Jet Fuel (1639 ppm S), PM1412 Aircraft-Jet Fuel (100-550 ppm S), PM1413 Aircraft-Jet Fuel (CFM56-3B), and PM1414 Aircraft-Jet Fuel (RB211).

Table 1. $PM_{2.5}$ speciation profile for aircraft—jet fuel

Species Name	*SAROAD*	*Weight Percentage (%)*			
		PM1411: Aircraft-Jet Fuel (1639ppm S)	PM1412: Aircraft-Jet Fuel (130-550ppm S)	PM1413: Aircraft-Jet Fuel (CFM56-3B)	PM1414: Aircraft-Jet Fuel (RB211)
Ammonium	12301	6.6844	6.9074	5.0895	2.3354
Antimony	12102			0.0827	
Bromine	12109		0.0192	0.0080	
Calcium	12111			0.2044	0.0453
Chloride	12203				0.8531
Insol-chlorine	12202		0.0695		
Chromium	12112		0.0253		0.0198
Copper	12114		0.2086		
EC	12116	16.6156	20.8942	48.4017	77.9415
Indium	12131			0.0608	0.0510

Species Name	*SAROAD*	*Weight Percentage (%)*			
		PM1411: Aircraft-Jet Fuel (1639ppm S)	PM1412: Aircraft-Jet Fuel (130-550ppm S)	PM1413: Aircraft-Jet Fuel (CFM56-3B)	PM1414: Aircraft-Jet Fuel (RB211)
Iron	12126			0.0633	0.0822
Magnesium	12140		0.1115		
Manganese	12132		0.0177	0.0170	
NCOM	11103	3.5428	6.2583	4.0085	1.6665
Nickel	12136		0.0355		0.0170
OC	11102	23.6184	41.7219	26.7234	11.1102
Phosphorous	12152			0.0878	
Potassium	12180		0.0865		
Insol-potassium	65312	3.5268	0.4841	0.6335	1.0912
Silicon	12165	0.5093	0.3866	0.1437	
Silver	12166		0.0652		
Sulfate	12403	44.4993	22.2435	14.2028	4.7332
Thallium	12173	0.1464			
Titanium	12161	0.1655	0.0051		
Zinc	12167		0.0157		
Other	12999	0.6915	0.4442	0.2728	0.0535
Total		*100.0000*	*100.0000*	*100.0000*	*100.0000*

The comparison between these profiles clearly shows that the amount of sulfur in the fuel is directly related to the PM emissions and composition. The sulfate content is 44.5% in PM1411 (1639 ppm S) representing higher sulfur fuel combustion; while there is only 4.7 to 22.2% sulfate in other profiles tested with regular Jet fuel sulfur level (130-550 ppm). Jet-A fuel is the predominant fuel used in commercial aircraft engines and its sulfur level is limited to 0.3% weight maximum; however, in practice, Jet-A sulfur content ranges between 0.04 and 0.06% (about 400 and 600 ppm) and lower sulfur jet fuels become available while diesel fuel sulfur levels drop [6]. Therefore, PM1411 is suggested to be used only when the fuel sulfur content is emphasized as 1600 ppm or higher.

In addition to the impact of fuel sulfur, the type of the aircraft engine also affects the composition of the PM exhaust. The simplified speciation profile plot (Figure 1) shows relatively high EC content in PM1413 (48.4%) and PM1414 (77.9%), compared to PM1411 (16.6%) and PM1412 (20.1%). PM1413 is created based on the CFM56-3B engine test data. This older engine technology tends to have a slightly lower engine pressure ratio than the other CFM56 engine models (represented by PM1412). PM1414 is made from the test data of RB211 engine, which is an internally mixed engine and has the lowest bypass ratio of the turbofan engines tested. Since CFM56 is the most popular engine type operating in the commercial fleet, PM1412 will be assigned to the related CARB aircraft emissions categories unless the engine types of RB211 and CFM56-3B are specifically mentioned.

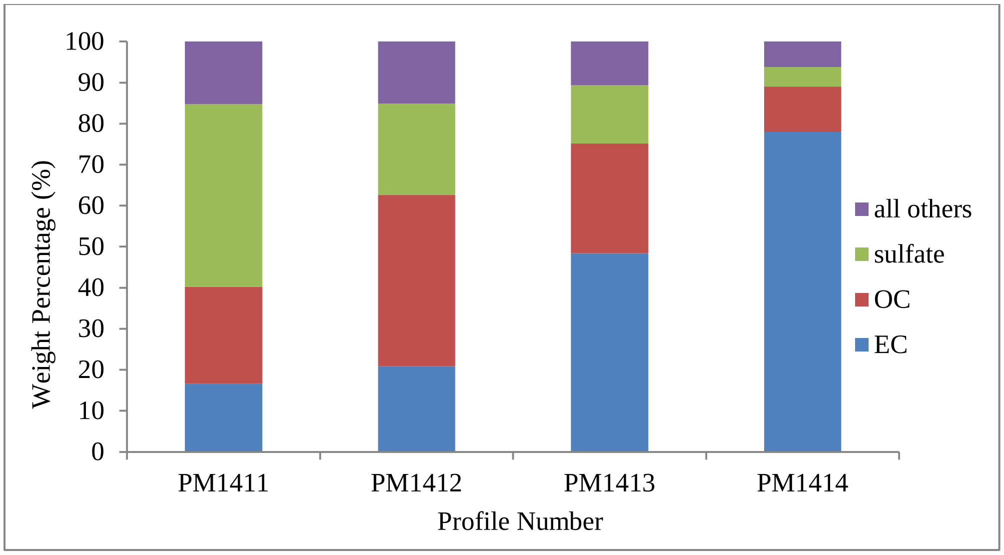

Figure 1. Simplified $PM_{2.5}$ speciation profiles (model species only) for aircraft—jet fuel

The new PM1412 demonstrates a comparable sulfate content (22.2% vs. 25%) and EC content (20.9% vs. 15%), compared to the currently in-use aircraft profile PM141. However, PM1412 consists of 41.7% OC while PM141 doesn't have any OC identified as a species.

Two assumptions related to these profiles are proposed in this work:

- In PM141, the current jet aircraft profile, the ratios of PM_{10}/TPM and $PM_{2.5}$/TPM are 0.976 and 0.967, respectively. Since no particle size distribution was measured in the APEX campaigns, the same PM_{10}/TPM and $PM_{2.5}$/TPM ratios from PM141 will be used for the new profiles (i.e., in the updated profiles it is assumed that PM_{10}/TPM = 0.976 and $PM_{2.5}$/TPM = 0.967).
- The source test and the associated chemical profile discussed above are based on source testing for fine PM exhaust. For the total PM profile update, a homogeneous chemical composition for all PM is assumed. That is, the chemical compositions of PM_{10} and TPM are assumed to be the same as that of fine PM (Table 1).

4 Estimated Impacts of the Profile Update on the Emission Inventory

The newly-developed profile, PM1412, will replace the current profile PM141 for the inventory categories associated with jet aircraft combustion. The related SCCs/EICs are summarized in Table 2.

Table 2. SCCs/EICs associated with jet aircraft

SCC/EIC	*Names*		
125	commercial	jet aircraft	taxi
126	commercial	jet aircraft	take-off
127	commercial	jet aircraft	climb-out
128	commercial	jet aircraft	cruise
129	commercial	jet aircraft	descent
131	commercial	jet aircraft	approach
47555	other aircraft	jet aircraft	commercial jet
47571	government aircraft	military	jet aircraft
47589	other aircraft	jet aircraft	civil jet aircraft
20300901	commercial	kero/naptha jet fuel	turbine: jp-4
20400112	engine testing	aircraft	jp-4 fuel
20400305	engine testing	turbine	kerosine/naptha
20400399	engine testing	turbine	other not classified
27501014	fixed wing aircraft	military	fixed wing: jp-4
27501015	fixed wing aircraft	military	fixed wing: jp-5
27502011	fixed wing aircraft	commercial	fixed wing: jet a
27505011	fixed wing aircraft	civil	fixed wing: jet a
27601014	rotary wing aircraft	military	rotary wing: jp-4
27601015	rotary wing aircraft	military	rotary wing: jp-5
27602011	rotary wing aircraft	commercial	rotary wing: jet a
27605011	rotary wing aircraft	civil	rotary wing: jet a
81080814000000	jet aircraft	military	jet fuel
81080814300000	jet aircraft	military	jet naphtha (jp-5)
81081014000000	jet aircraft	commercial	jet fuel
81081014500000	jet aircraft	commercial	jet a fuel
81081214000000	jet aircraft	civil	jet fuel
81081214500000	jet aircraft	civil	jet a fuel

Air quality modeling for PM involves five PM model species: OC, EC, sulfate, nitrate, and 'other'. Using Profile PM1412 to replace PM141, the changes in PM modeling species emissions are estimated in Table 3. Given the 2010 statewide annual average of jet aircraft emissions 8.37 tons/day [7], OC will increase 3.38 tons/day and EC will increases 0.48 tons/day by applying the new profile PM1412 to the related categories. Meanwhile, sulfate and nitrate emissions will drop 0.22 and 0.32 tons/day due to the profile change.

Table 3. Changes on emissions of $PM_{2.5}$ species for jet aircraft categories (2010)

State Annual Ave. Emissions	*Current PM141 (tons/day)*	*New PM1412 (tons/day)*	*Change*	
			Emissions (tons/day)	*Percentage*
OC	0	3.38	3.38	N/A
EC	1.21	1.69	0.48	39.3%
Sulfate	2.02	1.80	-0.22	-11.0%
Nitrate	0.32	0	-0.32	-100.0%
Other species	4.53	1.23	-3.31	-73.0%

5 Version Control

This section will be completed after management approval and after the CEIDARS FRACTION table and PMPROFILE table are updated. Version information from CEIDARS FRACTION table will be copied here.

References:

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3. Kinesy, J. S. *Characterization of Emissions from Commercial Aircraft Engines during the Aircraft particle Emissions eXperiment (APEX) 1 to 3*; U.S. Environmental Protection Agency: Washington DC, 2009.
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7. CEIDARS. In California Air Resources Board: 2012.