SUPPORTING INFORMATION

for:

**Physical characterization of the fine particle emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3**

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This document provides supplemental information and data as cited in the text of the published manuscript.

## 1. Sampling Probe

During APEX-1, -2, and -3, a single sampling probe located at the centerline of the engine exit plane was used at a distance of 15-, 30-, or 43-m behind the engine. Fig. S-1 shows a photo of the sampling probe used in all three APEX sampling campaigns at the 30-m location.

**Fig. S-1. Photo of APEX-1 30-m sampling probe.**

## 2. Measurement Parameters

Both continuous monitoring and time-integrated sampling was conducted during the three APEX sampling campaigns. A complete list of all parameters measured along with the sampling location, type of sample, and specific instruments used is shown in Table S-1 as installed in the Diesel Emissions Aerosol Laboratory (DEAL). The DEAL was used as the sampling platform for all APEX emissions sampling.

## 3. Test Engines

A total of nine different engine models were tested during the APEX program. Specifications for each engine tested are shown in Table S-2. Note in this table that different models of the same engine family are identified by the alpha-numeric characters behind the dash mark (e.g., the model number is 7B24 for the CFM56-7B24). Table S-2 also provides smoke number data as obtained during new engine certification per International Civil Aviation Organization (ICAO) requirements. Although smoke number was intended to reduce visible emissions, it is also a relative indicator of the PM emissions from the engine.

## 4. Experimental Matrix

A total of 24 tests were conducted by EPA during the three APEX sampling campaigns. Table S-3 provides the test number, aircraft and engine type, power conditions, and fuel flows evaluated during each test. It should be noted that the fuel flow rate values shown in the table are averages of all the data obtained under the same power (percent rated thrust) condition occurring during a test. In some cases, acceptable data may not be available for all periods at a particular thrust level and thus these values may not match those shown in Fig. 2 of the main paper. Fig. 2 of the main text shows the average fuel flows obtained only from those periods during a particular test that had valid nano-SMPS measurements.

**Table S-1.**

Measurements performed by the DEAL during APEX-1, -2, and -3.

| Parameter | Sampling Location | Measurement Technique | Type of Sample | Instruments and Sampling Media |
|---|---|---|---|---|
| PM-2.5 mass concentration | Background | Microbalance | Continuous | Rupprecht and Patashnick (now Thermo Electron) Series 1400a TEOM |
| | Background | Gravimetric analysis | Time-integrated | 47-mm Teflon filter with double quartz backup filters for collection of gas-phase "blow off" [a] |
| | Plume | Microbalance[h] | Continuous | Rupprecht and Patashnick Series 1105a TEOM |
| | Plume | APEX-2 & -3: QCM[h] | Continuous | SEMTECH Model RPM-100 particulate monitor + diluter |
| | Plume | Gravimetric analysis | Time-integrated | 47-mm Teflon filter with double quartz backup filters[a] |
| Particle size distribution | Background | Low pressure cascade impactor (aerodynamic diameter) | Continuous / time-integrated | Dekati ELPI |
| | Background | Electrical mobility classifier/condensation nuclei counter (electrical mobility diameter) | Continuous | APEX-1: TSI Model 3934 SMPS, Model 3071 A classifier, Model 3010 CPC<br>APEX-2 & -3: TSI Model 3936 SMPS (long), Model 3080 classifier, Model 3025a CPC, Model 3081 DMA |
| | Plume | Low-pressure cascade impactor (aerodynamic diameter) | Continuous / time-integrated | Dekati ELPI |
| | Plume | Electrical mobility classifier/condensation nuclei counter (electrical mobility counter) | Continuous | TSI Model 3936 SMPS (Nano). Model 3080 classifier, Model 3025a CPC, Model 3085 DMA |
| | Plume | APEX-1: electrical mobility classifier/condensation nuclei counter (electrical mobility counter)<br>APEX-2 & -3: electrical mobility classifier/electrometers (electrical mobility counter) | Continuous | APEX-1: TSI Model 3936 SMPS (long), Model 3080 classifier, Model 3025 CPC, Model 3081 DMA<br>APEX-2 & -3: TSI Model 3090 EEPS + diluter |
| PM-2.5 number concentration[c] | Background | Condensation nuclei counter | Continuous | Model 3025a CPC |
| | Plume | Condensation nuclei counter | Continuous | Model 3025a CPC + diluter |
| Elemental carbon/organic carbon | Background | Thermo-optical analysis (NIOSH Method 5040) | Time-integrated | Prefired 47 mm quartz filter |
| (EC/OC) | Plume | Thermo-optical analysis (NIOSH Method 5040) | Time-integrated | Prefired 47 mm quartz filter |
| | Plume | Optical attenuation/UV absorption (black carbon) | Continuous | TSI 3302a Diluter +Magee Model AE-2 Aethalometer[d] |
| PM semivolatile organic | Background | GC/MS | Time-integrated | Prefired 47 mm quartz filter with 4 backup PUF plugs.[a] |
| compounds (SVOCs) | Background | Low-pressure cascade impactor | Time-integrated | 12 aluminum foil ELPI stages + prefired quartz back-up filter[b] |
| | Plume | GC/MS | Time-integrated | Prefired 47 mm quartz filter with 4 backup PUF plugs.[a] |
| | Plume | Low-pressure cascade impactor | Time-integrated | 12 aluminum foil ELPI stages + prefired quartz back-up filter[b] |
| | Plume | UV analyzer (particle surface PAHs) | Continuous | EcoChem Model PAS 2000 |
| Total volatile PM + EC/OC | Plume | Gravimetric/thermo-optical analysis | Time-integrated | Dekati Model EKA-111 thermal denuder with parallel Teflon and double prefired quartz filters |
| PM inorganic water-soluble ions | Background | Ion chromatography | Time-integrated | Teflon filter |
| | Plume | Ion chromatography | Time-integrated | Teflon filter |

| Parameter | Sampling Location | Measurement Technique | Type of Sample | Instruments and Sampling Media |
|---|---|---|---|---|
| PM elemental composition | Background | XRF | Time-integrated | Teflon filter |
| | Plume | XRF | Time-integrated | Teflon filter |
| APEX-1 CO, $CO_2$, total VOCs | Background | IR absorption | Integrated bag[e] | Brüel & Kjær Model 1302 Photoacoustic Analyzer |
| | Plume | IR absorption | Continuous | Brüel & Kjær Model 1302 Photoacoustic Analyzer |
| APEX-2 & -3 $CO_2$ | Background | IR absorption | Continuous | Milton-Roy (CA Analytical) Model 5300A |
| | Plume | IR absorption | Continuous | Milton-Roy (CA Analytical) Model 5300A |
| Gas-phase NMOCs | Background | GC/MS/FID | Time-integrated | SUMMA-passivated canister |
| | Plume | GC/MS/FID | Time-integrated | SUMMA-passivated canister |
| Gas-phase carbonyl compounds | Background | HPLC | Time-integrated | DNPH impregnated silica gel cartridges with KI ozone scrubber cartridge |
| | Plume | HPLC | Time-integrated | DNPH impregnated silica gel cartridges with KI ozone scrubber cartridge |
| Sample temperature[f] | Plume tunnel | Thermocouple | Continuous | K-Type thermocouples; T-Type only on APEX-2 sampling probes |
| APEX-2 plume temperature | Plume | Thermocouples | Continuous | Multiple T-type thermocouples |
| APEX-2 plume velocity | Plume | Pitot tube | Continuous | Standard pitot tube plus differential pressure cell |
| APEX-2 meteorological parameters[g] | Background | Propeller anemometer & wind vane | Continuous | Vaisala MAWS weather station |

[a] Filter holder design per Federal Test Procedure (FTP) published in 40 Code of Federal Regulations (CFR), Part 86. “Blow off” are gas-phase semivolatile species that have been released from the particulate deposited on the primary filter by the air flow passing through the medium.
[b] Aluminum foil substrates from the ELPI were not analyzed due to insufficient mass.
[c] These measurements were redundant and the data were not used.
[d] The aethalometer measures “black” carbon which approximates elemental carbon content as determined from diesel engine testing at West Virginia University (Kinsey et al., 2006).
[e] Post-test analysis of time-integrated Tedlar bag sample collected over the entire test period.
[f] Temperature was not monitored in sampling lines.
[g] Meteorological data provided by collaborators during APEX-1 and -3.
[h] Data from these instruments are generally of low reliability and thus not reported in this paper.

CPC = Condensation Particle Counter
DMA = Differential Mobility Analyzer
DNPH = 2,4-Dinitrophenylhydrazine
EEPS = Engine Exhaust Particle Sizer
ELPI = Electrical Low Pressure Impactor
FID = Flame Ionization Detector
GC/MS = Gas Chromatography/ Mass Spectrometry
HPLC = High Performance Liquid Chromatography
IR = Infrared
NMOC = Nonmethane Organic Compound
NIOSH = National Institute for Occupational Safety and Health
PAH = Polycyclic Aromatic Hydrocarbon
PUF = Polyurethane Foam
QCM = Quartz Crystal Microbalance
SMPS = Scanning Mobility Particle Sizer
TEOM = Tapered Element Oscillating Microbalance
UV = Untraviolet
XRF = X-ray Fluorescence

**Table S-2.**

Engines Tested in APEX-1, -2 and -3

| Engine Model[a] | Airframe | Bypass Ratio[b] | Rated Thrust[b] (kN) | ICAO Smoke Number[c] | | | | Test Campaign/Test Number |
|---|---|---|---|---|---|---|---|---|
| | | | | T/O | C/O | App | Idle | |
| CFMI CFM56-2C1 | Boeing DC-8 | 6 | 97.86 | 6.0 | 3.0 | 2.6 | 2.2 | APEX 1 / All Tests |
| CFMI CFM56-7B24 | Boeing 737-700 | 5.2 | 107.7 | 12.6[d] | NA | NA | NA | APEX 2 / Test # 1 and 4 |
| CFMI CFM56-3B1 | Boeing 737-300 | 5.1 | 89.41 | 4.0 | 2.5 | 2.5 | 2.2 | APEX 2 / Test # 2; APEX 3 / Test # 1 and 11 |
| CFMI CFM56-3B2 | Boeing 737-300 | 5.1 | 98.30 | 6.0 | 3.0 | 2.5 | 2.2 | APEX 2 / Test # 3 |
| General Electric CJ610-8ATJ (Turbojet) Starboard | Lear Model 25 | na | 13.12 | NA | NA | NA | NA | APEX 3 / Test # 2 and 5 |
| Rolls Royce AE3007A1E Starboard[e] | Embraer ERJ145 | 4.8 | 33.70 | 1.0 | 0 | 0 | 0 | APEX 3 / Test # 3 and 4 |
| Pratt & Whitney 4158 Starboard | Airbus A300 | 4.6 | 258.0 | 8.1[d] | NA | NA | NA | APEX 3 / Test # 6 & Test #7 |
| Rolls Royce RB211-535E4B Starboard[e] | Boeing 757-324 | 4.1 | 191.7 | 7.3[d] | NA | NA | NA | APEX 3 / Test # 8 and 9 |
| Rolls Royce AE3007A1/1 Starboard[e] | Embraer ERJ145 | 4.8 | 34.74 | 1.0 | 0 | 0 | 0 | APEX 3 / Test # 10 |

[a] All engines are turbofan except as noted.

[b] Civil Turbojet/Turbofan Specifications http://www.jet-engine.net/civtfspec.html or International Civil Aviation Organization (ICAO) Databank Issue 15-C.

[c] New engine certification data taken from ICAO Engine Emissions Databank Issue 15-C. T/O = take-off; C/O = climb-out; App = approach; NA = not available.

[d] Maximum SN; no power specified.

[e] These are internally mixed-flow turbofan engines.

**Table S-3.**

Summary of Fuel Flow Rates Measured at Different Engine Power Levels for Each Test Conducted

| APEX | Test No.[a] | Aircraft | Engine | Fuel Type | Engine Conditions | Fuel Flow ($kg\ h^{-1}$) at Percent Rated Thrust[c] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 4 | 5.5 | 7 | 8.4 | 15 | 30 | 40 | 45 | 60 | 65 | 70 | 76 | 80 | 85 | 100 |
| 1 | EPA-1 | DC-8 | CFM56-2C1 | Base | | | | 436 | | | 992 | | | | | | | | 2819 | 2969 |
| | EPA-2 | | | | | | | 425 | | | 1023 | | | | | | | | 2860 | 3181 |
| | NASA-1 | | | | | 350 | 386 | 427 | | 560 | 1012 | 1252 | | | 1998 | | | | 2406 | 2906 |
| | NASA-1a | | | | | 336 | | | | | | | | 1922 | 2098 | 2252 | | | 2898 | 3127 |
| | EPA-3 | | | High sulfur | | | | 438 | | | 964 | | | | | | 2424 | | 2840 | 3116 |
| | NASA-2 | | | | | 345 | 381 | 413 | | 543 | 955 | 1235 | | 1855 | 2046 | 2191 | | | 2727 | 2984 |
| | NASA-3 | | | | | 347 | 382 | 405 | | 538 | 986 | 1255 | | 1846 | 2053 | 220 | | | 2758 | 3051 |
| | NASA-4 | | | High aromatic | | 345 | 381 | 401 | | 545 | 960 | 1220 | | 1850 | 2023 | 2157 | | | 2708 | 2978 |
| | NASA-5 | | | | | 345 | 395 | 410 | | 545 | 989 | 1292 | | 1930 | 2131 | 2247 | | | 2894 | 3176 |
| 2[d] | T4 | B737-700 | CFM56-7B24 | Fleet fuel | Cold[b] | 336 | | 418 | | | 1180 | 1544 | | | 2497 | | | | 4131 | |
| | | | | | Warm | 313 | | 381 | | | 1135 | 1498 | | | 2497 | | | | 4086 | |
| | | | | | Average | 325 | | 400 | | | 1158 | 1521 | | | 2497 | | | | 4109 | |
| | T2 | B737-300 | CFM56-3B1 | Fleet fuel | Cold | 341 | | 422 | | | 1099 | 1403 | | | 2193 | | | | 3528 | |
| | | | | | Warm | 345 | | 418 | | | 1067 | 1367 | | | 2184 | | | | 3559 | |
| | | | | | Average | 343 | | 420 | | | 1083 | 1385 | | | 2188 | | | | 3543 | |
| | T3 | B737-300 | CFM56-3B2 | Fleet fuel | Cold | 372 | | 440 | | | 1130 | 1444 | | | 2252 | | | | 3677 | |
| | | | | | Warm | 368 | | 422 | | | 1108 | 1412 | | | 2261 | | | | 3650 | |
| | | | | | Average | 370 | | 431 | | | 1119 | 1428 | | | 2256 | | | | 3664 | |
| 3 | T1 | B737-300 | CFM56-3B1 | Fleet fuel | Cold | 300 | | 397 | | 654 | 1136 | | 1618 | | 2260 | | | | 2903 | 3385 |
| | | | | | Warm | 300 | | 397 | | 654 | 1136 | | 1618 | | 2260 | | | | 2903 | 3385 |
| | | | | | Average | 300 | | 397 | | 654 | 1136 | | 1618 | | 2260 | | | | 2903 | 3385 |
| | T11 | B737-300 | CFM56-3B1 | Fleet fuel | Cold | 381 | | 431 | | 622 | 1090 | | 1530 | | 2179 | | | | 2815 | 3564 |
| | T2 | NASA Lear Model 25 | CJ610-8ATJ (turbojet) | Fleet fuel | Cold | | | 182 | | 304 | 452 | | 568 | | 760 | | | | 999 | 1226 |
| | | | | | Warm | | | 182 | | 304 | 454 | | 568 | | 763 | | | | | 1226 |
| | | | | | Average | | | 182 | | 304 | 453 | | 568 | | 762 | | | | 999 | 1226 |
| | T5 | NASA Lear Model 25 | CJ610-8ATJ (turbojet) | Fleet fuel | Cold | | | 227 | | 303 | 452 | | 567 | | 763 | | | | 1009 | 1226 |
| | | | | | Warm | | | 227 | | | 452 | | 567 | | 763 | | | | 1009 | 1226 |
| | | | | | Average | | | 227 | | 303 | 452 | | 567 | | 763 | | | | 1009 | 1226 |
| | T3 | Embraer ERJ 145 | AE3007A1E | Fleet fuel | Cold | | | | 174 | 238 | 389 | | 555 | | 805 | | | | 1082 | 1286 |
| | | | | | Warm | | | | 173 | 235 | 392 | | 563 | | 810 | | | | 1088 | 1299 |
| | | | | | Average | | | | 173 | 237 | 391 | | 559 | | 807 | | | | 1085 | 1293 |
| | T4 | Embraer ERJ 145 | AE3007A1E | Fleet fuel | Cold | | | | 168 | 239 | 385 | | 547 | | 788 | | | | 1050 | 1253 |
| | | | | | Warm | | | | 167 | 231 | 384 | | 549 | | 786 | | | | 1052 | 1252 |
| | | | | | Average | | | | 167 | 235 | 385 | | 548 | | 787 | | | | 1051 | 1252 |
| | T10 | Embraer ERJ 145 | AE3007A1/1 | Fleet fuel | Cold | | | | 179 | 233 | 372 | | 524 | | 750 | | | | 971 | 1171 |
| | | | | | Warm | | | | 178 | 231 | 371 | | 529 | | 767 | | | | 982 | 1180 |
| | | | | | Average | | | | 178 | 232 | 371 | | 526 | | 758 | | | | 976 | 1175 |
| | T6 | A300 | P&W 4158 | Fleet fuel | Cold | | | 610 | | 1014 | 2245 | | 3726 | | 5658 | | | 7026 | | |
| | | | | | Warm | | | 368 | | 1097 | 2465 | | 3834 | | 5658 | | | 7026 | | |
| | | | | | Average | | | 489 | | 1056 | 2355 | | 3780 | | 5658 | | | 7026 | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T7 | A300 | P&W 4158 | Fleet fuel | Cold | | 600 | 1035 | 2230 | 3688 | 5702 | 7100 | | |
| | | | | Warm | | 596 | | 2252 | | 5711 | 7200 | | |
| | | | | Average | | 598 | 1035 | 2241 | 3688 | 5706 | 7150 | | |
| T8 | B757 | RB211-535E4-B | Fleet fuel | Cold | 566 | 770 | 1191 | 2109 | 3178 | 4750 | | 6096 | |
| | | | | Warm | 437 | 654 | 1178 | 2131 | 3436 | 4691 | | 6449 | |
| | | | | Average | 501 | 712 | 1185 | 2120 | 3307 | 4720 | | 6273 | |
| T9 | B757 | RB211-535E4-B | Fleet fuel | Cold | 421 | 690 | 1221 | 2004 | 3068 | 4479 | | 6233 | 6966 |
| | | | | Warm | 506 | 668 | 1173 | 2037 | 3111 | 4551 | | 6307 | 6987 |
| | | | | Average | 464 | 679 | 1197 | 2021 | 3090 | 4515 | | 6270 | 6976 |

[a] Note that bleed air was extracted from the engine during tests EPA-1,-2, and -3 in APEX-1. No fuel flows were recorded by the airline during T1 of APEX-2.

[b] "Cold" refers to increasing power in a stepwise fashion, and "Warm" indicates reducing power in a stepwise fashion.

[c] Fuel flows provided by aircraft operator.

[d] Fuel flows for APEX-2, T1, were derived from the same power conditions for T4, since no data were provided by the aircraft operator for this test.

## 5. Relationship of PM Mass Emission Indices to Fuel Flow

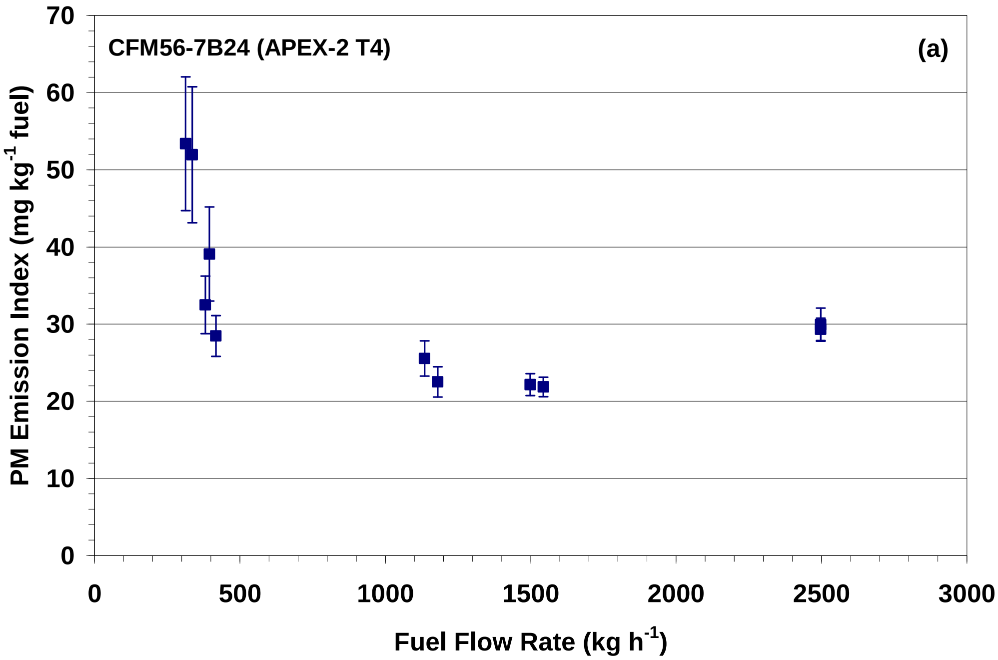
As discussed in the main text, a similar relationship between the PM mass emission index ($EI_m$) and increasing fuel flow was observed for all turbofan engines tested during the three APEX sampling campaigns. This observation is illustrated in Figure S-2 for a CFM56-7B24 turbofan engine tested in APEX-2 as compared to the CJ610-8ATJ turbojet engine sampled in APEX-3. As can be seen in this figure, a characteristic U-shaped curve of $EI_m$ vs. fuel flow was determined for the CFM56-7B24, whereas for the CJ610-8ATJ turbojet, the $EI_m$ increases linearly with increasing fuel flow.

## 5. Example Particle Size Distributions (PSDs)

All of the PSDs determined in the three APEX sampling campaigns generally contained a single primary mode for most engines and power conditions which was lognormally distributed. However, an accumulation mode was also observed at higher engine fuel flows (powers). The magnitude of this accumulation mode varied from engine to engine as illustrated in Figure S-3 for a CFM56-7B24 engine in APEX-2, and a CFM56-3B1 engine in APEX-3. As shown in the figure, the -7B24 model engine had relatively few accumulation mode particles in the PSD whereas the -3B1 model engine exhibited a very distinct accumulation mode at higher fuel flow.

## 6. Supporting Information Reference

Kinsey, J. S., Mitchell, W. A., Squier, W. C., Linna, K., King, F. G., Logan, R., Dong, Y., Thompson, G. J., Clark, N. N., 2006. Evaluation of methods for the determination of diesel-generated fine particulate matter: Physical characterization results. *Journal of Aerosol Science*, 37, 63-87.



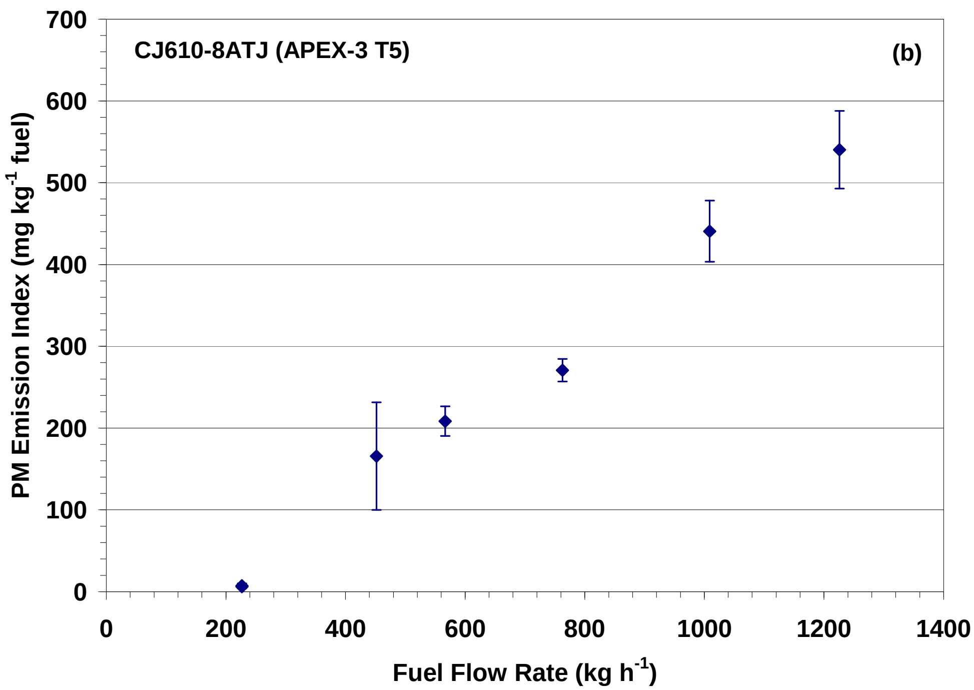




**Fig. S-2. PM mass emission index as a function of fuel flow as determined by the nano-SMPS for a: (a) CFM56-7B24 turbofan engine in Test 4 of APEX-2; and (b) CJ610-8ATJ turbojet engine in Test 5 of APEX-3.**

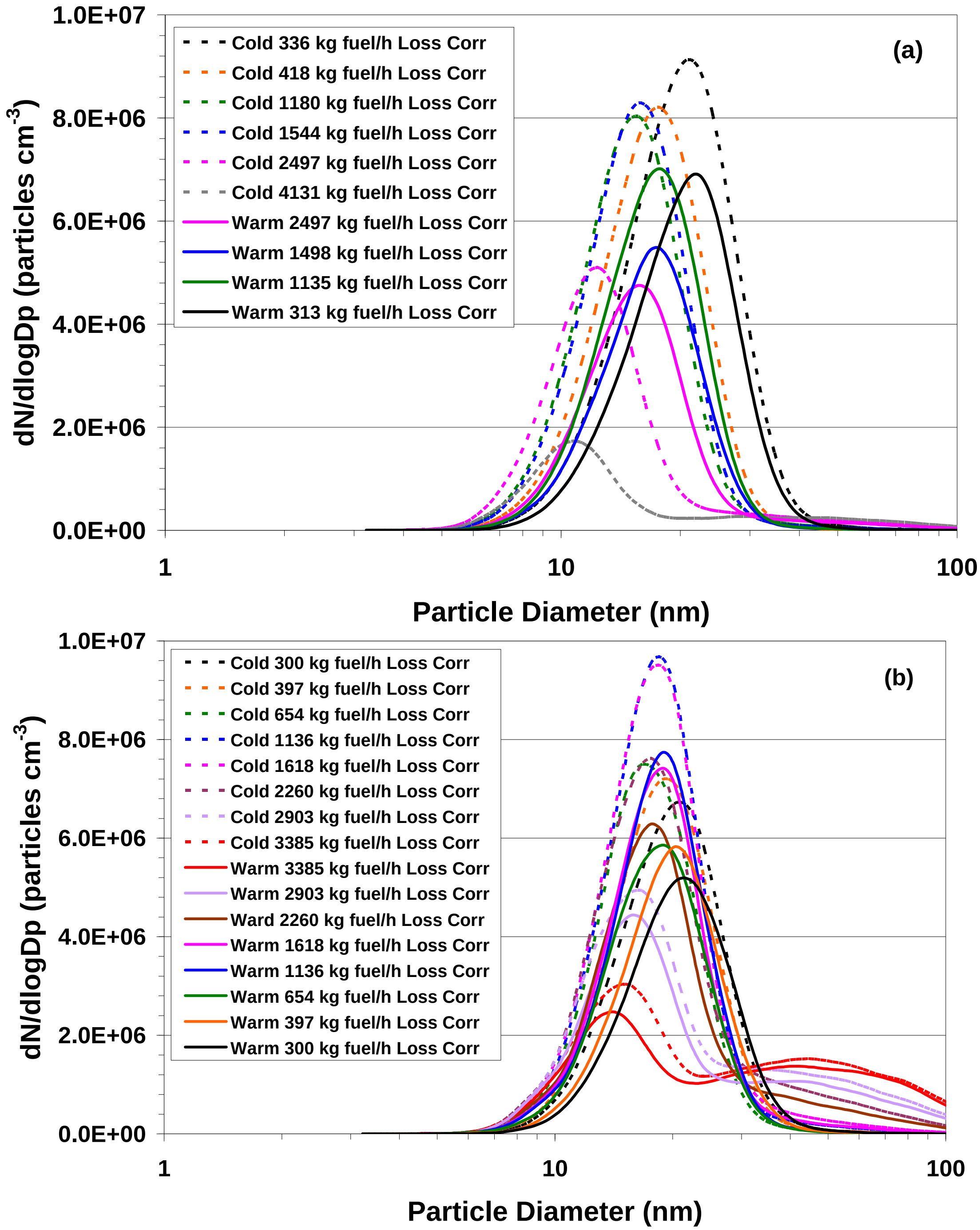



**Fig. S-3. Average particle size distributions by fuel flow and engine temperature as measured by the nano-SMPS for: (a) a CFM56-7B24 engine in Test 1 of APEX-2; and (b) a CFM56-3B1 engine in Test 1 of APEX-3. Note the prominent accumulation mode present at high fuel flow for the -3B1 model engine.**