Introduction to the Desert Research Institute, Nevada System of Higher Education

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Presented at:
NILU-Norwegian Institute for Air Research
Kjeller, Norway

April 25, 2014

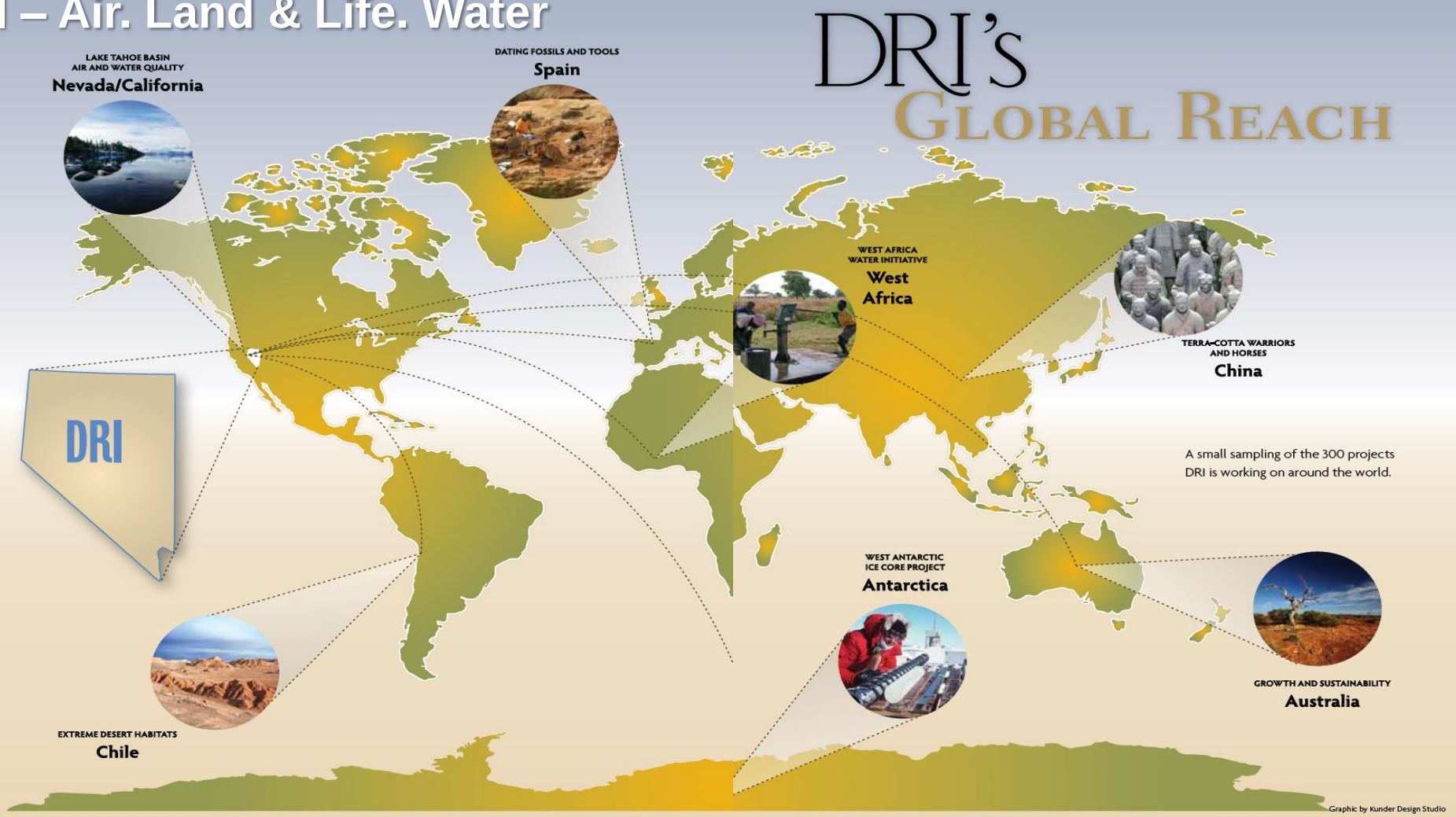
DRI
www.dri.edu

The Desert Research Institute (DRI) is located in the high desert of the American West

- Established in 1959 as part of University System
- 155 faculty, 230 support staff and 80 students
- Non-tenured, self-supporting faculty
- ~US$50 million/year, 8% from state, rest from grants and contracts
- Environmental studies in air, land, water, and energy

DRI's research is not limited to the desert, Nevada, or the United States

DRI – Air. Land & Life. Water



The Atmospheric Sciences Division has projects in the following areas

- Air quality emissions, ambient concentrations, and effects
- Atmospheric Measurement Systems
- Meteorology and Regional Climate
- Atmospheric Properties & Processes
- Atmospheric & Climate Modeling
- Climate Monitoring and Weather Modification
- Fire Sciences
- Clean Energy

Real-World Source Emissions Characterization

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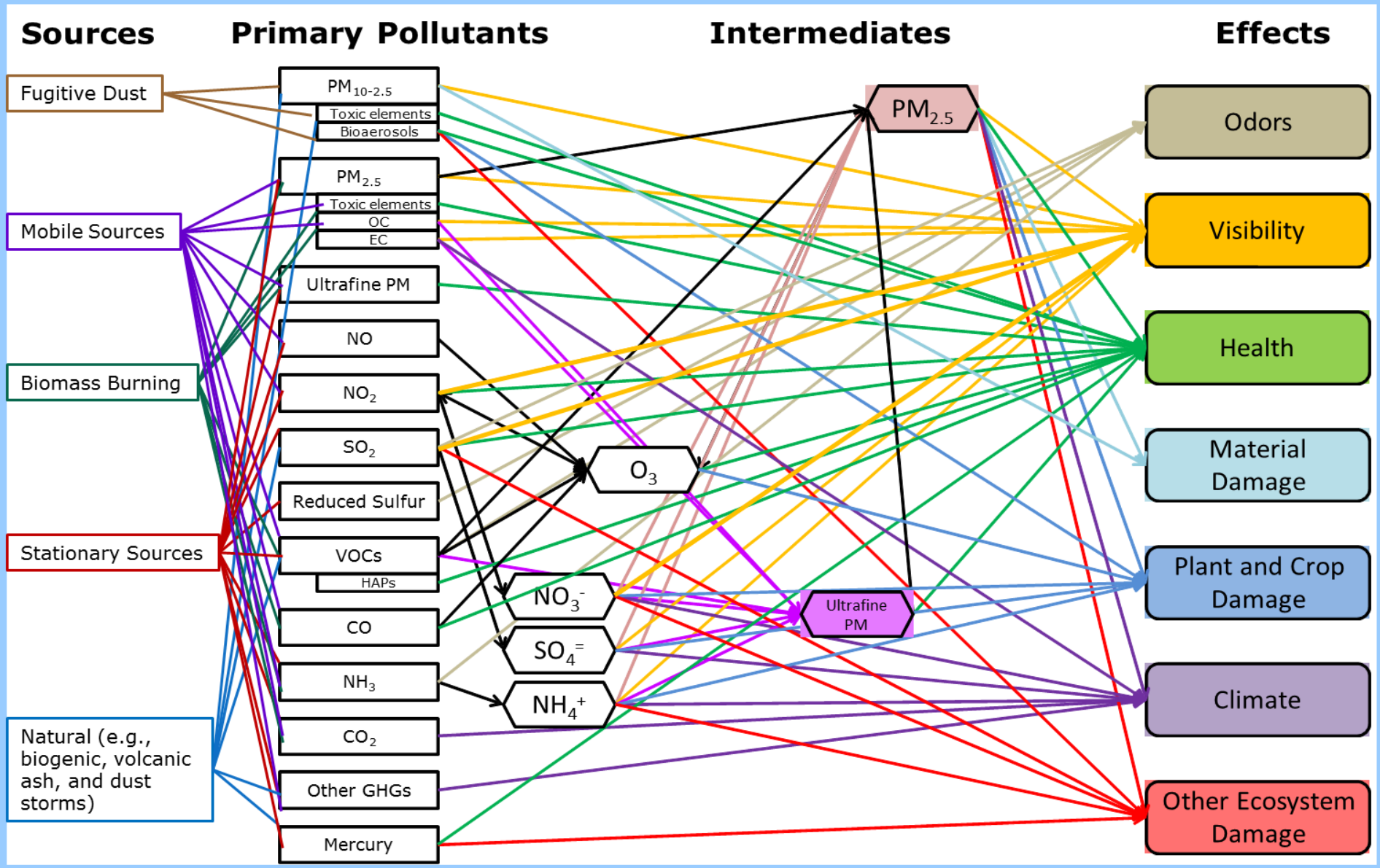
Objectives

- Explain U.S. approach to emission standards, emission certification, and compliance testing
- Contrast real-world multipollutant emission measurements with single-pollutant certification and compliance methods
- Evaluate emerging technologies for source emission measurements
- Identify improved approaches that make certification and compliance testing more compatible with real-world emissions and ambient air quality measurements

A multipollutant/multieffect approach to air quality management is emerging

(Emissions compliance testing should consider these future needs)



Chow, J.C.; Watson, J.G. (**2011**). Air quality management of multiple pollutants and multiple effects. *Air Quality and Climate Change Journal*, ***45(3):26-32.***
https://www.researchgate.net/publication/234903062_Air_quality_management_of_multiple_pollutants_and_multiple_effects?ev=prf_pub.

Real-world, multipollutant emission characteristics are needed to support national and global air quality management for many common sources

Stack emissions

Ship emissions

Home heating

Domestic cooking

Diesel exhaust

Flaming wildfire

Real-world emissions represent in-use hardware, processes, operating conditions, and fuels.

(This contrasts with most emission tests that are made for certification and compliance)

- **Certification:** Verify that a process design is capable of achieving emissions below a regulated limit. (e.g., FTP engine tests)
- **Compliance:** Determine that in-use processes are within permitted values (e.g., Pollution Under Control (PUC) tests, periodic stack tests, and opacity tests)
- **Emissions trading:** Relate actual emissions to allowances (e.g., continuous SO_2 monitors)
- **Emission inventories:** Real-world emissions for air quality modeling and planning
- **Source apportionment:** Speciated emissions for source and receptor modeling
- **Federal Test Procedure**

Emission inventories need more than just emission factors

- **Emission Factor:**
  Amount emitted per unit time or unit of activity.

- **Particle Size:**
  Determines transport and deposition properties.

- **Chemical Composition:**
  Fractional abundance of gaseous and particulate chemical components in emissions. Used for speciated inventory and to apportion ambient concentrations to sources.

- **Temporal Variation:**
  Emissions change on daily, weekly, seasonal, and annual cycles. Timing of emissions affects atmospheric transport and dilution as well as human exposure to air pollution.

Speciated emission inventories use emission characterization data to determine the relative importance of different source types

Component i emissions fluxes =

Σ_{ij} fraction of component i in source j

x emission factor (mass/activity) for source j

x activity of source j

x [particle size fraction]

x [control efficiency]

x [temporal profile]

U.S. EPA has established many emission limitation standards in the Code of Federal Regulations (CFR) for which compliance must be determined

(Many of these are adopted by other countries without considering more modern and useful alternatives)

- **Title 40, Part 60-Standards of performance for new stationary sources.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y7.0.1.1.1.
- **Title 40, Part 63-National emission standards for hazardous air pollutants for source categories.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y10.0.1.1.1.
- **Title 40, Part 85-Control of pollution from mobile sources.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y19.0.1.1.1.
- **Title 40, Part 86-Control of emissions from new and in-use highway vehicles and engines.** , http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y19.0.1.1.2.
- **Title 40, Part 89-Control of emissions from new and in-use nonroad compression-ignition engines.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y21.0.1.1.3.
- **Title 40, Part 87-Control of air pollution from aircraft and aircraft engines.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y21.0.1.1.1.
- **Title 40, Part 90-Control of emissions from nonroad spark-ignition engines at or below 19 kilowatts.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y21.0.1.1.4 .
- **Title 40, Part 92-Control of air pollution from locomotives and locomotive engines.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y21.0.1.1.6.
- **Title 40, Part 94-Control of emissions from marine compression-ignition engines.** http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=58ca7d63cbd732624780bdb648af1159&r=PART&n=40y21.0.1.1.8.

Different test procedures are specified for different sources and pollutants

(Certification testing evaluates a design for specific fuels and operating conditions)

Example for residential wood heater (CFR 40, Part 60, Subpart AAA)

§ 60.532 Standards for particulate matter.

(1) An affected facility equipped with a catalytic combustor shall not discharge into the atmosphere any gases which contain particulate matter in excess of a weighted average of 4.1 g/hr (0.009 lb/hr). Particulate emissions during any test run at any burn rate that is required to be used in the weighted average shall not exceed the value calculated for "C" (rounded to 2 significant figures) calculated using the following equation:

(2) An affected facility not equipped with a catalytic combustor shall not discharge into the atmosphere any gases which contain particulate matter in excess of a weighted average of 7.5 g/hr (0.017 lb/hr). Particulate emissions shall not exceed 15 g/hr (0.033 lb/hr) during any test run at a burn rate less than or equal to 1.5 kg/hr (3.3 lb/hr) that is required to be used in the weighted average and particulate emissions shall not exceed 18 g/hr (0.040 lb/hr) during any test run at a burn rate greater than 1.5 kg/hr (3.3 lb/hr) that is required to be used in the weighted average.

§ 60.534 Test methods and procedures.

Test methods and procedures in appendix A of this part, except as provided under § 60.8(b), shall be used to determine compliance with the standards and requirements for certification under §§ 60.532 and 60.533 as follows:

(a) Method 28 shall be used to establish the certification test conditions and the particulate matter weighted emission values.

(b) Emission concentrations may be measured with either:

(1) Method 5G, if a dilution tunnel sampling location is used, or

(2) Method 5H, if a stack location is used.

Large industrial sources have emission limits

(Periodic compliance tests are conducted to assure that emissions are within those limits)

Example for cement production emissions

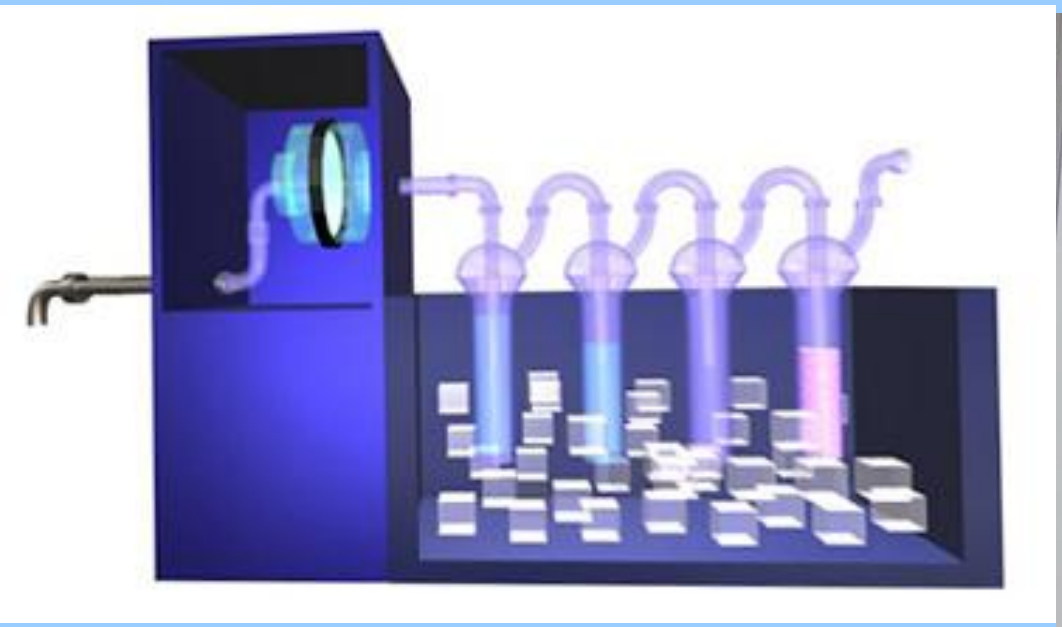
(CFR 40, Part 63, Subpart LLL)

TABLE 1—EMISSIONS LIMITS FOR KILNS, CLINKER COOLERS, RAW MATERIAL DRYERS, RAW AND FINISH MILLS

	If your source is a (an):	And the operating mode is:	And if is located at a:	Your emissions limits are:	And the units of the emissions limit are:	The oxygen correction factor is:
1.	Existing kiln	Normal operation	Major or area source	PM 0.07 D/F 0.2 Mercury 55 THC [3] 24	lb/ton clinker ng/dscm (TEQ) lb/MM tons clinker ppmvd	NA 7 percent NA 7 percent
2.	Existing kiln	Normal operation	Major source	HCl 3	ppmvd	7 percent
3.	Existing kiln	Startup and shutdown	Major or area source	Work practices (63.1346(f))	NA	NA
4.	New kiln	Normal operation	Major or area source	PM 0.02 D/F 0.2 Mercury 21 THC [3] 24	lb/ton clinker ng/dscm (TEQ) lb/MM tons clinker ppmvd	NA 7 percent NA 7 percent
5.	New kiln	Normal operation	Major source	HCl 3	ppmvd	7 percent
6.	New kiln	Startup and shutdown	Major or area source	Work practices (63.1346(f))	NA	NA
7.	Existing clinker cooler	Normal operation	Major or area source	PM 0.07	lb/ton clinker	NA
8.	Existing clinker cooler	Startup and shutdown	Major or area source	Work practices (63.1348(b)(9))	NA	NA
9.	New clinker cooler	Normal operation	Major or area source	PM 0.02	lb/ton clinker	NA
10.	New clinker cooler	Startup and shutdown	Major or area source	Work practices (63.1348(b)(9))	NA	NA
11.	Existing or new raw material dryer	Normal operation	Major or area source	THC [3] 24	ppmvd	NA
12.	Existing or new raw material dryer	Startup and shutdown	Major or area source	Work practices (63.1348(b)(9))	NA	NA
13.	Existing or new raw or finish mill	All operating modes	Major source	Opacity 10	percent	NA

[1] The initial and subsequent PM performance tests are performed using Method 5 or 5I and consist of three 1-hr tests.

Method 5 is right out of the 1950s, but it is still the mostly widely used emission testing method used today for total PM (TSP)



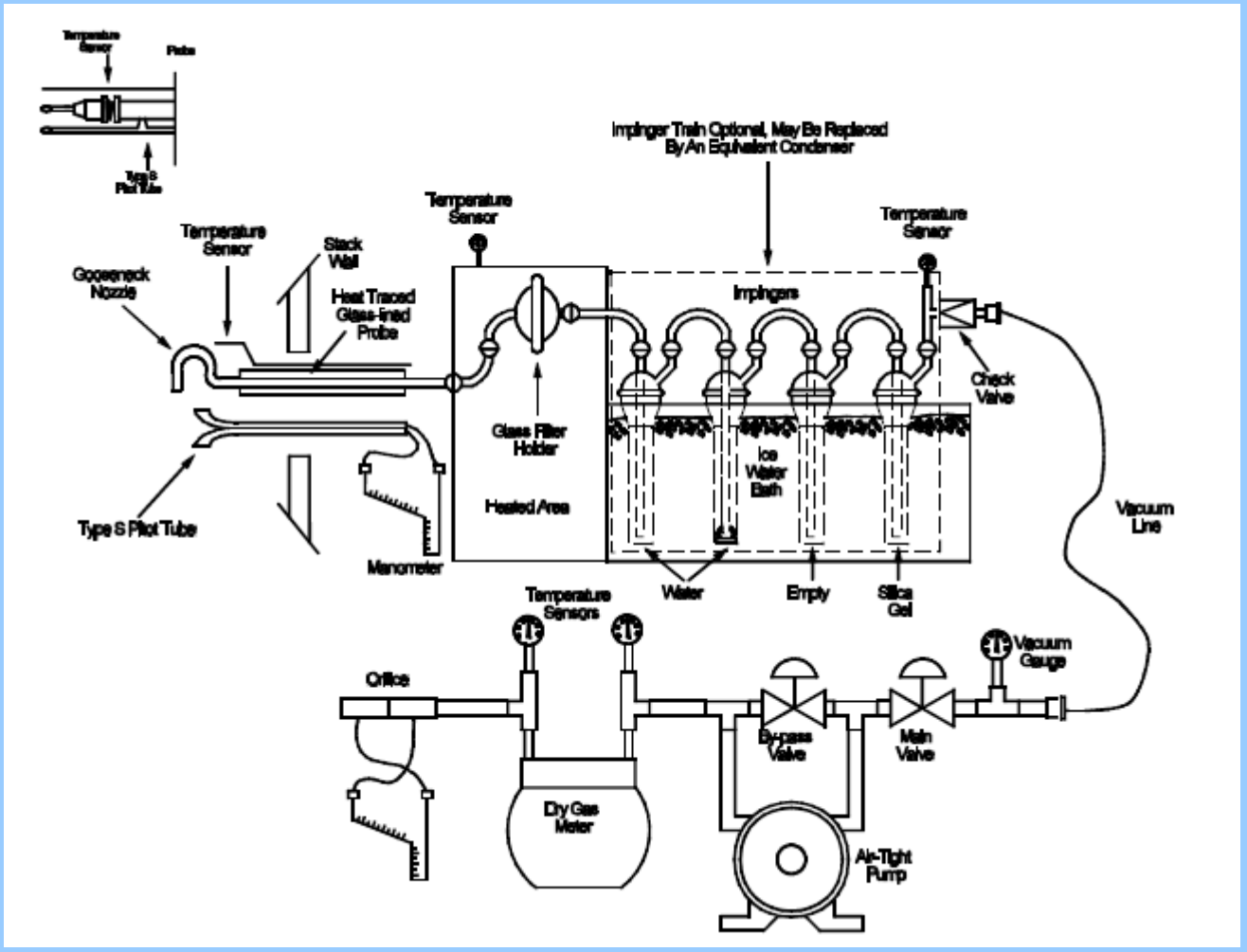
Samples are drawn through a heated (120 14 C) glass fiber filter with the filtered gas passing through 2 chilled water-filled impingers (1 &2), air (3), and silica gel (4).

A buttonhook nozzle is placed in the stack at the end of a heated probe. Nozzle diameters can be selected to match the nozzle flow rate with the stack flow rate

Watson, J.G.; Chow, J.C.; Wang, X.L.; Kohl, S.D.; Chen, L.-W.A.; Etyemezian, V. (**2012**). Overview of real-world emission characterization methods. In *Alberta Oil Sands: Energy, Industry, and the Environment*, Percy, K. E., Ed.; Elsevier Press: Amsterdam, The Netherlands, 145-170.

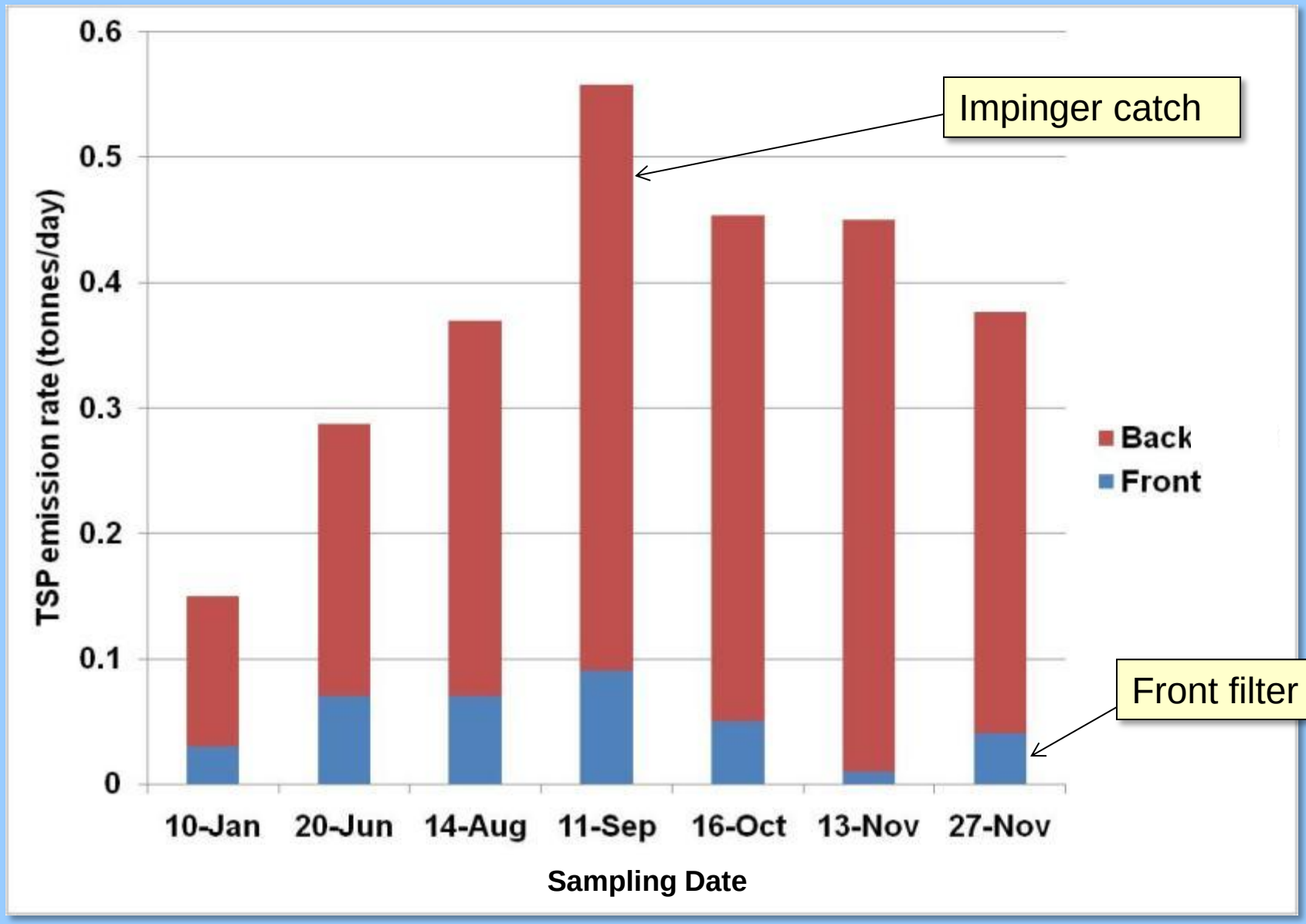
Method 5 uses a heated filter followed by glass impingers in ice to collect condensable particulate matter

- Glass-fiber filter (contains contaminants and adsorbs vapors) weighted before and after sampling
- Impinger analysis ("Individual States or control agencies requiring this information shall be contacted as to the sample recovery and analysis of the impinger contents.")
- Brush loose particles from probe and rinse with acetone



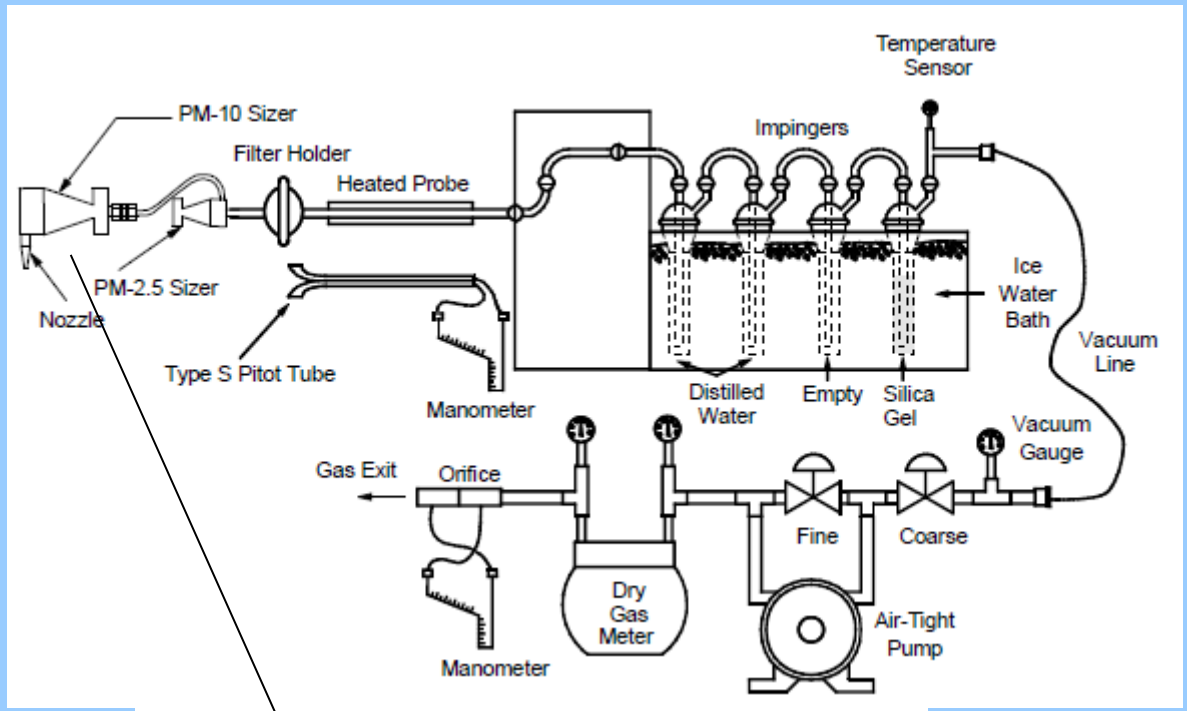
- **U.S.EPA** (**2000**). Method 5. Particulate matter (PM), Determination of particulate matter emissions from stationary sources. prepared by U.S. EPA, Research Triangle Park, NC, http://www.epa.gov/ttn/emc/promgate/m-05.pdf.
- **U.S.EPA** (**2013**). Title 40, Part 60, Appendix A-3-Test methods 4 through 5I. *Code of Federal Regulations*, http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=1&SID=58ca7d63cbd732624780bdb648af1159&ty=HTML&h=L&r=APPENDIX&n=40y8.0.1.1.1.0.1.1.3.

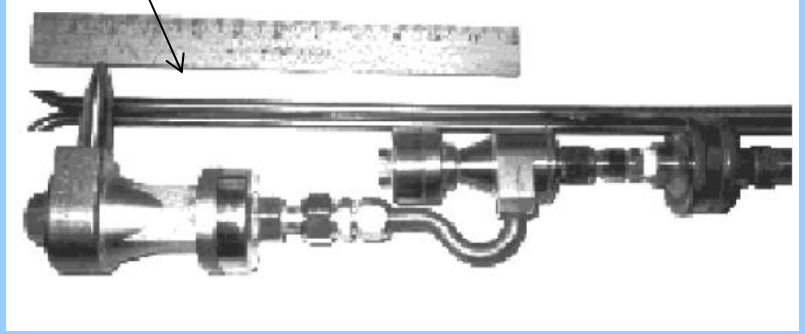
Hot stack (filter/impinger) sampling measures too low for the hot filter and too high for the impingers



Method 201A is specific for PM_{10}, with an option for $PM_{2.5}$ size selection–impingers are still used

- Nonreactive, nondisintegrating glass fiber, quartz, or polymer filter without organic binder
- Desiccate filter at 20.± 5.6 °C (68 ± 10.0 °F) >24 hr and weigh at intervals of >6 hr six hours to a constant weight. Alternatively, filters may be oven-dried at 104 °C (220 °F) for 2-3 hrs, desiccated for 2 hrs, and weighed
- Use a nylon or fluoropolymer brush and an acetone rinse to recover particles from the combined cyclone/filter sampling head

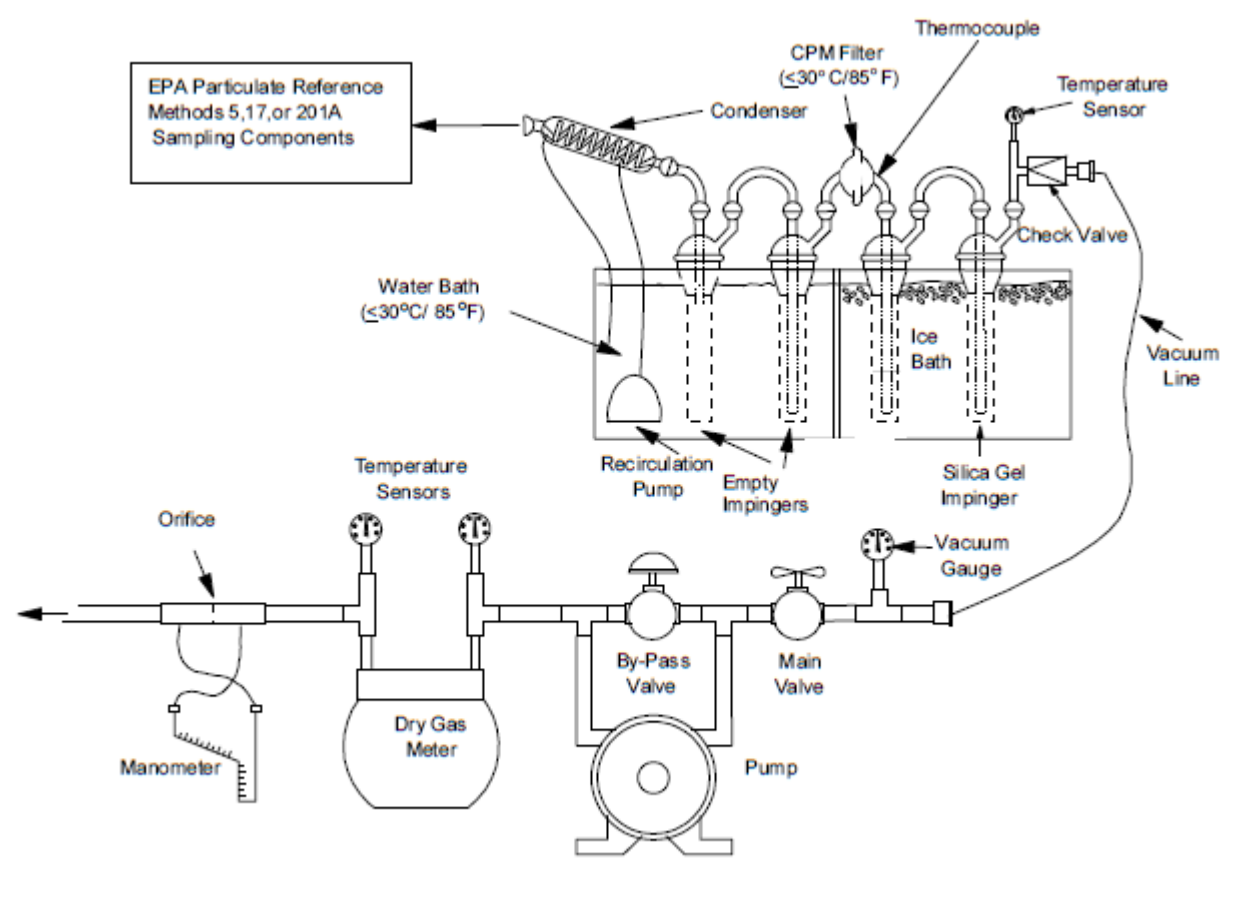




U.S.EPA (**2010**). Method 201A - Determination of PM_{10} and $PM_{2.5}$ Emissions From Stationary Sources (Constant Sampling Rate Procedure): 55 FR 14246 04/17/90 (Appendix M of 40 CFR 51). prepared by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Technical Support Division, Research Triangle Park, NC, http://www.epa.gov/ttn/emc/promgate/m-201a.pdf.

Method 202 (modified in 2010) specifies the impinger (condensable) catch as a separate procedure

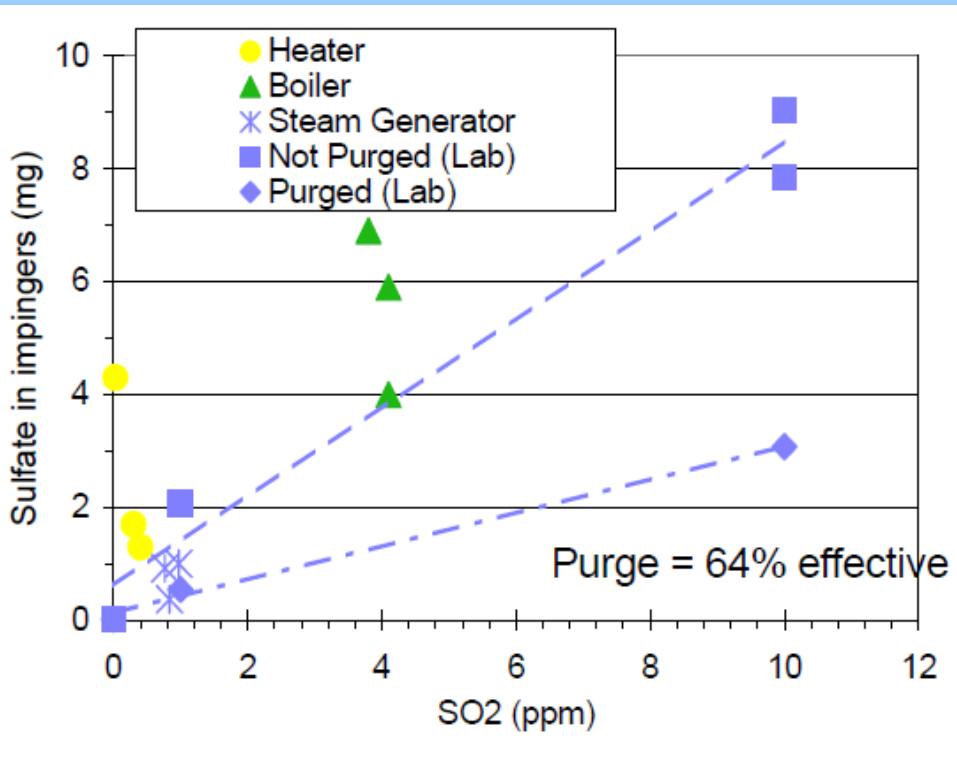
- Impingers 1 and 2 are left empty with a filter between impingers 2 and 3
- Water from moist stack gas still condenses in the "dry" impingers
- Pure nitrogen gas is run over the impingers immediately after sampling to remove dissolved SO_2 before it changes to $SO_4^=$
- The backup filter is weighed to determine the condensable catch

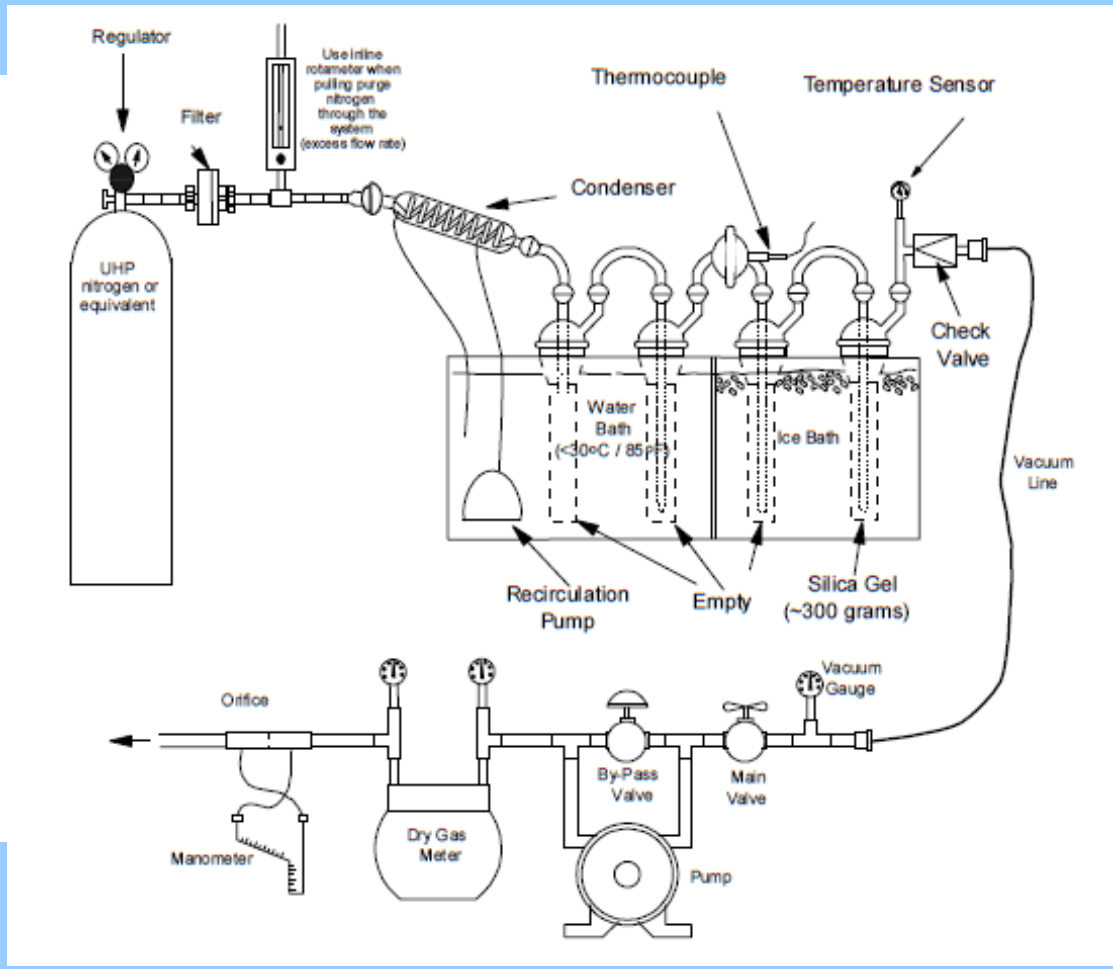


U.S.EPA (**2010**). Method 202 - Dry Impinger Method for Determining Condensible Particulate Emissions from Stationary Sources: (Appendix M of 40 CFR 51). prepared by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Technical Support Division, Research Triangle Park, NC, http://www.epa.gov/ttn/emc/promgate/m-202.pdf.

When impingers are extracted, much of what is found is dissolved (and oxidized) SO_2, not condensable particles

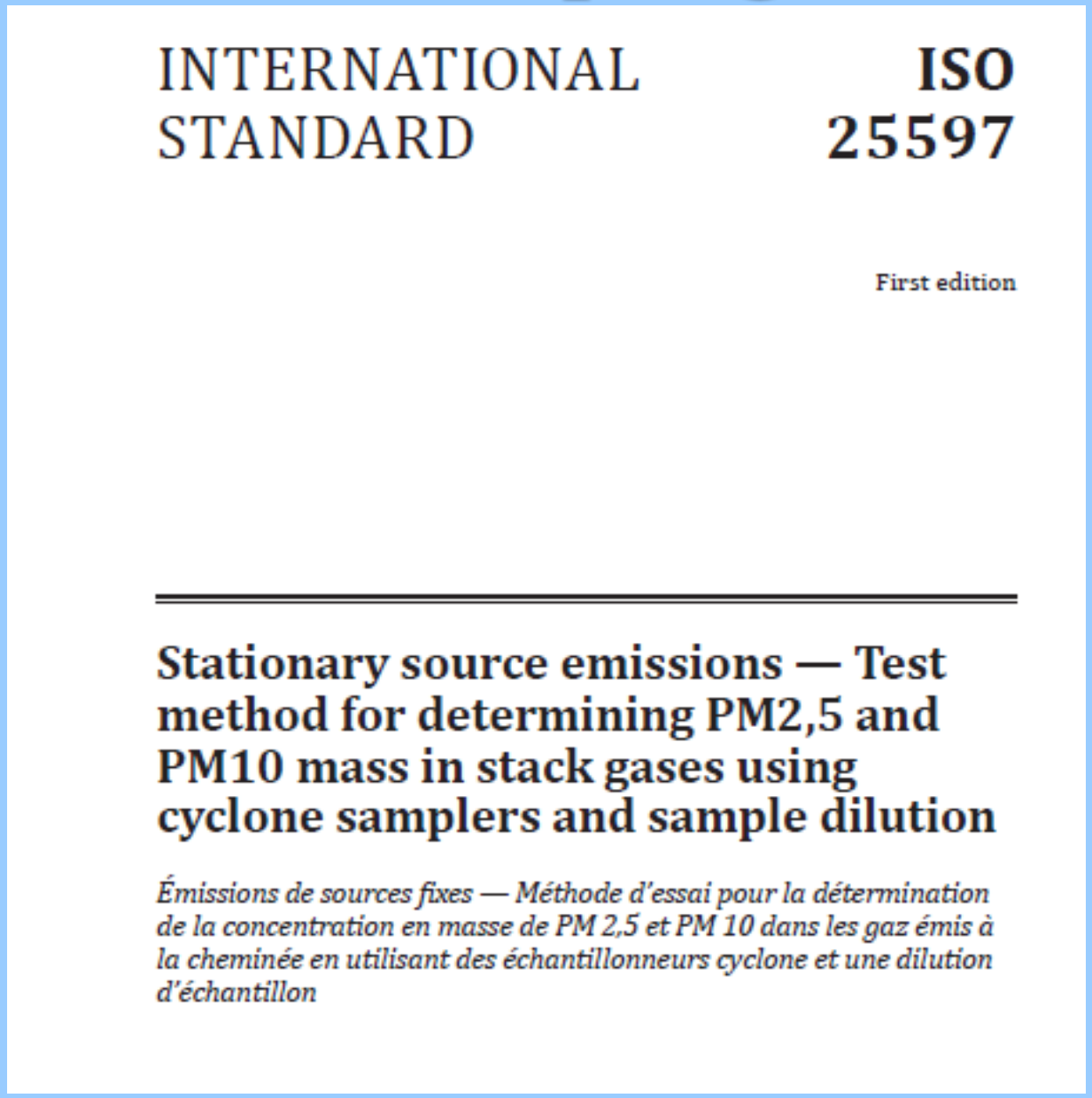
(Some of this is removed by purging the impingers with nitrogen prior to extraction)





Chang, M.-C.O.; England, G.C. (**2004**). Development of fine particulate emission factors and speciation profiles for oil and gas-fired combustion systems: Update-Critical review of source sampling and analysis methodologies for characterizing organic aerosol and fine particulate source emission profiles. prepared by GE Energy & Environmental Research Corporation, Irvine, CA, for Technikon LLC, McClellan, CA; www.nyserda.ny.gov/-/media/Files/Publications/Research/Environmental/EMEP/08_CriticalReviewUpdate_R1-V0.pdf.

ISO-25597:2013 provides guidance for dilution sampling of stationary sources



INTERNATIONAL STANDARD

ISO 25597

First edition

Stationary source emissions — Test method for determining PM2,5 and PM10 mass in stack gases using cyclone samplers and sample dilution

Émissions de sources fixes — Méthode d'essai pour la détermination de la concentration en masse de PM 2,5 et PM 10 dans les gaz émis à la cheminée en utilisant des échantillonneurs cyclone et une dilution d'échantillon

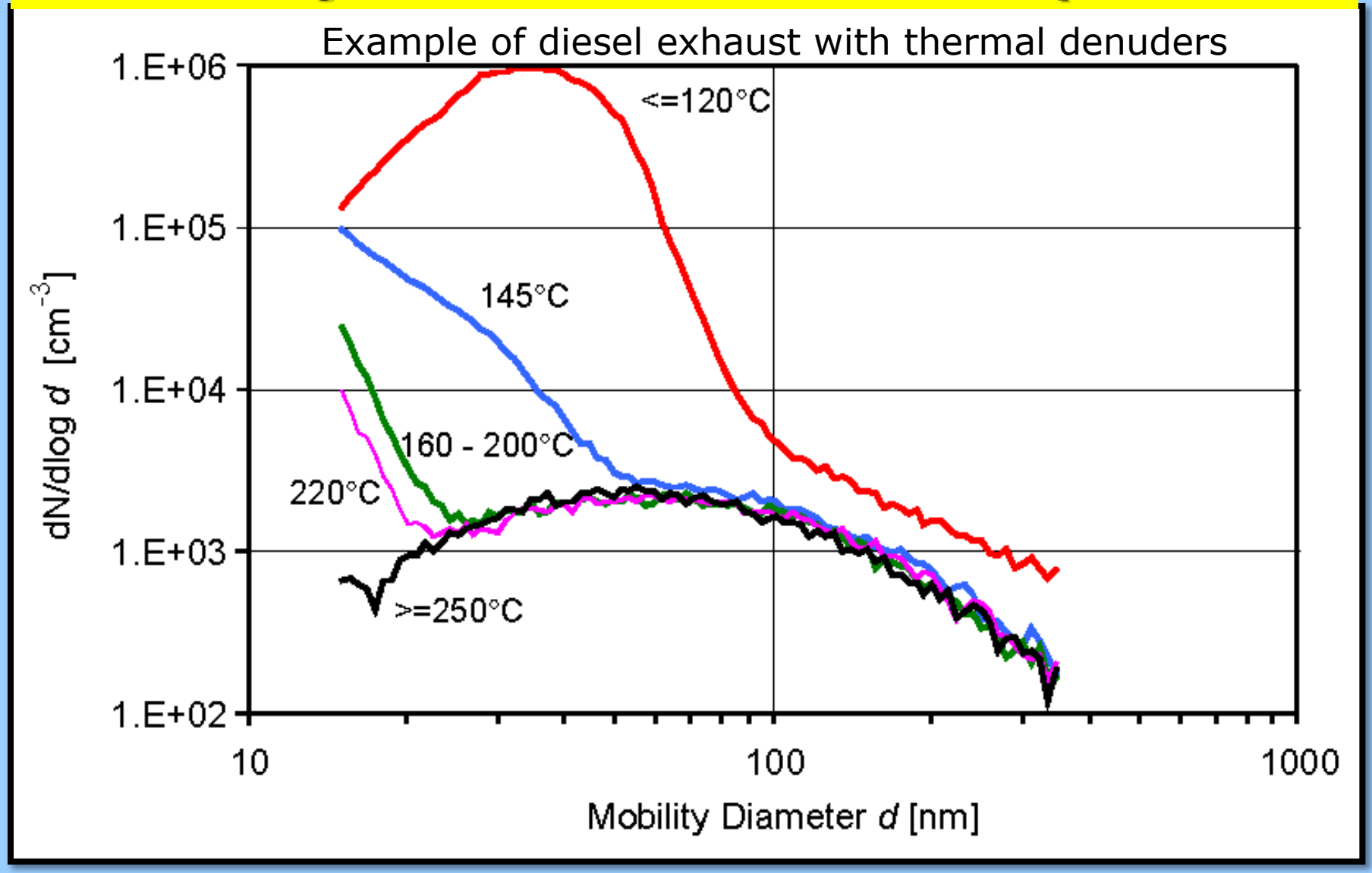
- Philosophy is to increase comparability between source and ambient measurements
- Offers substantial flexibility for multipollutant measurements in a single test
- Provides a good starting point for improving certification and compliance testing

ISO (**2013**), International Standards Organization. Prepared by International Organization for Standardization, Geneva, Switzerland, http://www.iso.org/iso/home.html.

There are good reasons to collect condensable particles

(Modern control devices remove most of the primary particles, but pass condensable vapors)

Preceding thermal denuders remove some ultrafine particles



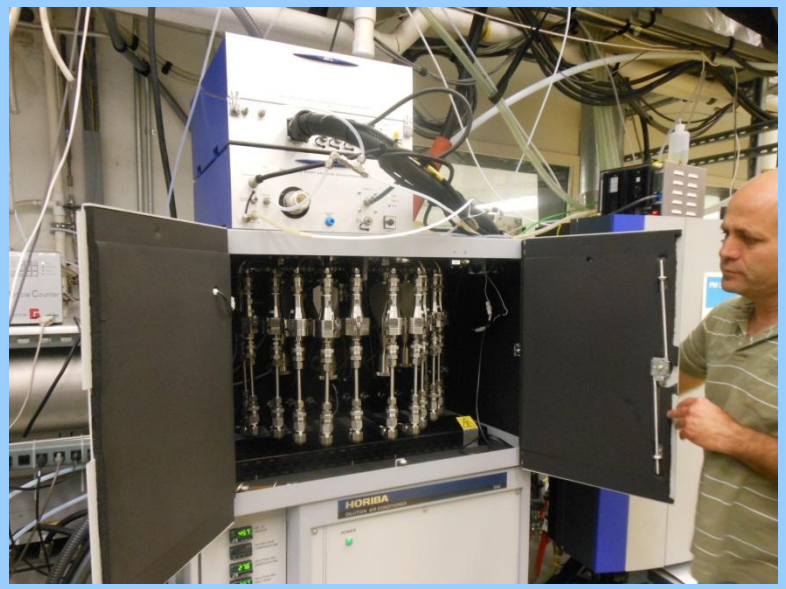
Burtscher, H. (**2005**). Physical characterization of particulate emissions from diesel engines: A review. *J. Aerosol Sci.*, **36**(7):896-932.

This type of sampling is common for gasoline- and diesel-engine exhaust used for on-road and non-road source testing

Hot exhaust is cooled (to ~50 C) in a dilution chamber at ARB's Haagen-Smit Laboratory

Gases and particles accumulate in Teflon bags for three different phases of operation

Filter samples are acquired with homogeneous deposits for chemical characterization



Sequential filter samples and continuous instruments sample directly from the dilution chamber to obtain better information on the engine cycle

Different stationary and mobile source test methods give different values for the same type of emissions

Dilution tunnel and sampling ports for vehicle exhaust

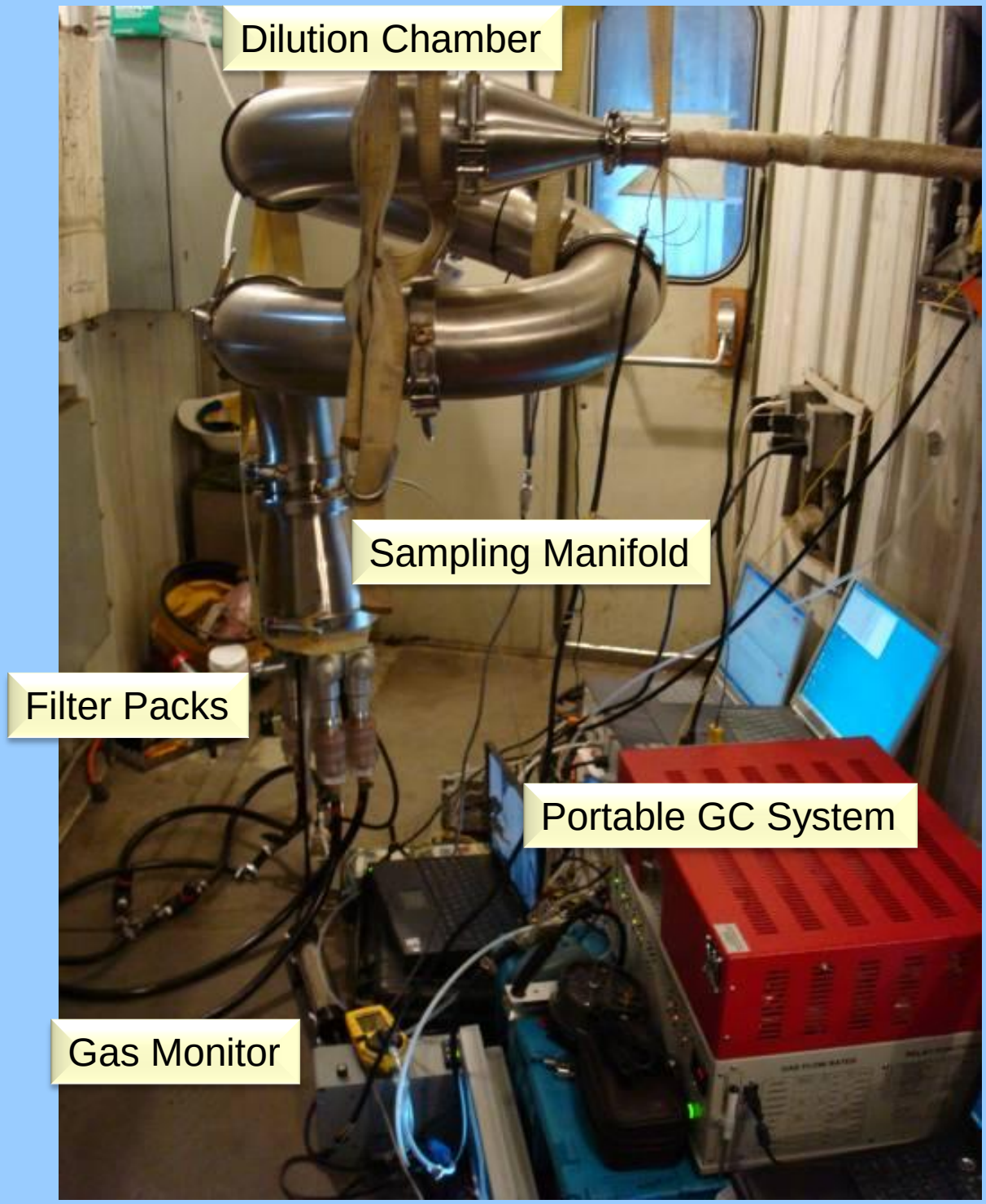
Put generator on wheels and move it and it is certified by dilution sampling

Install the generator permanently and it is certified by hot stack sampling and yields different emissions

Dilution sampling collects condensables and allows for measurement of many chemical components

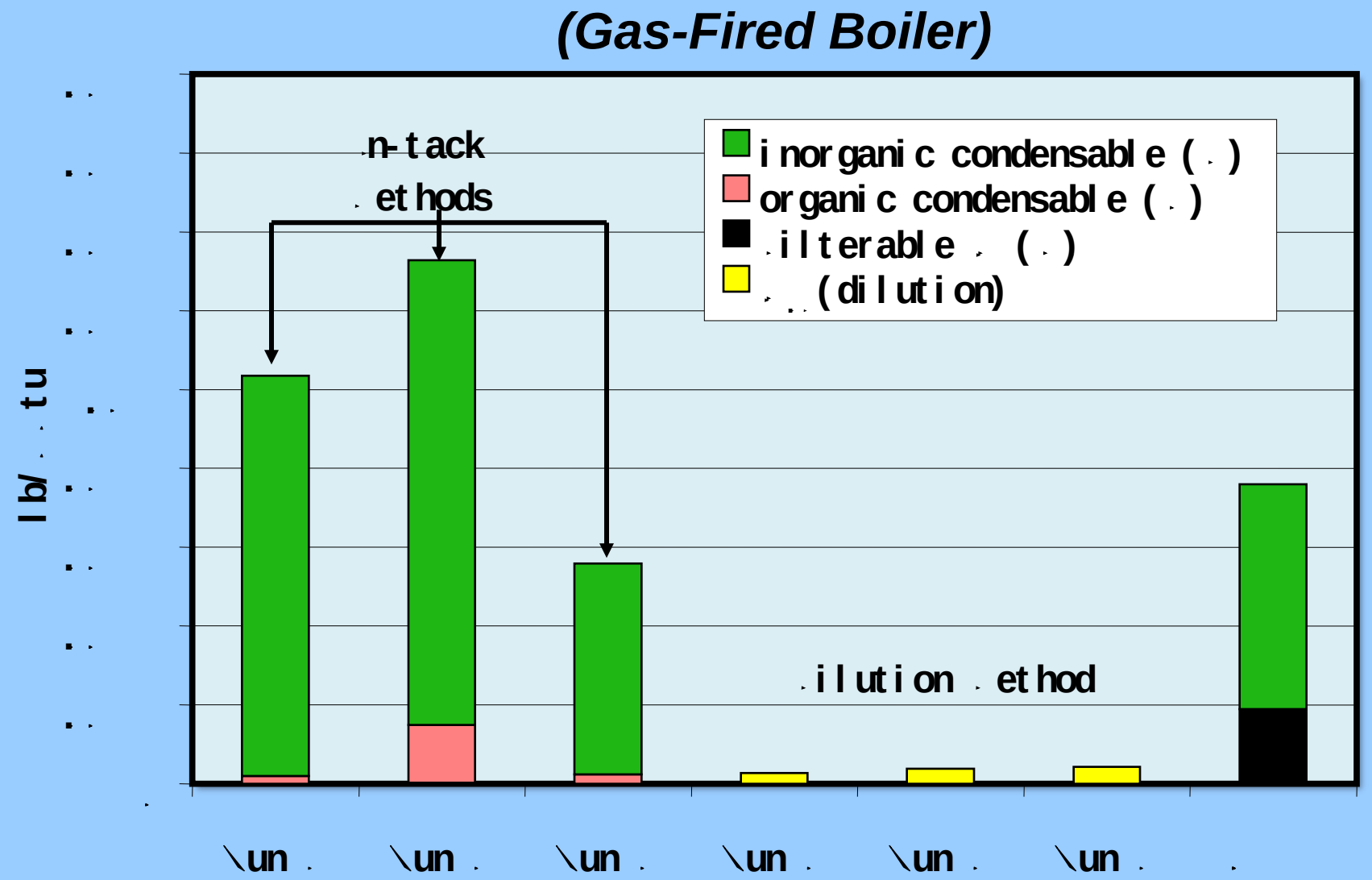
Six two-hour samples:

- Dilution ratio (22 – 45X)
- Residence time (28.2 sec)
- Stack and diluted temperatures (86-497 F)
- Stack velocity (18.0-59 m/sec)



Watson et al. (2013) 145–170

Dilution sampling provides a more realistic estimate of $PM_{2.5}$ emission rates than hot stack sampling



England, G.C.; Wien, S.; Zimperman, R.; Zielinska, B.; McDonald, J. (**2001**). Gas fired boiler test report site A: Characterization of fine particulate emission factors and speciation profiles from stationary petroleum industry combustion sources. Report Number 4703; prepared by American Petroleum Institute, Washington, DC, http://api-ep.api.org/filelibrary/ACF4B.pdf.

The front filter of Method 5 has long been known to underestimate emissions for condensable organic carbon vapors

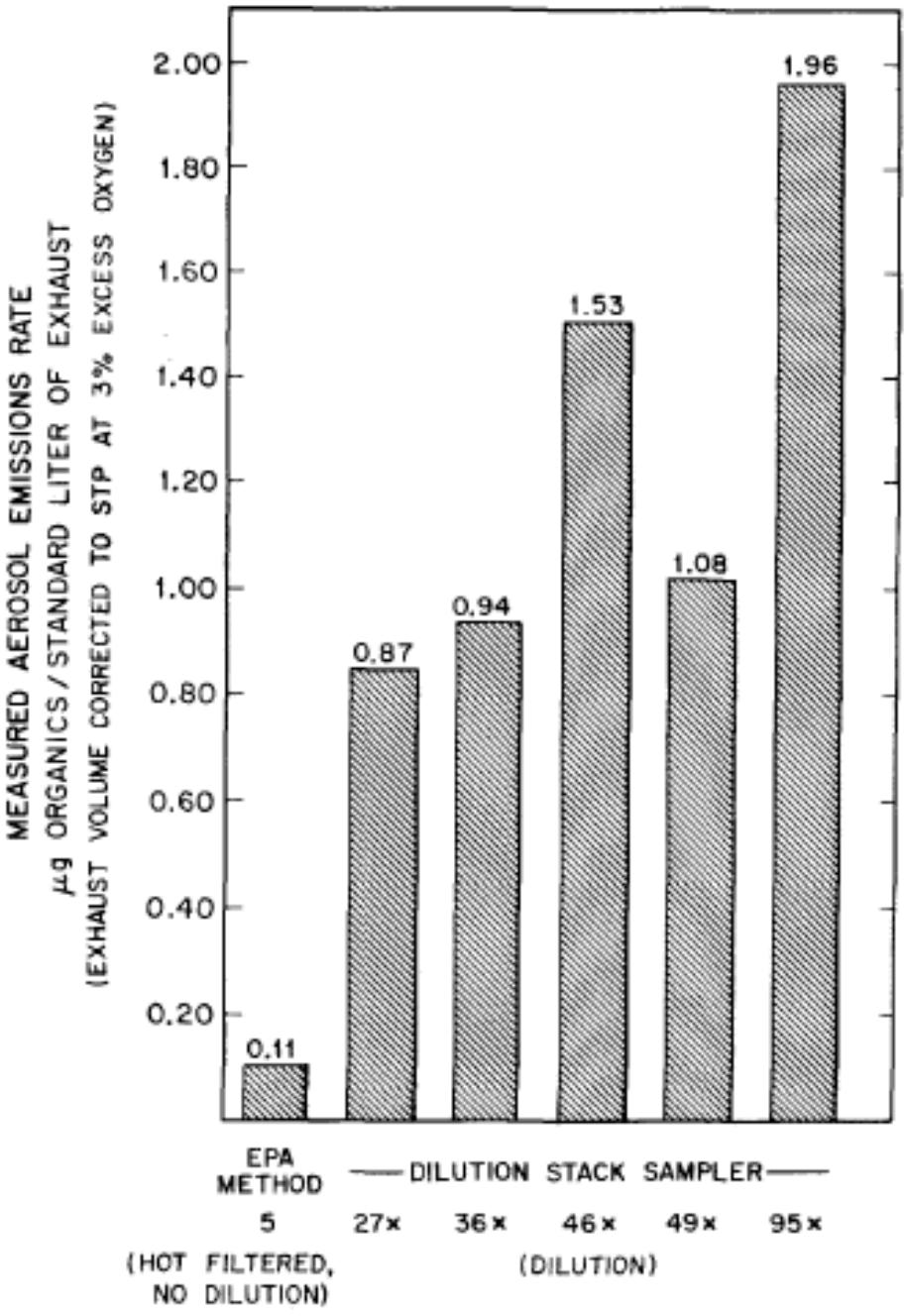


FIGURE 5. Organic carbon collected by filtration vs. dilution sampling procedure for distillate oil-fired industrial boiler.

Hildemann, L.M.; Cass, G.R.; Markowski, G.R. (**1989**). A dilution stack sampler for collection of organic aerosol emissions: Design, characterization and field tests. *Aerosol Sci. Technol.,* 10(10-11):193-204. http://www.tandfonline.com/doi/pdf/10.1080/02786828908959234.

More complete tests on gas-fired boilers show front filter underestimates and impinger catch overestimates PM emissions

Table 5. Comparison between dilution sampler results and other data for gas combustion units.

Source	Combustor Type	PM2.5[a]	Total PM_{10}[cb]	Filterable PM_{10} (FPM)	Fraction of Total PM_{10} (%)	Condensable PM_{10} (CPM)	Fraction of Total PM_{10} (%)
AP-42[36]	External combustor/NG		75[c,d]	19[c]	25	56[d]	75
AP-42[36]	Internally fired/NG gas turbine		66[c,d]	19[dc]	29	47[d]	71
Hildemann et al.[37]	Home appliances/NG	1.1					
API/A	Boiler/RG	0.36	99[d,e]	1.6[e]	2	97[d]	98
API/B	Process heat/RG	0.54	52[d,e]	6.4[e]	12	46[d]	88
API/C	Steam generator/NG	0.56	13[d,e]	0.8[e]	6	12[d]	94
Alpha	Process heat/RG	0.52	84[d,e]	5.9[e]	7	78[d]	93
Bravo	NGCC plant/supplemental firing and SCR	2.5	32[d,e]	2.9[e]	9	30[d]	91
Charlie	Process heat/NG	1.6	11[d,e]	1.0[e]	9	10[d]	91
Delta	Institutional boiler/NG[f]	5.3	13[g]			13[g]	
Echo	NGCC power plant with oxidized catalyst and SCR	1.3					

Notes: NG = natural gas; RG = refinery gas; emission factors in lb/MMBTU (10^{-4}). [a]Data from dilution tunnel method; data is for $PM_{2.5}$ and includes solid and condensed material; [b]AP-42 emission data based on reported PM_{10} estimates; likely comparable with $PM_{2.5}$ data, because gas combustors emit mainly fine particles; [c]Data collected using hot filter methods (EPA Method 5, 201, 201a); [d]Data collected using wet impinger methods (e.g. EPA Method 202); [e]Data collected using hot filter method (CTM 040); [f]Data probably biased high from NG testing after oil firing and high-filter blank levels; [g]PM measured by controlled condensation method.

Dilution

Filter+Impinger

Front filter

Impinger

England, G.C.; Watson, J.G.; Chow, J.C.; Zielinska, B.; Chang, M.-C.O.; Loos, K.R.; Hidy, G.M. (**2007**). Dilution-based emissions sampling from stationary sources: Part 1. Compact sampler, methodology and performance. *J. Air Waste Manage. Assoc.*, ***57(1):65-78.*** ***http://www.tandfonline.com/doi/pdf/10.1080/10473289.2007.10465291.***

England, G.C.; Watson, J.G.; Chow, J.C.; Zielinska, B.; Chang, M.-C.O.; Loos, K.R.; Hidy, G.M. (**2007**). Dilution-based emissions sampling from stationary sources: Part 2. Gas-fired combustors compared with other fuel-fired systems. *J. Air Waste Manage. Assoc.*, ***57 (1):79-93.*** ***http://www.tandfonline.com/doi/pdf/10.1080/10473289.2007.10465304.***

Organic carbon and sulfates disappear at higher temperatures in ship stack emissions

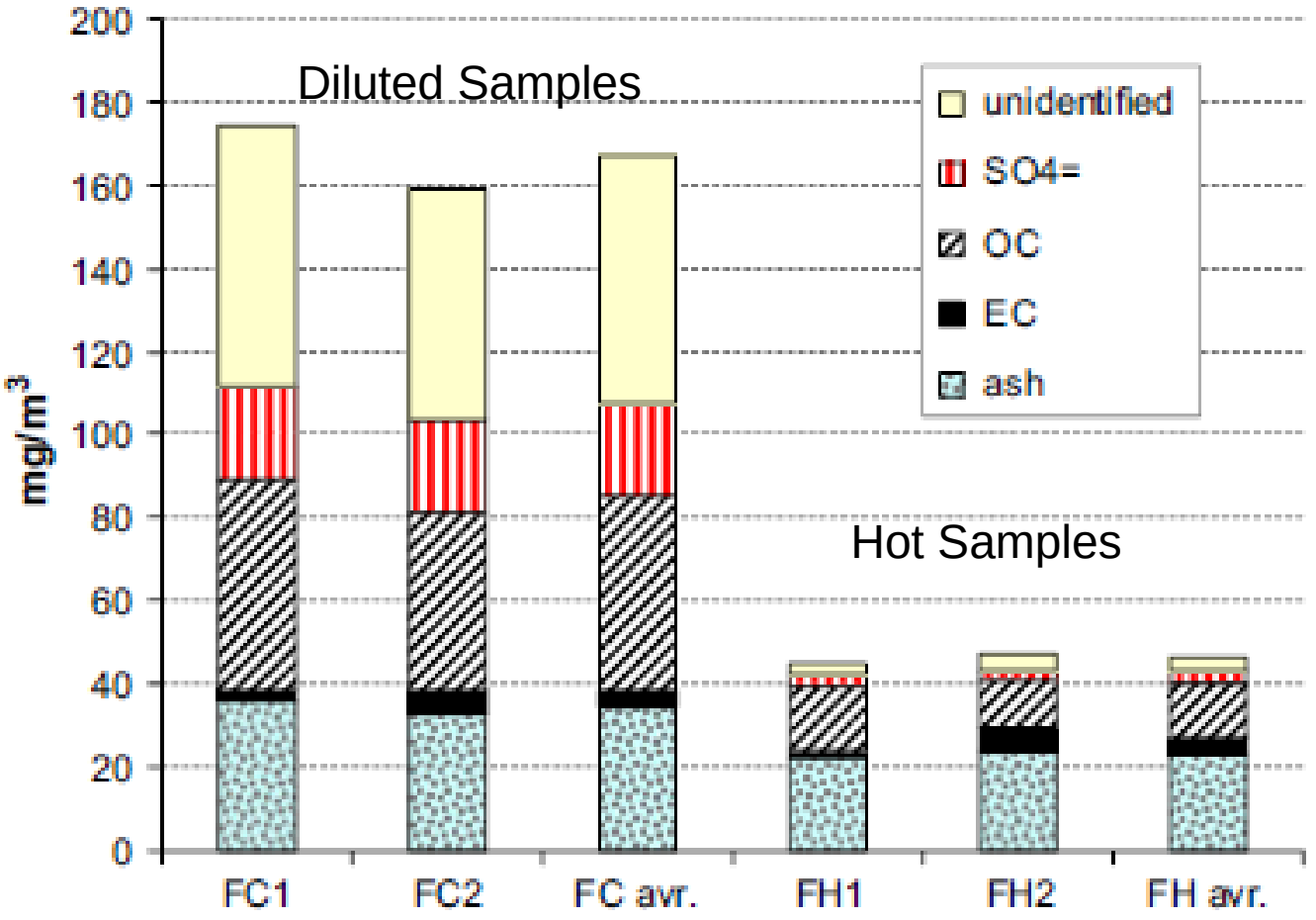
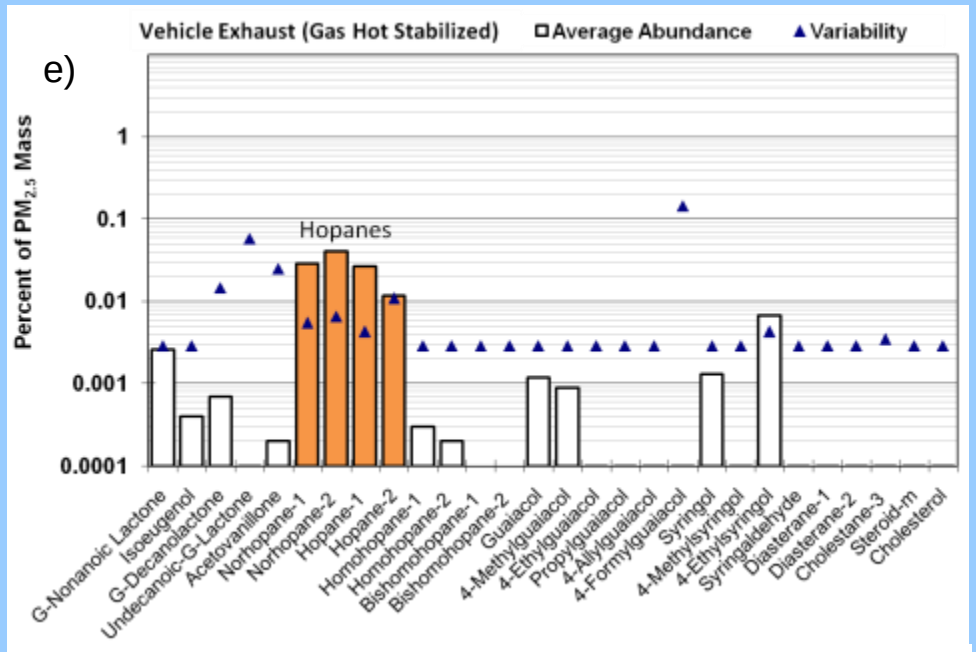


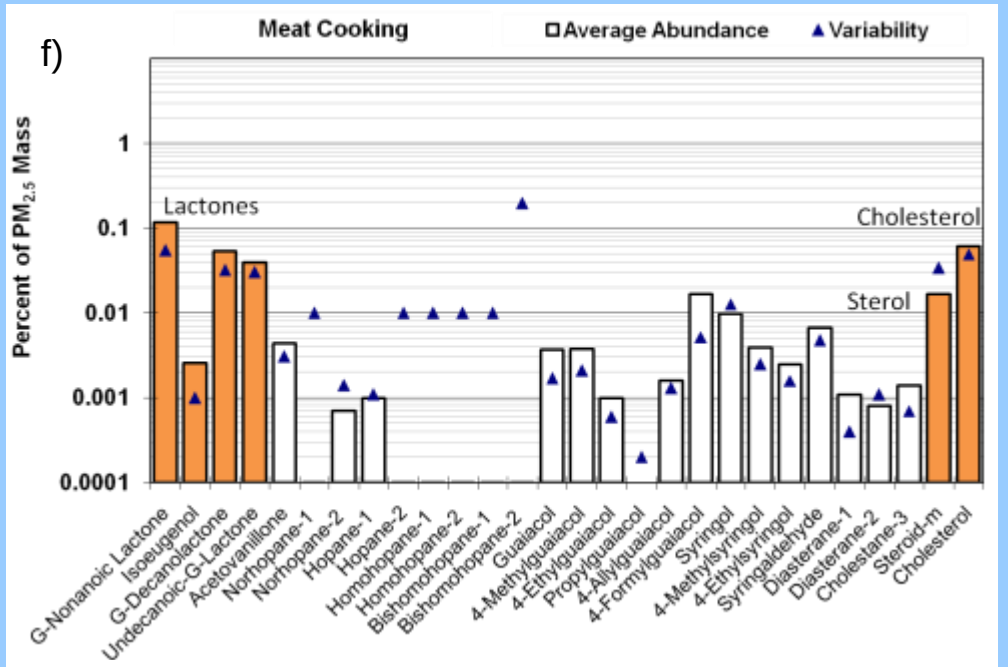
Fig. 3. Composition of PM (as mg m^{-3} exhaust gas) collected on filters in the diluted (FC) and hot (FH) exhaust gas. FC1, FC2, FCavr. and FH1, FH2, FHavr. are individual filter samples and their average values collected in the diluted and hot exhaust, respectively.

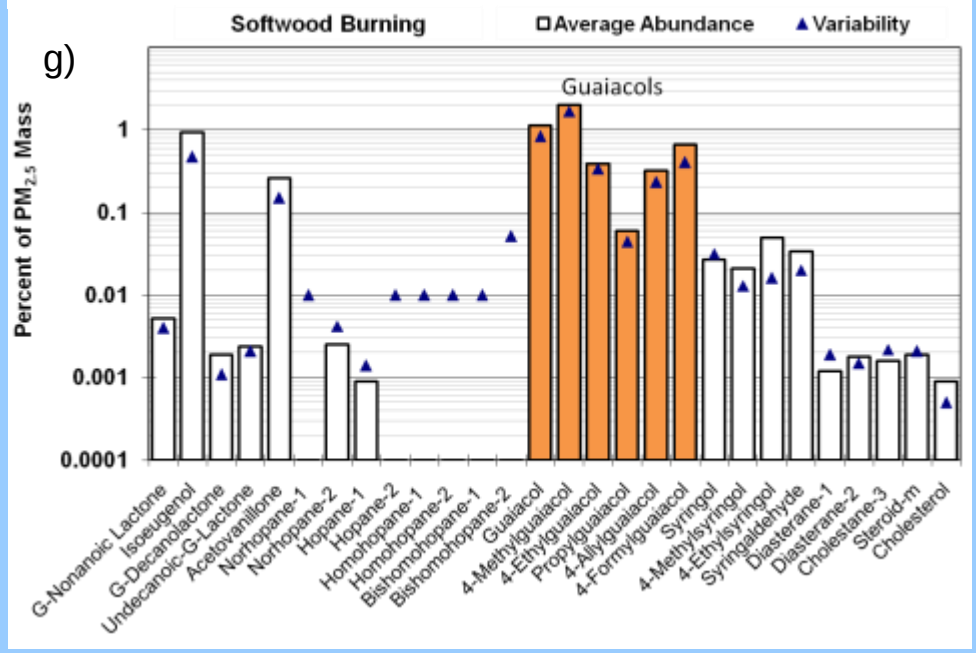
Moldanova, J.; Fridell, E.; Popovicheva, O.B.; Demirdjian, B.; Tishkova, V.; Faccinetto, A.; Focsa, C. (**2009**). Characterisation of particulate matter and gaseous emissions from a large ship diesel engine. *Atmos. Environ.*, ***43(16):2632-2641.***

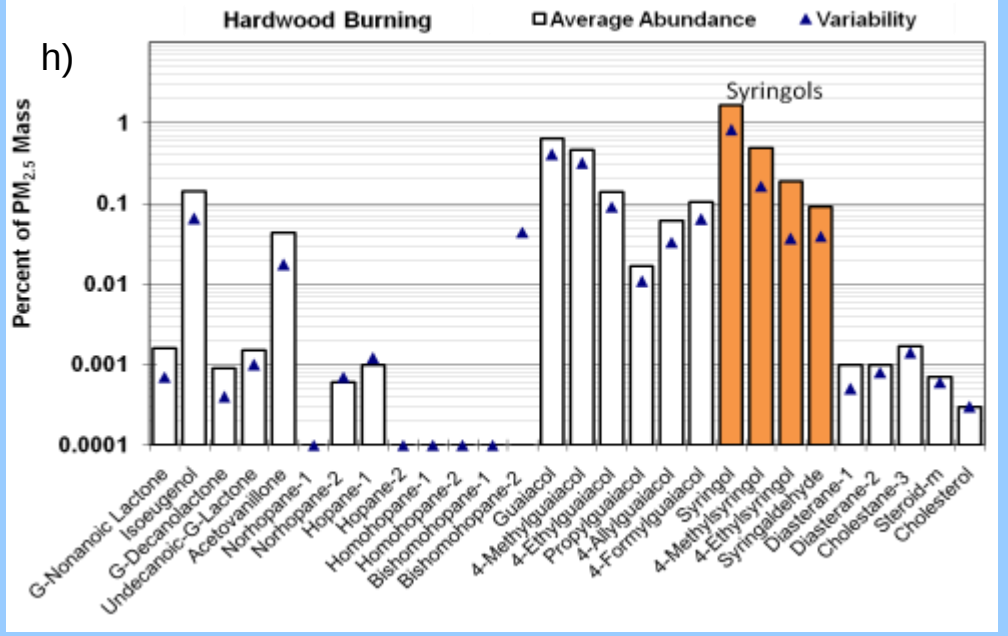
Condensable organic compounds are important source markers

(e.g., lactones, hopanes, guaiacols, syringols, steranes, and sterols)



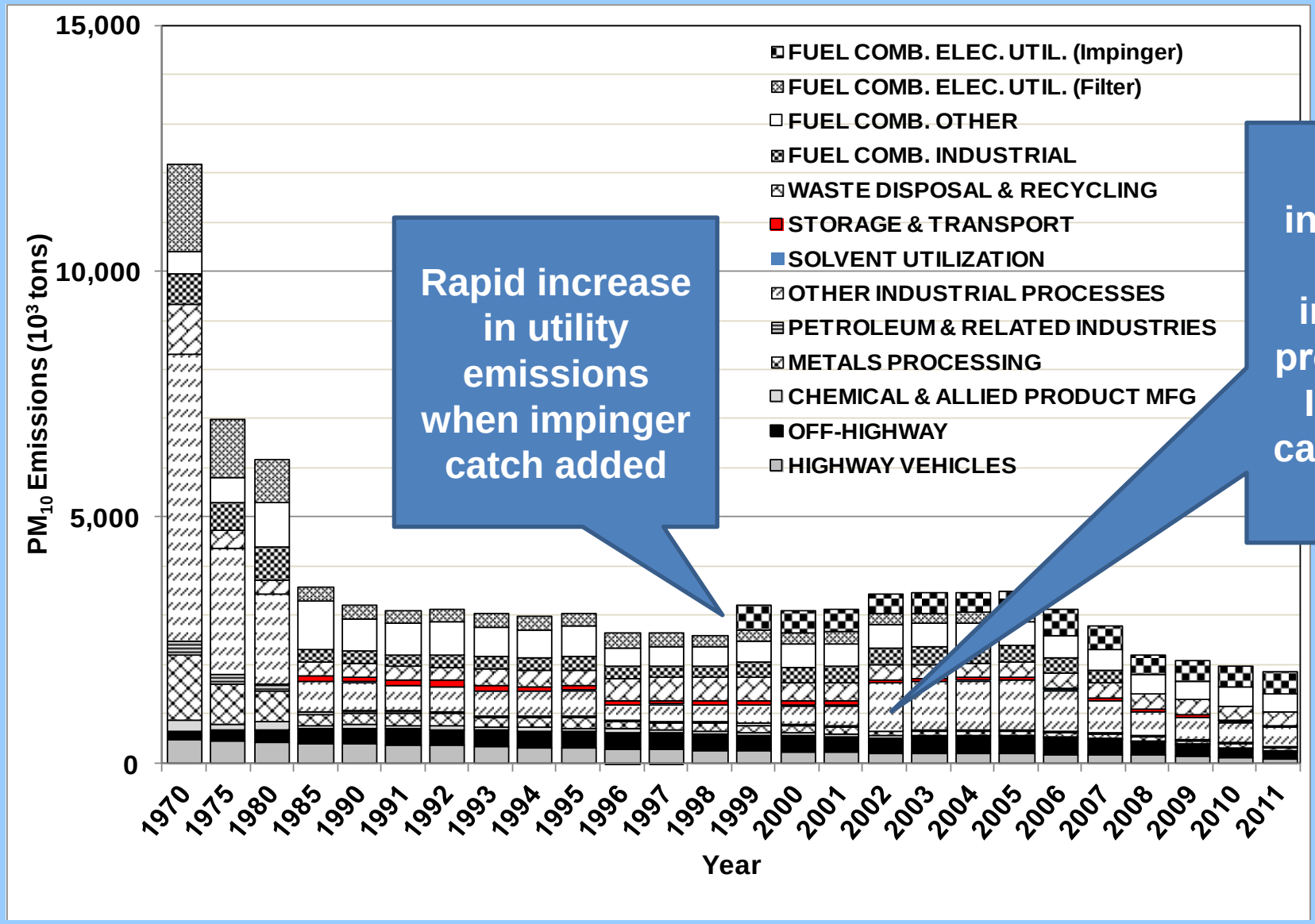






Adding the "condensable" fraction elevated U.S. utility $PM_{2.5}$ emissions by 400% in the National Emissions Inventory

(Most of these data are from AP-42 emission factors)

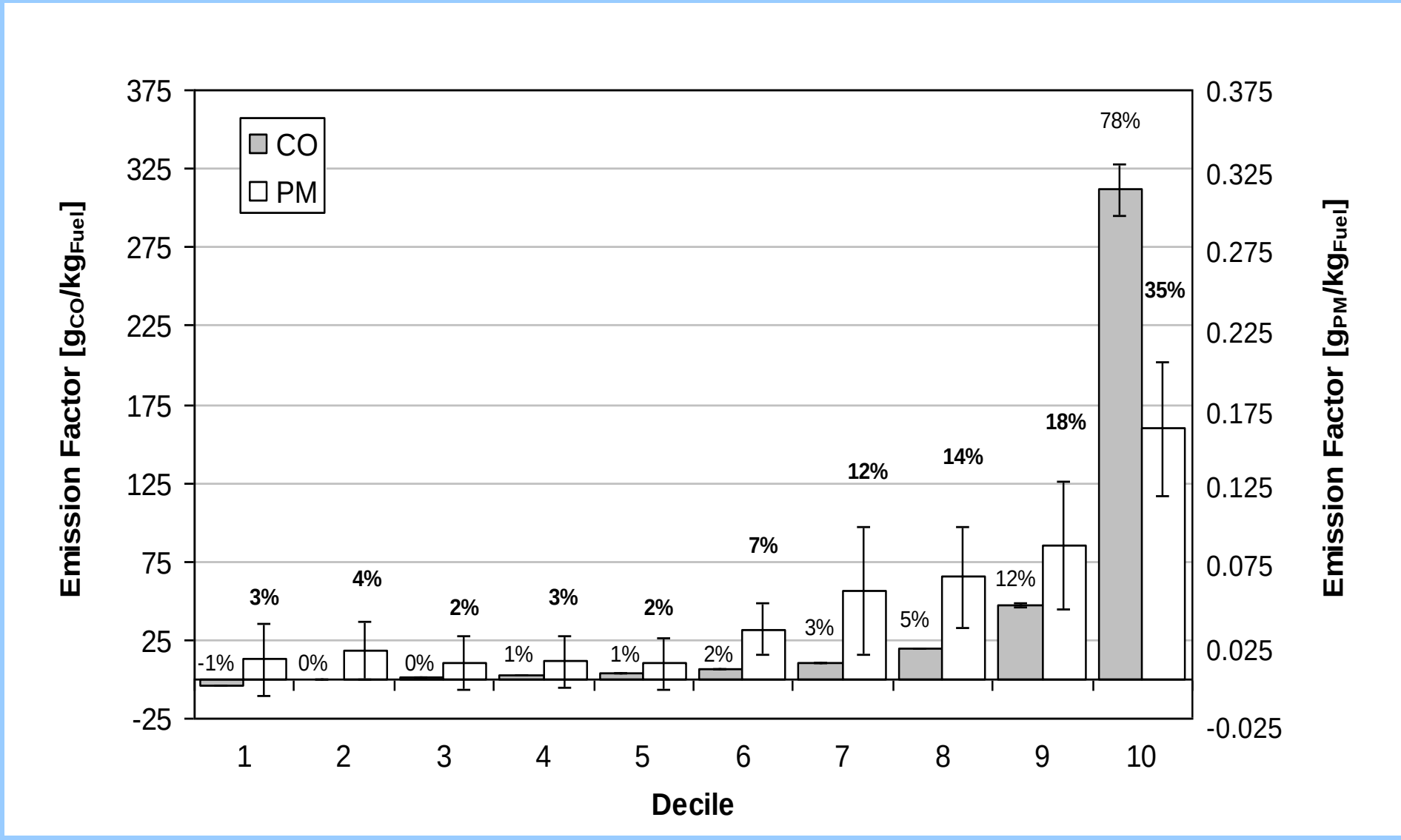


Percy, K.E. (**2012**). *Alberta Oil Sands: Energy, Industry, and the Environment*. Elsevier Press: Amsterdam, The Netherlands

Real-world engine emissions are often higher than estimates derived from certificaiton tests

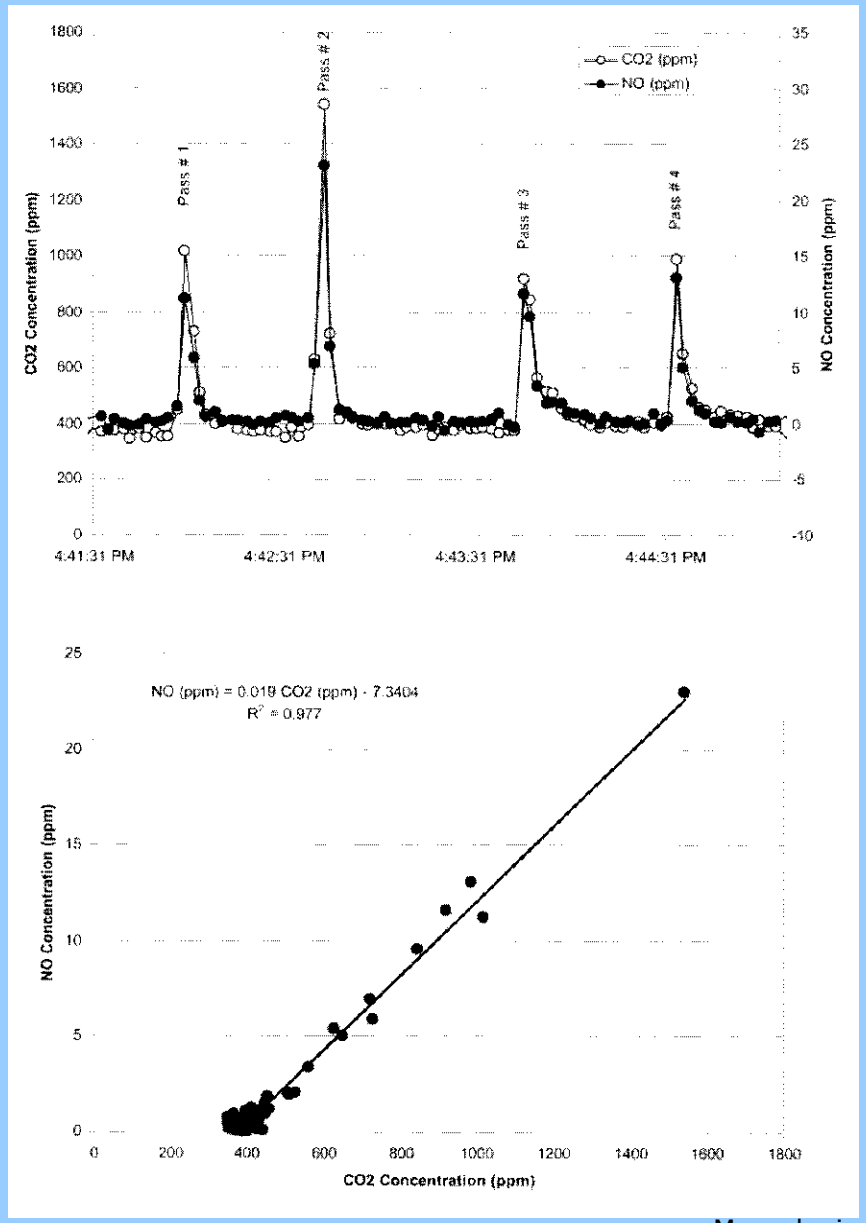
(Courtesy of Doug Lawson, DOE National Renewable Energy Laboratory ww.cleanairinfo.com/slcf/agenda.htm)

Real-world emission tests demonstrate that average emission factors do not represent the emissions distribution



Mazzoleni, C.; Moosmüller, H.; Kuhns, H.D.; Keislar, R.E.; Barber, P.W.; Nikolic, D.; Nussbaum, N.J.; Watson, J.G. (2004). Correlation between automotive CO, HC, NO, and PM emission factors from on-road remote sensing: Implications for inspection and maintenance programs. *Transport. Res.*, **D9**:477-496.

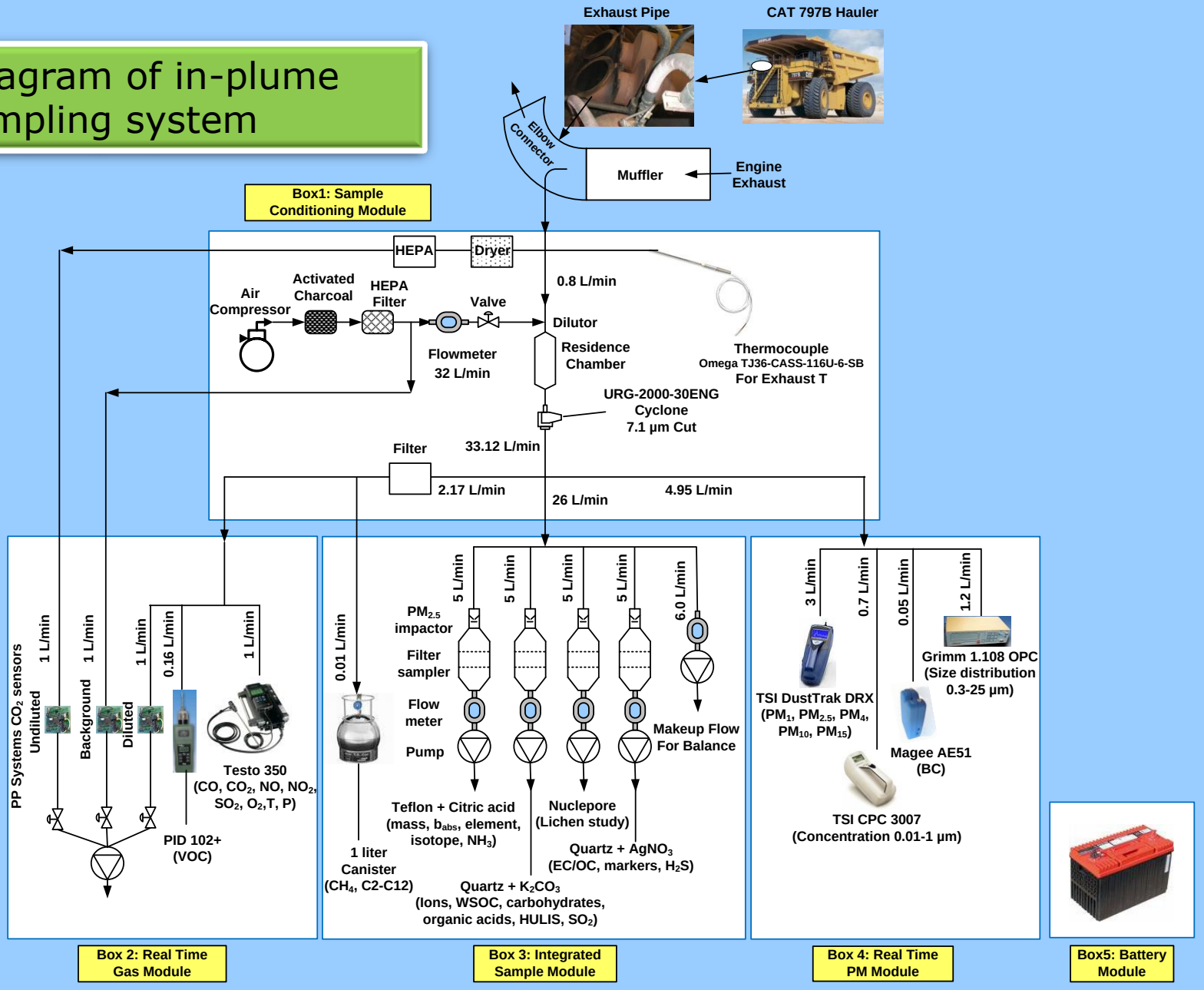
Fuel-based emission rates measured by cross-plume and in-plume sensors normalize emissions to CO_2, then relate to fuel consumed



Mazzoleni et al. (2004a,2004b) *Transport Res., JAWMA*

More complex portable detection systems are becoming available to obtain a wider range of multipollutant measurements

Flow diagram of in-plume sampling system



Wang et al., 2012

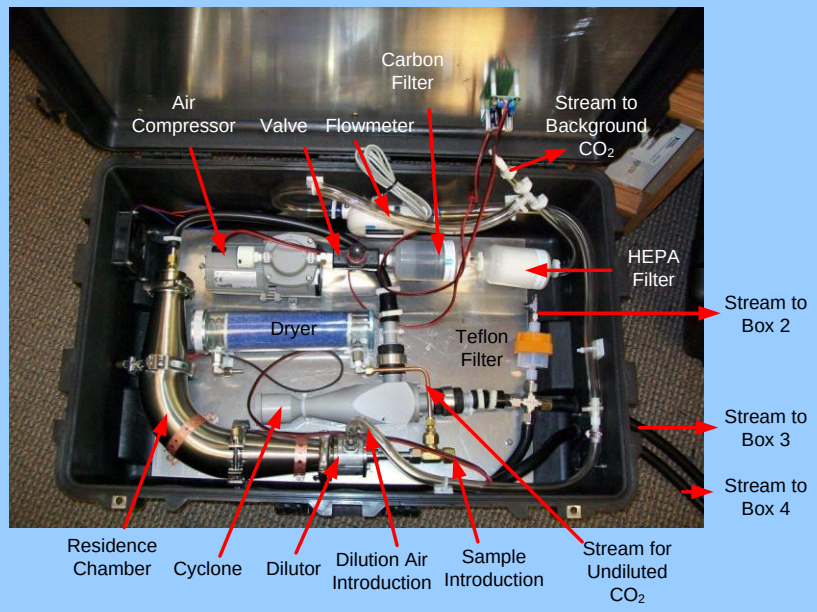
Microsensors are used when they are available and tested

Observables	Instrument	Acquisition Time
Total aromatic VOC (isobutylene referred; ppm)	HNU Photoionization Detector (PID) Analyzer (Pembroke, MA, USA) 	1 second
CO, CO_2, NO, NO_2, SO_2, and O_2 (ppm)	Testo Electrochemical Emission Analyzer (Sparta, NJ, USA) 	1 second
Tailpipe, diluted, and background CO_2 concentrations (ppm)	PP System NDIR CO_2 analyzers (Amesbury, MA, USA) 	1.5 seconds
PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{15} (μg/m³)	TSI DustTrak Light Scattering/OPCDRX (Shoreview, MN, USA) 	1 second
Particle number concentration; 10 nm to 2.5 μm (#/cm³)	TSI Condensation Particle Counter (Shoreview, MN, USA) 	1 second
$PM_{2.5}$ Black (880 nm) and Brown (350 nm) carbon (μg/m³)	Magee filter transmittance micro-Aethalometer (Berkeley, CA, USA) 	1 second

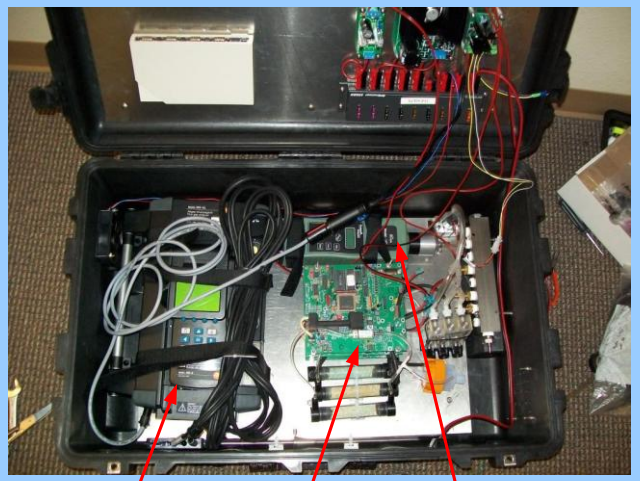
More compact and continuous in situ sensors are desired

(Dilution sampling system)

Sample Conditioning Module (#1)

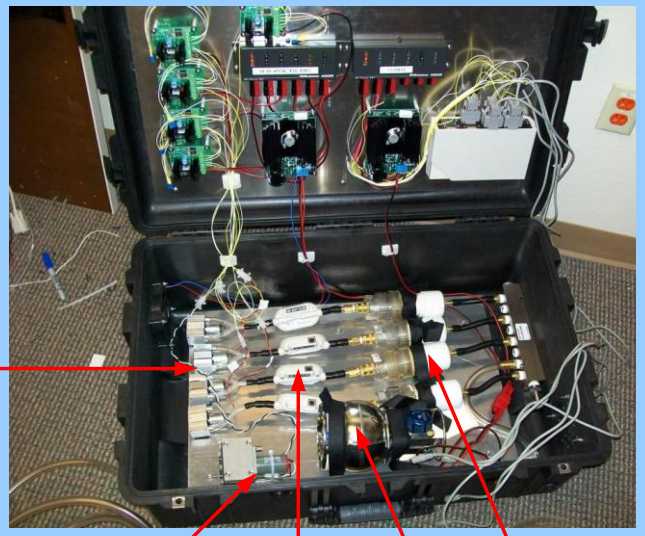


Real-time Gas Module (#2)

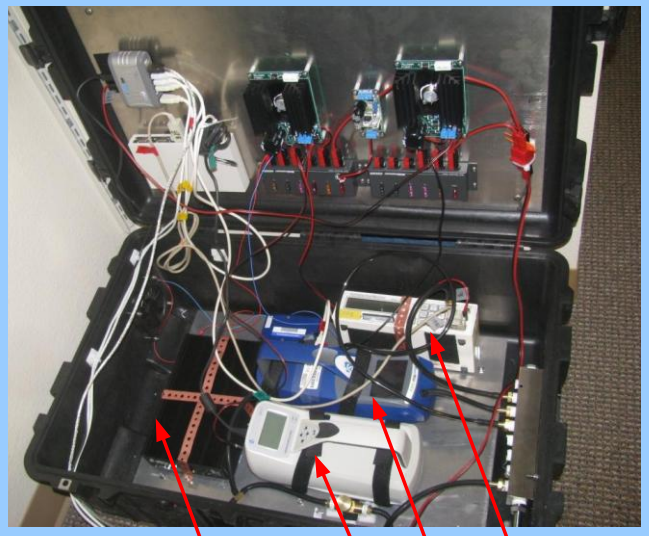


Caterpillar 797B Heavy Hauler (345 tons)

Integrated Sample Module (#3)



Real-time PM Module (#4)



Battery (#5)

Each module measures = 80 cm L × 52 cm W × 32 cm H

In-situ measurements are complemented by extracting more information from integrated samples

Filter pack sampling for $PM_{2.5}$ and precursor gases

$PM_{2.5}$ Impactor	$PM_{2.5}$ Impactor	$PM_{2.5}$ Impactor	$PM_{2.5}$ Impactor
Channel 1 (5 L/min)	Channel 2 (5 L/min)	Channel 3 (5 L/min)	Channel 4 (5 L/min)
Teflon-membrane filter Mass, light transmission, rare-earth elements, elements, isotopes	Quartz-fiber filter Ions (Cl^-, NO_2^-, NO_3^-, $PO_4^=$, $SO_4^=$, NH_4^+, Na^+, Mg^{++}, K^+, Ca^{++}), total WSOC, WSOC classes[a], Carbohydrates, organic acids, HULIS	Quartz-fiber filter OC, EC, carbon fractions, carbonate, ~130 alkanes, alkenes, PAHs, hopanes, and steranes	Teflon filter Lichen study mass and elemental analysis or morphological analysis
Citric acid-impregnated cellulose-fiber filter NH_3 as NH_4^+	Potassium carbonate-impregnated cellulose-fiber filter SO_2 as $SO_4^=$	Silver nitrate-impregnated cellulose-fiber filter H_2S as S	

[a] Neutral compounds (NC)
Mono /dicarboxylic acids (MDA)
Polycarboxylic acids (PA)

Canisters and sampling for volatile organic compounds (VOCs)

2, 4 - Dinitrophenylhydrazine (DNPH) cartridge sampling for carbonyls

Real-world sampling uses on-board instruments to sample plumes and normalize concentrations to CO_2 and fuel carbon content to obtain emission factor in g-pollutant/kg-fuel

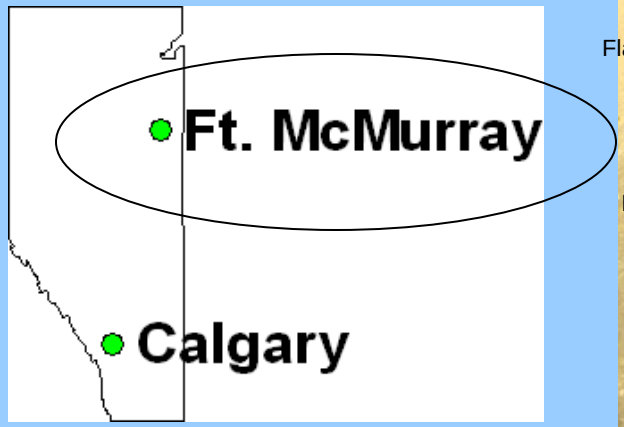
Caterpillar 797B Heavy Hauler (345 tons)

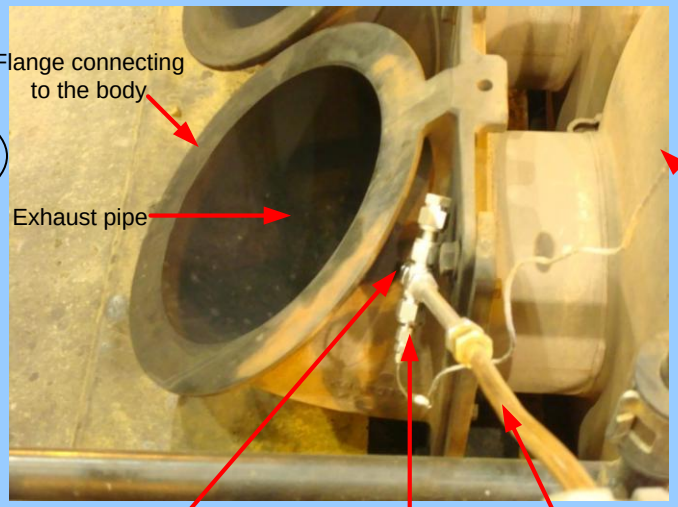
Samples drawn from exhaust pipe.
No interference with vehicle operations.

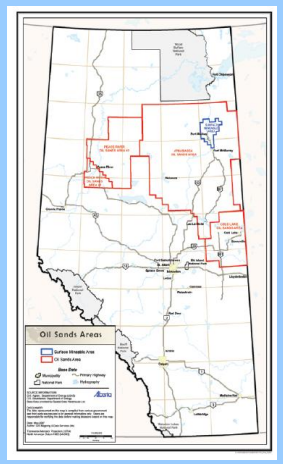
- Battery powered
  - Particle light scattering (b_{scat}; normalized to filter mass)
  - Particle size distribution
  - Black carbon (two wavelengths)
  - Volatile organic compounds (VOCs)
  - Gases
    - O_2
    - CO_2
    - CO
    - NO
    - NO_2
    - SO_2
    - H_2S
  - Filter-based samples

Watson et al. (2013)

Sampling port is connected to the exhaust pipe (muffler outlet)





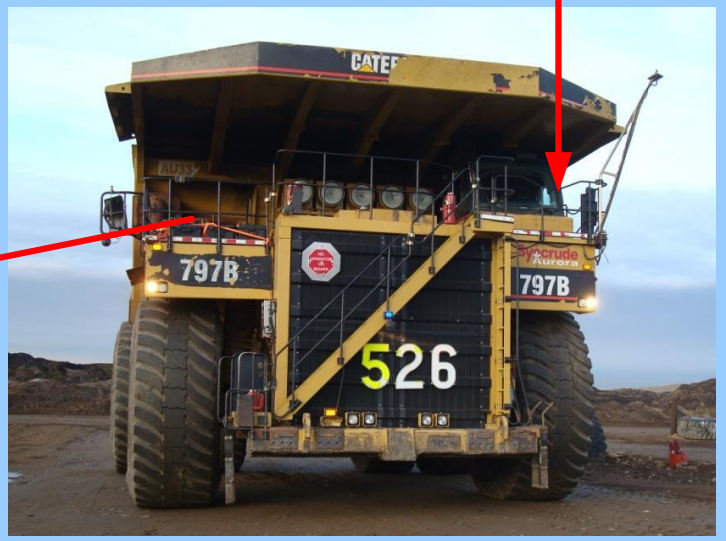


Athabasca Oil Sands Region

Sampling Modules

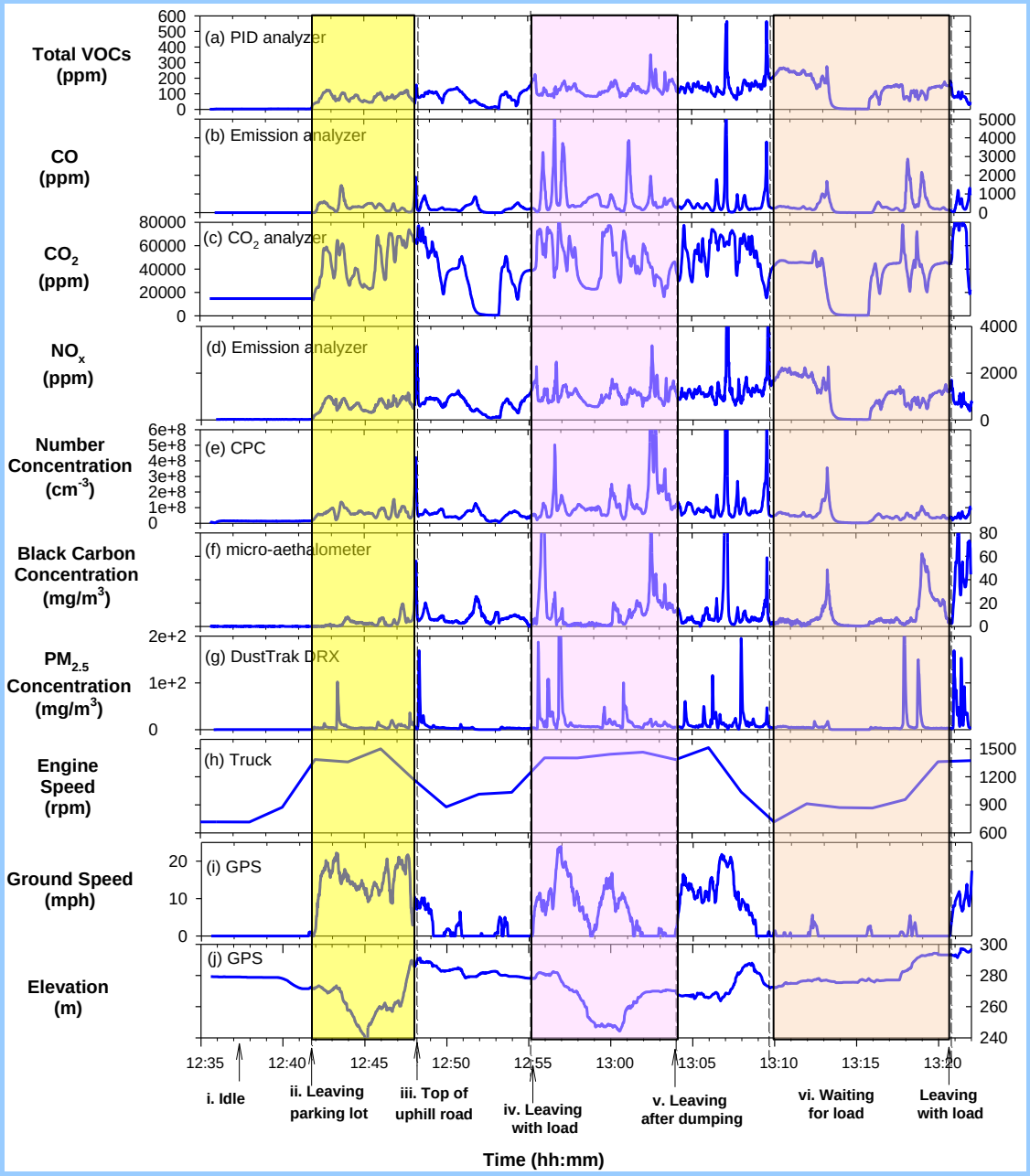
Sampling Platform

Driver Cabin



Watson et al. (2012) 145–170

Emission concentrations vary by operating condition
(time series)

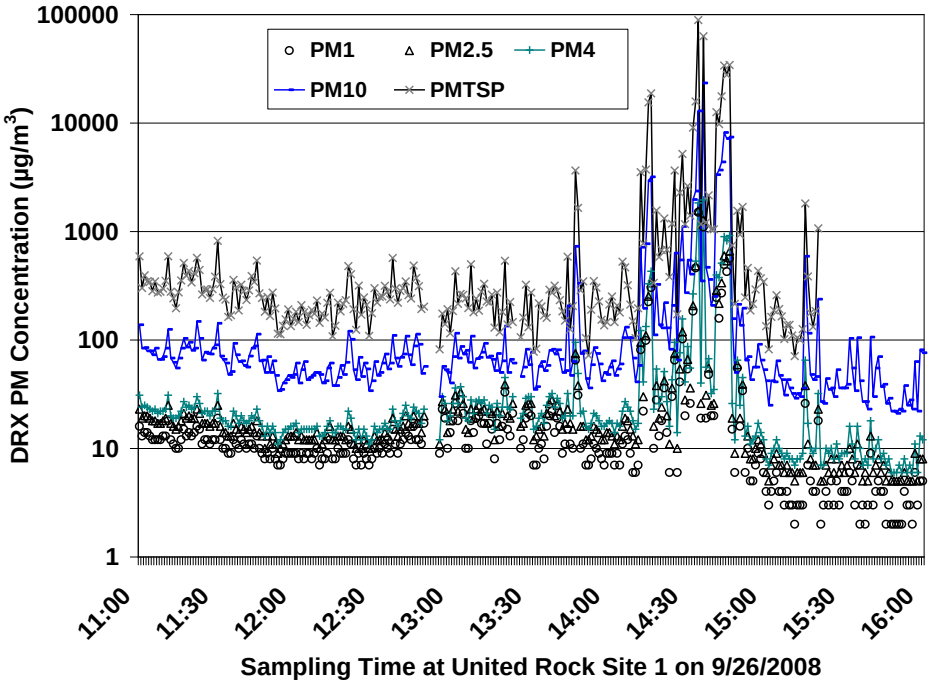


i. Idling: Concentration stable and low.
ii. Leaving parking lot: All concentrations increase.
iii. Top of uphill: Spikes of concentrations.
iv. Leaving with load: high concentration spikes when accelerating.
v. Leaving after dumping: concentration spikes when climbing uphill.
vi. Waiting for load: low concentration except when moving forward in line.

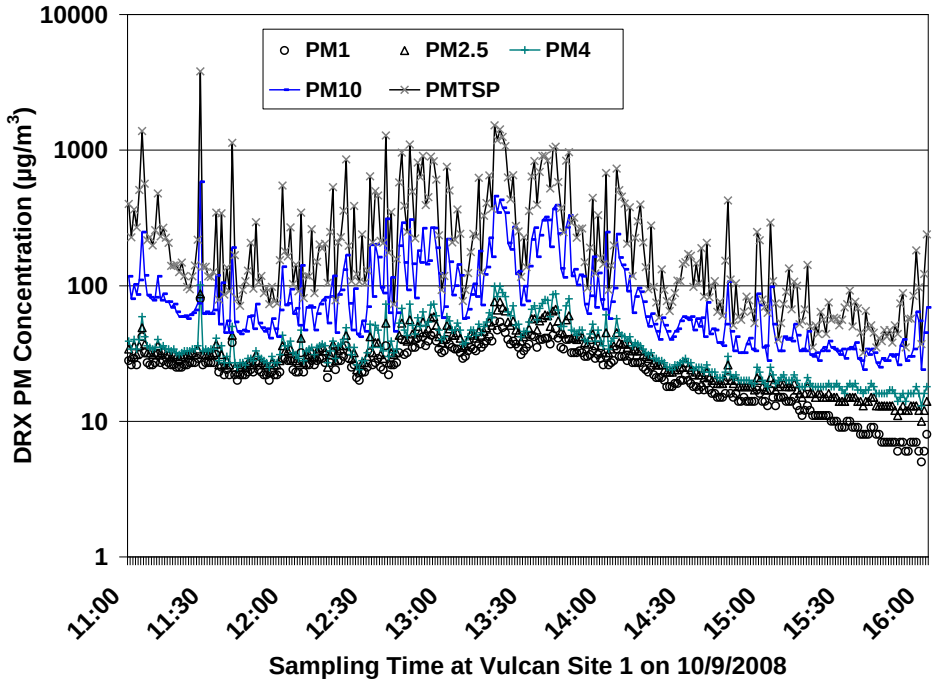
Watson et al. (2012) 145–170

Rapid particle size measurements separate nearby from distant emitters

Facility A



Facility B

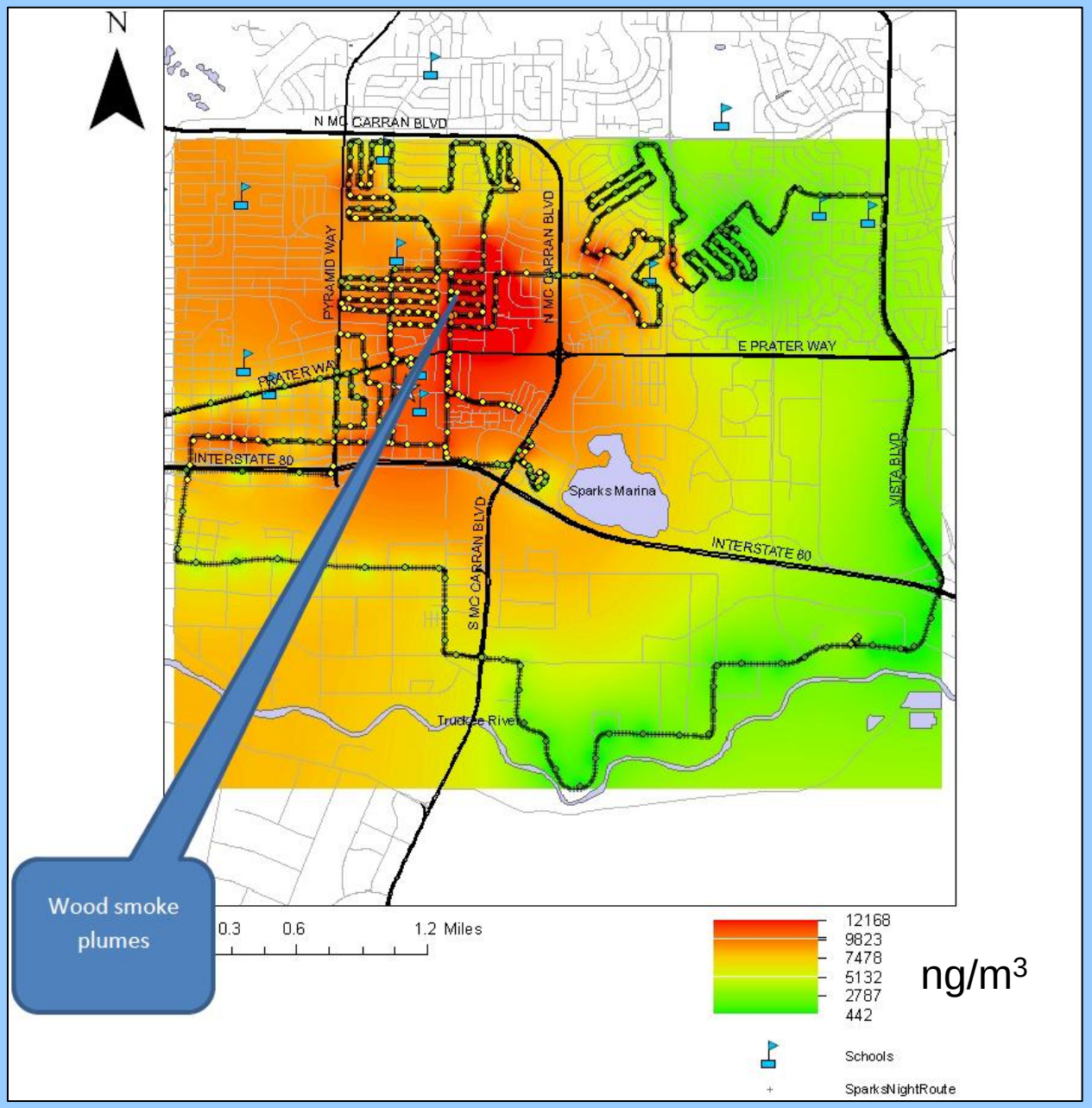


Watson et al. (2011) *AAQR*

* Using TSI DustTrak DRX

Incremental absorption at short wavelengths allows for mapping the zone of influence of residential woodburning

Wintertime evening spatial distribution of brown carbon in Sparks, NV, shows a relatively small footprint of effects in a low-income neighborhood heating with solid fuels



Recommended activities for real-world emission testing

- Don’t use the old hot filter/impinger stack testing method. Do use dilution sampling
- Integrate multiple gas/particle measurements with a single source test
- Ensure comparability between emission testing and ambient sampling methods
- Establish region-specific source profiles and emission factor data bases

Conclusions

- Resources used for certification and compliance tests would yield more useful results if they were directed toward more real-world emission testing
- A variety of modern emission characterization methods exist that can practically obtain real-world emission factors, profiles, and activity levels for emission inventories
- Source-specific multi-pollutant profiles and emission rates can improve air quality management practices and address multiple effects

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