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RESEARCH AND DEVELOPMENT HIGHLIGHTS:

MOBILE SENSORS AND APPLICATIONS FOR AIR POLLUTANTS

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NOTATION

(This list includes acronyms and abbreviations used in this report and the companion master table that summarizes sensor information from the literature reviewed; these notations include abbreviations used to streamline those summaries. Selected acronyms and abbreviations that are only used in limited tables are defined within those tables.)

ac	acute
ACGIH	American Conference of Governmental Industrial Hygienists
AEGL	acute exposure guideline level (National Research Council)
AFC	automated fare collection
Ag	silver
AI	ambient intelligence
a-IGZO	amorphous indium gallium zinc oxide
AIHA	American Industrial Hygiene Association
AL	action level
Al	aluminum
Al_2O_3	aluminum oxide
Alg/Mod	algorithm/modeling
ANL	Argonne National Laboratory
API	application programming interface
app	application
AQI	Air Quality Index
AR	augmented reality
As	arsenic
A/SR	activity/speech recognition
ATSDR	Agency for Toxic Substances and Disease Registry
Au	gold
avg	average
AVS	automated voltammetric system
AZO	aluminum-doped zinc oxide
BaP	benzo[a]pyrene
BC	black carbon
BTEX	benzene, toluene, ethylbenzene, xylene(s)
BTX	benzene, toluene, xylene(s)
C	ceiling (OSHA PEL value)
ºC	degree(s) centigrade (Celsius)
C8-MPN	n-octanethiolate-monolayer-protected gold nanoparticle(s)
C8-PBP	Pt_2Cl_4(1,3-butadiene)(pyridine)$_2$
CA	context awareness
CAA	Clean Air Act
CAAQS	California Ambient Air Quality Standards (California EPA)
CAFO	concentrated animal feeding operation
CalEPA	California Environmental Protection Agency
CAS RN	Chemical Abstracts Service Registry Number
CEAS	cavity enhanced absorption spectroscopy
CEGL	continuous exposure guideline level(s)
CEL	continuous exposure limit
CEMS	continuous emissions monitoring system(s)

NOTATION *(Cont'd.)*

CH_4	methane
C_2H_2	acetylene
C_2H_4	ethylene
C_4H_6	1,3-butadiene
C_6H_6	benzene
CH_2O	formaldehyde
C_2H_4O	acetaldehyde
C_3H_4O	acrolein
chr	chronic
Cl_2	chlorine
cm	centimeter(s)
cm^3	cubic centimeter(s)
CNT	carbon nanotube(s)
CO	carbon monoxide
CO_2	carbon dioxide
$COCl_2$	cobalt(II) chloride
concn	concentration
COSPEC	correlation spectroscopy
CPB	cell phone-based
Cr	chromium
Cr(VI)	hexavalent chromium
CSA	camphor sulfonic acid
CTL	cataluminescence
Cu	copper
CVD	chemical vapor deposition
1-D	one-dimensional
3-D	three-dimensional
d	day(s)
DAQ	data acquisition
DARPA	Defense Advanced Research Projects Agency
DB	data broadcasting
dBm	decibel-milliwatt
DC	direct current
DCE	dichloroethylene
D/DM	database/data mining
DDP	distributed data processing
DFB	distributed feedback (laser)
DHHS	U.S. Department of Health and Human Services
DHS	U.S. Department of Homeland Security
DIY(er[s])	do-it-yourself(er[s])
DNA	deoxyribonucleic acid
DNT	dinitrotoluene
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRIFT	diffuse reflectance infrared Fourier transform (spectroscopy)
DTRA	Defense Threat Reduction Agency

NOTATION *(Cont'd.)*

E. coli	*Escherichia coli*
EA	exposure assessment
EEGL	emergency exposure guidance level
EEL	emergency exposure limit
EIS	embedded/integrated sensor
e-nose	electronic nose
EPA	U.S. Environmental Protection Agency
ERPG	emergency response planning guideline
ET-O	economic trade-offs
eV	electron volt(s)
EVS	Environmental Science Division (DOE/Argonne)
FAA	Federal Aviation Administration
FBAR	(thin-)film bulk acoustic resonator
FDMS	filter dynamics measurement system
FEHWCVD	field-enhanced hot wire chemical vapor deposition
FID	flame ionization detector
F/S-PSU	fixed/semi-portable sensor unit
ft	foot (feet)
FTIR	Fourier transform infrared spectroscopy
Ga	gallium
GaN	gallium nitride
GC	gas chromatograph(y)
GF	cyclosarin
GHG	greenhouse gas
GPRS	general packet radio service
GPS	global positioning system
GSM	global system for mobile communications
H_2	hydrogen
HAP	hazardous air pollutant(s)
HBCD(s)	hexabromocyclododecane(s)
HC	hydrocarbon(s)
HCl	hydrogen chloride, or hydrochloric acid
HCN	hydrogen cyanide
HDI	hexamethylene diisocyanate
HF	hydrogen fluoride
Hg	mercury
HI	hazard index
hr	hour(s)
H_2S	hydrogen sulfide
H_2SO_4	hydrogen sulfate, sulfuric acid
HWCVD	hot wire chemical vapor deposition
HWG	hollow waveguide
Hz	hertz
ICT	information and communication technology(ies)
i.d.	internal diameter

NOTATION *(Cont'd.)*

ID	identifier
IDE	interdigitated electrode
IDLH	immediately dangerous to life or health (NIOSH)
IDT	interdigitated transducer
IGZO	indium gallium zinc oxide (also $InGaZnO_4$)
in.	inch(es)
In_2O_3	indium oxide
IOM	Institute of Medicine
IP	ionization potential
IR	infrared
IRIS	integrated risk information system (EPA)
ITO	indium-tin oxide
IUR	inhalation unit risk (EPA)
JS	Java script
K	Kelvin
keV	kiloelectronvolt(s)
kg	kilogram(s)
kHz	kilohertz
km	kilometer(s)
kV	kilovolt(s)
LA	location awareness
La-Sr-FeO_3	lanthanum-strontium-iron oxide
LB	Langmuir-Blodgett
lb	pound(s)
LCD	liquid crystal display
LDA	linear discriminant analysis
LDL	lower detection limit
LED	light-emitting diode
LEL	lower explosive limit
LIBS	laser-induced breakdown spectroscopy
LIDAR	light detection and ranging
LPAS	laser photoacoustic spectroscopy
LPG	liquefied petroleum gas
m	meter(s)
m^3	cubic meter(s)
mA	milliampere(s)
max	maximum
MEG	military exposure guideline (DoD)
MEK	methyl ethyl ketone
MEMS	microeletromechanical system(s)
mg	milligram(s)
mg/m^3	milligram(s) per cubic meter (air)
MgO	magnesium oxide
µg	microgram(s)
$µg/m^3$	microgram(s) per cubic meter (air)

NOTATION *(Cont'd.)*

µm	micron(s)
µs	microsecond(s)
MIM	metal-insulator-metal
min	minute(s)
MIR	mid-infrared (spectroscopy)
mL	milliliter(s)
MLIAS	multiple-line integrated absorption spectroscopy
mm	millimeter(s)
Mn	manganese
mo	month(s)
MoO_3	molybdenum trioxide
MOS	metal oxide semiconductor(s)
MoS	mobile sensing
MPa	megapascal
MRL	minimal risk level (ATSDR)
MS:MMP	mountable sensor: micro- and miniature-scale platform
M-SS	multi-sensor system
mW	milliwatt(s)
MW	molecular weight
MWCNT	multi-walled carbon nanotube(s)
N	nitrogen atom (nitride)
N_2	nitrogen gas
NAAQS	National Ambient Air Quality Standard(s) (EPA, CAA)
NASA	National Aeronautics and Space Administration
NATA	National-Scale Air Toxics Assessment (EPA)
NEMA	National Electrical Manufacturers Association
NH_2	amine
NH_3	ammonia
NH_4	ammonium
Ni	nickel
Ni-Cr	nickel-chromium
NIH	National Institutes of Health
NiMH	nickel-metal hydride (battery)
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
nm	nanometer(s)
NO	nitric oxide
N_2O	nitrous oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxide(s)
NRC	National Research Council
NSF	National Science Foundation
NST	nanoscale technology
O_2	oxygen
O_3	ozone
OEHHA	Office of Environmental Health Hazard Assessment (CalEPA)
OEL	occupational exposure level

NOTATION *(Cont'd.)*

OP	organophosphate(s)
OPC	optical particle counters
ORD	Office of Research and Development (EPA)
OSHA	U.S. Occupational Safety and Health Administration
PAAEMA	poly(2-(acetoacetoxy)ethyl methacrylate)
PAC	protective action criteria (DOE)
PAH	polycyclic aromatic hydrocarbon(s)
PANi	polyaniline
Pb	lead
PBDE	polybrominated diphenyl ether(s)
PC	personal computer
PCA	principal component analysis
PCB	polychlorinated biphenyl(s)
PCP	pentachlorophenol(s)
P/CS	participatory/citizen sensing
Pd	palladium
PDA	personal digital assistant
PDMS	polydimethylsiloxane
PEGL	permissible exposure guidance level (NRC/DoD)
PEL	permissible exposure limit (OSHA)
PFC	perfluorocarbon(s)
pg	picogram(s)
PH_3	phosphine
PID	photoionization detector
p-i-n	diode with semiconductor stack of p-type, intrinsic, and n-type materials
p-IUR	provisional inhalation unit risk (EPA)
PM	particulate matter
PM_1	PM with an aerodynamic diameter of a nominal 1 micron or less
$PM_{2.5}$	PM with an aerodynamic diameter of a nominal 2.5 microns or less
PM_{10}	PM with an aerodynamic diameter of a nominal 10 microns or less
PMTFPS	poly[methyl(3,3,3-trifluoropropyl)siloxane]
PO	project officer
PoANIS	poly(o-anisidine)
PPB	photonic pass band
ppb	part(s) per billion
PPEGL	permissible public exposure guidance level (NRC/DoD)
ppm	part(s) per million
PPRTV	provisional peer reviewed toxicity value (EPA)
ppt	part(s) per trillion
PPy	polypyrrole
p-RfC	provisional reference concentration (EPA)
PS	prediction service
Pt	platinum
$PtCl_2$	platinum(II) chloride
PTR-LIT	photon-transfer reaction linear ion trap
QCL	quantum cascade laser(s)
QCM	quartz crystal microbalance

NOTATION *(Cont'd.)*

R&D	research and development
RBC	risk-based concentration (EPA)
REL	recommended exposure limit (NIOSH)
REL	reference exposure level (CalEPA)
resp	response (time)
RfC	reference concentration (EPA)
RFID	radio frequency identification
RS	radar system
RSC	risk-specific concentration (EPA)
RSL	Regional screening level(s) (EPA Regions)
RS/M	remote sensor/monitoring
RSS	received signal strength
RTR	reel-to-reel
sec	second(s)
SAW	surface acoustic wave
SC	sensor calibration
SD	secure digital
SEM	scanning electron microscope
SF	slope factor
Si	silicon
SMAC	spacecraft maximum allowable concentration (NRC/NASA)
SN/C	social networking/computing
SnO_2	tin dioxide
SnO_x	tin oxide
SO_2	sulfur dioxide
SO_4	sulfate
SO_x	sulfur oxide(s)
SOA	service-oriented architecture
SNS	social networking services
SPME	solid phase micro-extraction (fiber)
STEL	short-term exposure limit (OSHA)
subc	subchronic
SVOC	semivolatile organic compound(s)
SWCNT	single-walled carbon nanotube(s)
SWV	square wave voltammetry
TCE	trichloroethylene
TD	thermal desorption
TD-FTIR-HWG	thermal desorption Fourier transform infrared hollow waveguide
TDI	2,4-toluene diisocyanate
TDLAS	tunable diode laser absorption spectroscopy
temp	temperature
TEOM	tapered element oscillating microbalance
Ti	titanium
TiO_2	titanium dioxide
TLV	threshold limit value (ACGIH)
TNT	trinitrotoluene
TWA	time-weighted average

NOTATION *(Cont'd.)*

ubicomp	ubiquitous computing
UEL	upper explosive limit
UF	uncertainty factor
UFFI	urea-formaldehyde foam insulation
UFP	ultrafine particle(s)
UPSIDE	unconventional processing of signals for intelligent data exploitation
UR	unit risk (EPA)
USB	Universal Serial Bus
USDA	U.S. Department of Agriculture
UTL	upper tolerance limit
UV	ultraviolet
UV abs	ultraviolet absorption
UV vis	ultraviolet visible
UVNS	ultraviolet non-solarizing (e.g., optical fiber)
V	volt(s)
VA	volt-ampere(s)
VAC	volt(s) alternating current
VDC	volt(s) direct current
VMU	vehicle-mounted unit
VOC	volatile organic compound(s)
VP	vapor pressure
VR	virtual reality
VR/S	virtual reality/sensing
VS	visual sensing
W	watt(s)
W-B	Web-based
wk	week(s)
WO_3	tungsten trioxide
WSN	wireless sensor network
wt %	weight percent
XML5	Extensible Markup Language 5
XRF	X-ray fluorescence
yr	year(s)
YSZ	yttria-stabilized zirconia
ZnO	zinc oxide
ZrO_2	zirconium dioxide

CONVERSION TABLE 1 Units of Area, Length, Mass, and Volume

Multiply	By	To Obtain
English/Metric Equivalents		
acre (ac)	4,047	square meter (m^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3) *(= 10^6 cm^3)*
foot (ft)	0.3048	meter (m)
inch (in.)	2.540	centimeter (cm)
inch (in.)	25,400	micron (µm, or micrometer)
mile (mi)	1.609	kilometer (km)
ounce (oz.)	28.35	gram (g)
pound (lb)	0.4536	kilogram (kg)
short ton (tons)	907.2	kilogram (kg)
short ton (tons)	0.9072	metric ton (t)
square foot (ft^2)	0.09290	square meter (m^2)
square yard (yd^2)	0.8361	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
yard (yd)	0.9144	meter (m)
Metric/English Equivalents		
centimeter (cm)	0.3937	inch (in.)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
gram (g)	0.03527	ounce (oz.)
kilogram (kg)	2.205	pound (lb)
kilogram (kg)	0.001102	short ton (tons)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
micron (µm, or micrometer)	0.00003937	inches (in.)
milliliter (mL)	0.0002642	gallon (gal)
square kilometer (km^2)	0.3861	square mile (mi^2)
square meter (m^2)	0.0002471	acre (ac) *(1 ac = 43,560 ft^2)*
square meter (m^2)	10.76	square foot (ft^2)
square meter (m^2)	1.196	square yard (yd^2)

CONVERSION TABLE 2 Gas Concentration Equivalents in Air[a]

Pollutant	Concentration		
	ppm	*mg/m³*	*µg/m³*
Acetaldehyde	1	1.801	1,801
Acrolein	1	2.291	2,291
Ammonia	1	0.696	696
Benzene	1	3.193	3,193
1,3-Butadiene	1	2.211	2,211
Carbon monoxide	1	1.145	1,145
Formaldehyde	1	1.227	1,227
Hydrogen sulfide	1	1.393	1,393
Methane	1	0.656	656
Nitrogen dioxide	1	1.880	1,880
Ozone	1	1.962	1,962
Sulfur dioxide	1	2.619	2,619

[a] Values are at 25°C (or 298.15 K), and 1 atmospheric pressure (or 1013.25 millibars).

This relationship can be expressed as: mg/m^3 = (molecular weight/24.5) × ppm.

For other temperatures and pressures, the following equation can be used:

$$\text{concentration in mg/m}^3 = \frac{\text{pressure (millibar)} \times \text{molecular weight (g/mole)}}{83.144621 \times \text{temperature (K)}} \times \text{concentration in ppm}$$

(Note that standard temperature and pressure (STP) conditions are 0º Celsius (273 K) rather than 25ºC. However, using standard pressure (1 atm) and a reference temperature of 25ºC is commonly accepted practice in the air monitoring community.)

EXECUTIVE SUMMARY

ES.1 STUDY CONTEXT

The public has long been interested in understanding what pollutants are in the air they breathe so they can best protect their environmental health and welfare. The current air quality monitoring network consists of discrete stations with expensive equipment operated by state and local agencies. Because both the number of stations and the pollutants they measure are limited, location-specific data are relatively sparse. Thus, actual concentrations to which individuals are exposed each day are generally unknown. Significant advances in mobile sensors and software applications offer unique opportunities for citizen-based sensing that could ultimately help fill these gaps. The Innovation Team of the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) is leading an initiative to understand the state of progress for mobile sensors and applications for air pollutants. Key objectives are to identify opportunities for strengthening current monitoring programs and to catalyze and facilitate community-based monitoring.

ES.2 APPROACH

Literature Review

A review of selected literature was conducted to support the EPA initiative for next-generation air monitoring. This review began in late 2011 and primarily focused on the period from 2010 to early 2012. More than 1,000 information sources were evaluated in pursuing relevant data, including patent database entries, journal articles, abstracts and papers in conference and workshop proceedings, meeting presentations available online, and organizational web pages. The latter were particularly useful as gateways to recent sensor and app developments, as were compilations from recent meetings. Nearly half the resources reviewed contained relevant information, notably for technologies, sensing techniques, and architectures and infrastructures.

Study Pollutants

More than 100 measurands were identified from the literature review. To further focus the assessment, 14 pollutants were selected for targeted study. This set was determined based on an evaluation of the most recent National-Scale Air Toxics Assessment (NATA) and inputs from EPA Program and Regional Offices that reflected community interests. Consisting of a dozen gases plus particulate matter (PM) and lead (Pb), this set reflects several key emission sources and pollutants of interest for fenceline communities, children, and personal health protection.

- Six criteria pollutants: carbon monoxide (CO), lead, ozone (O_3), nitrogen dioxide (NO_2), PM, and sulfur dioxide (SO_2).
- Five hazardous air pollutants (HAPs): acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde.
- Three indicator pollutants: ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4).

Target Concentrations

Two types of concentrations were compiled for the study pollutants, to serve as practical targets for comparing reported sensor detection levels. The first category consists of health-based

benchmarks that have been established by EPA and other organizations to protect human health under various conditions, ranging from one-time (acute) to daily (chronic) exposures. These benchmarks can be organized into three exposure situations or conditions:

- Emergency response guides established for the general public (including sensitive subgroups such as children) for exposures lasting up to one day, commonly 8 hours or less.

- Ambient air quality standards and guidelines established for the general public, as above, for continuous exposures that extend over a lifetime.

- Occupational standards and guidelines established for the workforce: Noncontinuous exposures (e.g., discrete work shifts with evening and weekend breaks) that extend over an adult working life (decades).

The second set of comparison concentrations consists of example pollutant concentrations that have been reported for various settings and time intervals. The settings cover both indoor to outdoor air, including for specific conditions such as freeway tunnel exits and forest fires. The time intervals reflected include discrete measurements and annual averages. Together these established exposure benchmarks and example reported concentrations provide anchors for assessing sensor detection capabilities, toward identifying related gaps and opportunities to inform targeted research investments.

ES.3 FINDINGS

Selected insights from the review of recent literature for mobile sensors and apps are highlighted below.

Sensing Techniques and Technology

- The sensing techniques reflected in the literature reviewed can be grouped into three categories: chemistry, spectroscopy, and ionization. These categories are listed in order of their prominence, with chemistry and spectroscopy dominating the research and development highlighted for mobile sensors.

- Nanotechnology, which is grouped within the chemistry technique, is a major research theme. From a limited follow-on check of subsequent literature extending into 2013, this trend appears to be sustained. Advances include development of nanomaterials of different compositions, shapes, and sizes that can function as stand-alone sensing materials or can be added to other sensor components (e.g., films or electrodes) to improve sensitivity, selectivity, and sensor response time.

- Relatively few studies were found to reflect ionization techniques such as mass spectrometry and gas chromatography systems with photoionization and flame ionization detectors in mobile sensors or systems.

Pollutant Coverage

- Mobile sensors identified from both the targeted (study set) and broader literature review appear to emphasize gases, notably the criteria pollutants.

- Chemical-specific particle sensors appear to constitute a current gap. No research sensors were found for Pb in air; laser-induced breakdown spectroscopy (LIBS) may represent a potential opportunity area for this pollutant.

- The relatively few PM sensors identified are expensive, and they are generally mass-based rather than chemical species-specific. Microelectromechanical systems (MEMS) may represent a potential opportunity area for a broadly affordable, mobile PM sensor. Nanoelectromechanical systems are also being pursued.

- Novel systems that use commercial sensors (or commercial systems alone) are prevalent for a number of the study pollutants, including several criteria pollutants. This finding is not unexpected given the long-standing regulatory status of those pollutants.

- Although research sensors or novel systems with commercial sensors were identified for several of the study HAPs, sensors for acrolein and 1,3-butadiene appear limited. Opportunities exist for developing lower-cost mobile sensors for these (and other) pollutants, with general interest in such pollutants potentially increasing in the near term due to emerging emission sources such as natural gas (notably shale gas) development and biomass conversion facilities.

- Lower-cost sensors for benzene also represent an important area for research and development, to fill this sensor gap and address practical information needs.

- Sensor systems that address multiple pollutants have commonly been modular, with individual plug-ins to measure one pollutant at a time. Sensor arrays integrated into mobile systems represent an expanding opportunity area for all-in-one multipollutant sensing.

Detection Levels

In addition to the limitations for particle sensors indicated above, pollutant-specific insights from the comparison of detection capabilities to target concentrations for the study gases follow.

- Current reported detection capabilities may not be sufficient to address the suite of health-based benchmarks and example concentrations identified for the range of settings and conditions considered in this evaluation.

- The detectability of illustrative values identified in this review is unknown for several study pollutants, including acrolein. In part, this situation reflects a reporting issue, because the detection range and/or maximum concentration tested is often missing from the research literature, notably for contaminants beyond the gaseous criteria pollutants. (The reported capability of a sensor to detect a relatively low concentration does not necessarily translate to the same ability at a higher concentration, and vice versa.) In addition, research results commonly reflect controlled conditions that may not directly translate to field applications. More complete reporting of research sensor detection ranges and field validation of these capabilities would improve detectability determinations.

- In terms of standards and guidelines, the reported sensor information indicates that most health-based concentrations are potentially detectable by various research sensors or novel systems that use commercial sensors, particularly for the criteria pollutants. However, the relatively low (protective) guideline concentrations for continuous lifetime exposures for certain HAPs may not be readily detected (including for acrolein; note similar limitations apply to commercial sensors for this compound).

- Regarding detection limits, it is important for sensors to be able to measure environmentally relevant pollutant concentrations, recognizing the range of concentrations to which people are exposed under various circumstances. For example, sensors would need to measure background levels in evaluating the protectiveness of routine or chronic exposures or in assessing baseline conditions for natural settings. Approaches to increase sensitivity such as via nanomaterials in films, coatings, or other reactive surfaces of chemical sensors represent an ongoing opportunity.

- Relatively simple spectroscopic approaches may be well suited for situations in which the detection level needed is relatively high, such as during emergency or episodic high-pollution events, including wildfires, or in urban areas with chronic high emissions from traffic or industrial facilities.

Architecture/Infrastructure

- General architecture: Portable, handheld and vehicle-mounted architectures are relatively common; less common are wearable sensors. Sensor systems that leverage existing infrastructure components (such as fixed and mobile elements of transportation systems from the local to the national level) represent an opportunity for continued advancements. (To illustrate, the City of San Francisco outlined an initiative that involves attaching sensors to fixed infrastructure to assess exposures to pollutants from vehicle exhaust, while cross-country trucks outfitted with simple sensors are collecting data along their routes.) With regard to whether such initiatives would be broadly sustainable, issues include who would pay and what advantages would be conferred.

- Devices: Sensor components are commonly integrated with mobile phones, tapping Bluetooth/wireless networks. The trend toward increased use of other devices such as tablets represents a further opportunity for mobile sensors and systems.

- Supporting infrastructure: Traditional field monitors are commonly supported by substantial infrastructure to assure environmental controls. Reducing and eliminating such housing and other support infrastructure while assuring reliable, automated operation under a range of environmental conditions (with humidity and other interferents) represents a continuing opportunity area for mobile sensors.

- Size and mobility: Mindful of the trade-off between size and sensitivity (which is affected by the detection area), the trend is toward increasingly miniature sensors from centimeter- to millimeter-scale and below. Spectroscopic and ionization sensors are currently limited to a few cm, even with mirrors in cell pathways. Where larger sensors are warranted, although they may not be suited for cell phones or wearable accessories (e.g., watch or clip), they can be mounted to vehicles or other features/infrastructure to support monitoring at the neighborhood level to community and metropolitan scales.

- Sensitivity: Research to improve sensitivity includes the use of nanomaterial coatings to increase reactive surface areas for chemical sensors. For spectroscopic and ionization sensors, measures to increase sensitivity (i.e., lower the detection limits) include use of pre-concentrators and tailored light sources as well as optimized light path designs.

- Selectivity and specificity: Chemical-specific measurement is a common issue, notably in variable field conditions with multiple pollutants and interferents (e.g., high relative humidity). Improvements being pursued in recent research include filtration mechanisms and highly selective sorption media, with multiple-sensor arrays or electronic noses also representing opportunities in this area.

- Response time: A number of studies are focusing on reducing the sensor response time, both to reduce power consumption and to facilitate real-time measurements, which are particularly important in dynamic environments. While nanomaterials are being used to reduce response times for chemical sensors (by increasing reactive surface areas), this increased reactivity can translate to a longer recovery time or can limit the sensor to a single use. Similarly, although pre-concentrators can reduce response times for spectroscopic and ionization sensors, the lag time required to accumulate a concentration of pollutant sufficient to initiate the rapid response phase remains an issue. Thus, improving response time represents an ongoing opportunity area for mobile sensor research.

- Power consumption: Power requirements can be reduced by implementing a periodic sampling approach, e.g., rather than sampling continuously, taking measurements only when the sensor is in motion or at targeted times of the day when pollutants or concentrations are expected to be changing or to be relatively high. Energy can also be conserved by conducting passive versus active sampling campaigns. An evaluation of novel detection techniques related to energy conservation indicates that reducing operational temperatures, warm-up periods, and sampling times can reduce power consumption as well as associated maintenance needs (and costs).

- Cost: Lower-cost mobile sensors are commonly qualitative or semiquantitative, such as those relying on colorimetric techniques to indicate the presence of a pollutant or class but not a specific concentration. More expensive sensor systems (such as those with combined fixed and mobile architectures) may be indicated when data quality needs are high (e.g., for enforcement purposes). Reducing system costs while maintaining high-quality data represents an ongoing opportunity area.

- Energy sources: Novel energy sources (including human) and optimized sampling regimens (e.g., targeted spatiotemporal campaigns guided by pollutant behaviors and fate) offer opportunities for lower power use and more broadly affordable systems.

- Accuracy, precision, reliability and durability: Accurate and precise measurements under dynamic field conditions across a wide variety of climatic and meteorological conditions represent a continuing opportunity area for lower-cost mobile sensors. Extensive sensor networks and saturation-sampling approaches (via concurrent deployment of a large number of sensors) can facilitate comparisons across multiple readings to assess sensor drift and link appropriate calibration and other maintenance needs. Combined fixed and mobile sensor systems and advances such as Web 4.0/Internet of things represents opportunities for autocalibration. Opportunity areas

for improved durability include reducing replacement or tuning needs for sensing media and developing less expensive, reliable environmental controls (e.g., to address such factors as humidity and other interferents).

Data Quality, Sharing, Management, and Analysis

- Algorithms and approaches for consistent data processing, quality assurance and control, and data scrubbing (an error correction technique), transformation, integration, visualization, and analysis represent active research areas.

- Fit for purpose is a key consideration for the type and quality of sensor data. With anticipated needs ranging from compliance assessment and enforcement to establishing environmental baselines and informing personal health decisions, the nature of the data quality requirements differ across applications. The fit-for-purpose design of mobile sensors and associated data systems represents an evolving opportunity area, to align the technologies and software infrastructure to user needs across a variety of existing programs and initiatives.

- Advances such as cloud computing and visualization tools are facilitating the development and implementation of extensive networks for data upload, storage, integration, display, and evaluation over time, including the ability to conduct comparisons across readings. Tools highlighted in the research literature reviewed include CaliBree (a self-calibration system for mobile sensor networks), Quintet (share sensing resources among sensor devices), and Halo (facilitate the rendezvous of mobile sensors with static infrastructure).

- Core protocols and platforms that underlie data collection, integration, sharing, storage, and other data management systems represent ongoing opportunity areas. Frameworks adaptable to multiple data sources, types, and uses (from facility compliance reporting and enforcement to establishing environmental baselines and personal health management) are being pursued to help strengthen the sharing, integration, and quality assurance efforts for massive data sets.

- Privacy is a key concern related to citizen sensing. Tools for stripping data of identifiers and other anonymizing techniques represent active research areas.

- Increasing automation and interconnectivity offer potential opportunities for increased data coverage and integrated analyses, including collective autocalibration and self repair (e.g., via the Internet of Things/Web 4.0, which has been described as an entire web as a single operating system with information flowing from any point to any other).

Mobile Applications

- Only a limited number of mobile apps have been established for air quality, so this area represents a key opportunity for research and development.

- Pollutants addressed by the existing apps are limited, reflecting the general lack of data for pollutants other than the standard criteria set. Spatial coverage is also relatively sparse per existing data limitations. Data availability often lags behind the collection period. Recognizing the underlying limitations, development needs for mobile apps

include addressing a much larger set of pollutants and providing real-time, high-resolution spatial coverage across community, neighborhood, and individual scales.

- Computing advances indicated above provide opportunities for enhancing mobile apps to accommodate real-time data upload, integration, distribution, display, and interpretation. Providing context for that interpretation would increase the overall usefulness of these apps. Considerations include links to existing standards and guidelines as well as to previous data for that setting and similar settings (ranges and averages), in addition to local, regional, and national trends. Beyond links to comparison values, explanations would also be important (such as the exposure duration addressed by a given standard or guideline, or the time frame represented by an historical average).

- Indicators such as smart tags, alarms, and other notifications or warning features triggered by measured pollutant levels also represent a research opportunity area for mobile apps. A number of questions underlie this development area, including who would define the warnings, on what basis, and for which pollutants.

- User interface design and programming components are active research areas toward developing reliable interfaces that are stable across devices, that can accommodate the rapid evolution of mobile phones and tablets, and that can be adapted to individual user preferences.

Leveraging

- Do-it-yourselfers (DIYers) illustrate the evolving landscape of opportunity for citizen participation in environmental monitoring.

- Leveraging the many organizations supporting related research and citizen capital represents an opportunity for significantly increasing the characterization of air quality nationwide. Collateral programmatic benefits including baselining for climate change and adaptation planning, as well as exposure monitoring for environmental health initiatives.

- Extending beyond integrated arrays for multipollutant sensing, links to biosensors (e.g., per personalized medicine applications) combined with insights from sensors for other measurands offer opportunities for multipurpose sensing systems.

- Effective and efficient data and knowledge management approaches are being pursued, with an eye toward common standards, infrastructure, and software for reporting, accessing, sharing, storing/archiving, and maintaining data, considering both raw and transformed data and topical syntheses and reports.

- Opportunity areas for mobile apps include providing high-resolution spatial coverage (including at community and local scales) with displays for a full suite of pollutants.

These and other insights from recent research highlighted in this report and the companion summary table are offered to help frame the EPA ORD roadmap for next-generation air monitoring.

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1 INTRODUCTION

This report was prepared as part of the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) initiative on mobile sensors and apps for air pollutants. A key goal is to enhance community awareness and citizen involvement in environmental monitoring and health protection programs. Additional goals are to facilitate compliance and enforcement activities to improve and maintain air quality. The need underlying this initiative is summarized in Section 1.1, the purpose and scope of this report are described in Section 1.2, and the report organization is outlined in Section 1.3.

1.1 TRADITIONAL AIR POLLUTION MONITORING AND CURRENT OPPORTUNITY

A substantial number of air pollutants have been linked with adverse health effects, including those associated with releases ranging from vehicle exhaust to industrial processes. Understanding pollutant exposures is key to developing and implementing effective health protection programs. The current standard system for monitoring air pollutants consists of discrete stations with large, fixed sensors that are too expensive to be feasible for citizen-based monitoring. These standard systems focus on a limited set of pollutants, in particular the six criteria pollutants for which National Ambient Air Quality Standards (NAAQS) have been established. Because both the number of these stations and the pollutants they measure are limited, spatial and chemical coverage is relatively sparse.

For this reason, the pollutant levels to which individuals and communities are exposed is largely unknown. Human exposures are dynamic and local variations are large because they are affected by personal behaviors and activity levels as well as proximity to sources, the nature of airborne releases, local meteorology, land use/land cover, and other factors. Thus, measurements from regional metropolitan stations are unable to represent exposure levels at the local scale. Pollutant concentrations at the neighborhood and individual levels constitute key information needed to advance the development of practical health protection measures.

Recent advances in mobile sensing and related software applications (apps) provide a valuable opportunity for addressing this need. Emerging detection technologies and techniques hold significant promise for future cheap, mobile sensors that could fill in a network of air quality data across the country. Concurrent developments in sensor architectures and information/ communication technologies (ICT), including apps, translate to opportunities for integrated systems such as distributed sensor networks that can complement the existing monitoring programs and facilitate community involvement.

1.2 PURPOSE AND SCOPE OF THIS REPORT

The purpose of this report is to provide an overview of recent research relevant to mobile sensing of air pollution. The objective is to identify gaps as well as opportunities, to guide investments toward making low-cost mobile sensors available to a wide variety of prospective users, including individual citizens.

The science and technology literature on sensing technologies and techniques for air pollutants is vast and growing. Because the purpose of this review is to indicate recent trends for mobile sensors, rather than provide a comprehensive evaluation of current literature, the scope was focused by several key considerations, as follows.

- *Size*: Small, portable devices are the primary target. In some cases, larger sensors are included to consider technologies that might present an opportunity for development of more mobile devices in the future.

- *Development phase*: Sensors in an early stage of research and development to those nearing deployment are the main focus. Commercial sensors incorporated into novel sensor systems are also included.

- *Time frame*: The main emphasis is on literature information from 2010 to early 2012. Some earlier publications are also included, for trends and other relevant context.

- *Pollutant*: An illustrative set was selected to guide the more detailed literature search.

The scope also includes practical context for assessing sensor detection capabilities. This context is provided by two types of concentration values:

- *Exposure benchmarks*: Many agencies have established standards and guidelines for chemicals in air as part of implementing specific health and safety programs. These values range from emergency response guidelines to workplace standards and reference concentrations considered safe for the general public over a lifetime of exposures. Referred to as exposure benchmarks, these values serve as points of comparison for assessing detection capabilities and opportunities for *situation-specific* applications.

- *Measured concentrations*: A number of pollutants have been measured in a variety of settings over different time periods. These include indoor and outdoor air, in urban and rural areas that include settings where pollutants are markedly elevated, such as fires and busy freeways. Some data reflect snapshot measurements while others reflect systematic, long-term sampling programs. These illustrative concentrations provide practical context for *setting-specific* applications.

Finally, sensing technologies and techniques are a key emphasis of this report. Information on architectures and infrastructures for mobile sensors, including associated software, are also included. Additional details are presented in supporting tables compiled separately from this report (Raymond et al. 2013).

1.3 REPORT ORGANIZATION

This report is organized as follows:

- Chapter 2 summarizes the approach for conducting the literature search, developing the candidate set of pollutants, and organizing the data.

- Chapter 3 provides results of the literature search, including the pollutant sets, main categories of sensor technologies/techniques, and highlights of associated architectures/infrastructures and apps. Also included are figures (graphical arrays) that compare reported sensor detection levels to exposure benchmarks and example measured concentrations.

- Chapter 4 describes gaps and opportunities for mobile sensors and apps for air pollutants.
- Chapter 5 gives a brief summary that highlights key findings of this report.
- Chapter 6 acknowledges contributors to this report.
- Chapter 7 lists selected information resources reviewed for this report.
- Appendix A offers additional information about the literature search.
- Appendix B presents an overview of exposure benchmarks and information sources.
- Appendix C illustrates the role of environmental fate for air pollutants in air, to illustrate the type of setting-specific information (such as relative humidity) and associated fate products that can be used guide the development of integrated sensor systems.
- Appendix D presents example concentrations of selected pollutants, organized in tables designed to support data compilations for specific locations or regions of interest.
- Appendix E provides supporting details about the sensors in Chapter 3 graphical arrays.
- Appendix F briefly describes the sensing technologies and techniques reflected in this report.
- Appendix G presents an evaluation of selected air quality apps.

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2 APPROACH

The approach used to conduct the literature search is outlined in Section 2.1, development of the candidate pollutant set is described in Section 2.2, and the general process for organizing the information retrieved is summarized in Section 2.3. The general approach for searching and reviewing the literature is illustrated in Figure 2-1, and supporting details are presented in Appendix A.

2.1 LITERATURE SEARCH

Recognizing the extent of science and technology research relevant to mobile sensors and apps, the purpose of this literature search is to identify general trends rather than provide a comprehensive review. For this reason, the search focused primarily on information available online. Information resources include:

- Journal articles, research reports, and other technical publications;
- Conference proceedings, presentations, and other meeting highlights;
- Patent databases, application and granting summaries;
- Organizational websites, including Federal, state, and international, agencies; academic, national laboratory, and other research organizations; industry; and communities.

This search was conducted in two phases. The first phase was initiated in fall 2011 and involved a broad search targeting abstracts and summaries, not limited to specific chemicals. Its objectives were three-fold. First, an open approach would limit inadvertent omissions of key technologies or techniques and avoid skewing suggested trends. Second, capturing a variety of sensed parameters could offer additional insights into promising detection techniques for related pollutants. Third, the measurands identified in a broader search would help guide selection of the representative set of pollutants to be assessed in more detail.

The second phase of the literature search focused on a smaller set of pollutants, determined from inputs by EPA ORD, Program and Regional scientists, combined with insights from Phase I. This phase involved pursuing further details for sensing technologies/techniques, architectures/infrastructures, exposure benchmark, and illustrative concentrations in air by accessing full papers, reports, presentations, and other documentation. The information compiled included details about the size, stage of development, and cost, as well as automation and network capabilities, power requirements, response time, interferences, and other operating conditions. In some cases, additional information was obtained from the individual researchers. Most of this phase was conducted in winter to early spring 2012. Targeted follow-on searches continued through 2013.

2.2 CANDIDATE POLLUTANTS

More than 40 pollutants of interest were identified during the early framing stage of this project. These candidate pollutants reflected the following considerations:

- Criteria pollutants, i.e., those for which National Ambient Air Quality Standards (NAAQS) have been established.

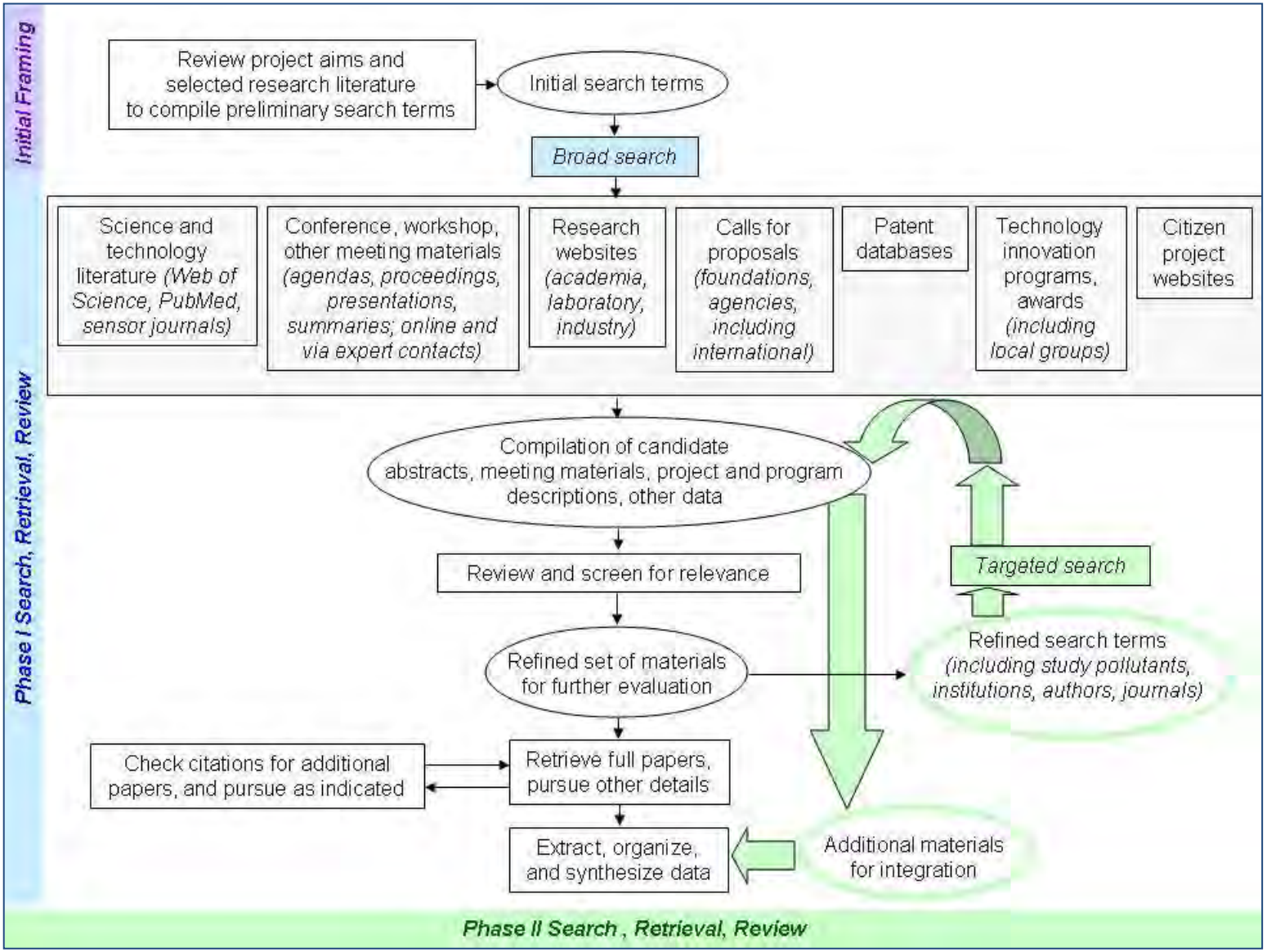

FIGURE 2-1 Literature Search Approach

- Key pollutants from the National-Scale Air Toxics Assessment (NATA) study (EPA 2011), notably those identified as risk drivers and contributors. This set includes chemicals listed as Hazardous Air Pollutants (HAPs) pursuant to the Clean Air Act Amendments of 1990 and the subset subsequently evaluated as urban air toxics.

- Pollutants of potential interest to fenceline communities.

- Selected pollutants of interest to the EPA Children's Health Program.

These candidate pollutants are summarized in Tables 2-1 through 2-4. Tables 2-2 and 2-3 offer two ways of summarizing the categories EPA used to identify key pollutants for the 2005 NATA assessment (EPA 2011), "Drivers" and 'contributors" are largely based on the magnitude of the risk estimate and the number of people affected. The two types of health effects considered are: incremental risk of getting cancer over a lifetime, and the hazard index, which represents the potential for noncancer effects (as the ratio of the exposure level to a "safe" daily level).

2.3 DATA COMPILATION

Results of the initial literature search were first compiled by information resource (e.g., patent database or Ubicomp conference proceedings) then organized by common topic. The three main topics are:

- Pollutants and other measured parameters (collectively referred to as measurands), such as temperature and relative humidity.

- Sensor technologies and techniques.

- System architecture and infrastructure approaches, and associated apps.

Two additional themes are:

- Exposure benchmarks

- Example concentrations in air.

A number of data compilations were developed and refined during the literature review process, as illustrated in the appendices. For example, Appendix A presents early tables that illustrate data extraction and summary compilations. Similarly, details underlying the compilation of exposure benchmarks are presented in Appendix B. Practical context that integrates environmental fate considerations is presented in Appendix C, to illustrate how such information can help frame the development of multi-pollutant sensors. Example outlines for compiling measurement data for specific locations or regions are presented in Appendix D. In compiling a summary of the original search results, entries were coded with identifiers (IDs) to facilitate topical sorts, e.g., by pollutant or sensing technique. The master summary table is organized alphabetically by measurand, and within that by sensor technology/technique (Raymond et al. 2013). A smaller subset table provides information for sensors considered for the graphical arrays that compare detection levels to exposure benchmarks and example concentrations in air; that table is presented in Appendix E. Results of limited additional check searches are also presented in Appendix E. These "working" tables reflect the technology/ technique groupings described in Appendix F. An overview of selected air quality apps is included in Appendix G.

TABLE 2-1 Key Pollutants from the 2005 National-Scale Air Toxics Assessment[a]

Health Risk Driver		Health Risk Contributor	
National	**Regional**	**National**	**Regional**
Acrolein	Benzene	Acetaldehyde	1,3-Dichloropropene
Formaldehyde	Chlorine	Acrylonitrile	Methylene chloride
	Diesel particulate matter (PM)	Arsenic compounds	Nickel compounds
	Hexamethylene diisocyanate (HDI)	1,3-Butadiene	
	Hydrochloric acid	Carbon tetrachloride	
	Manganese compounds	Chromium compounds	
	Naphthalene	Coke oven emissions	
	Polycyclic aromatic hydrocarbons (PAHs)	1,4-Dichlorobenzene	
	2,4-Toluene diisocyanate (TDI)	Ethylbenzene	
		Ethylene oxide	
		Tetrachloroethylene	

[a] Source: EPA (2011). Lighter font is used to indicate that the health effect characterization for the given chemical or category of chemicals is based on a noncancer effect; regular font is used to indicate that the basis is cancer risk.

TABLE 2-2 Risk Characterization Categories Used to Identify Main Pollutants[a]

Number of People Exposed *(or more)*	**Cancer Risk**			**Noncancer Hazard Index (HI)** >1.0
	≥10^{-4}	≥10^{-5}	≥10^{-6}	
25 million		National driver	National contributor	National driver
1 million		Regional driver		
10,000	Regional driver			Regional driver

TABLE 2-3 Estimated Risks and Number of People Exposed per Pollutant Category[a]

Risk Characterization Category	**National Scale**		**Regional Scale**		
	Driver	***Contributor***	***Driver***		***Contributor***
Cancer					
Risk exceeds:	10^{-5}	10^{-6}	10^{-5}	10^{-4}	10^{-6}
Number exposed (or higher):	25 million	25 million	1 million	10,000	1 million
Noncancer					
Hazard index (HI) exceeds:	1.0		1.0		
Number exposed (or higher):	25 million		10,000		

[a] Tables 2-2 and 2-3 offer two ways of summarizing the characterization categories EPA used to identify key pollutants from the 2005 NATA assessment (EPA 2011). As defined in the overview of that assessment:

- Cancer risk represents the upper-bound lifetime cancer risk (i.e., a plausible upper limit to the true probability that an individual will contract cancer over a 70-year lifetime as a result of a given hazard, such as exposure to a toxic chemical). This risk can be measured or estimated in numerical terms (e.g., one chance in a million).
- HI = sum of hazard quotients for substances that affect the same target organ or system. Because different pollutants may cause similar adverse health effects, it is often appropriate to combine hazard quotients associated with different substances to understand the potential health risks associated with aggregate exposures to multiple pollutants.

More information regarding the bases for determining drivers and contributors can be found in EPA (2011).

TABLE 2-4 Candidate Pollutants for the Review of Recent Research Sensors[a]

Air Pollutant	Children's Health	Region 6 Fenceline Communities	NATA		Criteria Pollutant (NAAQS)	EPA (2008) Detection Report
			c	*nc*		
Acetaldehyde			*N*			
Acrolein				**N**		
Acrylonitrile			*N*			
Arsenic compounds			*N*			x
Benzene		x	**R**			x
1,3-Butadiene		x	*N*			x
Carbon monoxide (CO)					x	
Carbon tetrachloride			*N*			
Chlorine				*R*		x
Chromium compounds			*N*			
1,4-Dichlorobenzene			*N*			
1,1-Dichloroethylene (1,1-DCE)		x				
1,3-Dichloropropene			*R*			
Ethylbenzene		x	*N*			x
Ethylene oxide			*N*			x
Formaldehyde			**N**			x
Hexabromocyclododecanes (HBCDs)	x					
Hexamethyl diisocyanate				*R*		
Hydrochloric acid				*R*		x
Hydrogen sulfide		x				x
Lead	x				x	
Manganese compounds		x		*R*		
Mercury	x					($HgCl_2$-Hg)
Methane		x				
Methylene chloride			*R*			
Naphthalene			**R**			
Nickel compounds			*R*			
Nitrogen oxides/dioxide (NOx/NO_2)					x	x
Ozone					x	x
Particulate matter (PM)					x	
Coke oven emissions			*N*			
Diesel PM				*R*		
Perchlorate	x					
Perfluorocarbons (PFCs)	x					
Phthalates	x					
Polybrominated diphenyl ethers (PBDEs)	x					
Polychlorinated biphenyls (PCBs)	x					x
Polycyclic aromatic hydrocarbons (PAHs)			**R**			
Sulfur oxides/dioxide (SOx/SO_2)					x	x
Tetrachloroethylene			*N*			
Trichloroethylene		x				
Toluene						x
2,4-Toluene diisocyanate		x		*R*		
Xylene		x				x

[a] This list reflects inputs from EPA staff in the Children's Health Program and Region 6, the criteria pollutants, and key pollutants from NATA (EPA 2011) – including risk or hazard **drivers (bold font)**, and risk or hazard *contributors* (*in italics*); c = cancer risk *(not assessed for diesel PM),* N = national risk (driver or contributor), NAAQS = National Ambient Air Quality Standards, NATA = National-Scale Air Toxics Assessment, nc = noncancer hazard (driver or contributor), R = regional risk contributor. EPA (2008) served as a resource for benchmarks and fate context.

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3 RESULTS AND DISCUSSION

3.1 INITIAL LITERATURE SEARCH

More than 400 sensors and systems were identified in the literature reviewed. Some of these are novel sensors, while others are novel devices that incorporate commercial sensors. Together, these sensors and systems address more than 100 pollutants and other measurands (objects of measure), as highlighted in Table 3-1.

Non-pollutant measures include location, acceleration, temperature, and relative humidity. Both temperature and humidity provide important context for assessing pollutant transformations and subsequent fate products in air, as well as operating constraints that can affect sensor suitability. (Additional information regarding the role of chemical fate in guiding potential development of multi-pollutant sensors is presented in Appendix C.) Further details on the sensors and measurands are available in the supporting master table compiled from the overall literature review (Raymond et al. 2013).

3.2 STUDY POLLUTANTS

The initial candidate list of more than 40 pollutants that were identified from the NATA report (EPA 2011) and inputs from EPA Regional and Program staff was winnowed to 14 pollutants, based on further context gained from the initial literature search. In selecting a representative study set, it was important to include both gases and particles because respective sensing techniques differ. Additional factors considered included the types of activities, events, and processes that led to their presence; their prevalence; and implications for human health and welfare. Example emission sources for the study pollutants are included in Table 3-2.

The fourteen pollutants that comprise the study set comprise:

- Six *criteria pollutants*: carbon monoxide (CO), lead (Pb), ozone (O_3), nitrogen dioxide (NO_2), particulate matter (PM), and sulfur dioxide (SO_2).

- Five *hazardous air pollutants* (HAPs): acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde.

- Three *indicator pollutants*: ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4).

The latter three are indicators of various airborne releases, including:

- Emissions from *nuisance* sources: For example, ammonia, hydrogen sulfide, and methane are nuisance indicators of landfill and livestock operations.

- *Greenhouse gas* (GHG) emissions: Methane is a key GHG indicator.

- Emissions from specific *activities, events, or processes*: For example, benzene, methane, and hydrogen sulfide may be indicators of natural gas exploration.

Regarding their physical state in air, lead and PM are particles and the other twelve are gases.

TABLE 3-1 Air Pollutants and Other Measurands[a]

I. Gas *(in air)*		II. Particle	
A. Criteria Pollutants			
Compliance Priority	***Also of Interest***	***Compliance Priority***	***Also of Interest***
Carbon monoxide (CO)	Carbon dioxide (CO_2)	Lead	*Further PM:*
Nitrogen dioxide (NO_2)		Particulate matter, PM	Aerosol, nanoaerosol
Nitric oxide (NO)		PM_{10}	Dust
Nitrogen oxides (NOx)		$PM_{2.5}$	Exhaust-auto, vehicle
Ozone (O_3)		PM_1	Exhaust-diesel
Sulfur dioxide (SO_2)		PM-black carbon, elemental carbon	Exhaust-gasoline
Sulfur oxides (SOx)		PM-ultrafine particle	Exhaust-tailpipe
		PM-nanoparticle	Mass-vehicle exhaust
B. Other Air Pollutants			
Risk Priority	***Also of Interest***	***Risk Priority***	***Also of Interest***
Acetaldehyde	Acetone	Arsenic compounds	Ammonium (NH_4)
Acrolein	Amine	Chromium compounds	Benzo(a)pyrene (BaP)
Acrylonitrile	Benzaldehyde	Coke oven emissions *(also see PM)*	Cyclosarin (GF)
Ammonia (NH_3, NH_3-N)	n-Butanol	Hexabromocyclododecanes (HBCDs)	Dinitrotoluene (DNT)
Benzene	Chloroform	Lead	Trinitrotoluene (TNT)
1,3-Butadiene	Decane	Manganese compounds	Sarin
Carbon dioxide	Diethyl ether	Mercury	Soman
Carbon tetrachloride	Ethanol	Nickel compounds	
Chlorine	Ethyl acetate	Polycyclic aromatic hydrocarbons	
1.4-Dichlorobenzene (p-)	Exhaust gas (S)	Perchlorate	
1,1-Dichloroethylene (-DCE)	Hexane	Phthalates	
1,3-Dichloropropene	Isobutene	Polybrominated diphenyl ethers	
Ethylbenzene	Isopropanol	Polychlorinated biphenyls (PCBs)	
Ethylene oxide (oxirane)	Mercury vapor		
Formaldehyde	Methanol		
Hexamethyl diisocyanate	Methyl ethyl ketone		
Hydrochloric acid (HCl)	Oxygen		
Hydrogen sulfide (H_2S)	Phenol		
Methane (CH_4)	Propane		
Methylene chloride	Sulfur, sulfide		
Naphthalene	1,1,1-Trichloroethane		
Perfluorocarbons (PFCs)	Trimethylamine		
Tetrachloroethylene	1,2,4-Trimethylbenzene		
Toluene			
Trichloroethylene			
Xylene			
Toluene			
C. Other Chemicals			
Beer, wine, vodka	Mixture: NO_2-NH_3	Chemical explosives	
Chemical agents	Odor	Hydrocarbons	
Gas-combustible	Organic vapors	Organophosphates (OPs)	
Gas-liquid petroleum	VOCs	Pesticides (other)	
Gas-natural	Vehicle exhaust (S)	Smoke	
Mercaptans			

TABLE 3-1 *(Cont'd.)*	
D. Physical and Environmental Parameters	**E. Biological/Physiological Parameters**
Altitude, elevation	Blood gas
Illumination, light (visible, including light pollution)	Cotinine (nicotine metabolite)
Motion, acceleration (including earthquake)	Electrolytes
Noise, sound, voice	Glucose
Position, location	Hormone residues
Pressure-air, barometric	Nicotine
Radiofrequency, RSS (received signal strength)	pH
Rainfall	**F. Microbial Agents, Seasonal Events**
Relative humidity	Biological agent
Solar radiation	*E. coli*
Temperature	Viruses
Ultraviolet light	Phenology (bud burst)
Wind speed, wind direction	Bird migration

[a] This table highlights selected measurands identified from the Phase I literature review. "Compliance priority" indicates criteria pollutants. "Risk priority" indicates importance based on the 2005 National-Scale Air Toxics Assessment (EPA 2011), Regional inputs for fenceline communities, and the EPA children's health program. Polybrominated diphenyl ethers are commonly abbreviated as PBDEs, and polycyclic aromatic hydrocarbons are commonly abbreviated as PAHs. The Phase I literature search results covered many of these priority chemicals. Note that several biological/physiological parameters and microbial agents/seasonal events identified from the literature search are listed in Sections E and F, respectively. Because the current effort focuses on sensors for air pollutants, such measures are not discussed further in this report.

TABLE 3-2 Pollutant Study Set[a]

Pollutant	Formula or Abbreviation	Air Pollutant Category and Type		
		Criteria	***HAP***	***Indicator***
1. Acetaldehyde	C_2H_4O		Gas	
2. Acrolein	C_3H_4O		Gas	
3. Ammonia	NH_3			Gas
4. Benzene	C_6H_6		Gas	
5. 1,3-Butadiene	C_4H_6		Gas	
6. Carbon monoxide	CO	Gas		
7. Formaldehyde	CH_2O		Gas	
8. Hydrogen sulfide	H_2S		*(see footnote)*	Gas
9. Lead	Pb	Particle		
10. Methane	CH_4			Gas
11. Nitrogen dioxide	NO_2	Gas		
12. Ozone	O_3	Gas		
13. Particulate matter	PM	Particle		
14. Sulfur dioxide	SO_2	Gas		

[a] Pollutants are listed with their primary category. The criteria pollutants are the six for which NAAQS have been established. HAPs (hazardous air pollutants) were identified in the 1990 amendments to the Clean Air Act. Hydrogen sulfide was inadvertently included in that original list and subsequently removed, but it is still subject to accidental release provisions; it is also an indicator for various emission sources. Regarding indicators, ammonia, methane, and hydrogen sulfide are nuisance indicators of sources such as landfills and livestock facilities; methane and hydrogen sulfide are indicators for natural gas development; and methane is a key greenhouse gas (GHG) indicator.

The number of sensors found for each study pollutant in the literature reviewed is shown in Figure 3-1. Criteria pollutants are common sensor targets, as are several volatile organic compounds (VOCs). Carbon monoxide was most frequently sensed (addressed by 63 sensors overall), followed by nitrogen dioxide, PM, ammonia, sulfur dioxide, benzene, formaldehyde, ozone, hydrogen sulfide, acetaldehyde, methane, acrolein, and 1,3-butadiene.

No sensors were found for atmospheric lead particulates. Although limited information was found for sensing lead ions in water, this report focuses on air pollutants so that research is not included in this report.

For the HAPs in the study set (all of which are VOCs), two of the top NATA cancer risk drivers (see Table 2-1) are addressed by more than a dozen sensors each. These two pollutants are benzene (a regional risk driver) and formaldehyde (a national risk driver). Eleven sensors were found for one of the two national risk contributors, acetaldehyde. In contrast, only two sensors each were identified for the other national risk driver, acrolein, and for the other national risk contributor, 1,3-butadiene.

3.2 EXPOSURE BENCHMARKS

Exposure benchmarks are standards and guidelines established for chemicals in air by a number of organizations under specific health and safety programs. Included in this set are the air quality regulations established by EPA for six criteria pollutants in outdoor air, i.e., the NAAQS. The overall suite of benchmarks covers different exposure durations for various situations and in some cases different health effect levels, thus serving as practical points of comparison for the detection levels reported for research sensors. That is, the range of established benchmarks helps frame which technologies and techniques may be suited for a given situation or not, for example, to assess whether a certain sensor is "fit for purpose" among the range of purposes addressed by these benchmarks. Another aspect of this is proper comparison by the device (e.g., to avoid false alarms when a 24-hr benchmark is exceeded by a 1-hour value). These health and safety benchmarks can be organized into three categories that reflect the target group and situation or setting addressed:

- Emergency response (general public): Typically a single exposure lasting up to 8 hours.
- Outdoor air (general public): Continuous exposures, extending to a lifetime (70 years).
- Occupational exposure (adult workers): Workplace noncontinuous exposures (per breaks between work shifts) over the work life (decades).

Federal and state agencies and several national organizations have established standards and guidelines for chemicals in air to address specific program responsibilities and needs. These agencies include U.S. EPA, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, Agency for Toxic Substances and Disease Registry (ATSDR); U.S. Department of Labor, Occupational Safety and Health Administration (OSHA); U.S. Department of Defense, Department of the Army, Army Public Health Command; California EPA (CalEPA); National Academies, National Research Council (NRC); National Institute for Occupational Safety and Health (NIOSH); American Industrial Hygiene Association (AIHA); and American Conference of Governmental Industrial Hygienists (ACGIH). A benchmark overview is given in Table 3-3, and further information is provided in Section 3.5.1 and Appendix B.

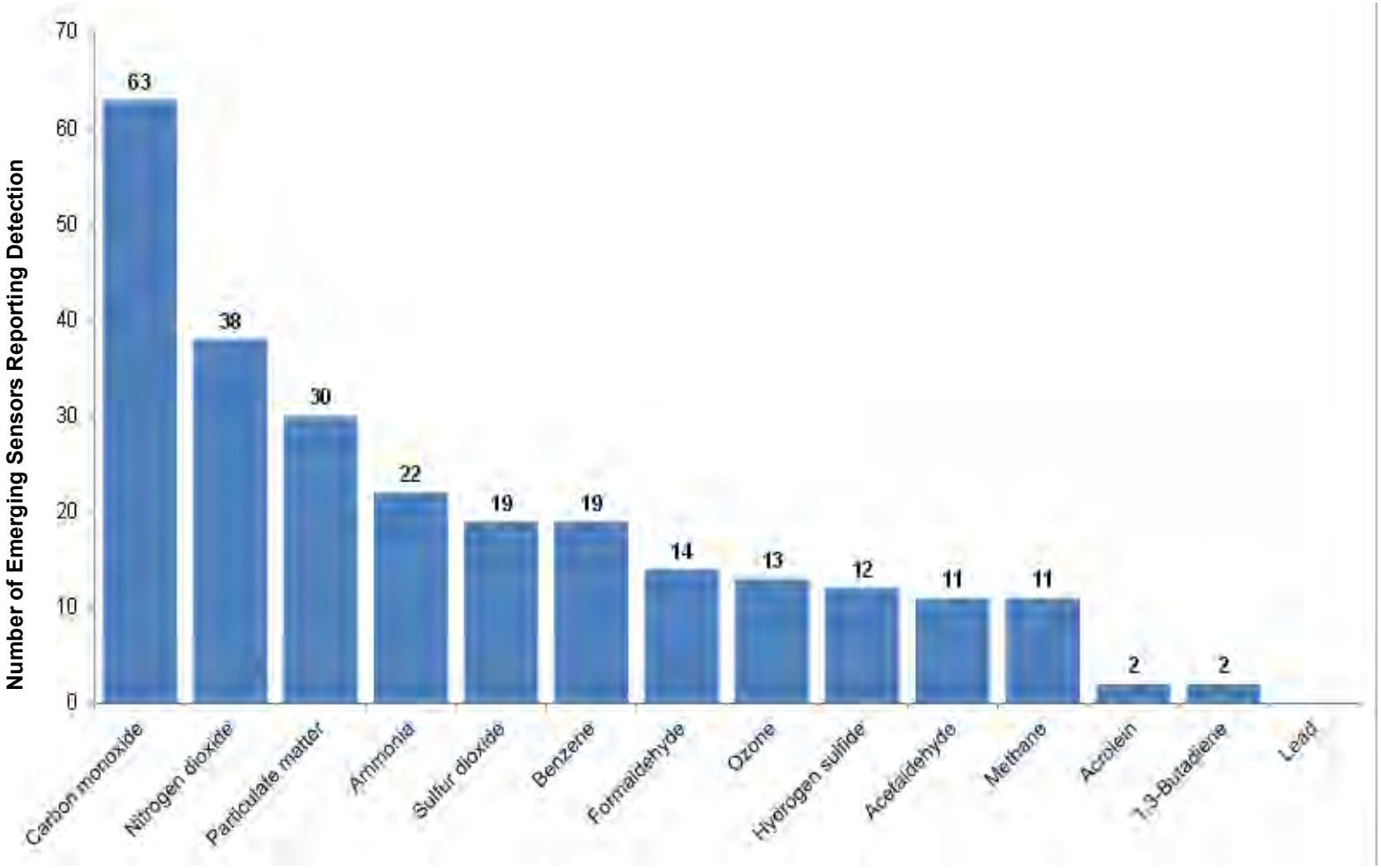


FIGURE 3-1 Number of Sensors Reported to Detect the Study Pollutants

(Counts include sensors that indicate the study pollutant, including systems involving novel architecture and infrastructure approaches.)

TABLE 3-3 Overview of Selected Inhalation Benchmarks[a]

Benchmark and Organization	Summary Description	Target Group	Exposure Duration
AEGL: Acute Exposure Guideline Level *(NRC/EPA, DOE)*	Limits for acute airborne exposure to guide emergency planning and response; targets single release/exposure	General public	10 min, 30 min, 1 hr, 4 hr, 8 hr
CEGL: Continuous Exposure Guidance Level *(NRC/DoD)*	Ceiling concentrations for continuous exposures to avoid adverse health effects, immediate or delayed	Submarine personnel	90 d
EEGL: Emergency Exposure Guidance Level *(NRC/DoD)*	For rare emergency, ceiling to not cause irreversible harm or prevent performance of essential tasks	Submarine personnel	15 min, 1 hr, 6 hr
IDLH: (level) Immediately Dangerous to Life or Health *(NIOSH)*	Maximum airborne concentration from which a worker could escape after a short exposure without harm or irreversible side effects	Worker	30 min
MEG: Military Exposure Guideline *(DoD Army)*	Concentration for intakes in moderate and arid climates to produce minimal to no adverse effects (can adjust for the general public by scaling intake)	Deployed military personnel	1 hr 8 hr 1 to 14 d 1 yr
MRL: Minimal Risk Level *(ATSDR)*	Concentration based on no adverse noncancer effects from continuous exposures (note duration terms differ from EPA definitions)	General public	Chronic (≥1 yr) Intermediate (15-364 d) Acute (1-14 d)
PEGL: Permissible Exposure Guidance Level *(NRC/DoD)*	Repeated exposure of personnel during military training exercises	Military personnel	8 hr/d, 1, 2, 5 d/wk
PEL: Permissible Exposure Limit *(OSHA)*	Enforceable worker standard; can be a time-weighted average (TWA, 8 hr), short-term limit (STEL, 15 min), ceiling (C, to not exceed; if direct monitoring is not sufficient, ceiling assessed as 15-min TWA)	Worker	8 hr/d, 40 hr/wk, yrs
PPEGL: Permissible Public Exposure Guidance Level *(NRC/DoD)*	Repeated accidental exposure of the public living or working near a military training facility	General public	8 hr/d, 1, 2, 5 d/wk
PPRTV: Provisional Peer-Reviewed Toxicity Value *(EPA ORD)*	Similar derivation process as for reference concentration and unit risk, for provisional RfC (p-RfC) and inhalation unit risk (p-IUR)	General public	Chronic/lifetime
RBC or RSC: Risk-Based or Risk-Specific Concentration *(EPA ORD)*	Concentration corresponding to a given target risk level (10^{-4}, 10^{-5}, or 10^{-6}), calculated from the inhalation unit risk (IUR)	General public	Chronic/lifetime
REL: Recommended Exposure Limit *(NIOSH)*	Guideline recommended for substances or conditions that may be hazardous in the workplace; TWA, STEL, and/or ceiling	Worker	10 hr/d, 40 hr/wk, yrs

TABLE 3-3 Overview of Selected Inhalation Benchmarks[a]

Benchmark and Organization	Summary Description	Target Group	Exposure Duration
RfC: Reference Concentration *(EPA ORD)*	Estimate of continuous daily inhalation exposure concentration likely to be without appreciable risk of adverse noncancer effect over lifetime, including for sensitive groups	General public	Chronic/lifetime (limited set for shorter durations, e.g., acute, 24 hr)
REL: Reference Exposure Level *(Cal EPA OEHHA)*	Concentration associated with no adverse effect, considering cancer and noncancer	General public	Chronic/lifetime Acute/1 hr, 8 hr
RSL: Regional Screening Level *(EPA Regions)*	Risk-based concentrations based on generic exposure assumption, used as initial screening concentration for contaminated sites (e.g., Superfund)	General public	Chronic/lifetime
SMAC: Spacecraft Maximum Allowable Concentration *(NRC/NASA)*	Limits that monitor and control traces of gas in a spacecraft cabin, to avoid noncancer effects	Astronauts	1 hr, 24 hr 7 d, 30 d, 180 d
TLV: Threshold Limit Value *(ACGIH)*	Health-based concentration for the workplace, designed for exposures without experiencing adverse health effects; can be a TWA, STEL and/or ceiling	Worker	8 hr/d, 40 hr/wk, throughout working yrs
UR: Unit Risk *(EPA ORD; used to calculate RBC, RSC)*	Plausible upper-bound probability of developing cancer from the exposure over lifetime; assumes continuous exposure at a unit concentration (e.g., 1 µg/m^3)	General public	Chronic/lifetime

[a] These benchmarks are listed alphabetically; shading indicates the application category: rose = emergency response; blue = occupational; green = ambient (continuous exposures that extend to a lifetime). Note that benchmarks for the general public include sensitive subpopulations. In deriving these values, the standard adult is taken to be 70 kg, and inhalation rates assumed for occupational and public (residential) exposures are generally 10 m^3 and 20 m^3/d, respectively.

For benchmarks that address less-than-lifetime exposures, depending on the chemical and the underlying study, some shorter-duration values may also be relevant for longer exposure durations, e.g., where the underlying study(ies) addresses the longer period. Conversely, benchmarks for shorter durations can also provide useful context for longer exposures (considering time scaling, depending on the nature of the effect), and they can also serve as bounding indicators. Note many of the guideline values undergo regular review to keep pace with evolving scientific knowledge.

In addition to benchmarks for the general public, occupational exposure levels (OELs) can also provide useful context for assessing sensor detection capabilities and potential opportunities. This context is not only with regard to considering "fit-for-purpose" opportunities for such settings, these values may also be considered in assessing some public exposures (e.g., as illustrated following the World Trade Center disaster, for pollutants without public benchmarks.)

3.3 EXAMPLE CONCENTRATIONS IN AIR

Pollutant concentrations in air result from a wide variety of releases, and Table 3-4 highlights common emission sources for the study pollutants. Illustrative concentrations for the study pollutants are shown in Table 3-5, together with example emission sources.

TABLE 3-4 Pollutant Study Set and Associated Emission Sources[a]

Pollutant	Example Sources									
	Vehicle exhaust	Oil and gas production, petroleum facilities	Fossil fuel mining, power plants	Metal smelting, refining facilities	Pulp and paper mills	Landfills	Agriculture, livestock	Waste incinerators	Biodiesel production, biomass combustion	Tobacco smoke
1. Acetaldehyde	✓				✓	✓	✓	✓	✓	✓
2. Acrolein	✓	✓	✓						✓	✓
3. Ammonia						✓	✓			
4. Benzene	✓	✓	✓		✓					✓
5. 1,3-Butadiene	✓	✓						✓	✓	✓
6. **Carbon monoxide**	✓		✓	✓				✓	✓	✓
7. Formaldehyde	✓	✓	✓		✓			✓	✓	✓
8. Hydrogen sulfide		✓	✓		✓	✓	✓	✓		
9. **Lead**	✓	✓	✓	✓				✓		
10. Methane		✓	✓			✓	✓		✓	
11. **Nitrogen dioxide**	✓	✓	✓	✓		✓		✓	✓	✓
12. **Ozone**	✓	✓	✓	✓						
13. **Particulate matter**	✓	✓	✓	✓	✓		✓	✓	✓	✓
14. **Sulfur dioxide**	✓	✓	✓	✓	✓	✓		✓		✓

[a] Criteria pollutants (in bold font) are those for which National Ambient Air Quality Standards have been established. (Note that vehicle exhaust was a source of sulfur dioxide in the past, less so today). Of the remaining eight, six (all but ammonia and methane) were in the original list of HAPs (hazardous air pollutants) from the 1990 amendments to the Clean Air Act. Hydrogen sulfide was inadvertently included in the original list and subsequently removed, but it is still subject to accidental release provisions. All three indicators (ammonia, hydrogen sulfide, and methane) are nuisance pollutants associated with livestock operations. Hydrogen sulfide and methane are also indicators for natural gas development (as is the HAP benzene), and methane is a key greenhouse gas (GHG) indicator.

Example sources: Some are indirect; e.g., ozone is formed by the reaction of precursors, VOCs and nitrogen oxides (such as from vehicle exhaust) in sunlight; similarly, photochemical oxidation of hydrocarbon combustion products forms formaldehyde. See Table 3-5 for supporting data and information sources. Note that many of these pollutants are also emitted in indoor environments (e.g., homes and workplaces), in some cases in higher concentrations than in outdoor air.

TABLE 3-5 Example Airborne Concentrations and Emission Sources for the Study Pollutants[a]

Pollutant (concn unit)	National Ambient Air Quality Standards		Illustrative Concentrations		Example Emission Sources	Selected Information Resources
	Averaging Time	*Concn*	*Concn*	*Context*		
Criteria Pollutants						
Carbon monoxide *(ppm by volume)*	8 hr *(not to be exceeded more than once a yr)*	9	0.12	Northern hemisphere	Vehicle exhaust (dominant source), with smaller amounts possibly from petroleum refineries, petrochemical plants, gas and coal-burning power plants, coke oven plants, biomass combustion, wildfires and controlled burns *(incomplete combustion)*	ATSDR (2012) (ToxGuide) http://www.atsdr.cdc.gov/toxguides/toxguide-201.pdf ATSDR (2012) (Toxicological Profile) http://www.atsdr.cdc.gov/ToxProfiles/tp201-c6.pdf EPA (2000) (Air Quality Criteria) http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=18163
			0.04	Southern hemisphere		
	1 hr *(not to be exceeded more than once a yr)*	35	5	Busy traffic conditions		
			0.5-5	Home without gas stove		
			5-15	Home with gas stove		
Lead *(µg/m³)*	3 mo *(rolling average)* *(not to be exceeded)*	0.15	0.015	2010 per annual maximum 3-month average	Lead smelting and refining facilities, steel welding and cutting operations, battery manufacturing plants, radiator repair shops, rubber and plastic production facilities, printing facilities, waste incinerators, leaded gasoline combustion, firing ranges, and construction activities	EPA (2012) (Air Trends) http://www.epa.gov/airtrends/lead.html ATSDR (2007) (ToxGuide) http://www.atsdr.cdc.gov/toxguides/toxguide-13.pdf ATSDR (2007) (Toxicological Profile) http://www.atsdr.cdc.gov/toxprofiles/tp13-c6.pdf
			<0.05	2002 ambient air		
			0.11	Mean for indoor air, per EPA Region 5 survey		

Pollutant (concn unit)	National Ambient Air Quality Standards		Illustrative Concentrations		Example Emission Sources	Selected Information Resources
	Averaging Time	*Concn*	*Concn*	*Context*		
Nitrogen dioxide *(ppb)*	Annual *(mean)*	53	10	2012 annual mean	Vehicle exhaust, coal-burning power plants, petroleum and metal refining facilities, wood burning	EPA (2012) (Air Trends) http://www.epa.gov/airtrends/nitrogen.html EPA (2012) (Our Nation's Air) http://www.epa.gov/airtrends/2011/ EPA (2008) (Integrated Science Assessment for Oxides of Nitrogen) http://www.epa.gov/ncea/isa/
	1 hr *(98th percentile averaged over 3 yr)*	100	530	Busy traffic conditions; hourly average		
Ozone *(ppm)*	8 hr *(annual 4th highest daily maximum 8-hr concn averaged over 3 yr)*	0.075	0.07	2010 mean, per annual 4th maximum 8-hr average	Vehicle exhaust, power plants, refineries, chemical plants, industrial boilers *(formed by reaction of volatile organic compounds and nitrogen oxides with sunlight)*	EPA (2012) (Ground Level Ozone FAQ) http://www.epa.gov/glo/faq.html#where EPA (2012) (Air Trends) http://www.epa.gov/airtrends/ozone.html
$PM_{2.5}$ *($\mu g/m^3$)*	Annual *(primary and secondary means, averaged over 3 yr)*	12	10	2010 mean, per seasonally weighted annual average	Vehicle exhaust, fossil fuel combustion, industrial processes, wood burning, agricultural operations, construction and demolition activities	EPA (2012) (Air Trends) http://www.epa.gov/airtrends/pm.html EPA (2010) (Report on the Environment) http://cfpub.epa.gov/eroe/index.cfm?fuseaction=detail.viewInd&lv=list.listbyalpha&r=231331&subtop=341 EPA (2004) (Looking at Trends) http://www.epa.gov/air/airtrends/aqtrnd04/pmreport03/pmlooktrends_2405.pdf
		15				
	24 hr *(98th percentile, averaged over 3 yr)*	35	11.5	2006-2008 mean, per annual average		
PM_{10} *($\mu g/m^3$)*	24 hr *(not to be exceeded more than once a yr on average over 3 yr)*	150	51	2009 mean, 24-hr average		
			63	2010 mean, per annual 2nd maximum 24-hr average		

Pollutant (concn unit)	National Ambient Air Quality Standards		Illustrative Concentrations		Example Emission Sources	Selected Information Resources
	Averaging Time	*Concn*	*Concn*	*Context*		
Sulfur dioxide *(ppb)*	1 hr *(99th percentile of 1-hr daily maximum concn averaged over 3 yr)*	75	2.2	2010 mean, annual arithmetic average	Power generation, fuel combustion, industrial processes such as refining and smelting, volcanoes	EPA (2012) (Air Trends) http://www.epa.gov/airtrends/sulfur.html ATSDR (1998) (Toxicological Profile) http://www.atsdr.cdc.gov/ToxProfiles/tp116-c5.pdf
	3 hr *(not to be exceeded more than once a yr)*	500	600-3,000	Breathing zone of forest fires		
Additional Study Pollutants						
Acetalde-hyde *(ppb)*	*Not applicable*		0-0.8	Rural regions (Point Barrow, Alaska; Whiteface Mountain, New York)	Cigarette smoke, incomplete combustion processes (tailpipe exhaust and fires), photochemical oxidation of hydrocarbons, agricultural burning, wildfires, fireplaces, woodstoves, cooking, building materials, nail polish remover	CalEPA Air Resources Board (1993) http://www.oehha.org/air/toxic_contaminants/html/acetaldehyde.htm NTP (2011) (Report on Carcinogens) http://ntp.niehs.nih.gov/ntp/roc/twelfth/profiles/Acetaldehyde.pdf EPA (1992, 2000) (Hazard Summary) http://www.epa.gov/ttnatw01/hlthef/acetalde.html
			1.6-2.8	South Coast Air Basin (California), 24-hr sample averages		
			2.8 (5 µg/m^3)	Ambient air, average		
			32	Los Angeles, ambient		
			3-15	Indoor, California		
			113	Indoor, with smokers, California		
			28-3,600 (0.05-6.4 mg/m^3)	Diesel exhaust		
			780-4,900 (1.4-8.8 mg/m^3)	Gasoline exhaust		
Acrolein	*Not applicable*		0.5-3.2	Outdoor air	Vehicle exhaust, biomass	ATSDR (2007) (ToxGuide)

Pollutant (concn unit) (ppb)	National Ambient Air Quality Standards		Illustrative Concentrations		Example Emission Sources	Selected Information Resources
	Averaging Time	*Concn*	*Concn*	*Context*		
			<0.02-12	Indoor residential air	conversion and biodiesel production facilities, heating fats, tobacco smoke	http://www.atsdr.cdc.gov/toxguides/toxguide-124.pdf
Ammonia *(ppb)*	*Not applicable*		0.3-6	Global average	Fertilizer production plants, household cleaning products (and production facilities), animal excreta and decaying organic matter, volcanoes	ATSDR (2004) (ToxGuide) http://www.atsdr.cdc.gov/toxguides/toxguide-126.pdf
Benzene *(ppb)*	*Not applicable*		0.58	Metropolitan areas	Vehicle exhaust, gas stations, tobacco smoke, natural gas development	ATSDR (2007) (ToxGuide) http://www.atsdr.cdc.gov/toxguides/toxguide-3.pdf ENVIRON (2012) (Hydrofracking: Air Issues and Community Exposure) http://lawweb.colorado.edu/law/centers/nrlc/events/hottopics/Kaden%20PPT%20(1-27-12_.pdf
			0.36-1.4	Ambient outdoor air, annual mean, 2009 (10^{th}-90^{th} percentile range)		
1,3-Butadiene *(ppb)*	*Not applicable*		0.04-1	Cities and suburban areas	Vehicle exhaust, manufacturing plants, burning rubber or plastic, burning wood, forest fires, tobacco smoke	ATSDR (2012) (ToxGuide) http://www.atsdr.cdc.gov/toxguides/toxguide-28.pd
			0.1	Outdoor air (Texas 2003 annual average; excluding point source downwind monitors)		Texas (2007) http://www.ncbi.nlm.nih.gov/pubmed/17011534

Pollutant (concn unit)	National Ambient Air Quality Standards		Illustrative Concentrations		Example Emission Sources	Selected Information Resources
	Averaging Time	*Concn*	*Concn*	*Context*		
Formalde-hyde *(ppb)*	*Not applicable*		0.4	Mean, natural background	Photochemical oxidation of hydrocarbon combustion products (88%), power plants, incinerators, unvented gas or kerosene heaters, carpets and permanent press fabrics, wood product manufacturing (plywood, furniture), automobile exhaust, cigarette smoke, latex paints, varnishes, fingernail polish and remover, preserved specimens	ATSDR (1999) (Toxicological Profile) http://www.atsdr.cdc.gov/toxprofiles/tp111.pdf EPA (2007) (Technology Transfer Network, Air Toxics Web site) http://www.epa.gov/ttnatw01/hlthef/formalde.html#ref1 CalEPA OEHHA (2001) (Children's Environmental Health Protection Act) http://www.oehha.org/air/toxic_contaminants/pdf_zip/formaldehyde_final.pdf EPA (2012) (Introduction to Indoor Air Quality) http://www.epa.gov/iaq/formaldehyde.html WHO (2001) (Air Quality Guidelines) http://www.euro.who.int/__data/assets/pdf_file/0014/123062/AQG2ndEd_5_8Formaldehyde.pdf
			0.2-6	Rural and suburban areas		
			1-20	Urban areas		
			21-98	California, monitored classrooms (mean-max)		
			20-4,000	Indoor air		
			83 (100 µg/m^3)	Conventional homes (mean, Southern California)		
			0.8 (0.5, 0.1)	Odor threshold (lower reflects sensitive noses)		
			9.1	Heavy traffic, inversions (short-term peaks)		
			45 (≤83)	Manufactured homes (mean, mobile homes)		
			<100 (mean ≤50; 25-60 µg/m^3)	Homes without urea-formaldehyde foam insulation (UFFI)		
			>300	Homes with substantial pressed wood products		

Pollutant (concn unit)	National Ambient Air Quality Standards		Illustrative Concentrations		Example Emission Sources	Selected Information Resources
	Averaging Time	*Concn*	*Concn*	*Context*		
Hydrogen sulfide *(ppb)*	*Not applicable*		0.11-0.33	Ambient air	Pulp and paper mills, petroleum refineries, natural gas production plants, geothermal power plants, coke oven plants, iron smelters, food processing plants, swine containment facilities and other CAFOs, manure handling, wastewater treatment facilities, swamps, stagnant water, volcanoes, natural gas development	ATSDR (2006) (ToxGuide) http://www.atsdr.cdc.gov/toxguides/toxguide-114.pdf ENVIRON (2012) (Hydrofracking: Air Issues and Community Exposure) http://lawweb.colorado.edu/law/centers/nrlc/events/hottopics/Kaden%20PPT%20(1-27-12_.pdf Purdue Extension (2007) (CAFOs) http://www.extension.purdue.edu/extmedia/ID/cafo/ID-358-W.pdf
			<1	Urban air		
			0.4-2.4	Homes near concentrated animal feeding operations (CAFOs)		
			>90	Homes near industrial facilities		
Methane *(ppm)*	*Not applicable*		2.2	Natural atmosphere	Fossil fuel mining and distribution (including natural gas and petroleum systems), livestock, landfills, biomass burning (including wildfires), wetlands, rice cultivation, stationary and mobile combustion, natural gas development	New England Waste Services of Vermont, Inc. (2006) http://www.anr.state.vt.us/DEC/wastediv/solid/documents/NEWSVTAttachF.pdf Alberta Environmental Protection, CH2M Gore and Storrie Limited (1999) http://www.environment.gov.ab.ca/info/library/5847.pdf
			600,000	Unlined landfills (average)		

[a] These illustrative concentrations represent data from an online search to indicate the variety of concentrations to which people could be exposed in different types of settings and over different time frames (e.g., short-term peaks to annual averages). The values in this table are generally rounded to two significant figures. Similar summaries of example concentrations in air for selected pollutants are provided in Appendix D. Those tables illustrate how data inputs from EPA Regional staff and others interested in region- and setting-specific compilations could be organized to inform community-based initiatives. National Ambient Air Quality Standards (NAAQS) are only established for six criteria pollutants. Values for lead, nitrogen dioxide (annual mean), ozone, $PM_{2.5}$ (24-hour), and PM_{10} are joint primary-secondary standards. Carbon dioxide, nitrogen dioxide (1-hour), $PM_{2.5}$ (annual mean of 12 $\mu g/m^3$), and sulfur dioxide (1-hour) are primary standards, while $PM_{2.5}$ (annual mean of 15 $\mu g/m^3$), and sulfur dioxide (3-hour) are secondary standards. Primary standards are defined to protect public health, including sensitive populations; secondary standards protect public welfare, including protecting against decreased visibility and damage to animals, crops, vegetation and buildings. The NAAQS entries (concentrations and averaging times) do not correspond to the example ambient levels in the adjacent column. Additional resources for methane include: EPA (2013) (Methane Emissions); http://epa.gov/climatechange/ghgemissions/gases/ch4.html, and EPA (2013) (Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010); http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

As evident from Table 3-5, selected pollutant measurements are available for a number of settings and time periods, including for areas with common ambient emission sources (e.g., vehicle exhaust) as well as emergency response-related settings (e.g., breathing zone of forest fires). Given the variety of community interests across different regions, companion tables are provided in Appendix D to facilitate the organization of pollutant measurement data for locations of interest to specific communities.

Also included in Table 3-5 are the regulatory standards for the criteria pollutants, as points of comparison for their example measurements. As described in the preceding section, like ambient measurements, the NAAQS and other exposure benchmarks provide practical context for assessing sensor detection capabilities. Both benchmark concentrations and example concentrations in air are plotted with sensor detection levels in the graphical arrays for each study pollutant presented in Section 3.5, to facilitate comparisons and frame the evaluation of gaps and opportunities for different settings and situations.

3.4 SENSOR TECHNOLOGIES AND TECHNIQUES

3.4.1 Sensing Categories

The sensors highlighted in this report are organized into three main categories based on the underlying detection technique: chemical interaction (hereafter referred to as chemistry or chemical techniques), spectroscopy, and ionization. A brief description of these categories and underlying sensing principles follows, additional information is provided in Appendix F. The numbers of sensors identified in these categories from the literature reviewed is presented in Table 3-6.

Chemistry

This sensing technique involves contact-based chemical interactions. This category includes solid-state sensors with a chemical film that reacts with a gas to produce a signal, e.g., due to a change in mass or electrical properties. That signal is then analyzed to indicate the presence and/or concentration of the given pollutant. Sensors in this category are divided into four groups in this report to help highlight active research areas:

- Electrochemical sensors – typically an electrochemical cell with a solid or liquid electrolyte; the chemical reaction of an incoming substance at the working electrode creates an electrical potential difference between that electrode and the reference electrode. Metal oxide semiconductors (MOS), also referred to as chemiresistors, and electrochemical membranes account for most entries in this category.

- Nanotechnology-based sensing materials – including nanocrystalline metal oxides, carbon nanotubes (CNTs), and organic nanocomposites; these materials can be used as stand-alone sensing films and can also be incorporated into other sensor systems.

- Polymer films – including hybrid films, with thin-film organic polymers providing conductive or fluorescent surfaces.

- Surface acoustic wave (SAW) sensors – with a chemical film that selectively adsorbs a gas, producing a change in mass, detected by a change in surface-propagating waves.

TABLE 3-6 Technologies/Techniques Reflected in Research Sensors and Systems[a]

Technology/Technique	Number	Pollutants
Chemistry	**73**	
Electrochemical *(notably MOS and membrane sensors)*	*30*	Acetaldehyde, acetone, alcohols, ammonia, benzene, CO, carbon dioxide, formaldehyde, NO_2, NOx, phenolate, PM, VOCs
Nanotechnology-based	*28*	Acetaldehyde, ammonia, benzene, CO, carbon dioxide, formaldehyde, hydrogen sulfide, methane, NO_2, oxygen, SO_2, VOCs
Polymer film	*10*	Acetaldehyde, ammonia, CO, formaldehyde, trinitrotoluene
Surface acoustic wave	*5*	Hydrogen sulfide, NOx
Spectroscopy	**57**	
Absorption	*19*	Ammonia, benzene, CO, NO_2, SO_2, explosives
Emission	*18*	Acrolein, ammonia, hydrogen sulfide, SO_2, VOCs
Laser absorption	*15*	Acrolein, BTEX, CO, NO_2, PM, VOCs
LIDAR	*4*	Ammonia, hydrogen sulfide, NO_2, O_3, PM
Light scattering	*1*	PM
Ionization	**5**	
Mass spectrometry	*3*	PM-ultrafine particles (UFPs), VOCs
Gas chromatography	*2*	BTEX, other VOCs
Other	**3**	PM

[a] The numbers in bold font represent the totals for each of the four categories. Counts include duplicates because some devices/technologies contain components that cross multiple categories. Also, these values reflect a number of pollutants/parameters reported in the literature reviewed, not just those comprising the study set; for example, trinitrotoluene (TNT) and others are included n this summary. Sensors using the LIDAR technique were found as part of the literature review and are included in this table; however, they are not generally considered to be portable and are not included in subsequent count figures. Note that metal oxide semiconductors (MOS) and electrochemical membrane sensors dominate within the electrochemical group.

Spectroscopy

Spectroscopic techniques rely on chemical-specific emission and/or absorption spectra that result from molecules interacting with an energy source such as light. Commonly referred to as optical sensors, these devices identify pollutants based on their absorption or emission characteristics. These sensors can be further grouped as follows:

- Absorption spectroscopy – based on absorption peak patterns and intensities using infrared (IR), ultraviolet (UV), or visible light.
- Laser absorption spectroscopy – including quantum cascade lasers (QCLs), tunable diode lasers, and organic microlasers that operate at a specific light frequency range.
- Emission spectroscopy.
- Light scattering, or nephelometry.

Light detection and ranging (LIDAR) is another spectroscopic technique identified in the literature search; this sensing technique is based on back-scattered light from interaction with a laser or other light source. Although LIDAR detectors are not currently used in mobile sensing

(thus are not reflected in the accompanying figure), they could potentially represent an opportunity for future research. Laser-induced breakdown spectroscopy (LIBS) is another technique that might represent a future opportunity, although it was not reflected as such in the literature reviewed. This technique uses a high-power, pulsed laser beam to induce a plasma that vaporizes, atomizes, and excites the sample gas, and the identity and concentration of the substance are then determined from the intensities of the resulting atomic emissions.

Ionization

This sensing technique involves identifying pollutants on the basis of their ions. A gas chromatograph (GC) is frequently placed in front of ionization detectors for selective separation, and some mass spectrometers also use front-end chromatography to achieve selection. Three groups of sensing techniques within this category are:

- Photoionization detection – which measures the ionization potential (IP) of gases at or below the frequency of light emitted from an ultraviolet (UV) lamp. Concentrations are determined by the extent of ion deposition on the collecting electrode resulting from photon absorption. Photoionization detectors (PIDs) often serve as detectors in GC systems. (Note that PIDs, including commercial sensors, are not reflected in the sensors highlighted in Table 3 6.)

- Flame ionization detection – which involves mixing a sample gas with hydrogen then introducing a flame, and collecting the released electrons at electrodes where the energy is converted to electrical output signals. Flame ionization detectors (FIDs) commonly serve as detectors in GC systems.

- Mass spectrometry – which consist of an ion source, analyzer, detector, and data recorder; several aspects of these systems can be changed to address the specific chemical species to be measured. Major ion formation techniques include electron impact ionization, chemical ionization, fast atom bombardment, electroscopy ionization, and matrix-assisted laser desorption ionization. Analyzers include magnetic, electrostatic, quadrupole, ion trap, time of flight, and Fourier transform ion cyclotron resonance. Detector components include secondary electron multipliers, photomultipliers, and multi-channel plates.

3.4.2 Technology/Technique Trends for Mobile Sensors

Of the 138 studies reviewed that focus on research sensors: spectroscopic and chemical techniques dominate for the selected set of pollutants (see Table 3-6 and Figure 3-2). Chemical techniques are reflected in 73 studies while 57 reflect spectroscopy, five reflect ionization, and three use other methods such as microelectromechanical systems (MEMS). Note that nano-electromechanical systems are also being developed. Counts for subcategories within the three main categories are also included in Figure 3-2. Electrochemical and nanotechnology-based sensors (grouped with chemical techniques) lead the subcategories. Chemical techniques are most common across all measurands and also for the study set, as shown in Figure 3-3. Insights from this limited set indicate no broad-spectrum sensor exists, i.e., no single technology/technique can detect all 14 (see Figure 3-3). However spectroscopic techniques are reported for all but one (lead), and chemical techniques apply to all but three (acrolein, lead, and ozone). Many commercial sensors are available for ozone, including electrochemical sensors; but this review focuses on research sensors and novel systems, and these were not found for ozone. Three pollutants are sensed by all three techniques: PM, benzene, and 1,3-butadiene.

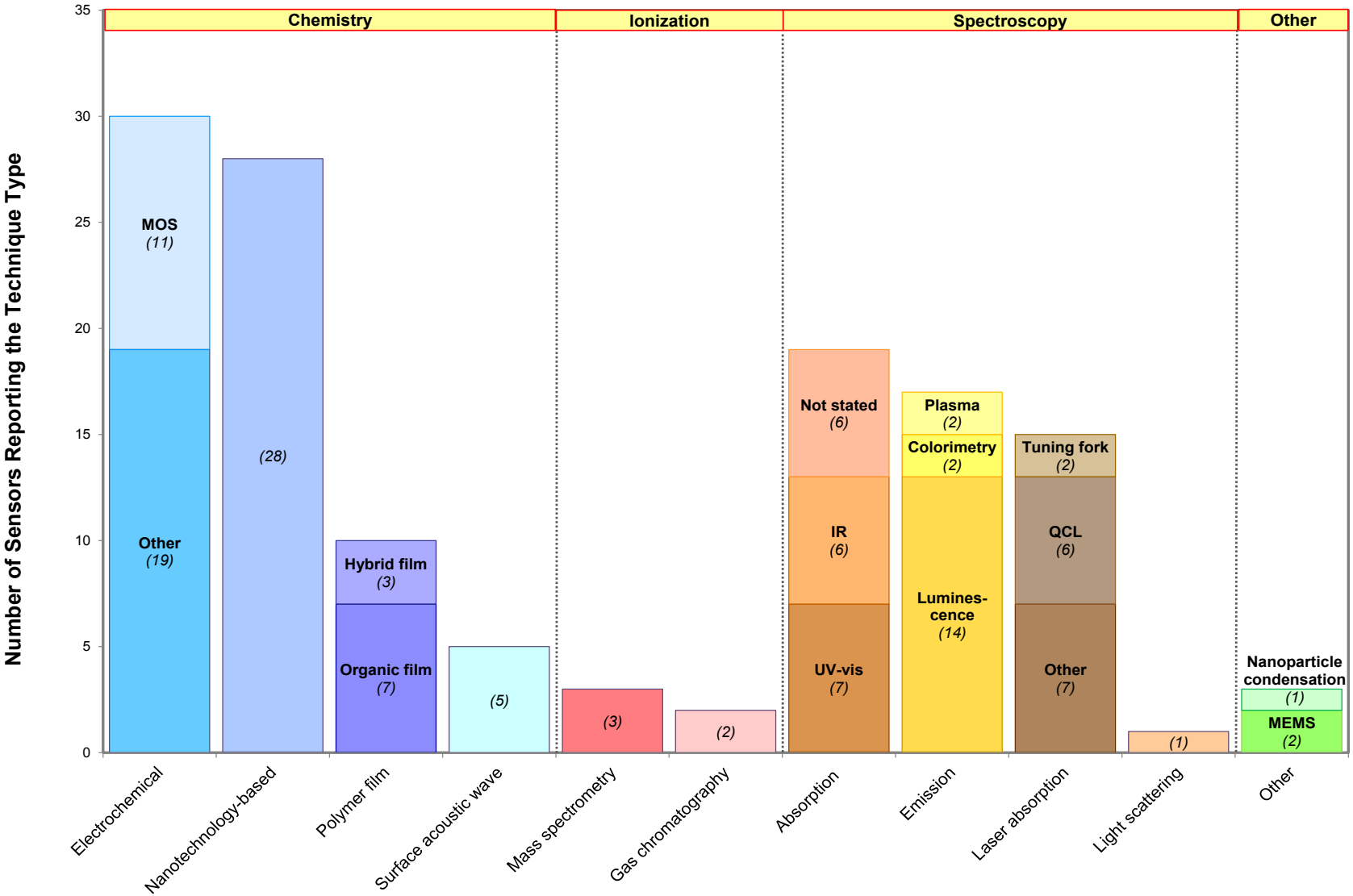


FIGURE 3-2 Detection Techniques Highlighted in Recent Research Literature

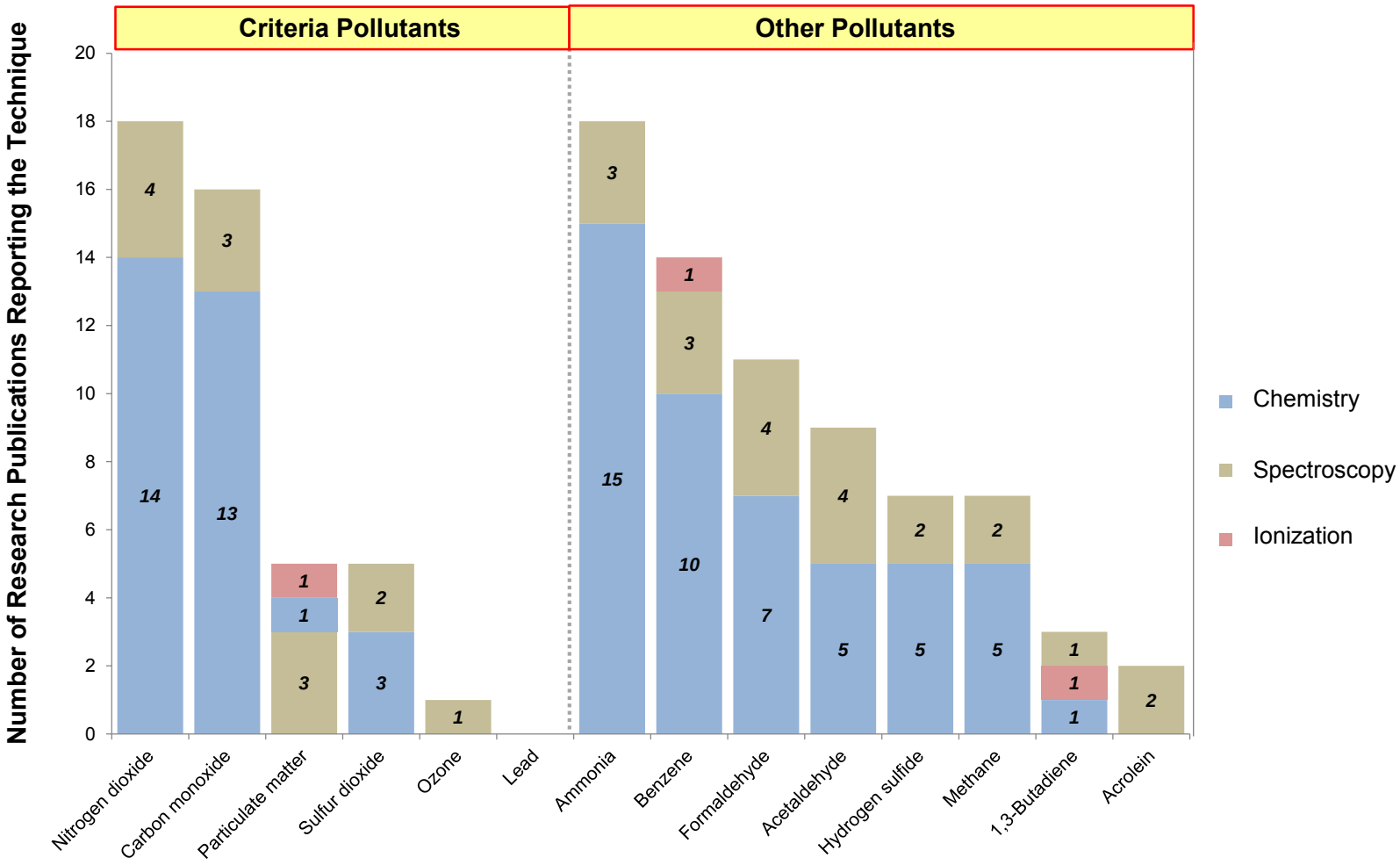


FIGURE 3-3 Detection Techniques Reflected in Sensors and Systems for the Study Pollutants

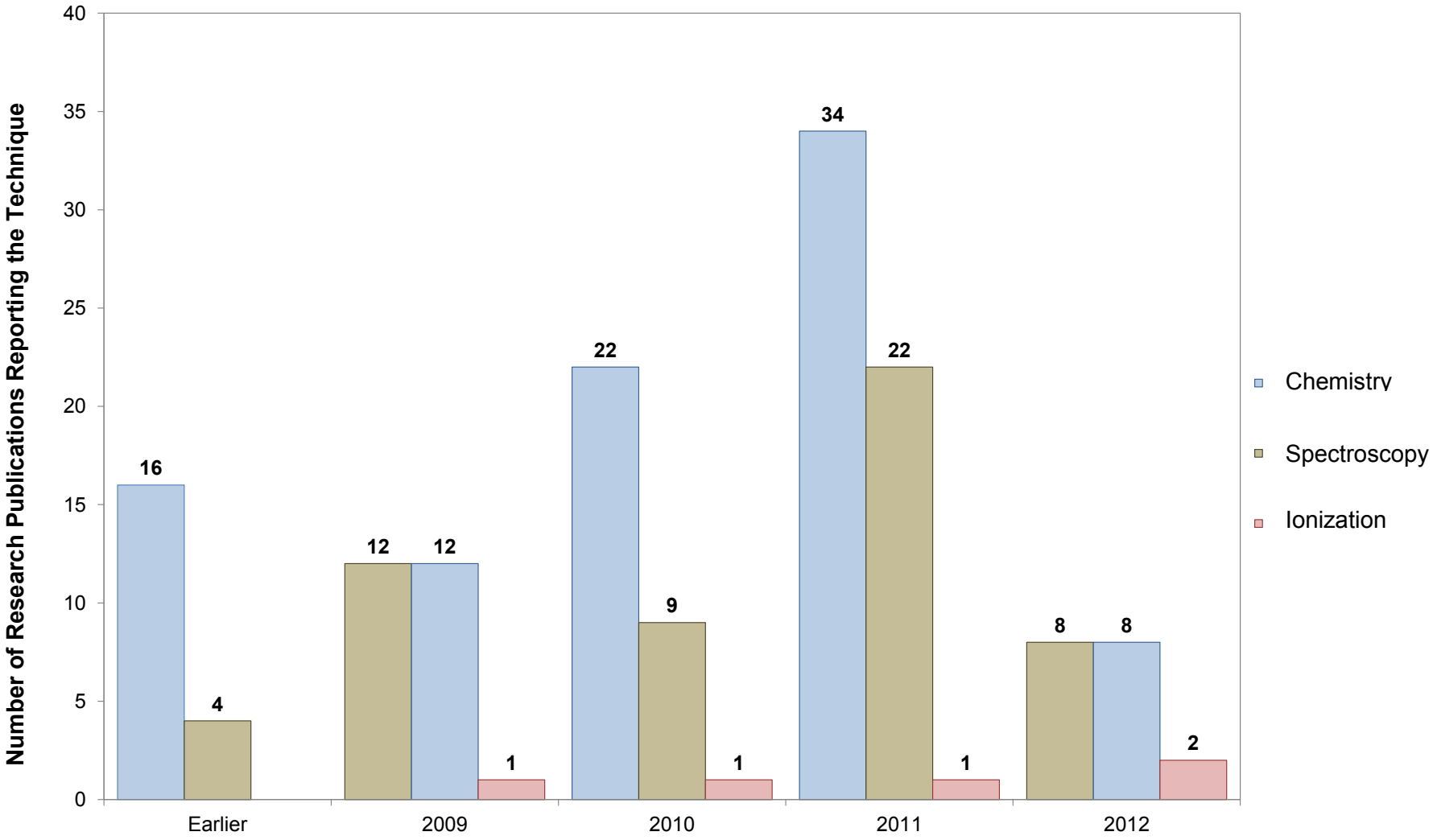


FIGURE 3-4 Technology/Technique Counts by Year *(2010 to early 2012)*

To assess recent trends, the number of research studies distributed across the three main sensing techniques is plotted by year in Figure 3-4. Publications for sensors focusing on chemical techniques increased substantially in 2011 and have continued to increase since then. Note that this figure only reflects publications from the beginning of 2012; subsequent checks of selected literature through 2012 confirm this trend, with nanotechnology also continuing to play a prominent role. Similar results are indicated for spectroscopic techniques. Most of the recent research focuses on refining existing technologies and techniques to gain improvements such as smaller size, greater sensitivity, and lower power consumption, rather than developing wholly new approaches. For example, nanoparticle coatings are being added and light frequencies are being altered to increase the sensitivity of various devices, and many spectroscopic sensors are incorporating nanotechnology to improve portability.

3.5 DETECTION CAPABILITIES

From the literature reviewed, nearly 170 sensors were reported to detect at least one of the 14 air pollutants studied. These include research sensors as well as novel systems that incorporate commercial sensors. Summary information for these sensors and systems is tabulated in Appendix E (Tables E-1 and E-2), which also includes reference levels for commercial sensors that were selected to represent standard sensors for those pollutants. Of these sensors, more than 70% (118 of 166) identify the sensing technique. About half (87) report a lower detection limit (LDL) or similar value (i.e., minimum tested concentration), and less than a quarter (37) include an upper limit of quantitation or maximum tested concentration. The sensing techniques for each pollutant are summarized in Table 3-7 together with the LDLs where available. The lowest (most protective) benchmark concentration is included with the pollutant (in the first column) as context for this overview of potential detection capabilities. (Note this lowest benchmark is also included with others in graphical arrays to facilitate comparisons, as described in Section 3.5.1.) The LDLs that achieve this lowest benchmark are shaded green, the others are shaded blue. When no LDL was identified, an 'x' is used to signify that technique is reported for the given pollutant. A blank cell indicates the technique was not identified for that pollutant (e.g., see the row for lead, for which no research sensors were found). The only commercial sensors included in this table are those used in novel sensor systems. Information from studies that only addressed sensor architectures and infrastructures is presented in Section 3.6 (also see Raymond et al. [2013]).

3.5.1 Graphical Arrays of Exposure Benchmarks and Reported Sensor Detection Levels

Graphical arrays have been created for each of the study pollutants to compare reported sensor detection levels with established exposure benchmarks. Array elements are described below.

Selected Benchmarks

Benchmarks have been established by EPA and other agencies to protect the health and safety of the general public and workers under various conditions. The selected benchmarks presented in the arrays are organized according to four time periods (labeled at the top of each array) to reflect the exposure durations addressed: acute, short term, subchronic, and chronic. The symbols plotted on these arrays identify the concentration of the benchmark (y-axis) for the given exposure duration (x-axis). Shading indicates the benchmark category: (1) rose signifies emergency response levels for the general public, only lasting up to a day (primarily to 8 hr); (2) green signifies continuous ambient exposures for the general public, extending over a lifetime; and (3) blue indicates occupational noncontinuous exposures for adult workers over a working life.

TABLE 3-7 Detection Capabilities for Selected Sensing Technologies/Techniques
(concentrations are ppm for gases, µg/m³ for particles)[a]

Pollutant (concentrations are as ppm except as noted, for lead and PM)	Sensing Technology/Technique										
	Chemistry				Ionization		Spectroscopy				
	Electro-chemical	*Nano-based*	*Polymer film*	*SAW*	*Mass spectrometry*	*GC element*	*Absorption*	*Emission*	*Laser absorption*	*LIDAR*	*Light scattering*
Acetaldehyde *RBC: 0.000278*	x	0.01	0.025					0.25	x		
Acrolein *RfC: 8.73E-7*								x	0.003		
Ammonia *MRL chronic: 0.1*	x	3.1	20				1			x	
Benzene *RBC: 0.0004*	x	0.05	17100			0.1	0.001	x	0.00235		
1,3-Butadiene *RBC: 1.36E-5*		9.5				0.5	0.0095	0.001			
Carbon monoxide *NAAQS (8-hr av): 9.0*	0.2	100	80				x		10		
Formaldehyde *RBC: 6.5E-5*	0.05	0.01					0.106	0.001			
Hydrogen sulfide *RfC: 0.001*		0.002		x			x	0.001		x	
Lead *CalEPA IUR/RBC: 0.0833 µg/m³*											
Methane *MEG-negligible effect (1 hr): 2,830*		125					5				
Nitrogen dioxide *NAAQS (as annual avg): 0.053*	0.02	0.01	x				x		0.12	0.001	
Ozone *NAAQS (as 8-hr avg): 0.075*										0.001	
Particulate matter *NAAQS (annual avg):12 µg/m³*	x				x				x	x	x
Sulfur dioxide *NAAQS (as 1-hr avg): 0.075*		0.01					0.4	0.001			

[a] This table reflects LDLs reported for these techniques and pollutants in the research literature reviewed. (While commercial sensors may have lower LDLs, this report focuses on research sensors so data for commercial sensors alone were not pursued for this compilation.) The lowest exposure benchmark is included for comparison (the IRIS RBCs correspond to the 10^{-6} risk level; concentrations are ppm for gases and mass-based for lead and PM. The LDLs that achieve this lowest benchmark are shaded green, the others are shaded blue. An x (with yellow shading) indicates the technique has been reported to detect the pollutant but the concentration was not identified. An empty cell indicates the technique has not been identified for that pollutant (e.g., none were found for lead in air).

Gas chromatography (GC) is reflected as a selective element of the sensor system; the main detector could be a photoionization, flame ionization or mass spectrometry detector. LDLs shown here for benzene and 1,3-butadiene are for a system that uses GC to separate the two gases, which are then detected by a commercial MOS sensor.

It is important to clarify that this report focuses on research sensors and novel systems, rather than commercial sensors. Thus, many commercial sensors exist that are not included in the figures and tables of this report. For example, a variety of commercial sensors are available for ozone, including a number of electrochemical sensors, yet the chemistry entries for ozone are blank in this table. This simply means no research and development sensors or novel sensor systems were found for ozone in the literature review.

The graphical arrays that compare exposure benchmarks to detection levels are presented for the pollutants in alphabetical order in Figures 3-5 through 3-18. An interpretation guide for the symbols and shading used in these arrays is provided in Table 3-8. The symbol color indicates the effect severity for benchmarks with tiered effects (e.g., acute exposure guideline levels, AEGLs). A dashed line indicates the benchmark concentration applies across that indicated. Where a series of concentrations have been established for different exposure durations for a given benchmark (e.g., 10-min, 30-min, 1-hr, 4-hr, and 8-hr values for certain emergency response values), the corresponding symbols are connected by a line of the same color.

TABLE 3-8 Guide to Distinguishing Types of Benchmarks in the Graphical Arrays

Shape	Target Group and Setting	Nature of Exposure
◇	General public, emergency response	Discrete exposures lasting up to 8 hr
□	General public, routine ambient	Continuous exposures, to lifetime (70 yr)
△ ○	Adult worker, occupational	Noncontinuous exposures (work shifts over working life (e.g., 25+ yr)
Shading-Outline	**Health Effect Level / Nature**	**Effect Notes**
○ ◆	Above this level, effect could be severe	Examples: AEGL-3, IDLH
◆	Above this, effect could be serious, irreversible	Example: AEGL-2
◆	Above this, effect could be mild, reversible	Example: AEGL-1
△ ○	Occupational, OSHA regulatory standard Occupational, other/recommended limit	Not all permissible exposure limits (PELs) are strictly health based (some reflect technical feasibility)
□	Level considered safe for the general public	Includes downward adjustments to assure safe margin of exposure across general population including sensitive subgroups

To illustrate how this is represented on a graphical array, see the lines connecting multiple-duration benchmark concentrations for acetaldehyde AEGL values in Figure 3-5. The AEGL-1 values remain constant across these 5 time intervals, as seen from the flat gold line through the gold diamonds. In contrast, while the AEGL-2 and AEGL-3 values are the same for the first two intervals (as indicated by the flat orange line between the orange diamonds plotted at 10 min and 30 min, and the flat red line between the parallel red diamonds), the benchmark

concentrations for the AEGL-2 and AEGL-3 decrease over the next three intervals as indicated by the angled line connecting those respective diamonds. Not all guidelines are shown on these graphical arrays. For example, additional guidelines exist for many of the pollutants, notably OELs established for military personnel and specialized exposure settings (e.g., spacecraft and submarines). Those benchmarks are only tapped for methane because the more common health-based benchmarks (available for the other pollutants) have not been established for this compound. (See the introductory text of Appendix B for further information regarding the methane benchmarks.) Complementary figures are provided in Section 3.5.2 to compare sensor detection levels with illustrative concentrations in air for eleven study pollutants. Few example concentrations were found for the other three – ammonia, benzene, and 1,3-butadiene. Thus, these examples are included in the graphical arrays for exposure benchmarks (Figures 3-7 through 3-9) to streamline those presentations.

Selected Sensors

The sensors listed in the graphical arrays are primarily from studies that focus on sensing technology/technique; a few are from studies that focus on the architecture/infrastructure approach and incorporate a commercial sensor in a novel system. In addition, one or two commercial sensors (depending on the pollutant) that are considered to represent a standard accepted sensor for that pollutant are included on the arrays as points of reference, to guide the assessment of needs and opportunities. (For example, if a commercial detector already cost-effectively measures CO at the concentration of interest, or if another commercial sensor can measure a nuisance indicator at the odor threshold, then research investments would not be expected to target sensor development for those pollutants.) Further details about the sensors shown on these arrays are presented in Appendix E (Table E-1). A brief interpretation guide for the sensors plotted on the graphical arrays is provided below.

- Each sensor is identified with a small label. This label lies on a relatively thick horizontal line, which represents the reported LDL or minimum tested concentration, where reported. Its position is not related to the data recording time or instrument response time.
- The vertical line extending up from this label indicates the reported range of detection (where available). This vertical line ends at the upper limit of quantification or greatest tested concentration, which is represented by a short horizontal bar.
- The identifier number in the sensor label corresponds to the number in the summary table in Appendix E (Table E-1), where further information is provided for each plotted sensor.
- The font and line colors for the research sensors are darker than those for systems involving commercial sensors, so these primary sensors will stand out on the arrays.
- Devices that involve use of a commercial sensor in a novel system are distinguished by a lower-case "c" next to the identifier number. The font and lines used for these devices are a bit lighter than for the research sensors.
- Standard commercial sensors are also included in most arrays to provide further context for assessing detection gaps and opportunities. These reference sensors are denoted with an upper-case "C" next to the identifier number, as well as a star in that sensor box; the font and line colors for these standard commercial sensors are the lightest of all the sensors plotted on the arrays.
- An asterisk following the technique type or device name denotes the sensors for which the response time is reported to be 5 minutes or less. (See Appendix E for additional information regarding specific response times, where available.)

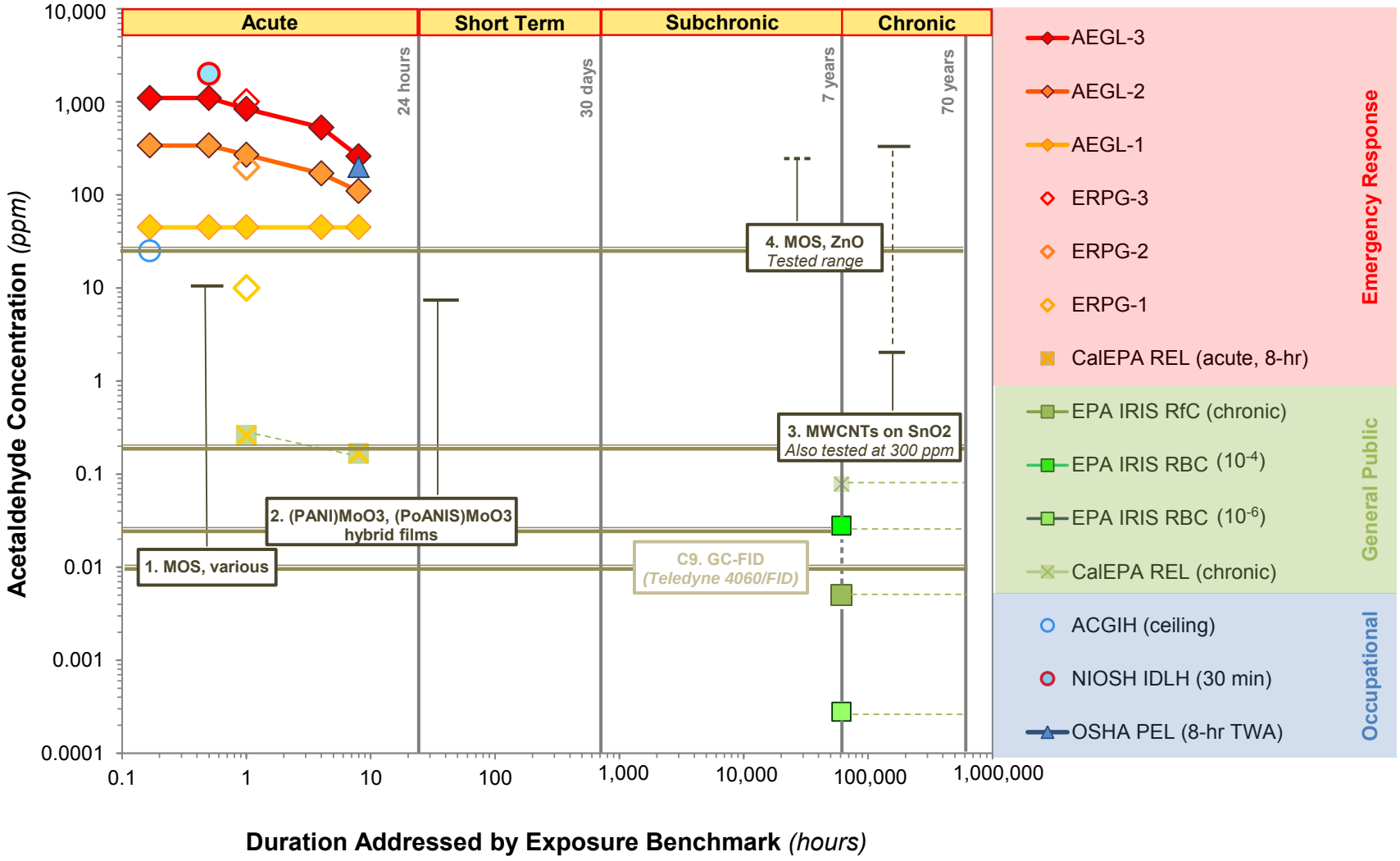


FIGURE 3-5 Acetaldehyde: Comparison of Detection Levels to Exposure Benchmarks

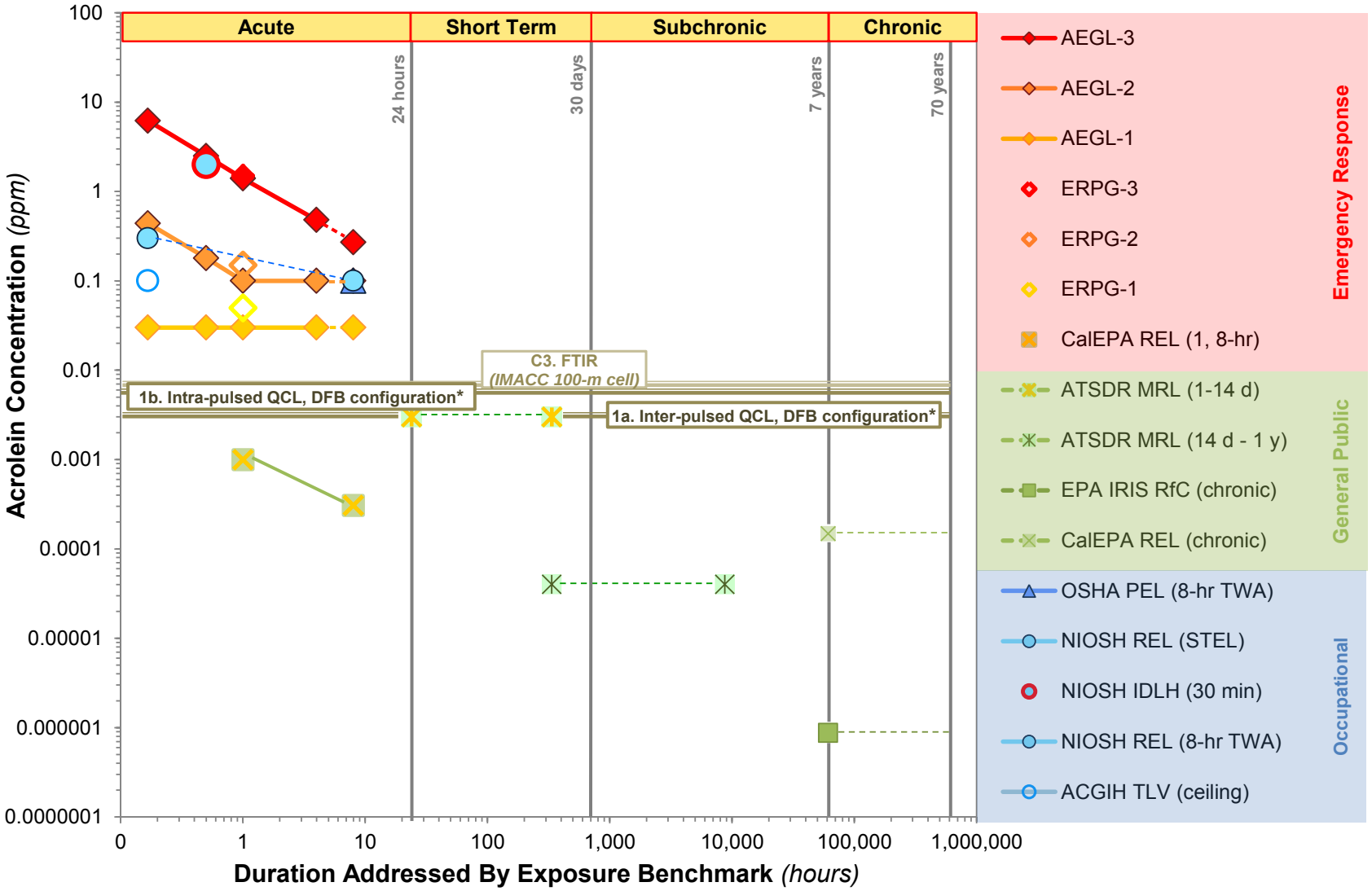
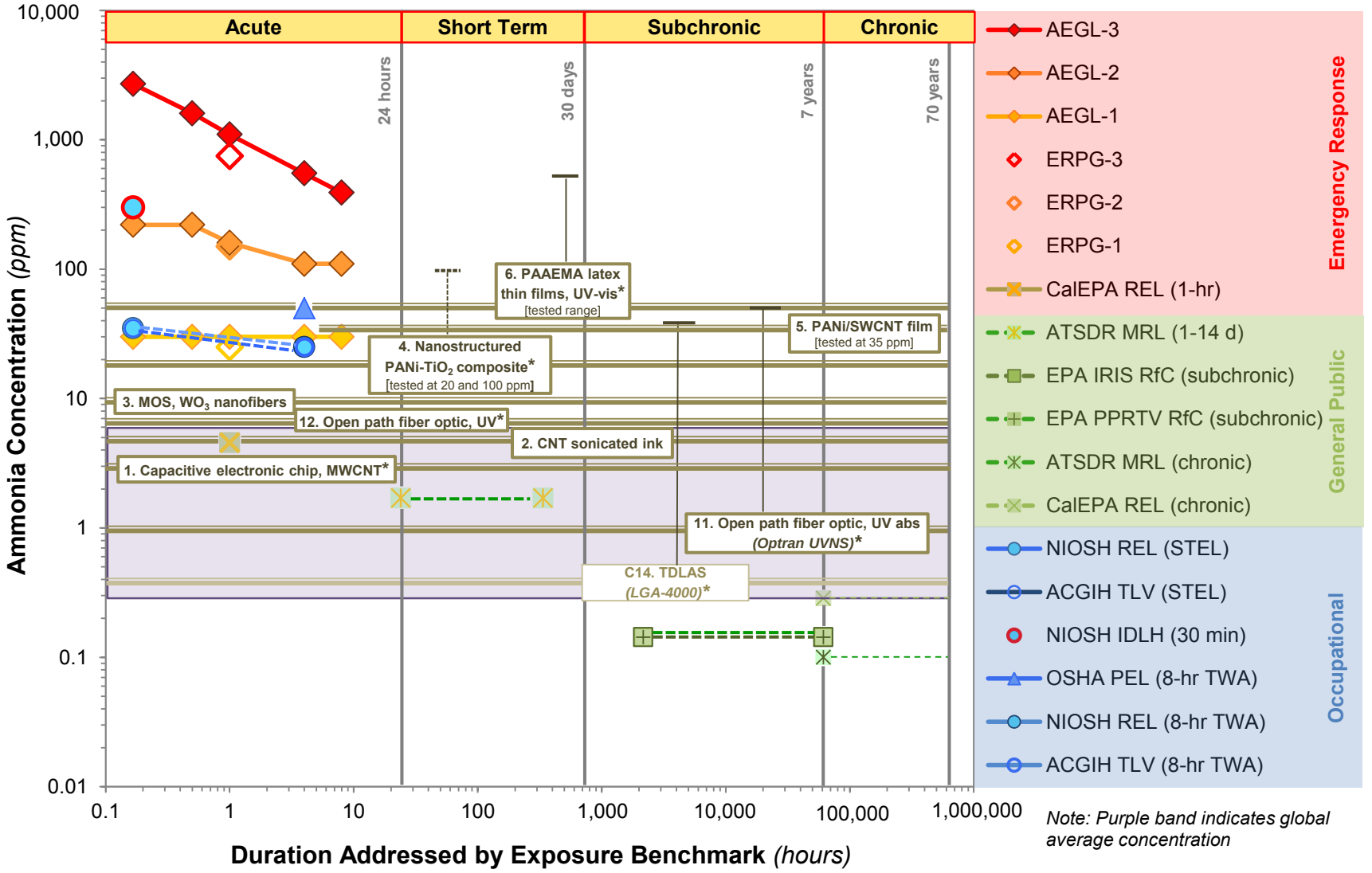
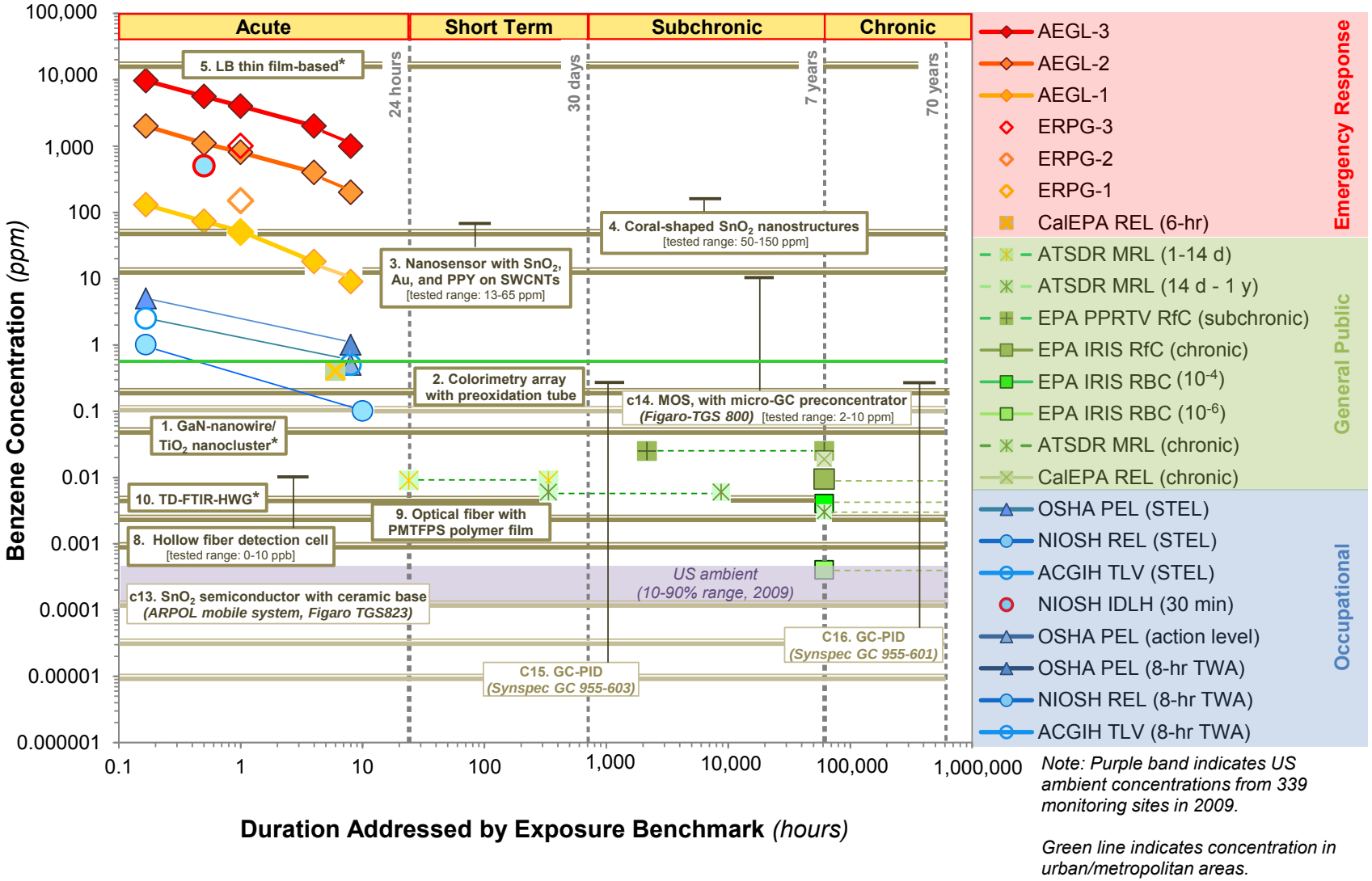


FIGURE 3-6 Acrolein: Comparison of Detection Levels to Exposure Benchmarks



Note: Purple band indicates global average concentration



Note: Purple band indicates US ambient concentrations from 339 monitoring sites in 2009.

Green line indicates concentration in urban/metropolitan areas.

FIGURE 3-8 Benzene: Comparison of Detection Levels to Exposure Benchmarks and Example Concentrations

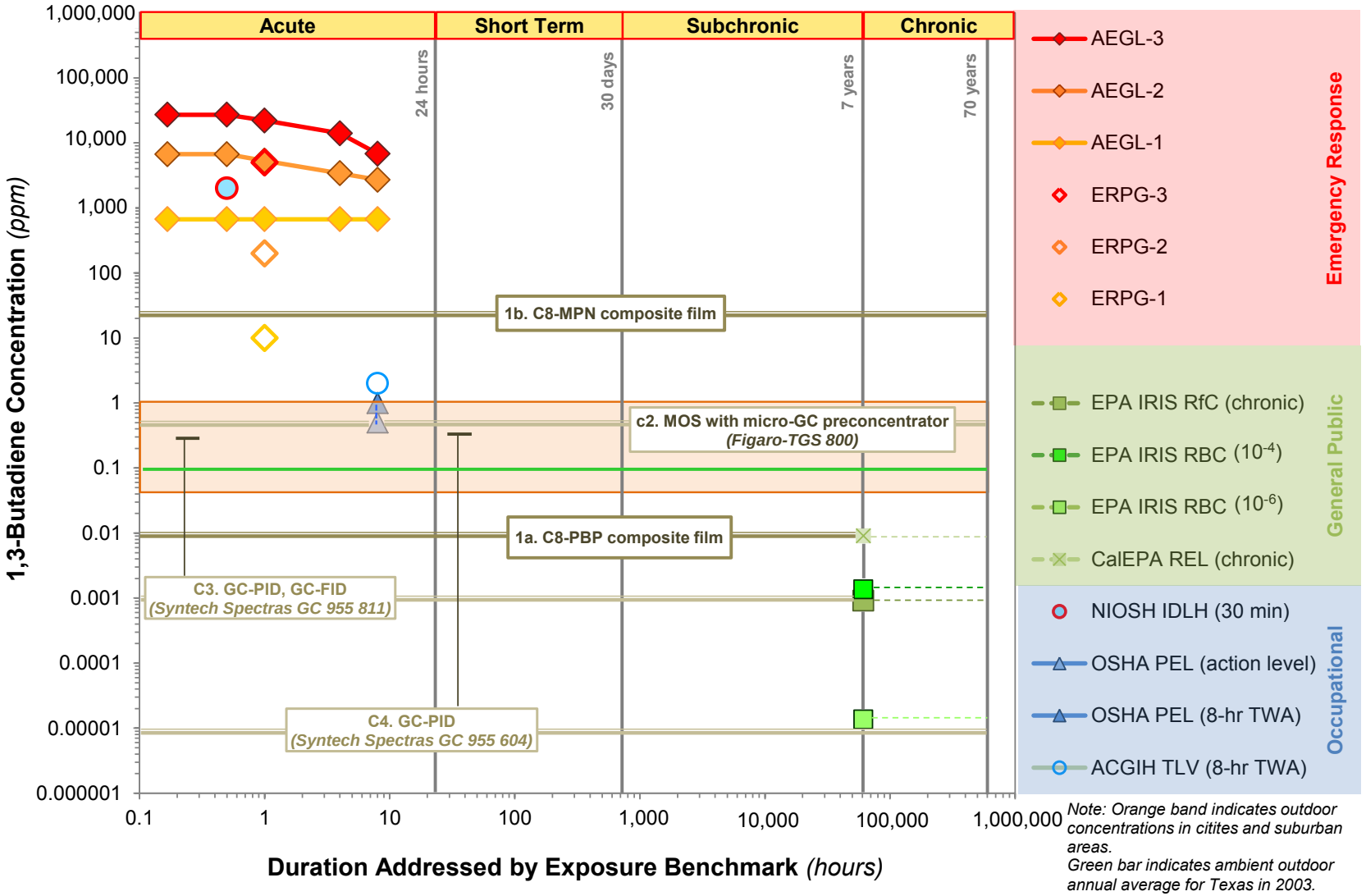


FIGURE 3-9 1,3-Butadiene: Comparison of Detection Levels to Exposure Benchmarks and Example Concentrations

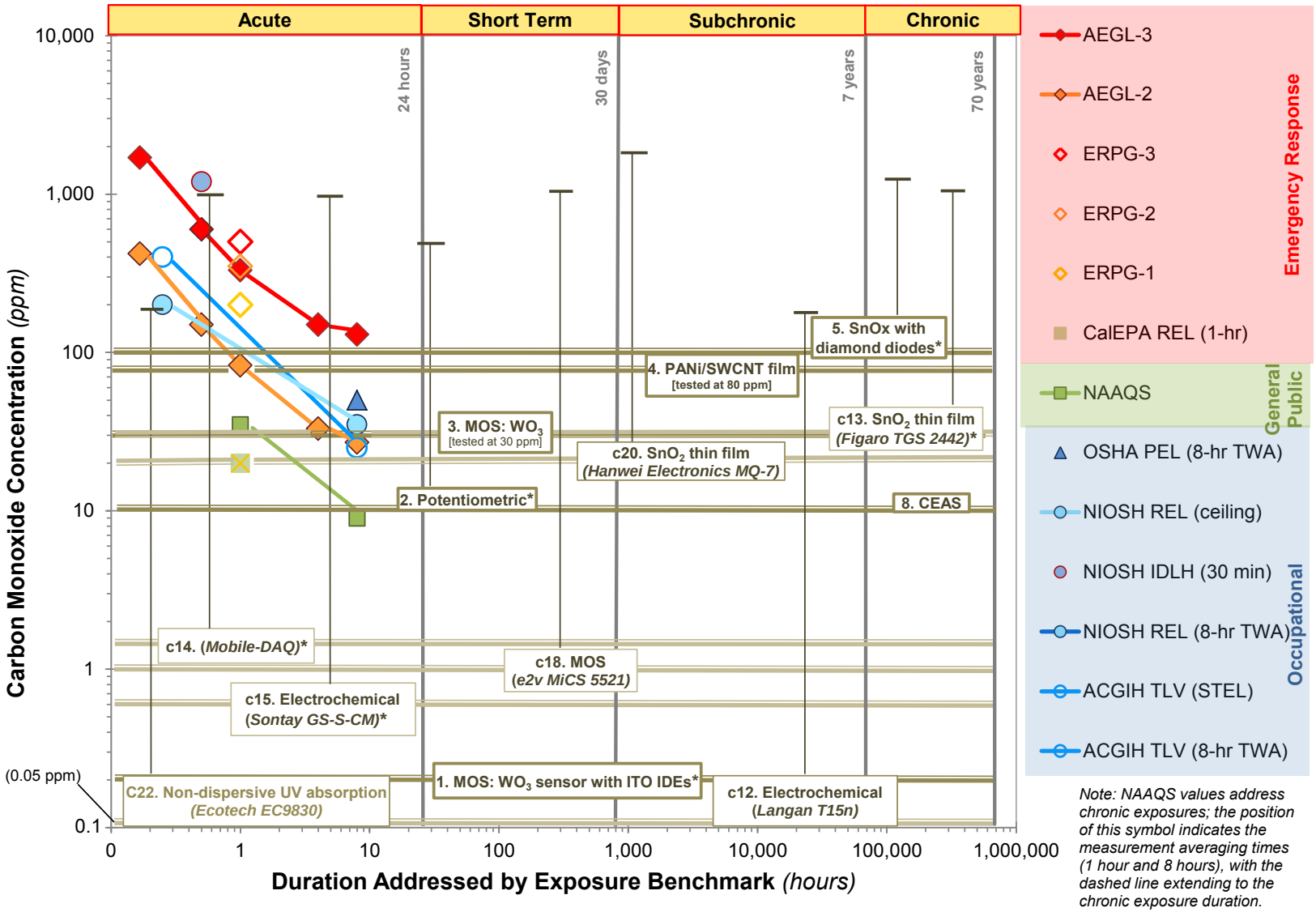


FIGURE 3-10 Carbon Monoxide: Comparison of Detection Levels to Exposure Benchmarks

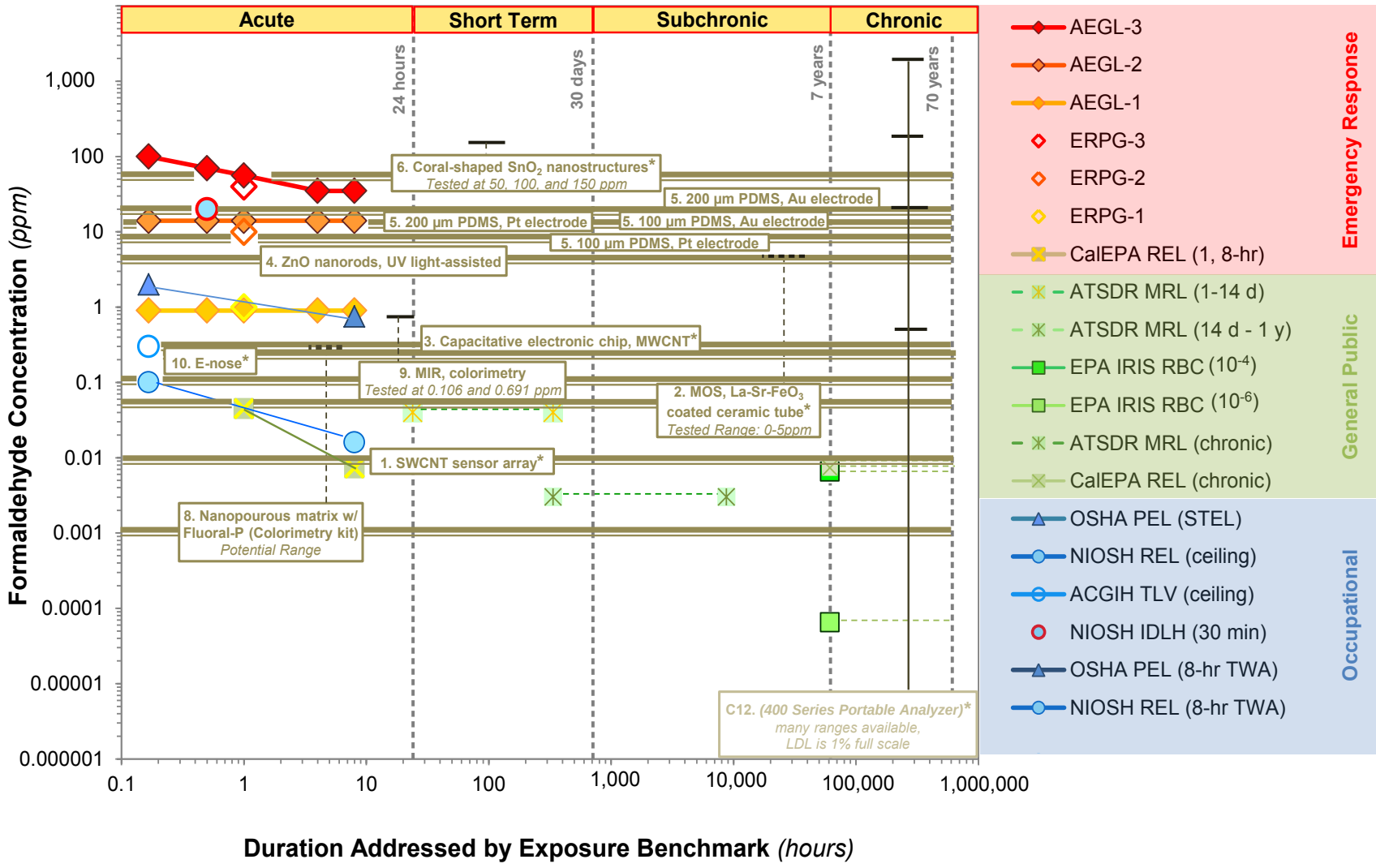


FIGURE 3-11 Formaldehyde: Comparison of Detection Levels to Exposure Benchmarks

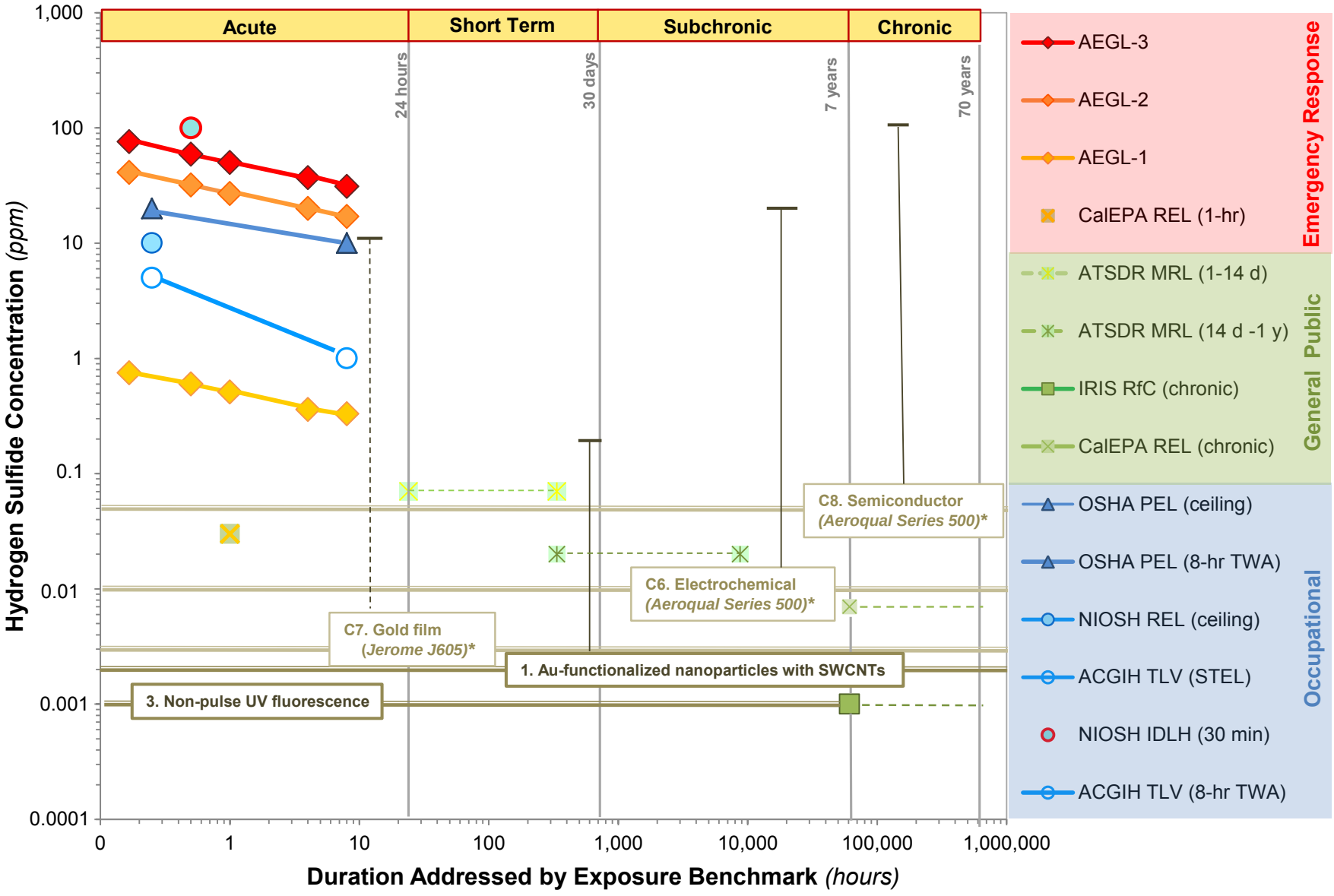


FIGURE 3-12 Hydrogen Sulfide: Comparison of Detection Levels to Exposure Benchmarks

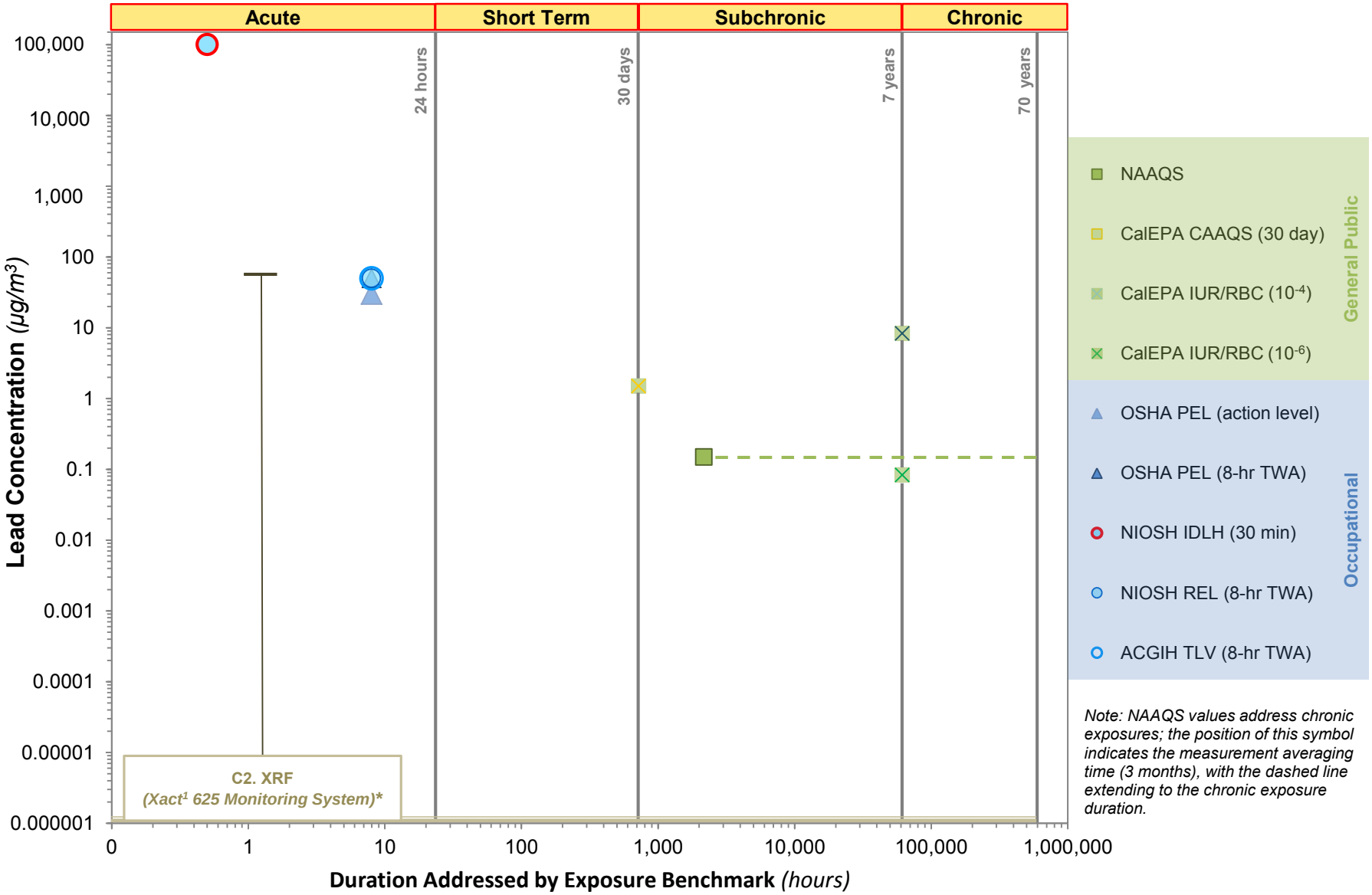


FIGURE 3-13 Lead: Comparison of Detection Levels to Exposure Benchmarks

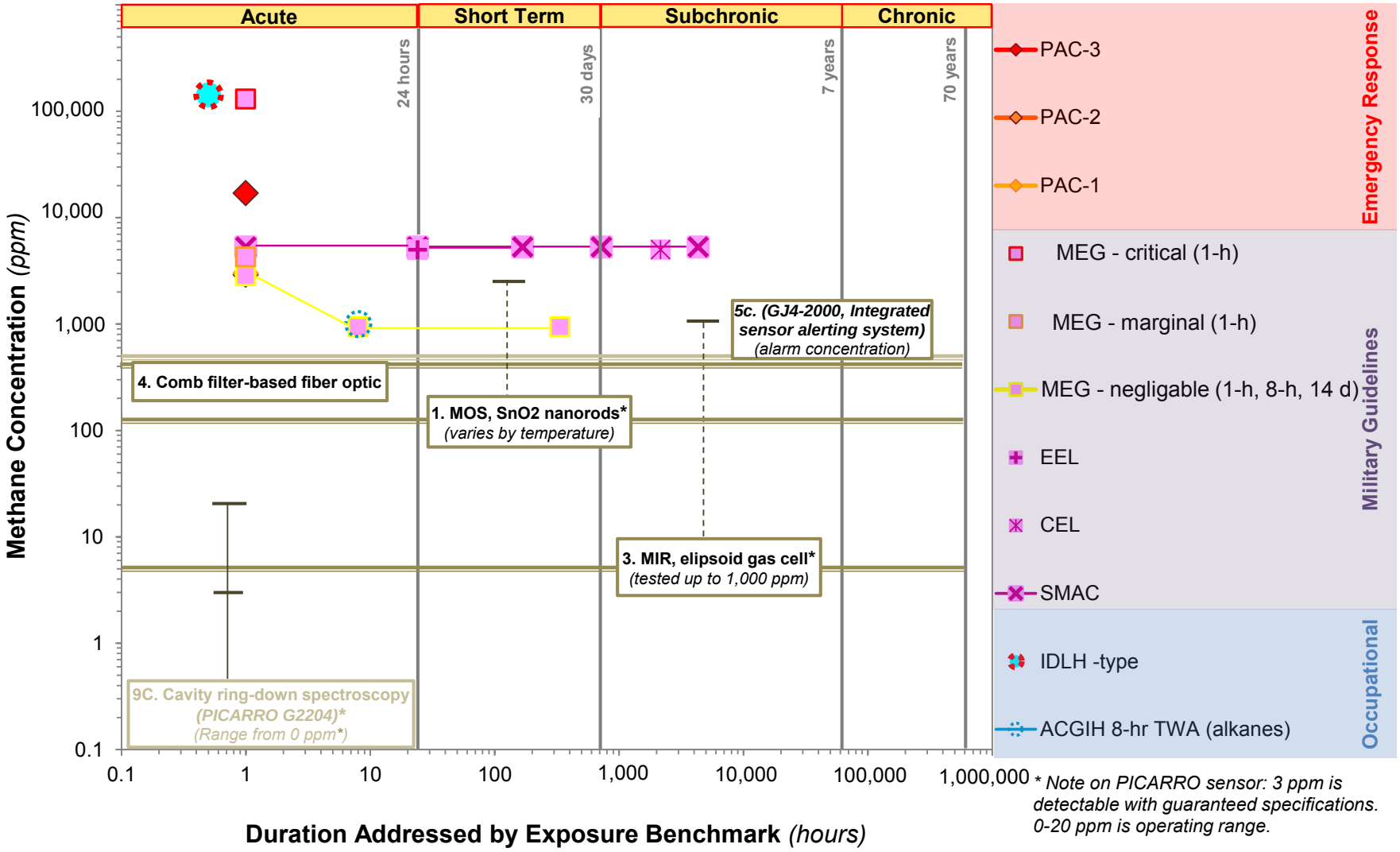


FIGURE 3-14 Methane: Comparison of Detection Levels to Exposure Benchmarks

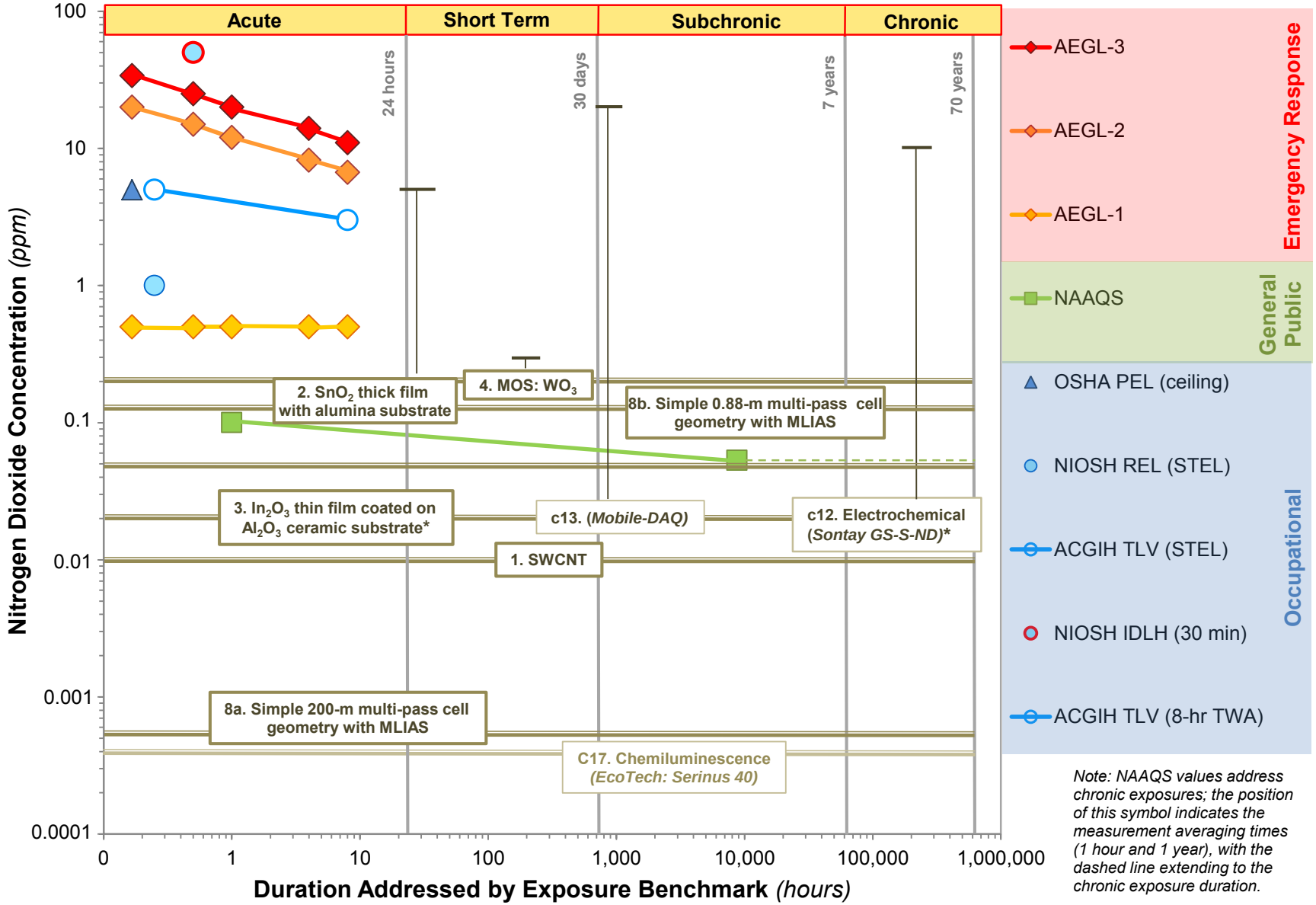


FIGURE 3-15 Nitrogen Dioxide: Comparison of Detection Levels to Exposure Benchmarks

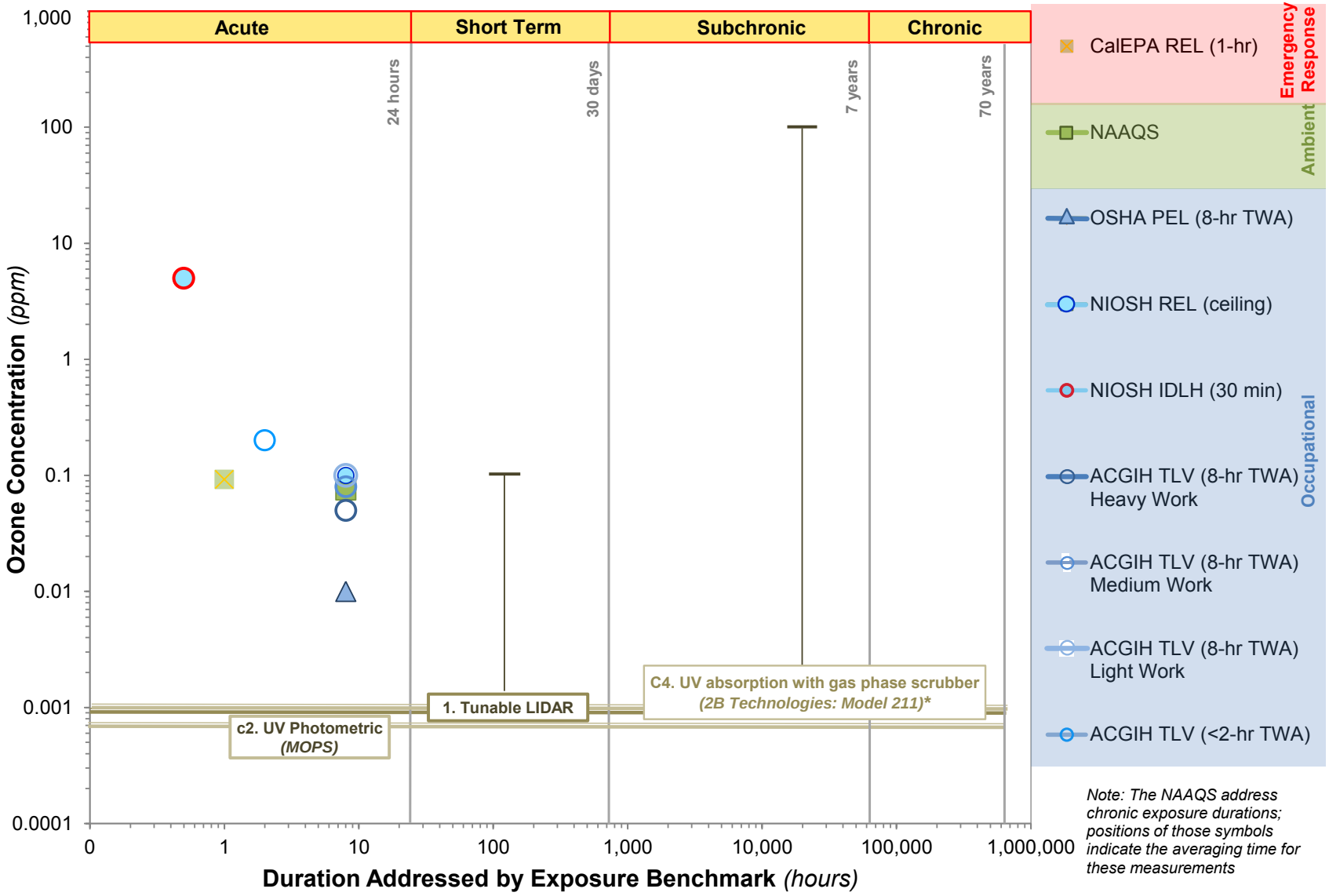


FIGURE 3-16 Ozone: Comparison of Detection Levels to Exposure Benchmarks

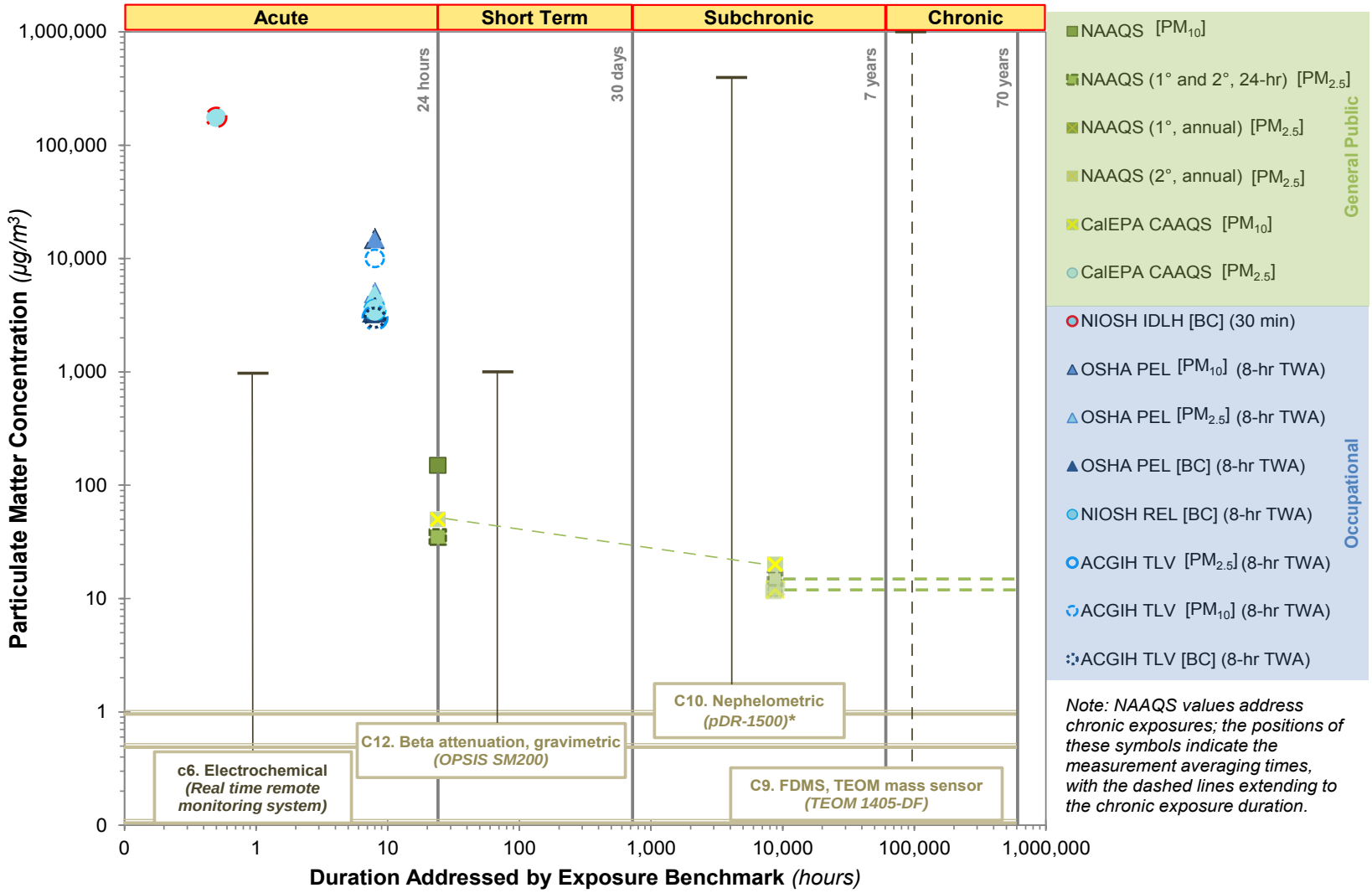
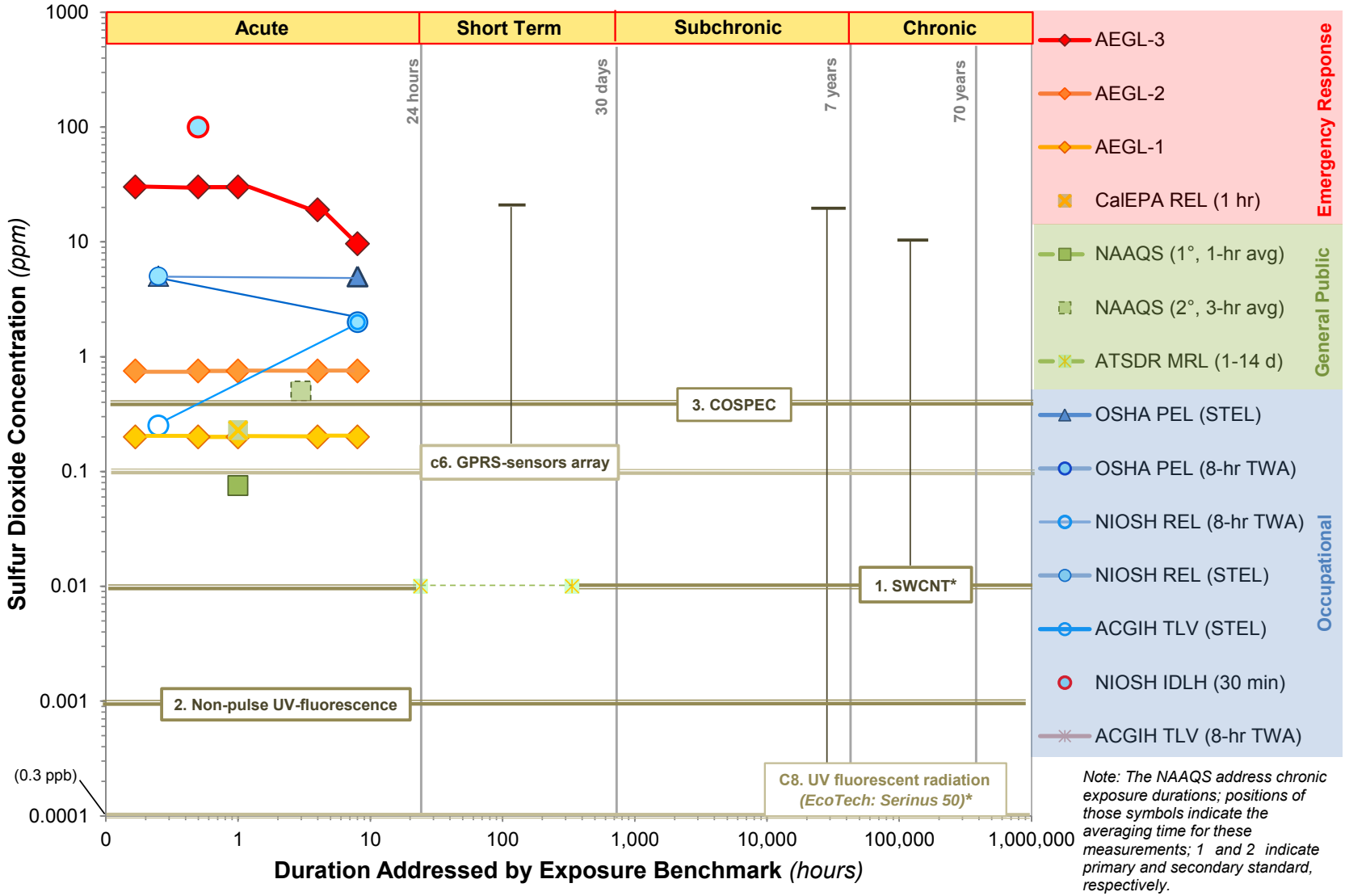


FIGURE 3-17 Particulate Matter: Comparison of Detection Levels to Exposure Benchmarks



Note: The NAAQS address chronic exposure durations; positions of those symbols indicate the averaging time for these measurements; 1 and 2 indicate primary and secondary standard, respectively.

FIGURE 3-18 Sulfur Dioxide: Comparison of Detection Levels to Exposure Benchmarks

From the information evaluated in this report, it appears that the criteria pollutant gases can be detected across the range of existing health-based benchmarks. Some electrochemical sensors are appearing to show promise for some gases, such as ozone and nitrogen dioxide, at the part per billion (ppb) level. However, rarely do current technologies achieve concentrations in that range (or in the ppm range for carbon monoxide), and that capability has long been a critical need for epidemiologists, in order to reduce some of the high uncertainty in the exposure estimates used for those studies. The same need to characterize individual exposures also applies to emerging personalized medicine studies.

Beyond the challenge of reliably detecting low concentrations, interferences also represent a difficult issue for gas sensors. Almost all will respond to interferences, and in some cases the response can be quite dramatic. Thus, not only do emerging sensors need to demonstrate detection capabilities in the low ppb range and lower, they must also demonstrate specificity, to be able to detect the pollutant gas of interest over a wide range of temperatures and environmental conditions, including in the presence of interferences. Many sensors have difficulty separating the target pollutant from interfering gases, which can result in high readings. See Chapter 4 for additional discussion of interferences.

Similar to the needs described above for the criteria pollutant gases, lead poses a substantial gap, and detection capabilities for this pollutant are quite limited. Thus, opportunities exist for developing smaller, less expensive, reliable, accurate sensors for all criteria pollutants over a range of temperatures and environmental conditions, including under high humidity and in the presence of interferences such as other gases. Because of the concern that even very low concentrations of lead can produce adverse health effects, research and development needs for sensors that can detect lead at sufficiently low levels are particularly pressing.

Several other pollutants may not be detectable across the range of health-based benchmarks, particularly at concentrations established for lifetime exposures. Only three pollutants were reported to be detected by a research or commercial sensor at the concentration corresponding to an incremental lifetime cancer risk of 10^{-4} and/or reference concentration (RfC) that represents a safe level for noncancer effects. These pollutants are benzene and 1,3-butadiene (HAPs) and hydrogen sulfide (indicator pollutant). (Regarding 1,3-butadiene, CalEPA [2013] recently proposed new reference exposure levels, notably 297 ppb for acute (1-hr) exposures, 13 ppb for 8-hr exposures, and 3 ppb for chronic exposures, which is lower than the extant value shown in Figure 3-9.)

Four pollutants – acetaldehyde, acrolein, ammonia, and formaldehyde – are potentially detectable at concentrations corresponding to 10^{-4} risk but not at the lower concentration corresponding to an incremental risk of 10^{-6} (point of departure) and/or at the RfC established to protect against adverse noncancer effects. (As a note for formaldehyde, the commercial sensor reflected on the graphical array can detect concentrations ranging from 0 to 20, 200, or 2000 ppm, with a minimum of 1.0% full scale).

Regarding benchmarks for higher concentrations, such as emergency response or occupational levels, it appears that these levels could potentially be detected but this cannot actually be determined without further information in some cases. Sensor response time is an important aspect of sensing capabilities, and that is not accounted for in the arrays; thus, the "effective detection capability" for short-duration benchmarks is not known. For example, even if a sensor could detect a concentration at or below a level established for the 10-minute emergency response level or a 15-minute ceiling value for the workplace, the sensor response and recovery time may not be sufficient for that concentration to be measured during the target time interval.

To illustrate, if the response time were 20 minutes or the device needed 20 minutes to refresh between sampling, then the pollutant could easily be missed during that measurement period even if the concentration were high.

A second important qualification for the initial findings is that for some sensors, because of incomplete reporting, it is not known whether certain pollutant concentrations could be detected or not. That is, the detection range is missing from many research publications, and in others the range only reflects the predetermined concentrations tested. Furthermore, many of the sensor capabilities reported in these research highlights have not been validated, including many LDLs, detection ranges, and accuracies. Without that information, no definitive statements can be made regarding sensor capabilities, including whether a given sensor can detect relatively high concentrations such as for emergency response situations. In fact, for a number of sensing technologies/techniques, high concentrations could potentially overwhelm the sensing substrate (such as a film), thus making it difficult to assure that the pollutant would be detected during the short intervals addressed by those guidelines.

3.5.2 Plots of Example Concentrations and Sensor Detection Levels

As complements to the graphical arrays (which compare reported sensor detection levels to exposure benchmarks), additional plots were developed to compare reported detection levels to example pollutant concentrations listed in various studies, to help frame the evaluation of gaps and opportunities. These further practical comparisons are shown in Figures 3-19 through 3-30. (As noted in Section 3.5.1, because little information was found to suggest illustrative concentrations for ammonia, benzene, and 1,3-butadiene, the example concentrations for these pollutants are included in their graphical arrays, see Figures 3-7 through 3-9.)

The following observations are offered from the comparison of reported sensor detection capabilities for the study pollutants and example concentrations across a variety of settings, as illustrated in Figures 3-19 through 3-30.

Acetaldehyde: Sensors can potentially detect the higher concentrations shown in Figure 3-19, such as those identified for gasoline and diesel exhaust, ambient Los Angeles air; and smoking households. However, the example ambient average and illustrative concentrations for the California air basin and regions in New York and Alaska fall below the reported detection levels, so many concentrations across the U.S. may not be addressed.

Acrolein: The sensors identified (inter- and intra-pulsed QCL) might be able to detect the higher example concentrations shown for indoor and outdoor air, but they would not be able to detect other concentrations shown in this range. In any case, even the concentrations reported here must be considered somewhat uncertain, given the continuing difficulties involved in accurately measuring this chemical in air.

Ammonia: Several research sensors can potentially detect the concentration range indicated for the global ambient average (see Figure 3-7).

Benzene: Two commercial sensors (GC-PIDs) and a novel system that incorporates a commercial sensor can potentially detect benzene concentrations in the example range represented on Figure 3-8 (U.S. ambient levels for 2009). However, the detection levels reported for the sensors found for this report lie above that range.

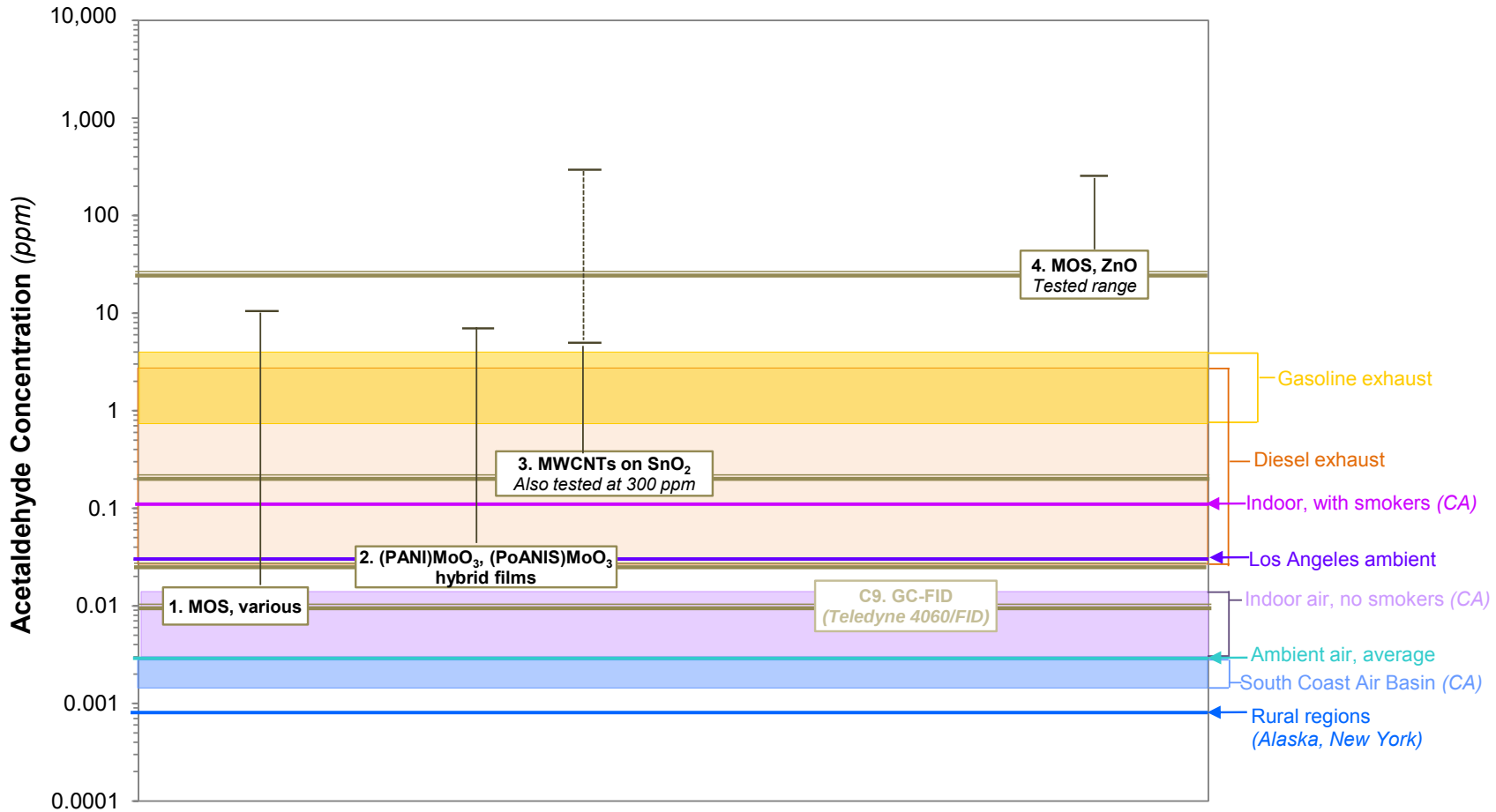


FIGURE 3-19 Acetaldehyde: Comparison of Detection Levels to Example Concentrations

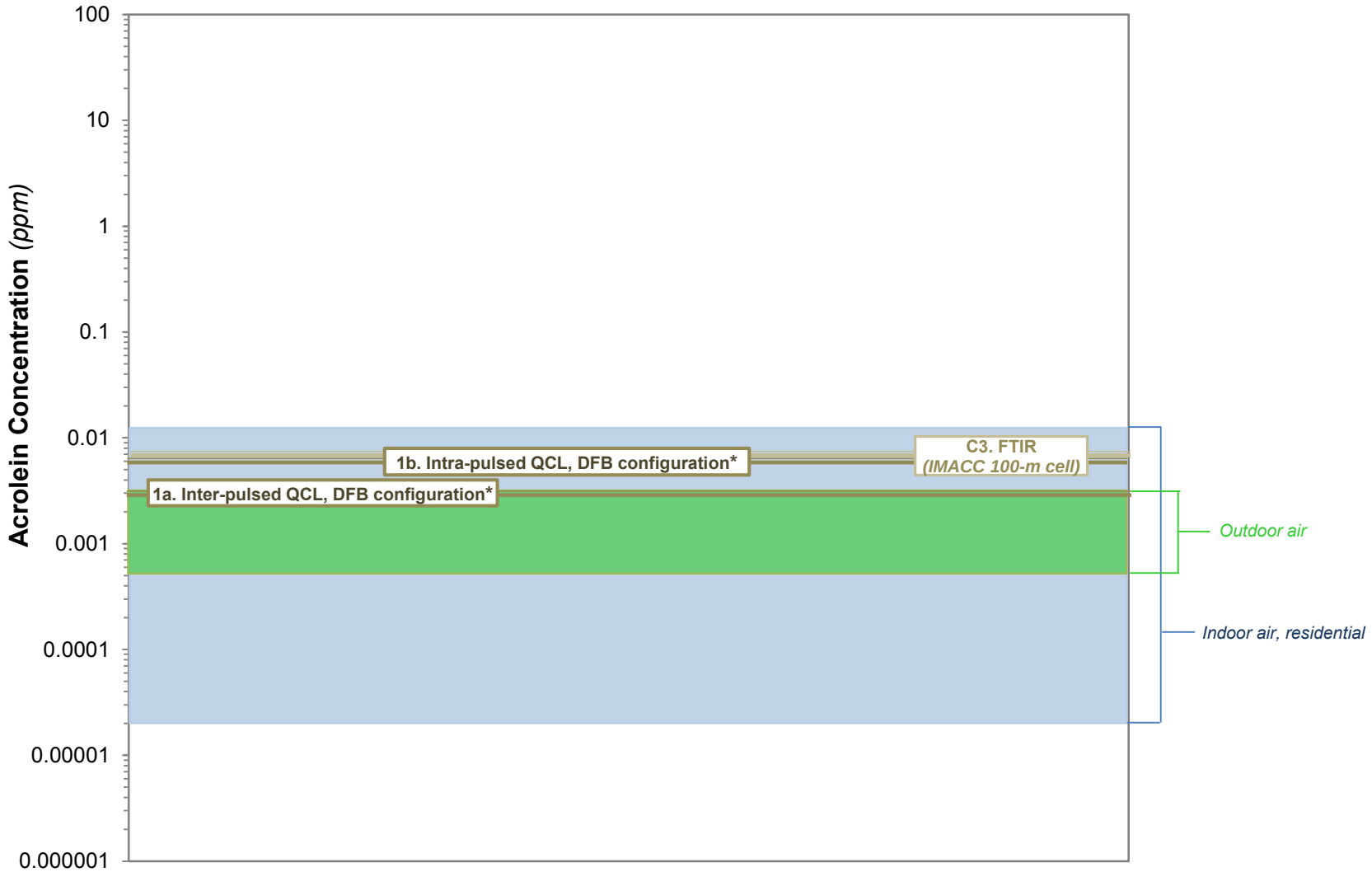
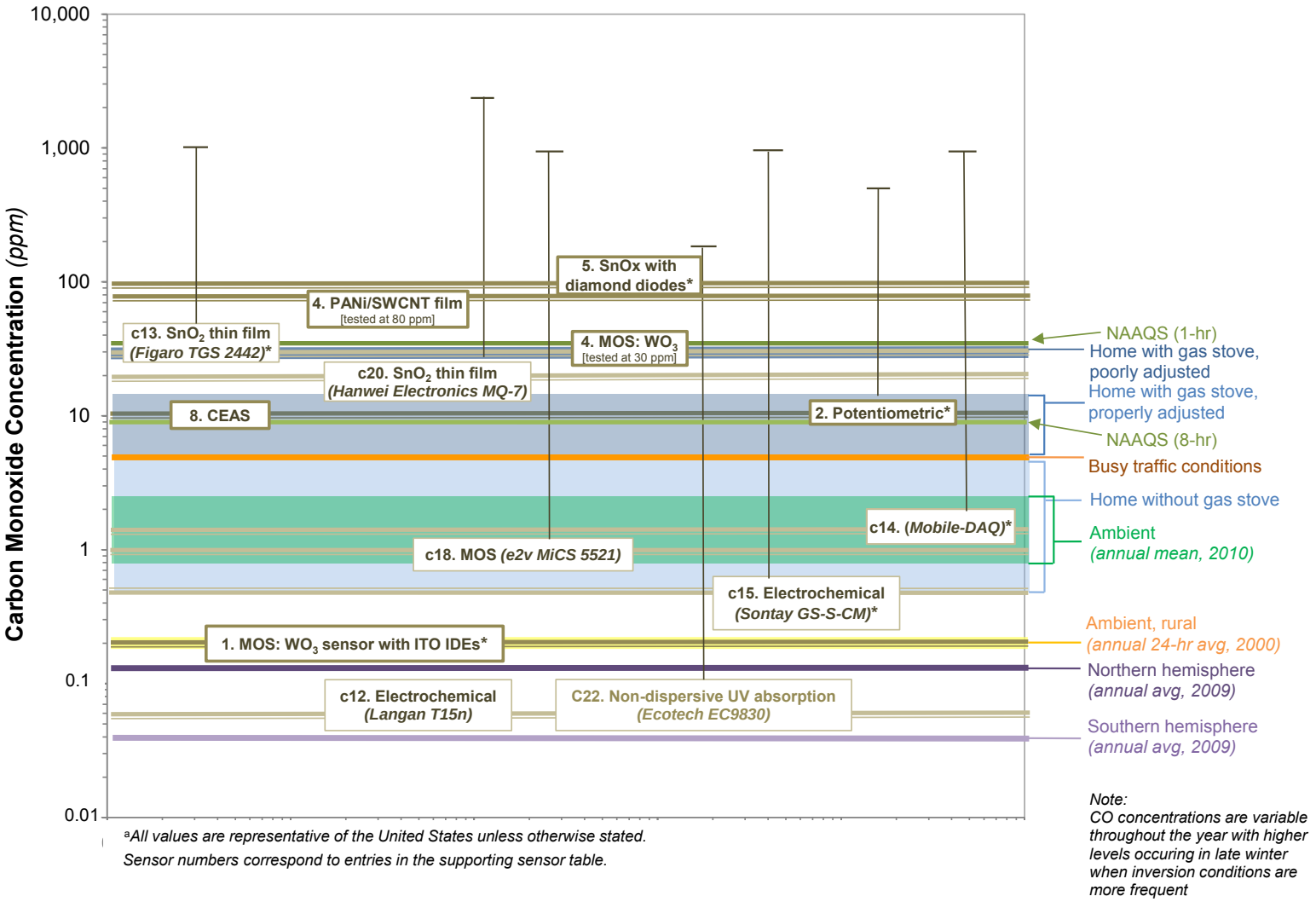


FIGURE 3-20 Acrolein: Comparison of Detection Levels to Example Concentrations

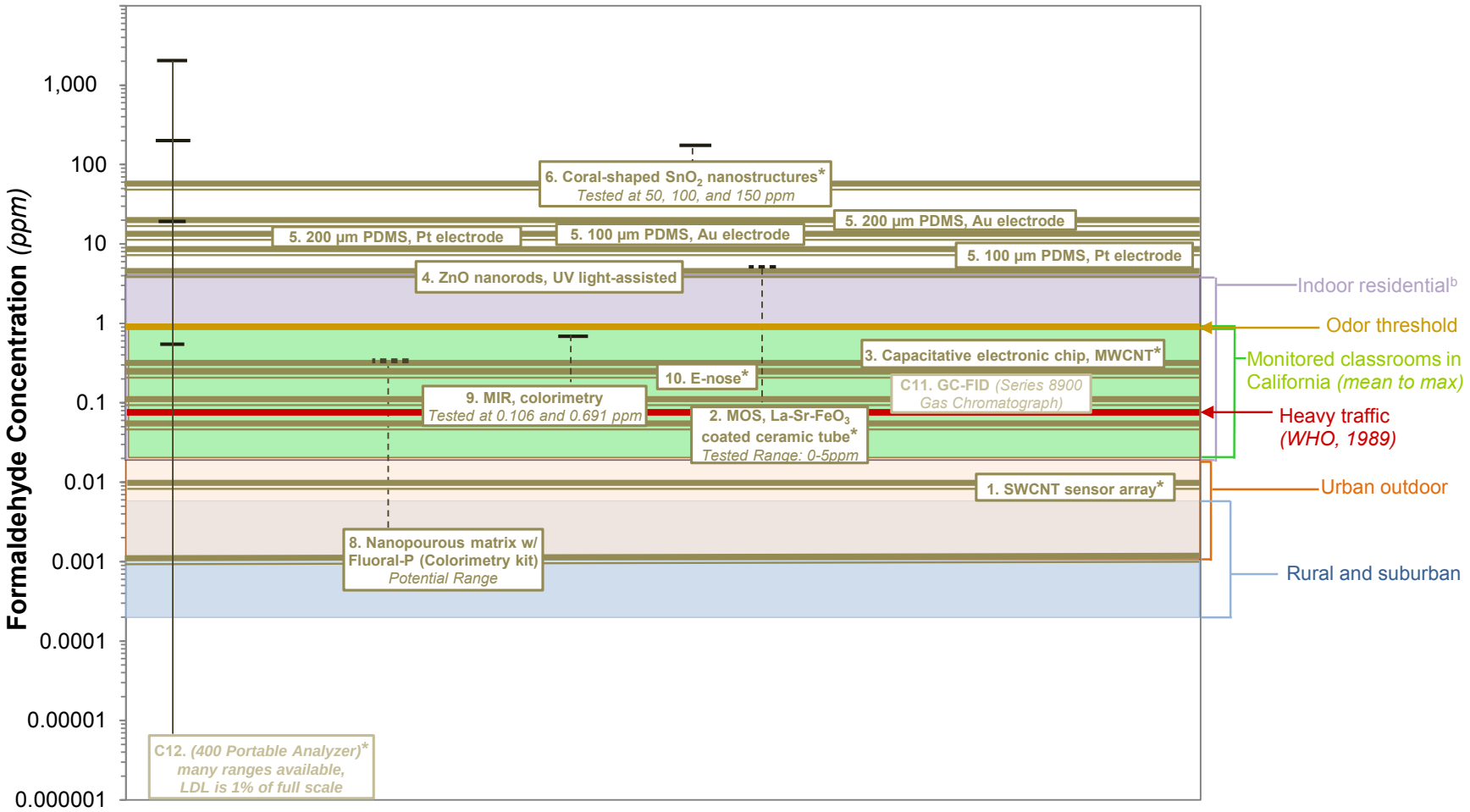


[a]*All values are representative of the United States unless otherwise stated.*

Sensor numbers correspond to entries in the supporting sensor table.

FIGURE 3-21 Carbon Monoxide: Comparison of Detection Levels to Example Concentrations

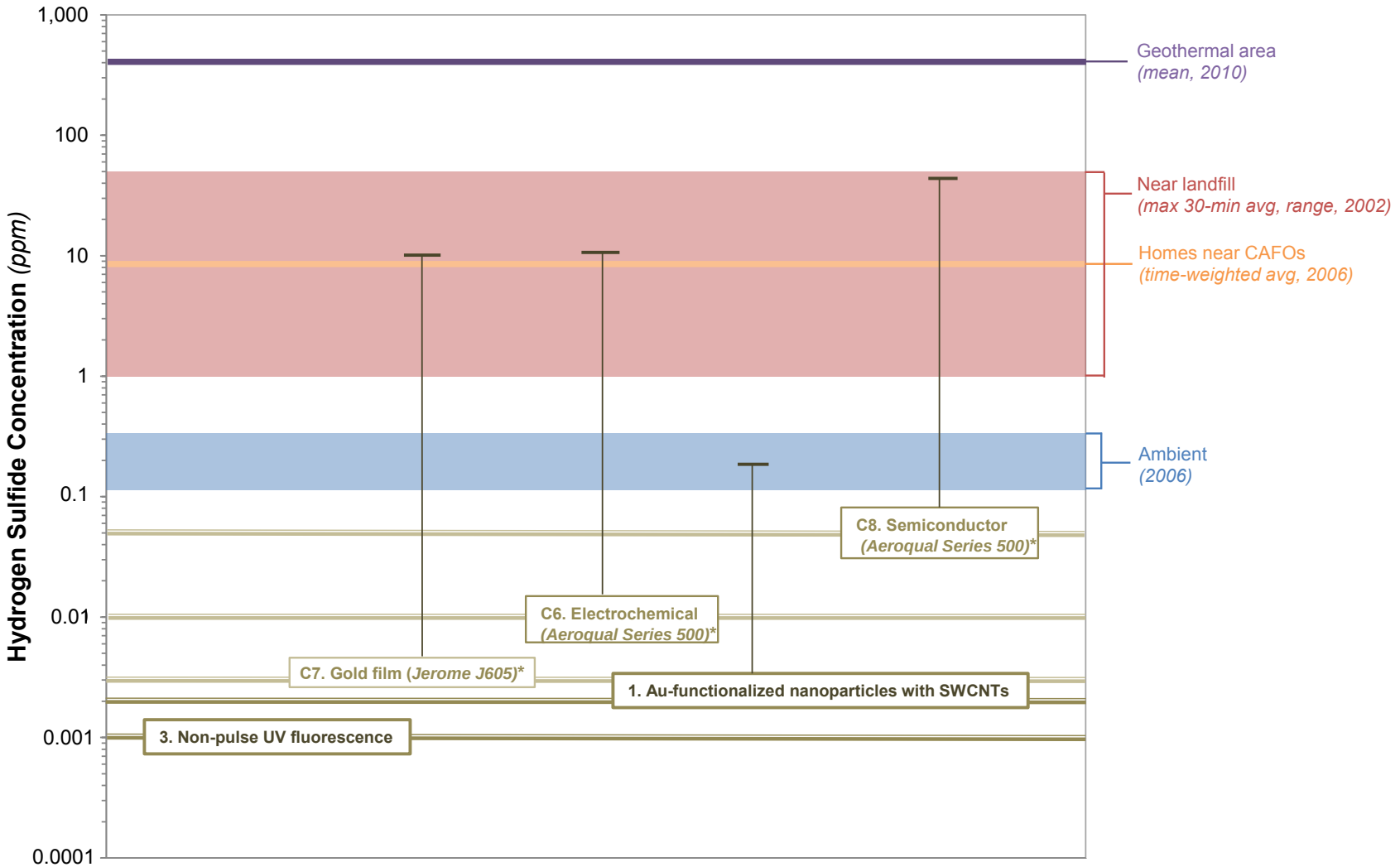
(Note that the Langan T15n can reasonably detect concentrations of 0.1 ppm, but values below that level are considered uncertain.)



[a] *All values are representative of the United States unless otherwise stated*

Sensor numbers correspond to entries in the supporting sensor table.

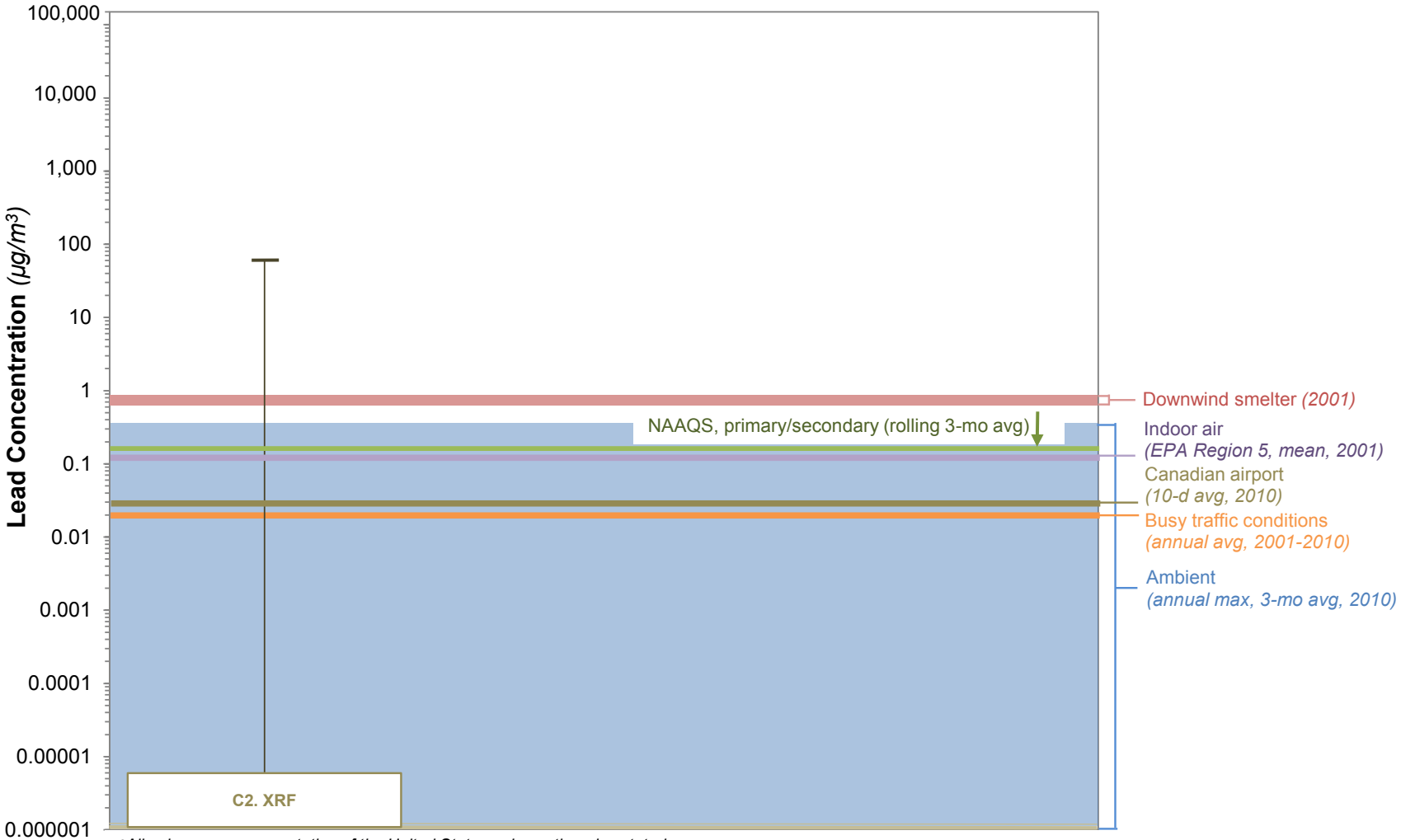
[b] *Indoor residential concentrations vary widely due to differences in room sizes, air exchange rates, and emission sources (such as gas space heaters, gas stoves with or without pilot lights, and fireplaces).*



[a]*All values are representative of the United States unless otherwise stated.*

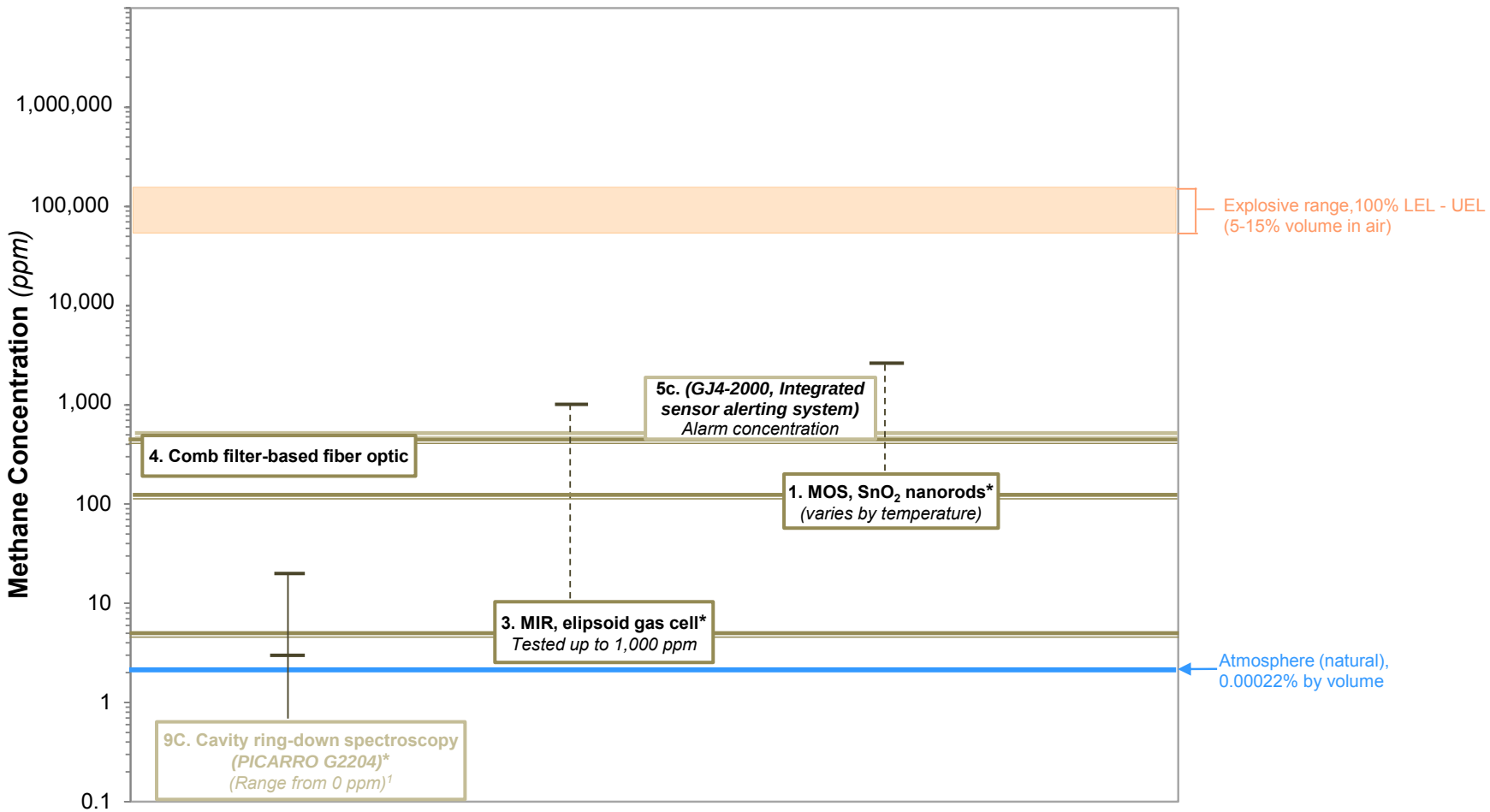
Sensor numbners correspond to entries in the supporting sensor table.

F

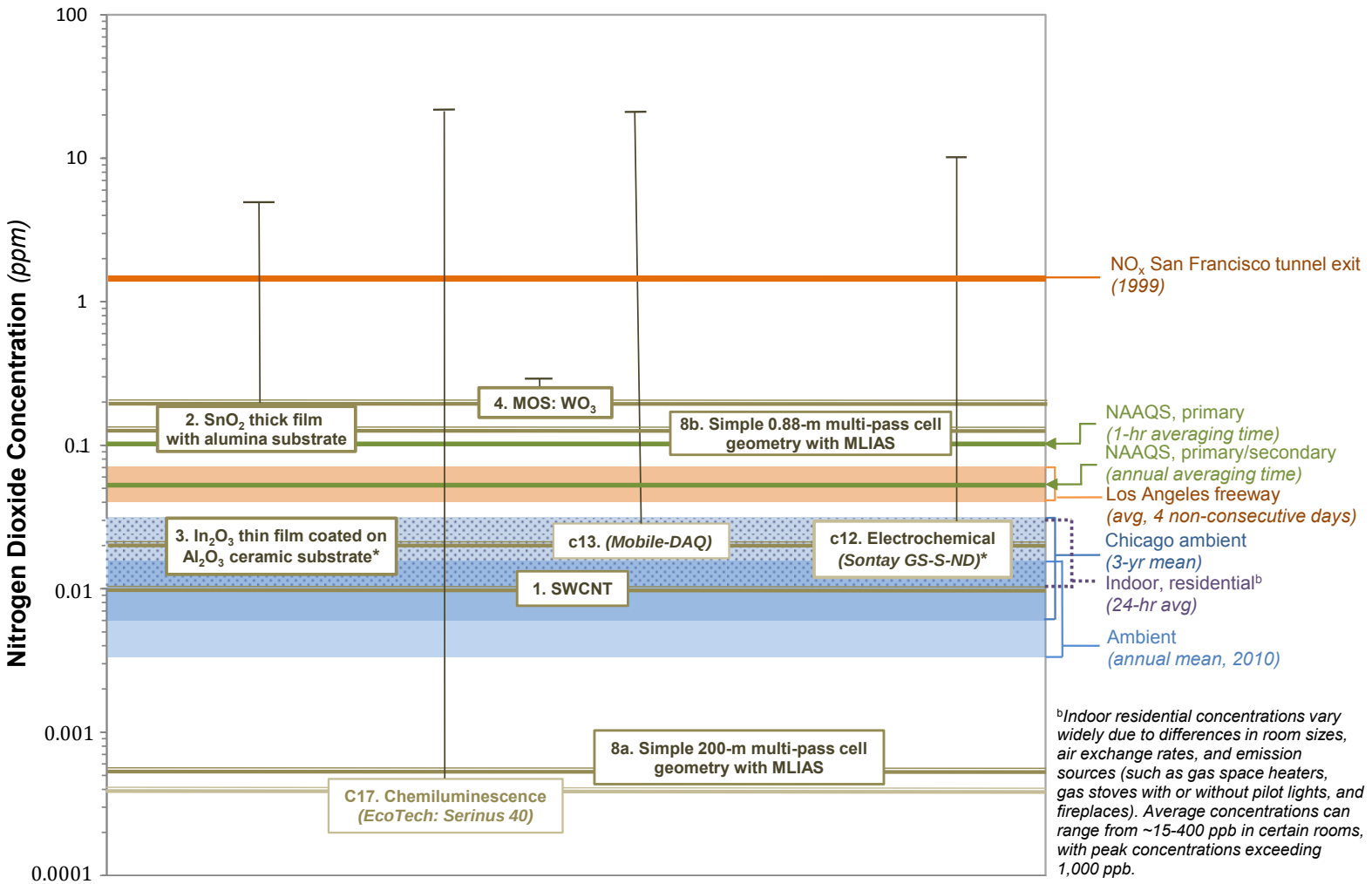


[a]All values are representative of the United States unless otherwise stated.
Sensor numbers correspond to entries in the supporting sensor table.

FIGURE 3-24 Lead: Comparison of Detection Levels to Example Concentrations



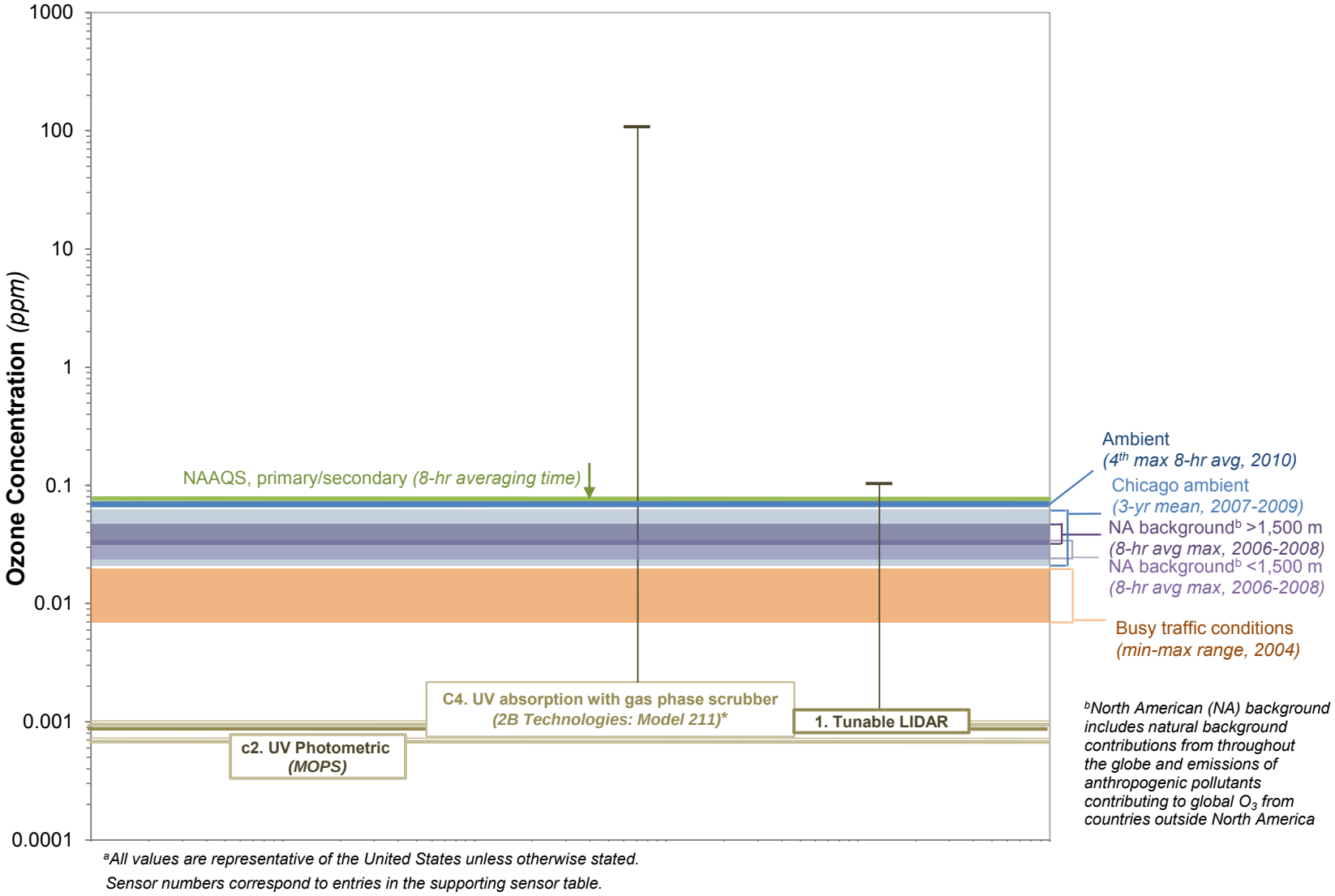
[1]3 ppm is detectable with guaranteed specifications; 0-20 ppm is operating range.



[a] *All values are representative of the United States unless otherwise stated. Sensor numbers correspond to entries in the supporting sensor table.*

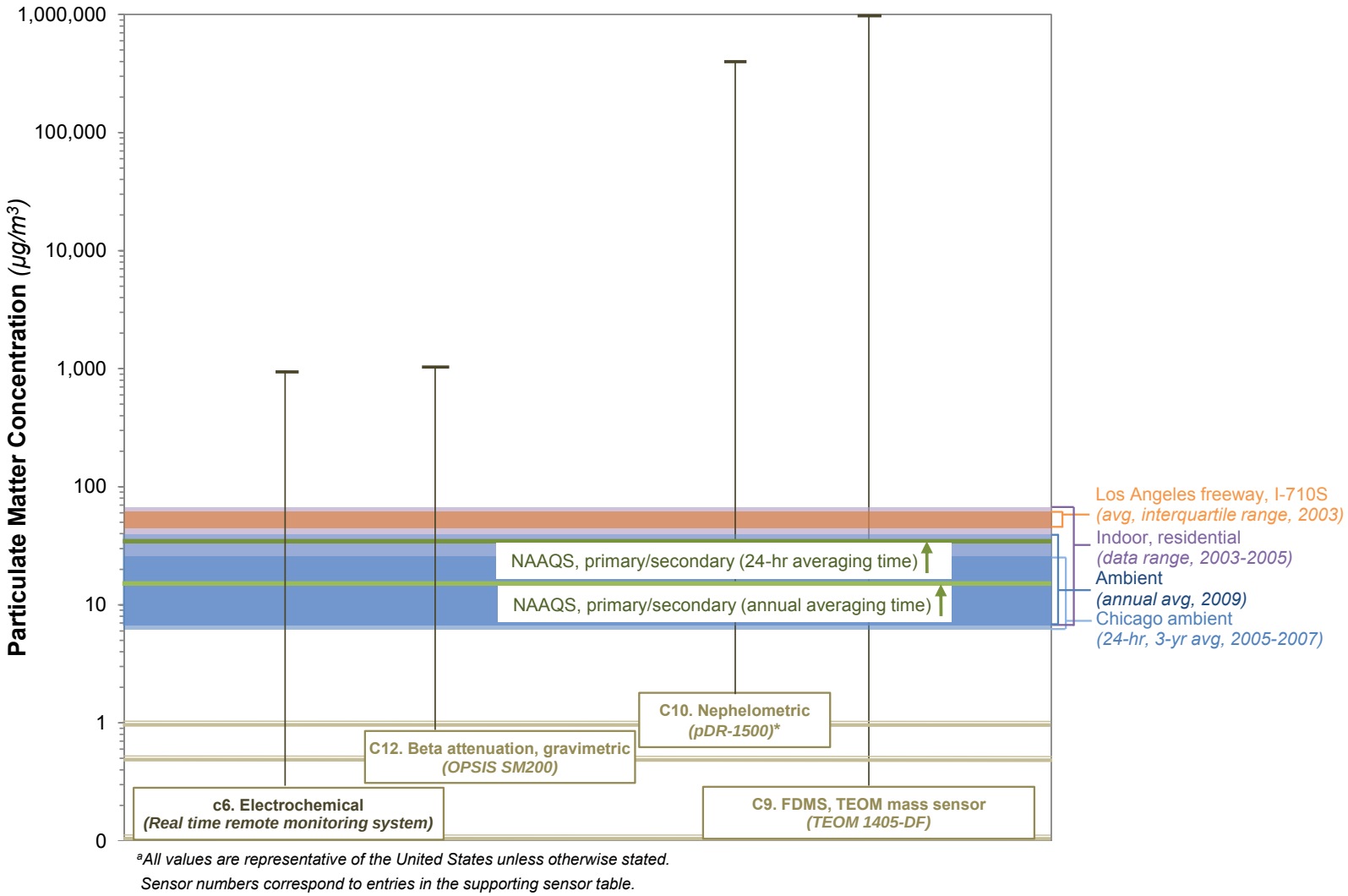
FIGURE 3-26 Nitrogen Dioxide: Comparison of Detection Levels to Example Concentrations

(Note that some electrochemical sensors appear to show promise at the ppb level for some gases, like NO_2 and ozone.)



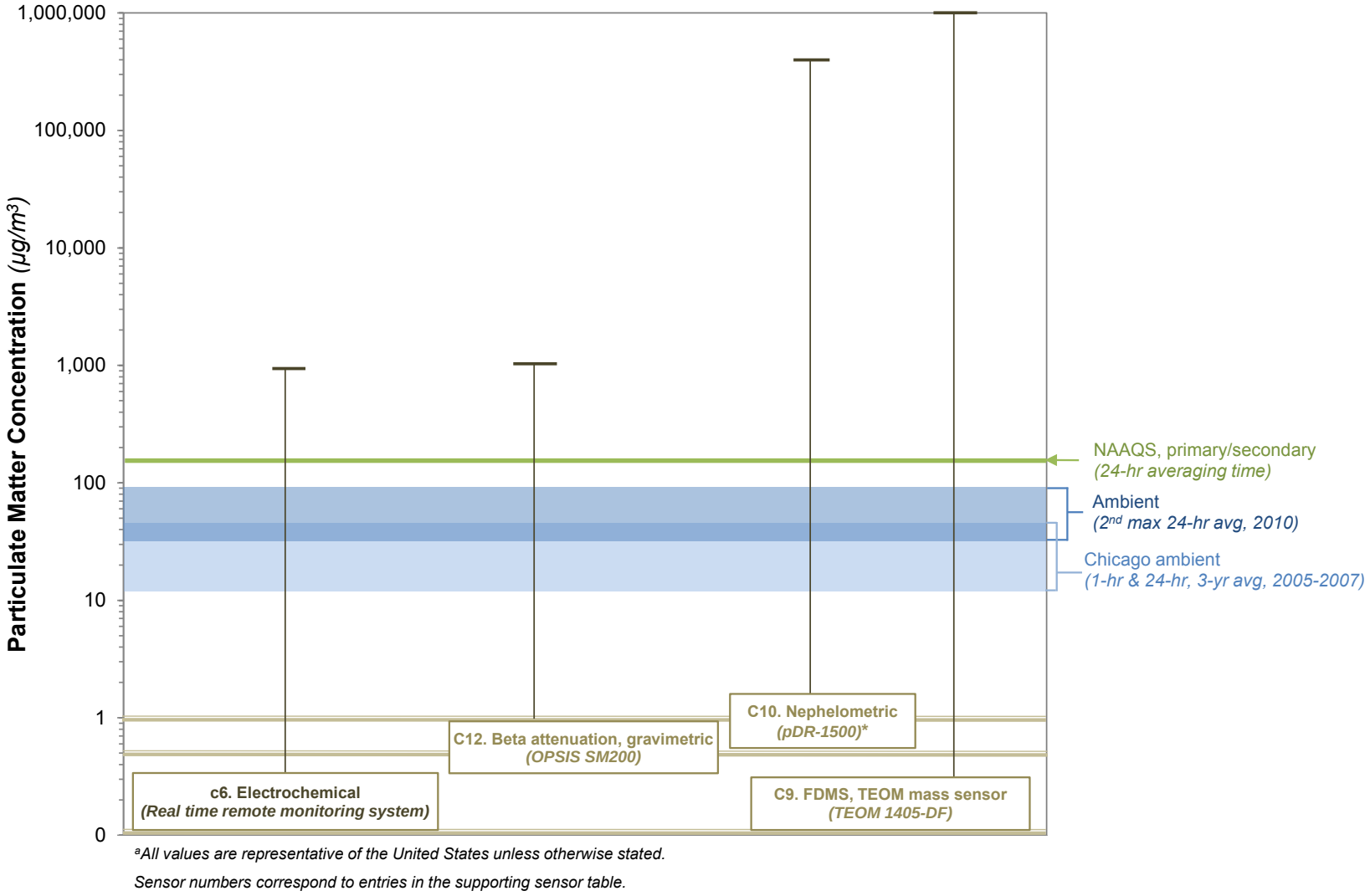
aAll values are representative of the United States unless otherwise stated.
Sensor numbers correspond to entries in the supporting sensor table.

FIGURE 3-27 Ozone: Comparison of Detection Levels to Example Concentrations



[a]*All values are representative of the United States unless otherwise stated.*
Sensor numbers correspond to entries in the supporting sensor table.

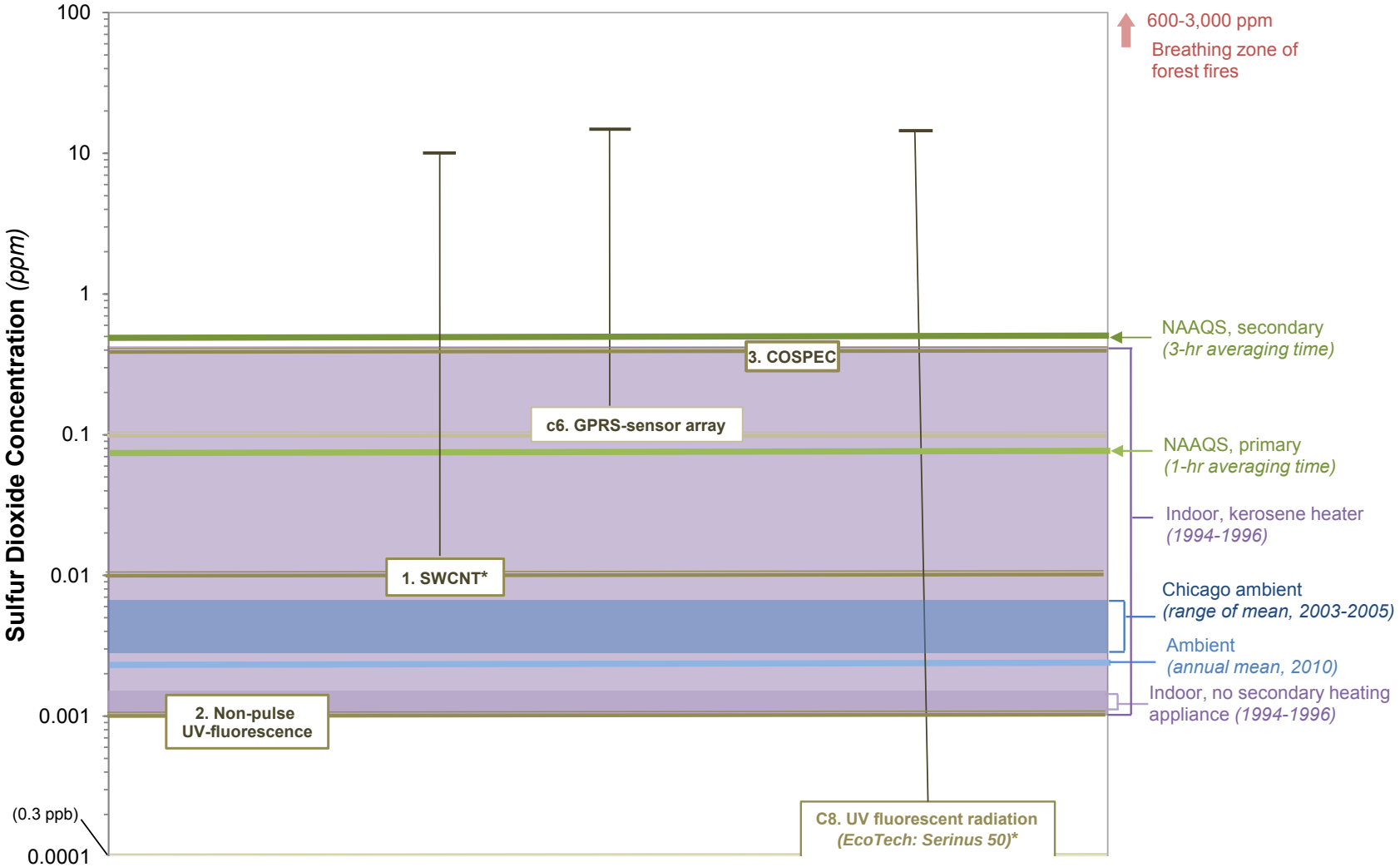
FIGURE 3-28 $PM_{2.5}$: Comparison of Detection Levels to Example Concentrations



[a]*All values are representative of the United States unless otherwise stated.*

Sensor numbers correspond to entries in the supporting sensor table.

FIGURE 3-29 PM_{10}: Comparison of Detection Levels to Example Concentrations



[a]*All values are representative of the United States unless otherwise stated.*
Sensor numbers correspond to entries in the supporting sesnor table.

F

1,3-Butadiene: Two commercial sensors (GC-PID and GC-FID) can detect concentrations in the range identified for outdoor concentrations for cities and suburban areas, as well as the outdoor annual average for Texas reported for 2003 (see Figure 3-9). The reported detection level for one novel system that uses a commercial sensor (MOS with micro-GC pre-concentrator) also lies within the range for cities and urban areas. However, it is not clear whether the composite film research sensor can detect those levels (the LDL lies below that ambient range but no detection range is identified). A companion research sensor based on the same technique lies well above the example concentration range for cities and urban areas.

Carbon monoxide: Commercial sensors can detect the example concentrations reported for this compound, as can a novel system that uses a commercial electrochemical sensor. Note that this sensor (Langan) can detect concentrations to about 1 ppm, but below that level the values are highly uncertain. As with many sensors and systems being developed or refined, the device can report a value, but whether it should (per validity) is a different matter. Some research sensors could potentially detect the higher example concentrations shown. They might also be able to detect some of the lower concentrations (the LDL lies below those ranges), but this is not known because the detection range was not reported.

Formaldehyde: Reported detection levels for several research sensors lie within the example concentration ranges identified for several settings, including residential homes and classrooms (California), as well as in urban areas, heavy traffic zones, and the upper range of rural and suburban outdoor concentrations.

Hydrogen sulfide: Commercial sensors can potentially detect this pollutant at the example concentrations shown. One research sensor (based on gold-functionalized nanoparticles with carbon nanotubes) might also be able to detect concentrations represented by the general ambient U.S. level from 2006. It is not clear whether a second research sensor (non-pulse UV fluorescence) can also potentially measure that level, because the reported LDL is much lower and no detection range was reported for that sensor.

Lead: The one commercial sensor identified for lead in air can detect the example concentrations shown, including the ambient U.S. concentration from 2010.

Methane: The reported LDLs of the research sensors for methane are higher than the natural atmospheric concentration, but least two could potentially detect this compound below its alarm concentration and explosive level. A novel system that uses a commercial sensor can also potentially detect methane at the alarm level.

Nitrogen dioxide: Research sensors can potentially detect this compound at the example ambient concentrations reported both for Chicago and the United States; the same finding applies for a commercial sensor that uses chemiluminescence and a novel sensor system that uses a commercial electrochemical sensor.

Ozone: A research sensor (using a tunable LIDAR technique) can potentially be used to measure ozone at the example concentrations reported, and the same finding applies for a commercial sensor that uses UV absorption. It is not clear if the novel sensor system that uses a UV photometric commercial sensor can detect these ambient levels, because the reported LDL lies below the example concentrations and no detection range was reported for that sensor.

Particulate matter: Commercial sensors (gravimetric and mass-based) are reported to detect PM at the example concentrations identified, and a novel system using a commercial (electrochemical) sensor designed for real-time remote monitoring can also potentially detect those levels.

Sulfur dioxide: Sensors can potentially detect indoor concentrations reported for homes with certain heating appliances; however, they may not be well suited to detecting the high example concentrations reported, such as in the breathing zone of forest fires.

3.6 ARCHITECTURE AND INFRASTRUCTURE APPROACHES AND APPS

The status of architecture and infrastructure for research sensors covers all stages of research and development, extending to patent applications, and commercially available products. The architectures/infrastructures can be organized into three general categories: (1) physical devices, (2) user interface design/programming, and (3) other approaches – such as data broadcasting and distributed data processing. These categories are further subdivided and described in the following sections. The number of sensing devices that reflect these architecture/infrastructure categories is summarized in Table 3-9 and illustrated in Figure 3-31. Note that not all subgroups in this section directly apply to sensors and apps for air pollutants. Nevertheless, having been included in relevant workshops and meetings (notably for ubiquitous computing), they provide a glimpse of related aspects of this active research area that may offer "cross-training" insights for the development and implementation of citizen sensor systems.

3.6.1 Physical Devices

***Cell phone-based* sensing** (27) – The cell phone group of devices utilize mobile phones as mobile sensing units. This group includes sensors mounted directly in/on mobile phones, downloadable apps, user interfaces, and imbedded processing technology. In general, these devices are typically used to collect data and/or detect environmental pollutants; transmit and share data across wireless networks; and process and analyze data, match outcomes, and interpret results from either a source database or sensor network within the user's proximity to enable real-time monitoring. Location is also commonly recorded by cell phone devices. The few detection methods or techniques that were identified for the cell phone-based sensor group include: colorimetrics, vibration, ultrasound, global positioning system (GPS), participatory sensing, user generated content, classification algorithms, and signal processing. The devices cover most stages of development from the research phase through commercial availability. Air pollutants detected by these mobile devices, as identified in the records, primarily include vehicle emissions and greenhouse gases, such as CO, CO_2, O_2, NO_x, SO_x, and PM. Other chemicals and parameters that can be measured include: formaldehyde, black carbon, temperature, humidity, UV radiation, activity, noise, location, and weeds.

Embedded/integrated sensor (7) – This group of sensors if embedded or integrated in something another object for a new or novel application, such as a musical instrument for respiratory therapy, thin flexible substrate applied to a floor to detect the presence and whereabouts of users using electromagnetic radiation sensing, animated fabric for multi-sensory communication, or cell phone for smart home management. In general, these devices detect sound, gestures, and movement, including pressure, vibration, acceleration, and gyroscope data. However, another device in this group combines multiple separate gas sensors into a single integrated sensor for detection of airborne gases, including CO, CO_2, NO_2, H_2S, and CH_4. These embedded or integrated sensors cover most stages of development from the research phase through design prototype.

TABLE 3-9 Categories and Counts for Architecture/Infrastructure[a]

Category for Architecture/Approach	Number
Physical Device	
Cell phone-based sensing	27
Embedded/integrated sensor	7
Fixed/semi-portable sensor unit	66
Handheld sensor	51
Mountable sensor	59
Nanoscale technology	50
Robotics	8
Vehicle-mounted unit	44
Wearable sensor	23
User Interface Design/Programming	
Activity/speech recognition	16
Algorithm/modeling	38
Ambient intelligence	6
Augmented reality	5
Context awareness	10
Database/data mining	5
Location awareness	23
Mobile sensing	11
Multi-sensor system	9
Participatory/citizen sensing	23
Remote sensing/monitoring	11
Sensor calibration	1
Social networking/computing	13
Ubiquitous computing	14
Virtual reality sensing	5
Visual sensing	11
Web-based system	10
Wireless sensor network (WSN)	54
Other	
Data broadcasting	3
Distributed data processing	1
Economic tradeoffs	2
Exposure assessment	8
Prediction service	1
Radar system	1

[a] These entries are organized alphabetically within each of the three general groups. See Figure 3-31 for the display organized by total counts. Note that these categories and subgroups are not exclusive, so the numbers include duplicate or multiple counts.

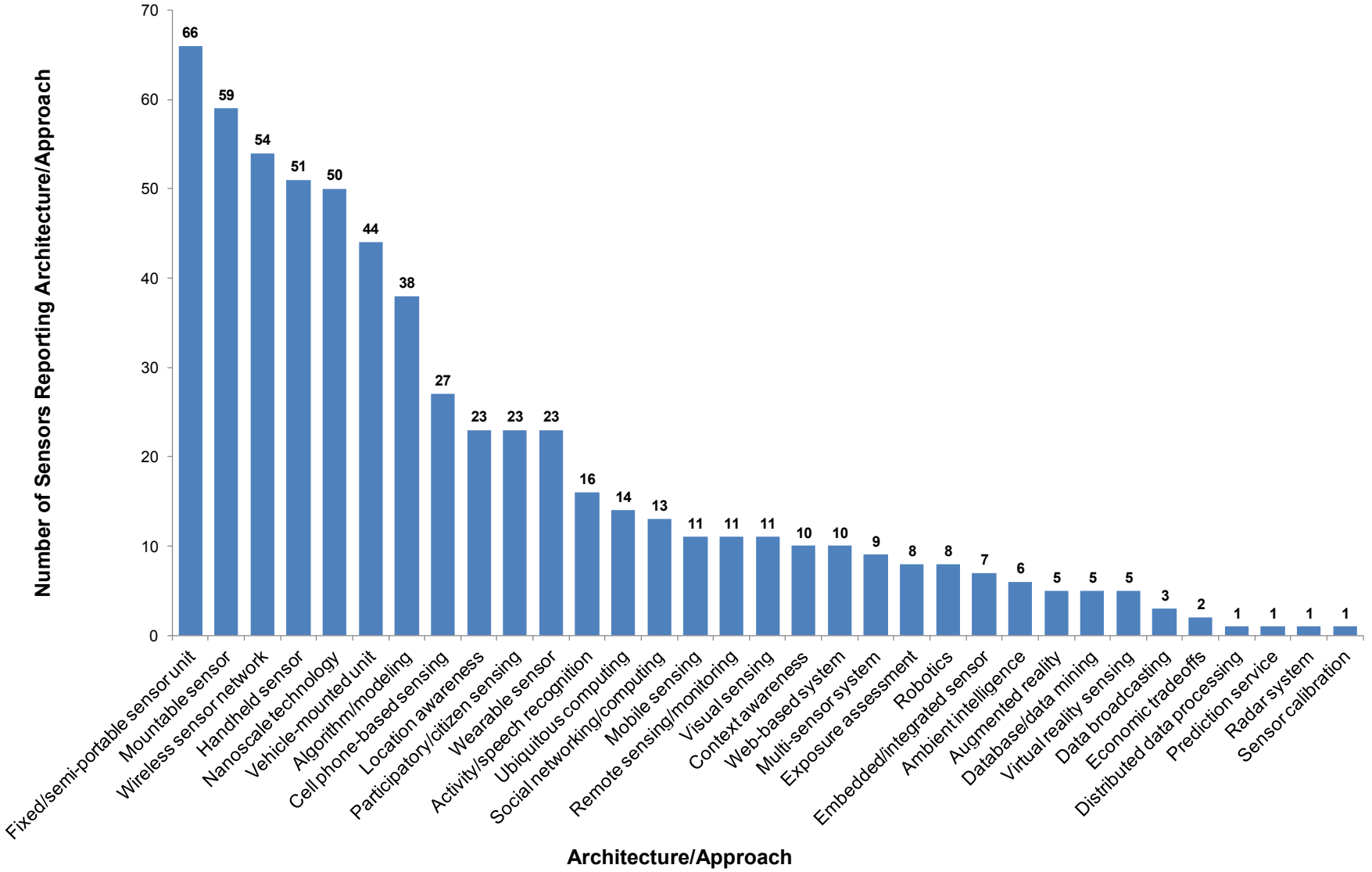


FIGURE 3-31 Number of Sensors Using Selected Architecture/Infrastructure Approaches

Fixed/semi-portable sensor unit (66) – The primary purposes identified for the fixed/semi-portable sensor units are environmental pollutant detection, air quality monitoring, emissions identification, concentration estimation, and data collection. A number of these devices also have the capability to simultaneously measure for multiple pollutant gases, store data, compare measurements against standards, perform modeling, and output data and information to a display unit. In addition, some units have the potential for wireless communication and Bluetooth network connection. These devices range from shoebox, to suitcase, to table/bench top, to refrigerator size; they cover most stages of development from the research phase through commercial availability.

In general, sampling is done a variety of ways, including automated active air sampling, continuous monitoring, and ambient air diffusion, and measure pollutants with and without filter collection. The detection methods or techniques identified for the fixed/semi-portable sensor group include: colorimetrics, photonics, UV fluorescence, laser-induced fluorescence, spectroscopy, refractometry, diffuse illumination, IR, optics, thermography, ion chromatography, gravimetrics, capacitance, semiconductance, resonance, potentiometrics, acoustics, photoacoustics, olfactometry, biosensing, immunoassay, polymerase chain reaction, differential absorbance, optical absorbance, UV absorbance, participatory sensing, and accelerometry.

Some examples of applications in which fixed/semi-portable sensor units have been used include: traffic and vehicle emissions studies; filtering and removal of pollutants; electronic nose for detecting odorous gases; pollution hotspots identification and dispersion modeling of pollution clouds; alarms in industrial settings to warn workers when potentially dangerous of unusual situations are detected; soil gas and penetration studies to detect emission from soil to the atmosphere or leaks from underground storage facilities; monitoring practices at landfills; and earthquake location and magnitude detection.

Fixed/semi-portable sensor units are used to detect numerous greenhouse and exhaust gases, including: CO, CO_2, O_3, NO_2, N_2O, NH_3, H_2S, SO_2, SO_x, CH_4, VOCs, HCs, PM, PM_{10}, $PM_{2.5}$, and PM_1. They are also identified in the records as being able to detect a wide variety of other chemicals: acrolein, formaldehyde, acetone, BTEX, chloroform, p-dichlorobenzene, ethanol, ethyl acetate, MEK, phenol, phenolate, isopropanol, styrene, 1,1,1-trichloroethane, 1,2,4-trimethylbenzene, water pollutants, pesticides, hormone residue, phosphate, chemical and biological agents, and chemical explosives. Many of the devices can also measure temperature, pressure, UV, humidity, odors, acceleration, power consumption, and movement.

Handheld sensor (51) – In general, the handheld devices detected or monitored for air pollutants, chemicals, environmental contaminants, and/or other various compounds (e.g., explosives, allergens, *E. coli* bacteria). Some of the sensor units identified the potential for wireless/Bluetooth connectivity. Where identified, these devices ranged from the size of a thumb to that of a shoe box. The devices cover most stages of development from the research phase through commercial availability.

The detection methods or techniques identified for the handheld sensor group include: colorimetrics, photonics, photoionization, spectroscopy, thermography, IR, optics, interferometry, electrochemistry, electromagnetism, conductance, resonance, harmonics, olfactometry, bioluminescence, gas chromatography, and absorbance.

The handheld sensors primarily measure airborne pollutants, including: CO, CO_2, O_2, O_3, NO, NO_2, NO_x, NH_3, SO_2, SO_x, H_2, H_2S, VOCs, hydrocarbons (HCs), and UFPs (ultrafine particles). Other chemicals specifically identified include: Cl_2, $COCl_2$, methylene chloride, black carbon, formaldehyde, chloroform, 1,3‑butadiene, n‑butanol, alcohol, ethylene, methanol, acetic acid, acrylic acid, dichloromethane, pentane, propane, styrene, hydrogen cyanide (HCN), phosphine (PH_3), pentachlorophenol (PCP), perchloryethylene, trichloroethylene, solvent fumes (BTEX, chlorinated VOCs, solvents used in adhesives, paint and paint strippers, and varnishes), Cr(VI), explosives (e.g., TNT and dinitrotoluene, DNT), amine, odorant, and chemical warfare agents (such as sarin, soman, or GF). Other parameters measured include: temperature, humidity, noise, odors, blood sugar, allergens, and molds.

Mountable sensor: micro- and miniature-scale platforms (59) – Sensors in the mountable micro- and miniature-scale platform group have been used to sense environmental pollutants, including to monitor air quality and detect nanoparticles. The traditional (primary) application has been in vehicles (e.g., within automobile exhaust systems), for which a wide variety of electrochemical sensors has been used. A subgroup of these devices can detect motion and position to enable learning, track movement, and facilitate augmented reality. Micro-scale detectors and monitoring devices commonly use sensor arrays, remote sensing, WSNs, and service-oriented architecture (SOA).

These sensors are generally smaller than the handheld sensors but larger than the nano-scale ones, and are commonly designed to be affixed to a mobile device (e.g., chip or circuit board size), such as MP3 players and cell phones, for personal monitoring. Some benefits identified related to micro- and miniature-scale sensor units include: small, inexpensive, low power, sustainable (e.g., could use solar cells or power-scavenging and energy-harvesting techniques). The devices cover most stages of development from the research phase through prototype development and testing. In general, research continues to improve sensor detection range, efficiency, baseline stability, sensing properties, and understanding of the sensing mechanism.

The detection methods or techniques identified for the mountable micro- and miniature-scale sensor group include: photonics, luminescence, fluorescence, spectroscopy, spectrophotometry, diffuse illumination, thermography, thermoelectrics, optics, X-ray diffraction, energy dispersive X-ray analysis, scanning electron microscope (SEM), optoelectrics, electrochemistry, magnetics, electrometry, resistance, conductance, semiconductance, capacitance, impedance, thick and thin film microelectrics, voltammetry, acoustics, olfactometry, GPS, gas chromatography, amperometry, absorbance, accelerometry, radio frequency identification (RFID), and classification algorithms.

Micro- and miniature-scale mountable sensors are commonly used to detect air pollutants and components of exhaust gas, including: CO, CO_2, O_2, NO_2, NO_x, NH_3, H_2S, SO_x, CH_4, VOCs, HCs, PM, and PM_1. Other chemicals also identified in the records include formaldehyde, benzaldehyde, acetaldehyde, decane, isobutene, acetone, BTEX, chloroform, amine, trimethylamine, alcohol, methanol, ethanol, isopropanol, benzo[a]pyrene (B[a]P), trichloroethylene, and trace explosives. In addition, many of these sensors can also measure temperature, humidity, odors, biomarkers (e.g., glucose, blood gas, pH, and electrolytes), sound, voice, position, and movement.

Nanoscale technology (50) – In general, the purposes of nanoscale sensors are to detect a specific chemical or environmental pollutant, notably with higher sensitivity (i.e., lower detection limits). The detection methods or techniques identified for the nanosensor group include: colorimetrics, photonics, spectroscopy, optics, chemiluminescence, electrochemistry,

resistance, chemoresistance, conductance, transconductance, capacitance, resonance, amperometry, absorbance, and adsorbance.

For the sensor element architecture, nanoparticles are typically made into nano-sized crystals, tubes, wires, thin films, porous matrixes, sensor pads, or sensor arrays, which are used as the detector element. These nanotechnology-based sensor elements are then typically integrated into wearable, handheld, or mobile detectors and monitoring devices. Nanotechnology is reflected in a number of sensors in the research, prototype development, and testing phases.

The nanoscale sensors identified in this literature review are able to detect a wide variety of air pollutants, including: CO, CO_2, O_2, NO, NO_2, NH_3, H_2S, SO_2, VOCs, HCs, PM, PM_1, and nanoparticles. These technologies are also identified as capable of detecting many other chemicals, such as: acrolein, formaldehyde, decane, hexane, styrene, MEK, acetone, ethyl acetate, BTEX, chloroform, phenol, ethanol, isopropanol, diethyl ether, organophosphates, p-dichlorobenzene, 1,1,1-trichloroethane, 1,2,4-trimethylbenzene, mercury vapor (elemental Hg), Cr(VI), chemical warfare agents (e.g., sarin, soman, or GF), explosives (e.g., TNT and DNT), and microbes such as *E. coli*. Such sensors have also been designed to measure light and odors.

Robotics (8) – Robots are used in conjunction with sensor systems to collect data and/or carry out specific tasks based on the results of the data collection and monitoring. The robotic units found in the records are identified as being able to detect air pollutants, such as CO, PM, natural gas, liquid petroleum gas, smoke, and RFID tags. For example, an autonomously navigating robot used for disaster management that is equipped with air quality sensors and the ability to search for disaster survivors; a robot vacuum cleaner linked to a monitoring unit that is wirelessly signaled to turn on when cleaning is deemed necessary; robots outfitted with an electronic noses to collect environmental data while completing urban hygiene tasks (e.g., cleaning pedestrian areas and collecting garbage); or an autonomous robot capable of searching an area for RFID-tagged items and uploading the location information into a database. These units cover most stages of development from the research phase through design prototype and patent application.

Vehicle-mounted unit (44) – This group includes sensors mounted on baby carriages, shopping carts, bicycles, cars, airplanes, and public transportation vehicles (e.g., buses). Position of these units generally includes placement in or near a: bicycle basket, bicycle helmet, car window control unit, vehicle exhaust system, and vehicle roof. The devices are generally used to measure, collect, monitor, and analyze real-time environmental pollutant and related parameter data (e.g., emissions levels, temperature, humidity, wind speed, and traffic density) inside and outside the vehicle. Some units are used to filter air for the user (e.g. baby in a carriage). The detection methods or techniques identified for vehicle mounted sensor units include: spectroscopy, IR, electrochemistry, selective catalytic reduction, impedance, microwaves, ultrasound, pressure, depth, weight, GPS, participatory sensing, and user generated content.

Information gathered is commonly linked to spatial attribute data (e.g., time, date, and GPS coordinates) that can be combined with web-based applications to track and map results over specific areas. Many of these vehicle mounted units use wireless sensor networks (WSNs) to facilitate information exchange between users; transmit data to a central database for querying, processing, and storage; and allow online access by the public. The devices cover most stages of development from the research phase through commercial availability.

Vehicle mounted sensors primarily measure airborne pollutants, including vehicle exhaust and many greenhouse gases, as identified: CO, CO_2, O_3, NO_2, NO_x, NH_4, NH_3, SO_2, SO_x, H_2S, CH_4, VOCs, non-methane HCs, black carbon, PM_{10}, $PM_{2.5}$, PM_1, and UFPs. Other chemicals and parameters specifically identified include: benzene, formaldehyde, natural gas, propane, temperature, pressure, humidity, wind speed, noise, location, and traffic density.

Wearable sensor (23) – In general, the purposes of wearable sensors are for monitoring personal air quality, location, and/or movement. Sensors are typically placed in or on wearable items, such as a shirt, mask, hat, eyeglasses, necklace, or ring. The devices cover most stages of development from the research to prototype phase.

The wearable sensors identified primarily measure airborne pollutants, including CO, CO_2, O_3, NO_2, NO_x, SO_x, H_2S, CH_4, VOCs, PM, and UFPs (ultrafine particles). Other chemicals and parameters specifically identified include metal oxide gas, black carbon, contagious viruses, temperature, pressure, humidity, light, UV radiation, location, and movement.

3.6.2 User Interface Design and Programming

Activity/speech recognition (16) – Systems that use activity and/or speech recognition detect a wide variety of information. Some of this data are physical parameters, such as motion, gestures, pressure, vibration, electromagnetic radiation, speech, and audio level; other information is virtual, such as computer activity and application use. Applications include: activity and sound recognition; location detection; position classification; proximity sensing; occupancy sensing and prediction; eye movement analysis; gesture recognition and interaction; speech and gesture enabled multi-modal user interface; 3-D cell phone interaction; object manipulation; availability sharing systems; cell phone ringtone interaction system.

Algorithm/modeling (38) – Records in the algorithm/modeling group cover research and developed applications that define, build, and present various algorithms and models for: data tracking, management, processing and exchange; information extraction, retrieval, and presentation; image analysis; data mining and fusion; location identification; outcomes prediction; voice, speech, and sound detection; optimization analysis; and data visualization and mapping. Some specific examples include: air quality analysis and monitoring; pollutant/contaminant detection, source identification, concentration distribution, and dispersion; and multi-sensor data systems control. In general, applications utilize both collected and historic data, and can leverage WSNs, Bluetooth, and data acquired from smartphones.

Algorithms specifically identified include: heuristic algorithms; classification algorithms for pattern matching and voice activator detection; authentication and encryption algorithms to protect communication over wireless networks; change detection algorithms to identify suspicious user activity and potential threats; dimensionality reduction algorithm to retrieve and present information. Models specifically identified include the: integer programming model; two-dimensional stochastic model; two-level hybrid fusion model; spatiotemporal model; three-dimensional mapping; multi-component model; user activity model; and relevant context mode.

Ambient intelligence (6) – In general, ambient intelligence refers to electronic environments and/or devices that are sensitive and responsive to the presence of people and work in concert to support people in carrying out their everyday life. Examples identified include: a lambent display on a shopping trolley intended to "nudge" (or induce) people when choosing what to buy; a digital appliance that encourages the act of smiling; a way to communicate with the public

beach conditions; an item recommendation based on customer interests and past behavior; a way to inform and communicate with field security and law enforcement personnel.

Augmented reality (5) – Augmented reality (AR) is a live, direct or indirect, view of a physical, real-world environment whose elements are augmented by computer-generated sensory input such as sound, video, graphics or GPS data. The records identified in this research area specifically discuss: a multi-level visualization system based on the distance between the user and sensor nodes, to support end-user management of WSN status information; a novel terminal (e.g., eyeglasses) that can supply AR service and allow users to carry on hand-free operations (e.g., cell phone, or wheelchair control); a system that connects people in different locations through enriched multi-sensory communication using gesture-based screen interaction, ambient pictures on an animated tablecloth, and message transmission; a system that expands projected augmentations in wide area by using visible light communication and wireless RFID technology; and how and where to use sensors to maximize their efficiency and ensure only the most relevant data are used and presented visually.

Context awareness (10) – In general, context awareness in computing can be defined as the use of information that characterizes a situation related to the interaction between humans, applications, and the surrounding environment, and provide task-relevant information and/or services to a user. The efforts in this area leverage smartphones, Bluetooth technologies, and WSNs. Context-aware applications and research included: user grouping methods; contextual and personalized recommendations without any explicit user input; activity and device position recognition; online/offline tracking and integration; location detection; usage pattern tracking; creation of narrative events for status updates; adaptive duty-cycling of the sensor activity; investigation of intelligibility for uncertain context-aware applications; user activity modeling; aid to field security and law enforcement personnel; and travel assistant application for special needs passengers in public transit environments.

Database/data mining (5) – The database/data mining group contains records that involve the compilation, organization, analysis, or extraction of data. In general, the databases presented are designed to be user-friendly, making it easy for users to access, locate, and share of data.

Location awareness (23) – Location awareness refers to devices, such as cell phones, that can passively or actively determine their location. The location data, which is also often link to time, is then commonly correlated with air pollution data, environmental conditions (e.g. to estimate exposure), geographical context (e.g., maps), traffic patterns and density, and social networks. Other research in this area relates to privacy protection and control of a user's location data.

Mobile sensing (11) – Mobile sensing involves the use of mobile devices (e.g., cell phones or vehicles) to measure, gather, process, characterize, and communicate information. The data gathered by these devices relates to a variety of matters, including: location, traffic patterns, activity, motion, sound, social mechanisms, interpersonal relationships, query history, and privacy protection.

Multi-sensor system (9) – Multi-sensor systems combine two or more senor technologies in a single device to collect data, monitor conditions, and potentially feed into intelligent control systems. A few examples that use these types of systems, as identified: intelligent environmental control system for a greenhouse that collects and stores real-time parameters that can be fused with historical data; air quality monitoring system for an automobile that correlates the impact of gas temperature and flow rate on SO_2 monitoring; intelligent indoor air

quality control system for health care centers that allows for continuous monitoring of air in multiple rooms and is capable of detecting hazardous gas leaks; human lifestyle indicators recorder that collects and compiles data (e.g., temperature, humidity, illumination intensity, presence of people, lights on or off, and open or closed doors) to identify wasted resources; urban scanning systems that acquire mass quantities of real-time information (e.g., traffic estimation data, real-time energy efficiency, calculation of optimal travel routes, and pollution maps) from multiple sources of different types of data and make it available on a cloud network; soil erosion and non-point source pollution monitoring system for a reservoir area; and heterogeneous long-term water monitoring system that collects and stores real-time water quality parameters such as pH, temperature, conductivity, turbidity, and dissolved oxygen.

Participatory/citizen sensing (23) – Participatory sensing is the concept of using members of the public to collect data and information, typically through the use of mobile devices, to form a body of knowledge. The identified records indicated numerous topics for which of information gathered: pollutants; air and water quality; environmental conditions (e.g., temperature, humidity); energy consumption; galaxies; plant phenology; and weeds.

Remote sensing/monitoring (11) – Remote sensors and/or monitoring involve the acquisition of data and information about an object or phenomenon, without making physical contact with the object or area being investigated. Research and applications utilizing this type of sensing, as identified in the records, include: air pollution monitoring; vehicle emissions analysis; and facility monitoring (e.g., gases released from CAFOs).

Sensor calibration (1) – The single record that discussed sensor calibration addresses the question of whether low-cost sensors can be calibrated to provide sufficiently accurate information about levels of pollution to support further scientific investigation.

Social networking/computing (13) – In general, social computing can be broadly defined as computational facilitation of social studies and human social dynamics, as well as the design and use of information and communication technologies that consider social context (e.g., social networks). The records identified in this group discuss a variety of applications, including: research on energy-use and energy conservative behaviors of consumer individuals; mobile-phone based social and behavioral sensing system that combines extremely rich data collection in terms of signals, dimensionality, and throughput, together with the ability gain insights on intricate social mechanisms and to conduct targeted experimental interventions (e.g., increasing physical activity) with study populations. Also included are mobile social network aggregators that integrate social networking services into the mobile device user interface and recommends new content that is likely to be interesting to the user; mobile social service for an office environment that is used to record a user's position and allow users to efficiently manage office resources and connect other colleagues; and a smart makeup system that helps users find new makeup methods for use with their daily cosmetics. Additional topics include location-based information fusion for mobile navigation that leverages static public online information with users' location-based social network resources to provide real-time exploration in novel environments; a study of three visualization types (text-, map-, and time-based) for social sharing of past locations; research related to targeted location-sharing privacy attacks; and modeling social and geographical context based on co-location networks in human mobility datasets. Further applications include use of context-based awareness cues in status updates, especially in SNSs (Social Networking Services); new method for public communication about ambient water conditions through investigation of novel ways to measure ambient quality and make this information available as a public resource; and research exploring which features of

interpersonal relationships influence personal information sharing with friends and social groups.

Ubiquitous computing (14) – Ubiquitous computing (ubicomp) is a method of information processing based on the fact that computers have been thoroughly integrated and embedded into everyday objects and activities, making them effectively invisible to the user, but able to collect and communicate information. The research in this area leverages smartphone and Bluetooth technologies. Specific research and applications identified in the records that utilize ubicomp involve: new perspective on everyday biomarkers that utilize the lens of organic and non-digital sensing to reflect on current sensing paradigms; the design of personal informatics tools that effectively assists people's reflection on collected data; a zero-configuration spatial localization system for networked devices based on ambient sound sensing; mapping interaction qualities identified in private and work contexts; transferring information from mobile devices to personal computers by using vibration and an accelerometer; supplying AR service and allow users to carry on hand-free operations; a line of prototypical products for future homes that simulate and stimulate emotion; using a mobile application to assist in the capture of the contextual information for diabetics using self-care devices; the design and evaluation of school-based ubicomp that treats the school as a social institution; exploration on the extent that data, recorded by automated fare collection (AFC) systems of public transport authorities, offers the possibility to both build and measure future of travel-based ubicomp applications; research to establish the theoretical foundations for the design of mechanisms for forgetting and develop and evaluate the framework and its interfaces for users to control these mechanisms; the design systems that rely on sensing and recording, but also account for privacy concerns of users; a persuasive sleep application that involves self-monitoring and feedback features to help people be aware of their sleep habits; and new modes of collaborative human navigation.

Virtual reality sensing (5) – Virtual reality (VR) is a term that applies to computer-simulated environments that can simulate physical presence in places in the real world, as well as in imaginary worlds. The records identified in this research area specifically discuss: the creation and study of haptic (i.e., tactile feedback) devices for both blind and sighted people that provide sensory augmentation; the electrical stimulation of the gustation (e.g., sense of taste) for a human; a technique that enables controlling of CD ratio by finger height and movement above the touch surface for multi-scale navigation tasks; and an availability sharing system designed to balance the costs and benefits between the interrupter and the interruptee.

Visual sensing (11) – Visual sensing involves the use of visual images to extract, characterize, and interpret information and data about the three-dimensional world. Applications utilizing this type of sensing, as identified in the records, include: real-time roadway emissions estimation using visual traffic measurements; airflow and light monitoring devices; air quality evaluation and modeling using surveillance data; colorimetric detection of a contaminant, which can activate an alert system; smile recognition to encourage the act of smiling; use of thermal imaging to track disaggregated appliance usage; and item location finder.

Web-based system (10) – The web-based category contains records that use an accessible web portal to submit, access, manage, analyze, and monitor data and results. Areas that were identified as using a web interface: air quality, emissions, mapping and visualization, route planning, personal health, water consumption, plant phenology, and web history.

Wireless sensor network (WSN) (54) – Wireless sensor networks (WSNs) generally consist of a collection of spatially distributed autonomous sensor nodes for data acquisition, transmission, and distribution, which is monitored and controlled at a central management point. These

networks are used in and for a variety of applications, including and as identified in the records: air, noise, and water pollution monitoring; traffic conditions indication; travel route calculation; weather and monitoring of environmental conditions; hazard identification; exposure; asthma management; data visualization and identification of gaps; geographic location and mapping; jamming attack model; energy consumption; power charging; parking management; and voice activation.

3.6.3 Other Systems and Data Features

Data broadcasting (3) – In general, data broadcasting is the transmittal and distribution of data over a wide area by means of digital signals (e.g. radio waves). The records in this category discuss applications for digital signage systems and mobile phones.

Distributed data processing (1) – The single record for distributed data processing discussed a tool that boosts the data handling and trial-and-error process of the signal processing.

Economic tradeoffs (2) – The studies in this group discuss a link between sensor use and money. One of the studies uses sensor technology to investigate the value of sensor information enhancing the control of perishable goods to decrease waste, thus increasing profit (and consequently reducing greenhouse gases). The other study evaluated economic micro-incentive compensation for participants wearing sensors in high-burden studies (e.g. extended durations) and how these strategies affect compliance with study protocol, data quality, and participant retention.

Exposure assessment (8) – A number of research studies looked at the use of portable and personal monitors to measure and monitor pollutant concentrations, as well as to address exposure. The devices in this category are located outside and inside of schools, at bus stops, on and along roadways, and on individual persons. Specific pollutants detected by this group of devices include: UFP, CO, CO_2, O_3, PM, vehicle exhaust, benzene, black carbon, nicotine, cotinine, and PAHs.

Prediction service (1) – The single record included in this category described a service that provides household water usage data, consumption projection, and regional demand forecasting for both short-term and med-term.

Radar system (1) – The research under this category involves space-based surveillance and detection and sensor development for missile defense that focuses on electronic attach and protection techniques, tracing and sensor fusion, vulnerability analysis, space-time adaptive processing.

3.7 HIGHLIGHTS OF RECENT FEDERAL RESEARCH ACTIVITIES

Sensor research is ongoing at a number of federal agencies and national laboratories. Especially significant is the Exposure Biology Research Program in the National Institutes of Health (NIH), National Institute of Environmental Health Sciences (NIEHS). This $20 million research effort is pursuing technologies and assays to precisely measure human exposures and modifying factors, toward producing sensitive, high-throughput, potentially portable systems that can measure exposures to environmental agents and their impacts on human biology. (See *http://www.niehs.nih.gov/research/supported/dert/sphb/programs/sbir/topics/ebp/index.cfm*.) On a much smaller scale, highlights of selected recent research at several laboratories and other agencies are presented in Tables 3-10 and 3-11.

TABLE 3-10 Highlights of Recent Sensor Research Led or Funded by Federal Agencies

Agency	Research *(with publication year or weblink)*	Selected Highlights
DOE Office of Biological and Environ-mental Research	Self-calibrating Balloon-Borne Methane Gas Sensor *(Southwest Sciences, Inc., 2011, grant renewed 2013) http://www.sbir.gov/sbirsearch/detail/373544*	Research to develop a self-calibrating, low mass, greenhouse gas sensor to be deployed on meteorological balloons to cover wide geographic areas; a similar methane-only sensor is also being developed.
	Diode laser sensor for methane detection on an unmanned aerial vehicle *(Southwest Sciences, Inc., 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop a small, light-weight diode laser sensor for methane (3300 nm range) that can be deployed on an unmanned aerial vehicle.
	Isotopic CO2 Instrumentation for UAV Measurements *(Southwest Sciences, Inc., 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research for rapid and precise measurement of isotopic carbon dioxide for unmanned aerial vehicles.
	Lightweight Integrated Optical Sensor for Atmospheric Measurements on Mobile Platforms *(Physical Sciences Inc., 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop a sensor for materials of national security interest, environmental monitoring, and industrial manufacturing.
	Airborne Sensor for Aerosol Precursors *(Vista Photonics, Inc., 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop an airborne sensor for monitoring ammonia at atmospheric concentrations.
	Infrared Laser Direct Absorption Spectroscopy for Carbon Isotope Measurements from UAVs *(Aerodyne Research, Inc., 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop light-weight infrared laser spectrometer to measure isotopologues of carbon dioxide and methane.
	Highly sensitive, low-power, and low-weight gas analyzer for UAVs *(Mesa Photonics, Llc, 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop a light-weight, compact sensor for greenhouse gases that can be deployed on unmanned aerial vehicles.

Agency	Research *(with publication year or weblink)*	Selected Highlights
DOE Office of Biological and Environ-mental Research *(cont'd.)*	Compact QCL spectrometer for carbon isotopologue measurements from Small UAVs *(Physical Sciences Inc., 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop a highly sensitive sensor for monitoring stable isotopes of carbon dioxide.
	Low Cost Small Sample Volume High Precision Carbon Dioxide Analyzer *(Li-cor Biosciences, 2013) http://science.energy.gov/~/media/sbir/pdf/awards%20abstracts/fy13/FY13-Phase-1-Release-1Final.pdf*	Research to develop a high-precision, low-cost sensor for carbon dioxide in the atmosphere.
National Aeronautics and Space Administra-tion	DISCOVER – AQ *(2011)*, *http://www.nasa.gov/mission_pages/discover-aq/news/DAQ-20110622.html*	Research to improve methods for aerial pollution monitoring via aircraft; ideally, the data collected will be combined with ground-collected measurements to provide a more complete picture of air quality.
	TEMPO (Tropospheric Emissions: Monitoring of Pollution) *(2012), http://www.nasa.gov/home/hqnews/2012/nov/HQ_12-390_TEMPO_Instrument.html*	Research in collaboration with the Smithsonian Astrophysical Observatory, to accurately measure tropospheric pollution concentrations of ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, and aerosols with high resolution in North America using a space-based instrument attached to a satellite. (Completion of the structure is expected in 2017.)
	JPL E-nose *(2013), http://www.nasa.gov/mission_pages/station/research/experiments/32.html*	Research to train this device to identify and quantify various pollutants at concentrations from one-third to three times the 24-hr spacecraft maximum allowable concentration value.
National Science Foundation	Various projects funded in 2013 (these and others can be found via the award search engine using keyword “sensor”)	Research themes include mobile sensors, carbon dioxide sensors, sensors for combustion applications, data quality and cloud infrastructures, health monitoring, radiation monitoring, and energy harvesting. Awards since 2010 include miniaturization attempts, sensor network development, greenhouse gas detection, data analysis methods, wearable sensors, and sensors aimed to improve fuel efficiency.
U.S. Depart-ment of Agriculture	Development of optical fiber sensors and sensor array for continuous monitoring of ammonia spatial distribution in animal feedlots *(West Texas A&M University, 2013)*	Research to develop optical chemical sensor (evanescent wave absorption) networks for in-situ, real-time, long-term continuous monitoring for ammonia distribution in CAFOs, to inform air quality research as well as site emission control and measurement activities.

TABLE 3-11 Highlights of Selected Research Activities at DOE National Laboratories

Laboratory	Research *(publication year or weblink)*	Selected Highlights
Ames	Microwave and terahertz sensing using slab-pair-based metamaterials *(2012)*	Testing metamaterial structure that can be used to measure gas concentrations by evaluating the electrical permittivity of the material between a pair of metamaterial slabs. Tested materials include silicon, and low-density polyethylene.
Argonne	Sensors and materials research *(http://www.anl.gov/security/sensors-materials*)	Mobile sensors to detect nuclear and radiological materials, chemical and biological agents, and explosives. Recent developments include millimeter-wave systems that track biometrics and detect chemicals, gases, and radiation as well as carbon-based nanomaterials and nanostructures that enhance the performance of nanoscale devices.
	Photoacoustic spectroscopy (PAS) system for remote detection of explosives, chemicals, and special nuclear materials *(2012)*	PAS can be used to remotely sense chemicals in an open environment; gases can be detected several meters from the target.
	NOx/O_2 Sensors for High Temperature Applications (*http://web.anl.gov/eesa/pdfs/success_stories/49_NOX-O2_Sensors_v4.pdf*)	Simultaneously measures NOx and O_2 in vehicle engines; the sensor has a self-contained reference gas system, is compact, cheap, and easy to produce.
Brookhaven	In-situ spectro-microscopy on organic films: Mn-phthalocyanine on Ag(100) *(2013)*	Research on metal phthalocyanines for potential use in chemical sensors.
Idaho	Instrumentation, control, and intelligent systems; sensors *(https://inlportal.inl.gov/portal/server.pt?open=514&objID=5325&mode=2&)*	Research on sensors that use advanced mass spectrometry and ion mass spectrometry modeling software to detect trace explosives, as well as sensors for high-temperature tests, and portable isotopic neutron spectroscopy used for handheld detection of concealed bulk explosives as part of munitions inspections.
Lawrence Berkeley	Low power, fast, selective nanoparticle-based hydrogen sulfide gas sensor *(2012)*	Small, low-cost, low-power, nanomaterial-based gas sensor with high selectivity for hydrogen sulfide and no significant cross sensitivity for hydrogen, water, or methane.
	Available technologies for licensing and further R&D *(http://www.lbl.gov/Tech-Transfer/techs/lbnl1850.html; http://www.lbl.gov/Tech-Transfer/techs/lbnl2689.htm; http://www.lbl.gov/Tech-Transfer/techs/lbnl2349.html)*	Miniature airborne particle mass monitor: power need of <100 mW, can measure picogram of material, prototype costs $100. Compact microchip gas sensor: hydrogen microchip sensor for real-time detection and analysis of hazardous gas levels. Membrane and receptors for highly selective gas-phase sensing: insensitive to humidity changes, portable and low cost.

Laboratory	Research *(publication year or weblink)*	Selected Highlights
Lawrence Livermore	NOx sensor development *(2012)*	Impedance metric sensor to measure NOx in vehicle exhaust at <5-100 ppm; low cost, close to commercial development, licensed by EmiSense Technologies.
	A block-based MC-SURE algorithm for denoising sensor data streams *(2012)*	Algorithm to denoise real sensor streaming data; enables blind optimization of the denoising parameter of a wide class of filters.
Los Alamos	MotionCast for mobile wireless networks *(2013)*	Research on mobile ad-hoc networks for use used when infrastructure for communication are limited (e.g., for mobile air quality sensors carried by citizen scientists); the emphasis is on capacity and connectivity.
	Sensors: Theory, algorithms, and applications *(2012)*	Highlights recent advances, current work, and future needs; investigates information patterns obtained by sensor measurements, mathematical approaches encompassing dynamic systems and statistical techniques, application specific approaches, and other related research.
	Routing for wireless multi-hop networks *(2013)*	Generic routing model to use as a foundation for wireless multi-hop routing protocol analysis and design.
Oak Ridge	Sensors and controls research (*http://www.ornl.gov/sci/ees/mssed/sst/projects.shtml*)	Very low power, wireless microsensor array (to measure CO_2, humidity, temperature, occupancy); also, in-situ fuel cells to measure temperature and humidity, vehicle exhaust (ammonia, nitrogen oxides, and oxygen), harsh environment sensing (inductive noise thermometry), and others; recent research is on perovskite oxides for use in electrochemical sensors.
Pacific Northwest	NOA: A scalable multi-parent clustering hierarchy for WSNs *(2012)*	Tool to reduce the amount of data sent to sinks, which reduces the cost of overhead by reducing the cost of network setup.
Sandia	Microelectronics, sensors, MEMS, and photonics research (*https://ip.sandia.gov/category.do/categoryID=20*)	Research on microsystems and constituent components, including chemical sensors, microelectronics, displacement sensors, hybrid microsystems, and others.
Savannah River	Sensors development research (*http://srnl.doe.gov/sens_dev.htm*)	Research emphasizes modifying available instruments for particular situations and building robust systems that can operate for years in harsh environments. Technology research areas include fiber-optic sensors, remote chemical analysis, Sol-Gel indicator sensors, remote robotic sensor systems, and environmental sensors which are used to measure environmental pollutants and various chemical concentrations or physical properties including ammonia, hydrogen, temperature, and humidity.

4 GAPS AND OPPORTUNITIES

Gaps and opportunities for mobile sensors and apps have been identified from a review of recent literature, illustrated by a targeted evaluation of fourteen representative air pollutants. These gaps and opportunities are organized into two main topics: (1) sensing technologies and techniques; and (2) architecture and infrastructure approaches, including software applications.

4.1 SENSOR TECHNOLOGIES AND TECHNIQUES

4.1.1 Specific Pollutants

Most portable sensors are designed for gases, so particles represent a substantial gap. No mobile research sensors were found for lead. Techniques for this metal and others are primarily lab-based, with associated time lags and costs. LIBS represents an opportunity technique for lead, but the ability to detect low concentrations is not known. Similar constraints apply for PM, and current methods are expensive ($1,000 to $20,000 and higher). Furthermore, they are non-specific (e.g., mass-based via filtration), so chemical identities are not determined. A MEMS based on the acoustic-wave microbalance sensing principle represents an opportunity area. The cost might be less than $100.

Among the gases, acrolein represents a key gap for mobile sensors. Few were found to address this HAP, which is a national risk driver per NATA and is also associated with emerging emission sources such as biodiesel production. Health-based concentrations established for lifetime exposures are difficult to reliably measure, even with large, fixed systems. Thus, further research and development to produce mobile sensors for this compound would be useful. A second gas that could benefit from targeted research and development is 1,3-butadiene. Relatively few sensors (and only one research sensor initiative) are identified for this chemical. Given its status as a national risk contributor per NATA and the nature of its emission sources (including from emerging natural gas development), further research to pursue mobile sensors for this compound could also be broadly beneficial.

A practical needs assessment to prioritize pollutant targets, seeking inputs from parties ranging from agencies to industry and citizen groups, could help guide investments for targeted research. Cross-walking the results with ongoing research collaborations to identify leveraging opportunities would expedite progress. A good example of a needs assessment can be found in the recent EPA NCEA initiative for nanotechnology/nanomaterials risk assessment. Using a comprehensive environmental assessment (CEA) approach, knowledge gaps and research needs have been identified and prioritized with interesting tools that may be useful, particularly structured techniques for soliciting and incorporating input from experts with diverse backgrounds. (See http://cfpub.epa.gov/ncea/CFM/nceaQFind.cfm?keyword=Nanomaterials.)

4.1.2 Detection Levels

Gaps in sensor detection levels compared with exposure benchmarks are summarized in Table 4-1. (A blank cell indicates the benchmark has not been established; an "x" indicates the concentration may be detected; a "?"' indicates it is not known if the benchmark concentration can be detected, e.g., absent a reported detection range; and dark shading indicates a gap for that detection capability.) This summary indicates that gaps may exist for concentrations established as safe for continuous lifetime exposures for four of the fourteen study pollutants. Three are HAPs – acetaldehyde, acrolein, and formaldehyde, and the fourth is an indicator pollutant − ammonia.

TABLE 4-1 Reported Ability to Detect Exposure Benchmark Concentrations[a]

Pollutant	Emergency Response						General Public											Occupational								
	AEGL/PAC			ERPG			RfC		RBC		MRL			CalEPA REL			NAAQS	CAAQS	IDLH	PEL	NIOSH REL			TLV		
	1	*2*	*3*	*1*	*2*	*3*	*IRIS*	*PPRTV*	*10^{-4}*	*10^{-6}*	*ac*	*subc*	*chr*	*ac*	*subc*	*chr*					*C*	*STEL*	*8-hr*	*C*	*STEL*	*8-hr*
Acetaldehyde	x	?	?	x	x	?			x					x		x			?	x				x		
Acrolein	?	?	?	?	?	?					x								?	?		?	?	?		
Ammonia	x	x	?	x	x	?					x			x					x	x		x	x		x	x
Benzene	?	?	?	x	?	?	x	x	x	x	x	x	x	x		x			?	x		x	x		x	x
1,3-Butadiene	?	?	?	?	?	?	x		x	x						x			?	x						?
Carbon monoxide	x	x	x	x	x	x								x			x		x	x	x		x		x	x
Formaldehyde	x	x	x	x	x	x			x	x*	x	x	x	x		x			x	x	x		x	x		
Hydrogen sulfide	x	x	x				x				x	x		x		x			x	x	x				x	x
Lead																	x	x	?	x			x			x
Methane	?	?	?																							
Nitrogen dioxide	x	x	?														x		?	x		x			x	x
Ozone														x			x		x	x	x					x
Particulate matter																	x	x	x	x			x			x
Sulfur dioxide	x	x	?								x			x			x		?	x		x	x		x	x

[a] An empty cell indicates the benchmark is not available. Dark (red) shading indicates a benchmark exists but the concentration has not been reported as detected. An 'x' in green shading indicates the concentration could potentially be detected by a research or commercial sensor either at a reported LDL or within the reported detection range. The "?" in yellow shading indicates it is not clear from the information reviewed whether the concentration can be detected or not; for example, if an LDL is below the benchmark but the detection range is not identified, higher concentrations/interference may limit detection at the higher level. Risk-based concentrations (RBCs) correspond to the target risk levels shown. Note the CalEPA RBC for lead (not shown here) can be detected. For exposure durations, general public: ac = acute, chr = chronic, subc = subchronic. Note the acute MRL which extends multiple days, is grouped with "emergency" values on the arrays. Lead and PM entries reflect commercial sensors only. For methane, the entries reflect protective action criteria; the entries for other pollutants in the first three columns reflect AEGLs. For ozone, 8-hr TLVs (as TWA) are available for light, medium, and heavy work; a 2-hr TWA is also available.

An underlying gap involves basic data reporting. That is, a number of research studies indicate a given pollutant is sensed by the technology/technique but do not report a detection level or range. Thus, some gaps could be addressed by improving the rigor of scientific reporting.

Detection capability gaps are not limited to mobile sensors, as even fixed commercial systems can experience difficulties in measuring health-based concentrations identified as protective for continuous, chronic exposures. To illustrate, in aiming to detect a much higher concentration than the RfC, the NIOSH method for acrolein notes the accuracy limitation (i.e., it does not meet the criterion for a valid method; note the NIOSH REL-TWA is 0.1 ppm and the STEL is 0.3 ppm). Similarly, the standard OSHA method targets a detection level that is orders of magnitude higher than the RfC. Further monitoring context can be gained by considering chemical fate in air. With a half-life of less than a day (and fate products including CO and formaldehyde, also in the pollutant study set), real-time monitoring would be useful, and the nature of the emissions would help guide the appropriate detection target (e.g., ongoing emissions would align with continuous chronic exposures). Integrating fate context in such a way provides an opportunity to guide multi-pollutant sensing considerations (see Section 4.2).

Opportunity areas for acrolein involve techniques that move beyond the standard absorbent-desorption to gas chromatograph method, such as:

- Proton-transfer reaction linear ion trap (PTR-LIT) mass spectrometer.
- Fluorescence, using polyfluorophore sensors built on a DNA scaffold.

4.1.3 Response Time

Response time affects utility of mobile sensors for real-time data collection and has an impact on power consumption. Use of nanomaterials has helped improve response time, as has the addition of pre-concentration techniques to GC systems, for example, as sensors generally respond faster when concentration is higher. However, this improvement may be offset by the lag time for the pre-concentrator to gather enough of the pollutant to trigger a response (as an example, the concentration time identified for a spectroscopic sensor was three minutes).

Benefits of a faster response time include:

- Lower power consumption (e.g., a quick response would allow MOS sensors that require internal heating devices to operate for short intervals, thus conserving energy).
- Ability to capture conditions in real time, particularly important for dynamic conditions.

4.2 ARCHITECTURE AND INFRASTRUCTURE APPROACHES AND AIR QUALITY APPS

4.2.1 Size/Mobility

Relatively little quantitative information was found for the size of research sensors and systems. Although specific measurements are provided for a handful of devices, in most cases the characterization is qualitative (e.g., "small" or "very small"); for those, photos or other images were pursued to provide more descriptive information where possible. Reported and inferred sizes range from nanoscale; to micro and miniature scale; to thumb, bar of soap, shoe box, and suitcase-sized; to refrigerator and mobile laboratory-sized.

In terms of implications for sensing techniques, research efforts in each of the three main technique categories acknowledge the need for mobile sensors with a similar degree of sensitivity and reliability as established fixed sensing units. Sensors based on chemical techniques, especially those using nanomaterials, are particularly amenable to small sensor size. For a sensor to be practical, the smallest sensing material size has been estimated to be about 1 cubic centimeter (cm^3) (Honicky 2011). However, the decreased size of these sensing materials corresponds to a smaller reactive surface area which results in a lower sensitivity. Nearly two-thirds of the literature reviewed reflects research and/or development for handheld or very small sensing units, or the use of nanoscale materials to increase sensitivity.

Spectroscopy-based sensors are also affected by size constraints. Even with the use of reflective mirrors, detection cell paths may need to be at least a few centimeters in length to ensure proper laser pathlines (Honicky 2011). Similar to chemical absorption- or reaction-based sensors, the decreased size results in higher LDL values (i.e., decreased sensitivity). About one-third of this literature reviewed reports advancements in developing small handheld devices and/or use of nanoscale materials with this sensing technique.

4.2.2 Power Requirements

Power consumption is a key contributor to sensor costs, so energy conservation is an active research area. The driver for power consumption is the length of time the monitoring will be performed. For example, if only spot measurements were needed throughout the day (e.g., totaling less than 4 to 8 hours), then existing batteries such as a common cell phone ion battery would be more than adequate. However, if 24-hour continuous measurements were needed, then an alternative power supply would be required or additional capacity (more batteries) would need to be added to the system (and regularly replaced).

The substantial power requirements of electrochemical techniques are widely recognized, including the high operational temperatures required for MOS sensing. For this reason, a number of researchers are working to develop techniques that would allow room-temperature operation, in order to reduce power consumption and also potentially reduce response time. These techniques include doping existing MOS sensing films with functional layers and developing novel polymer films operable at room temperature (Nomani et al. 2011; He et al. 2012). Note that rapid response would also allow for a very brief "on" period, resulting in less energy consumption; it would facilitate periodic (pulse, burst, or intermittent) sampling that could be optimized for the setting, target pollutant, and energy use. As another example, UV-induced room-temperature sensing has been found useful for low-power operation, longer sensor lifetime, and fast on/off capabilities (Aluri et al. 2011).

Emerging opportunities for novel power sources range from photovoltaic films to biological and mechanical sources, including energy transfer from humans (e.g., footsteps and heartbeat). That is, in addition to pursuing low power-consumption components, opportunities are being pursued for novel power sources and self-powered devices. Recent nanotechnology research efforts have illustrated the potential to successfully harvest ambient energy from solar, mechanical, biomechanical, and thermal sources. "Nanogenerators" that can convert these sources of energy to electrical energy in real time have been used to power small LEDs or LCDs. Hybrid nanogenerators capable of harvesting energy from more than one source to increase the feasibility and reduce environmental limitations are being pursued, as is the development of self-charging power cells in which the nanogenerator and battery are hybridized into a single component (Wang et al. 2012).

Air velocity or wind is one of the sources of ambient energy being studied for harvesting to power mobile sensors. Research on a self-powered, battery-free, air velocity and temperature sensing system indicated such a system could be used for short-range monitoring, with airflow velocities as low as 3 m/s in an air duct (Sardini and Serpelloni 2011). These systems could potentially be modified for mobile or mounted sensing units (e.g., on a bicycle or vehicle). A key condition for self-powered units is that the power needed to run all individual units must be less than the power harvested from the environment, which drives the need for low-power components.

4.2.3 Sensitivity, Selectivity, and Multiple-Pollutant Sensing

To offset the reduced sensitivity that accompanies a smaller sensor size, researchers have been investigating methods for increasing sensor surface area. These include adding nanoscale materials (e.g., nanoparticles and SWCNTs) that can react with the desired pollutant to a previously established sensing film. Recent research activities pursuing electrochemical techniques that can detect components of a gas mixture have identified modified polymer films as potential candidates for select chemicals; however the overviews of two studies on this topic did not appear to include concentration measurements (Yang 2010; Kim et al. 2010). Thus, this area constitutes both a gap and opportunity.

The development of customizable sensor arrays (sometimes referred to as electronic noses or e-noses) is also an active research area. Selecting specific, small gas sensors that can be operated in a single handheld device would make it possible to detect a range of gases, customized to a given location and pollutants suite. While this would be more convenient, one challenge is assuring sound mechanisms for addressing interference to prevent false readings. To illustrate, selected examples of pre-concentration techniques that facilitate detection at lower concentrations, as well as potentially boosting selectivity (based on media used) include:.

- Spectroscopic technique with pre-concentration and thermal desorption; concentration cells: Materials are selected for placement into a separate cell into which the sample air is initially drawn; these materials are specifically chosen to promote selective adsorption. After some interval (e.g., three minutes), the selected gas is desorbed by a heating process and travels to the detection cell. Because all the target gas is released at once, the concentration measured in the detection cell at any one time is increased.

- Chemical technique, semiconductor: pre-oxidation tube increases sensitivity to formaldehyde.

4.2.4 Cost

Bridging the gap between traditional, very expensive pollutant monitors to widely affordable, portable sensors is central to the current sensor initiative. Striking progress has already been made in producing mobile sensors for reasonable cost. For example, simple systems can be easily assembled for on the order of $100 or less using materials readily available from local hardware stores and online. (Examples include the Air Quality Egg, light-up detectors built into $4 weather balloons, and more.)

Replacing expensive system components with affordable alternatives is an ongoing research theme. As an example, researchers at the Korea Institute of Science and Technology found that using conductive electrodes in MOS sensors in place of the traditional platinum sensors increased sensor response and decreased fabrication costs (Shim et al. 2011). Others have

investigated using absorption at low-irradiation light intensities to address the issue of increased cost of photoelectric gas sensor (Peng et al. 2011).

Although MOS sensors are relatively inexpensive, this generally translates to lower sensitivity than alternate spectroscopy or ionization techniques (which are typically more bulky and costly). Batch and microfabrication and 3-D printing are among the opportunity areas being pursued to improve sensing capabilities while reducing costs.

Some sensor systems, such as those using GC-PID, are sensitive to external environmental factors including relative humidity and temperature. Required climate control features add both capital costs and operation and maintenance costs to the sensor system, including related to power consumption. One aim of the current initiative is to identify opportunities for developing lower-cost, reliable mobile sensors and systems that do not require such infrastructure support, by limiting the control elements needed without a corresponding power drop.

4.2.5 Field Performance

Gap areas and opportunities include:

- Reliability and durability of sensors and systems in field conditions – with opportunities including replacement, regeneration and reuse of sensor components, and extension of maintenance schedules.
- Long-term stability and autocalibration represent current gaps – with opportunities including self-healing and autocalibration networks, such as via Web 4.0/Internet of Things, and tapping physical infrastructure for joint fixed-mobile sensor calibration hubs.
- Operator training – mobile sensing provides an opportunity for a new "operator corps" to effect widespread participatory sensing with much more user-(operator-)friendly monitoring devices; in tandem with greatly reduced operating complexity compared to traditional monitoring systems, resources such as e-learning, social media, educational programs (e.g., in the GO3 model), and DIY networks create a strong opportunity for addressing the "trained operators" issue for mobile sensing.

Technology/technique and architecture/infrastructure gap and opportunity areas discussed in Sections 4.1 and 4.2 are highlighted in Tables 4-2 and 4-3, with an illustration comparing commercial and research sensors for carbon monoxide presented in Table 4-4. Supporting context for Tables 4-2 through 4-4 is provided as follows.

Cost: Depending on the monitoring needs for a given situation (including detection level), relatively cheap technologies are increasingly available, such as metal oxide versus spectroscopic sensors. Incorporating novel sensor components into existing hardware (such as smartphones) to harness associated data analysis and transmission capabilities can reduce system costs.

Mobility: Trade-offs between sensor mobility-size and accuracy-precision are common. Automatic calibration networks and integrated/hybrid systems represent opportunity areas for research. Hybrid systems could involve joint fixed and mobile sensors (including sensors affixed to existing infrastructure); they could also involve handheld portable sensors combined with vehicle-mounted larger devices with higher precision/accuracy, such as BikeNet (sensors mounted on bicycles), CommonSense (sensors mounted on street sweepers), or sensors mounted on taxi cabs.

TABLE 4-2 Highlights of Sensor Gaps/Limitations and Opportunities[a]

Feature	Gaps	Potential Solutions / Advances	Issues / Research Opportunities
Cost	Affordability for widespread use	Pursue cheaper technologies (e.g., metal oxide vs. spectroscopic sensors). Use less expensive materials (e.g., coated glass electrodes vs. platinum electrodes; low vs. high light irradiation sources). Mass produce to reduce cost; note the sensors should not require expensive infrastructure to function properly.	Increase sensing capabilities of cheaper technologies. Could potentially reduce sensing capabilities. Mass production could follow public demand for personal exposure information, for example (especially if easy to use, e.g., integrated into popular devices such as a mobile phones).
Mobility	Easy to carry	Pursue portable/handheld devices, recognizing some technologies are more amenable to miniaturization than others (e.g., chemical vs. spectroscopic and ionization sensors). Leverage for hybrid systems, supplement with larger mounted sensors (e.g., on cars, bikes).	Typical trade-off between size and sensing capabilities. Not amenable to indoor applications, location limitations for vehicle-mounted sensors.
Energy consumption	Sustained energy conservation (e.g., to increase battery life between charges)	Reduce sampling time, reduce warmup period. Non-continuous sampling: select times for discrete vs. continuous sampling (e.g., when air quality is expected to be poorer or conditions change, or when in transit vs. stationary); can be useful when pollutant patterns are known (e.g., when concentrations are likely elevated). Delay data upload (GPS/concentration) to optimize energy-efficiency (e.g., upload while charging the device). Decrease operational temperature (e.g., for MOS). Use passive vs. active sensing to reduce energy associated with drawing air into the sensor. Integrate energy-producing devices that use textile fibers to harvest mechanical, vibrational and hydraulic energy and convert to electrical energy to power nanodevices.	Capture real-time, daily air pollutant concentration spectrum, optimize pulse vs. continuous sampling based on pollutant and setting characteristics and data use/decision needs and objectives. Facilitate real-time data upload (applies to charged units, not battery-powered devices). Nanomaterials can continue to be explored (e.g., the operational temperature was reduced to 300ºC in one case, still much higher than room temperature operation for polymer-film sensors). Tap ongoing innovative research on novel energy sources and energy harvesting.

TABLE 4-2 Highlights of Sensor Gaps/Limitations and Opportunities[a]

Feature	Gaps	Potential Solutions / Advances	Issues / Research Opportunities
Sensitivity-selectivity	High sensitivity and selectivity is a current gap for lower-cost sensors	Add hardware and software to account for interferences (including humidity, temperature, air flow, barometric pressure).	Additional components typically increase cost and energy consumption; might be accommodated by mass fabrication.
		Choose pre-concentration materials chosen based on composition for selectivity of target substances and ability to deliver molecules to sensing elements in more concentrated bursts to increase sensitivity.	Time to reach desired pre-concentration rates may be increased if the concentration is low, resulting in increased sampling and response times.
		Use multiple sensing elements (e.g., sensor arrays, e-noses).	Possible increased maintenance needs, cost.
		Pursue humidity-assisted gas sensing to improve selectivity.	Has been applied to SO_2/NO_2 differentiation. More research is needed for application to other pollutants of interest.
		Use chemical coatings that only allow certain particles (based on electric potentials) to reach the sensing device.	
	Interference control	Use front-end filter/screen interferences.	
	Sensor drift	Harness super-sampling and automated sensor calibration networks; software tools include CaliBree, Quintet, and Halo.	Adding components typically increases cost and energy consumption; a possible cost reduction from mass fabrication would be at least somewhat offset by additional software.
		Increase desorption rate of chemicals and interferents such as water molecules from reactive chemical films.	

TABLE 4-2 Highlights of Sensor Gaps/Limitations and Opportunities[a]

Feature	Gaps	Potential Solutions / Advances	Issues / Research Opportunities
Response, recovery, and analysis time	Identification of exposure context (e.g., environmental setting, concurrent activity)	Include technology that "hears" ambient noise and classifies its spectral features to identify the measurement environment. Include an accelerometer. Enhance software, e.g., building on Intel's Place Lab or MIT's Cricket Indoor Locator (note Place Lab requires a radio beacon to estimate position, so although this example is not practical for general use it illustrates the basic concept).	Continued research and development is indicated for such technologies; adding components to sensor systems can increase cost and/or energy consumption, depending on the component (note a common 3-axis accelerometer is about $10). Typically governed by energy constraints, sensor technology and sampling preferences.
	Response time	Depends on specific application needs, constraints, and preferences. Can Increase reactive surface area in chemical sensors; could be achieved using nanoparticles.	Hazardous and unreliable purification techniques (dissolving in solutions such as dichlorobenzene) for CNTs results in increased cost of production. Use of other materials has been successful. Increasing reactive surface typically greatly increases recovery time. Added cost is also an issue.
	Recovery time	Expose to UV light or heating elements. Increase chemical desorption rates.	
Climate control	Reliable field operation (without a relatively large climate control infrastructure)	Pursue technologies that do not require climate control and/or include components that account for environmental factors (e.g., sensors in which the current in metal oxide filaments is altered per temperature and humidity; such as for the Air Quality Egg).	Technology changes to improve field operations typically come at the expense of other capabilities; additional components can increase cost and/or energy consumption.

[a] Information resources include:

Place Lab: Intel, http://www.intel-research.net/Publications/Seattle/100220061038_340.pdf: estimates location (ubiquitously) by scanning for fixed radio beacons (802.11 access points [WiFi or Bluetooth] and GSM cell towers). Works indoors and outdoors, and can run on laptops, PDAs, and cell phones. Privacy addressed by not needing any network connection or server-based infrastructure. Less accurate than GPS (can estimate location within 15 to 20 meters if three distinct beacons are seen in a 10-s window), but can cover nearly all user locations. Developed in tandem BeaconPrint, a program used for place learning (the location cannot be estimated without a beacon database).

Cricket: MIT, http://cricket.csail.mit.edu/.

Air quality egg: http://airqualityegg.wikispaces.com/AirQualityEgg.
CNT hazards and costs: http://scitechdaily.com/mit-team-uses-carbon-nanotubes-to-draw-gas-sensors/; http://www.azonano.com/article.aspx?ArticleID=3107.

Quintet and Halo: Eisenman (2008): People-Centric Mobile Sensing Networks; http://www.ists.dartmouth.edu/library/440.pdf.

TABLE 4-3 Highlights of Advantages and Limitations for Selected Technologies-Techniques[a]

Sensing Technology/ Technique	Advantages	Limitations
Electrochemical	1. User-friendly 2. Requires very little power to operate; operates at ambient temperature 3. Linear response over a wide concentration range 4. Relatively sensitive (very sensitive to diverse VOCs) 5. Very fast sampling	1. Noise and drift in electronics can impact accuracy and precision of measurements 2. Smallest practical sensor = 1 cm^3 3. Larger = more precise and accurate 4. Can be sensitive to temperature and extreme humidity 5. Have short life spans (1-2 years)
Spectroscopic	1. Laser can be tuned to measure one or more specific gases 2. Accuracy can be very high 3. Can detect relatively inert compounds (does not rely on chemical reactions)	1. Typically at least a few centimeters long (minimum distance required for laser), and difficult to improve upon existing detection limits (limited by optical cross section, absorption cross section, and other factors) 2. Components are typically more expensive for spectroscopic sensors than electrochemical and MOS sensors
Metal oxide	1. Available off the shelf 2. Low cost 3. Very small 4. Good for identifying relative concentration changes	1. Better for reasonably reactive gases, not for inerts 2. Requires high power to heat metal oxide (250-500ºC) 3. Very sensitive to environmental factors 4. Requires extensive calibration 5. Have short life spans (1-2 years)
MEMS with resonator technology (e.g., FBAR)	1. Detects PM 2. Very, very small 3. Manufacturing process is already tuned for high volume, low cost; currently used in some mobile phones (note FBAR represents the technique whereby mechanical stress is converted to an electrical signal)	1. Still under research (one feature under study is high power air pump for controlled flow rate resulting in high energy consumption) 2. Does not detect gases

[a] MEMS: microelectromechanical systems; FBAR is a thin-film, bulk acoustic resonator technology.

TABLE 4-4 Example Comparison of Limitations and Opportunities for Three CO Sensors[a]

Feature	Commercial Sensor System: *Ecotech Serinus 30*	R&D Sensor System: *Solid electrolyte sensor*	Household Sensor: *Kidde Digital CO*
Cost *Opportunity*	Relatively high *Could potentially lower, e.g., via large-scale manufacturing-marketing*	(Not identified) *≤ to household sensor price*	~$30 Decrease cost
Mobility *Opportunity*	Yes, but ~40 lbs *Reduce system size (to handheld)*	Setup could be miniaturized *Reduce system size*	Mounted in outlet; 13 in. width Pursue portability, reduce size
Energy consumption *Opportunity*	99-132 VAC, 198-264 VAC 47-63 Hz *Decrease, optimize*	(Not identified)	120 VAC
Sensitivity-selectivity *Opportunity*	0.04-200 ppm (LDL 20 ppb) – highly selective for CO *Increase sensitivity*	10-500 ppm (detection limit: 0.5 ppm); also detects VOCs & hydrocarbons; high selectivity *Increase sensitivity*	30-999 ppm (+/- 20%); also detects smoke
Analysis/response time *Opportunity*	Response time: 60 seconds *Reduce warmup, response times*	Response time: <1 min; continuous *Reduce response/warmup times (noncontinuous)*	Continuous sampling/readout
Other operating factors *Opportunity*	0-40°C; regular calibration *Decrease maintenance requirements*	*Pursue autocalibration (e.g., via network)*	7-year life
Operator type *Opportunity*	Trained *Make user friendly for general public*	Trained *Make user friendly for general public*	General public

[a] The first two sensors have networking capabilities and concentration displays; the household sensor includes the latter but no networking.

R&D Sensor-System: Information highlighted from Kida et al. (2010). *Application of a Solid Electrolyte CO_2 Sensor for the Analysis of Standard Volatile Organic Compound Gases.* Analytical Chemistry, 82(8):3315-3319, http://pubs.acs.org/doi/full/10.1021/ac100123u (Kyushu University, Fukuoka Japan; Dept. Energy and Materials Sciences). Note: this represents a relatively early stage of research so information for some table entries is not yet known; it has only been tested in the laboratory (not the field).

Energy consumption: Reducing sample acquisition time can significantly reduce energy consumption. Moving from continuous sampling to discontinuous (pulse) sampling within longer time intervals or during specific times of the day could conserve energy. Opportunities for energy conservation include reducing the duration of each measurement and decreasing warmup times. Some sensor technologies such as those based on metal oxides require a high power heater for operation. Transmitting collected data from the sensor to the network database also consume energy. Delaying data upload until the sensor is being charged can help reduce that consumptions (e.g., for situations where real-time data are not needed).

Sensitivity-selectivity/interferences: Interferences are a common problem for research sensors, including from other chemicals, humidity, temperature, barometric pressure, and air flow rate. Performance can be enhanced by either keeping key interferents constant or otherwise accounting for variability. Hardware options exist to address some sources of interference, but at a cost. Precision can also be increased by super-sampling approaches, which would involve deploying a large number of mobile sensors (e.g., hot spots where people frequently congregate would offer an opportunity for super-sampling and collective calibration).

Analysis/response time: Because mobile sensors take measurements in many places, context needs to be attributed to each sample for data to be useful. Research opportunities being pursued include incorporating capabilities into the device that provide this context across multiple setting. For example, audiosensing for ambient noise with classification of the spectral features is being used to indicate the sampling environment. Accelerometers are being used to indicate the level of activity during data collection (common for sensors embedded in cell phones). Response time is related to energy consumption; warmup times differ by technology, and different sensors take samples over different intervals. Note the emphasis for response time is not so much taking as many samples as quickly as possible but rather what type of sampling regimen is well suited and most efficient for purpose of the given monitoring. It is very important for sensor readouts to place the concentration in context of the exposure benchmark. For example, a 1-minute value that exceeds an 8-hour or 24-hour standard might not produce adverse health effects and could cause unnecessary concern if the readout is separated from that key information context.

Other operating factors: Calibration/data quality is one of the most important issues for mobile sensors. Minimal drift over a long time is desired. For some situations, such as super-sampling (in which sensors are close to each other), tools exist for manually calibrating the sensors within a large network so sampling results can be compared across sensors and drift can be assessed (e.g., with CaliBree). Also described in research literature are tools to tap other sensing resources from nearby devices and to rendezvous with static infrastructure, such as Quintet and Halo, respectively (Eisenman 2008). Because ambient concentrations are typically low, even a slight drift can produce unreliable results. Software advancements are needed to detect malfunctioning sensors to avoid throwing off the automatic calibration system (or including those data). Also, incorporating hardware that can account for changes in humidity and temperature reduces the extensive climate-control infrastructure needs. Sensors need to have the ability to be interference-free or take such changes into account, including changes in humidity and temperature.

4.2.6 Mobile Applications

An overview of several online air quality resources (including EPA 2012b) and free mobile applications is presented in Appendix G, together with a demonstration of selected Android apps (Temple [2012]). Also included in Appendix G are user comments that have been posted online for three apps, reflecting inputs from more than 60 users reported from April 2012 to February 2013 (Table G-1, tapping Aesthetikx [2012], ALA [2013], and EPA [2013c]). These comments are ordered within three main topic areas (value, data coverage, and user interface), first in order of the user rating (e.g., comments rated highest are grouped first within a category), and then in order of the comment date. (Note the date provides some context for progressive versions of the apps, as the version and the mobile device used are not reported in all cases.)

The example demonstration of air quality apps in Appendix G indicates several issues for current mobile apps:

- Data coverage: Limited to a fixed monitoring station from the nearest urban center, and data are only available for major cities. Without further information to fill in current spatial gaps, it cannot be known if such data are representative across community, neighborhood, and individual scales.

- Pollutant coverage: Limited to two pollutants: $PM_{2.5}$ and ground-level ozone. The air quality index (AQI) map application does not differentiate between the two. (Note in most cases, the air quality is represented by a number associated with the AQI.)

- Update frequency: The frequency of AQI updates varied for certain areas and monitors. Forecasting is affected in those areas for which data are updated less frequently.

- User interface, and inconsistencies.

Online reviews and ratings indicate many of the same concerns. The value of the app concept is highly regarded (collective rating of 4.5 out of 5), which affirms that mobile apps represent a clear opportunity area. The main gaps are associated with data coverage (collective rating of 1.4) and the user interface (collective rating of 2.3).

4.2.7 Data Quality and Data Management

Quality and quantity are key issues for data collected by mobile sensors, in terms of both practical utility and the management approaches and systems needed for the enormous amounts of data generated. Regarding the first issue, data quality objectives are key – as the purpose for which the data are collected drives the quality expectations (to assure they are "fit for purpose"). Regulatory requirements and guidance exist for data quality for specific enforcement or compliance purposes, including guidance for ambient air quality data. For example, the recent list of designated reference and equivalent methods for criteria pollutants (EPA 2012a) emphasizes the importance of using each method "in strict accordance with its associated operation or instruction manual and with applicable quality assurance procedures."

Recognizing that substantial amounts of data are used for many other purposes beyond regulatory programs, it is useful to consider the nature of the data warranted for various uses. For example, the quality of data needed to guide an individual's plan for outdoor activities (e.g., to avoid strenuous activities when a given pollutant concentration is high) would be much

different than that for reporting facility emissions and fenceline concentrations under specific state or federal compliance programs. In many cases, qualitative or semiquantitative data (such as may result from a low-cost colorimetric approach) will be sufficient for the intended purpose. Thus, tiered approaches (or "banding") for indicating appropriate data quality and management standards and tools are expected to play an important roles in addressing air quality for data from mobile sensors. It is vital to assure that readouts are compared to appropriate benchmarks so that measured values are not compared to benchmarks with much different averaging times.

Big data represents an emerging research area, as a number of agency, national laboratory, industry, and other research efforts aim to develop and implement effective ways of dealing with the explosion of data being generated (e.g., as illustrated by the open government initiative, see data.gov). With continuing advances in high-performance computing, a new breed of smart supercomputers is being tapped to tackle the enormous amounts of data being generated; for air quality alone, the volume of data (which is already extremely large) will markedly increase under the vision of widespread mobile sensing. New statistical approaches including scalable and parallelizable numerical algorithms are being developed to address the much more complex data analytics challenges created by massive data sets. Parallel advancements in data storage and access approaches and systems, such as cloud computing, also provide opportunities for addressing the vast scale of data to be generated by mobile sensors.

In the age of ubiquitous computing, ongoing internet advances provide a strong opportunity for addressing the huge amounts of air quality data envisioned. In less than twenty years, the evolution of the world wide web has been remarkable – beginning with the "web of cognition" (1.0) and morphing to a web of communication (2.0), cooperation (3.0), and integration (4.0) (Aghaei et al. 2012). As described by Larson (2012), Web 1.0 was content creation by the few, with software on local machines and reliance on desktop computers. The Web 2.0 era saw content creation by the many, emergence of social technologies and both local and web-based software, and the use of mobile phones and tablets. With Web 3.0, content was being created by the majority, web participation was common, and software was in the cloud. In the current era, Web 4.0, meaning is being created by the majority, operating systems are in the cloud, desktop computers, mobile phones, and tablets have been joined by iTV, and augmented data layers are common. Sustained advancements will continue to provide strong opportunities for uploading, distributing, sharing, visualizing, storing, and maintaining data from mobile sensors.

A further important consideration for citizen-based sensing relates to privacy/ethics, such as issues related to location tagging and human subject constraints. Approaches for addressing these issues include tools that can decouple, aggregate, anonymize and otherwise transform data to provide appropriate protection.

4.3 PARTNERSHIPS

4.3.1 Funding Sources: Leveraging

Many U.S. and international organizations have funded research relevant to mobile sensors and apps for air pollutants. Funding agencies include the U.S. Department of Agriculture (USDA); Department of Defense (DoD), including the Air Force Office of Scientific Research and Army Research Office, Defense Advanced Research Projects Agency (DARPA), Defense Threat Reduction Agency (DTRA); Department of Energy (DOE); Department of Homeland Security (DHS); Department of Transportation (DOT), including Federal Aviation Administration (FAA); EPA, National Aeronautics and Space Administration (NASA); Department of Health and Human Services (DHHS), including NIH, NIEHS ; National Science Foundation (NSF) and other

foundations; and U.S. Department of Commerce, National Institute of Standards and Technology (NIST). For example, EPA ORD has been very active in promoting and leveraging partnerships, including through several recent workshops in Research Triangle Park, NC, and Washington, DC; NIEHS has also hosted workshops and webinars to convene researchers active in this area, and both agencies are collaborating on these efforts.

Private-sector funding sources include Motorola, Exxon Mobil, Microsoft, Nokia, Intel, and others. As an indication of new opportunities, individual citizens are also playing a role in funding mobile sensor initiatives, including via crowdsourcing platforms such as Kickstarter. Leveraging is being pursued at multiple levels including via agency work group, researcher collaborations, research-community initiatives, and community-centered projects with DIYers. Programs such as *AIRNow* and the *Weather Underground* serve as examples for expanded collaboration, including internationally. Topics being addressed include harmonization and open source approaches for standards, protocols, platforms, and networks.

4.3.2 Education and Participation Initiatives

Student-centered programs have played an important role in promoting awareness of mobile sensing for air pollutants that is expected to continue and increase. Programs such as the G03 project (focused on schoolchildren awareness of atmospheric pollution) and Air Quality Egg provide a strong foundation for related initiatives. Similar successes include the Bucket Brigade (developed to assist fenceline communities), Common Sense, and AIR by Preemptive Media. Such community-centered sensing projects have demonstrated extensive networking capabilities with associated integration and visualization of air quality data contributed by citizen users.

The DIY community is increasingly active. A number of online resources are available to facilitate mobile sensing projects. For example, step-by-step instructions can be found for a wide variety of projects via Explore Instructables.com and SparkFun.com. Tutorials and product information can be found for an extensive suite of DIY projects, including air and weather sensors. The SparkFun Inventor's Kit for Arduino is an example of a resource that guides beginners through the construction of 14 basic circuits and can be modified to include individual pollutant sensors. Basic materials for DIYers include an Arduino board (a platform compatible with a number of sensor inputs) and small sensor units that can be purchased preassembled or in parts for hands-on activities. Individual "plug-and-play" pollutant-specific sensors can be purchased through SparkFun or directly from standard manufacturers such as Hanwei and Figaro. The nonprofit AirCast initiative is a nice example of active engagement, with citizens building their own sensor devices using information and materials from a common source for the DIY community, including (remote) international participants.

Opportunities for increased awareness and creative citizen involvement are tapped via open challenges (e.g., My Air, My Health; C3: Collect, Construct, Change) and gamifying approaches. A key aim of the mobile sensors and apps initiative is to facilitate participatory sensing, and a number of successful programs serve as examples, from Project BudBurst to NightSky. Additional lessons can be learned from citizen-based sensing associated with incidents such as Fukushima. Insights gained from a wide variety of recent participatory sensing projects frame opportunities for enhancing the citizen involvement element of the current EPA initiative for next-generation air monitoring.

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5 SUMMARY

This report highlights recent research relevant to mobile sensors and apps for air pollutants.

Study Pollutants

Fourteen pollutants (two solids and twelve gases) provided context for practical applications:

- Criteria pollutants: Carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide.
- HAPs: Acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde.
- Indicators: Ammonia, hydrogen sulfide, and methane.

Sensor Targets

- Most mobile sensors detect gases; criteria pollutant gases appear to be adequately covered.
- No mobile sensors were found for lead; particulate matter (PM) options are also limited.
- Research sensors or novel systems with commercial sensors exist for the indicator pollutants and most of the HAPs, but sensors for acrolein and 1,3-butadiene are limited.

Sensing Technology/Technique

- Technique: These can be grouped into three main categories: chemical, spectroscopic, and ionization techniques (in order of prominence per the selected literature reviewed); the first two are most active and growing.
- Technology: Nanotechnology is a dominant theme in recent air pollutant sensor research.

Detection Capabilities

- Health-based guidelines: Most levels appear to be detectable based on reported sensor capabilities, except for the lower (protective) concentrations for four pollutants: acetaldehyde, acrolein, ammonia, and formaldehyde.
- Ambient measurements: Acrolein, lead, and methane are among the pollutants for which common ambient levels could be difficul**t** to detect.
- Commercial sensors and novel systems that use commercial sensors dominate over strictly research sensors for many of the chemicals.

Architecture/Infrastructure and Apps

- Architecture: Portable, handheld and vehicle-mounted architectures are relatively common; less common are wearable sensors. The trend is increasingly small and mobile.
- Infrastructure: Sensor components are increasingly integrated with mobile phones, tapping Bluetooth/wireless network links. User interface design and programming components are highly active research areas, and a limited set of air quality apps exist.

Gaps

- Particle sensors, including chemical-specific sensors, are generally lacking; multipollutant sensors in a single small, affordable system (rather than modular plug-ins) are needed.
- Detection capabilities are not sufficiently low to address the full range of benchmarks and example air concentrations for the pollutants studied (or others of interest to communities).
- Field reliability and durability of sensors/systems are not yet assured over a range of environmental conditions (including less expensive measures for addressing drift, interferences and local climatic conditions).
- Algorithms and approaches are needed for consistent data processing, quality assurance and control, and data scrubbing, transformation, integration, visualization, and analysis.
- Effective and efficient data and knowledge management approaches are needed, including standards and protocols, infrastructure, and software for reporting, accessing, sharing, storing/archiving, and maintaining data, considering both raw and transformed data and topical syntheses.
- Apps that provide high-resolution spatial coverage for community, local, and individual scales are needed, with displays for a full suite of pollutants. Also needed are reliable user interfaces across multiple devices, extending beyond mobile phones to include tablets and other emerging systems, as well as supporting content for data interpretation (e.g., links to health-based standards and other measurements relevant to that setting).

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Opportunities

- Nanotechnology-based advancements in sensing technologies/techniques and sensor systems provide a strong opportunity for increasingly mobile sensors.
- Integrated sensor arrays for multi-pollutant sensing, as well as links to biosensors (e.g., personalized medicine applications) combined with insights from sensors for other measurands, offer opportunities for multipurpose systems.
- Novel energy sources (including human) and optimized sampling regimens (e.g., super sampling and targeted sampling guided by pollutant behaviors and fate) offer opportunities for lower power use and more affordable systems.
- Hybrid fixed-mobile systems that leverage existing infrastructure represent opportunities for practical field applications.
- Greater automation and expanding networks also offer opportunities for higher performance, including autocalibration and self repair (e.g., Internet of Things/Web 4.0).
- Real-time data collection, upload, integration, distribution, display, and interpretation via user-friendly apps represent opportunities for platforms that extend beyond smartphones. Ongoing advances in cloud computing and related systems offer opportunities for more efficient data sharing and management.
- Leveraging systems, organizational resources, and citizen capital represents an opportunity for achieving the goal of nationwide air quality data coverage and context for guiding environmental health management measures from personal to regional and national scales. Collateral programmatic benefits including intermediate baselining for climate change and adaptation planning, increased awareness of personal exposure and health, and other related environmental health and impact analyses programs.

6 ACKNOWLEDGEMENTS

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7 SELECTED INFORMATION RESOURCES

(A number of information resources are also provided in individual tables and supporting notes.)

ACGIH (American Conference of Governmental Industrial Hygienists) (2012). *2012 TLVs and BEIs: Based on the Documentation of the Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*, Cincinnati, OH.

Aesthetikx (2012). *Air Quality, Android Application*; https://play.google.com/store/apps/details?id=com.aesthetikx.airquality&feature=search_result#?t=W251bGwsMSwxLDEsImNvbS5hZXN0aGV0aWt4LmFpcnF1YWxpdHkiXQ *(page indicates last update was Feb. 22, 2012; online reviews were posted April 12 through Aug. 9, 2012; last accessed Feb. 18, 2013)*.

Aghaei, S., M.A. Nematbakhsh, and H.K. Farsani (2012). *Evolution of the World Wide Web: from Web 1.0 to Web 4.0.* International Journal of Web & Semantic Technology*,* 3(1):1-10 (Jan.); http://airccse.org/journal/ijwest/papers/3112ijwest01.pdf.

ALA (American Lung Association) (2013). *State of the Air, Android Application*; http://www.lung.org/healthy-air/outdoor/state-of-the-air/app.html; https://play.google.com/store/apps/details?id=com.reddeluxe.sota *(page indicates last update was Oct. 24, 2012; online reviews were posted June 18 through Dec. 8, 2012; last accessed May 22, 2013)*.

Aluri, G.S., A. Motayed, A.V. Davydov, et al. (2011). *Highly Selective GaN-Nanowire/ TiO_2-Nanocluster Hybrid Sensors for Detection of Benzene and Related Environment Pollutants*. Nanotechnology*,* 22. Retrieved from http://iopscience.iop.org/0957-4484/22/29/295503/pdf/0957-4484_22_29_295503.pdf.

ATSDR (Agency for Toxic Substances and Disease Registry) (2013). *Minimal Risk Levels (MRLs).* (Jan.); http://www.atsdr.cdc.gov/mrls/index.asp *(page last updated Mar. 6; last accessed May 22).*

Beirne, S., B.M. Kieman, C. Fay, C. Foley, B. Corcoran, A.F. Smeaton, and D. Diamond (2010). Autonomous Greenhouse Gas Measurement System for Analysis of Gas Migration on Landfill Sites. 2010 IEEE Sensors Applications Symposium Proceedings. Accessed from IEEE Xplore at http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5439422&tag=1.

Caland, F., S. Miron, D. Brie, and C. Mustin (2011). *A Candecomp/Parafac Approach to the Estimation of Environmental Pollutant Concentrations Using Biosensors*. IEEE Statistical Processing Workshop*.* Retrieved from http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5967826&isnumber=5967628.

CalEPA (California EPA) (2012a). *All OEHHA Acute, 8-hour and Chronic Reference Exposure Levels (chRELs) as on February 2012.* Office of Environmental Health Hazard Assessment (OEHHA), Sacramento, CA (February 9); http://www.oehha.org/air/allrels.html *(page last accessed May 22, 2013).*

CalEPA (2013). *Proposed Reference Exposure Levels for 1,3-Butadiene [09/11/12].* OEHHA, Sacramento, CA; http://oehha.ca.gov/air/hot_spots/106990_2012.html *(draft last revised on March 1; page last accessed May 22)*.

Yang, C.H. (2010*). Development of Nanosensor to Detect Mercury and Volatile Organic Vapors*. Retrieved from http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/3060/D_Yang_Chang%20Heng_a_2010.pdf?sequence=1.

Eisenman, S.B. (2008). *People-Centric Mobile Sensing Networks*; http://www.ists.dartmouth.edu/library/440.pdf.

ERG (Eastern Research Group) (2011). *Advancements in Air Monitoring using Fence Line and Network Sensors: Currently Available and Promising Technologies*. Prepared for E. Thoma, U.S. EPA, Air Pollution Prevention and Control Division, ORD National Risk Management Research Laboratory, Research Triangle Park, NC (Rev. 0, Oct. 31).

EPA: see U.S. EPA.

Guan, J. and S. Wang. (2009). *Application of Integrate Sensor in Gas Alert System of Coal Mine*. Accessed from IEEE Xplore at http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5072745&isnumber=5072599.

He, J., T.-Y. Zhang, and G. Chen (2012). *Ammonia Gas-Sensing Characteristics of Fluorescence-based Poly(2-(acetoacetoxy)ethyl methacrylate) Thin Films*. Journal of Colloid and Interface Science, 373 (1): 94-101. Retrieved from http://www.sciencedirect.com/science/article/pii/S0021979711014512.

Honicky, R.E. (2011). *Towards a Societal Scale, Mobile Sensing System*; http://www.eecs.berkeley.edu/Pubs/TechRpts/2011/EECS-2011-9.pdf (UCB/EECS-2011-9).

Kida, T., M.-H. Seo, S. Kishi, et al. (2010). *Application of a solid electrolyte CO_2 sensor for the analysis of standard volatile organic compound gases.* Analytical Chemistry, 82(8): 3315-3319.

Kim, I., K.-Y. Dong, B.-K. Ju, et al. (2010). *Gas Sensor for CO and NH_3 Using Polyaniline/CNTs Composite at Room Temperature*. Proceedings of 10th IEEE International Conference on Nanotechnology Joint Symposium with Nano Korea. Retrieved from http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5697782&isnumber=5697724&tag=1.

Larson, L. (2012). *Web 4.0: The Era of Online Customer Engagement* (Jan. 5); http://www.business2community.com/online-marketing/web-4-0-the-era-of-online-customer-engagement-0113733 *(page last accessed May 22, 2013).*

Lenntech (2012). *Water Treatment Solutions, Calculators, Parts per Million (ppm) Converter.* http://www.lenntech.com/calculators/ppm/converter-parts-per-million.htm *(last accessed May 22, 2013).*

Lozenko, S., M. Lebental, J. Lautru, et al. (2011). *Specific (bio-)chemical Sensing with Organic Microlasers.* CLEO EUROPE/EQEC, 12th European Quantum Electronics Conference. Retrieved from http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5943699&isnumber=5942420.

Mariano, S., W. Wang, G. Brunelle, Y. Bigay, and T.-H. Tran-Thi (2010). *Colorimetric Detection of Formaldehyde: A Sensor for Air Quality Measurements and a Pollution-warning Kit for Homes*. 2010 First International Conference on Sensor Device Technologies and Applications. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5632112&isnumber=5632098&tag=1

NIOSH (National Institute for Occupational Safety and Health) (2010). *NIOSH Pocket Guide to Chemical Hazards*; http://www.cdc.gov/niosh/npg/default.html *(page last reviewed Jan. 30, 2012; accessed May 22, 2013).*

Nomani, Md.W.K., D. Kersey, J. James, et al. (2011). *Highly Sensitive and Multidimensional Detection of NO_2 using In_2O3 Thin Films*. Sensors and Actuators B, 160: 251-259. Retrieved from http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511006861&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=a9efb7781a0624784753f0979694f695/1-s2.0-S0925400511006861-main.pdf.

NRC (National Research Council). (2013). *Acute Exposure Guideline Levels Program.* via http://dels.nas.edu/global/best/AEGL-Welcome *(last accessed May 22, 2013).*

Peng, L., et al. (2011). *Improvement of Formaldehyde Sensitivity of ZnO Nanorods by Modifying with $Ru(dcbpy)_2(NCS)_2$.* Sensors and Actuators B, 160(1):39-45 (Dec).

Raymond, M., D. Wyker, T. Raymond, M. Finster, B. Temple, and M. MacDonell (2013). *Literature Highlights Relevant to Mobile Sensors and Apps for Air Pollutants*. (Complementary table to this report.) (Feb. 19).

Sardini, E., and M. Serpelloni (2011). *Self-Powered Wireless Sensor for Air Temperature and Velocity Measurements with Energy Harvesting Capability.* IEEE Transactions on Instrumentation and Measurement, 60(5):1838-1844 (May).

Sekine, Y. and R. Katori (2009). *Indoor Air Quality Monitoring via IT Network*. ICROS-SICE International Joint Conference 2009, Fukuoka International Congress Center, Japan. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5333246&isnumber=5332438&tag=1

Shim, Y.-S., et al. (2011). *Transparent Conducting Oxide Electrodes for Novel Metal Oxide Gas Sensors.* Sensors and Actuators B, 160(1):357-363 (Dec.)

Temple, B. (2012). *Air Quality Monitoring: Citizen Sensing Initiative*. Prepared in fulfillment of the requirement of the Office of Science, Department of Energy's Science Undergraduate Laboratory Internship, Environmental Science Division, Argonne National Laboratory (Aug.).

U.S. EPA (U.S. Environmental Protection Agency) (2008). *Risk-Based Criteria to Support Validation of Detection Methods for Drinking Water and Air*, EPA/600/R-08/021 (Oct.); http://cfpub.epa.gov/si/si_public_record_report.cfm?address=nhsrc/&dirEntryId=188648 *(page last updated and accessed May 22, 2013).*

U.S. EPA (2011). *National-Scale Air Toxics Assessment*, and *Summary of Results for the 2005 National-Scale Assessment*; http://www.epa.gov/ttn/atw/nata2005/05pdf/sum_results.pdf, http://www.epa.gov/nata2005/ *(page last updated May 21, 2012; last accessed May 22, 2013).*

U.S. EPA (2012a). *AirData*; http://www.epa.gov/airdata/ *(page last updated Sep. 27, 2012; last accessed May 22, 2013).*

U.S. EPA (2012b). *List of Designated Reference and Equivalent Methods* (Dec. 17); http://www.epa.gov/ttnamti1/files/ambient/criteria/reference-equivalent-methods-list.pdf, via http://www.epa.gov/ttnamti1/methods.html *(page last updated Dec. 20, 2012; last accessed May 22, 2013).*

U.S. EPA (2013a). *Integrated Risk Information System (IRIS);* online database; National Center for Environmental Assessment, Washington, DC; http://www.epa.gov/IRIS *(chemical-specific pages last updated and accessed May 22, 2013).*

U.S. EPA (2013b). *Provisional Peer-Reviewed Toxicity Values for Superfund (PPRTV)*, online resource of the National Center for Environmental Assessment, Washington, DC, hosted by Oak Ridge National Laboratory; http://hhpprtv.ornl.gov/ *(page not dated; last accessed May 22).*

U.S. EPA (2013c). *AIRNow, Android Application*; https://play.google.com/store/apps/details?id=com.saic.airnow *(page indicates last update was March 23, 2012; most recent comment posted Apr. 24, 2013; last accessed May 22)*.

Wang, Z. L., G. Zhu, Y. Yang, S. Wang., and C. Pan (2012). *Progress in Nanogenerators for Portable Electronics.* Materials Today, 15(12): 532-543 (Dec.).

APPENDIX A:

SUPPORTING DETAILS FOR THE LITERATURE SEARCH APPROACH

APPENDIX A:
SUPPORTING DETAILS FOR THE LITERATURE SEARCH APPROACH

A.1 INITIAL FRAMING ACTIVITIES

A.1.1 Pollutants

As part of initial framing for the literature search, early inputs from EPA Program and Region staff regarding pollutants of interest were compiled in Table A-1.

TABLE A-1 Program and Regional Inputs to the List of Candidate Pollutants[a]

Air Pollutant	Basis
Acrolein	National Air Toxics Assessment (NATA), national hazard driver
Benzene	NATA regional risk driver
1,3-Butadiene	NATA national risk contributor
Carbon monoxide (CO)	Criteria pollutant
1,1-Dichloroethylene	Risk driver, soil vapor intrusion
Ethylbenzene	Risk driver, soil vapor intrusion; NATA national risk contributor
Formaldehyde	NATA national risk driver
Hexabromocyclododecanes (HBCDs)	Children's health program, flame retardant
Hydrogen sulfide	Emissions indicator
Lead	Children's health program; criteria pollutant
Mercury	Children's health program
Methane	Emissions indicator
Nitrogen oxides/dioxide (NOx/NO_2)	Criteria pollutant
Ozone	Criteria pollutant
Particulate matter (PM)	Criteria pollutant; from NATA: diesel PM, coke oven emissions
Perchlorate	Children's health program
Perfluorocarbons (PFCs)	Children's health program
Phthalates	Children's health program
Polybrominated diphenyl ethers (PBDE)	Children's health program, flame retardant
Polychlorinated biphenyls (PCBs)	Children's health program
Sulfur oxides/dioxide (SOx/SO_2)	Criteria pollutant
Toluene	Children's health program
Trichloroethylene	Risk driver, soil vapor intrusion
Xylene	Children's health program

[a] This list includes inputs provided by EPA Program and Regional staff to the ORD innovation team for air pollutant sensors and apps. In addition to these candidates, other hazardous air pollutants (HAPs) are also expected to be of interest across multiple programs and projects. Supporting context provided with selected Regional input for several compounds, included risk-based concentrations in parts per billion by volume (ppbv) corresponding to a 10^{-5} risk (probability of getting cancer over a lifetime, per an assumed continuous exposure using current toxicity values and default residential exposure assumptions for that screening evaluation). Those concentrations were considered as part of the evaluation of sensor detection levels presented in Chapter 3.

A.1.2 Search Terms

Early framing searches were conducted to identify terms for the broader literature search. Candidate terms identified at this early stage are presented below (Table A-2). Core terms include air, quality, toxics, contaminant, hazardous, pollutant/pollution, HAP, measurement, monitoring, citizen, community; mobile, portable, miniature, sensor; technology, smartphone.

TABLE A-2 Candidate Search Terms

Actuator(s)
Aerosol (sensor)
Air/emissions
Air pollutant/pollution
Air quality
Air toxic(s)
Airborne contaminant
Ambient air monitoring
Ambient air quality
Analyzer (portable)
Android
App, application
Architecture (mobile sensor, access point, back end)
Automate(d)/automatic
Autonomous (semi-)

Background (noise)
Badge (sensor)
Biosensor
Blackberry
Browser
BZ (breathing zone) monitor

Chemical (pollutant, sensor)
Chip
Citizen science/scientist
Cloud (computing, services)
Colorimetric (array)
Commercial sensor
Commercial product
Communication
Community
Community-led/-based
Compact
Components (sensor)
Computer (-aided, -assisted)
Configuration
Criteria air pollutant(s)
Crowd source(d)/sourcing
Cumulative exposure
Cumulative risk

Data access
Data aggregation
Data analysis
Data collection
Data curation/curator
Data delivery
Data distribution
Data download
Data flow
Data format
Data infrastructure
Data management
Data processing
Data push
Data quality
Data refresh/reload
Data sharing
Data storage/storing
Data stream(ing)
Data structure
Data update (updating)
Data upload(ing)
Data validation
Data verification
Data visualization
Demonstration/demo
Deploy/deployment
Detection level/limit
Detector
Device (end device)
Digital (imaging)
Distributed control
Distributed network
Download (app, data)
Dynamic
Electronic
Embed(ded)
ENS/embedded network sensing
Engineer/ed/ing
Environment
Environmental app
Environmental contaminant
Environmental contamination
Environmental data
Environmental informatics
Environmental measurement
Environmental monitoring
Environmental observation(s)
Environmental pollutant
Environmental pollution
Equipment
Eye on earth

Fenceline community
Fenceline monitor
Fenceline sensor
Field demonstration
Field deployment
Field detection/detector
Field implementation
Field measure/ment
Field monitor/ing
Field sensing/sensor
Film (sensor)
Filter (noise)
Fixed sensor
Flash
Fluorescent (fluorescence)

Gamify
Gas (sensor)
Geoprocessing
Geo-reference(d)
GeoRSS feed

(TABLE A-2, Cont'd.)

Geospatial
Geostatistics
GIS/geographic information system(s)
GO3
Google earth
GPS/global positioning system
Graphics

Handheld (hand-held)
Hardware
HAP(s)
Hazardous air pollutant(s)
Hazardous chemical(s)

ICT/ information and communication technology(ies)
Image/imaging
Industry/industrial
Informatics
Infrastructure
Innovation/innovative
Install(ation) (app)
Interface (graphical, web)
Internet
Interoperability
Ionization (ionizer)
Iphone

Laser
Localized algorithm(s)
Locational
Luminescent, luminescent(nce)

Maintenance
Manufacture(r)(ing)
Map(s)
Mashup
MEMS /microelectricomechanical
Micro
Microsensor
Miniature/miniaturized
Mobile app
Mobile aware
Mobile measurement
Mobile monitor(ing)
Mobile phone
Mobile sensor
Monitoring data
Multiple air pollutants
Multiple exposures
Multiple sensors
Multiple toxics

NAAQS/ National Ambient Air Quality Standard(s)
Nanosensor
Network sensing
Noise (filter)

Observations & measurements (O&M)
Open data (linked)
Open database license
Open platform, system
Operating/operation(s)
Optimum/optimize

Palm
Participation/participatory (sensing)
Personal device
Personal/personnel monitor
Personal exposure assessment
Personal exposure monitoring
Photo (electric, ionization)
Pilot (project, study)
Platform (cross-, hardware)
Plug-in
Pollutant(s)/pollution
Portable
Position(al) (sensors)
Product, production (cost)
Prototype

QA, QA/QC
Quality assurance
Quality control

R&D/research & development
Rapid (analyzer, analysis)
Raw data
Recognizer (recognition, voice)
Record
Real-time (data collection)
Real-time (feedback)
Real-time (monitor/monitoring)
Replacement

Self-configuring/ed (system)
Sensing/sensor
Sensor accuracy
Sensor array
Sensor capability/capabilities
Sensor component
Sensor cost
Sensor deployment
Sensor-enabled
Sensor performance
Sensor platform
Sensor precision
Sensor requirements
Sensor sensitivity
Sensor size
Sensor system
Sensor technology
Sensor validation
Shake (function)
Signal
Signal (processing)
Small-scale
Smartphone
Smart sensors
Social media
Software
Spatial data
Spectroscopy/spectroscopic

Tag(ging)
Technology(ies)
Test (demonstration, field)
TIC(s)/toxic industrial chemical(s)
Toxic(s)/toxicant
Trace(r)
Track(er)(ing)

Unified (sensor)
Untethered (wireless)
Usablenet

(TABLE A-2, Cont'd.)

VGI/volunteered geographic information
Visualization/visualize

Wearable (sensor, monitor)
Web 2.0 / 3.0
Web app
Web-based information system(s)
Web-enabled
Web processing service
Web service interface
Wireless

A.2 PHASE I SEARCH

A broad online search of recent literature was initiated in late 2011 and continued into early 2012. Its focus was mobile sensor technologies and associated architecture/infrastructures and applications.

A.2.1 Scope

The search focused on the following considerations:

- Sensor size: Small, handheld
- Portability: Mobile / easy to carry
  (Note: Fixed sensors are considered when part of a combined system or if transition to a portable system is indicated in the near term.)
- Stage: Research and development, to prototype
  (Note: Commercial sensors are included when they are part of a novel sensing device or system.)
- Cost: Low
  (Note: Per the research and development focus, it is recognized that this information will not be available in many cases; ultimate goal: $10 or less.)
- Detection limit: ppb or lower (recognizing many will be ppm)
- Date: 2010-2012
- Language: English preferred (others not excluded)

A.2.2 Online Resources

A number of standard searches were conducted during this initial phase, tapping online databases via Web of Science, Web of Knowledge, PubMed, and others, using tools such as RefMan. Further searches ranged from general Google searches (including for paper retrievals) to targeted searches of specific journals, institutions, and researchers as identified from initial reviews.

INSPEC/Physics Abstracts

This heavily indexed database covers the fields of physics, electrical engineering and electronics, computers and control, information technology and mechanical and production engineering, as well as cross-disciplinary subjects such as materials science and nanotechnology. Two initial searches conducted in Phase I (not limited by language) were:

1. Classification Codes covering “sensor” AND indexed keywords for air pollution; search limited to records from 2010-present.

Year Published=(2010-2012) AND Classification=(B7230 OR B6250K OR A0670D OR A8280T OR C3240 OR A8780B) AND Topic=((environment* or (air pollution) or (air quality) or (air toxic*) or (air and emission*) or (airborne contaminant*) or (air pollutant*) or (air monitor*))) AND (Uncontrolled Index=((environment* or (air pollution*))) OR Controlled Index=((environment* or (air pollution*))))

2. Classification Codes covering "air pollution" AND indexed keywords for sensors; this search was limited to records from 2010-present.

   Year Published=(2010-2012) AND Classification=(A8670L OR A9260T OR B7720 OR C3310G) AND Topic=(((sensor or sensors or microsensor* or nanosensor* or biosensor* or detector*)))

   Results of Set 1 and Set 2 were combined and screened for those with words and synonyms for portable/miniature.

   Topic=((portable or mobile or (low cost) or (small size*) or (miniature*) or (micro-portable) or wireless or handheld or (hand held) or personal or (small scale) or smartphone or app or wearable or (citizen science) or (citizen scientist*) or fenceline))

   These results were further limited by keywords in the controlled index or uncontrolled index fields:

   UI=((air pollution) or (air quality) or (air toxic*) or (air and emission*) or (airborne contaminant*) or (air pollutant*) or (air monitor*) or (toxic gas*)) OR CIX=((air pollution) or (air quality) or (air toxic*) or (air and emission*) or (airborne contaminant*) or (air pollutant*) or (air monitor*) or (toxic gas*))

   UI = Uncontrolled Index
   CIX = Controlled Index

   Classification codes considered include:

A0670D	Sensing and detecting devices
A8280T	Chemical sensors
A8670L	Measurement and control techniques and instrumentation in environmental science
A8780B	Biosensors
A9260T	Air quality and air pollution
B6250K	Wireless sensor networks
B7230	Sensing devices and transducers
B7720	Pollution detection and control
C3240	Transducers and sensing devices
C3310G	Pollution control

Chemical Abstracts, Scifinder

A general search for air pollution sensors was conducted for the past two years. Scifinder identifies relevant Chemical Abstracts records, including journal articles, worldwide patents and patent applications.

Web of Science

The Web of Science (WoS) / Science Citation Index covers all the core peer-reviewed scientific literature. Because the indexing is minimal, records appear quickly in the WoS database. This database was searched for relevant 2011-2012 records as a check, to catch papers that may have been missed by the INSPEC and Chemical Abstracts searches.

The WOS does not include all the further indexing available in some other databases so records can be incorporated into the database much more quickly than other database publishers. (This search duplicates some results from Physics and Chemical Abstracts searches.)

Full publications were pursued via the Argonne library system (access to most IEEE articles and AIP conference papers.

Patent Searches

Additional searches were conducted to complement the Chemical Abstracts search using free tools available via the internet, including the Google database and others highlighted below. (Further patent data could be obtained by a patent searcher tapping commercial patent databases.)

1. WIPO – Patentscope, www.wipo.int. This resource was searched for mentions of air pollution sensor in patent documents and international patent applications (PCT) for 2011.

2. US Patent & Trademark Office USPTO. This resource was searched for recent patents and patent applications for air pollution sensors.

3. Espacenet. This resource includes European patents, WIPO patents and Japanese patents. It was searched using "smart search" for recent patents and patent applications for air pollution sensors.

Additional Conference Searches

Simple searches were conducted for "portable or mobile or handheld or miniature" and " air pollution" and "sensors." Engineering Index results were reasonably productive, as those keywords were included in the controlled vocabularies.

Results included abstracts from a search on the Engineering Index platform, and a compilation with links and references to presentations at recent (2009-2011) professional society conferences.

In many cases, relevant abstracts or session descriptions were culled from the websites because formal proceedings volumes were not available. (Note some conferences encourage participants to submit their research to peer-reviewed journals, so some of these presentations are expected to be addressed via other searches designed to tap journals.)

A.3 PHASE II SEARCH

Results of the broad initial search served as the foundation for the more extensive search and retrieval activities in Phase II. These searches followed a similar approach as for Phase I, tapping similar databases and other online resources.

A.3.1 Targeted Searches

Phase II involved a number of targeted searches, including pollutant-specific searches that focused on the study set determined from collaborator inputs and insights from Phase I.

Searches also targeted specific authors, organizations, journals, conferences, and projects that were identified during Phase I as particularly promising.

A.3.2 Secure Searches

Active research is being conducted in support of homeland security-related applications, to support intelligence, security, and defense applications. A targeted search was conducted in a secure facility at Argonne. Results were similar to those from the search of the open literature so they are not discussed further in this report.

A.3.3 Expert Contacts

Colleagues and other experts were contacted during this phase to obtain selected materials not available online (including several conference presentations and proceedings). For example, electronic and hard copy proceedings were obtained for recent ICT conferences (e.g., Ubicomp and Pervasive) to support the compilations and evaluations for research on architecture/infrastructure and application.

A.4 RETRIEVAL, EXTRACTION, AND DATA COMPILATION

Information from the literature search was reviewed, research reports and other publications retrieved, and summary data extracted. The data were then organized and compiled into summary tables to facilitate topical searches and sorts (e.g., by pollutant or by sensing technology/technique).

To illustrate, an example table compiled early in Phase II from journals and organizational websites is provided as Table A-3. Shading indicates results for a pollutant-specific search of to identify sensors for benzene. An example data summary from a patent search prior to compilation in a summary table is presented in Table A-4.

The combined iterative searches and data reviews, extractions, and compilations produced a master sensor table (Raymond et al. 2013) and topical subsets, including those prepared from pollutant-specific sorts. As an example, a subset table is presented in Appendix E to provide summary details for the sensors considered in creating the graphical arrays presented in Section 3.5.

A similar process of search, retrieval, extraction, and compilation was followed to prepare the companion summary table for architecture/infrastructure including software apps.

TABLE A-3 Preliminary Data Compilation for Research Sensors Highlighting the Subset for Benzene[a]

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
20	Duke University *Yang, Chang-Heng* *(Masters thesis, funding source not identified but refers to "NASA needs")*	http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/3060/D_Yang_Chang%20Heng_a_2010.pdf?sequence=1 *[July 2010]*	Nanosensors made of conducting polypyrrole (PPy) and tin dioxide (SnO_2) on single-walled nanotubes (SWNTs)		Re-search					VOCs: benzene, MEK, hexane, xylene		Fast and sensitive for individual chemicals, but not found in this study to be successful for mixtures.
29	Guangzhong University, Environmental Science and Engineering Institute (China) *Cao, X., Tao, Y., Li, L., Liu, Y., Peng, Y., Li, J.* *(Funding: National Natural Science Foundation of China, Natural Science Foundation of Guandong Province, Science and Technology Project Foundation of Guangdong Province)*	http://onlinelibrary.wiley.com/doi/10.1002/bio.1174/full *[2009, Luminescence, 26:5-9]*	Cataluminescence (CTL, type of chemolumi-nescence produced by catalytic oxidation reactions on surface of solid catalyst)	5 mm ceramic heating tube within 12 mm quartz tube	Re-search		Y_2O_3 nanoparticle sensor (Y_2O_3 coated on ceramic heating tube; catalytic reaction when exposed to ethyl acetate, resulting CTL intensity is measured)	Not indicated	Yes	Ethyl acetate	500 ppb	Sensitivity in presence of other vapors; interference caused by formic acid, *n*-hexane, toluene, acetic acid, benzene, formaldehyde, and ethanol at respective % levels of 0.52, 5.75, 8.63, 0.46, 2.81, 1.03, 21.1.

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
74	University of Bahkesir (Turkey) Departments of Physics and Chemistry *Acikbas, Y., Capan, R., Erdogan, M., and Yukruk, F.*	http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S092540051100 6551&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=0388683803395c4afcf870fed42e0795/1-s2.0-S09254005110065 51-main.pdf *[2011, Sensors and Actuators B, 160:65-71]*	Fluorescence (mass change using a quartz crystal microbalance [QCM] measurement system during influence of gas molecules adsorbed on or diffusing into a thin film surface, deposited on glass or quartz crystal substrate by Langmuir-Blodgett [LB] thin film deposition technique)		Re-search		Solid-state fluorescence sensing device with perylene bisimides acting as a fluorescence probe, using a novel perylene molecule (perylene-dimide [FY1] material)			Chloroform, isopropyl al-cohol Also tested: benzene, toluene, and ethyl alcohol	Chloroform 3.9×10^{-4} Hz/ppm (at 1.5×10^{4} ppm)	Large, fast, reproducible results for these two chemicals.

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
94	University of Illinois at Urbana-Champaign *Hengwei, L., Jang, M., Suslick., K.S.* *(Funding: NIH Genes, Environment, and Health Initiative)*	http://www.scs.illinois.edu/suslick/documents/jacs.2011.preox.pdf *[Oct. 2011]*	"Optoelectronic nose" using disposable colorimetric sensor array and pre-oxidation tube packed with chromic acid on silica (nanoporous pigments with pre-oxidation technique)	Bench-top (tube and array); flatbed scanners used for imaging; prototype handheld array is under develop-ment	Re-search		Laboratory (in addition to work on a handheld prototype, work is under way on a wearable device for fast, cheap, highly sensitive personal monitoring of VOC vapors)		Yes	Phenol, others 20 VOCs tested, including acetone, BTEX, chloroform, p-dichloro-benzene, ethanol, ethyl acetate, formalde-hyde, MEK, phenol, isopropanol, styrene, 1,1,1-tri-chloro-ethane, 1,2,4-tri-methyl-benzene	Limits of detection improved to an average 1.4% of respective permissible exposure limit concen-trations (improved sensing of less-reactive VOCs)	Color changes of array are concentration-dependent, provides semiquantita-tive analysis; changes in relative humidity (a problem for prior electronic nose technologies) do not generally affect the response even at low analyte concentra-tions.

#	**Research Organization** *(authors, funding)*	**Weblink/ Citation, Year**	**Detection Technique**	**Size**	**Stage**	**Cost** *($K)*	**Device**	**Network Capa-bility**	**Auto-mated**	**Pollutant/ Parameter**	**Detection/ Sensitivity**	**Operation-Application Notes**
103	University of Michigan, Department of Environmental Health Sciences *Kim, S.K., Chang, H., Zellers, E.T.* *(Funding: DoD ESTCP and NSF Engineering Research Centers Program; devices fabricated in Lurie Nanofabrication Facility, part of NNI Network supported by NSF)*	http://www.chem.ntnu.edu.tw/~chemweb/download/ac201788q.pdf *[2011, Analytical Chemistry, 83(18):7198-7206]*	Gas chroma-tography (field microsystem)	Portable	Re-search proto-type		Microsensor array	Autono-mous operation with laptop	Via laptop	Trichloro-ethylene among 11 VOCs tested Also shows promise for BTEX (with modification of pretrap for transfer from atmosphere to sampler)	11 ppb TCE	A pump brings in and scrubs air, which is then heated and transferred to two micro-columns for analyte separation and VOC detection by microsensors.

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
109	University of Sheffield, Department of Physics and Astronomy *AlQahtani, Hadi, and colleagues* King Saud University (Saudi Arabia), Department of Physics *(AlQ, H.)* *(Funding: King Saud University, UK Engineering and Physical Sciences Research Council [doctoral training and post-doctoral fellowship], and European Commission Experienced Research Marie Curie fellowship under the 'FlexSmel' Training Network)*	http://pdn.sciencedirect.com/science?_ob=MiamilmageURL&_cid=271353&_user=1722207&_pii=S0925400511007222&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=a9b2a8baaf63a476c64f548981a8d09d/1-s2.0-S0925400511007222-main.pdf *[2011, Sensors and Actuators B, 160:399-404]*	Resistance (with resulting current driven into a virtual ground by a current/voltage converter)				Gold core/shell nanoparticle (Au-CSNP) film on glass substrate (processed by the Langmuir-Schäfer [LS] printing method)			Decane (for odor detection relative to the lower explosive limit, LEL) (the response is weaker but still significant for toluene and xylene)	15 ppm (about 1/600th the LEL of 8,000 ppm)	Resistance is weakly dependent on temperature

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
7	Ben-Gurion University of the Negev (Israel) *Eltzov, E., Pavluchkov, V., Burstin, M., Marks, R.S.*	http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S09254005110008 9X&_check=y&_origin=article&_zone=toolbar&_coverDate=20-Jul-2011&view=c&originContentFamily=serial&wchp=dGLbVlk-zSkzS&md5=6c590f4c870fff04f6f44961ad25eab1/1-s2.0-S092540051100089X-main.pdf *[2011, Sensors and Actuators B, 155:859-867]*	Bioluminescence (bacteria on end face of fiber optic)	Field bio-sensor	Re-search		Biolumi-nescent bacteria, *E. coli* strains (notably TV1061) immobilized on the end face of a portable fiber optic biodetector	Online capabilities		Chloroform Toluene was also tested	6.65 ppb chloroform	Bacteria are immobilized in alginate layers on the fiber optic.

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
14	Chinese Academy of Sciences, Research Center for Biomimetic Functional Materials and Sensing Devices, Institute of Intelligent Machines Meng, Fan-Li, Huang, Zing-Jiu, and colleagues, also at Anhui Polytechnic University *(Funding: One Hundred Person Project of the Academy, National Natural Science Foundation of China, National Basic Research Program of China, and Anhui Provincial Natural Science Foundation)*	http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S09254005100818X&_check=y&_origin=search&_zone=rslt_list_item&_coverDate=2011-03-31&wchp=dGLzVBA-zSkzV&md5=ff0be4989bfbde8f28e9d5daeb7bfae9/1-s2.0-S092540051000818X-main.pdf *[2011, Sensors and Actuators B, 153:103-109]*	Capacitance response; chip with a dielectric medium (silica and gases) and two electrodes, one of Si and gold (Au) and the other of MWCNT and Au	Very small	Re-search		Paper film-based capacitive electronic chip by spray-casting MWCNT suspension; also with self-oriented carbon nanotube on top surface of gold electrode	Not indicated		Formalde-hyde ammonia toluene	Formalde-hyde: 300 ppb ammonia: 3.1 ppm toluene: 7.4 ppm	Liquid samples placed in sample chamber, nitrogen used as carrier gas to flow through the chamber.

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
72	Universiti Putra, Malaysia Electrical and Electronic Department *Abadi, M.H.S., Hamidon, M.N., Shaari, A.H., Abdullah, N., Wagiran, R., Misron, N.*	*[2011, Sensors & Transducers Journal, 125(2):76-88]*	Metal oxide semicon-ductance		Re-search		Array gas sensor formed by semicon-ductor oxides; SnO_2 nanopower with different weight % platinum powders	Not indicated		Alcohols: ethyl, isopro-panol, and methanol; hydro-carbons (xylene, isobutene), acetone; exhaust gas com-ponents	Sensitive to sub ppm of applied species, very sensitive to gases above 10 ppm	
17	FLIR Systems, Inc.	http://www.epa.gov/etv/vt-ams.html *(Nov. 2010)*	IR imaging (temperature/ emissivity differences between natural IR radiation and thermal emission or absorption of leaking gas)	Portable camera	Avail-able	65-80	FLIR GasFindIR Midwave (MW) Camera (passive IR camera)	Not indicated		1,3-buta-diene acetic acid acrylic acid benzene methylene chloride (dichloromet hane) ethylene methanol pentane propane styrene	Minimum, g/hr: 1,3-buta-diene1.3; acetic acid <0.02; acrylic acid 0.92; benzene 0.35; ethylene 0.35; methanol 0.28; MeCl 4.9; pentane <0.28; propane <0.44; styrene 0.35	ETV field test conducted in Freeport TX

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
18	Gas Imaging Technologies, LLC	http://www.epa.gov/etv/vt-ams.html *(Nov. 2011)*	Imaging spectrometry	Portable camera	Avail-able	89	Sherlock VOC (passive IR camera)	Not indicated		As above	Minimum, g/hr: 1,3-buta-diene 8.0; acetic acid 1.7; acrylic acid 0.92; benzene 3.2; ethylene 3.3; methanol 2.1; methyleneCl >70; pentane 0.83; propane 0.88; styrene 15	

#	Research Organization *(authors, funding)*	Weblink/ Citation, Year	Detection Technique	Size	Stage	Cost *($K)*	Device	Network Capa-bility	Auto-mated	Pollutant/ Parameter	Detection/ Sensitivity	Operation-Application Notes
12	Dräger Safety Inc. (Gas Detection Systems) 505 Julie Rivers Suite 150 Sugarland, TX 784-78-28471 800-230-5029	http://www.draeger.us/PublishingImages/Dr%c3%a4ger%20Bio-Check%20Formaldehyde/indoor_pollutants_br_9044567_en.pdf	Collection tube (sample sent to lab for analysis)	Small tube	Avail-able		Dräger Bio-Check Solvents	Not indicated (personal home use)		Solvents: "Different solvents can be detected simultane-ously." Overview infers BTEX (petrol stations or traffic fumes), chlorinated VOCs (dry cleaners), as well as solvents used in adhesives, paint and paint strippers, and varnishes.		Collection tube sent to Dräger for lab analysis.

TABLE A-4 Example Data Retrieval: Selected Results of a Targeted Patent Search *(prior to compilation in a summary table)*

A hybrid separation and detection device for chemical detection and analysis

By: Tao, Nongjian; Forzani, Erica; Iglesias, Rodrigo; Tsow, Francis; Assignee: Arizona State University, USA; Patent Information Mar. 17, 2011, WO 2011031500, A2; Application: Aug 25, 2010, WO 2010-US46702; Priority: Sep 14, 2009, US 2009-242256P; Source: PCT Int. Appl., 39pp., Patent, 2011, CODEN: PIXXD2 Accession Number: 2011:327719, CAN 154:342741, CAPLUS; Language: English

Abstract

The present invention provides a device that makes it possible to perform real-time detection and anal. of BTEX components in real samples using an inexpensive and miniaturized hybrid specific binding-sepn. device.

The device may be used in occupational health and safety applications as well as for toxicol. population studies to det. the presence of org. volatile components in an air sample. Priority Application: US 2009-24225 6P

A portable sensor system for air pollution monitoring and malodours olfactometric control

Suriano, D.1; Rossi, R.1; Alvisi, M.1; Cassano, G.1; Pfister, V.1; Penza, M.1; Trizio, L.2; Brattoli, M.2; Amodio, M.2; De Gennaro, G.2 Source: Lecture Notes in Electrical Engineering, v 109 LNEE, p 87-92, 2012, Sensors and Microsystems, AISEM 2011 Proceedings; ISSN: 18761100, E-ISSN: 18761119; ISBN-13: 9781461409342; DOI: 10.1007/978-1-4614-0935-9_15; Conference: 16th Conference on Italian Association of Sensors and Microsystems, AISEM 2011, February 7, 2011 - February 9, 2011; Publisher: Springer Verlag; Author affiliations: 1 ENEA, Brindisi Technical Unit for Technologies of Materials, Brindisi, Italy; 2 Department of Chemistry, University of Bari, Lenviros Srl, Bari, Italy

Abstract: A portable sensor-system based on solid-state gas sensors has been designed and implemented as proof-of-concept for environmental air-monitoring applications and malodours olfactometric control. Commercial gas sensors (metal-oxides, n-type) and nanotechnology sensors (carbon nanotubes, p-type) are arranged in a configuration of array for multisensing and multiparameter devices. Wireless sensors at low-cost are integrated to implement a portable and mobile node, that can be used as early-detection system in a distributed sensor network. Real-time and continuous monitoring of hazardous air-contaminants (e.g., NO2, CO, SO2, BTEX, etc.) has been performed by in-field measurements. Moreover, monitoring of landfill gas generated by fermentation of wastes in a municipal site has been carried out by the portable sensor-system. Also, it was demonstrated that the sensor-system is able to assess the malodours emitted from a municipal waste site and remarkably compared to the olfactometry method based on a trained test panel. © 2012 Springer Science+Business Media, LLC. (12 refs.); Database: Compendex

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Title: Gas Nanosensor Design Packages Based on Tungsten Oxide: Mesocages, Hollow Spheres, and Nanowires

Author(s): Nguyen Duc Hoa; El-Safty, S.A.

Source: Nanotechnology Volume: 22 Issue: 48 Pages: 485503 (10 pp.) Published: 2 Dec. 2011

Treatment: Practical, Experimental

Abstract: Achieving proper designs of nanosensors for highly sensitive and selective detection of toxic environmental gases is one of the crucial issues in the field of gas sensor technology, because such designs can lead to the enhancement of gas sensor performance and expansion of their applications. Different geometrical designs of porous tungsten oxide nanostructures, including the mesocages, hollow spheres and nanowires, are synthesized for toxic gas sensor applications. Nanosensor designs with small crystalline size, large specific surface area, and superior physical characteristics enable the highly sensitive and selective detection of low concentration (ppm levels), highly toxic NO_2 among CO, as well as volatile organic compound gases, such as acetone, benzene, and ethanol. The experimental results showed that the sensor response was not only dependent on the specific surface area, but also on the geometries and crystal size of materials. Among the designed nanosensors, the nanowires showed the highest sensitivity, followed by the mesocages and hollow spheres-despite the fact that mesocages had the largest specific surface area of 80.9 $m^2 g^{-1}$, followed by nanowires (69.4 $m^2 g^{-1}$), and hollow spheres (6.5 $m^2 g^{-1}$). The nanowire sensors had a moderate specific surface area (69.4 $m^2 g^{-1}$) but they exhibited the highest sensitivity because of their small diameter (~5 nm), which approximates the Debye length of WO_3. This led to the depletion of the entire volume of the nanowires upon exposure to NO_2, resulting in an enormous increase in sensor resistance.

Controlled Indexing: air pollution; gas sensors; nanosensors; nanowires; organic compounds; porous materials; toxicology; tungsten compounds

Uncontrolled Indexing: Debye length; nanowire sensor; ethanol; benzene; acetone; organic compound gas; low concentration detection; specific surface area; crystalline size; porous nanostructure; environmental toxic gas sensor application; hollow sphere; mesocages; gas nanosensor design packaging; WO_3

Classification Codes: A8280T Chemical sensors; A0710C Micromechanical and nanomechanical devices and systems; B7230L Chemical sensors; B7230M Microsensors and nanosensors; B0580 Powders and porous materials (engineering materials science); B7720 Pollution detection and control

Chemical Indexing: WO3/int O3/int O/int W/int WO3/bin O3/bin O/bin W/bin

International Patent Classification: B82B1/00

Author Address: Nguyen Duc Hoa; El-Safty, S.A.; Nat. Inst. for Mater. Sci. (NIMS), Tsukuba, Japan.

Publisher: IOP Publishing Ltd., UK

Title: Mesoporous SnO(2) sensor prepared by carbon nanotubes as template and its sensing properties to indoor air pollutants

Author(s): Li, HH (Li, Huihua); Meng, FL (Meng, Fanli); Sun, YF (Sun, Yufeng); Liu, JY (Liu, Jinyun); Wan, YT (Wan, Yuteng); Sun, B (Sun, Bai); Liu, JH (Liu, Jinhuai)

Editor(s): Li M; Yu D

Source: 2010 SYMPOSIUM ON SECURITY DETECTION AND INFORMATION PROCESSING **Book Series:** Procedia Engineering **Volume:** 7 **Pages:** 172-178 **DOI:** 10.1016/j.proeng.2010.11.026 **Published:** 2010

Cited Reference Count: 23

Abstract: An effort has been made to develop a kind of mesoporous SnO(2) gas sensor for detecting indoor air pollutants such as ethanol, benzene, meta-xylene. Mesoporous SnO(2) material has been prepared by sol-gel method joined into multiwall carbon nanotubes as template. The field emission scanning electron microscope (FSEM) was used to characterize the samples, by which the mesoporous structure of SnO(2) was obviously observed. The investigation results suggest that the as-prepared mesoporous SnO(2) has a good response and reversibility to indoor environmental air pollutants. At last, the selectivity of the mesoporous sensor was investigated.

Document Type: Proceedings Paper

Conference: 2010 Symposium on Security Detection and Information Processing PEOPLES R CHINA 2010

Conference Title: 2010 Symposium on Security Detection and Information Processing

Conference Location: PEOPLES R CHINA

Author Keywords: mesoporous SnO(2); gas sensor; indoor air pollutants

KeyWords Plus: NANOWIRES; GROWTH; NANOPARTICLES; BATTERY

Addresses: [Li, HH; Meng, FL; Sun, YF; Liu, JY; Wan, YT; Sun, B; Liu, JH] Chinese Acad Sci, Inst Intelligent Machines, Res Ctr Biomimet Funct Mat & Sensing Devices, Hefei 230031, Peoples R China

Subject Category: Engineering

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29-char Source Abbrev.: PROCEDIA ENGINEER

APPENDIX B:

OVERVIEW OF EXPOSURE BENCHMARKS

APPENDIX B:
OVERVIEW OF EXPOSURE BENCHMARKS

This appendix supplements the information given in Section 3.2. Exposure benchmarks are standards and guidelines for chemicals in air that have been established by a number of organizations for specific health and safety programs. These concentrations serve as useful points of comparison for the detection levels reported for research sensors. A number of benchmarks were compiled to serve as a practical foundation for assessing sensor gaps and opportunities. An overview description of these benchmarks is provided in Table B-1, together with the set of study pollutants for which they have been established (as reflected in the graphical arrays in Section 3.5).

The primary sources of health-based benchmarks are EPA databases, including toxicity values for continuous exposures from the Integrated Risk Information System (IRIS) database (EPA 2013a), and related benchmarks in the Provisional Peer Reviewed Toxicity Value (PPRTV) database (EPA 2013b). Similar benchmarks for the general public such as minimal risk levels (MRLs) established by the Agency for Toxic Substances and Disease Registry (ATSDR 2013) and reference exposure levels from California Office of Environmental Health Hazard Assessment (OEHHA) (CalEPA 2012) are also reflected in the tables and figures in Chapter 3.

Additional health-based values include concentrations defined for acute and short-term exposures to guide emergency response measures for the general public. Such values include acute exposure guideline levels (AEGLs) established by the National Research Council (NRC). Further health-based guides recommended by the NRC for continuous exposures over weeks to months include spacecraft maximum allowable concentrations (SMACs) as well as continuous exposure guideline levels (CEGLs) for submarines. Benchmark values recommended the NRC and the chemicals for which they have been developed are summarized in Table B-2. Additional information is included at the end of that table for occupational benchmarks established by the National Institute for Occupational Safety and Health (NIOSH) and U.S. Army; information is also provided for selected CalEPA reference exposure levels established for the general public.

Occupational exposure levels (OELs) also provide useful context for assessing sensor detection capabilities and potential opportunities. (For example, such limits were considered in assessing health risks associated with the World Trade Center collapse, notably for pollutants for which other reference values were not available.) Table B-3, which was prepared during the initial phase of this project when the candidate set was still being developed, highlights OELs for selected pollutants and illustrates the range of limits available within this benchmark category alone. Illustrative bar graphs of benchmarks for the general public and for workers established for arsenic and benzene are presented in Figures B-1 and B-2.

For methane, standard health-based guidelines have not been developed for the general public because it is biologically inert, although it can be an asphyxiant as well as explosive at high concentrations. Loss of consciousness can result when methane concentrations are high enough to displace oxygen in air below a certain level. Military guidelines for confined spaces are based on oxygen displacement and explosive characteristics, while ACGIH classifies methane as a simple asphyxiant and does not establish a TLV. In evaluating methane for the SMAC, the NRC suggests 5,300 ppm based on 0.1% of the lower explosive limit and the expectation that consciousness would be maintained at oxygen levels above 18%. To displace oxygen below that threshold, methane would need to be 14.3% by volume in air, or 143,000 ppm; this concentration is used as an IDLH-equivalent value on the graphical array.

TABLE B-1 Overview of Exposure Benchmark Bases and Selected Pollutants

Benchmark	Organization	Definition	Duration	Study Pollutants	Reference
General Public: Emergency Response, Acute Exposures *(up to 8 hours)*					
AEGL: Acute Exposure Guidance Level	National Research Council (NRC), in coordination with / U.S. EPA and U.S. Department of Defense (DoD)	Threshold exposure concentrations for rare, emergency exposures to airborne chemical releases, divided into three levels of increasing severity for each exposure time duration. 1 = Non-disabling and reversible mild discomfort, irritation, or asymptomatic nonsensory effects. 2 = Irreversible or serious long lasting adverse health effects. 3 = Life-threatening health effects or death.	10 min 30 min 1 hr 4 hr 8 hr	Acrolein, ammonia, benzene, 1,3-butadiene, carbon monoxide, formaldehyde, hydrogen sulfide, nitrogen dioxide, sulfur dioxide	NRC 2009 (and others)
ERPG: Emergency Response Planning Guideline	Emergency Response Planning Committee of the American Industrial Hygiene Association (AIHA)	Maximum airborne concentration to which the general public could be exposed for 1 hour in rare, emergency releases without experiencing or developing the following (based on severity level) : 1 = Adverse health effects. 2 = Irreversible or serious health effects 3 = Life-threatening effects.	1 hr	Acrolein, ammonia, benzene, 1,3-butadiene, carbon monoxide, formaldehyde,	AIHA 2011
PAC: Protective Action Criteria	U.S. Department of Energy (DOE); Subcommittee on Consequence Assessment and Protective Actions (SCAPA)	PACs are reported as AEGL, ERPG, or TEEL values (hierarchy preference order), as available and appropriate. The three benchmark levels are defined as followed, each associated with increasing severity of health effects and higher levels of exposure. 1 = Mild, transient health effects 2 = Irreversible or serious health effects which may impair ability to take protective action measures (e.g., escape) 3 = Life-threatening effects	1 hr	Methane	DOE 2012 (PAC Database, Revision 27)

Benchmark	Organization	Definition	Duration	Study Pollutants	Reference
General Public: Ambient Exposures *(continuous, 1 day to a lifetime)*					
NAAQS: National Ambient Air Quality Standards	U.S. EPA	Outdoor air concentrations not to be exceeded for six criteria pollutants. Primary standards are meant for public health protection including for sensitive populations. Secondary standards are meant for protection of public welfare, including against decreased visibility and damage to animals, crops, vegetation, and buildings.	Chronic (averaging times include: 1 hr, 2 hr, 3 hr, 8 hr, 24 hr, 3 mo, annual)	Carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter (PM_{10}, $PM_{2.5}$), sulfur dioxides	U.S. EPA 2012 (last updated)
EPA IRIS RBC: Risk-Based Concentration	U.S. EPA	Based on cancer risk: Concentration associated with a target risk level of 10^{-4} or 10^{-6} for carcinogenic effects (calculated from the inhalation unit risk, IUR).	Chronic (7 yr-lifetime)	Benzene, 1,3-butadiene, formaldehyde	U.S. EPA 2013, IRIS database
EPA IRIS RfC: Reference Concentration	U.S. EPA	Based on noncancer effects: An estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious, noncarcinogenic (for most substances) effects during a lifetime.	Subchronic (2-7 yr) Chronic (7 yr-lifetime)	Acrolein, ammonia, benzene, 1,3-butadiene, hydrogen sulfide	U.S. EPA 2013, IRIS database
EPA PPRTV RfC: Provisional Peer-Reviewed Toxicity Value RfC	U.S. EPA	As described above for the IRIS RfC. (PPRTVs reflect a similar derivation process as the IRIS values, while the extent of external peer review differs.)	As above	Ammonia, benzene	U.S. EPA 2013 (PPRTV database)
ATSDR MRL: Minimal Risk Level	Agency for Toxic Substance and Disease Registry (ATSDR)	Estimate of daily human exposure likely to be without appreciable risk of adverse non-cancer effect over given exposure duration, based on target organ/most sensitive effect; set below levels that might cause adverse health effects in people most sensitive to such substance-induced effects, based on current information; intended as screening levels for hazardous waste sites, for target organ/most sensitive effect.	Acute (1-14 d) Intermediate (15-365 d) Chronic (>365 d)	Acrolein, ammonia, benzene, formaldehyde, hydrogen sulfide	ATSDR 2013, MRL list
CalEPA REL: **R**eference Exposure Level	CalEPA Office of Environmental Health Hazard Assessment (OEHHA)	Concentration at or below which no adverse health effects are anticipated; based on most sensitive, relevant, adverse effect reported in medical and toxicological literature; designed to protect the most sensitive individuals in the population by inclusion of margins of safety; since margins of safety are incorporated to address data gaps and uncertainties, exceeding the REL does not automatically indicate an adverse health impact.	1 hr 6 hr 8 hr Chronic	Acrolein, ammonia, benzene, 1,3-butadiene, formaldehyde, hydrogen sulfide, ozone	CalEPA OEHHA 2013

Benchmark	Organization	Definition	Duration	Study Pollutants	Reference
CAAQS California Ambient Air Quality Standard	CalEPA, OEHHA	Maximum allowable concentration in ambient air without threatening the health of the public, including sensitive populations.	Similar to NAAQS	Lead, PM_{10}, $PM_{2.5}$	CalEPA ARB 2009
Occupational: Workplace Exposures *(noncontinuous, work shifts extending over a work life)*					
PEL: **TWA, STEL, C, AL** Permissible Exposure Limit: Time-Weighted Average, Short-Term Exposure Limit, Ceiling, and Action Level	Occupational Safety and Health Administration (OSHA)	The TWA is a time-weighted average concentration for an 8-hour workday during a 40-hour workweek. (Levels must not be exceeded during any 8-hour workshift during a 40-hour workweek.) A STEL is a 15-minute TWA exposure and should not be exceeded at any time during a work day. A ceiling should not be exceeded at any time during a work day.	8 hr	Acrolein, ammonia, benzene, 1,3-butadiene, carbon monoxide, formaldehyde, hydrogen sulfide, lead, ozone, PM_{10}, $PM_{2.5}$ (and black carbon), sulfur dioxide	OSHA 2006
REL: **TWA, STEL, C** Recommended Exposure Limit (same categories as for the PEL above)	National Institute for Occupational Safety and Health (NIOSH)	As described above for the PELs, except that the REL TWA is a time-weighted average concentration for up to a 10-hour workday during a 40-hour workweek. (A STEL is a 15-minute TWA exposure and should not be exceeded at any time during a work day. A ceiling REL should not be exceeded at any time.)	10 hr 10 min 15 min	Acrolein, ammonia, benzene, carbon monoxide, formaldehyde, hydrogen sulfide, lead, nitrogen dioxide, ozone, black carbon (PM), sulfur dioxide	NIOSH 1994
IDLH: Immediately Dangerous to Life or Health	NIOSH	Exposure level below which a person should be able to escape without loss of life or accrual of delayed irreversible health effects, including impairment of vision which may prevent or delay escape. This value was established to ensure employee escape given failure of a respiration device. IDLH values have been established for 85 substances meeting the OSHA definition of a potential occupational carcinogen.	30 min	Acrolein, ammonia, benzene, 1,3-butadiene, carbon monoxide, formaldehyde, hydrogen sulfide, lead, nitrogen dioxide, ozone, black carbon (PM)	NIOSH 2010

Benchmark	Organization	Definition	Duration	Study Pollutants	Reference
TLV: **TWA, STEL, C** Threshold Limit Value	American Conference of Governmental Industrial Hygienists (ACGIH)	Time-weighted average concentration to which most workers may be exposed daily without adverse health effects. For ozone, values are available for three work activity levels: light, medium, and heavy.	2 hr 8 hr 15 min	Acrolein, ammonia, benzene, 1,3-butadiene, carbon monoxide, formaldehyde, hydrogen sulfide, lead, methane (representing alkanes), nitrogen dioxide, ozone, PM_{10}, $PM_{2.5}$, black carbon, sulfur dioxide	ACGIH 2011
Occupational: Special Environments *(Army Field Deployment, Submarine, and Spacecraft)*					
MEG Military Exposure Guideline	US Army Public Health Command (USAPHC)	Concentration for intakes in moderate and arid climates, with the lowest guidelines designed to result in negligible/minimal or no adverse effects for deployed military personnel.	1 hr 8 hr 14 d 1 yr	Methane	USAPHC 2010
EEGL, CEGL Emergency and Continuous Exposure Guidance Levels	National Research Council (National Academies)	Exposure levels for confined work space, for exposures continuing 1 day to 3 months, for submarines.	24 hr 90 d	Methane	NRC 1984
SMAC Spacecraft Maximum Allowable Concentration	NRC / National Aeronautics and Space Administration (NASA)	Limit for traces of substance in the closed-loop atmosphere of a spacecraft cabin, continuous exposure; to not compromise performance of specific tasks during emergency conditions (short term: 1 to 24 hr) or cause serious or permanent toxic effects, for continuous exposures extending 7 to 180 d (long term).	1 hr 24 hr 7 d 30 d 180 d	Methane	NRC 1994

[a] The "study pollutants" column identifies those pollutants for which the indicated benchmark has been established (and is reflected in the graphical array.

Note typical health-based benchmarks are not available for methane, so Army and other benchmarks for the specialized occupational environments are included for this compound, as well as the PAC value for emergency response (because no AEGLs have been established).

TABLE B-2 Exposure Benchmark Sources

I. National Research Council
(National Academies of Science)

A. AEGLs

Volume 1 *(2000)*
http://books.nap.edu/catalog.php?record_id=10043
Aniline
Arsine
Monomethylhydrazine
Dimethylhydrazine

Volume 2 *(2002)*
http://books.nap.edu/catalog.php?record_id=10522
Phosgene
Propylene glycol dinitrate
1,1,1,2-Tetrafluoroethane (HFC-134A)
1,1-Dichloro-1-fluoroethane (HCFC-141B
Hydrogen cyanide

Volume 3 *(2003)*
http://books.nap.edu/catalog.php?record_id=10672
Nerve agents GA, GB, GD, GF, and VX
Sulfur mustard
Methyl isocyanate
Diborane

Volume 4 *(2004)*
http://books.nap.edu/catalog.php?record_id=10902
Chlorine
Hydrogen chloride
Hydrogen fluoride
Toluene 2,4- and 2,6-diisocyanate
Uranium hexafluoride

Volume 5 *(2007)*
http://books.nap.edu/catalog.php?record_id=11774
Chlorine dioxide
Chlorine trifluoride
Cyclohexylamine
Ethylenediamine
Hydrofluoroether-7100 (H 7100)
(40% methyl nonafluorobutyl ether,
60% methylnonafluoroisobutyl ether)
Tetranitromethane

Volume 6 *(2008)*
http://www.nap.edu/catalog.php?record_id=12018
Allylamine
Ammonia
Aniline
Arsine
Crotonaldehyde, trans and cis-trans
Dimethylhydrazine
Iron pentacarbonyl
Monomethylhydrazine
Nickel carbonyl
Phosphine + 8 metal phosphides

Volume 7 *(2009)*
http://books.nap.edu/catalog.php?record_id=12503
Acetone cyanohydrin
Carbon disulfide
Monochloroacetic acid
Phenol

Volume 8 *(2010)*
http://books.nap.edu/catalog.php?record_id=12770
Acrolein
Carbon monoxide
1,2-Dichloroethene (cis, trans, cis-trans)
Ethyleneimine
Fluorine
Hydrazine
Peracetic acid
Propylenimine
Sulfur dioxide (subsequently revisited)

Volume 9 *(2010)*
http://books.nap.edu/catalog.php?record_id=12978
Bromine
Ethylene oxide
Furan
Hydrogen sulfide
Propylene oxide
Xylenes (m-, o-, p-)
PBPK modeling white paper

Volume 10 *(2011)*
http://books.nap.edu/catalog.php?record_id=13247
N,N-Dimethylformamide
Jet propellant fuels 5 and 8
Methyl ethyl ketone
Perchloromethyl mercaptan
Phosphorus oxychloride
Phosphorus trichloride
Sulfuryl chloride

TABLE B-2 ***(Cont'd.)***

(I. NRC, A. AEGLs, Cont'd.)

Volume 11 *(2012)*
http://books.nap.edu/catalog.php?record_id=13374
bis-Chloromethyl ether
Chloromethyl methyl ether
Selected chlorosilanes
Nitrogen oxides: Nitric oxide
Nitrogen dioxide
Nitrogen tetroxide
Vinyl chloride

Volume 12 *(2012)*
http://www.nap.edu/catalog.php?record_id=13377
Butane
Chloroacetylaldehyde
Chlorobenzene
Chloroform
Methyl bromide
Methyl chloride
Propane
Metal phosphides (see Volume 6):
- Aluminum phosphide
- Calcium phosphide
- Magnesium phosphide
- Magnesium aluminum phosphide
- Potassium phosphide
- Sodium phosphide
- Strontium phosphide
- Zinc phosphide

Chlorosilanes (see Volume 11):
- *Monochlorosilanes:*
  - Dimethyl chlorosilane
  - Methyl chlorosilane
  - Trimethyl chlorosilane
- *Dichlorosilanes:*
  - Dichlorosilane
  - Diethyl dichlorosilane
  - Dimethyl dichlorosilane
  - Diphenyl dichlorosilane
  - Methyl dichlorosilane
  - Methylvinyl dichlorosilane
- *Trichlorosilanes:*
  - Allyl trichlorosilane
  - Amyl trichlorosilane
  - Butyl trichlorosilane
  - Chloromethyl trichlorosilane
  - Dodecyl trichlorosilane
  - Ethyl trichlorosilane
  - Hexyl trichlorosilane
  - Methyl trichlorosilane
  - Nonyl trichlorosilane
  - Octadecyl trichlorosilane

(AEGLs Volume 12, Cont'd.)

- Octyl trichlorosilane
- Propyl trichlorosilane
- Trichloro(dichlorophenyl)silane
- Trichlorophenylsilane
- Trichlorosilane
- Vinyl trichlorosilane

Tetrachlorosilane

Volume 13 *(2013)*
http://www.nap.edu/catalog.php?record_id=15852
Boron trifluoride
Bromoacetone
Chloroacetone
Hexafluoroacetone
Perchloryl fluoride
Piperidine
Trimethoxysilane and tetramethoxysilane
Trimethylbenzenes

Volume 14 *(2013)*
http://www.nap.edu/catalog.php?record_id=18313
Agent BZ (3-quinuclidinyl benzilate)
Ethyl phosphorodichloridate
n-Hexane
Methanesulfonyl chloride
Nitric acid
Propargyl alcohol,
Vinyl acetate

(Note: Additional chemicals and updated information for a number of those listed above can be found in interim reports via the National Academies website, e.g., see links via: http://dels.nas.edu/Report/Acute-Exposure-Guidelines-Levels-Selected/12018. The National Academies website can also be searched, e.g., for "interim report of committee on acute exposure guideline levels")

TABLE B-2 *(Cont'd.)*

I. (NRC, Cont'd.)

B. SMACs

Volume 1 *(1994)*
http://www.nap.edu/catalog.php?record_id=9062
Acetaldehyde (75-07-0)
Ammonia (7664-41-7)
Carbon monoxide (630-08-0)
Formaldehyde (50-00-0)
Freon 113 (76-13-1)
Hydrogen (1333-74-0)
Methane (74-82-8)
Methanol (67-56-1)
Octamethyltrisiloxane (107-51-7)
Trimethylsilanol (1066-40-6)
Vinyl chloride (75-01-4)

Volume 2 *(1996)*
http://www.nap.edu/catalog.php?record_id=5170
Acrolein (107-02-08)
Benzene (71-43-2)
Carbon dioxide (124389)
2-Ethoxyethanol (110-80-5)
Hydrazine (302-01-2)
Indole (120-72-9)
Mercury (7439-97-6)
Methylene chloride (75-09-2)
Methyl ethyl ketone (78-93-3)
Nitromethane (75-52-5)
2-Propanol (67-63-0)
Toluene (108-88-3)

Volume 3 *(1996)*
http://www.nap.edu/catalog.php?record_id=5435
Bromotrifluoromethane (75-63-8)
1-Butanol (71-36-3)
tert-Butanol (75-65-0)
Diacetone alcohol (123-42-2)
Dichloroacetylene (7572-29-4)
1,2-Dichloroethane (ethylene diCl) (107-06-2)
Ethanol (64-17-5)
Ethylbenzene (100414)
Ethylene glycol (107-21-1)
Glutaraldehyde (111-308)
Trichloroethylene (79-01-6)
Xylene (95476)

Volume 4 *(2000)*
http://www.nap.edu/catalog.php?record_id=9786
Acetone (67641)
C3 to C8 Aliphatic saturated aldehydes
- Propanal (propionaldehyde) (171426-73-6)
- Butanal (n-butyraldehyde) (171339-76-7)

***(SMACs Volume 4**, cont'd.)**
- Pentanal (n-valeraldehyde) (110-62-3)
- Hexanal (caproaldehyde) (66-25-1)
- Heptanal (n-heptaldehyde) (111-71-7)
- Octanal (caprylaldehyde (124-13-0)

Hydrogen chloride (7647-01-1)
Isoprene (78-79-5)
Methylhydrazine (60-34-4)
Perfluoropropane/other aliphatic perfluoroalkanes
- Perfluoropropane (PFA3) (76-19-7)

Polydimethylcyclosiloxanes
- Hexamethylcyclotrisiloxane (541-05-9)
- Octamethylcyclotetrasiloxane (556-67-2)
- Decamethylcyclopentasiloxane (541-02-6)

Dichlorofluoromethane (Freon 21) (75-43-4)
Chlorodifluoromethane (Freon 22) (75-45-6)
Triichlorofluoromethane (Freon 11) (75-69-4)
Dichlorodifluoromethane (Freon 12) (75-71-8)
4-Methyl-2-pentanone (108-10-1)
Chloroform (67-66-3)
Furan (110-00-9)
Hydrogen cyanide (74-90-8)

Volume 5 *(2008)*
http://books.nap.edu/catalog.php?record_id=12529
Acrolein (107-02-08) *(Vol 2)*
C3 to C8 Aliphatic saturated aldehydes *(Vol 4)*
Ammonia (7664-41-7) *(Vol 1)*
Benzene (71-43-2) *(Vol 2)*
n-Butanol (71-36-3) *(Vol 3)*
C2-C9 Alkanes
- Ethane (C2) (78-84-0)
- Propane (C3) (74-98-6)
- Butane (C4) (106-97-8)
- Pentane (C5) (109-66-0)
- Hexane (C6) (110-54-3)
- Heptane (C7) (142-82-5)
- Octane (C8) (111-65-9)
- Nonane (C9) (111-84-2)

Carbon dioxide (124389) *(Vol 2)*
Carbon monoxide (630-08-0) *(Vol 1)*
1,2-Dichloroethane (EDC) (107-06-2) *(Vol 3)*
Dimethylhydrazine *(57-14-7)*
Ethanol (64-17-5) *(Vol 3)*
Formaldehyde (50-00-0) *(Vol 1)*
Limonene (5989-27-5)
Methanol (67-56-1) *(Vol 1)*
Methylene chloride (75-09-2) *(Vol 2)*
Propylene glycol (57-55-6)
Toluene (108-88-3) *(Vol 2)*
Trimethylsilanol (1066-40-6) *(Vol 1)*
Xylenes *(Vol 1)*

TABLE B-2 ***(Cont'd.)***

I. (NRC, Cont'd.)

C. EEGLs and CEGLs
(Emergency and Continuous Exposure Guidance Levels)

Volume 1 *(2007)*
http://books.nap.edu/catalog.php?record_id=11170
Acrolein (107-02-8)
Carbon dioxide (124-38-9)
Carbon monoxide (630-08-0)
Formaldehyde (50-00-0)
Hydrazine (302-01-2)
Methanol (67-56-1)
Monoethanolamine (141-43-5)
Nitric oxide (10102-43-9)
Nitrogen dioxide (10102-44-0)
Oxygen (7782-44-7)

Volume 2 *(2008)*
http://books.nap.edu/catalog.php?record_id=12032
Ammonia (7664-41-7)
Benzene (71-43-2)
2,6-Di-tert-butyl-4-nitrophenol (728-40-5)
Freon 12 (difluorodichloromethane) (75-71-8))
Freon 114 (dichlorotetrafluoroethane)
(76-14-2)
Hydrogen (1333-74-0)
2190 Oil mist/turbine oil (2190 TEP)
(64742-54-7)
Ozone (7782-44-7)
Surface lead (7439-92-1)
Toluene (108-88-3)
Xylene (1330-20-7)
- m-Xylene (108-38-3)
- o-Xylene (95-47-6)
- p-Xylene (106-42-3)

Volume 3 *(2009)*
http://books.nap.edu/catalog.php?record_id=12741
Acetaldehyde (75-07-0)
Hydrogen chloride (7647-01-0)
Hydrogen fluoride (7664-39-3)
Hydrogen sulfide (7783-06-4)
Propylene glycol dinitrate (6423-43-4)

(Additional information resources for exposure benchmarks are listed on the following page.)

TABLE B-2 *(Cont'd.)*

II. NIOSH

A. Emergency Response Safety and Health Database (includes AEGLs and OELs)
http://www.cdc.gov/niosh/ershdb/about.html *(page last updated February 2012)*

Includes:
Aluminum phosphide (7803-51-2)
Ammonia (7664-41-7)
Arsenic oxide (1303-28-2)
Benzene (71-43-2)
BZ (6581-06-2)
Chlorine (7782-50-5)
Hydrogen cyanide (AC) (74-90-8)
Hydrogen fluoride (7664-39-3)
Mercury (elemental) (7439-97-6)
Methyl alcohol (67-56-1)
Tear gas (2-chloroacetophenone) (532-27-4)

B. NIOSH Pocket Guide (includes PELs, RELS, and IDLHs)
http://www.cdc.gov/niosh/npg/default.html *(page last reviewed January 2012)*

Includes an extensive number of chemicals:

III. U.S. Department of Defense (DoD)/Army

Technical Guide 230, Environmental Health Risk Assessment and Chemical Exposure Guidelines for Deployed Military Personnel *(July 2010)*
http://phc.amedd.army.mil/PHC%20Resource%20Library/TG230.pdf

Includes a considerable number of chemicals

IV. Ca/EPA OEHHA

Reference Exposure Levels (RELs)
http://oehha.ca.gov/air/allrels.html

Includes:
Acetaldehyde (75-07-0)
Acrolein (107-02-8)
Acrylic acid
Acrylonitrile (107-13-1)
(and many others)

TABLE B-3 Example Occupational Exposure Limits for Selected Pollutants of Interest[a]

Pollutant	CAS RN	Concentration Limit *(µg/m³ or as listed)*	Benchmark Type	Notes
Arsenic (As, inorganic, including trivalent)	7440-38-2	10	PEL	
		2	REL-C	Ceiling value; NIOSH also indicates a half-mask air-purifying respirator with high-efficiency filter, or a half-mask supplied air respirator, is needed at 100 µg/m³
		10	TLV	0.003 ppm
		1.1	MEG air, 1 yr	
Benzene	71-43-2	3,200	PEL	1 ppm
		320	REL	0.1 ppm (conversion 3.19 mg/m³); identified as one of the RELs based primarily on technical factors (feasibility, detection limit)
		1,600	TLV	0.5 ppm (half the PEL, 5 times the REL)
		8,000	TLV-STEL	2.5 ppm
		55	MEG air, 1 yr	
Carbon dioxide	124-38-9	9,000,000	PEL	5,000 ppm *(0.5%)*; note EPA OPP (1991) indicated chronic intermittent exposures to 1.08% or 1,000 ppm for brewery workers, compared to the natural concentration of 0.03% or 300 ppm
			REL	
			TLV	
		54,000,000	TLV-STEL	30,000 ppm
		14,000,000	CEGL, 90 d	
		2,200,000	MEG air, 1 yr	
Carbon monoxide	630-08-0	55,000	PEL	50 ppm
		40,000	REL	35 ppm (given as 40 mg/m³, with a conversion factor of 1.15 mg/m³)
		29,000	TLV	25 ppm (half the PEL and 5/7 the REL)
		140,000	CEGL, 90 d	
		7,000	MEG air, 1 yr	
Chlorine	7782-50-5	3,000	PEL-C	1 ppm (3 mg/m³)
		1,500	REL-C	0.5 ppm (half the PEL ceiling)
			TLV	
		2,900	TLV-STEL	1 ppm
		290	MEG air, 14 d	
		4	MEG air, 1 yr	
1,2-Dichloroethane (ethylene dichloride)	107-06-2	200,000	PEL	50 ppm
		40,000	TLV	10 ppm
		4,000	REL	1 ppm (4 mg/m³)

TABLE B-3 Example Occupational Exposure Limits for Selected Pollutants of Interest[a]

Pollutant	CAS RN	Concentration Limit *(µg/m³ or as listed)*	Benchmark Type	Notes
1,2-Dichloroethane (ethylene dichloride) cont'd.		8,000	REL-STEL	2 ppm
		180	MEG air, 1 yr	
		50	TLV	As inhalable fraction and vapor
Diesel engine exhaust (for some as carbon black, with PAHs; see notes)	1333-86-4	3,500	PEL	For carbon black
			TLV	
		100	REL	C black in the presence of PAHs
		3.4	MEG air, 1 yr	For diesel engine emissions
Ethylbenzene	100-41-4	440,000	PEL, REL	100 ppm (435 mg/m³), rounded to two significant figures here
		87,000	TLV	20 ppm
		545,000	REL-STEL	125 ppm
		100,000	TLV-STEL-C	For aerosol
		2,100	MEG air, 1 yr	
		500,000	MEG air, 1 hr	Minimal effect (negligible value)
Ethylene oxide (Oxirane)	75-21-8	1,800	PEL	1 ppm; conversion given as 1.8 mg/m³
		180	REL	0.1 ppm; REL is identified as one of those based primarily on technical factors (feasibility, detection limit)
		9,000	PEL-STEL	5 ppm
		48	MEG air, 1 yr	
		2,000 (1,600)	TLV	1 ppm, 10 times the 0.1 ppm PEL, REL (at 1.55 mg/m³ per ppm)
		440	MEG air, 14 d	
Formaldehyde	50-00-0	900	PEL	0.75 ppm
		20	REL	0.016 ppm; one of those based primarily on technical factors (feasibility, detection limit)
		360	TLV -C	Short-term exposure limit ceiling is 0.3 ppm (40% of the PEL)
		2,500	PEL-STEL	2 ppm (2.46 mg/m³), rounded
		140,000	CEGL, 90 d	
		25	MEG air, 1 yr	
n-Hexane	110-54-3	1,800,000	PEL	500 ppm (10 times the REL and TLV)
		180,000	REL	50 ppm (180 mg/m³)
			TLV	
		1,400	MEG air, 1 yr	

TABLE B-3 Example Occupational Exposure Limits for Selected Pollutants of Interest[a]

Pollutant	CAS RN	Concentration Limit *(µg/m³ or as listed)*	Benchmark Type	Notes
Hydrogen chloride (HCl)	7674-01-0	7,000	PEL-C, REL-C	Ceiling values, 5 ppm (7 mg/m³); conversion given as 1.49 mg/m³
		3,000	TLV-STEL-C	2 ppm; short-term exposure limit ceiling
		14	MEG air, 1 yr	
		400	TLV	As F, given as 0.5 ppm (1/6 the PEL and REL of 3 ppm)
		1,500	MEG air, 14 d	
Hydrogen sulfide	7783-06-4	30,000	PEL-C	20 ppm is a ceiling value, as a 10-min maximum peak
		15,000	REL-C	10 ppm is a ceiling value, as a 10-min maximum peak
		1,400	TLV	listed as (10 ppm), which is the same as the REL-C1 ppm
		7,000	TLV-STEL	5 ppm
		14	MEG air, 1 yr	
Mercuric chloride, as mercury (inorganic) (for some, CAS is 7439-97-6, as metal)	7487-94-7	100	PEL-C	Ceilings are 0.1 mg/m³ (the REL-TWA for mercury vapor is half that, at 0.05 mg/m³)
			REL-C	
		25	TLV	For elemental and inorganic forms, as mercury
Nitrogen dioxide (NO_2)	10102-44-0	9,000	PEL-C	5 ppm; ceiling
		1,800	REL-STEL	1 ppm; short-term exposure limit
		380	TLV	0.2 ppm
		860	CEGL, 90 d	
		940	MEG air, 1 yr	
Nitrogen (nitric) oxide (NO)	10102-43-9	30,000	PEL, REL, TLV	25 ppm
		3,700	CEGL, 90 d	
		3,700	MEG air, 1 yr	Same value for 14 d
Ozone	10028-15-6	200	PEL	0.1 ppm (note (the TLV below is half the PEL, also as a TWA)
			REL-C	Ceiling value
		100	TLV	Listed is the lowest value, 0.05 ppm for heavy work; TLV is 0.2 ppm for 2 hr or less
		39	MEG air, 1 yr	
Polychlorinated biphenyls (PCBs), as Aroclors 1242 and 1254)	53469-21-9	1,000	PEL	REL also applies to other PCBs, including Aroclor 1254 (below)
			TLV	Same as the PEL, for chlorodiphenyl, 42% chlorine (skin)
		1	REL	
		340	MEG air, 1 yr	

TABLE B-3 Example Occupational Exposure Limits for Selected Pollutants of Interest[a]

Pollutant	CAS RN	Concentration Limit *(µg/m³ or as listed)*	Benchmark Type	Notes
PCBs *(cont'd.)*	11097-69-1	500	PEL	
			TLV	Same as the PEL, for chlorodiphenyl, 54% chlorine
		1	REL	REL also applies to other PCBs, including Aroclor 1254
		170	MEG air, 1 yr	Aroclor 1254
	53469-21-9	340	MEG air, 1 yr	Aroclor 1242
Sulfur dioxide	7446-09-5	13,000	PEL	5 ppm
		5,000	REL	2 ppm
		650	TLV-STEL	0.25 ppm
		520	MEG air, 14 d	
Sulfuric acid	7664-93-9	1,000	PEL, REL	
		3,000	PEL-STEL	
		200	TLV	For sulfuric acid as the thoracic fraction
		49	MEG air, 1 yr	Same value for 14 d
Toluene	108-88-3	750,000	PEL	200 ppm (750 mg/m³)
		380,000	REL	100 ppm (375 mg/m³, rounded here)
		75,000	TLV	20 ppm
		560,000	REL-STEL	150 ppm
		3,400	MEG air, 1 yr	
Xylenes	1330-20-7	440,000	PEL, REL	PEL and REL are 100 ppm (435 mg/m³, rounded here) for m-, o-, p-xylene (CAS 108-38-3, 95-47-6, and 106-42-3, respectively)
			TLV	100 ppm (for combined and the 3 isomers)
		651,000	TLV-STEL	150 ppm
		270	MEG air, 1 yr	For mixed o-, m-, and p-xylenes, and individually

[a] This table was developed at an early stage of the evaluation process to provide an example compilation for selected pollutants from the candidate set. See Table 3-2 for additional information regarding these benchmarks, including the application context.

C = ceiling; CAS RN = Chemical Abstracts Service Registry Number; CEGL = continuous exposure guidance level; MEG = military exposure guideline; NIOSH = National Institute for Occupational Safety and Health; PEL = permissible exposure limit; REL = recommended exposure limit; STEL = short-term exposure limit; TLV = threshold limit value.

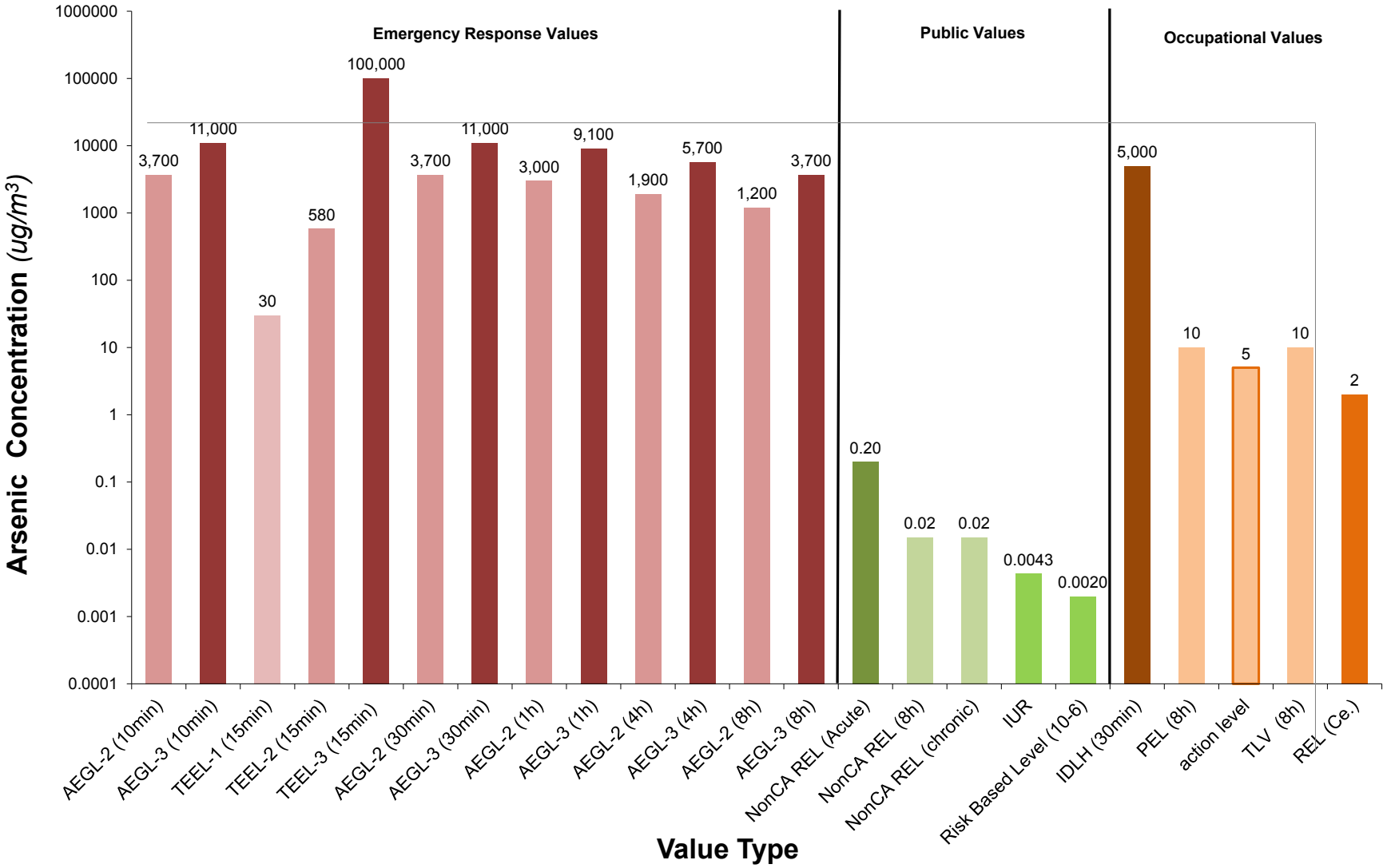

FIGURE B-1 Example Display of Selected Exposure Benchmark Values for Arsenic in Air

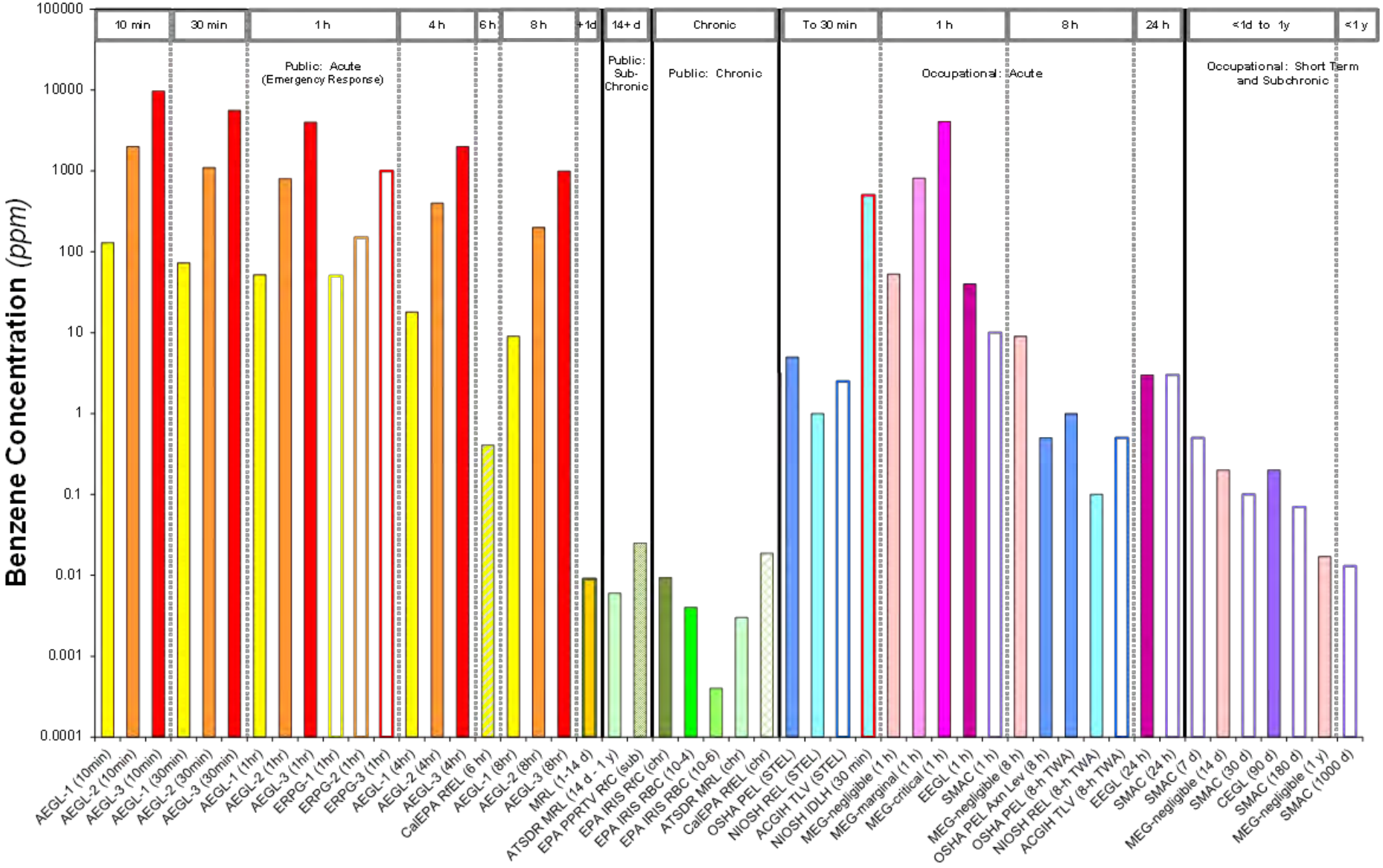

FIGURE B-2 Example Display of Benchmarks for Exposures to Benzene in Air

SELECTED REFERENCES

ACGIH (American Conference of Governmental Industrial Hygienists) (2011). *2011 TLVs and BEIs: Based on the Documentation of the Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*, Cincinnati, OH.

AIHA (American Industrial Hygiene Association) (2011). *ERPG/WEEL Handbook.*

ATSDR (2012). *Minimal Risk Levels (MRLs) List*. http://www.atsdr.cdc.gov/mrls/index.asp *(page last reviewed Mar. 6, 2013; last accessed May 22, 2013).*

CalEPA ARB (California Environmental Protection Agency, Air Resources Board) (2009). *California Ambient Air Quality Standards (CAAQS).* http://www.arb.ca.gov/research/aaqs/caaqs/caaqs.htm *(page last reviewed Nov. 24, 2009; last accessed May 22, 2013).*

CalEPA OEHHA (Office of Environmental Health Hazard Assessment) (2012). Acute, 8-hour and Chronic Reference Exposure Levels (chRELs) (as of February 2012).

U.S. DOE (2012). *Protective Action Criteria (PAC): Chemicals with AEGLs, ERPGs, and TEELS. 27th Revision*. http://www.atlintl.com/DOE/teels/teel.html *(page last accessed May 22, 2013).*

NIOSH (National Institute for Occupational Safety and Health) (2010). *NIOSH Pocket Guide to Chemical Hazards*. http://www.cdc.gov/niosh/npg/default.html*; (page last reviewed January 2012; last accessed May 22, 2013).*

NRC (National Research Council) (1994). *Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants, Volume 1*. http://www.nap.edu/catalog.php?record_id=9062

NRC (1984). *Emergency and Continuous Exposure Limits for Selected Airborne Contaminants Volume 1*. http://books.nap.edu/catalog.php?record_id=689.

OSHA (Occupational Safety and Health Administration) (2013). *Table Z-1 Limits for Air Contaminants*. 71 FR 12819. http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9992 *(page last accessed May 22, 2013).*

USAPHC (U.S. Army Public Health Command) (2010). *Environmental Health Risk Assessment and Chemical Exposure Guidelines for Deployed Military Personnel.* http://phc.amedd.army.mil/PHC%20Resource%20Library/TG230.pdf

U.S. EPA (U.S. Environmental Protection Agency) (2013). *Integrated Risk Information System* http://cfpub.epa.gov/ncea/iris/index.cfm?fuseaction=iris.showSubstanceList *(page last updated and accessed May 22, 2013)*.

U.S. EPA (2012). *National Ambient Air Quality Standards (NAAQS).* http://www.epa.gov/air/criteria.html *(last updated Dec. 14, 2012; last accessed May 22, 2013)*.

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APPENDIX C:

CONTEXT FOR CHEMICAL FATE IN AIR

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Chemical fate in air plays an important role in pollutant detection, for both discrete and continuous releases. Understanding this role can help guide research activities toward practical mobile sensors for air pollutants, including integrated multi-pollutant sensor systems. Supporting context is provided in this appendix.

Many chemicals (including a number of organic compounds) transform to other chemicals when released to air, in some cases within minutes to hours. As an indicator of how long a parent chemical would be expected to remain following a release, persistence is represented by its atmospheric half-life (the time it takes an initial amount to decrease by half).

Persistence can be affected by many factors, including physical state (e.g., gas, liquid, or particulate), chemical and physical reaction mechanisms, and setting-specific physical-chemical conditions such as temperature, relative humidity, sunlight, and the presence of other substances, including hydroxyl radicals (per their oxidizing potential). In many cases, different persistence intervals have been identified for a given chemical; these reflect the range of conditions addressed. For this reason, the example persistence intervals in this appendix are generally presented as ranges (e.g., "seconds to hours" or "days to weeks").

In addition to persistence, ambient conditions affect specific fate processes. Common processes include hydroxyl radical reaction and wet and dry deposition. The latter are the processes by which species are removed from the atmosphere and deposited on the Earth's surface. In wet deposition, chemical species are scavenged by hydrometeors, such as rain, fog, cloudwater, snow, and sleet. Dry deposition is primarily affected by the level of atmospheric turbulence, the chemical properties of the depositing species, and the nature of the surface itself (Seinfeld and Pandis 1996). For wet and dry deposition, where quantitative data were not found for this illustrative compilation, a general default of days is indicated. Depending on the compound and local/regional conditions, this could be hours (e.g., for highly reactive VOCs and short-chain alkanes) or weeks (for longer-chain alkanes). Dry deposition is much slower than wet, so the latter is more important for semivolatile compounds. Basic physicochemical properties considered in evaluating environmental fate (including volatilization from surface water to air) are described as follows.

- *Molecular weight* (*MW*) is the sum of the weights of the atoms present in a given compound, based on its formula. For this study, the MW (and formula) indicates the size (and complexity) of a given compound and can also indicate other properties such as vapor pressure (VP) and physical state at ambient temperatures, when those more specific measures are not known. The MW is also used to convert from parts per million (ppm) to mg/L or µg/L, or to mg/m^3 or µg/m^3, as indicated. For example, a value given as ppm in air can be multiplied by the MW and divided by 24.5 to convert it to mg/m^3 under standard temperature (25ºC) and pressure (1 atmosphere) conditions. (Note that gases are presented as volume per volume of air, e.g., ppm, and particles are presented as mass per volume of air, e.g., µg/m^3).

- *Henry's law constant (K_H)* provides a measure of how a chemical partitions between the liquid and gas phases at equilibrium in a closed system (ratio of to water solubility to a chemical's volatility). A chemical with a high Henry's law constant has a low tendency to volatilize and will stay in the water phase (when units are expressed as water

concentration over air concentration; note that K_H can also be expressed with the inverse units). The K_H indicates how much of a chemical may be released into the gas phase above the water compared with the amount dissolved in the aqueous phase. Even though this constant applies to a closed system at equilibrium, it can offer useful context for understanding the tendency of a chemical to evaporate, particularly in an open system, such as a water treatment basin, or in a home when the faucet is turned on. The K_H can be used to compare this tendency of a chemical to volatilize from water and to model partitioning for static or dynamic conditions. Chemicals with a K_H less than 1×10^{-5} atm-m^3/mole (or greater than 100 mole/L-atm) and a MW above 200 g/mole are considered unlikely to pose an inhalation hazard as a result of volatilization from drinking water in a residential setting (Andelman 1990).

- *Vapor pressure (VP)* is the pressure exerted by a chemical's vapor in equilibrium with its solid or liquid form at a given temperature. This can be used to calculate how fast the chemical will volatilize from the water surface or to estimate a Henry's law constant for chemicals that are not very soluble in water. The higher the VP, the greater the tendency for the chemical to form a gas. The VP can offer useful context regarding the tendency of a given chemical to volatilize from water to air. (Note that the K_H is a more useful value to predict partitioning from water to air.)

- *Atmospheric OH rate constant* is an indicator of the tropospheric lifetime of a given chemical (τ_c). It is controlled by reaction with the hydroxyl (OH) radical, $\tau_c = (k_{OH}[OH])^{-1}$, where k_{OH} is the first-order rate constant for the reaction of the OH radical with the chemical of interest, and [OH] is the concentration of the OH radical. Chemicals that react more rapidly with the OH radical have a larger atmospheric OH rate constant and a shorter lifetime in the troposphere. Chemicals with smaller k_{OH} values would have a longer atmospheric residence time than those with higher values.

These parameters are illustrated in Tables C-1 through C-3. Table C-2 illustrates values for selected physicochemical properties for the study pollutants, and Table C-3 illustrates the range of values for other chemicals.

TABLE C-1 General Categories for Parameters that Can Influence Chemical Fate in Air[a]

Parameter	General Categories and Examples		
	Low	***Medium***	***High***
Octanol-water partition coefficient: K_{ow}	<100	100 to 10,000	>10,000
Henry's constant: K_H *(mole/L-atm)*	<0.01 to 1	1 to 1000	>1000
Vapor pressure: VP *(mmHg)*	<0.001	0.001 to 1	>1
Solubility product: K_{sp}	$<1 \times 10^{-50}$	1×10^{-10} to 1×10^{-50}	$>1 \times 10^{-10}$
Water solubility: S_w *(ppm)*	<10	10 to 1000	>1000
Vapor pressure: VP *(mmHg)*	<0.001	0.001 to 1	>1
Melting point : MP (°C)	<0	0 to 100	>100
Boiling point: BP *(°C)*	<50	50 to 300	>300

[a] K_{ow} is the partition constant between water and octanol, which represents a generic "organic" phase; this coefficient is commonly used for organic chemicals (i.e., those containing carbon).

K_H is the distribution constant for a chemical between air and water phases, based on the partial pressure of the gas above the solution to its dissolved concentration; the extent to which a given gas dissolves in solution (here, water) is proportional to its pressure (Henry's law), and K_H is the proportionality constant for this relationship.

K_{sp} is the solubility product of inorganic compounds, which describes the equilibrium between the (excess) solid form and dissolved (or solvated) ions; it is used to determine if a solid is readily soluble in water and is a function of the water solubility, S_w.

VP is the pressure exerted by a vapor in equilibrium with its solid or liquid phase, typically used for a vapor in contact with its liquid (so it would represent the vapor-phase pressure of the pure liquid).

BP and MP, the boiling and melting points, are simple physical constants.

The values shown here simply illustrate the principles outlined above; other values could also be applied (e.g., example, a K_{sp} of 10^{-5} could be used as a delineator for "readily soluble" for one-molar electrolyte solutions, while formal water solubilities <0.003 mole/liter could indicate the compound is "not readily soluble").

TABLE C-2 Illustrative Parameter Values for the Study Pollutants[a]

Chemical	K_{ow} *(unitless)*	K_H *(mole/L-atm)*[a]	S_w *(ppm)*[a]	VP *(mmHg)*[a]	MP *(°C)*	BP *(°C)*
Acetaldehyde	0.457	15	1×10^{6}	902	-123	20.1
Acrolein	0.977	8.197	2.12×10^{5}	274	-87.7	52.6
Ammonia	1.698	62.5	310,000	7,752	-77.7	-33.35
Benzene	134.9	0.182	1,880	94.8	5.5	80.1
1,3-Butadiene	97.7	0.0135	735	2,110	-108.97	-4.5
Carbon monoxide	60.256	9.62×10^{-4}	23,000 @20°C	1.55×10^{8}	-205	-191.5
Formaldehyde	2.239	3,058	4×10^{5} @20°C	3,883	-92	-19.1
Hydrogen sulfide	1.698	0.12	4,100 @20°C	15,600	-85.49	-60.33
Lead			Insoluble	1.77 @ 1000°C	327.5	1,740
Methane	12.303	1.52×10^{-3}	22	4.66×10^{5}	-182.4	-161.5
Nitrogen dioxide	0.263	0.01	Reacts with H_2O	900	-9.3	21.15
Ozone	0.135	0.0113	f(P,T,pH); 1,060 at 0°C and pH 3.5	41,257 @ -12°C	-193	-111.9
Sulfur dioxide	0.0063	1.235	1.13×10^{5} @20°C	3,000	-72.7	-10

[a] These values are at 25°C (77°F) unless otherwise noted. Shading indicates the entry is not applicable/not available.

Particulate matter is not included in this table because it consists of a many species from both natural and anthropogenic sources, thus has no fixed physical or chemical properties (i.e., PM composition and associated properties vary by location and time).

Sources: ATSDR (2013); Kroschwitz (2004); NIH (2013); NOAA (2013); Seinfeld and Pandis (1996); SRC Inc. (2013).

TABLE C-3 Illustrative Parameter Values for Other Example Chemicals[a]

Chemical	K_{ow} *(unitless)*	K_H *(mole/[L-atm])*	K_{sp} *(unitless)*	S_w *(ppm)*	VP *(mmHg)*	MP *(°C)*	BP *(°C)*
Benzo(a)pyrene	1,300,000	2,200		0.001	5×10^{-9}	176.5	311
Dioxin *(2,3,7,8-TCDD)*	6,300,000	20		0.0002	1.5×10^{-9}	305	
Lead chloride *($PbCl_2$)*			1.6×10^{-5}	3,300			
Mercury *(Hg)*	4.2	0.12		0.06	0.002	-39	357
Mercury sulfide *(HgS)*			1.6×10^{-52}	2×10^{-21}			
PCBs	12,600,000	2.4		0.7	0.0005		
Pentachlorophenol	132,000	40,800		14	0.0001	174	309
Phenol	29	3,000		83,000	0.35	40.9	182
Toluene	540	0.15		526	28	-95	111
Trichloroethylene	260	0.1		1,280	69	-84.7	87.2

[a] Shading indicates the entry is not applicable/not available. Values are taken from various data sources; setting-specific information should be used to determine the appropriate value for a given assessment.

Three additional tables are included to illustrate how physicochemical properties and other technical information can be used to guide monitoring and detection efforts to address pollutant releases to air. Table C-4 highlights key fate processes and chemical products that could form in air following a given release. This table and the two that follow illustrate fate context for example chemicals beyond the initial study set. The initial entry for each parent chemical indicates the interval during which the initial fate process is expected, such as hydrolysis or hydroxyl radical oxidation. Subsequent intervals capture further fate processes as indicated. When the half-life information shown represents only a removal process (such as wet or dry deposition from air) rather than a change from the parent, that process is indicated without a fate product.

When no transformation is identified for a given chemical, removal is generally assumed to occur by deposition with a half-life of days to weeks; the actual time frame would depend on the physicochemical characteristics of the compounds and the particles onto which they sorb (including size), as well as location-specific meteorology and other factors. In many cases, the nature of the reaction is known but the specific fate product is not (common for many hydroxyl radical reactions), so fate products are not always available. Finally, for some chemicals, the hydrolysis half-life is similar to that for persistence in air. Thus in certain cases, hydrolysis products are included to indicate fate products that could be formed in moist (humid) air.

An overview of the fate and persistence context for these example chemicals in air is also illustrated in Table C-5, without the time component. This information can be combined with qualitative health information to provide context for detection levels (e.g., for mobile sensors) considering different methods and time frames, as illustrated in Table C-6. (The relative toxicity indicated in the right-most column of this table is based on EPA chronic toxicity values.)

TABLE C-4 Highlights of Persistence and Fate per Time Frame for Example Chemicals[a]

Contaminant	Persistence (Half-Life) and Key Fate/Removal Processes			
	Seconds-Hours	Days-Weeks	Weeks-Months	Months-Years
Arsenic (inorganic)		Deposition (arsenate, arsenite)		Arsenic (inorganic)
Benzene	Photooxidation: phenol, nitrophenols, nitrobenzene, formic acid, peroxyacetyl nitrate	Hydroxyl radical oxidation; deposition		
Chlorine	Atomic chlorine, hydrogen chloride, chlorinated hydrocarbons; and in moist air: hydrochloric and hypochlorous acids	Deposition		
1,2-Dichloroethane		Deposition	Hydroxyl radical oxidation	
Diesel engine exhaust	*Minutes to extended periods (e.g., years), depending on specific compound*			
Ethylbenzene	Oxidation	Oxidation and deposition		
Ethylene oxide (Oxirane)		In moist air: ethylene glycol	Hydroxyl radical oxidation	
Formaldehyde	Formic acid, hydrogen gas, carbon monoxide and dioxide, H radical, HCO radical	Deposition		
Hydrogen chloride (HCl)		Deposition		
Hydrogen sulfide (H_2S)		Sulfur dioxide, sulfates; deposition		
Mercuric chloride		Deposition		Multiple compounds
Nitric acid	In moist air: hydrogen and nitrate ions, NO_2 and NO	Deposition		
Nitrogen oxides, as NO_2			Nitrous and nitric acids, nitrite and nitrate salts	
Polychlorinated biphenyls (PCBs)		Hydroxyl radical oxidation, deposition	Hydroxyl radical oxidation, deposition	
Sulfur dioxide		Sulfurous acid, sulfur trioxide, sulfuric acid, and associated salts		
Sulfuric acid		Deposition		Sulfuric acid, sulfate
Toluene	Toluene-O_2 complex, ozone, nitrotoluene, peroxyacetylnitrate, peroxybenzoylnitrate, cresol, benzaldehyde, simple hydrocarbons	Same as first entry (at left), deposition	Same as first entry	
Xylenes	Glyoxal, methylglyoxal, other hydroxyl radical oxidation products	Deposition		

TABLE C-5 Summary of Key Fate Products and Processes for Example Chemicals[a]

Chemical	Fate Products	Fate Processes
Arsenic (including trivalent)	Arsenate, arsenite	Deposition
Benzene	Phenol, nitrophenols, nitrobenzene, formic acid, and peroxyacetyl nitrate	Hydroxyl radical oxidation, reaction with ozone and nitrate radicals
		Deposition (including wet)
Carbon monoxide	Carbon dioxide (note CO also accelerates the rate of ozone formation and the oxidation of nitric oxide to nitrogen dioxide)	Hydroxyl radical oxidation
Chlorine	Hydrochloric acid	Hydrolysis (in moist air)
	Hypochlorous acid	
	Atomic chlorine	Photolysis
	Hydrogen chloride	Reactions with atomic chlorine
	Chlorinated hydrocarbons	
1,2-Dichloroethane (ethylene dichloride)	Formyl and monochloroacetyl chloride	Hydroxyl radical oxidation
	Hydrogen chloride	
	Carbon monoxide	
	Carbon dioxide	
Ethylbenzene	Ethylphenols, benzaldehyde, acetophenone, and m- and p-nitroethylbenzene	Reaction with hydroxyl radicals and nitrogen radicals; deposition, notably wet/precipitation
Ethylene oxide (Oxirane)	Methane, ethane, water, carbon dioxide, simple aldehydes	Hydroxyl radical oxidation
	1,2-Ethanediol (ethylene glycol)	Hydrolysis (in moist air)
Formaldehyde	Hydrogen (gas)	Photolysis
	Carbon monoxide (CO)	
	Hydrogen radical (H·)	
	Formyl radical (HCO·)	
	Carbon dioxide (CO_2 from CO)	Oxidation
	Formic acid	Hydroxyl radical, nitrate oxidation
n-Hexane	Peroxyl radical	Hydroxyl radical reaction
	Aldehydes, ketones, nitrates	(also reaction with nitrate radicals)

Chemical	Fate Products	Fate Processes
Hydrogen chloride	Hydrochloric acid	Incorporated in cloud, rain, and fog water Deposition (wet and dry)
Hydrogen sulfide (H_2S)	Sulfur dioxide	Hydroxyl radical oxidation
	Sulfates	
Mercuric chloride	Elemental mercury	Exchange reaction
		Reduction (in moist air), deposition
Nitrogen oxides	Nitric oxide	Deposition, photooxidation, natural cycling
	Nitrogen dioxide (NO_2)	
Ozone	Oxygen	Natural decay, chemical instability, oxidation with organic materials, reaction with bacteria
Polychlorinated biphenyls (PCBs)	2-hydroxybiphenyl intermediate	Hydroxyl radical oxidation
	Chlorinated benzoic acid	Deposition
Sulfate *(also see sulfur oxides, sulfuric acid)*	Various sulfate ions	Deposition (wet, dry)
Sulfur oxides, sulfur dioxide *(also see above and next entry)*	Sulfur trioxide (combines with water to form sulfuric acid), sulfurous acid	Deposition (wet, dry) Photooxidation, e.g., in presence of hydrocarbons
	Sulfuric acid, sulfate	Catalytic oxidation in presence of PM containing iron or manganese compounds Reaction with ammonia
Sulfuric acid/hydrogen sulfate *(also see sulfate, sulfur oxides)*	Hydrogen ion, bisulfate, sulfate ions	Dissociation
		Deposition
Toluene	Cresol, benzaldehyde	Hydroxyl radical reaction Reaction with peroxy radicals (alkyl, aryl groups), ozone, and atomic oxygen
	Ring cleavage to simple hydrocarbons	Deposition
	Nitrotoluene, benzyl nitrate, ozone, peroxyacetylnitrate, and peroxybenzoylnitrate	Photolysis/reaction with NOx in air
Xylenes	Glyoxal ($C_2H_2O_2$) and methylglyoxal	Photooxidation, hydroxyl radical reaction
	Carbon dioxide and water (ultimately)	

[a] Successive transformation products are indicated by indenting. The identities of specific fate products are often not available (e.g., disappearance is noted, rather than new chemical produced).

TABLE C-6 Combined Persistence, Fate, and Toxicity Indicators for Example Chemicals[a]

Chemical	CAS RN	Formula or Symbol	Molecular Weight	General Persistence	Key Fate Process	Toxicity Indicator
Arsenic, inorganic	7440-38-2	As	74.9	Days	Deposition	Very high
Benzene	71-43-2	C_6H_6	78.1	Hours to days	Hydroxyl radical oxidation, nitrate and ozone radical oxidation, photooxidation, deposition	Moderate
Carbon monoxide	630-08-0	CO	28.0	Weeks	Oxidation; also naturally cycles	Very low
Chlorine	7782-50-5	Cl_2	70.9	Sec to minutes	Chemical reactivity	High
1,2-Dichloroethane	107-06-2	$C_2H_4Cl_2$	99.0	Weeks to months	Hydroxyl radical oxidation	Moderate
Diesel engine exhaust	Multiple	Various	Various	Minutes to years	Multiple (deposition, oxidation)	Moderate
Ethylbenzene	100-41-4	C_8H_{10}	106.2	Hours to days	Oxidation and deposition	Low
Ethylene oxide (Oxirane)	75-21-8	C_2H_4O	44.1	Weeks to months	Hydroxyl radical oxidation	Moderate
Formaldehyde	50-00-0	CH_2O	30.0	Hours to days	Photolysis, hydroxyl radical oxidation, deposition	Moderate
Gasoline (CAS is for vapors)	8006-61-9	C_5 to C_{12} hydrocarbons	(72.1 to 170.3)	Hours to months	(Depends on specific compound)	Low
n-Hexane	100-54-3	C_6H_{14}	86.2	Days	Hydroxyl radical oxidation	Low
Hydrogen chloride	7647-01-0	HCl	36.5	Days	Deposition	Moderate
Hydrogen sulfide	7783-06-4	H_2S	34.1	Days	Hydroxyl radical oxidation, deposition	High-mod
Mercuric chloride	7487-94-7	$HgCl_2$	271.5	Days	Deposition	High
Methanol	67-56-1	CH_4O	32.0	Days to weeks	Hydroxyl radical oxidation, deposition	Very low
Nitrogen dioxide	10102-44-0	NO_2	46.0	Days to weeks	Deposition, oxidation	Mod-low
Ozone	10028-15-6	O_3	48.0	Minutes	Conversion, oxidation	Mod-low
Polychlorinated biphenyls	1336-36-3	from $C_{12}H_9Cl$ to $C_{12}Cl_{10}$	186.7 to 498.7	Days to months	Deposition, hydroxyl radical oxidation	High-mod
Sulfate	14808-79-8	SO_4^{-2}	96.1	Days	Deposition	Moderate
Sulfur dioxide	7446-09-5	SO_2	64.1	Days	Photooxidation, deposition	Mod-low
Sulfuric acid/hydrogen sulfate	7664-93-9	H_2SO_4	98.1	Days	Dissociation, deposition	High-mod
Toluene	108-88-3	C_7H_8	92.1	Hours to days/mo	Hydroxyl radical oxidation, deposition	Very low
Xylenes	1330-20-7	C_8H_{10}	106.2	Hours	Free radical oxidation	Mod-low

Notes for Table C-6:

[a] This table highlights fate and persistence information for selected contaminants (including fate products) for which risk-based concentrations were identified from benchmarks relevant to chronic public exposures. The molecular weight represents the weight of one mole in grams (for compounds, this is the sum of the atomic weights of their components). The general formula for PCBs is $C_{12}H_{10-x}Cl_x$; the molecular weight shown here is from a representative range for these compounds.

For persistence and fate context, see companion tables. For some chemicals, several persistence values were found, reflecting differences in the conditions assessed by the underlying studies. In those cases, a range is given for the general persistence indicator (e.g., days to weeks). Long-term persistence indicators for compounds that are part of a natural biogeochemical cycle (e.g., nitrogen dioxide) are represented as years.

Qualitative toxicity indicators are included to indicate how fate, persistence, and toxicity can be integrated to help identify priority pollutants to be considered for air quality monitoring in a given setting; the relative toxicity context is based on EPA chronic toxicity values (see EPA 2013a, 2013b).

Additional important context for mobile sensing of air pollutants are seasonal and diurnal patterns. These patterns could be used to help guide planning for discrete vs. continuous sampling designed to reduce overall power consumption, by considering periods when pollutant concentrations are anticipated to be higher or to vary substantially. General information regarding seasonal and diurnal patterns for selected pollutants is offered below.

Gaseous air pollutants consist of primary and secondary pollutants. Primary pollutants are those released directly from a source into the air; carbon monoxide (e.g., from vehicle exhaust) is one example. In contrast, secondary pollutants are formed through chemical reactions of primary and/or other secondary pollutants in the atmosphere; ozone (formed by photochemical reaction with nitrogen oxides and VOCs) is an example. Spatial and temporal distributions of ambient concentrations depend on various factors such as the location and emission strength of the sources, chemical reactivity, wet and dry deposition, and meteorological conditions, such as wind speed and mixing heights. In most cases, ambient concentration levels tend to be proportional to the distance from the emission source. For example, emissions from onroad traffic such as carbon monoxide or benzene are higher along the roadways, and concentrations of sulfur dioxide and nitrogen oxides are higher around and downwind of coal-fired power plants.

Air pollutants with low or medium chemical reactivity are ubiquitous, i.e., they can be found near and far from their sources. As a rough guide, if emission strengths and depositions are constant diurnally and seasonally, ambient concentrations are a function of the variation in mixing height. Higher concentrations occur at night when a temperature inversion prevails, while lower concentrations occur during the day when vigorous mixing occurs up to the higher elevation. Typically, mixing height is highest in the early afternoon and lowest around sunrise.

Emissions and related ambient concentrations for most gaseous air pollutants are closely linked to energy use by the transportation sector, which peaks around early morning, decreases as the day proceeds, and peaks again in late afternoon. This behavior leads to the most commonly observed pattern of high ambient concentrations in the morning and evening hours for primary pollutants, and high concentrations during the afternoon hours for secondary pollutants, which are photochemically produced in the atmosphere from the primary pollutants.

Ozone is commonly known as a summertime pollutant. Seasonal and diurnal patterns of ozone are distinct compared with other air pollutants. The conditions conducive to high ozone concentrations typically include high temperature, low wind speed, intense solar radiation, and an absence of precipitation (NRC 1992). However, high temperature is not a necessary

condition, as evidenced by high-ozone episodes in winter.[1] In most central or downtown urban settings, ozone concentrations have been found to vary over a diurnal cycle with a minimum in the early morning hours before dawn and a maximum in the afternoon (typically from noon to 5 p.m.), but areas downwind of those settings have experienced daily maximum concentrations late afternoon and in the evening on occasion. At night, air pollutants are trapped in the shallow mixing layer caused by ground-based temperature inversion. In areas near large sources of nitrogen oxide, the nighttime minimum for ozone can be quite pronounced because of the rapid titration reaction between ozone and nitrogen oxides. In many urban areas, the nitrogen oxide source is strong enough to cause the complete nighttime disappearance of ozone, while concentrations close to background levels of 20 to 40 ppb have been reported for remote areas without nitrogen oxide emissions.

In contrast, carbon monoxide is a typical winter pollutant. Atmospheric levels are typically highest during the winter, because vehicles burn fuel less efficiently in cold weather, and with longer nighttime hours, a stronger inversion layer develops in the atmosphere that traps pollutants near the ground and prevents mixing with cleaner air above. Accordingly, the overnight buildup of carbon monoxide combined with morning rush-hour traffic emissions often result in exceedance (violations) of the ambient air quality standard in a limited area near intersections with heavy traffic volumes during the winter months.

Methane can be a pollutant of particular interest in certain locations, such as near concentrated animal feeding operations or areas of natural gas development. On the national to global scale, methane is the second most prevalent greenhouse gas among anthropogenic emissions, and pound for pound, it is estimated to be about 21 times more potent at warming the atmosphere than carbon dioxide. Its chemical lifetime in the atmosphere is estimated to be about 12 years. Methane sources are primarily continental (rather than oceanic), and because most of the world's land mass is in the northern hemisphere, the largest sources are there. Due to its relatively long atmospheric lifetime, methane has a nearly constant mixing ratio around the globe, with only a slight change in abundance across the intertropical convergence zone (ITCZ) near the equator.

[1] Recently, high ozone concentrations have been observed in several western rural areas during winter months, even when temperatures are below freezing. Sublette County, Wyoming, is the area in which wintertime high ozone levels were first identified. Daily maximum 8-hour ozone levels there have frequently exceeded the NAAQS level of 0.075 ppm in winter, mostly during January to March. The number of O_3 exceedance days is comparable to or higher than those in major U.S. metropolitan areas. These wintertime high ozone occurrences have been found at high-elevation monitoring sites, such as in southwest Wyoming, northeast Utah, and northwest of Colorado. Air quality modeling indicated that these high-ozone incidents during wintertime result from several factors: high solar radiation due to high elevation enhanced by high albedo caused by snow cover; shallow mixing height below temperature inversion; no or few clouds; stagnant or light winds; and abundant ozone precursors (such as NO_x and VOCs) from existing oil and gas development activities (Kotamarthi and Holdridge 2007; Morris et al. 2009). In particular, snow cover plays a crucial role in ultraviolet reflection and insulation from the ground, which reduces the surface heating that promotes the breakup of temperature inversions. Recent observations corroborate that the level of snow cover is closely related to high-ozone occurrences. Interestingly, ozone exceedances during the summer ozone season (lasting from spring to early fall) are rare in this area.

SELECTED REFERENCES

ATSDR (Agency for Toxic Substances & Disease Registry) (2013). Toxicological Profiles; http://www.atsdr.cdc.gov/toxprofiles/index.asp *(last accessed April 17)*.

Andelman, J.B. (1990). *Total Exposure to Volatile Organic Compounds in Potable Water*, Chapter 20, in: Significance and Treatment of Volatile Organic Compounds in Water Supplies, N.M. Ram, R.F. Christman, and K.P. Cantor (Eds.), Lewis Publishers, Chelsea, MI.

EPA (2013a). *Integrated Risk Information System (IRIS);* online database; National Center for Environmental Assessment, Washington, DC; http://www.epa.gov/IRIS *(page last updated May 8; last accessed May 22).*

EPA (2013b). *Provisional Peer-Reviewed Toxicity Values for Superfund (PPRTV)*, online resource of the National Center for Environmental Assessment, Washington, DC, hosted by Oak Ridge National Laboratory; http://hhpprtv.ornl.gov/ *(page not dated; accessed May 22).*

Kotamarthi, V.R., and D.J. Holdridge (2007). *Process-Scale Modeling of Elevated Wintertime Ozone in Wyoming*, ANL/EVS/R-07/7, prepared by Environmental Science Division, Argonne National Laboratory, for BP America (Dec.); http://www.ipd.anl.gov/anlpubs/ 2008/01/60757.pdf.

Kroschwitz, J.I. (2004). *Kirk-Othmer Encyclopedia of Chemical Technology*, Fifth Edition, John Wiley & Sons, Inc., Hoboken, NJ.

Morris, R.E., et al. (2009). Simulation of Wintertime High Ozone Concentrations in Southwestern Wyoming, presented at the *8th Annual CMAS Conference*, Chapel Hill, NC (Oct.); http://www.cmascenter.org/conference/2009/abstracts/morris_simulation_wintertime_2009.pdf.

NIH (National Institutes of Health) (2013). TOXNET (Toxicology Data Network), Hazardous Substances Data Bank (HSDB); http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB *(last modified December 10, 2011; accessed April 17).*

NOAA (National Oceanic and Atmospheric Administration) (2013). *Ozone, CAMEO Chemicals Version 2.4*; http://cameochemicals.noaa.gov/chemical/5102 *(last accessed April 17).*

NRC (National Research Council) (1992). *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, National Academy Press, Washington, DC.

Seinfeld, J.H., and S.N. Pandis (1996). *Atmospheric Chemistry and Physics, from Air Pollution to Climate Change*, John Wiley & Sons, Inc., New York, NY.

SRC Inc. (2013). *PHYSPROP*; http://www.srcinc.com/what-we-do/product.aspx?id=133 *(last accessed April 17).*

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APPENDIX D:

EXAMPLE CONCENTRATION SUMMARIES TO GUIDE REGIONAL AND LOCAL INPUTS

APPENDIX D:
EXAMPLE CONCENTRATION SUMMARIES TO GUIDE REGIONAL AND LOCAL INPUTS

Summary tables are presented in Chapter 3 for example concentrations of the study pollutants in air, to provide a practical basis for assessing reported sensor detection levels. Complementary tables are presented in this appendix, organized to facilitate data inputs by EPA Regional scientists and others interested in compiling selected location- or setting-specific summaries.

Example summaries for criteria pollutants are provided in Table D-1, including EPA Region-specific summaries for carbon monoxide, nitrogen dioxide, ozone, and particulate matter (both PM_{10} and $PM_{2.5}$). Example summaries for acrolein, ammonia, benzene, 1,3-butadiene, and hydrogen sulfide are provided in Table D-2.

TABLE D-1 Illustrative Concentrations of Criteria Pollutants in Air[a]

Information Basis *(location, time frame)*	**Criteria Pollutant** *(concentration unit)*							**Notes**
	CO (ppm)	**Lead** ($\mu g/m^3$)	**NO_2** (ppb)	**O_3** (ppb)	**PM_{10}** ($\mu g/m^3$)	**$PM_{2.5}$** ($\mu g/m^3$)	**SO_2** (ppb)	
EPA Regions								
Region 1	1.8		15	81	35	25 (9.4)		For EPA Region-specific data: CO: annual average for 2009; NO_2: annual average for 2009; O_3: 3-yr average for 2007-2009; PM_{10}: 24-hour, annual average for 2009; $PM_{2.5}$: 24-hour, 3-year average for 2007-2009 (with annual average concentrations in parentheses)
Region 2	1.3		17	76	52	28 (11)		
Region 3	1.7		12	77	42	30 (12)		
Region 4	1.7		8	74	36	26 (11)		
Region 5	1.4		13	73	41	30 (12)		
Region 6	1.7		11	75	53	22 (10)		
Region 7	1.6		8	65	41	25 (11)		
Region 8	2.2		16	73	76	28 (8.5)		
Region 9	1.9		16	77	63	33 (11)		
Region 10	2.0			60	51	31 (8.8)		
Other examples								
Ambient, annual means:								From EPA reports: *Air Trends* and *Report on Environment*
2012								
2010	1.6 (0.8-2.5)	0.11 (0-0.37)	10 (3.4-18)	72 (62-81)	63 (31-90)	10 (6.8-13)	2.2 (0.44-4.7)	CO: annual 2nd max, 8-hr avg; Pb: per annual max, 3-month avg; NO_2: annual avg; O_3: per annual 4th max 8-hr avg; PM_{10}: per annual 2nd max 24-hr avg; $PM_{2.5}$: seasonally weighted annual avg; SO_2: annual avg

Information Basis *(location, time frame)*	**Criteria Pollutant** *(concentration unit)*							**Notes**
	CO (ppm)	**Lead** ($\mu g/m^3$)	**NO_2** (ppb)	**O_3** (ppb)	**PM_{10}** ($\mu g/m^3$)	**$PM_{2.5}$** ($\mu g/m^3$)	**SO_2** (ppb)	
2009	1.8 (1.0-2.6)	0.09 (0.01-0.18)	14 (7-22)		51 (28-80)			CO: annual avg; Pb: annual avg; NO_2: annual avg; PM_{10}: annual mean per 24-hr avg
2007-2009				75 (64-85)				O_3: 3-yr avg
2006-2008						11.5 (7.8-15)		$PM_{2.5}$: 3-yr avg
2002		<0.05						Pb: from 2007 ATSDR ToxGuide
Regional								
Mid-Atlantic							3.3	SO_2: mean ambient 2003-2005
Midwest							2.3	SO_2: mean ambient 2003-2005
Northeast							1.2	SO_2: mean ambient 2003-2005
Southeast							1.3	SO_2: mean ambient 2003-2005
Annual					25 (16-35)	12 (8-16)	4 (1-8)	PM_{10}: 24-hr and 1-hr data, 3 yr avg period, 2005-2007, no seasonal weighting; $PM_{2.5}$: 24-hr, 3-yr avg, 2005-2007, no seasonal weighting; SO_2: mean, metropolitan area, with 2003-2005 averages
24-hour concentration				29 (14-45)	26 (9-46)	12 (4-23)	4 (1-10)	O_3: mean, 24-hr avg, 2007-2009; PM_{10}: 24-hr and 1-hr data, 3-yr avg, 2005-2007, no seasonal weighting; $PM_{2.5}$: 3-yr avg, 2005-2007, no seasonal weighting; SO_2: mean, metropolitan area, with 2003-2005 avgs
8-hour concentration				41 (23-60)				O_3: mean, 8-hr daily max, 2007-2009
1-hour concentration				29 (6-51)	27 (6-51)	10 (2-21)	4 (1-10)	O_3: mean, 1-hr avg, 2007-2009; PM_{10}: 1-hr data, 3-yr avg period, 2005-2007, no seasonal weighting; $PM_{2.5}$: 3-yr avg, 2005-2007, no seasonal weighting; SO_2: mean, metropolitan area, with 2003-2005 avgs
Northern hemisphere	0.12							
Southern hemisphere	0.04							
North America background <1,500 m				29 ± 8				O_3: March-August 2006-2008, per daily 8-hr avg, max (U.S.-only average is indicated as about 1 to 3 ppb higher)
North America background >1,500 m				40 ± 8				

Information Basis *(location, time frame)*	**Criteria Pollutant** *(concentration unit)*							**Notes**
	CO (ppm)	**Lead** ($\mu g/m^3$)	**NO_2** (ppb)	**O_3** (ppb)	**PM_{10}** ($\mu g/m^3$)	**$PM_{2.5}$** ($\mu g/m^3$)	**SO_2** (ppb)	
Geothermal							3.9	SO_2: mean concentration in geothermal area among regions of metropolitan Taipei (low traffic density areas)
Forest fires							600-3,000	SO_2: breathing zone of forest fires
Urban background		0.01					0.34-2	SO_2: Alberta communities, 7-day avg range, 5-wk sampling period
Example city (urban)			6-30	37 (19-57)	26 (11-45)	14 (6-25)	2.4-6.7	NO_2: Chicago, 3-yr mean (2008); O_3: Chicago, mean, 8-hr daily max, 2007-2009; PM_{10}: 24-hr and 1-hr data, 3 yr avg period, 2005-2007, no seasonal weighting; $PM_{2.5}$: 24-hr, 3-yr avg, 2005-2007, no seasonal weighting; SO_2: Chicago, range of mean, 2003-2005
Rural ambient				47 (<1500m) 60 (>1500m)			0.08-0.88	O_3: Great Smoky Mountain NP, median; SO_2: Alberta communities, 7-day avg range, 5-wk sampling period
Busy traffic	5	0.02	40-70	15 (7.3-19)		54 (44-60)		Pb: 2001-2010 annual avg; NO_2: Los Angeles freeway, nonconsecutive 4-day avg; O_3: Toronto roadway, 1-wk, August 2004, mean [min-max]; $PM_{2.5}$: freeway I-710S, mean, 4 days in spring, 2003 [avg interquartile range]
Tunnel			1,500					NO_2: NO_x, San Francisco tunnel exit, 1999
Airport		0.03						Pb: 10-day avg, Canadian airport, 2000 (0.30 max)
Neighborhood adjacent to airport		0.03-0.05						Pb: Santa Monica neighborhood, 155 m downwind
Downwind smelter		0.63-0.88						
Indoor air		0.11	10-30			20 (6.8-75)		Pb: 2001, mean from EPA Region 5 survey; NO_2: 24-hr avg; $PM_{2.5}$: two consecutive 3- to 4-day measurements collected biannually from urban homes (lower socioeconomic status) [data range]
Schools			15.5					NO_2: Australia, 12 wks, 6-hr/day, winter, electric or flued heater
Single-family home			10					NO_2: 2-wk mean
Multi-family home			23					NO_2: 2-wk mean
Home with electric stove			9					NO_2: 2-wk mean

Information Basis *(location, time frame)*	Criteria Pollutant *(concentration unit)*										Notes
	CO (ppm)		**Lead** ($\mu g/m^3$)	**NO_2** (ppb)		**O_3** (ppb)	**PM_{10}** ($\mu g/m^3$)	**$PM_{2.5}$** ($\mu g/m^3$)		**SO_2** (ppb)	
Indoor air, residential (by heating source)											NO_2, SO_2: median, one heating season (October-April) between 1994-1996, w/out heaters 1, 2-wk sampling period, w/ heaters 3-6, 2-wk sampling periods
Kerosene heater				17.7 (3.3-84)						6.4 (0.0-44)	
Gas space heater				54.8 (13-147)						0.9 (0.0-9.1)	
Fireplace				9.3 (2.8-80)						0.4 (0.0-7.2)	
Wood stove				11.2 (2.2-52)						0.3 (0.0-16)	
Without heaters above				13.5 (2.7-41)						0.2 (0.0-1.3)	
Home without gas stove	0.5-5										
Home with proper gas stove	5-15			26							CO: gas stove properly adjusted; NO_2: 2-wk mean, does not indicate if stove was properly adjusted
Home with improper stove	≥30										Gas stove not properly adjusted
Standards comparison											
National Ambient Air Quality Standard	**9**	**35**	**0.15**	**53**	**100**	**0.075**	**150**	**15**	**35**	**75**	
measurement averaging time	*8 hr*	*1 hr*	*rolling 3 mo*	*ann mean*	*1 hr*	*8 hr*	*24 hr*	*ann mean 3-yr*	*24 hr*	*1 hr*	

[a] This table was prepared to support regional and community inputs, e.g., to facilitate data compilation by EPA Regional staff and others (via entries provided in the upper portion of the table, with illustrative context for further comparisons provided in the rest of the table). CO = carbon monoxide; NO_2 = nitrogen dioxide; O_3 = ozone; PM_{10} = particulate matter ≤10-micron in diameter; $PM_{2.5}$ = PM ≤2.5-micron in diameter; SO_2 = sulfur dioxide.

The examples concentrations shown here represent U.S. values unless otherwise indicated; most ambient annual averages from the EPA Air Trends report are rounded to two significant figures; values in parentheses represent the 90th percentile range unless otherwise stated.

National Ambient Air Quality Standards are provided at the end of this table for comparison with the example concentrations shown for these criteria pollutants. The standards listed here reflect primary standards established for human health protection (averaging times for the measurements are given in parentheses beneath the concentration value); in some cases the primary standard also applies as the secondary standard – i.e., the NAAQS for lead, ozone, PM, and the

annual mean for nitrogen dioxide are joint primary-secondary standards. Not shown here is the separate secondary standard for sulfur dioxide (500 ppb); secondary standards are established to protect public welfare, including protecting against decreased visibility and damage to animals, crops, vegetation and buildings. Selected information sources are indicated below and in the companion Table D-2 (which presents example concentrations in air for selected pollutants beyond the six criteria pollutants); also see Table 3-5.

Carbon monoxide (CO)

ATSDR (2009). *ToxGuide* (http://www.atsdr.cdc.gov/toxguides/toxguide-201.pdf).

ATSDR (2009). *Toxicological Profile (Draft)* (http://www.atsdr.cdc.gov/ToxProfiles/tp201-c6.pdf).

EPA (2009). *Report on the Environment, Ambient Concentrations of Carbon Monoxide* (http://cfpub.epa.gov/eroe/index.cfm?fuseaction=detail.viewInd&lv=list.listbyalpha&r=231329&subtop=341).

EPA (2000). *Air Quality Criteria* (http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=18163).

Lead (Pb)

EPA (2012). *Integrated Science Assessment: Lead (Draft)* (http://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=235331).

Levin, R., M.J. Brown, M.E. Kashtock, D.E. Jacobs, E.A. Whelan, et al. (2008). *Lead Exposures in U.S. Children, 2008: Implications for Prevention*. Environ Health Perspect 116(10)1285-1293 (http://ehp03.niehs.nih.gov/article/info%3Adoi%2F10.1289%2Fehp.11241).

Also: Choel et al. (2006); Sabin et al. (2006).

Nitrogen dioxide (NO_2)

EPA (2008). *Integrated Science Assessment: Oxides of Nitrogen* (http://www.epa.gov/ncea/isa/).

EPA (2009). *Report on the Environment, Ambient Concentrations of Nitrogen Dioxide* (http://cfpub.epa.gov/eroe/index.cfm?fuseaction=detail.viewInd&ch=46&subtop=341&lv=list.listByChapter&r=231330)

Triche, E., K. Belanger, et al. (2005). *Indoor Heating Sources and Respiratory Symptoms in Nonsmoking Women*. Epidemiology,16(3):377-384.

Also: Westerdahl et al. (2005); Pilotto et al. (2004); Belanger et al. (2006); Strien et al. (2004).

Ozone (O_3)

EPA (2012). *Integrated Science Assessment: Ozone (Draft)* (http://www.epa.gov/ncea/isa/ozone.htm).

Also: Beckerman et al. (2008); Zhang et al. (2011).

Particulate matter (PM)

EPA (2009). *Report on the Environment, Ambient Concentrations of Particulate Matter* (http://cfpub.epa.gov/eroe/index.cfm?fuseaction=detail.viewInd&ch=46&subtop=341&lv=list.listByChapter&r=231331).

EPA (2009). *Integrated Science Assessment: Particulate Matter* (http://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=216546).

Baxter, L. K. (2007). *Predicting Residential Indoor Concentrations of Nitrogen Dioxide, Fine Particulate Matter, and Elemental Carbon Using Questionnaire and Geographic Information System Based Data.* Atmospheric Environment, 41(31):6561-6571 (http://www.sciencedirect.com/science/article/pii/S1352231007003718).

Fruin, S. (2008). *Measurements and Predictors of On-Road Ultrafine Particle Concentrations and Associated Pollutants in Los Angeles.* Atmospheric Environment, 42(2):207-219 (http://www.sciencedirect.com/science/article/pii/S135223100700859X).

Sulfur dioxide (SO_2)

EPA (2008). *Integrated Science Assessment: Sulfur Oxides – Health Criteria* (http://www.epa.gov/ncea/isa/soxnox.htm).

Kindzierski and Sembaluk (2001). In: *Review of the Health Risks Associated with Nitrogen Dioxide and Sulfur Dioxide in Indoor Air, Report to Health Canada* (https://circle.ubc.ca/bitstream/handle/2429/938/IAQNO2SO2full.pdf?sequence=8).

Triche, E., Belanger, K., et al. (2005). *Indoor Heating Sources and Respiratory Symptoms in Nonsmoking Women*. Epidemiology, 16(3):377-384.

TABLE D-2 Illustrative Concentrations of Five Hazardous Air Pollutants *(ppb)*[a]

Concentration Context	Acrolein	Ammonia	Benzene	1,3-Butadiene	Hydrogen sulfide	Notes
Area of interest						
EPA Region						
Community-based area						
Example Concentrations						
Ambient/outdoor air	0.5-3.2		0.85 (0.36-1.4)	0.1	0.11-0.33	Benzene: µg/m^3, annual mean, 2009 (10th-90th percentile range); 1.3-Butadiene: 2003 annual avg, Texas; excludes monitors downwind of point sources
Urban/metropolitan areas			0.58		<1	
Ambient, cities & suburbs				0.04-1		
Homes near CAFOs					0.4-2.4 8.4	Hydrogen sulfide: 2006, time-weighted avg (8.42 ppb), dominated by swine containment areas
Geothermal area					400	Hydrogen sulfide: mean concentration in geothermal area among regions of metropolitan Taipei
Indoor residential air	<0.02-12					
Near landfill					1-14	Hydrogen sulfide: Maximum 30-min rolling avg range, 2002 (2-wk, 15-min avg measurements) near Norridgewock landfill, Maine
Near industrial facilities				3.1	>90	1,3 -Butadiene: 5-yr avg, 1999-2003, downwind industrial point source, Milby Park monitor in Houston, Texas
Global average		0.3-6				

[a] This table was prepared to facilitate inputs from EPA Region staff and other interested parties to assess regional or local air quality data, with open entries at the top and example comparison values below. Values are as ppb and reflect U.S. data except as otherwise indicated. Selected information resources include:

Hydrogen sulfide (H_2S): Iowa (2006), *Modeling Hydrogen Sulfide Concentrations near CAFOs* (8.42ppb) (http://www.public-health.uiowa.edu/icash/research/H2S-near-CAFOs.html); Maine (2006), *Ambient Air Guidelines for Hydrogen Sulfide* (near landfill). (http://www.maine.gov/dep/waste/publications/documents/ambientairguidelines.pdf); Taipei (2010), Geothermal: sulfur-rich geothermal emissions elevate acid aerosol levels in metropolitan regions (http://www.ncbi.nlm.nih.gov/pubmed/20561610); California (1999), Odor detection threshold, geometric mean, 8 ppb (geometric standard deviation of 4) (Cal EPA).

1,3-Butadiene: Texas (2007), ambient and downwind of point source (http://www.ncbi.nlm.nih.gov/pubmed/17011534). (For others, also see Table 3-5.)

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APPENDIX E:

SUMMARY OF SENSORS REPRESENTED ON THE GRAPHICAL ARRAYS

APPENDIX E:

SUMMARY OF SENSORS REPRESENTED ON THE GRAPHICAL ARRAYS

The plots in Chapter 3 include small boxes listing example sensors that indicate where their detection levels fall compared with exposure benchmarks and illustrative concentrations in air for each pollutant. Supporting information for these sensors is summarized in Table E-1, as excerpted from the much larger master table that includes additional pollutants and other parameters (see Raymond et al. 2013).

Because gas and particle sensor technologies and techniques differ, the first level of organization for Table E-1 is by pollutant type: first gases, then particles. Within the gases, the criteria pollutants are listed first (carbon dioxide, nitrogen dioxide, ozone, and sulfur dioxide), followed by the other eight gases (acetaldehyde, acrolein, ammonia, benzene, 1,3-butadiene, formaldehyde, hydrogen sulfide, and methane). The two particulate criteria pollutants (PM and lead) are presented at the end.

Within each pollutant, the research sensors with new or modified detection techniques are listed first, grouped by detection principle (e.g., chemical, spectroscopy, and ionization), beginning with the lowest reported lower detection level (LDL) within each of these categories.

Where relevant, the research sensors that reflect a sensor system architecture incorporating a commercial sensor are listed next, again ordered by increasing reported LDL. The commercial sensors are listed last within each pollutant section.

The identifier (ID) listed in the first column corresponds to the numbers listed in the sensor boxes on the graphical arrays. An "np" in the ID column indicates that sensor was not plotted on the graphical array because no detection level or range was reported. A "c" indicates a commercial sensor used in a novel detection system; a C denotes a standard commercial sensor included for comparison.

A subsequent targeted literature search for chemical-based sensors conducted in early 2013 produced results summarized in Table E-2. This table is organized in a similar manner as Table E-1.

A number of acronyms and abbreviations are defined within the tables; the notation section at the front of this report includes additional definitions.

TABLE E-1 Detectors Displayed on Graphical Arrays for Detection Levels, Benchmarks, and Ambient Levels[a]

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Carbon Monoxide										
Detection Technique: Chemistry										
1	Korea Institute of Science and Technology (Republic of Korea) *Shim, Y.-S., Yoon, S.-J., et al.* *(Funding: Core Technology Materials Research & Development Program of Korea Ministry of Intelligence and Economy, and KIST Research Program)*	*Transparent conducting oxide electrodes for novel metal oxide gas sensors* [Aug. 2011, Sensors and Actuators B, 160:357-363] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511007155&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=96ca5099839c0ba48523ae38a59c54ac/1-s2.0-S0925400511007155-main.pdf	Metal oxide semi-conductor (MOS)	Thin film with transparent conducting oxide electrodes, tungsten trioxide (WO_3) and tin dioxide (SnO_2) thin-film (200 nm) sensors with indium-tin oxide (ITO) and Al-doped zinc oxide (AZO) films (200 nm) on glass substrates, 20-µm spacing of interdigitated electrodes	CO	Sub-ppm, limit 200 ppb (high transmittance, exceeds 75% of sensors at visible wavelengths)	~240 sec	Very small	Not indicated *(This column also includes brief notes related to the general sensor category, e.g., mountable.)*	Designed to replace traditional platinum (Pt) electrodes. Required annealing time of 53.3 hours; In_2O_3 and others doped with other ions (e.g., aluminum-doped zinc oxide and ITO) reduce cost. The work functions of Pt electrodes and ITO were 5.65 electron volts (eV) and 4.6 eV, respectively, with operating temperatures of 200-500°C.
2	Kyushu University, Fukuoka Japan Department of Energy and Materials Sciences *Kida, T., et al.*	*Application of a solid electrolyte CO_2 sensor for the analysis of standard volatile organic compound gases* [2010, Analytical Chemistry, 82(8):3315-3319]http://pubs.acs.org/doi/full/10.1021/ac100123u	Electro-chemical, potentio-metric	Solid electrolyte CO_2 sensor using NASICON ($Na_3Si_2Zr_2PO_4$; Na^+ conductor) as the solid electrolyte and binary carbonate (Li_2CO_3-$BaCO_2$) as the sensing layer	VOCs: ethanol, formalde-hyde, and toluene), CO, and hydro-carbons	Measures 10-500 ppm, standard gases; detection limited to around 0.5 ppm CO_2	<1 min		Computer-recorded electrometer readings (operating temperature of the CO_2 sensor) (Mountable)	VOCs are decomposed to CO_2 due to catalytic combustion, and the CO_2 is then detected using a solid-state CO_2 sensor; the operating temperature is 500°C.
3	University College London *Varsani, P., et al.* University of Auckland (New Zealand) *Binions, R.* *(Funding: EPSRC, Wolfson Trust, Royal Society, Dorothy Hodgkin fellowship)*	*Zeolite-modified WO_3 gas sensors – Enhanced detection of NO_2* [2011, Sensors and Actuators B, 160:475-482] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511007374&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=da16648f4b92533eb17ae36c6fe2c0ad/1-s2.0-S0925400511007374-main.pdf	MOS	Solid-state metal oxide screen printed WO_3 sensors modified by addition of acidic and catalytic zeolite layers	NO_2; also tested: CO, mixture of NO_2 and CO, acetone at 5 ppm	CO tested at 30 ppm	30-min response with 1-hr recovery		(Mountable)	Highly selective to NO_2, including in the mixture; potential for use in electronic nose technology for environmental monitoring. Zeolite layers were added to increase selectivity. The sensor operates at 350°C.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
4	Shinwoo Electronics Co., Ltd. *Kim, I.* Korea University (S. Korea) *Dong, K.Y., Ju, B.K.* Yonsei University (S. Korea) *Choi, H.H.*	*Gas sensor for CO and NH_3 using polyaniline/CNTs composite at room temperature* [2010, IEEE, International Conference on Nanotechnology Joint Symposium with Nano Korea] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5697782&isnumber=5697724	Polymer film, organic	Polyaniline (PANi)/single-walled carbon nanotube (SWCNT) film dispersed in sodium dodecyl sulfate and applied over titanium/gold (Ti/Au) electrodes of an interdigitated electrode (IDE) by photolithography	CO, NH_3; also benzene and NO_2	Indicates ppm levels (CO tested at 80 ppm, NH_3 at 35 ppm)	Fast response and recovery	5 mm x 17 mm, 480 µm thick		Demonstrates the use of PANi/ SWCNT composite-based sensor for mixed gas detection. The change in resistance of the sensor determines the presence of a single gas or mixture of gases. This composite has a large surface-to-volume ratio which makes it a good candidate for new gas sensors. The sensor operates at room temperature.
5	VLSI Technology Laboratory, National Cheng Kung University (Taiwan) *Juang, F.-R., Chiu, H.-Y., Fang, Y.K., Cho, K.-H., and Chen, Y.C.* *(Funding: National Science Council)*	*An n-SnO_x/i-diamond/p-diamond diode with nanotip structure for high-temperature CO sensing applications* [2012, IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6183505	Nano-based, chemical vapor deposition (CVD)	Palladium (Pd)/n-tin oxide (SnOx)/ i-diamond/p-diamond diodes prepared by field-enhanced hot-wire CVD (FEHWCVD) system on silicon substrate with nano-tip structures on SnOx sensing layer	CO; also CO_2, ethanol, NO	100 ppm ambient (91%), saturated above 1,200 ppm	~2 sec			Addresses emerging diamond-filmed nanostructures for more sensitivity to CO in ambient conditions under high temperatures. The p-i-n diamond diode was reported to have more sensing applications. The use of diamond tips instead of MOS sensors allows for lower operation temperatures (material band gap of 5.47 eV).
6 np	University of California San Diego *Sailor, M.J.* *(Funding: NSF and Air Force Office of Scientific Research)*	[Feb. 2003] http://sailorgroup.ucsd.edu/research/gassensors.html	Nano-based	Crystal made from nano-structured porous silicon (Si) film, detects shifts in Fabry-Perot fringes or resonance; nano-structured porous Si sensor pad	Chemical warfare agents, VOCs, CO, CO_2, O_2, and hydro-carbons			Portable, quarter-sized sensor pad for multiple chemical detection	(Handheld)	Porous Si sensor pad engineered to be green in presence of air then turn red in presence of the target chemical. Developer envisioned producing thousands of miniature sensor pads on a silicon chip the size of a quarter to quickly identify a wide range of chemical toxins.
7 np	Solapur University, Materials Research Laboratory (India) Bhabha Atomic Research Centre (India) *Pawar, S.G., Chougule, M.A., Patil, V.B.*	*Development of nanostructured polyaniline-titanium dioxide gas sensors for ammonia recognition* [2012, Journal of Applied Polymer Science, 125(2): 1418-1424], http://onlinelibrary.wiley.com/doi/10.1002/app.35468/full	Polymer film, hybrid	Nanostructured PANi-TiO_2 thin film deposited on glass substrate (1 mm-wide strips)	NH_3, CO		41 sec		(Fixed/semi-portable)	No response at room temperature for 20 ppm NH_3 using TiO_2 nanoparticles alone; needed to be operated at 200º C. Pure PANi composite showed little response, while the PANi-TiO_2 composite was the most responsive at room temperature. Response time decreased as NH_3 concentration increased, but so did recovery time (possibly due to lower desorption rate).

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Detection Technique: Spectroscopy										
8	Yanshan University (China) *Zhang, J., Cao, S., Guan, L.*	*Carbon monoxide gas sensor based on cavity enhanced absorption spectroscopy and harmonic detection* http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5230315&isnumber=5230050[2009, IEEE]	Laser absorp-tion	Harmonic detection, cavity enhanced absorption spectroscopy (CEAS); absorption detected at 1567 nm for CO	CO	10 ppm	5-hr cycle detec-tion		(Handheld)	Uses enhanced absorption spectroscopy and harmonic detection techniques in a fiber CO gas sensor. This system increases the distance of interaction between light and CO from that typically seen in a standard gas cell. Possible applications include increased sensing capabilities in mines, industrial settings, and homes. Reported power usage is 3.63 decibel-milliwatt (dBm).
9 np	Tianjin University (China) *Nan, G., Zhen-hui, D., Xue-hong, Z., Yan, W.* *(Funding: National High Technology Research and Development Program of China and the Natural Science Foundation of Tianjin)*	*Tunable diode laser absorption spectroscopy for sensing CO and CO_2 of vehicle emissions based on temperature tuning* [2011] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5914237&isnumber=5914233	Laser absorp-tion	Tunable diode laser absorption spectroscopy (TDLAS), 1580 nm distributed feedback (DFB) laser with thermoelectric cooler.	CO, CO_2 (vehicle emissions)				(Remote sensor)	Explores a broad-spectrum temperature tuning method by controlling the thermoelectric cooler in the laser diode. Temperature ranged from -7.6ºC to 30.8ºC, allowing a wavelength range of 4 nm. This method increased response speed and allows for the simultaneous detection of CO and CO_2. Applicable for remote detection of vehicle emissions.
10 np	Imperial College London *Polak, J., and others (including at Universities of Cambridge, Leeds, Newcastle, and Southampton)* *(Funding: Engineering and Physical Sciences Research Council and Department of Transport)*	[2009] http://www.wired.co.uk/news/archive/2009-06/30/pedestrians-and-cars-turned-into-pollution-sensors	Ultraviolet absorp-tion (UV abs)	Supported by ultrasound technology for traffic count	NO_x, SO_x, CO (up to 5 traffic pollutants)		5-sec interval	Pocket size	Data transmitted to base using mobile phones, locations tagged using Google Maps (Wearable and vehicle-mounted units)	12 static and 6 mobile sensors, 3 of which were on vehicles and 3 were carried by pedestrians.

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Novel Sensor Systems Using Commercial Sensors										
c 11	Jackson State University *Anjaneyulu, Y.* Jawaharlal Nehru Technological University *Jayakumar, I., Bindu, V.H.* Andhra Pradesh Pollution Control Board *Ramani, K.V.* Spectrochem Instruments *Rao, T.H.*	*Real time remote monitoring of air pollutants and their online transmission to the web using internet protocol* [2007, Environ Monit Assess, 124:371-381]] http://cardiff.academia.edu/SAGARESWARGUMMENENI/Papers/922566/	Electro-chemical various commer-cial	*(Real Time Remote Monitoring System)*	SO_2, NO, NO_2, CO, O_3, H_2S, PM_{10}, $PM_{2.5}$, hydro-carbons, mercap-tans	Varies per pollutant, within 0-200 ppm, or 0-50 µg/m^3 (mercaptans) CO: Range: 0-100 ppm	30 or 60 min		Ethernet network module, uploading to webpage (Remote sensor)	This device is a remotely monitored detection system that can be run on a 12-volt (12V) battery. The sensors can be set to collect data every 30 or 60 minutes, depending on user preference and weather conditions. Also measures environmental parameters (including temperature and humidity).
c 12	University of Canterbury (New Zealand) *Pattinson, W.*	*Cyclist exposure to traffic pollution: microscale variance, the impact of route choice and comparisons to other modal choices in two New Zealand cities* [2009] http://ir.canterbury.ac.nz/handle/10092/3687; http://ir.canterbury.ac.nz/bitstream/10092/3687/1/thesis_fulltext.pdf	Commer-cial sensors	Mobile sampling using 4 portable kits with sampling instruments; logging software Specifically used: Langan T15n for CO; GRIMM Dust Monitor (1.101, 1.107, 1.108) for PM; TSI 2007 Condensation Particle Counter for UFP, and Kestrel 4500 for meteorological data	CO, PM_{10}, $PM_{2.5}$, PM_1 and UFP	CO: range: 0-200 ppm resolution: 0.05 ppm			(Portable, vehicle-mounted units)	This outdoor study examined exposure to pollutants in various settings. The focus was on cars and bikes in urban settings. The study assessed cyclist exposures, with the kits in the front baskets of the bikes.
c 13	American University of Sharjah, Sharjah, UAE *Al Ali, A.R., Zual-kernan, I., Aloul, F.* *(Funding/resources: Computer Science and Engineering Department, American University of Sharjah, UAE)*	*A mobile GPRS-sensors array for air pollution monitoring* [2010, IEEE Sensors Journal, 10(10):1666-1671] http://www.aloul.net/Papers/faloul_sensors10.pdf	Sensor array (assume commer-cial)	24 sensors and 10 routers in a single-chip microcontroller *(GPRS-sensors array)*	CO, NO_2, SO_2	CO: range: 0-1,000 ppm resolution: <1.5 ppm	<25 sec	Shoebox	Online capabilities, single chip microcon-troller and global position system (GPS) to locate air pollution readings on Google Maps. (Vehicle-mounted unit)	Proposes an integrated system composed of a single-chip microcontroller, sensors for CO, NO_2, and SO_2, a general packet radio service (GPRS)-modem, and a GPS module. Public mobile networks are used to upload data to the Pollution Server, which is interfaced with Google maps; was deployed on the American University of Sharajah campus.

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c 14	Bharath University *Giri, R.K.*	*An Itinerant GPRS-GPS and sensors integration for atmospheric effluence screening* [2011, IJTES 2(2):152-157] http://www.sensaris.com/wp-content/uploads/old/2011/09/India-bus-GPRS-GPS-Air-sensing.pdf	Sensor array (assume commer-cial)	Several air pollution sensors *(Mobile-DAQ)*	CO, NO_2, SO_2	CO: range: 0-1,000 ppm resolution: <1.5 ppm	<25 sec	Mobile-DAQ unit roughly book size, sensor is 20 mm diameter and server is a laptop	Public mobile network; fixed internet-enabled monitoring server (pollution server) is interfaced to Google Maps to display real-time pollutant levels and locations in a metropolitan area (24 hr/7 d) (Vehi-cle-mounted unit)	System is composed of a single-chip microcontroller, air pollution sensors for CO, NO_2, and SO_2, GPRS-Modem, and GPS device. Data is transmitted to the Pollution Server, which is interfaced with Google Maps. Device was mounted on a bus, which was driven around the Bharath University of Chennai campus.
c 15	Universidade da Coruña (Spain) *Lopez-Pena, F., Varela, G., Paz-Lopez, A., Duro, R.J.* Universidad de Vigo (Spain) *Gonzalez-Castano, F.J.* *(Funding: Ministerio de Fomento of Spain)*	*Public transportation based dynamic urban population monitoring system* [2010, Sensors & Transducers, 8:13-25] http://www.sensorsportal.com/HTML/DIGEST/february_2010/P_SI_100.pdf *(CO sensor link: http://mkwheatingcontrols.co.uk/download/GS-S-CM.pdf)*	Commer-cial sensors (by Sontay, GS-S-CM CO sensor)		CO_2, CO, NO_2, SO_2, temp and relative humidity	CO: sub-ppm (ppb) Sontay: operating range: 0-100 or 1,000 ppm resolution: 0.5ppm	<30 sec	Desktop (from photos)	Bluetooth GPS; mobile sensing network includes distributed software to acquire, integrate, and geolocate sensor data ; linked to Google Maps application programming interface (API) (WSN) (Vehicle-mounted unit)	Public transportation buses were used as mobile sensing units to measure urban pollution; the device runs on two 12V batteries at an operating temperature between -30 and 60°C, with a life expectancy of 2 years. This research reflects the second stage, which follows the single sensor pilot study (using a car-mounted sensor) in Vigo.
c 16	University of South Florida and Universidad de Oviedo (Spain) *Mendez, D., et al.*	*P-Sense: A participatory sensing system for air pollution monitoring and control* [2011, IEEE Work in Progress Workshop at PerCom 2011] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5766902 *(Commercial sensor link:* http://www.figarosensor.com/products/5042pdf.pdf*)*	Electro-chemical (by Figaro and Sensirion)	*(P-Sense)*	CO_2, CO, combus-tible gases, air quality; also: temp and relative humidity	CO: range: 0 to 10,000 ppm baseline offset: +/- 10 ppm	<60 sec		Data transmitted to first-level integra-tor device, P-Sense; integrates digital and analog sensors with Blue-tooth-capable AVR-based board; WSN, mobile sensing network includes applica-tion server and PRO200 Sanyo cellular phone with GPS, Bluetooth.	Potential for citizen sensing applications. Challenges noted for broader implementation include: privacy (protection), security (need simple and energy-efficient mechanism), data validity (e.g., user could fake reading to avoid fine), data visualization (with gaps in location and time; consider Gandin Interpolation or optimal interpolation technique), and incentives (why participate?). Output current of 1.2~2.4 nA/ppm and an operating temperature range between -40 and 70°C.

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c 17	University of Cambridge *Kanjo, E.* *(Sponsors: O_2, Nokia, Symbian, Outspoken, Cambridge city Council, Thales)*	*Mobile phones as sensors* (presentation) http://www.admin.cam.ac.uk/offices/research/documents/local/events/downloads/sw/4.2-Kanjo.pdf		*(MobGeoSen)*	CO_2, CO, noise	CO: indicated limit: 0.5 ppm		Cell phone	Wireless communication network uses GPS coordinates (Cell phone-based)	This system uses mobile technology to obtain accurate readings both indoors and outdoors. It would run while the mobile device was active and could show the user their exposure as they traveled, via a Google Earth overlay.
c 18	Vanderbilt University, Institute for Software Integrated Systems *Völgyesi, P., et al.*	*Air quality monitoring with sensorMap*(2008, IEEE, and Int'l Confc on Info Processing in Sensor Networks) http://www.google.com/url?sa=t&rct=j&q=microsoft%20research%20sensors%20air%20pollutant&source=web&cd=8&ved=0CF0QFjAH&url=http%3A%2F%2Fciteseerx.ist.psu.edu%2Fviewdoc%2Fdownload%3Fdoi%3D10.1.1.157.1544%26rep%3Drep1%26type%3Dpdf&ei=D0YgT7aCBail2gXbtZWBDw&usg=AFQjCNFgTjs-go6sStpL48YV-Ru3BOqEMg	MOS	Commercial MiCS-5521 analog sensor *(MAQUMON-mobile air quality monitoring network)*	O_3, NO_2, and CO/VOC Also: temp and relative humidity	CO: indicated range: 1 to 1,000 ppm		Hand-held (infer from picture)	Measurements uploaded to server when car is in a WiFi hotspot, processed, then published on SensorMap portal (as contours, with time series data for given sensor and/or location); integrated Bluetooth module provides wireless interface for laptops or PDAs. (WSN) (Vehicle-mounted unit)	This vehicle-mounted sensor takes measurements every minute while the car is in motion (less often when stationary). Battery lasts a few hours, but the system can be constantly powered by the cigarette lighter when the car is moving, and power-intensive elements such as GPS, Bluetooth, and gas sensors can be turned off when the 2-axis MEMS accelerometer indicates the system is not in motion.
c 19 np	Northwestern University *Otto, J.S., Rula, J.P., Bustamante, F.E.*	[April 2009] http://www.aqualab.cs.northwestern.edu/publications/JOtto09C3R-TR.pdf *C3R-Participatory urban monitoring from your car* [April 2009] http://www.eecs.northwestern.edu/docs/techreports/2009_TR/NWU-EECS-09-10.pdf *(MQ7 CO gas sensor manufacturer page:* http://hwsensor.en.alibaba.com/product/285416574-209771110/MQ7_CO_carbon_monoxide_gas_sensor.html*)*	MOS (SnO_2)	Modified Hanwei Electronics MQ-7 CO sensor *(C3R)*	CO, temp, humidity.	CO: indicated range: 10-10,000 ppm (unmodified sensor)	90 sec	Shoebox	Communicates with other vehicles and agencies; each C3R node maintains a detailed air quality map that is shared with the driver, other vehicles, and public agencies. (Vehicle-mounted unit, participatory/ citizen sensing)	This is an outdoor vehicular networking system. This system uses 760 mW of power mostly for heating the sensing device. Interference may occur if wind or other factors cool the sensor below a necessary temperature. It takes 48 hr for the sensor to warm up, and it runs on a 90-sec cycle, with intermitted 60-sec purge cycles.

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c 20	Amrita University (India) *Freeman, J.D., Omanan, V., Ramesh, M.V.*	*Wireless integrated robots for effective search and guidance of rescue teams* [2011, IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5872919&isnumber=5872911	Infrared (IR) (by Hanwei Elec-tronics Co. Ltd.)	*(MQ-7, MQ-4, MQ-2, MQ-6 (all manufactured by Hanwei Electronics CO., Ltd.)*	CO, natural gas, liquid petroleum gas, smoke	CO: indicated range: 20-2000 ppm			Wireless sensor network, (WSN) precise location (GPS) Robot platform: ATMEGA328P microcontroller (Robotics)	Explores the application and technology required for a wireless sensor network for disaster management by use of autonomously navigating robots equipped with air quality sensors and the ability to search for disaster survivors. The search team's network is formed between two fixed nodes.
c 21 np	Sungkyunkwan University Foundation for Corporate Collaboration *Kim, W.J.*	*Bicycle navigation having air pollution measurement sensors, a method for storing the air pollution measurement (and more)* http://www.wipo.int/patentscope/search/en/detail.jsf?docId=KR10525661&recNum=1&docAn=1020090005097&queryString=FP:(1020090005097)&maxRec=1		Bicycle navigation system with air pollution measure-ment sensors, a method for storing the measurement, and a method for locating the road, to enable a mobile equipment user to find less polluted route (patent appl.)	CO, NO_2, SO_2			Mobile device	Unit transmits the measured data and GPS position to a storage server. (Vehicle-mounted unit)	A GPS navigation system for bicycles with embedded sensors that measure and transmit CO, NO_2, SO_2 concentrations along with GPS data.
Reference Commercial Sensor										
C 22	Ecotech	http://www.ecotech.com/gas-analyzers/co-analyzer	Non-disper-sive UV abs)	*(EC9830 CO analyzer)*	CO	Indicated range: 0-200 ppm; indicated limit: 50 ppb			Data access via RS232, USB interface, or Ethernet connector	Optional internal 12V direct current (DC) power supply allows sensor to be operated from a battery- or solar-powered source.
Nitrogen Dioxide										
Detection Technique: Chemistry										
1	Sungkyunkwan University (Korea) *Yao, F., Lee, Y.H., et al.* *(Funding: STAR-faculty program and World Class University program through KRF funded by MEST)*	*Humidity-assisted selective reactivity between NO_2 and SO_2 gas on carbon nanotubes* [2011, J. Materials Chemistry, 21:4502-4508] http://nanotube.skku.ac.kr/data/paper/Humidity-assisted_Fei%20Yao.pdf	Nano-based	Random-network SWCNTs in electrodes made with dip-pen method, with dichloroethane solution on Pt IDEs. Varying humidity level allows for selective gas detection	NO_2, SO_2	0.01 ppm	10 min	Small	Cites earlier results: NO_2 100 ppt with polymer-coated CNT SO_2 10 ppb with SWCNT, spectro-scopic analysis)	Pollutant diluted with other ambient air, added humidity, and transported to testing chamber. A 0.1V current is passed through the device. Sensor has an operating temperature of 150°C.

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2	Silpakorn University (Thailand), and others *Robert, O.P.; others* *(Funding: Thailand Research Fund; also supported by Office of the Higher Education Commission and others; e.g., Petro-Instruments Corp., Ltd. for sensor calibrations; NASA)*	*SnO_2 gas sensors and geo-informatics for air pollution monitoring* [2011, JOAM (J Optoelectronics and Advanced Materials), 13(5):560-564] http://modis.gsfc.nasa.gov/sci_team/pubs/abstract.php?id=04314; joam.inoe.ro/download.php?idu=2778	Nano-based	Nanotechnology-based SnO_2 gas sensor.SnO_2 thick film with alumina substrate from E2V Technologies; Pt electrodes	NO_2	Sensitivity <0.05-5 ppm (85% accuracy)			Data transferred to pocket PC linked via Bluetooth and GPS. Minnesota Mapserver 2009 used to monitor, view, retrieve NO_2 concentrations in real time. (Wearable, participatory/ citizen sensing)	Research goal is low-cost, simple, reliable, portable, real-time air pollution monitoring system for central Bangkok area.
3	University of South Carolina, *Nomani, Md.W.K., et al.* SENS4, LLC *James, J.* *(Funding: NSF, Army Research Office, and SENS4, LLC [through an NSF grant])*	*Highly sensitive and multidimensional detection of NO_2 using InO_3 thin films* [Aug. 2011, Sensors and Actuators B, 160:251-259] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511006861&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=a9efb7781a0624784753f0979694f695/1-s2.0-S0925400511006861-main.pdf	MOS	Fabricated sensor chip using In_2O_3 thin films (from Thinfilms, Inc.) as functionalization layers coated on an Al_2O_3 ceramic substrate, interdigitated metal fingers, 100 µm apart of Ti (5 nm)/ Au (50 nm) deposited atop the thin film	NO_2; also assessed: mixture of NO_2, NH_3	20 ppb (20% reduction in conductivity at this level)	A few sec		(Mountable)	20% reduction in conductivity at 20 ppb, normal temperature (20ºC); in a vacuum, In_2O_3 nanowires indicated sensitivity of 5 ppb; per an average ambient/ background level of 11 ppb, the concentration differential of 9 ppb is identified as responsible for the conduction change (indicating even more impressive sensitivity to the authors); the system can monitor minute deviations from the general average background value (30–50 mV) at a frequency of 1 kHz, at an operating temperature of >150ºC.
4	University College London *Varsani, P., et al.* University of Auckland (New Zealand) Queen Mary, University of London *Binions, R.* *(Funding: EPSRC, Wolfson Trust, Royal Society, Dorothy Hodgkin fellowship)*	*Zeolite-modified WO_3 gas sensors – Enhanced detection of NO_2* [2011, Sensors and Actuators B, 160:475-482] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511007374&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=da16648f4b92533eb17ae36c6fe2c0ad/1-s2.0-S0925400511007374-main.pdf	MOS	Solid-state metal oxide screen printed WO_3 sensors modified by addition of acidic and catalytic zeolite layers	NO_2; also tested: CO, 30 ppm, and mixture of NO_2 and CO, acetone at 5 ppm	NO_2: indicated range: 200-300 ppb (tested 50-400 ppb) in dry air	30- min re-sponse with 1-hr re-covery		(Mountable)	Highly selective to NO_2, including in the mixture; potential for use in electronic nose technology for environmental monitoring. Zeolite layers were added to increase selectivity. Sensor operates at 350ºC.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
5 np	Korea Advanced Institute of Science and Technology (Republic of Korea) *Cho, N.G., Kim, I.-D.* *(Funding: Korea Ministry of Research, Israel Ministry of Science & Technology)*	*NO_2 gas sensing properties of amorphous $InGaZnO_4$ submicron-tubes prepared by polymer fiber templating route* [Aug. 2011, Sensors and Actuators B, 160:499-504] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511007404&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=7220341a4a8ff1059a32e198b06fec69/1-s2.0-S0925400511007404-main.pdf	Nano-based	Semiconducting amorphous $InGaZnO_4$ submicron, thin wall hollow tubes	NO_2	100, 200, 400, 800 ppb (and higher)	"Varies"	Very small	Not indicated	Higher sensitivity may be due to much reduced interface area between sensing film and substrate, enhanced surface-depletion areas, and effective gas diffusion through porous tube networks; simple and versatile synthesis method indicates opportunities to control tube morphology, for a new class of building blocks for these gas sensors. 20 kV was applied to the sensor, which operates at 300°C.
6 np	Brno University of Technology (Czech Republic) *Hrdy, R., Vorozhtsova, M., Drbohlavova, J., Prasek, J., Hubalek, J.* *(Funding: Czech Ministry of Education and Grand Agency of Czech Republic)*	*Electrochemical transducer utilizing nanowires surface* [2010, IEEE, 33rd Int. Spring Seminar on Electronics Technology] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5547340&isnumber=5547245	Nano-based	TiO_2 modified Au nanowires applied to surface of sensing electrode	CO_2, NO_2, O_2, NH_3				(Mountable)	Operated at 5–30 keV in high vacuum mode. Sensor operates in a range between 300 and 400°C.
7 np	Shinwoo Electronics Co., Ltd. *Kim, I.* Korea University (S. Korea) *Dong, K.Y., Ju, B.K.* Yonsei University (S. Korea) *Choi, H.H.*	*Gas sensor for CO and NH3 using polyaniline/CNTs composite at room temperature* [2010, IEEE, International Conference on Nanotechnology Joint Symposium with Nano Korea] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5697782&isnumber=5697724	Polymer film	PANi/SWCNTs film dispersed in sodium dodecyl sulfate and applied over Ti/Au electrodes of an IDE by photolithography	CO, NH_3 (also benzene and NO_2)		Fast re-sponse. and re-covery	5 mm x 17 mm, 480 µm thick		This research demonstrates the use of PANi/SWNTs composite-based sensor for mixed gas detection. The changes in resistance of the sensor determine the presence of a single gas or mixture of gases. This composite has a large surface-to-volume ratio which makes it a good candidate for new gas sensors.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Detection Technique: Spectroscopy										
8a 8b	Adelphi University *Roa, G.N., Karpf, A.*	*A trace gas sensor at ppb sensitivity based on multiple line integration spectroscopy techniques* [2010, IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5499863&isnumber=549982	Laser absorp-tion multiple-line inte-grated absorp-tion spec-troscopy (MLIAS)	MLIAS with a multi-pass cell (12.5 cm and others) and pulsed quantum cascade laser (QCL) (from Daylight Solutions)	NO_2	8a: 530 ppt (200-m path) 8b: 120 ppb (0.88-m path)		Compact, portable	(Mountable)	Technology designed to be compact and portable, easy to operate, and low cost. Detector can monitor in real time. Explores use of QCLs to enhance detection sensitivity, varied cell sizes, and multi-pass geometry to increase sensitivity of NO_2 gas detection.
9 np	University of Mississippi *Uddin, W.* *(Funding: DOT)*	[2001] http://www.ncrste.msstate.edu/archive/projects/um/UM-CAIT-Laser-Year-1-Report-Final.pdf	Light detection and ranging (LIDAR)	Tunable LIDAR measure wavelengths between 2,500-11,000 Angstroms	O_3 or NO_2	1-100 ppb, at a range of several km			(Remote sensing)	In this study, the system was mounted in a plane and used to analyze traffic pollution in different areas of Mississippi.
10 np	Bogor Agricultural University (Indonesia) *Rustami, E., Azis, M., Maulina, W., Rahmat, M., Alatas, H., Seminar, K.B.* *(Funding: Beasiswa Unggulan Terpadu – Education Ministry of Republic of Indonesia, Bogor Agricultural University)*	*An integrated optical instrumentation for measuring NO_2 gas using one-dimensional photonic crystal* [2011, IEEE, International Conference on Instrumentation, Communication, Information Technology, and Biomedical Engineering, (Indonesia)] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6108658&isnumber=6108578&tag=1	UV-visible (UV-vis) absorp-tion	Integrated optical sensor with 1-D photocrystal, LED, and photodiode operating in NO_2 absorption range	NO_2				(Mountable)	A signal conditioning circuit consisting of a current to voltage converter, voltage follower, active low pass filter, and instrumentation amplifier was designed to better measure the output signal. Millivolt range
11 np	Bogor Agricultural University, Bogor Indonesia *Maulina, W., Rahmat, M., Rustami, E., et al.* *(Funding: Beasiswa Unggulan Terpadu – Education Ministry of Republic of Indonesia, Bogor Agricultural University Departments)*	*Fabrication and characterization of NO_2 gas sensor based on one-dimensional photonic crystal for measurement of air pollution index* [2011, IEEE, International Conference on Instru-mentation, Communica-tion, IT, and Biomedical Engineering (Indonesia)] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6108657&isnumber=6108578&tag=1	UV-vis absorp-tion	Photonic crystal fabricated by electron beam evaporation with photonic pass band (PPB) at 533 nm wavelength	NO_2 (dissolved in reagent)				(Fixed/semi-portable unit)	Device may be deployed as a sensor in an air pollution index measurement system. Sensor has an operating temperature of 300°C.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Novel Sensor Systems Using Commercial Sensors										
c 12	Universidade da Coruña (Spain) *Lopez-Pena, F., Varela, G., Paz-Lopez, A., Duro, R.J.,* Universidad de Vigo (Spain) *Gonzalez-Castano, F.J.* *(Funding: Ministerio de Fomento of Spain)*	*Public transportation based dynamic urban population monitoring system* [2010, Sensors & Transducers, 8:13-25] http://www.sensorsportal.com/HTML/DIGEST/february_2010/P_SI_100.pdf *(CO sensor link: http://mkwheatingcontrols.co.uk/download/GS-S-CM.pdf)*	Com-mercial sensors (by Sontay, GS-S-CM CO sensor)		CO_2, CO, NO_2, SO_2; also temp and relative humidity	NO_2: 0-10 ppm (<0.02 ppm)	<30 sec	Desktop (inferred from photos)	Bluetooth GPS; mobile sensing network includes distributed software to acquire, integrate, and geolocate data from sensors; linked to GoogleMaps API for data visualization. (WSN) (Vehicle-mounted unit)	Public transportation buses were used as mobile sensing units to measure urban pollution; the device runs on two12V batteries and operates between -30 and 60ºC. The device is reported to have a life expectancy of 2 years. This research reflects the second stage, which follows the single sensor pilot study (using a car-mounted sensor) in Vigo.
c 13	American University of Sharjah, Sharjah, UAE *Al Ali, A.R., Zualkernan, I., Aloul, F.*	*A mobile GPRS-sensors array for air pollution monitoring* [2010, IEE Sensors Journal, 10(10):1666-1671] http://www.aloul.net/Papers/faloul_sensors10.pdf	Sensor array (assume commer-cial)	24 sensors and 10 routers in a single-chip microcontroller *(GPRS-sensors array, Mobile-DAQ)*	CO, NO_2, SO_2	NO_2: range: 0-20 ppm limit: <0.02 ppm		Shoebox	Online capabilities, uses a single chip microcontroller and a GPS system to locate air pollution readings on Google Maps. (Vehicle-mounted unit)	Proposes an integrated system composed of a single-chip microcontroller, air pollution sensors for CO, NO_2, and SO_2, a GPRS-modem, and a GPS module. Public mobile networks are used to upload data to the Pollution Server, which is interfaced with Google maps; was deployed on the American University of Sharajah campus.
c 14	Bharath University, Department of Computer Science and Engineering *Giri, R.K.*	*An itinerant GPRS-GPS and sensors integration for atmospheric effluence screening* [2011, IJTES 2(2):152-157] http://www.sensaris.com/wp-content/uploads/old/2011/09/India-bus-GPRS-GPS-Air-sensing.pdf	Sensor array (assume commer-cial)	Several air pollution sensors	CO, NO_2, SO_2	NO_2: range: 0-20 ppm resolution: <0.02 ppm		Mobile DAQ: book size, sensor: 20 mm	Public mobile network; fixed internet-enabled monitoring server (pollution server) is interfaced to Google Maps to display real-time pollutant levels and locations in a metropolitan area (24 hr/7 d) (Vehi-cle-mounted unit)	System is composed of a single-chip microcontroller, air pollution sensors for CO, NO_2, and SO_2, GPRS-Modem, and GPS device. Data is transmitted to the Pollution Server, which is interfaced with Google Maps. Device was mounted on a bus, which was driven around the Bharath University of Chennai campus.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
c 15 np	Sungkyunkwan University Foundation for Corporate Collaboration *Kim, W.J.*	http://www.wipo.int/patentscope/search/en/detail.jsf?docId=KR10525661&recNum=1&docAn=1020090005097&queryString=FP:(1020090005097)&maxRec=1		Bicycle navigation system (GPS) with air pollution measurement sensors	CO, NO_2, SO_2			Mobile device	Unit transmits the measured data and GPS position to a storage server. (Vehicle-mounted unit)	A bicycle GPS navigation system with embedded sensors that measure and transmit CO, NO_2, SO_2 concentrations along with GPS data.
c 16 np	Jackson State University *Anjaneyulu, Y.* Jawaharlal Nehru Technological University *Jayakumar, I., Bindu, V.H.* Andhra Pradesh Pollution Control Board *Ramani, K.V.* Spectrochem Instruments *Rao, T.H.*	*Real time remote monitoring of air pollutants and their online transmission to the web using internet protocol* [2007, Environ Monit Assess, 124:371-381]] http://cardiff.academia.edu/SAGARESWARGUMMENENI/Papers/922566/	Electro-chemical various commer-cial sensors	*(Real Time Remote Monitoring System)*	SO_2, NO, NO_2, CO, O_3, H_2S, PM_{10}, $PM_{2.5}$, hydro-carbons, mercap-tans	Varies per pollutant, within 0-200 ppm, or 0-50 µg/m^3 (mercaptans)	30 or 60 min		Ethernet network module, uploading to webpage (Remote sensing)	This device is a remotely monitored detection system. It can be run on a 12V battery and operates between 55 and 125°C. The pollution sensors can be set to collect data every 30 or 60 minutes depending on user preference and weather conditions. Also measures environmental parameters such as temperature and humidity, as well as sound. (Meteorological monitoring system, Bruel and Kajaer sound level measurement system.)
Reference Commercial Sensor										
C 17	EcoTech	http://www.ecotech.com/gas-analyzers/nox-analyzer	Chemi-lumines-cence	*(EcoTech: Serinus 40)*	NO, NO_2, NO_x	Indicated range: 0-20 ppm LDL: <0.4 ppb				Indicates several system components to improve system integrity, power usage, and carbon footprint (99-132 volts alternating current (AC), 198-264 VAC 47-63 Hz).
Ozone										
Detection Technique: Spectroscopy										
1 np	University of Mississippi, Center for Advanced Infrastructure Technology *Uddin, W.* *(Funding: DOT)*	[2001] http://www.ncrste.msstate.edu/archive/projects/um/UM-CAIT-Laser-Year-1-Report-Final.pdf	LIDAR	Tunable LIDAR can measure wavelengths between 2,500-11,000 Angstroms	O_3 or NO_2	1-100 ppb, at a range of several km		System was mounted in plane	(Remote sensing, vehicle-mounted unit)	Analyzed traffic pollution in different areas of Mississippi.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Novel Sensor Systems Using Commercial Sensors										
c2	Pennsylvania State University *Cazorla, M., Brune, W.H.*	*Measurement of ozone production sensor* [2009, Atmospheric Measurement Techniques Discussion, 2:3339-3368] http://atmos-meas-tech-discuss.net/2/3339/2009/amtd-2-3339-2009.pdf	UV photo-metric, commer-cial sensor	11.3 L UV-transmit-ting Teflon film chambers, NO_2 to O_3 converting unit, and modified ozone analyzer (Thermo Scientific, Model 49i with ozone scrubber removed and temperature stabilization) *(MOPS: Measure-ment of Ozone Production Sensor)*	O_3 (measures production rate, can also study sensitivity of O_3 production to NO, using the NO convertor)	Indicated limit 0.67 ppb/hr for a 10-min average measurement			Not indicated (Fixed/semi-portable unit)	Compares O_3 production in one chamber with ambient air/normal conditions, and in a second chamber with O_3 production inhibited.
c3 np	Jackson State University *Anjaneyulu, Y.* Jawaharlal Nehru Technological University *Jayakumar, I., Bindu, V.H.* Andhra Pradesh Pollution Control Board *Ramani, K.V.* Spectrochem Instruments *Rao, T.H.*	*Real time remote monitoring of air pollutants and their online transmission to the web using internet protocol* [2007, Environ Monit Assess, 124:371-381]] http://cardiff.academia.edu/SAGARESWARGUMMENENI/Papers/922566/	Electro-chem, various commer-cial	Tapered element oscillating microbalance *(Real Time Remote Monitoring System)*	SO_2, NO, NO_2, CO, O_3, H_2S, PM_{10}, $PM_{2.5}$, hydro-carbons, mercap-tans	Ozone: Indicated range: 0-10 ppm; varies per pollutant, within 0-200 ppm	30 to 60 min		Ethernet network module, uploading to webpage (Remote sensing)	This device is a remotely monitored detection system that can be run on a 12V battery. The pollution sensors can be set to collect data every 30 minutes or every 60 minutes depending on user preference and weather conditions. Operates between -55 and 125°C. (Also measures temperature, pressure, rainfall, relative humidity, wind speed and direction, and sound; per meteorological monitoring system, Bruel and Kajaer sound level measurement system.)
Reference Commercial Sensor										
C4	2B Technologies *(an InDevR company)*	http://www.twobtech.com/model_106.htm	UV abs	Absorbs at 254 nm *(Ozone monitor model 106-L)*	O_3	Indicated range 0-100 ppm; resolution: 1 ppb precision and accuracy: higher of 2 ppb or 2% of reading	10 sec	Shoebox, laptop (4.5 lb)	USB and RS-232 output of time/ date, O_3 concen-tration, internal temperature, pressure; internal data logger, on-board microproc-essor. (Fixed/ semi-portable unit)	Intended for industrial settings, was used in the GO3 project. Unit requires 12V (500 mA, 6 W) of power (can be battery operated) and has a long-life pump (15,000 hr). Data can be averaged over 1 min, 5 min, and 1 hr. Available in standard or NEMA enclosure; components mounted on one printed circuit board.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Sulfur Dioxide										
Detection Technique: Chemistry										
1	Sungkyunkwan University (Korea) *Yao, F., Lee, Y.H., et al.* *(Funding: STAR-faculty program and World Class University program through KRF funded by MEST)*	*Humidity-assisted selective reactivity between NO_2 and SO_2 gas on carbon nanotubes* [2011, J. Materials Chemistry, 21:4502-4508] http://nanotube.skku.ac.kr/data/paper/Humidity-assisted_Fei%20Yao.pdf	Nano-based	Random-network SWCNTs in electrodes made with dip-pen method, with dichloroethane solution on Pt IDEs;. varying humidity level allows for selective gas detection	NO_2, SO_2	SO_2: indicated range: 0.01-10 ppm	4 sec	Small	Cites earlier results: NO_2 100 ppt with polymer-coated CNT SO_2 10 ppb with SWCNT, spectroscopic analysis)	Pollutant diluted with other ambient air, added humidity, and transported to testing chamber. A 0.1V current is passed through the device and the sensor operates at 150°C.
Detection Technique: Spectroscopy										
2	Wuhan Huali Environment Protection Science Technology Co., Ltd. *Wan, Y., Dai, B.*	*Atmospheric pollution monitoring gas sensor using non-pulse ultraviolet fluorescence method* [2010] http://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20101208&DB=worldwide.espacenet.com&locale=en_EP&CC=CN&NR=201666873U&KC=U&ND=4	Fluores-cence	Non-pulse UV fluorescence method	H_2S, SO_2	1 ppb as lowest level of detection			(Fixed/semi-portable unit)	Continuous monitoring of real-time concentrations of H_2S and SO_2 in air. Sensor reduces noise and has high anti-interference capability, which greatly improves the measurement accuracy and leads to more stable data.
3	Harbin Institute of Technology (China) *Lou, X.T., Somesfalean, G., Zhang, Z.G., Svanberg, S.*	*Sulfur dioxide measurements by correlation spectroscopy using an ultraviolet light-emitting diode* [2009, IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5196268&isnumber=5191447	Spectros-copy (correla-tion spectros-copy, CO-SPEC)	LED and UV range absorption	SO_2	0.4 ppm			(Fixed/semi-portable unit)	Demonstrates the use of LEDs with structureless emission in the UV region as sources for gas absorption measurements when combined with the COSPEC technique. Tested system is immune from interfering gases, pressure variations, and light intensity fluctuations.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Novel Sensor Systems Using Commercial Sensors										
c4	Jackson State University *Anjaneyulu, Y.* Jawaharlal Nehru Technological University *Jayakumar, I., Bindu, V.H.* Andhra Pradesh Pollution Control Board *Ramani, K.V.* Spectrochem Instruments *Rao, T.H.*	*Real time remote monitoring of air pollutants and their online transmission to the web using internet protocol* [2007, Environ Monit Assess, 124:371-381]] http://cardiff.academia.edu/SAGARESWARGUMMENENI/Papers/922566/	Electro-chemical various commer-cial	Tapered element oscillating microbalance *(Real Time Remote Monitoring System)*	SO_2, NO, NO_2, CO, O_3, H_2S, PM_{10}, $PM_{2.5}$, hydro-carbons, mer-captans	SO_2: indicated limit: 0.05 ppm	30 to 60 min		Ethernet network module, uploading to webpage (Remote sensing)	This device is a remotely monitored detection system that can be run on a 12V battery. The pollution sensors can be set to collect data every 30 minutes or every 60 minutes depending on user preference and weather conditions. Operates between -55 and 125ºC. (Also measures temperature, pressure, rainfall, relative humidity, wind speed and direction, and sound, per meteorological monitoring system, Bruel and Kajaer sound level measurement system.)
c5 np	Bharath University, Department of Computer Science and Engineering *Giri, R.K.*	*An itinerant GPRS-GPS and sensors integration for atmospheric effluence screening* [2011, IJTES 2(2):152-157] http://www.sensaris.com/wp-content/uploads/old/2011/09/India-bus-GPRS-GPS-Air-sensing.pdf	Sensor array (assume commer-cial sensors)		CO, NO_2, SO_2	SO_2: indicated range: 0-20 ppm resolution: <0.02 ppm		Mobile-DAQ unit is book size, sensor is 20 mm diameter and server is a laptop	Public mobile network; fixed internet-enabled monitoring server (pollution server) is interfaced to Google Maps to display real-time pollutant levels and locations in a metropolitan area (24 hr/7 d) (Vehi-cle-mounted unit)	System is composed of a single-chip microcontroller, air pollution sensors for CO, NO_2, and SO_2, GPRS-Modem, and GPS device. Data is transmitted to the Pollution Server, which is interfaced with Google Maps. Device was mounted on a bus, which was driven around the Bharath University of Chennai campus.
c6 np	American University of Sharjah, Sharjah, UAE *Al Ali, A.R., Zualkernan, I., Aloul, F.* *(Funding/resources: Computer Science and Engineering Department, American University of Sharjah, UAE)*	*A mobile GPRS-sensors array for air pollution monitoring* [2010, IEEE Sensors Journal, 10(10):1666-1671] http://www.aloul.net/Papers/faloul_sensors10.pdf	Sensor array (assume commer-cial)	24 sensors and 10 routers in a single-chip microcontroller *(GPRS-sensors array)*	CO, NO_2, SO_2	SO_2: indicated range: 0-20 ppm (<0.1 ppm)		Shoebox	Online capabilities, uses a single chip microcontroller and a GPS system to locate air pollution readings on Google Maps. (Vehicle-mounted unit)	Proposes an integrated system composed of a single-chip microcontroller, air pollution sensors for CO, NO_2, and SO_2, a GPRS-modem, and a GPS module. Public mobile networks are used to upload data to the Pollution Server, which is interfaced with Google maps; was deployed on the American University of Sharajah campus.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
c7 np	Xi'an University of Posts and Telecommunications (China) *Xiaoquiang, Z., Zuhou, Z.*	*Development of remote waste gas monitor system* [2010, International Conference on Measuring Technology and Mechanics Automation] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5460346&isnumber=5458485	Electro-chemical	Solid electrolyte layer, Au electrodes, Pt, Pb, heater, porcelain tube, double-layer steeless (steel) net, Ni- and Cu-plated ring, Bakelite, Ni- and Cu-plated pin.	CO_2, SO_2,	SO_2: indicated range: <1-2,000 ppm (<0.1) sensitivity: 400-700 nA/ppm in 10 ppm SO_2			GPS, GSM, Global System for Mobile Communications wireless transmission, secure digital (SD) memory (Remote sensing)	This research explores a system in which chimneys are monitored for several pollutant outputs and collected data are used to alert users/monitors of unhealthy emission levels. Collected data would be compared with national standards and alerts would go out if emission levels exceeded warning levels.
Reference Commercial Sensor										
C8	EcoTech	http://pdf.directindustry.com/pdf/ecotech/serinus-50-sulfur-dioxide-analyzer/50178-143935.html	UV fluores-cent radiation	*(Serinus 50 SO_2 Analyzer)*	SO_2	Indicated range: 0-20 ppm LDL: <0.3 ppb	60 sec to 95%	440 x 178 x 620 mm, bench 18.1 kg, rack 13.1 kg	USB port, data logging	This system requires 99-132 VAC, 198-264 VAC 47-63 Hz and can operate in 0-40ºC range. The sample flow rate is 675 cc/min, and the user can select the displayed concentration units.
Acetaldehyde										
Detection Technique: Chemistry										
1	University of Ferrara (Italy) *Giberti, A., Carotta, M.C., Fabbri, B., Gherardi, S., Guidi, V., Malagu, C.* *(Funding//support: Programma Operativo FESR, Spinner Regione Emalia-Romagna)*	*High-sensitivity detection of acetaldehyde.* [2012, Sensors and Actuators B, 174:402-405]	Nano-based	Set of nanostructured single and mixed metal oxides, including ZnO, SnO, TiO, and W_3O-SnO type. Created on alumina plates with gold contacts as a heater	Acetalde-hyde	0.1-10 ppm LDL: 10 ppb (0.010 ppm)		2 mm x 2 mm, 20-30µm thick		Sensors were tested in both dry and wet air at various temperatures to determine optimal operating conditions. Optimal range was 450-500ºC for all sensors, with ZnO performing the best. Wet air was reported to negatively affect reactions between acetaldehyde and sensing material. Sensors consume 0.6-1.0 W at working temperature and have the potential to be operated by grid connection or alkaline batteries. Each unit was tested 3 times and was reported to have good reproducibility.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
2	National Institute of Advanced Industrial Science and Technology (Japan) *Itoh, T., Matsubara, I., Shin, W., Izu, N., Nishibori, M.* *(Funding: New Energy and Industrial Technology Development Organization)*	*Preparation of layered organic-inorganic nanohybrid thin films of molybdenum trioxide with polyaniline derivations for aldehyde gases sensors of several tens ppb level.* [2008, Sensors and Actuators B, 128:512-520]	Polymer film, hybrid	MoO_3 with PANi and MoO_3 with PoANIS (poly(o-anisidine) thin film organic-inorganic hybrid on $LaAlO_3/SiO_2/Si$ substrate with gold comb-type electrodes	Acetalde-hyde, formalde-hyde	LDL: 25-400 ppb, (0.025-0.4 ppm Up to 7 ppm (acetalde-hyde)		~1 cm		Study aim is to create a sensing film appropriate for applications to ventilation systems in buildings that can detect at ppb level (instead of ppm). (PANi) MoO_3 film was reported to have the strongest response to formaldehyde, while (PoANIS)MoO_3 showed equal response to both. Baseline drift due to difficulties of gas desorption remained a problem, especially with acetaldehyde; the authors aim to address this limitation in future research.
3	University of Tehran (Iran) *Ahmadnia-Feyzabad, S., Khodadadi, A.A., Vesali-Naseh, M., Mortazavi, Y.*	*Highly sensitive and selective sensors to volatile organic compounds using MWCNTs/SnO2* [2012, Sensors and Actuators B, 166-167:150-155]	Nano-based	0.05 wt% and 0.10 wt% MWCNTs on SnO_2, screen printed on the surface of alumina substrate with gold electrodes	Acetalde-hyde, acetone, ethanol, toluene, TCE	All tested at 300 ppm, acetalde-hyde also tested: 0.2-5 ppm				Gases were tested over a range of temperatures at 300 ppm. Optimal response for acetaldehyde was reported to be at 200ºC. The addition of MWCNTs increased sensor selectivity by 2.4 times for acetaldehyde with significant responses to sub-ppm concentrations.
4	Chonbuk National University (South Korea) *Rai, P., Yu, Y.-T.* *(Funding: Post-BK21 Program Ministry of Education and Human-Resource Development and the National Research Foundation)*	*Citrate-assisted hydrothermal synthesis of single crystalline ZnO nanoparticles for gas sensor applications* [2012, Sensors and Actuators B, 173:58-65]	Nano-based	ZnO nanoparticles synthesized via hydrothermal method	Acetalde-hyde, CO, NO_2, ethanol	Tested ranges: CO: 10-1000 ppm ethanol and acetaldehyde 25-250 ppm NO_2: 5-100 ppm				Gases were tested over a range of temperatures (27-250ºC) and concentrations. The maximum response for acetaldehyde was recorded at 250 ppm and 400ºC. Response decreased with decreasing temperature. Recovery time for ethanol and acetaldehyde was poor when compared to that of CO.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Detection Technique: Spectroscopy										
5 np	Institute of Environmental Pollution and Health, School of Environmental and Chemical Engineering, University Shanghai *Huang, J, Feng, Y L, Xiong, B, Fu, J.M., Sheng, G.Y.*	*Ambient levels of carbonyl compounds in Shanghai, China* [2009] http://www.ncbi.nlm.nih.gov/pbumed/19927828	High-performance liquid chromatography (HPLC)-UV		Formaldehyde, acetaldehyde, acetone, 2-butanone				(Multisensor system)	HPLC-UV was used to separate acrolein from acetone
6 np	National Research Council of Canada, Institute for Research in Construction (Canada) *Deore, B., Diaz-Quijada, A., Wayner, D. D.M., Stewart, D., Won, D.Y., Waldron, P.* *(Funding: NRC of Canada, ICT sector)*	*An electronic nose for the detection of carbonyl species* [2011, ECS Transactions, 35(7):83-88] http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc54483.pdf	Luminescence, polymer	Solution casting polymer (polyaniline and polypyrrole derivatives) at a given doping level on a glass substrate with or without four Au lines (electrodes) with respective pads to align with commercial probe head)	Formaldehyde; also tested acetaldehyde	250 ppb formaldehyde at 44% relative humidity ("real world" conditions)	5-60 sec		Not indicated (Mountable)	Polyaniline and polypyrrole derivatives interact with a carbonyl group to produce measureable changes in resistivity, which can be used for e-nose (electronic nose) sensing of carbonyls (reaction between carbonyl and nitrogen spurs molecular recognition).
7 np	Science and Engineering services Inc., *Prasad, C.R., Lei, J.* Mass Tech Inc. *Shi, W., Li, G.* Pranalytica Inc. *Dunayevskiy, I., Patel, C.K.N.*	*Laser photoacoustic sensor for air toxicity measurements* [2012, Advanced Environmental, Chemical, and Biological Sensing Technologies IX, Society of Photoelectric engineers] http://proceedings.spiedigitallibrary.org/mobile/proceeding.aspx?articleid=1353801	Spectroscopy, laser	Laser photoacoustic spectroscopy (LPAS) sensor, broadband measurement with one or more tunable laser sources, infrared (IR) QCL, external cavity grating tuner	HAPS (benzene, formaldehyde, acetaldehyde) simultaneously	A few ppb	3 min		Not indicated	This technology is reported as being capable of simultaneously measuring several HAPs (per preliminary spectral pattern recognition algorithm).

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8 np	*Yong-Hui, L., Xiao-An, C., Fu-Gao, C., et al.*	*A gaseous acrolein sensor based on cataluminescence using ZrO_2/MgO composite* [2011, Chinese Journal of Analytical Chemistry, 39(8):1213-1217]	Catalumi-nescence (CTL), nano-com-posite	Nanosized ZrO_2/MgO composite	Acrolein Also tested: acetalde-hyde, methanol, benzene, toluene, dimethyl-benzene	Indicated limit: 1.65 mL/m^3				Optimal temperature was reported to be 269ºC. Optimal gas flow was found to be 200 mL/min. Optimal wave length was reported to be 425 nm.
Reference Commercial Sensor										
9C	Teledyne Technologies	http://www.teledyne-ai.com/products/4060.asp	Gas chromato graph-flame ionization detector (GC-FID)	*(4060/FID)*	Acetalde-hyde	Indicated limit (per vendor input): 10 ppb				Real time data including chromatograms which can be superimposed to verify repeatability. Gas chromatography allows sensing of single or multiple components from an air stream which may include interferents.
Acrolein										
Detection Technique: Spectroscopy										
1a 1b	University of Alberta, Edmonton (Canada). Department of Chemistry, Department of Electrical and Computer Engineering *Manne, J., Lim, A., Tulip, J., Jager, W.* *(Funding: Canada Foundation for Innovation, Natural sciences and Engineering Research Council of Canada, and an Alberta Ingenuity Postdoctoral Fellowship)*	*Sensitive detection of acrolein and acrylonitrile with a pulsed quantum cascade laser* [2011, Applied Physics B., 107: 441-447] http://www.springerlink.com/content/tk0w6v2k3v3t0208/fulltext.pdf	QCL, inter- and intra-pulsed, spectros-copy	Inter-pulse: 5-10 ns, 2.3 cm^{-1} frequency scan Intra-pulse: up to 500 ns, 2.2 cm^{-1} spectral window; multipass Herriot cell configuration with a 250-m path length	Acrolein, acrylo-nitrile	Inter-pulsed: acrolein limit: 3 ppb; intra-pulsed: acrolein limit: 6 ppb	~10 sec		(Fixed/semi-portable unit)	Uses a pulsed, distributed feedback QCL to detect acrolein. Using a room-temperature mercury-cadmium-telluride detector resulted in a cryogen-free spectrometer.

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2 np	*Yong-Hui, L., Xiao-An, C., Fu-Gao, C., et al.*	*A gaseous acrolein sensor based on cataluminescence using ZrO_2/MgO composite* [2011, Chinese Journal of Analytical Chemistry, 39(8):1213-1217]	Lumines-cence	Nanosized ZrO_2/MgO composite	Acrolein and others	Indicated limit: 1.65 mL/m^3				Optimal temperature was reported to be 269ºC. Optimal gas flow was reported to be 200 mL/min. Optimal wave length was reported to be 425 nm.
Reference Commercial Sensor										
C3	Industrial Monitor and Control Corporation	http://www.ftirs.com/ProductsServices/ExtractiveMonitoring.aspx	Extractive Fourier transform (FT) IR cell	100 meter cell	Acrolein and others	Acrolein: limit: 7 ppb		100 m (towed behind trailer)	(Fixed/semi-portable unit)	Cells can be heated to >200ºC; intended for industrial monitoring and process control; may be customized per consumer needs.
Ammonia										
Detection Technique: Chemistry										
1	Chinese Academy of Sciences *Meng, F.-L., Huang, Z.-J., and colleagues, also at Anhui Polytechnic University* *(Funding: One Hundred Person Project of the Academy, National Natural Science Foundation of China, and others)*	*Electronic chip based on self-oriented carbon nanotube microelectrode array to enhance the sensitivity of indoor air pollutants capacitive detection* [2011, Sensors and Actuators B, 153:103-109] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S092540051000818X&_check=y&_origin=search&_zone=rslt_list_item&_coverDate=2011-03-31&wchp=dGLzVBA-zSkzV&md5=ff0be4989bfbde8f28e9d5daeb7bfae9/1-s2.0-S092540051000818X-main.pdf	Nano-based	Compares nanotube-based electronic chip (Si dielectric medium, Au and Si electrodes) with self-oriented MWCNTs microelectrode array	Formalde-hyde ammonia toluene	Ammonia: 3.1 ppm	<10 sec	Very small	Not indicated (Mountable)	Response time is limited by the time it takes to load and remove analyte from the chip. Liquid samples placed in sample chamber, nitrogen used as carrier gas to flow through the chamber.
2	Georgia Tech (GT) University *Tentzeris, M.* *Naishadham, K.* *(Funding: NSF)*	http://www.gtri.gatech.edu/casestudy/paper-based-wireless-sensors; http://www.gtri.gatech.edu/casestudy/polymer-coated-optical-sensor-explosives-detection	Nano-particle	Sonicated ink containing functionalized CNTs with silver (Ag) nanoparticles in emulsion on paper via inkjet printer	NH_3 (for trace explo-sives, chemical is attracted to polymer coating)	Indicated limit: 5 ppm		Compact	(Mountable)	Can potentially be used to detect explosives at distance. Wireless sensor nodes need relatively little power; could use thin-film batteries, solar cells or power-scavenging and energy-harvesting techniques; GT Research Institute is investigating passive operation with no power consumption.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
3	Hanyang University, (South Korea) *Nguyen, T.-A.; Kim, Y. S.; and others, including at Pusan National University*	*Polycrystalline tungsten oxide nanofibers for gas-sensing applications* [Aug. 2011, Sensors and Actuators B 160:39-45] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511007519&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=220df24b26528d3d69cd1fb06c53dc98/1-s2.0-S0925400511007519-main.pdf	Nano-particle	WO_3 nanofibers (40-nm diameter) Si wafer stuck to Al foil with pair of comb-shaped (interdigitated) Au electrodes formed on SiO_2/Si substrate, sensing area is 3 x 10 mm^2 with electrode gap of 300 µm	NH_3	Indicated limit: 10 ppm	>1 hr	Stick of gum	Not indicated	Study analyzed the practicality of electrospun tungsten oxide nanofibers for NH_3 detection. It was reported that the optimal operating temperature for this device is 300ºC because at this temperature the response times are at their lowest and sensing is most accurate.
4	Solapur University, Materials Research Laboratory (India) Bhabha Atomic Research Centre (India) *Pawar, S.G., Chougule, M.A., Patil, V.B.*	*Development of nanostructured polyaniline-titanium dioxide gas sensors for ammonia recognition* [2012, Journal of Applied Polymer Science, 125(2): 1418-1424], http://onlinelibrary.wiley.com/doi/10.1002/app.35468/fullpdf	Polymer film, hybrid	Nanostructured 0-50% PANi-TiO_2 (fabricated by spin coating technique) thin film deposited on glass substrate (1 mm wide strips)	NH_3, ethanol, methanol. NO_2, H_2S	NH_3: 20 ppm and 100 ppm tested Others tested at 100 ppm	72 sec at 20 ppm NH_3; 41 sec at 100 ppm NH_3		(Fixed/semi-portable unit)	No response at room temperature for 20 ppm NH_3 using TiO_2 nanoparticles alone; needed to be operated at 200º C. Pure PANi composite showed little response, while the PANi-TiO_2 composite was the most responsive at room temperature. Response time decreased as NH_3 concentration increased, but so did recovery time (possibly per lower desorption rate).
5	Shinwoo Electronics Co., Ltd. *Kim, I.* Korea University (S. Korea) *Dong, K.Y., Ju, B.K.* Yonsei University (S. Korea) *Choi, H.H.*	*Gas sensor for CO and NH_3 using polyaniline/CNTs composite at room temperature* [2010, IEEE, International Conference on Nanotechnology Joint Symposium with Nano Korea] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5697782&isnumber=5697724	Polymer film	PANi/SWCNTs film dispersed in sodium dodecyl sulfate and applied over Ti/Au electrodes of an IDE by photolithography	CO, NH_3 (also benzene and NO_2)	ppm level (CO tested at 80 ppm, NH_3 at 35 ppm)	Fast re-sponse and recov-ery	5 mm x 17 mm, 480 µm thick		Demonstrates the use of PANi/SWNTs composite-based sensor for mixed gas detection. The changes in resistance of the sensor determine the presence of a single gas or mixture of gases. This composite has a large surface-to-volume ratio which makes it a good candidate for new gas sensors.
6	The Hong Kong University of Science and Technology (China), *He, J., Zhang, T-Y., Chen, G.*	*Ammonia gas-sensing characteristics of fluorescence-based poly(2-(acetoacetoxy)-ethyl methacrylate) thin films* [2012, Journal of Colloid and Interface Science, 373: 94-101]	Organic polymer film (also spectros-copy: fluores-cence)	PAAEMA latex thin films cast onto quartz discs; UV-Vis spectra emitted (275 nm)	NH_3	Tested range: 54-540 ppm	80 sec at 54 ppm <30 sec at 540 ppm			Response time increases as concentration of NH_3 decreases. Operates at room temperature.

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7 np	University of South Carolina, *Nomani, Md.W.K., et al.* SENS4, LLC *James, J.* *(Funding: NSF, Army Research Office, and SENS4, LLC [through an NSF grant])*	*Highly sensitive and multidimensional detection of NO_2 using InO_3 thin films* [Aug. 2011, Sensors and Actuators B, 160:251-259] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511006861&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=a9efb7781a0624784753f0979694f695/1-s2.0-S0925400511006861-main.pdf	MOS	Interdigitated metal fingers, 100 µm, a part of Ti (5 nm)/ Au (50 nm) deposited on In_2O_3 thin film (from Thinfilms Inc.) coated on Al_2O_3 ceramic substrate	NO_2; also assessed: mixture of NO_2, NH_3		A few sec		(Mountable)	20% reduction in conductivity at 20 ppb, normal temperature (20ºC); in a vacuum, In_2O_3 nanowires indicated sensitivity of 5 ppb; per an average ambient/ background level of 11 ppb, the concentration differential of 9 ppb is identified as responsible for the conduction change (indicating even more impressive sensitivity to the authors); the system can monitor minute deviations from the general average background value (30–50 mV) at a frequency of 1 kHz, at an operating temperature of >150ºC.
8 np	University of Bayreuth *Schönauer, D.; Sichert, I., Moos, R.*	*Vanadia doped-titania SCR catalysts as functional materials for exhaust gas sensor applications* [2011, Sensors and Actuators B, 155:199-205] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400510009159&_check=y&_origin=search&_zone=rslt_list_item&_coverDate=2011-07-05&wchp=dGLbVlV-zSkzS&md5=5e39e5ec94296bcd2c2177384bd57895/1-s2.0-S0925400510009159-main.pdf	MOS	Selective catalytic reduction catalyst; materials are based on vanadia-doped tungsten-titania gas sensing films	NH_3 (tested with gas containing NO_X)			Small	Not indicated (Mountable)	Reported to provide accurate results for ammonia detection around 500°C. NO_2 sensitivity is ~17%; in the presence of CO and H_2, 8% sensitivity; when water concentration increases from 0-3%, 3% sensitivity
9 np	Brno University of Technology (Czech Republic) *Hrdy, R., Vorozhtsova, M., Drbohlavova, J., Prasek, J., Hubalek, J. (Funding: Czech Ministry of Education and Grand Agency of Czech Republic)*	*Electrochemical transducer utilizing nanowires surface* [2010, IEEE, 33rd Int. Spring Seminar on Electronics Technology] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5547340&isnumber=5547245	Nano-based	TiO_2 modified Au nanowires applied to surface of sensing electrode	CO_2, NO_2, O_2, NH_3				(Mountable)	Operated at 5–30 keV in high vacuum mode with an operating temperature range between 300 and 400ºC.

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10 np	Linkoping University *Pearce, R., Soderlind, F., Hagelin, A., Kall, P.O., Yakimova, R., Spetz, A.L.* Chalmers University of Technology *Becker, E., Skoglundh, M.*	*Effect of water vapour on gallium doped zinc oxide nanoparticle sensor gas response* [2009, IEEE Sensors, Conference] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5398276&isnumber=5398121	Nano-based	Gallium (Ga)-doped ZnO nanoparticle sensor, resistor type	O_2, NO, NO_2, H_2, CO, NH_3			~10 mm (per image)		Investigated effects of background water vapor and oxygen on the response of nanoparticle Ga-doped ZnO resistive sensors in high temperature applications to detect O_2, NO, NO_2, H_2, CO, and NH_3. The presence of water vapor increased the response and recovery rates and improved baseline stability. Responsiveness was reported to decrease in humid environments as the gas concentration increased, thought to be caused by competing reaction mechanisms. These mechanisms require more studies using DRIFT spectroscopy to determine surface species. Operates at 500ºC.
Detection Technique: Spectroscopy										
11	University of Limerick (Ireland) *O'Keeffe, S., Manap, H., Dooly, G., Lewis, E.*	*Real-time monitoring of agricultural ammonia emissions based on optical fibre sensing technology* [2010, IEEE Sensors Conference] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5690821	UV absorp-tion	2 ultraviolet nonsolarizing (UVNS) optical fibers (644 nm), 60-cm stainless steel gas cell, HR2000 spectrometer (Ocean Optics)	NH_3	Indicated range: 1-50 ppm	4 sec		(Fixed/semi-portable unit)	This system is used in confined areas to determine the amount of ammonia in the space with real-time measurements by using an optical fiber sensor system that detects in the UV absorption region.
12	University of Limerick (Ireland) *Manap, H., Dooly, G., Muda, R., O'Keeffe, S., Lewis, E.* *(Funding: Higher Education Authority, PRTLI cycle 4 for Environmental and Climate change, University of Malaysia, Ministry of Higher Education)*	*Cross sensitivity study for ammonia detection in ultra violet region using an optical fibre sensor* [2009, Third International Conference on Sensor Technologies and Applications] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5210951&isnumber=5210828	UV absorp-tion	200-230 nm UV range	NH_3	Indicated limit: 7 ppm (estimated)	<3 sec		(Fixed/semi-portable unit)	Investigates the use of UV light sources to detect NH_3 in an optical fiber sensor. Using UV as a light source reduces sensor sensitivity to other gases (namely water vapor) in the ambient air. A computer using SpectraSuite software enables acquisition of spectrometer data in real time. Future studies on this technique plan to include finding the lowest concentration detectable by the sensor and the integration of a commercial NH_3 sensor for more accurate concentration verification.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
13 np	Utah State University, University of Iowa; (Iowa); Space Dynamics Laboratory (SDL) (Utah) *Hipps, L., Silva, P., (UT State); Zavyalov, V.V., Wllkerson, T., Bingham, G.E. (SDL), others* *(Funding: USDA)*	http://www.sdl.usu.edu/programs/aglite; http://www.ars.usda.gov/is/AR/archive/aug06/ames0806.pdf	LIDAR	Scanning 3-color LIDAR FTIR *(Aglite)*	PM and gases, including NH_3, H_2S, NO_x			Large suitcase	(Remote sensing)	Has been used to monitor an entire CAFO facility (e.g., swine finishing) and other sources, including multiple diffuse source dairy, cotton gin, and almond harvesting. The goal is to measure amount of CO_2, CH_4, N_2O, and other greenhouse gases released from soil into the atmosphere and determine how different crop- and soil-management methods affect these exchanges.
Reference Commercial Sensor										
C 14	Teledyne Technologies	http://www.teledyne-ai.com/pdf/lga-4000.pdf	Laser absorp-tion, TDLAS	Transmitter: diode laser, laser driver, HMI modules, realizing diode laser driving, spectrum data processing; receiver: photo-electric sensor, signal processing and purge control modules *(Process LaserGas Analysis System, Model LGA-4000)*	O_2, CO, CO_2, water, H_2S, HF, HCl, HCN, NH_3, CH_4, C_2H_2, C_2H_4	NH_3: Indicated limit: 0.4 ppm Indicated range: 0-40 ppm (other pollutant info provided via link)	<1 sec		RS485/GPRS/ Bluetooth digital interface (Fixed/semi-portable unit)	Useful in almost any environment, including high temperatures, pressures, dust densities, and corrosion; requires a 24 volts direct current (VDC) (220 VAC optional, <20 W), as well as 0.3-0.8 MPa, 99.99% N_2 purging gas; is operable between -30 and 60ºC (ambient temp); calibration and maintenance recommended <twice yearly depending on application. No cross interference reported from other gas species, dust or gas parameter fluctuations. Real-time, in-situ and continuous measurement options.
Benzene										
Detection Technique: Chemistry										
1	National Institute of Standards and Technology and others *Aluri, G.S., Motayed, A., Davydov, A.V., Oleshko, V.P., et al.* *(Funding: NSF, NIST)*	*Highly selective GaN-nanowire/TiO_2-nanocluster hybrid sensors for detection of benzene and related environment pollutants* [2011, Nanotechnology, 22(29)] http://iopscience.iop.org/0957-4484/22/29/295503/pdf/0957-4484_22_29_295503.pdf	Nano-particles	Hybrid chemical sensors with functionalized gallium nitride (GaN nanowires with TiO_2 nanoclusters; UV-induced sensing	Benzene, related aromatics	Benzene: Indicated limit: 50 ppb	~60 sec for ppm levels, ~180 sec for ppb levels			UV-induced room-temperature sensing allows for low-power operation, longer lifetime, and fast on/off capabilities Hybrid sensor technology for standard microfabrication techniques. A devised mechanism that could qualitatively explain the observed sensing behavior. Operates at temperatures greater than 150ºC.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
2	University of Illinois at Urbana-Champaign *Hengwei, L., Jang, M., Suslick., K.S.* *(Funding: NIH Genes, Environment, and Health Initiative)*	*Preoxidation for colorimetric sensor array detection of VOCs* [2011, JACS, 133:16786-16789] http://www.scs.illinois.edu/suslick/documents/jacs.2011.preox.pdf	Pre-oxidation	Vapor stream passes through chromic acid and silica-coated pre-oxidation tube before colorimetric array	Phenol and others, including benzene; 20 VOCs	Benzene: 0.20 ppm within 1.4% of OSHA PEL		Benchtop	(Fixed/semi-portable unit)	Optimum response was reported using a disposable 2-cm by 3-mm i.d. Teflon tubing with 30 mg of chromic acid on silica. The pre-oxidation agent must be newly prepared for each testing cycle. VOC vapors were produced by bubbling nitrogen through the pure compound. Color changes of the array are concentration-dependent and provide semi-quantitative analysis; changes in relative humidity were not reported to generally affect the response even at low analyte concentrations.
3	Duke University *Yang, C.-H.*	*Development of nanosensor to detect mercury and volatile organic vapors* [July 2010, thesis] http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/3060/D_Yang_Chang%20Heng_a_2010.pdf?sequence=1	Nano-based (various)	Nanosensor with SnO_2, Au and polypyrrole (PPy) on SWCNTs	Hg, VOCs: benzene, methyl ethyl ketone (MEK), hexane, xylene	Indicated as ppb; benzene: sensitivity -2% in 13-65 ppm range				Fast and sensitive for individual chemicals, but not found in this study to be successful for mixtures.
4	Chinese Academy of Sciences *Y. Wan, H. Li, J. Liu, F. Meng, Z. Jin, L. Kong, and J. Liu* *(Funding: "973" State Key Project of Fundamental Research for Nano science and Nanotechnology, the National Natural Science Foundation of China, and others)*	*Sensitive detection of indoor air contaminants using a novel gas sensor based on coral-shaped tin dioxide nanostructures* [2012, Sensors and Actuators, 165:24-33] http://ac.els-cdn.com/S092540051200106 2/1-s2.0-S0925400512001062-main.pdf?_tid=601aeea1c25ade4743a4b104952fcec2&acdnat=1339604316_9f65193ca1a171af77fb721afc87e2dc	Nano-based	Coral-shaped SnO_2 nanostructures, prepared by hydrothermal/ annealing processes coated on Al_2O_3 tubes, Ni-Cr heater wire	Benzene, formal-dehyde, toluene and acetone	Benzene: tested range: 50-150 ppm				Real-time gas sensing used to detect contaminants in indoor air; coral-shaped receptacles gave faster results. Response to gases is increased when particle size is reduced. Operates between 350 and 400°C.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
5	University of Bahkesir, Department of Physics and the Department of Chemistry (Turkey) *Acikbas, Y., Capan, R., Erdogan, M., Yukruk, F.*	*Thin film characterization and vapor sensing properties of a novel perylenediimide material* [2011, Sensors and Actuators B, 160(1):65-71] http://ac.els-cdn.com/S092540051100651/1-s2.0-S0925400511006551-main.pdf?_tid=2d70fc366b81a28413614e0ef142fb98&acdnat=1338392430_f688fab1cb35779ecbff302d5582f45f	Polymer thin film	LB thin film-based, N,N'-(glycine t-butylester)-3,4,9,10-perylendediimide) thin film deposition, QCM, Au electrodes	Chloro-form, benzene, toluene, ethyl alcohol and isopropyl alcohol	Chloroform: Indicated limit: 15,300 ppm; benzene: Indicated limit: 17,100 ppm; toluene: Indicated limit: 18,600 ppm	3 sec re-sponse, 4 sec recov-ery		(Mountable)	Requires a 4-sec recovery period. Absorbance was measured over many Langmuir–Blodgett (LB) thin films. Operates at room temperature.
6 np	Dalian University of Technology (China) *Wang, J.; Wu, W.; and colleagues (Chen, X.R., Yao, P.J., Ji, M., Qi, J.Q.)* *(Funding: National Natural Science Foundation of China)*	*Detection of indoor formaldehyde concentration using $LaSrFeO_3$-doped SnO_2 gas sensor* [2010, Key Engineering Materials, 437:349-353] http://www.ets.ifmo.ru:8101/tomasov/konferenc/AutoPlay/Docs/Volume%203/6_51.pdf	MOS	MOS SnO_2 (2 wt % doped with La-Sr-FeO_3 as ceramic tube coating, electrodes and sensors then affixed	Formalde-hyde (also tested: ethanol, methanol, and benzene)		120 sec	Very small	Not indicated (Mountable)	Evaluated with N vapor in testing chamber. Highest response occurred when the sensor reached a temperature of 370ºC. The response of this sensor to alcoholate gases was higher than the response to formaldehyde and will be improved by integrating sensor arrays and neural networks. For the described experiment the sensors were aged at 5V for 240 hr and operate at 370ºC.
7 np	Shinwoo Electronics Co., Ltd. *Kim, I.* Korea University (S. Korea) *Dong, K.Y., Ju, B.K.* Yonsei University (S. Korea) *Choi, H.H.*	*Gas sensor for CO and NH_3 using polyaniline/CNTs composite at room temperature* [2010, IEEE, International Conference on Nanotechnology Joint Symposium with Nano Korea] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5697782&isnumber=5697724	Polymer film	PANi/SWCNTs film dispersed in sodium dodecyl sulfate and applied over Ti/Au electrodes of an IDE by photolithography	CO, NH_3 (also benzene and NO_2)		Fast re-sponse and recov-ery	5 mm x 17 mm, 480 µm thick		This research demonstrates the use of PANi/SWNTs composite-based sensor for mixed gas detection. The changes in resistance of the sensor determine the presence of a single gas or mixture of gases. This composite has a large surface-to-volume ratio which makes it a good candidate for new gas sensors.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Detection Technique: Spectroscopy										
8	NIT Microsystem Integration lab, Microsensor Research Group (Japan) *Camou, S., Horiuchi, T., Haga, T.*	*Ppb level benzene gas detection by portable BTX sensor based on integrated hollow fiber detection cell* [2006, IEEE Sensors] http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04178603	UV-vis absorp-tion	SBA16 mesoporous silica as pre-concentrator, two pumping systems, Al-coated hollow fiber inside glass cell, with optical fibers	Benzene, BTX (benzene, toluene, xylene)	Benzene: Indicated limit: 1 ppb (concentra-tion range tested: 0-10 ppb)	~20 min (until precon-centra-tor satura-tion)	Portable		Benzene is diluted in nitrogen carrier gas. Originally tested for indoor usage so the benzene could be isolated. It is not known if it will work with other ambient particles in the air.
9	University of Aveiro (Portugal) and ISEIT/Viseu-Instituto Piaget, Estrada do Alto do Gaio (Portugal) *Silva, L.I.B., Rocha-Santos, T.A.P., Duarte, A.C.* *(Funding: FCT [Portugal] for project, and Ph.D. grant)*	*Remote optical fibre microsensor for monitoring BTEX in confined industrial atmospheres* [2009, Talanta, 78(2):548-552] http://ac.els-cdn.com/S0039914008008886/1-s2.0-S0039914008008886-main.pdf?_tid=123fc547c2b1754bf3971075f3d0ba6e&acdnat=1337968655_7377646dee760377c14ed17841fa094b	Laser absorp-tion (optical fiber)	Monomode optical fiber coated with nanometric poly[methyl(3,3,3-trifluoropropyl)siloxane] (PMTFPS) polymer film	Benzene, BTEX (benzene, toluene, ethylben-zene, xylene)	Indicated limit: 0.00235 ppm	A few sec per sub-stance; 9 min total for all	Portable, compact	(Handheld)	Applied to air monitoring in a confined industrial environment at 150ºC. Allows for *in situ* and real-time remote (60-m maximum) monitoring. Performance compared to that of a GC-FID device.
10	Georgia Institute of Technology *Young, C.R., Menegazzo, N., et al.* from Exxon Mobile and the University of Ulm (Germany) *(Funding/support: Exxon Mobil and Engineering Company, Exxon Mobil Biomedical Sciences, Inc.)*	*Infrared hollow waveguide sensors for simultaneous gas phase detection of benzene, toluene, and xylenes in field environments* [2011, Anal. Chem., 83:6141-6147] http://pubs.acs.org/doi/pdfplus/10.1021/ac1031034	Thermal desorp-tion (TD)-FTIR-hollow wave-guide (HWG)	TD as a pre-concentration step, HWG to propagate mid-infrared (MIR) radiation from light source and serves as a miniaturized cell.	BTX	Indicated limit: 5 ppb	~43 sec		(Fixed/semi-portable unit)	Direct and selective real-time detection of BTX using thermal desorption. Results validated by GC-FID and compared to commercially available prototypes.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
11 np	Arizona State University *Tsow, F., Forzani, E., Rai, A., Wang, R., and others* *(Funding: NIH/NCI, Motorola, Arizona State University)*	*A wearable & wireless sensor system for real-time monitoring of toxic environmental volatile organic compounds* [2009, IEEE Sensors Journal, 9(12):1734-1740] http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5291983	Laser absorp-tion (tuning fork)	Array of polymer-modified quartz crystal tuning fork, custom built filter, frequency change detection circuit	VOCs, BTEX	"Beyond OSHA's requirement for benzene"		Cell phone	Bluetooth technology, wireless, graphic user interface software with Visual Studio (Microsoft) in cell phone (Wearable)	Uses sensor cartridge, sample delivery and conditioning components, electronic circuits for signal processing, and wireless communication chip; allows for upgrades and easy disposal of old tuning forks. Studies were performed to demonstrate capabilities with interfering chemicals such as perfume and a BTEX gas mixture; 5-minute exposure cycles require 10- to 15-minute purging periods.
12 np	*Yong-Hui, L., Xiao-An, C., Fu-Gao, C., et al.*	*A gaseous acrolein sensor based on cataluminescence using ZrO_2/MgO composite* [2011, Chinese Journal of Analytical Chemistry, 39(8):1213-1217]	Cata-lumines-cence	Nanosized ZrO_2/MgO composite	Acrolein Also tested: acetalde-hyde, methanol, benzene, toluene, dimethyl-benzene					Optimal temperature was reported to be 269ºC. Optimal gas flow was reported to be 200 mL/min. Optimal wave length was reported to be 425 nm.
Novel Sensor Systems Using Commercial Sensors										
c 13	Gdansk University of Technology, with ARMAAG Foundation (Poland) *Kaulski, R., et. al* *(Funding: Environmental Protection and Water Management Fund of Gdansk Province)*	*Mobile system for on-road measurements of air pollutants* [2010, AIP Review of Scientific Instruments, 81(4)] http://rsi.aip.org/resource/1/rsinak/v81/i4/p045104_s1?view=fulltext	MOS (by Figaro)	SnO_2 MOS with ceramic base in ARPOL system	Benzene, NO_2, NO_x, CO, CO_2	Benzene: Indicated limit: 0.0125 ppb		Mobile	Uploads to webpage (Vehicle-mounted unit)	Results collected over several 24-hour cycle test periods.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology: Type	Sensor Technology: Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
c 14	Universitat Rovira I Virgili (Spain), Universite de Franche Comte (France), Universite de Lorraine Lahlou (France), and the Gas Sensors Group with the National Centre of Microelectronics (Spain) *Lahlou, H., Sanchez, J.B., Mohsen, Y., Vilanova, X., et. Al*	*A planar micro-concentrator/injector for low power consumption microchromatographic analysis of benzene and 1,3-butadiene* [2012, Microsyst Technol,18: 489-495] *Towards a GC-based microsystem for benzene and 1,3-butadiene detection: Pre-concentration characterization* [2011, Sensors and Actuators B, 156: 680-688]	GC, pre-concen-trator	Commercial sensor with low power consumption GC microsystem	Benzene, 1,3-butadiene	Benzene Indicated limit: 0.1 ppm; 1,3-butadiene Indicated limit: 0.5 ppm; tested range: 2-10 ppm				This pre-concentrator was tested in the presence of benzene and 1,3-butadiene concentrations normally too low for the commercial sensor to detect. 1.02 mW/ºC power consumption level. Operates at 25ºC.
Reference Commercial Sensors										
C 15	Synspec	http://www.synspec.nl/pdf/GC955-600_Bu_Be.pdf	Photoio-nization detector (PID), GC	*(GC 955-603 Benzene and 1,3-butadiene sensor)*	Benzene and 1,3-butadiene	Benzene indicated range: 9.4 ppb to 0.3 ppm	15-min cycle time		(F/S-PSU)	Meant for ambient air sensing with a 15-minute cycle time (220 VAC, 100 volt-amperes (VA); 110 VAC available).
C 16	Synspec	http://www.synspec.nl/pdf/GC955-600_BTX.pdf	PID, GC	*(GC 955-601 Benzene/BTEX analyzer)*	Benzene, BTEX	Indicated range: 0.032 ppb to 0.3 ppm	15-min cycle time		(Fixed/semi-portable unit)	Meant for ambient air sensing with a 15-minute cycle time (230 VAC, 100 VA; 115 VAC available).
1,3-Butadiene										
Detection Technique: Electrochemistry										
1a 1b	University of Michigan, Ann Arbor *Rowe, M.P., Steinecker, W.H., Zellers, E.T.*	*Exploiting charge-transfer complexation for selective measurement of gas-phase olefins with nanoparticle-coated chemiresistors* [2007, Analytical Chemistry, 79: 1164-1172] http://pubs.acs.org/doi/pdfplusfull/10.1021/ac061305k	Nano-based, chemo-resistor, polymer, UV-vis	Charge-transfer mediated olefin selective sensing system with chemiresistors coated in composite films of C8-MPN and $PtCl_2$ complexes.	Ethane, ethylene, n-butane, 1,3-butadiene, ethyl-benzene, styrene, n-octane, 1-octene	a. C8-PBP : Indicated limit 9.5 ppb b. C8-MPN: Indicated limit 24,000 ppb	5 min expo-sure period		IMACC Software Suite includes FTIR control and data server, scripting engine and editor, quanti-zation method development tools, configurable FTIR monitor UI, and a synthetic to background tool.	5-minute exposure period is mentioned (see article for more detection capabilities) Additional modules are available to integrate data and alarms to external systems.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology: Type	Sensor Technology: Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Novel Sensor Systems Using Commercial Sensors										
c2	Universitat Rovira I Virgili (Spain), Universite de Franche Comte (France), Universite de Lorraine Lahlou (France), and the Gas Sensors Group with the National Centre of Microelectronics (Spain) *H., Sanchez, J.B., Mohsen, Y., Vilanova, X., Berger, F., et. al.*	*A planar micro-concentrator/injector for low power consumption microchromatographic analysis of benzene and 1,3-butadiene* [2012, Microsyst Technol,18: 489-495] *Towards a GC-based microsystem for benzene and 1,3-butadiene detection: Pre-concentration characterization* [2011, Sensors and Actuators B, 156: 680-688] http://www.springerlink.com/content/428336485jlm3822/fulltext.pdf	Com-mercial sensor, GC micro-system	Planar micro-concentrator/ injector	Benzene, 1,3-butadiene	Benzene: Indicated limit: 0.1 ppm; 1,3-butadiene Indicated limit: 0.5 ppm; tested: 2.5-10 ppm				This pre-concentrator was tested in the presence of benzene and 1,3-butadiene concentrations normally too low for the commercial sensor to detect; requires low amounts of power. 1.02 mW/°C power consumption level. Operates at 400°C.
Reference Commercial Sensors										
C3	Synspec	http://www.synspec.nl/pdf/GC955-600-800_POCP.pdf	FID, PID	*(GC 955-811 Ozone Precursors Fraction C2-C5)*	1,3-butadiene and others	1,3-butadiene: Indicated range: 1-300 ppb	Semi-con-tinuous 30-min cycle		Chromatograms are stored on PC hard disk and can be transferred by network and modem connection. Output options are available for communication with other data logging systems. (Fixed/semi-portable unit)	This sensor can be used to analyze hydrocarbons emitted by traffic as well as those in industrial or household processes. Hydrocarbons are concentrated on a cooled trap, allowing low detection levels, and the PID detects unsaturated compounds while the FID detects saturated compounds (220 VAC, 200 VA; 110 VAC available).
C4	Synspec	http://www.synspec.nl/pdf/GC955-600_Bu_Be.pdf	PID, GC	*(GC 955-603 Benzene and 1,3-butadiene sensor)*	Benzene and 1,3-butadiene	1,3-butadiene: Indicated range: 9.05 ppt to 0.3 ppm	15-min cycle		(Fixed/semi-portable unit)	Meant for ambient air sensing with a 15-minute cycle time (220 VAC, 100 VA; 110 VAC available).

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Formaldehyde										
Detection Technique: Chemistry										
1	NASA Ames Research Center (CA) *Lu, Y., Meyyappan, M., Li, J.* *(Funding: NASA)*	*A carbon-nanotube-based sensor array for formaldehyde detection* [2011, Nanotechnology 22(5)] http://iopscience.iop.org/0957-4484/22/5/055502/pdf/0957-4484_22_5_055502.pdf	Nano-based	32 sensor array of SWCNTs including Pd-doped, Rh-loaded, ZnO- and nanoAu-coated, and polyethylene-imine functionalized	Formalde-hyde	10 ppb	18 sec		Not indicated	Response time of seconds, room temperature operation; research to create an e-nose for crew in the International Space Station. 200 to 400ºC operating temperature.
2	Dalian University of Technology (China) *Wang, J.; Wu, Wei; and colleagues (Chen, X.R., Yao, P.J., Ji, M., Qi, J.Q.)* *(Funding: National Natural Science Foundation of China)*	*Detection of indoor formaldehyde concentration using $LaSrFeO_3$-doped SnO_2 gas sensor* [2010, Key Engineering Materials, 437:349-353] http://www.ets.ifmo.ru:8101/tomasov/konferenc/AutoPlay/Docs/Volume%203/6_51.pdf	MOS	MOS SnO_2 (2 wt% doped with La-Sr-FeO_3 as ceramic tube coating, electrodes and sensors then affixed	Formalde-hyde (also tested alco-holates: ethanol, methanol, and benzene)	Formalde-hyde indicated limit: 50 ppb (tested in range of 0-5 ppm) *(limits not given for others)*	120 sec	Very small	Not indicated (Mountable)	Evaluated with N vapor in testing chamber. Response was highest when the sensor reached 370ºC. The response of this sensor to alcoholate gases was higher than the response to formaldehyde and will be improved by integrating sensor arrays and neural networks. For the described experiment the sensors were aged at 5V for 240 hr and operate at 370ºC.
3	Chinese Academy of Sciences *Meng, F.-L., Huang, Z.-J., and colleagues, also at Anhui Polytechnic University* *(Funding: One Hundred Person Project of the Academy, National Natural Science Foundation of China, National Basic Research Program of China, and Anhui Provincial Natural Science Foundation)*	*Electronic chip based on self-oriented carbon nanotube microelectrode array to enhance the sensitivity of indoor air pollutants capacitive detection* [2011, Sensors and Actuators B, 153:103-109] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S092540051000818X&_check=y&_origin=search&_zone=rslt_list_item&_coverDate=2011-03-31&wchp=dGLzVBA-zSkzV&md5=ff0be4989bfbde8f28e9d5daeb7bfae9/1-s2.0-S092540051000818X-main.pdf	Nano-based	Compares electronic chip (Si dielectric medium, Au and Si electrodes) with self-oriented MWCNTs microelectrode array	Formalde-hyde ammonia toluene	Formalde-hyde: 300 ppb	<10 sec	Very small	Not indicated (Mountable)	Response time is limited by the time it takes to load and remove analyte from the chip. Liquid samples placed in sample chamber, nitrogen used as carrier gas to flow through the chamber.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
4	Hunan Cultural University (China), and others *Peng, Liang, and others* *(Funding: National Natural Science Foundation of China, Start Foundation of Hunan Agricultural University, National Science and Technology Major Projects, and National Environmental Protection Public Welfare Program)*	*Improvement of formaldehyde sensitivity of ZnO nanorods by modifying with $Ru(dcbpy)_2(NCS)_2$* [2011, Sensors and Actuators B, 160:39-45] http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=271353&_user=1722207&_pii=S0925400511006381&_check=y&_origin=browse&_zone=rslt_list_item&_coverDate=2011-12-15&wchp=dGLzVlk-zSkzV&md5=6a80f667c84fe21eee0fefa4be2ff8d3/1-s2.0-S0925400511006381-main.pdf	Nano-based	UV light-assisted gas sensor made of ZnO nanorods dispersed in ETOH and dripped on ITO, modified with RuN3	Formalde-hyde; also tested: ethanol, diethyl ether; responses were lower, indicating more acces-sible oxidation of formalde-hyde	5 ppm				Ambient (room temperature) conditions. Response decreases with increasing relative humidity. (Absorption is at low irradiation light intensity; addresses the issue of increased cost of the photoelectric gas sensor with high irradiation light intensity.)
5	Gdansk University of Technology, Gdansk, Poland *Gebicki, J.*	*A prototype of electrochemical sensor for measurements of carbonyl compounds in air* [2011, Electroanalysis, 23(8):1958-1966] http://onlinelibrary.wiley.com/doi/10.1002/elan.201100164/abstract	Electro-chemical, square wave voltam-metry (SWV)	Composed of Pt and Au electrodes, ionic liquid 1-hexyl, 3-methylimidazolium bis(trifluoromethane sulfonyl)imide as an electrolyte and a PDMS membrane	Benzalde-hyde, formalde-hyde	LOQ (200 um thickness, Pt and Au electrodes respectively) = 37 and 61 ppm LOQ (100 um thickness, Pt and Au electrodes, respectively) = 29 and 40 ppm *Limit of Quantification (LOQ) = 3 LOD*			Not indicated (Mountable)	Prototype of an electrochemical sensor for measuring selected VOCs; square wave voltammetry using a low quantification limit due to elimination of capacity current. 50 mV amplitude, 10 Hz frequency and a scan step of 5 mV. Sensor materials functioned for 3 months in a reproducible manner with a 5% standard deviation in results.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
6	Chinese Academy of Sciences *Y. Wan, H. Li, J. Liu, F. Meng, Z. Jin, L. Kong, and J. Liu* *(Funding: "973" State Key Project of Fundamental Research for Nano Science and Nanotechnology, the National Natural Science Foundation of China, and others)*	*Sensitive detection of indoor air contaminants using a novel gas sensor based on coral-shaped tin dioxide nanostructures* [2012, Sensors and Actuators, 165:24-33] http://ac.els-cdn.com/S0925400512001062/1-s2.0-S0925400512001062-main.pdf?_tid=601aeea1c25ade4743a4b104952fcec2&acdnat=1339604316_9f65193ca1a171af77fb721afc87e2dc	Nano-based	Coral-shaped nanostructures, prepared by hydrothermal/ annealing processes coated on Al_2O_3 tubes, Ni-Cr heater wire. Energy bandgap of 3.62 eV at 300ºK	Benzene, formalde-hyde, toluene and acetone	Tested at 50, 100, and 150 ppm	<30 sec for 50 ppm			Real-time gas sensing used to detect contaminants in indoor air; coral-shaped receptacles gave faster results. Response to gases is increased when particle size is reduced. Operates between 350 and 400ºC (optimal temperature of 200ºC). Smaller particulate size was reported to be correlated with higher sensor response.
7 np	Beijing Yadu Air Pollution Tre *Feng Jiang; Dongfang Liu; Xiaocong Ma*	*Patent application for a formaldehyde gas sensor* [Application number: CN2101104419 20100201] http://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20100714&DB=worldwide.espacenet.com&locale=en_EP&CC=CN&NR=101776640A&KC=A&ND=4	Electro-chemical	Composed of gas inlet shell, filter layer, supporting shell, MEC, and electrodes.	Formalde-hyde				(Fixed/semi-portable unit)	Sensor detects formaldehyde gas under the normal temperature, while reducing the affection of other gases in the air, so the detection result is more accurate.
Detection Technique: Spectroscopy										
8	Francis Perrin Laboratory (France) *Mariano, S., Wang, W., Brunelle, G., Tran-Thi, T.H.,* Start-up Ethera, Minatec Enterprises (France) *Bigay, Y.*	*Colorimetric detection of formaldehyde: sensor for air quality measurements and a pollution-warning kit for homes* [2010, IEEE, 1st International Conference on Sensor Device Technologies and Applications] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5632112&isnumber=5632098&tag=1	Colorim-etry, electro-chemical	Colorimetry kit with nanoporous matrix doped with Fluoral-P	Formalde-hyde	Potentially 1-250 ppb	Exposed for 10-30 min	12x5x2 mm	(Visual)	Sensor could be applied to a wide range of concentrations by varying the exposure flux (to be addressed in further studies). For a duration of 1620 minutes, only 0.068% of Fluoral-P (4-amino-3-penten-2-one) was consumed, meaning a few hundred measurements could be obtained with starting materials.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
9	Tokai University (Japan) *Sekine, Y., Katori, R.*	*Indoor air quality monitoring via it network colorimetric monitoring of formaldehyde in indoor environment using image transmission of mobile phone* [2009, ICROS-SICE International Joint Conference (Japan)] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5333246&isnumber=5332438	MIR, Colorimetry detection	Reagent grade HCl, NaOH, ZnO, KIO4, AHMT, HCHO solution and agar powder	Formaldehyde	Tested at 0.85 and 0.13 mg/m^3 *(0.691 and 0.106 ppm, respectively)*	Decreases when concentration increases	~Size of a quarter (per photo)	Image transmission via mobile phone (Visual, cell phone-based)	Colorimetric detection of formaldehyde expresses concentrations as variances in degree of color change of the colorimetric reagent. These results may be interpreted differently from user to user and leads to uncertainty and inconsistent data collection. This project investigates a system in which a mobile phone may be used to take and send pictures of the color change to a laboratory where a laboratory operator would determine the proper interpretation of colorimetric test results.
10	National Research Council of Canada, Institute for Research in Construction (Canada) *Deore, B., Diaz-Quijada, A., Wayner, D. D.M., Stewart, D., Won, D.Y., Waldron, P.* *(Funding: NRC of Canada, ICT sector)*	*An electronic nose for the detection of carbonyl species* [2011, ECS Transactions, 35(7):83-88] http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc54483.pdf	Luminescence, polymer	Solution casting polymer (polyaniline and polypyrrole derivatives) at a given doping level on a glass substrate with or without four Au lines (electrodes) with respective pads to align with commercial probe head	Formaldehyde also tested acetaldehyde	250 ppb formaldehyde at 44% relative humidity ("real world" conditions)	5-60 sec		Not indicated (Mountable)	Polyaniline and polypyrrole derivatives interact with a carbonyl group to produce measureable changes in resistivity, which can be used for e-nose (electronic nose) sensing of carbonyls (reaction between carbonyl and nitrogen spurs molecular recognition).
11 np	Universiti Teknologi Mara (Selangor) *Masrie, M., Adnan, R.* Universiti Industry Selangor (Selangor) *Ahmad, A.*	*A novel integrated sensor system for indoor air quality measurement* [2009, IEEE, 5th International Colloquium on Signal Processing and Its Applications] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5069260&isnumber=5069167	Spectroscopy, IR	3 MIR LEDs, detection by photodiode (lambda 3600 nm) and photoresistor (4300 nm)	CO_2, CO, formaldehyde	Abstract states 1ppm, but detailed results given only for CO_2			(Embedded/ integrated sensor)	Used for indoor air quality measurement.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Reference Commercial Sensors										
C 12	Interscan Corporation	http://www.gasdetection.com/wp-content/uploads/hcho_monitoring_instruments_and_systems.pdf		*400 Series Portable Analyzer*	Formalde-hyde	Minimum: 1.0% of full scale Accuracy: ±1.0% of full scale Range options (for portable analyzers): 0-1999 ppm, 0-199.9 ppm, 0-19.99 ppm, and 0-0.5 ppm.	Lag time: >1 sec 30 sec to 90%, 8 sec to 50% of final value. 30 sec to 10% original value	Portable analyzer: 7" x 8.875" x 4" (4.5 lbs)	Full data acquisition, archiving, and reporting capabilities available	Company claims this unit can withstand the toughest of field conditions and is "reliable for decades." Many different variations are available. Flexible features include: detection range, continuous monitoring, multi-point systems, rack mounting, alarm systems, and more. The company also provides a chart detailing estimated concentrations of interfering gases required to cause a 1 ppm deflection on the analyzer. Sensor drift reported as less than ±2.0% of full scale (24 hr). Sampling rate is adjustable from once per second to once every 10 hours.
Hydrogen Sulfide										
Detection Technique: Chemistry										
1	University of California-Riverside *Mubeen, S. et al.* *(Funding: NIH Genes, Environmental and Health Initiative, and the Fundamental R&D Program for Core Technology of Materials funded by the Ministry of Knowledge Economy, Republic of Korea)*	*Gas sensing mechanism of gold nanoparticles decorated single walled carbon nanotubes* [2011, Electroanalysis, 23(11): 2687-2692.] http://deshusses.pratt.duke.edu/files/deshusses/u31/pdf/ja87.pdf	Nano-based	Hybrid Au-functionalized SWCNT nanostructures on gold electrode (working electrode), Pt wire and chlorinated Ag wire as reference electrode, 100 nm thick SiO2 as dielectric layer	H_2S	Indicated range: 2-200 ppb				Sensitivity for H_2S depends on the number of gold nanoparticles;, the sensing function was independent of the extra nanoparticles.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
2 Np	University of Malaya (Malaysia) *Moghavvemi, M., Attaran, A.*	*Design of a low voltage 0.18 um CMOS surface acoustic wave gas sensor* [2011, Sensors and Transducers, 125(2):22-29] http://www.sensorsportal.com/HTML/DIGEST/february_2011/P_747.pdf	Surface acoustic wave (SAW)	IDT antennas coated with thin film WO_3. Frequency shifts from 300-500 MHz	H_2S	Potentially detects H_2S change at a $100^{-12}g/cm^2$ change in mass		Shoebox	(Mountable)	Two interdigitated transducers (IDT) on a substrate, which determines the wavelength. 1.8V power requirement.
Detection Technique: Spectroscopy										
3	Wuhan Huali Environment Protection Science Technology Co., Ltd. *Y. Wan; B. Dai*	*Atmospheric pollution monitoring gas sensor using non-pulse ultraviolet fluorescence method* [2010, Patent application] http://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20101208&DB=worldwide.espacenet.com&locale=en_EP&CC=CN&NR=201666873U&KC=U&ND=4	UV fluor-escence	Gas sensor optical platform, electronic measuring control system, gas reforming device, peripheral interface	H_2S, SO_2	H_2S indicated LDL: 1 ppb			(Fixed/semi-portable unit)	Continuous monitoring of real-time concentrations of H_2S and SO_2 in air. Sensor reduces noise and has high anti-interference capability, which greatly improves the measurement accuracy and leads to more stable data.
4 np	Utah State University, University of Iowa; US Department of Agriculture/Agriculture Research Service, National Soil Tilth Laboratory (Iowa); Space Dynamics Laboratory (SDL) (Utah) *Hipps, L., Silva, P., (UT State); Zavyalov, V.V., WIlkerson, T., Bingham, G.E. (SDL), et al.* *(Funding: USDA)*	http://www.sdl.usu.edu/programs/aglite; http://www.ars.usda.gov/is/AR/archive/aug06/ames0806.pdf	Spectros-copy	Scanning 3-color LIDAR Fourier Transform Spectrometer *(Aglite)*	PM and gases, including NH_3, H_2S, NO_x			Vehicle-portable, (from photos, main elements appear to be roughly the size of a large suitcase)	(Remote sensing)	Has been used to monitor entire CAFO facility (e.g., swine finishing) and others, including multiple diffuse source dairy, cotton gin, and almond harvesting. (Goal is to measure amount of CO_2, CH_4, N_2O, and other greenhouse gases released from soil into the atmosphere and determine how different crop- and soil-management methods affect these exchanges.)

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
Novel Sensor Systems Using Commercial Sensors										
c5	Jackson State University *Anjaneyulu, Y.* Jawaharlal Nehru Technological University *Jayakumar, I., Bindu, V.H.* Andhra Pradesh Pollution Control Board *Ramani, K.V.* Spectrochem Instruments *Rao, T.H.*	*Real time remote monitoring of air pollutants and their online transmission to the web using internet protocol* [2007, Environ Monit Assess, 124:371-381]] http://cardiff.academia.edu/SAGARESWARGUMMENENI/Papers/922566/	Various commercial	Tapered element oscillating microbalance *(Real Time Remote Monitoring System)*	SO_2, NO, NO_2, CO, O_3, H_2S, PM_{10}, $PM_{2.5}$, hydrocarbons, mercaptans	H_2S: 0-10 ppm	30 to 60 min		Ethernet network module, uploading to webpage (Remote sensing)	This device is a remotely monitored detection system. It can be run on a 12V battery. The pollution sensors can be set to collect data every 30 minutes or every 60 minutes depending on user preference and weather conditions. Also measures environmental parameters such as temperature and rainfall, and sound, per meteorological monitoring system, Bruel and Kajaer sound level measurement system.)
Reference Commercial Sensors										
C6	Aeroqual	http://www.gas-sensing.com/aeroqual-hydrogen-sulfide-sensor-0-10-ppm-eh.html	Electrochemical	Gas sensitive electrochemical *(Aeroqual Hydrogen Sulfide Sensor Head 0-10 ppm)*	H_2S	Indicated range: 0-10 ppm, minimum: 0.01 ppm, max: 20 ppm; res: 0.01 ppm	<60 sec	Hand-held	(Handheld)	Uses diffusion sampling method and operates in the temperature range of -20-40º C. Sensor head is compatible with any Series-200, -300 or -500 Aeroqual monitor.
C7	Arizona Instrument LLC	http://www.azic.com/downloads/brochures/Jerome®%20J605%20Brochure.pdf	Electrochemical	Gold film *(Jerome J605)*	H_2S	Indicated range: 3 ppb-10 ppm, resolution: 20 ppt	Varies, 12-52 sec	11 ft x 6 ft x 6.5 ft	On-board data logging, USB interface, data storage capability of 20,000 samples	This device has an internal battery (rechargeable NiMH), AC power supply/charger, and external battery pack or car accessory cable of 12 VCD; JEROME requires a 0-40º C operational environment free of condensation and explosives. The company recommends annual factory calibrations and intermittent user checks with the functional test module.

ID	Organization *Author (Funding)*	Abbreviated Citation	Sensor Technology: Type	Sensor Technology: Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
C8	Aeroqual	http://www.gas-sensing.com/aeroqual-hydrogen-sulfide-sensor-0-50-ppm-ht.html	Semicon-ductor	Gas sensitive semiconductor *(Aeroqual Hydrogen Sulfide Sensor Head 0-50 ppm)*	H_2S	Indicated range: 0-50 ppm, minimum: 0.05 ppm, maximum: 100 ppm; res: 0.01 ppm	<60 sec	Hand-held	Data interface to PC/ onboard data logging and direct to PC (Handheld)	Uses diffusion sampling method and operates in the temperature range of -20-40ºC. Sensor head is compatible with any Series-200, -300 or -500 Aeroqual monitor.
Methane										
Detection Technique: Chemistry										
1	NASA Glenn Research Center *Biaggi-Labiosa, A., Lebron-Colon, F., Evans, L.J., Xu, J.C., Hunter, G.W., Berger, G.M., Gonzalez, J.M.*	*A novel methane sensor based on porous SnO2 nanorods: room temperature to high temperature detection.* [Oct. 2012, Nanotechnology, 23]	Nano-based	Porous SnO2 nanorods (~5 nm) synthesized using MWCNTs as templates	CH_4	0.25% CH4 in air, 125-2500 ppm (depends on temperature of operation. 100-500ºC capable of entire range, 25ºC capable of 2500 ppm only)	5-50 sec Note response time decreases as concentration increases	Micro-sensor		Authors consider this the first of its type for methane; operated at room temperature and exhibited a wide temperature range (25-500ºC). Optimal sensitivity reported at 300ºC. Authors note sensor may be used for personal health and environmental monitoring. Sensor reported to have low power consumption, be easy to use and cheap to produce in batch fabrication. (Sensitivity: ratio of sensor conductance in presence of the gas minus the baseline conductance measured in air.)
2 np	Shanzt University, Tatyuan (China), Hong Kong Baptist University *Li, Z., Zhang, J., Zhou, Y., Shuang, S., Dong, C., Choi, M.M.F* *(Funding: Hundred Talent Programme of Shanxi Province, Shanxi International S&T Cooperation Program , National Natural Science Foundation, Shanxi Scholarship Council)*	*Electrodeposition of palladium nanoparticles on fullerene modified glassy carbon electrode for methane sensing* [May 2012, Electrochimica Acta]	Nano-based	Nanocomposite of Pd nanoparticles-modified fullerene by electrodeposition on a glassy carbon electrode	CH_4	0.19-0.55%		3 mm diameter glassy carbon elec-trode		Reported to have higher sensitivity and selectivity compared to bare glassy carbon electrodes, pristine C60 modified glassy carbon electrodes, and palladium nanoparticle-modified glassy carbon electrodes. Stable and demonstrated reproducible results. Operation at room temperature is preferred, to prolong sensor life and minimize explosion risk. CO and CO_2 were not found to interfere with measurements, while H_2 and NH_3 did interfere slightly.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Detection Technique: Spectroscopy										
3	Jilin University, State Key Laboratory on Optoelectronics, College of Electronic Science and Engineering, College of Material Science and Engineering *Zheng, C-T, Wang, Y-D., et al.* *(Funding: Science and Technology Council of China, National Natural Science Foundation of China, Science and Technology Department of Jilin Province)*	*Performance enhancement of a mid-infrared CH_4 detection sensor by optimizing an asymmetric ellipsoid gas-call and reducing voltage-fluctuation: Theory, design and experiment* [Aug. 2011, Sensors and Actuators B, 160(1):389-398] http://www.sciencedirect.com/science/article/pii/S0925400511007210	Spectros-copy, MIR, asym-metric ellipsoid gas cell	Asymmetric ellipsoid light-collector gas cell (ALCGC) as absorption pool, light collector, MIR wire source, and dual-channel detector (multi-pass)	CH_4	5 ppm minimum detection limit 6-7 ppm sensitivity range under 1,000 ppm concentration level Improvements are expected to lower this to 1 ppm and below	<6 sec	Sensing 3.8 cm / 1.5 cm	(Mountable)	
4	Huazong University of Science and Technology (China), Nanyang Technological University (Singapore) *Liu, D., Fu, S., Tang, M., Shum, P.*	*Comb filter-based fiber-optic methane sensor system with mitigation of cross gas sensitivity* [Oct. 2012, IEEE, 30(19):3103-3109]	Spectros-copy, gas cell	Polarization-maintaining photonic crystal fiber-based Sagnac loop filter, gas cell with multiple reflections, p-i-n photodetector; fiber optical sensor	CH_4	450 ppm		Range of component sizes (largest is DVD player sized)		Designed to remotely monitor methane in a coal mine, the sensor system has three parts: host machine with all signal processing functions, gas cell, and alarm device. An optical fiber links the host machine to the remote gas cell. The alarm device is activated when CH_4 reaches explosive levels.
Novel Sensor Systems Using Commercial Sensors										
5c	Changzhou Institute of Technology (China) *Guan, J., Wang, X*	*Application of integrated sensor in gas alert system of coal mine* [2009, IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5072745&isnumber=5072599		Integrated sensor alerting system *(MSP430)* JHAT-FM-CO JHAT-FM- H_2S 3011-CO_2 GJ4-2000-CH_4. Chip: 430149	CO, H_2S, CO_2, CH_4, NO_2, and marsh gas	Voice alerts are set at: CH4: 500 ppm H2S: 50 ppm CO2: 500 ppm		Small, fit in mining helmet	(Embedded/ integrated sensor)	Design combines 4 separate gas sensors into single integrated sensor small enough to be installed in a mining helmet for real-time monitoring (deployed in coal mine). When concentrations of any monitored gas exceeds specified levels, the wearer would hear a voice alert reminding of proper safety precautions and procedures. Sensor contains a location device as a further safety element.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
6c np	Polytechnic University of Bucharest (Romania) *Tudose, D.S., Patrascu, T.A., Voinescu, A., Tataroiu, R., Tapus, N.*	*Mobile sensors in air pollution measurement* http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5961035&isnumber=5960999	Thick film metal oxide semi-conductor sensors (from Figaro)	*(Mobile Unit)*	CO, NO_x, hydrocarbons, NH_4, H_2S, gasoline and diesel exhaust, natural gas, propane, CH_4, CO_2	CO_2: 350-10,000 ppm (1.5 min) NOx: 0.3-10 ppm (30 sec) CO, HC: 10-10,000 ppm (30 sec) NH_4: 50-300 ppm (2 min)	30-120 sec	Portable, car interface	Users are able to select different gases and view concentrations overlaying a map of the city. Publicly accessible through on-line web interface. GPRS connection for computer transfer. GPS capable. Temporary memory buffer periodically relayed to a central on-line repository. Real-time web-interface (Vehicle-mounted unit)	This unit is meant to be embedded in a car and relies on the car's power supply. Information on current pollution readings could be provided to the driver. Various sensor 'plugs' would be available to attach to the device based on user preference. Device can be connected to any commercially available memory card via a SD card Interface.
7c np	Dublin City University (Ireland) *Beirne, S., Kiernan, B., Fay, C., Foley, C., Corcoran, B., Smeaton, A.F., Diamond, D.* *(Funding: Environmental Protection Agency, Ireland, and SFI)*	*Autonomous greenhouse gas measurement system for analysis of gas migration on landfill sites* [2009,IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5439422&isnumb4:er=5439372	Spectros-copy, IR	Sensors from Dynament Ltd. CO2 = IRCEL-CO2, CH4 = IRCEL-CH4, Humidity sensor from Honeywell (HIH-4000-001), Temperature sensor from Thermometrics (DKF103N5)	CH_4, CO_2	0-100% volume			Fully automated. Short range: communication to laptop Long range: Bluetooth. Data are sent in SMS format Yes (Fixed/semi-portable unit)	Investigates an autonomous gas sensing platform prototype for monitoring gases as an alternative to current manual monitoring practices at landfills. IR gas sensors integrated into a bespoke platform are fully automated and take measurements twice daily from borehole wells. The sampling chamber contains four sensors: IR gas sensors for CO_2 and CH_4, a humidity sensor, and a temperature sensor. The system was not yet optimized for energy efficiency. Because of the connection to Bluetooth network, landfill operators can be alerted if CH_4 or CO_2 concentration flares occur. Powered by a 12V 7Ah lead acid battery (system sustained for 7 wks, with 2 sampling cycles/day).

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
8cnp	Dong-Eui University Industry-Academic Cooperation Foundation *Yun Sik Yu; Jae Cheon Sohn*	*Apparatus for Measuring Methane Gas Emission Amount in Case of Ruminant Respiration* http://www.wipo.int/patentscope/search/en/detail.jsf?docId=KR30060407&recNum=1&docAn=1020090104099&queryString=FP:(1020110047462)&maxRec=1			CH_4			Mask	(Wearable)	Mask comprised of a methane gas detection module and a volume meter for measuring the amount of air emitted during ruminant respiration. Detection module is comprised of an inlet and outlet, with a gas sensor mounted in between.
Reference Commercial Sensor										
9C	Picarro	https://picarro.box.com/shared/zsg6r84mka	Cavity ring-down spec-troscopy	*PICARRO G2204 Methane and Hydrogen Sulfide Analyzer*	CH_4, H_2S	(requires air-like matrix) Precision (5.0 s): 2 ppb Range: 0-3 ppm specifications guaranteed; 0-20 ppm operating range	Interval: 5 sec Rise/ fall: <5.0 sec	17" w x 7" h x 17.5" d, 46 lbs and separate external pump: 7.5" w x 4" h x 11" d, 10 lbs	Delivers real-time data to Google Earth plume maps. Reported to identify plume origins down to specific buildings.	This sensor can be benchtop or rack-mounted. Operational temperature is 10-35°C, and storage temperature is -10-50°C. Sensor power requirements are as follows: 10-240 VAC, 47-63 Hz (auto-sensing), <260 w start-up (total); 110 W (analyzer), 35 W (pump) at stead state. Maximum drift over 8 hours is reported as <4 ppb. Reported to take continuous readings at 65 mph with 30 readings per minute.
Lead										
Novel Sensor System Using Commercial Sensor										
1	National Institute for Occupational Safety and Health (NIOSH) *Harper, M., Pacolay, B., Hintz, P., Bartley, D.L., Slaven, J.E., Andrew, M.E.*	http://www.cdc.gov/niosh/mining/pubs/pdfs/pxaoo.pdf	X-ray fluores-cence (XRF)	X-ray fluorescence analyzer	Pb	0-5,000 µg/m^3	4 min	Portable		Airborne lead is collected on sample filters that are then presented to the XRF analyzer; this system has been tested in industrial environments, including mining, manufacturing, and recycling.
Reference Commercial Sensor										
C2	Pall Corporation	http://www.pall.com/main/OEM-Media-Membranes-and-Materials/Product.page?id=54709	Reel-to-reel (RTR), XRF	*(Xact 625 Monitoring System - Fence-Line Monitor (FLM))*	Pb	10 pg/m^3 to 57µg/m^3	~20 sec	2 ft x 2 ft x 4 ft	(Fixed/semi-portable unit)	Continuous sensing, designed for use near fencelines of industrial facilities and in complex urban environments; power requirement: 120 VAC/60 Hz at 20 amps.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
Particulate Matter (PM)										
Detection Technique: Chemistry										
1 np	United States Patent Application Publication US 2012/0059598 A1 *Yokoi, S., Sakurai, T.*	*Particulate matter detection device* [2012, Patent application] http://www.freepatentsonline.com/y2012/0059598.html	Electro-chemi-cal, poten-tio-metric	Measuring ion current of charged particulate matter using a pair of electrodes by applying voltage signal and measuring electric characteristics *(Particulate Matter Detection Device)*	PM					Detects particulate matter in air/exhaust.
Detection Technique: Nanoparticle Condensation										
2 np	University of Cincinnati *Son, S.Y.*	*Water vapor uptake on aerosol particles – determination of condensation coefficient of water on nanoparticles under forced convection conditions* [2011] http://aaarabstracts.com/2011/viewabstract.php?paper=568	Nano-particles	Promotes droplet growth by heterogeneous condensation on nanoparticles.	PM_1				Not indicated (Mountable)	Water kept at an elevated temperature forms supersaturated conditions inside a porous chamber, where an air stream carries through nanoparticles. The nanoparticles are exposed to the supersaturated conditions and grow, and can then be accounted for using numerical investigations.
Detection Technique: Spectroscopy										
3 np	University of Nevada – Reno, College of Science; with Desert Research Institute; commercialized by Droplet Measurement Technology of Boulder, CO *Arnott, P., Arnold, I.*	*TTO licenses Arnott's next-gen air quality monitor* [March 2011] http://www.unr.edu/nevada-today/news/2011/tto-licenses-arnotts-next-gen-air-quality-monitor	Photo-acoustic	System includes lasers, mirrors, flexible tubes, and wires *(Photoacoustic Extinctiometer (PAX))*	PM, aerosols relevant for climate change and visibility			Suitcase size, 20 lb (down from 80 lb)	(Fixed/semi-portable unit)	Beta-versions are in use by researchers at LBL and Bay Area Air Quality District, Max Planck Institute for Chemistry in Europe, and Mexico City; Droplet aims to produce many more that will be a fraction of the cost to users. (Researchers are working on developing a "truly miniature device that may find use as an on-board sensor for real-time black carbon air pollution emission control".)

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description (Name)	Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
4 np	Utah State University, University of Iowa; Space Dynamics Laboratory (SDL) (Utah) *Hipps, L., Silva, P., (UT State); Zavyalov, V.V., Wllkerson, T., Bingham, G.E. (SDL), and others* *(Funding: USDA)*	http://www.sdl.usu.edu/programs/aglite; http://www.ars.usda.gov/is/AR/archive/aug06/ames0806.pdf	LIDAR	Scanning 3-colorlidar LIDAR FTIR *(Aglite)*	PM and gases, including NH_3, H_2S, NO_x			Suitcase	(Remote sensing)	Has been used to monitor an entire CAFO facility (e.g., swine finishing) and others sources, including multiple diffuse source dairy, cotton gin, and almond harvesting. The goal is to measure the amount of CO_2, CH_4, N_2O, and other greenhouse gases released from soil into the atmosphere and determine how different crop- and soil-management methods affect these exchanges.
5 np	Thermo Scientific *K. Goohs, J. Hiss, M. Rossmeisl, D. Kita*	*A hybrid method for PM CEMS* AAAR Conference 2009 (presentation) http://stratusllc.com/uploads/PM_CEMS_White_Paper.pdf	Light scattering		PM				(Fixed/semi-portable unit)	Introduces a light-scattering configuration with continuous mass referencing for source emissions and ambient air monitoring applications. Light scattering demonstrates potential for continuous PM monitoring because it can configure to measure an angle relative to the applicable light source and it is sensitive enough to measure most size particles within a plume.
Novel Sensor Systems Using Commercial Sensors										
c6	Jackson State University *Anjaneyulu, Y.* Jawaharlal Nehru Technological University *Jayakumar, I., Bindu, V.H.* Andhra Pradesh Pollution Control Board *Ramani, K.V.* Spectrochem Instruments *Rao, T.H.*	*Real time remote monitoring of air pollutants and their online transmission to the web using internet protocol* [2007, Environ Monit Assess, 124:371-381]] http://cardiff.academia.edu/SAGARESWARGUMMENENI/Papers/922566/	Electro-chemical, PM analyzer various commer-cial	R&P series 1400a TEOM *(Real Time Remote Monitoring System)*	SO_2, NO, NO_2, CO, O_3, H_2S, PM_{10}, $PM_{2.5}$, hydro-carbons, mercap-tans	Varies per pollutant, within 0-200 ppm, or 0-50 µg/m^3 (mercaptans) CO: Indicated range: 0-100 ppm	30 or 60 min		Ethernet network module, uploading to webpage (Remote sensing)	This device is a remotely monitored detection system. It can be run on a 12V battery. The pollution sensors can be set to collect data every 30 or 60 minutes depending on user preference and weather conditions. Also measures environmental parameters such as temperature and humidity.

ID	Organization ***Author*** *(Funding)*	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Re-sponse Time	Size	Automation and Network Capability	Application and Operation Notes
c7	Bogor Agricultural University (Indonesia) *Azis, M., Rustami, E., Maulina, W., Rahmat, M., Alatas, H., Seminar, K. (Funding/support: Beasiswa Unggulan Terpadu – Education Ministry of Republic of Indonesia, and various Departments in Bogor Agricultural University)*	*Measuring air pollutant standard index (ISPU) with photonics crystal sensor based on wireless sensor network (WSN)* [2011, IEEE, International Conference on Instrumentation, Communication, Information Technology, and Biomedical Engineering, (Indonesia)] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6108656&isnumber=6108578	Optical, photonic crystal	(Sensor developed from previous research at this institution)	CO, SO_2, NO_2, O_3, PM_{10}				WSN, desktop and web applications to display data in real time and non-real time. (Fixed/semi-portable unit)	Investigates use of information systems of the air pollutant standard index and photonics crystal sensors to monitor air pollution and collect data by wireless communication.
c8 np	NASA-Glenn Research Center *Greenberg, P.S., Hyatt, M.J.*	*Instrumentation and sensor technologies for the measurement and detection of lunar dust* [2009, IEEE] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4839566&isnumber=4839294&tag=1			PM (lunar dust)				(Mountable)	Study conducted because appropriate sensor and detection technologies for lunar dust are unavailable.
c9 np	Stanford University *Acevedo-Bolton, V. Klepeis, N.E., Jiang, R. Cheng, K., Ott, W.R., Hildemann, L.M.*	*Employee and patron exposure to pollutants in a Northern California casino* ISES 2009 (poster)		Stationary sensors and portable sensors place on different employees	$PM_{2.5}$, real-time $PM_{2.5}$, nicotine, cotinine, PAH, ultrafine particles, CO_2					Sensors tracked the amount of contaminants in the air of a California casino and used gathered data and patron counts to estimate the air change rates over time. A mass balance model was used to evaluate how the data on nicotine correlated with the indoor $PM_{2.5}$ measurements.
Reference Commercial Sensors										
C 10	Thermo Fisher Scientific	http://thermoscientific.com/ecomm/servlet/productsdetail_11152_L11036_89583_11961321_-1	Gravi-metric	*(pDR-1500, personal DataRAM Aerosol Monitor)*	PM particle size of maximum response 0.1-10 µm	Indicated range: 0.001 to 400 mg/m^3	1 sec	Shoebox	(Fixed/semi-portable unit)	Requires 70 to 450 mA in run mode, 32 mA in ready mode.

ID	Organization *Author* (Funding)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response Time	Size	Automation and Network Capability	Application and Operation Notes
			Type	Description (Name)						
C 11	Thermo Scientific	http://www.thermo.com/eThermo/CMA/PDFs/Product/productPDF_3275.pdf	Filter dynamics measurement system (FDMS), tapered element oscillating micro-balance (TEOM) mass sensor	*(Thermo Scientific Ambient Particulate Monitor TEOM® 1405-DF)*	PM_{10} and $PM_{2.5}$	0 to 1,000,000 µg/m^3 resolution: 0.1 µg/m^3, precision: 2.0 µg/m^3 (1-hr avg), 1.0 µg/m^3 (24-hour avg), accuracy for mass measurement 0.75%	6 min	17 in. x 19 in. x 55 in.	(Fixed/semi-portable unit)	This device is made for indoor and commercial readings of ambient PM concentrations even in the presence of volatile materials. It requires between 47 and 63 Hz of power to operate.
C 12	Enviro Technology Services plc	http://www.et.co.uk/products/air-quality-monitoring/particulate-monitoring/opsis-sm200-beta-attenuation-particulate-monitor-gravimetric-sampler/	Geiger counter	*(OPSIS SM200 Beta-attenuation Particulate Monitor / Gravimetric Sampler)*	PM_{10} and $PM_{2.5}$	0.5 µg/m^3 to 1,000 µg/m^3	1-24 hr		(Fixed/semi-portable unit)	Primarily used for modern monitoring stations. Uses 800 W of power and has a long cycle period of sampling.

[a] This table highlights sensor technologies/techniques reported in selected conference proceedings, poster abstracts, peer-reviewed journals, and university and other organization (e.g., company) web pages; at the time of the publications reviewed, these sensors were in the research and development stage. Also included are two types of commercial sensors: (a) those that are part of a novel sensing system ("Sensor Systems Using Commercial Sensors" as appropriate), and (b) representative standard sensors that serve as points of comparison ("Reference Commercial Sensor"). Research focused only on networks, architecture, or mobile applications for mobile sensors that do not identify a specific sensor or technology/technique are not included in this table.

The table is organized by pollutant, starting with the four criteria pollutant gases (shaded green), followed by four additional gases (shaded pink), and then the two particulate criteria pollutants (shaded yellow). This organization results in some sensors being repeated because they can detect multiple pollutants. Within each pollutant section, the entries are further grouped by general detection technique, in order of decreasing sensitivity (i.e., most sensitive listed first). Sensors without reported detection capabilities are listed at the end of the technology category.

The ID (identifier) in the left column corresponds to the sensor boxes plotted on the benchmark-sensor arrays. Note that only sensors with reported detection levels appear on those arrays; np = not plotted. c = commercial sensor used in a novel detection system; C = standard commercial sensor included for comparison.

A number of acronyms and abbreviations are defined within the entries; others are provided in the notations section at the front of this report.

TABLE E-2 Additional Recent Literature for Mobile Sensors for Air Pollutants[a]

#	Sort Codes P	Sort Codes T	Sort Codes A	Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology Type	Sensor Technology Description *(Name)*	Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
Acetaldehyde											
Chemical											
	acetaldehyde	C		Universidade de Sao Paulo (Brazil) *Li, R.W.C., et al.* *(FAPESP and CNPq)*	*Low cost selective sensor for carbonyl compounds in air based on a novel conductive poly(p-xylene) derivative* [2009, Materials Science and Engineering C. 29(1):426-429]	Conducting polymer	Poly(p-xylene) (PPX) doped with CSA (camphor sulfonic acid)	Acetaldehyde, benzaldehyde, acetone, butanone (shows good discrimination)		Response: 2 sec recovery: <10 sec	No significant drift of the background conductance after several exposures. Power consumption: <1 µW. Demonstrated good reproducibility over 20 repetitive exposure/recovery cycles. Sensors have been tested for more than 3 months and still respond well. No change in conductance in the presence of humidity (due to hydrophobic characteristics of the polymer). Total sensor cost: <$1. Operates at room temperature.
E-nose											
	acetaldehyde	e-nose		Semiconductor Physics Institute (Lithuania), University of Brescia (Italy) *Setkus, A., et al.* *(WOUNDMONITOR)*	*Analysis of the dynamic features of metal oxide sensors in response to SPME fiber gas release* [2010, Sensors and Actuators B. 146(2):539-544]	MOS	Metal oxide (MOx) sensor array	VOCs, specifically those emitted from infected wounds (acetone, acetic acid, acetaldehyde, and butyric acid)	3-4 ppm		Time-dependent release of VOCs from a solid phase micro-extraction (SPME) fiber.
Acetic acid											
Chemical											
	acetic acid	C		Ehime University (Japan), National Institute for Materials Science (Japan) *Mori, M., et al.* *(Japan Science and Technology Agency)*	*Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air* [2009, Sensors and Actuators B. 143(1):56-61]	Potentiometric	Pt/YSZ/Pt (platinum/ yttria-stabilized zirconia/ platinum) structure	VOCs, specifically acetic acid, methyl ethyl ketone, ethanol, benzene, toluene, o- and p-xylene	Sub-ppm	Ethanol response: 4-204 sec (quickest for 0.5 ppm at 500°C) recovery: 190-480 sec (quickest for 1 ppm at 500°C)	400-500°C, highest response at 400°C. Increased temperatures decreased sensitivity but modified response and recovery times. Analysis of multidimensional plots of sensor output at various temperatures suggests possible selective sensing of different VOCs.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
E-nose											
	acetic acid	e-nose		Semiconductor Physics Institute (Lithuania), University of Brescia (Italy) *Setkus, A., et al. (WOUNDMONITOR)*	*Analysis of the dynamic features of metal oxide sensors in response to SPME fiber gas release* [2010, Sensors and Actuators B. 146(2):539-544]	Metal oxide	MOx sensor array	VOCs, emitted from infected wounds (acetone, acetic acid, acetaldehyde, and butyric acid)	3-4 ppm		Time dependent release of VOCs from a SPME fiber.
Acetone											
Chemical											
	acetone	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al.* *(Shanghai Pujiang Program, State Key Laboratory of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, and the National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1):63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance recovery: begins 3-5 sec after injection of dry air	

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	acetone	C		Isalamic Azad University (Iran), K. N. Toosi University of Technology (Iran) *Amini, A., Ghafarinia, V.*	*Utilizing the response patterns of a temperature modulated chemoresistive gas sensor for gas diagnosis* [2011, IOP Conf. Ser.: Mater. Sci. Eng. 17 012408]	Commer-cial (modified)	Staircase heating voltage waveform applied to micro-heater for SnO_2 gas sensor.	Acetone, 1-butanol, ethanol, methanol	Tested: 50-1700 ppm		Operation between 50 and 400°C yielded unique vectors for methanol, ethanol, 1-butanol, and acetone, suggesting potential for selectivity. The sensor was exposed for five 40-sec segments.
	acetone	c		Shivaji University (India), Chonnam National University (South Korea), Solapur University (India) *Pawar, R.C., et al. (University Grants Commission, New Delhi)*	*Surfactant assisted low temperature synthesis of nanocrystalline ZnO and its gas sensing properties*. [2010, Sensors and Actuators B. 151(1):212-218]	Nano-materials	Vertically aligned ZnO nanorods on glass (MOS)	Acetone, ammonia, liquefied petroleum gas (LPG), ethanol	Tested: 2000 ppm		High sensitivity for acetone. Low operating temperature (tested 200-450°C). Optimal sensitivity and response time at 275°C.
	acetone	C		University of Massachusetts Lowell *Li, X., et al. (National Science Foundation)*	*Fabrication and integration of metal oxide nanowire sensors using dielectrophoretic assembly and improved post-assembly processing* [2010, Sensors and Actuators B. 148(2):404-412]	MOS nanowires	Metal oxide nanowires (indium, tin, and indium-tin). Dielectro-phoretic (DEP) assembly onto interdigitated micro-electrodes	Acetone, chloroform, ethanol, methanol, propanol, and benzene.	1 ppm (potentially ppb)	Response: 10 sec recovery: 8-10 min	Good repeatability, however, recovery time increases when exposed to greater concentrations of substance. No response to 1500 ppm was observed below 200°C; performance was enhanced when 440°C was reached. Determined that further optimization of ITO composition may improve sensitivity and selectivity of the sensors. Oxygenated organic compounds cause a higher response than aromatic or chlorinated compounds.

#	Sort Codes			Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	acetone	C		Universidade de Sao Paulo (Brazil) *Li, R.W.C., et al.* *(FAPESP and CNPq)*	*Low cost selective sensor for carbonyl compounds in air based on a novel conductive poly(p-xylene) derivative* [2009, Materials Science and Engineering C. 29(1):426-429]	Conducting polymer	Poly(p-xylene) (PPX) doped with CSA	Acetaldehyde, benzaldehyde, acetone, butanone (shows good discrimination)		Response: 2 sec recovery: <10 sec	No significant drift of the background conductance was observed after several exposures. Power consumption: <1 µW. Good reproducibility over 20 repetitive exposure/ recovery cycles. Sensors have been tested for more than 3 months and still respond well. No change in conductance in the presence of humidity (due to hydrophobic characteristics of the polymer). Total sensor cost: <$1. Operates at room temperature.
E-nose											
	acetone	e-nose		Saratov State Technical University (Russia), Southern Illinois University at Carbondale, Northeastern University *Sysoev, V.V., et al.* *(Fullbright scholarship and RFBR grant and NSF)*	*The electrical characterization of a multi-electrode odor detection sensor array based on the single SnO_2 nanowire* [2011, Thin Solid Films. 520(3):898-903]	e-nose	SnO_2 wedge-like nanowire, multielectrode odor detection sensor array; functionalized by deposition of Pd nanoparticles	Acetone, 2-propanol, CO, and H_2			Fabricating metal oxide single crystals in shape of nanowires is cost effective.
	acetone	e-nose		Semiconductor Physics Institute (Lithuania), University of Brescia (Italy) *Setkus, A., et al.* *(WOUNDMONITOR)*	*Analysis of the dynamic features of metal oxide sensors in response to SPME fiber gas release* [2010, Sensors and Actuators B. 146(2):539-544]	e-nose	MOx sensor array	VOCs, specifically those emitted from infected wounds (acetone, acetic acid, acetaldehyde, and butyric acid)	3-4 ppm		Time-dependent release of VOCs from a SPME fiber.

#	Sort Codes			Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
Ammonia											
Chemical											
	NH3	C		ENEA (Italy) *Penza, M., et al.*	*Functional characterization of carbon nanotube networked films functionalized with tuned loading of Au nanoclusters for gas sensing applications* [2009, Sensors and Actuators B. 140(1):176-184]	Chemi-resistor	Gold functionalized CNTs	NO_2, NH_3, CO, N_2O, H_2S, SO_2	Sub-ppm: NO_2, H_2S and NH_3 200 ppb NO_2 Negligible response for CO, N_2O, and SO_2		Operational temperature range is 20-250°C.
	NH3	C		Hanoi University of Science and Technology *Van Quy, N., et al.*	*Gas sensing properties at room temperature of a quartz crystal microbalance coated with ZnO nanorods* [2011, Sensors and Actuators B. 153(1):188-193]	Nano-materials	Quartz crystal microbalance coated with ZnO nanorods	Ammonia	Tested at 50, 100, and 200 ppm	Response: 226-239 sec recovery: 294-398 sec	High selectivity to NH_3 over LPG, N_2O, CO, NO_2, and CO_2. Mechanism appears reversible when flushed with air. Good reproducibility (same response over 3 cycles) and high stability are reported.
	NH3	C		Kyushu University (Japan), Japan Society for the Promotion of Sciences (Japan) *Plashnitsa, V.V., et al.* *(MEXT, The Grant-in-Aid for Scientific Research on Priority Area, Nanoionics)*	*Zirconia-based electrochemical gas sensors using nano-structured sensing materials aiming at detection of automotive exhausts* [2009, Electrochimica Acta. 54(25):6099-6106]	Potentio-metric	YSZ-based planar sensors using nano-structured sensing electrodes	Ammonia, NO_2, CO, CH_4, C_3H_8, C_3H_6, NO	Highly selective at 20-200 ppm		This sensor may be appropriate for harsh environments (600°C) such as automotive exhausts. Sensing characteristics (sensitivity, response time, recovery time) are dependent on sputtering time of Au sensing electrodes.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	NH3	c		Shivaji University (India), Chonnam National University (South Korea), Solapur University (India) *Pawar, R.C., et al. (University Grants Commission, New Delhi)*	*Surfactant assisted low temperature synthesis of nanocrystalline ZnO and its gas sensing properties*. [2010, Sensors and Actuators B. 151(1):212-218]	Nano-materials	Vertically aligned ZnO nanorods on glass (MOS)	Acetone, ammonia, LPG, ethanol	Tested: 2000 ppm		High sensitivity for acetone. Low operating temperature (tested 200-450°C). Best sensitivity and response achieved at 275°C.
	NH3	C		Solid State Physics Laboratory (India) *Raj, V.B., et al. (University Grants Commission, DST and Defense Research and Development Organization)*	*Cross-sensitivity and selectivity studies on ZnO surface acoustic wave ammonia sensor* [2010, Sensors and Actuators B. 2(3):517-524]	SAW	ZnO coated one-port SAW	Ammonia (cross sensitivity analyzed for VOCs)	Tested: 590-120,000 ppm	90% response in 20 sec	Ammonia can be distinguished from other tested gases by examining the direction of frequency shift (positive for ammonia and negative for the rest of the test gases). Good sensitivity, selectivity, reversibility, and repeatability. Tested sensor detected ammonia in humid environments without degrading sensor performance.
E-nose											
	NH3	enose		Chinese Academy of Sciences (China), Anhui Polytechnic University (China) *Meng, F.-L., et al. (Chinese Academy of Sciences, National Natural Science Foundation of China, National Basic Research Program of China, Anhui Provincial Natural Science Foundation)*	*Electronic chip based on self-oriented carbon nanotube microelectrode array to enhance the sensitivity of indoor air pollutants capacitive detection* [2011, Sensors and Actuators B. 153(1):103-109]	e-nose	Electronic chip with self-oriented CNT microelectrode array	Formaldehyde (best response), toluene (lowest response), ammonia		Response: "tens of seconds" recovery: slowest for toluene	Use of self-oriented CNTs reduces noise and less response to water (weak adsorption between CNTs and water molecules.

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	P	T	A			Type	Description *(Name)*				
Benzene											
Chemical											
	benzene	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al.* *(Shanghai Pujiang Program, State Key Laboratory of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, and the National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1):63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance recovery: begins 3-5 sec after injection of dry air	
	benzene	C		Ehime University (Japan), National Institute for Materials Science (Japan) *Mori, M., et al.* *(Japan Science and Technology Agency)*	*Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air* [2009, Sensors and Actuators B. 143(1):56-61]	Potentio-metric	Pt|YSZ|Pt structure	VOCs, specifically acetic acid, methyl ethyl ketone, ethanol, benzene, toluene, o- and p-xylene	Sub-ppm	Ethanol response: 4-204 sec (quickest for 0.5 ppm at 500°C) recovery: 190-480 sec (quickest for 1 ppm at 500°C)	400-500°C, highest response at 400°C. Increased temperatures decreased sensitivity and modified response and recovery times. Analysis of multidimensional plots of sensor output at various temperatures suggests possible selective sensing of different VOCs.

#	Sort Codes			Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	benzene	C		University of Massachusetts Lowell *Li, X., et al.* *(National Science Foundation)*	*Fabrication and integration of metal oxide nanowire sensors using dielectrophoretic assembly and improved post-assembly processing* [2010, Sensors and Actuators B. 148(2):404-412]	MOS nanowires	Metal oxide nanowires (indium, tin, and indium-tin). Dielectro-phoretic (DEP) assembly onto interdigitated micro-electrodes	Acetone, chloroform, ethanol, methanol, propanol, and benzene.	1 ppm (potentially ppb)	Response: 10 sec recovery: 8-10 min	Good repeatability, however, recovery time increases when exposed to greater concentrations of substance. No response to 1500 ppm was observed below 200°C; performance was enhanced when 440°C was reached. Further optimization of ITO composition may improve sensitivity and selectivity of the sensors. Oxygenated organic compounds cause a higher response than aromatic or chlorinated compounds.
Benzaldehyde											
Chemical											
	benzaldehyde	C		Universidade de Sao Paulo (Brazil) *Li, R.W.C., et al.* *(FAPESP and CNPq)*	*Low cost selective sensor for carbonyl compounds in air based on a novel conductive poly(p-xylene) derivative* [2009, Materials Science and Engineering C. 29(1):426-429]	Conduc-ting polymer	Poly(p-xylene) (PPX) doped with CSA	Acetaldehyde, benzaldehyde, acetone, butanone (shows good discrimination)		Response: 2 sec recovery: <10 sec	No significant drift of the background conductance after several exposures. Power consumption: <1 µW. Good reproducibility over 20 repetitive exposure/ recovery cycles. Sensors have been tested for more than 3 months and still respond well. No change in conductance in the presence of humidity (due to hydrophobic characteristics of the polymer). Total estimated sensor cost: <$1. Operates at room temperature.
1-Butanol											
Chemical											
	1-butanol	C		Isalamic Azad University (Iran), K. N. Toosi University of Technology (Iran) *Amini, A., Ghafarinia, V.*	*Utilizing the response patterns of a temperature modulated chemoresistive gas sensor for gas diagnosis* [2011, IOP Conf. Ser.: Mater. Sci. Eng. 17 012408]	Commer-cial (modified)	Staircase heating voltage waveform applied to micro-heater for SnO_2 gas sensor.	Acetone, 1-butanol, ethanol, methanol	Tested: 50-1700 ppm		Operation between 50 and 400°C yielded unique vectors for methanol, ethanol, 1-butanol, and acetone, suggesting potential for selectivity. The sensor was exposed for five 40-sec segments.

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	P	T	A			Type	Description *(Name)*				
Butanone											
Chemical											
	butanone	C		Universidade de Sao Paulo (Brazil) *Li, R.W.C., et al.* *(FAPESP and CNPq)*	*Low cost selective sensor for carbonyl compounds in air based on a novel conductive poly(p-xylene) derivative* [2009, Materials Science and Engineering C. 29(1):426-429]	Conduc-ting polymer	Poly(p-xylene) (PPX) doped with CSA	Acetaldehyde, benzaldehyde, acetone, butanone (shows good discrimination)		Response: 2 sec recovery: <10 sec	No significant drift of the background conductance after several exposures. Power consumption: <1 µW. Good reproducibility over 20 repetitive exposure/ recovery cycles. Sensors have been tested for more than 3 months and still respond well. No change in conductance in the presence of humidity (due to hydrophobic characteristics of the polymer). Total sensor cost: <$1. Operates at room temperature.
Butyric acid											
E-nose											
	butyric acid	e-nose		Semiconductor Physics Institute (Lithuania), University of Brescia (Italy) *Setkus, A., et al.* *(WOUNDMONITOR)*	*Analysis of the dynamic features of metal oxide sensors in response to SPME fiber gas release* [2010, Sensors and Actuators B. 146(2):539-544]	Metal oxide (MOx)	MOx sensor array	VOCs, specifically those emitted from infected wounds (acetone, acetic acid, acetaldehyde, and butyric acid)	3-4 ppm		Time-dependent release of VOCs from a SPME fiber.
Carbon monoxide											
Chemical											
	CO	C		ENEA (Italy) *Penza, M., et al.*	*Functional characterization of carbon nanotube networked films functionalized with tuned loading of Au nanoclusters for gas sensing applications* [2009, Sensors and Actuators B. 140(1):176-184]	Chemi-resistor	Gold functionalized CNTs	NO_2, NH_3, CO, N_2O, H_2S, SO_2	Sub-ppm: NO_2, H_2S and NH_3 200 ppb NO_2 negligible response for CO, N_2O, and SO_2		Operational temperature: 20-250°C.

#	Sort Codes			Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	C O	C		Korea University (Republic of Korea) *Kim, Y.-S., et al.*	*CuO nanowire gas sensors for air quality control in automotive cabin* [2008, Sensors and Actuators B. 135(1):298-303]	Nano-materials	CuO nanowires grown by thermal oxidation of Cu foil. P-type oxide semiconductor	CO, NO_2	Tested: 10, 50, 100 ppm CO; 1-5 ppm, 10, 50 and 100 ppm NO_2		Sensor resistance was reported to decrease with NO_2 concentrations between 30 and 100 ppm, and increase with NO_2 concentrations between 1 and 5 ppm. Resistance increased with exposure to 10, 50, and 100 ppm of CO. Sensor was tested at 300°C and 370°C, using 300 mW and 400 mW of power, respectively.
	C O	C		Kyushu University (Japan), Japan Society for the Promotion of Sciences (Japan) *Plashnitsa, V.V., et al.* *(MEXT, The Grant-in-Aid for Scientific Research on Priority Area, Nanoionics)*	*Zirconia-based electrochemical gas sensors using nano-structured sensing materials aiming at detection of automotive exhausts* [2009, Electrochimica Acta. 54(25):6099-6106]	Potentio-metric	YSZ-based planar sensors using nano-structured sensing electrodes	Ammonia, NO_2, CO, CH_4, C_3H_8, C_3H_6, NO	Highly selective at 20-200 ppm		This sensor may be appropriate for harsh environments (600°C) such as automotive exhausts. Sensing characteristics (sensitivity, response time, recovery time) seem to be dependent on sputtering time of Au sensing electrodes.
	C O	C		Rosemount Analytical Inc., Kurt-Schwabe Institute for Measuring Sensor Technology (Germany) *Shuk, P., et al.* *(German Federal Ministry of Economics and Rosemont Analytical Inc.)*	*New advanced in situ carbon monoxide sensor for the process application* [2009, International Journal of Ionics. 15(2):131-138]	Potentio-metric	Mixed potential solid electrolyte with sensing electrodes based on composite with various semi-conducting oxides	CO (interferents analyzed: CO_2, H_2O, O_2, SO_2)	~5 ppm	Response: 25-30 sec at 550°C; 15-20 sec at 650°C	Good reproducibility and stability in hazardous combustion environment (tested at power plant). Sensor demonstrated little to no cross sensitivity to H_2O, and no cross sensitivity to CO_2; however, there was cross sensitivity to O_2 +/-15 ppm. After exposure to 1,000 ppm SO_2, CO sensor sensitivity increased by 50%, but response was stable and reproducible.

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	P	T	A			Type	Description *(Name)*				
	C O	C		Shiraz University (Iran), Persian Gulf University (Iran) *Javadpour, S., et al.*	*Morpholine doped poly(3,4-ethylenedioxy) thiophene–poly(styrene-sulfonate) as a low temperature and quick carbon monoxide sensor* [2009, Sensors and Actuators B. 142(1):152-158]	Polymer film	Poly(3,4-ethylenedioxy) thiophene-poly(styrene-sulfonate) (PEDOT/PSS thin films). Fe, Al, and morpholine were added	CO		Response: 5 sec	This thin film was reported to produce a better response and reversibility time than other tested polymer sensing films (PANi or polypyrrole). Un-doped sensor responds more to general air than it does to just CO (50% vs. 2%). Mixture of air and CO results in a better response, but doping appears to improve the sensing capabilities. Combining the polymer with the Fe-Al-morpholine as a doping compound reduced the effect of moisture and improved response to CO (only 5% unstable increase in the resistance).
	C O	C		Universitat de Barcelona (Spain), Ecole Nationale Superieure de Mines de Saint-Etienne (France), Proprietes et Modelisations des Solides (France) *Morata, A., et al.*	*Development and characterisation of a screen-printed mixed potential gas sensor* [2008, Sensors and Actuators B. 130(1):561-566]	Potentio-metric	Screen printing	CO (in the presence of O_2 and NO_2)	Tested: 10, 15, 50, 100, 150, and 200 ppm for CO; 3, 5, 7, and 10 ppm for NO_2	0-3000 sec depending on concentra-tion	Baseline drifts slightly for lower working temperatures. Results show that NO_2 has a very small effect on the sensors response to CO when both species are introduced together. Sensor response does not vary appreciably after 20 hours of continuous operation. Tested at temperatures ranging from 530 to 580°C.
E-nose											
	C O	e-nose		CNR-IMM-Istituto per la Microelettronica ed i Microsistemi, University Campus (Italy), ITC-irst – Microsystems Division, (Italy) *Francioso, L., et al.*	*Linear temperature microhotplate gas sensor array for automotive cabin air quality monitoring* [2008, Sensors and Actuators B. 134(2):660-665]	e-nose	MOS, MEMS	CO, NO_2, SO_2			Investigates a temperature gradient electronic nose for increasing sensitivity. Total power consumption below 130 mW with power supplied to voltage heater. Temperature was increased in a 100°C-wide temperature window. Sensor exhibited faster response times for higher temperatures (300-400°C) and higher gas concentrations. Signal was lost when sensor was operated below 280°C. Sensor was exposed to injected gas for 30 minutes, followed by 90 minutes of recovery in dry air. Principal component analysis (PCA) was used to identify and analyze patterns in data.

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	P	T	A			Type	Description *(Name)*				
	co	e-nose		Saratov State Technical University (Russia), Southern Illinois University at Carbondale, Northeastern University *Sysoev, V.V., et al.* *(Fullbright scholarship and RFBR grant and NSF)*	*The electrical characterization of a multi-electrode odor detection sensor array based on the single SnO_2 nanowire* [2011, Thin Solid Films. 520(3):898-903]	e-nose	SnO_2 wedge-like nanowire, multielectrode odor detection sensor array; functionalized by deposition of Pd nanoparticles	Acetone, 2-propanol, CO, and H_2			Fabricating metal oxide single crystals in shape of nanowires may be cost effective.
Carbonyl sulfide											
Chemical											
	carbonyl sulfide	c		Matheson Tri-Gas Inc. *Chase, D., et al.*	*Pyrolysis-electrochemical sensor for monitoring carbonyl sulfide levels in ambient air* [July 1, 2010] http://www.electroiq.com/articles/sst/print/volume-53/issue-7/features/ehs/pyrolysis-electrochemical-sensor.html	Commer-cial	Honeywell Analytics	Carbonyl sulfide	Tested: 50-100 ppm		Typical response ranged from 12-14% of the gas depending on humidity. 15% increase in response was observed as relative humidity increased from 1 to 100%. This commercial sensor is typically used to monitor process tools, gas cabinets, valve manifold boxes, ambient air and other areas where gases are generated.

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	P	T	A			Type	Description *(Name)*				
Chloroform											
Chemical											
	chloroform	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al.* *(Shanghai Pujiang Program, State Key Laboratory of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, and the National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1): 63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance recovery: begins 3-5 sec after injection of dry air	
	chloroform	C		University of Massachusetts Lowell *Li, X., et al.* *(National Science Foundation)*	*Fabrication and integration of metal oxide nanowire sensors using dielectrophoretic assembly and improved post-assembly processing* [2010, Sensors and Actuators B. 148(2):404-412]	MOS nanowires	Metal oxide nanowires (indium, tin, and indium-tin). Dielectro-phoretic (DEP) assembly onto interdigitated micro-electrodes	Acetone, chloroform, ethanol, methanol, propanol, and benzene.	1 ppm (potentially ppb)	Response: 10 sec recovery: 8-10 min	Good repeatability, however, recovery time increases when exposed to greater concentrations of substance. No response to 1500 ppm was observed below 200°C; performance was enhanced when 440°C was reached. Further optimization of ITO composition may improve sensitivity and selectivity of the sensors. Oxygenated organic compounds seem to cause a higher response than aromatic or chlorinated compounds.

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	P	T	A			Type	Description *(Name)*				
Ethanol											
Chemical											
	ethanol	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al.* *(Shanghai Pujiang Program, State Key Laboratory of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, and the National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1):63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance recovery: begins 3-5 sec after injection of dry air	
	ethanol	C		Ehime University (Japan), National Institute for Materials Science (Japan) *Mori, M., et al.* *(Japan Science and Technology Agency)*	*Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air* [2009, Sensors and Actuators B. 143(1):56-61]	Potentio-metric	Pt|YSZ|Pt structure	VOCs, specifically acetic acid, methyl ethyl ketone, ethanol, benzene, toluene, o- and p-xylene	Sub-ppm	Ethanol response: 4-204 sec (quickest for 0.5 ppm at 500°C) recovery: 190-480 sec (quickest for 1 ppm at 500°C)	400-500°C, highest response at 400°C. Increased temperatures decreased sensitivity but modified response and recovery times. Analysis of multidimensional plots of sensor output at various temperatures suggests possible selective sensing of different VOCs.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	ethanol	C		Isalamic Azad University (Iran), K. N. Toosi University of Technology (Iran) *Amini, A., Ghafarinia, V.*	*Utilizing the response patterns of a temperature modulated chemoresistive gas sensor for gas diagnosis* [2011, IOP Conf. Ser.: Mater. Sci. Eng. 17 012408]	Commer-cial (modified)	Staircase heating voltage waveform applied to micro-heater for SnO_2 gas sensor.	Acetone, 1-butanol, ethanol, methanol	Tested: 50-1700 ppm		Operation between 50 and 400°C yielded unique vectors for methanol, ethanol, 1-butanol, and acetone, suggesting potential for selectivity. The sensor was exposed for five 40-sec segments.
	ethanol	c		Shivaji University (India), Chonnam National University (South Korea), Solapur University (India) *Pawar, R.C., et al. (University Grants Commission, New Delhi)*	*Surfactant assisted low temperature synthesis of nanocrystalline ZnO and its gas sensing properties* [2010, Sensors and Actuators B. 151(1): 212-218]	Nano-materials	Vertically aligned ZnO nanorods on glass (MOS)	Acetone, ammonia, LPG, ethanol	Tested: 2000 ppm		High sensitivity for acetone. Low operating temperature (tested 200-450°C). High sensitivity and fast response at 275°C.
	ethanol	C		University of Massachusetts Lowell *Li, X., et al. (National Science Foundation)*	*Fabrication and integration of metal oxide nanowire sensors using dielectrophoretic assembly and improved post-assembly processing* [2010, Sensors and Actuators B. 148(2):404-412]	MOS nanowires	Metal oxide nanowires (indium, tin, and indium-tin). Dielectro-phoretic (DEP) assembly onto interdigitated micro-electrodes	Acetone, chloroform, ethanol, methanol, propanol, and benzene.	1 ppm (potentially ppb)	Response: 10 sec recovery: 8-10 min	Good repeatability, however, recovery time increases when exposed to greater concentrations of substance. No response to 1500 ppm was observed below 200°C; performance was enhanced when 440°C was reached. Further optimization of ITO composition may improve sensitivity and selectivity of the sensors. Oxygenated organic compounds seem to cause a higher response than aromatic or chlorinated compounds.

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	P	T	A			Type	Description *(Name)*				
E-nose											
	ethanol	C		University of Southern California *Chen, P.-C., et al.* *(National Science Foundation)*	*A nanoelectronic nose: a hybrid nanowire/carbon nanotube sensor array with integrated micromachined hotplates for sensitive gas discrimination* [2009, Nanotechnology. 20(12)]	e-nose	Chemical sensor array composed of individual In_2O_3 nanowires, SnO_2 nanowires, ZnO nanowires, and SWCNTs with integrated micro-machined hot plates for sensitive gas discrimination	H_2, ethanol, NO_2			Sensor was exposed to three gas injection pulses of different concentrations and compositions, both at room temperature and at 200°C (avoids complications due to moisture interference). The bending energy induced by adsorption is different for different materials, which could allow for gas discrimination in an e-nose system. Sensor behavior was reproducible with small (<1%) error bars.
Formaldehyde											
E-nose											
	formaldehyde	enose		Chinese Academy of Sciences (China), Anhui Polytechnic University (China) *Meng, F.-L., et al.* *(Chinese Academy of Sciences, National Natural Science Foundation of China, National Basic Research Program of China, Anhui Provincial Natural Science Foundation)*	*Electronic chip based on self-oriented carbon nanotube microelectrode array to enhance the sensitivity of indoor air pollutants capacitive detection* [2011, Sensors and Actuators B. 153(1):103-109]	e-nose	Electronic chip with self-oriented CNT microelectrode array	Formaldehyde (best response), toluene (lowest response), ammonia		Response: "tens of seconds" recovery: slowest for toluene	Use of self-oriented CNTs reduces noise and less response to water (weak adsorption between CNTs and water molecules.

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	P	T	A			Type	Description *(Name)*				
Hydrogen											
Chemical											
	H2	C		Los Alamos National Laboratory, ESL ElectroScience *Sekhar, P.K., et al.* *(DOE office of Vehicle Technologies, DOE Hydrogen Fuel Cell and Infrastructure Programs)*	*Application of commercial automotive sensor manufacturing methods for NOx/NH_3 mixed potential sensors for on-board emissions control* [2010, Sensors and Actuators B. 144(1): 112-119]	Potentio-metric	ITO/YSZ/Pt configuration (indium tin oxide/yttria-stabilized zirconia/ platinum)	H_2	Tested: 1,000-20,000 ppm	Response: 3-7 sec	Responds in real-time to varying concentrations of H_2 (1000-20,000 ppm). Cross sensitivity to C_3H_6 (propylene), but not to NO, NO_2, NH_3, or CO. Lower power consumption, compact, simple operation, fast response, direct voltage read out, conducive to commercialization. Sensitivity varied between 0.135 and 0.167 V. Baseline signal ranged from 0-0.04 V.
E-nose											
	H2	e-nose		Saratov State Technical University (Russia), Southern Illinois University at Carbondale, Northeastern University *Sysoev, V.V., et al.* *(Fullbright scholarship and RFBR grant and NSF)*	*The electrical characterization of a multi-electrode odor detection sensor array based on the single SnO_2 nanowire* [2011, Thin Solid Films. 520(3):898-903]	Nano-materials	SnO_2 wedge-like nanowire, multielectrode odor detection sensor array; functionalized by deposition of Pd nanoparticles	Acetone, 2-propanol, CO, and H_2			Fabricating metal oxide single crystals in shape of nanowires may be cost effective.

#	Sort Codes			Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	H2	C		University of Southern California *Chen, P.-C., et al.* *(National Science Foundation)*	*A nanoelectronic nose: a hybrid nanowire/carbon nanotube sensor array with integrated micromachined hotplates for sensitive gas discrimination* [2009, Nanotechnology. 20(12)]	e-nose	Chemical sensor array composed of individual In_2O_3 nanowires, SnO_2 nanowires, ZnO nanowires, and SWCNTs with integrated micro-machined hot plates for sensitive gas discrimination	H_2, ethanol, NO_2			Sensor was exposed to three gas injection pulses of different concentrations and compositions, both at room temperature and at 200°C (avoids complications due to moisture interference). The bending energy induced by adsorption is different for different materials, which could allow for gas discrimination in an e-nose system. Sensor behavior was reproducible with small (<1%) error bars.
Hydrogen sulfide											
Chemical											
	H2S	C		ENEA (Italy) *Penza, M., et al.*	*Functional characterization of carbon nanotube networked films functionalized with tuned loading of Au nanoclusters for gas sensing applications* [2009, Sensors and Actuators B. 140(1): 176-184]	Chemi-resistor	Gold functionalized CNTs	NO_2, NH_3, CO, N_2O, H_2S, SO_2	Sub-ppm: NO_2, H_2S and NH_3 200ppb NO_2 Negligible response for CO, N_2O, and SO_2		Operational temperature: 20-250 °C.
	H2S	C		JiLin University *Liang, X., et al.* *(Natural Science Foundation of China and National Science Fund for Distinguished Young Scholars of China)*	*Solid-state potentiometric H_2S sensor combining NASICON with Pr_6O_{11}-doped SnO_2 electrode* [2007, Sensors and Actuators B. 125(2):544-549]	Potentio-metric	Sodium super ionic conductor (NASICON) and Pr6O11-doped SnO2 sensing electrode	H_2S	5-50 ppm at 200-400 C	Response: 4-8 sec recovery: 12-30 sec	This sensor demonstrated good linear relationship between EMF and the logarithm of H_2S concentration. The results were an improvement over those obtained for pure SnO_2. Sensor demonstrates selectivity against SO_2, NO_2, CH_4, and CO.

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	P	T	A			Type	Description *(Name)*				
	H2S	C		Tongji University (China), Hunan University (China) *Zhang, F., et al.*	*CuO nanosheets for sensitive and selective determination of H_2S with high recovery ability* [2010, J. Phys. Chem. 114:19214-19219]	Nano-materials	CuO leaf-like nanosheet (p-type semiconductor properties)	H_2S	LOD: 2 ppb Linear Range: 20 ppb – 1.2 ppm	Response: 4 sec recovery: 9 sec	Results suggest that sensitivity and recovery time are highly dependent on the working temperature (optimum reported to be 240°C). Negligible responses reported for 100-fold higher concentrations of N_2, O_2, NO, CO, NO_2, and H_2.
Liquid petroleum gas											
Chemical											
	LPG	c		Shivaji University (India), Chonnam National University (South Korea), Solapur University (India) *Pawar, R.C., et al. (University Grants Commission, New Delhi)*	*Surfactant assisted low temperature synthesis of nanocrystalline ZnO and its gas sensing properties* [2010, Sensors and Actuators B. 151(1):212-218]	Nano-materials	Vertically aligned ZnO nanorods on glass (MOS)	Acetone, ammonia, LPG, ethanol	Tested: 2000 ppm		Demonstrated good sensitivity for acetone at a low operating temperature (tested 200-450°C). Best sensitivity and fast response reported at 275°C.
Methane											
Chemical											
	methane	C		Beijing University of Chemical Technology (China), Case Western Reserve University *Chen, A., et al. (National Natural Science Foundation of China and Beijing Natural Science Foundation)*	*Methane gas-sensing and catalytic oxidation activity of SnO_2-In_2O_3 nanocomposites incorporating TiO_2* [2008, Sensors and Actuators B. 135(1):7-12]	Chemi-resistive	$InO_{1.5}$ – SnO_2 nanocompo-sites incorporating TiO_2	methane			Concluded that the selectivity of the MOS may have been aided by addition of more metal oxides. Overall performance depended on composition and operational temperatures. Addition of TiO_2 was reported to improve the response to methane and better select against CO.

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	P	T	A			Type	Description *(Name)*				
	methane	c		Jadavpur University (India) *Basu, P.K., et al.*	*Low temperature methane sensing by electro-chemically grown and surface modified ZnO thin films* [2008, Sensors and Actuators B. 135(1): 81-88]	Thin film	Planar resistive and metal-insulator-metal sensors using electro-chemically grown nano-crystalline-nanoporous ZnO thin films modified by dipping in an aqueous solution of $PdCl_2$	Methane	1% methane in nitrogen and 1% methane in air	Response: planar: 5 sec, metal-insulator-metal (MIM): 2.7 sec recovery: planar: 22.7 sec, MIM:16 sec	Operational temperatures were reduced to 70 and 100°C for each of the two configurations.
	methane	C		Kyushu University (Japan), Japan Society for the Promotion of Sciences (Japan) *Plashnitsa, V.V., et al.* *(MEXT, The Grant-in-Aid for Scientific Research on Priority Area, Nanoionics)*	*Zirconia-based electrochemical gas sensors using nano-structured sensing materials aiming at detection of automotive exhausts* [2009, Electrochimica Acta. 54(25):6099-6106]	Potentio-metric	YSZ-based planar sensors using nano-structured sensing electrodes	Ammonia, NO_2, CO, CH_4, C_3H_8, C_3H_6, NO	Highly selective at 20-200 ppm		This sensor is appropriate for harsh environments (600°C) such as automotive exhausts. Sensing characteristics (sensitivity, response time, recovery time) are dependent on sputtering time of Au sensing electrodes.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
Methanol											
Chemical											
	methanol	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al. (Shanghai Pujiang Program, State Key Lab of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, & National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1):63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance Recovery: begins 3-5 sec after injection of dry air	
	methanol	C		Isalamic Azad University (Iran), K. N. Toosi University of Technology (Iran) *Amini, A., Ghafarinia, V.*	*Utilizing the response patterns of a temperature modulated chemoresistive gas sensor for gas diagnosis* [2011, IOP Conf. Ser.: Mater. Sci. Eng. 17 012408]	Commer-cial (modified)	Staircase heating voltage waveform applied to micro-heater for SnO_2 gas sensor	Acetone, 1-butanol, ethanol, methanol	Tested: 50-1700 ppm		Operation between 50 and 400°C yielded unique vectors for methanol, ethanol, 1-butanol, and acetone, suggesting potential for selectivity. The sensor was exposed for five 40-sec segments.

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	P	T	A			Type	Description *(Name)*				
	methanol	C		University of Massachusetts Lowell *Li, X., et al.* *(National Science Foundation)*	*Fabrication and integration of metal oxide nanowire sensors using dielectrophoretic assembly and improved post-assembly processing* [2010, Sensors and Actuators B. 148(2):404-412]	MOS nanowires	Metal oxide nanowires (indium, tin, and indium-tin). Dielectro-phoretic (DEP) assembly onto interdigitated micro-electrodes	Acetone, chloroform, ethanol, methanol, propanol, and benzene	1 ppm (potentially ppb)	Response: 10 sec recovery: 8-10 min	Good repeatability, however, recovery time increases when exposed to greater concentrations of substance. No response to 1500 ppm was observed below 200°C; performance was enhanced when 440°C was reached. Further optimization of ITO composition may improve sensitivity and selectivity of the sensors. Oxygenated organic compounds cause a higher response than aromatic or chlorinated compounds.
Methyl ethyl ketone											
Chemical											
	MEK	C		Ehime University (Japan), National Institute for Materials Science (Japan) *Mori, M., et al.* *(Japan Science and Technology Agency)*	*Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air* [2009, Sensors and Actuators B. 143(1):56-61]	Potentio-metric	Pt|YSZ|Pt structure	VOCs, specifically acetic acid, methyl ethyl ketone, ethanol, benzene, toluene, o- and p-xylene	Sub-ppm	Ethanol response: 4-204 sec (quickest for 0.5 ppm at 500°C) recovery: 190-480 sec (quickest for 1 ppm at 500°C)	400-500°C, highest response at 400°C. Increased temperatures decreased sensitivity but modified response and recovery times. Analysis of multidimensional plots of sensor output at various temperatures suggests possible selective sensing of different VOCs.

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	P	T	A			Type	Description *(Name)*				
NOx											
Chemical											
	N Ox	C		The Ohio State University *Yang, J.-C., Dutta, P.K.D.* *(DOE NETL)*	*Promoting selectivity and sensitivity for a high temperature YSZ-based electrochemical total NOx sensor by using a Pt-loaded zeolite Y filter* [2007, Sensors and Actuators B. 125(1):30-39]	Potentio-metric	Study examines Pt electrode covered with Pt containing zeolite Y (PtY) and WO3 as electrode materials	NOx (interferents: CO, propane, NH_3, CO_2, O_2, and H_2O)			WO_3 is used as sensing electrode due to its poor reactivity with NOx (assumes that and unmodified NOx species will reach the WOx/YSZ to produce a more sensitive response).
Nitrogen dioxide											
Chemical											
	N O2	C		*Achhab, M., Shanack, H., Schierbaum, K.*	*NO_2 sensing properties of WO_3 nanorods grown on mica* [2011, Physica Status Solidi A. 208(6):1229-1234]	Nano-materials	One-dimensional WO_3 nanostructures with gold electrodes	NO_2	~0.1 ppm (transient WO_3 needles)	Response: "quick" recovery: slow, 10,000 sec using mica substrate	Sensor is more sensitive towards NO2 with increased humidity, up to 40%. Maximum operation temperature was reported to be 260°C, due to limited gold contact stability. A drift was observed at concentrations over 0.4 ppm which may be attributed to temperature effects from the internal heater.
	N O2	C		Chiang Mai University (Thailand), National Electronics and Computer Technology Center (Thailand) *Kruefu, V., et al.*	*Selectivity of flame-spray-made Nb/ZnO thick films towards NO_2 gas* [2011, Sensors and Actuators B. 156(1):360-367]	Nano-materials	Unloaded ZnO and niobium (Nb)/ZnO nanoparticles for the detection of NO_2 (semiconducting gas-sensing behavior)	NO_2	Tested: 0.1-4 ppm Limit: 20 ppb (est.)	Response: 27 sec with 4 ppm NO_2 at 300°C	Detection limit is estimated to be 20 ppb, however testing is limited to 100 ppb due to gas mixing capability of the system. Sensor recovers to within 10% of baseline value after several NO_2 exposures. Selectivity to NO_2 was tested with C_2H_3OH, CO, and acetone. Authors reported good selectivity to 4 ppm NO_2 concentration at 350°C. Niobium enhances NO_2 adsorption reaction.

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	P	T	A			Type	Description *(Name)*				
	NO2	C		ENEA (Italy) *Penza, M., et al.*	*Functional characterization of carbon nanotube networked films functionalized with tuned loading of Au nanoclusters for gas sensing applications* [2009, Sensors and Actuators B. 140(1):176-184]	Chemi-resistor	Gold functionalized CNTs	NO_2, NH_3, CO, N_2O, H_2S, SO_2	Sub-ppm: NO_2, H_2S and NH_3 200 ppb NO_2 Negligible response for CO, N_2O, and SO_2		Operational temperature: 20-250°C.
	NO2	C		Korea University (Republic of Korea) *Kim, Y.-S., et al*	*CuO nanowire gas sensors for air quality control in automotive cabin* [2008, Sensors and Actuators B. 135(1):298-303]	Nano-materials	CuO nanowires grown by thermal oxidation of Cu foil. P-type oxide semiconductor	CO, NO_2	Tested: 10, 50, 100 ppm CO; 1-5 ppm, 10, 50 and 100 ppm NO_2		Sensor resistance was reported to decrease with NO_2 concentrations between 30 and 100 ppm, and increase with NO_2 concentrations between 1 and 5 ppm. Resistance increased with exposure to 10, 50, and 100 ppm of CO. Sensor was tested at 300°C and 370°C, using 300 mW and 400 mW of power, respectively.
	NO2	C		Kyushu University (Japan), Japan Society for the Promotion of Sciences (Japan) *Plashnitsa, V.V., et al.* *(MEXT, The Grant-in-Aid for Scientific Research on Priority Area, Nanoionics)*	*Zirconia-based electrochemical gas sensors using nano-structured sensing materials aiming at detection of automotive exhausts* [2009, Electrochimica Acta. 54(25):6099-6106]	Potentio-metric	YSZ-based planar sensors using nano-structured sensing electrodes	Ammonia, NO_2, CO, CH_4, C_3H_8, C_3H_6, NO	Highly selective at 20-200 ppm		This sensor is appropriate for harsh environments (600°C) such as automotive exhausts. Sensing characteristics (sensitivity, response time, recovery time) are dependent on sputtering time of Au sensing electrodes.
	NO2	C		University of Leeds *Xiong, W., and Kale, G.M.*	*Electrochemical NO_2 sensor using a $NiFe_{1.9}Al_{0.1}O_4$ oxide spinel electrode* [2007, Anal. Chem.. 79(10:3561-3567]	Solid state	(Sc2O3)0.08 (ZrO2)0.92 (ScSZ) electrolyte solid and NiFe1.9Al0.1) 4 oxide spinel electrode	NO_2		Response: 8 sec recovery: 10 sec	Sensor response is rapid, reproducible at 703°C and 740°C (appropriate for automobile applications), and selective against O_2, CO, and CH_4.

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	NO2	C		University of Massachusetts Lowell *Surwade, S.P., et al.* *(University of Massachusetts Lowell, MTC-funded Nanomanufac-turing Center for Excellence, NSF)*	*Nitrogen dioxide vapor detection using poly-o-toluidine* [2009, Sensors and Actuators B. 143(1): 454-457]	Conduct-ing polymer film	Doped thin film conducting polymer (poly-o-toluidine) deposited on plastic substrates	NO_2	Tested: 10-100 ppm		Reaction on polymer film can be reversed with UV irradiation for <2 minutes if exposed to concentrations between 10 and 100 ppm. Without UV exposure, recovery took 45-90 minutes.
E-nose											
	NO2	e-nose		CNR-IMM-Istituto per la Microelettronica ed i Microsistemi, University Campus (Italy), ITC-irst – Microsystems Division, (Italy) *Francioso, L., et al.*	*Linear temperature microhotplate gas sensor array for automotive cabin air quality monitoring* [2008, Sensors and Actuators B. 134(2): 660-665]	e-nose	MOS, MEMS	CO, NO_2, SO_2			Investigates a temperature gradient electronic nose for increasing sensitivity. Total power consumption below 130 mW with power supplied to voltage heater. Temperature was increased in a 100°C-wide temperature window. Sensor exhibited faster response times for higher temperatures (300-400°C) and higher gas concentrations. Signal was lost when sensor was operated below 280°C. Sensor was exposed to injected gas for 30 minutes, followed by 90 minutes of recovery in dry air. PCA was used to identify and analyze patterns in data.
	NO2	C		University of Southern California *Chen, P.-C., et al.* *(National Science Foundation)*	*A nanoelectronic nose: a hybrid nanowire/carbon nanotube sensor array with integrated micromachined hotplates for sensitive gas discrimination* [2009, Nanotechnology. 20(12)]	e-nose	Chemical sensor array composed of individual In_2O_3 nanowires, SnO_2 nanowires, ZnO nanowires, and SWCNTs with integrated micro-machined hot plates for sensitive gas discrimination	H_2, ethanol, NO_2			Sensor was exposed to three gas injection pulses of different concentrations and compositions, both at room temperature and at 200°C (avoids complications due to moisture interference). The bending energy induced by adsorption is different for different materials, which could allow for gas discrimination in an e-nose system. Sensor behavior was reproducible with small (<1%) error bars.

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	P	T	A			Type	Description *(Name)*				
Nitric oxide											
Chemical											
	NO	C		Florida International University, Inje University (Republic of Korea) *Verma, V.P., et al.* *(Dissertation Year Fellowship from University Graduate School, Florida International University)*	*Nitric oxide gas sensing at room temperature by functionalized single zinc oxide nanowire* [2010, Materials Science and Engineering. 171(1-3): 45-49]	Nano-materials	Cr nanoparticle decorated single ZnO nanowire sensor	NO	46% sensitivity for 10 ppm. LOD: 1.5 ppm	Recovery: 20 sec using UV light	In this system, Cr particles act as a catalyst to transform NO into NO_2, which can then be detected at room temperature. The sensor is reported to be selective for NO when tested with N_2, CO and CO_2 gases. Sensor functioned well even after 10 days.
	NO	C		I-Shou University (Taiwan) *Wang, S.-H., et al.* *(National Science Council)*	*A nitric oxide gas sensor based on Rayleigh surface acoustic wave resonator for room temperature detection* [2011, Sensors and Actuators B. 156(2): 668-672]	SAW	Rayleigh SAW resonator with polyaniline/ tungsten oxide nano-composite thin film	NO (selective against NO_2 and CO_2)	1.2ppm frequency shift when exposed to 138 ppb	Response and recovery: 20-80 sec	Exhibited reversibility and repeatability. Room temperature operation.
	NO	C		Kyushu University (Japan), Japan Society for the Promotion of Sciences (Japan) *Plashnitsa, V.V., et al.* *(MEXT, The Grant-in-Aid for Scientific Research on Priority Area, Nanoionics)*	*Zirconia-based electrochemical gas sensors using nano-structured sensing materials aiming at detection of automotive exhausts* [2009, Electrochimica Acta. 54(25): 6099-6106]	Potentio-metric	YSZ-based planar sensors using nano-structured sensing electrodes	Ammonia, NO_2, CO, CH_4, C_3H_8, C_3H_6, NO	Highly selective at 20-200 ppm		This sensor is appropriate for harsh environments (600°C) such as automotive exhausts. Sensing characteristics (sensitivity, response time, recovery time) are dependent on sputtering time of Au sensing electrodes.

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	P	T	A			Type	Description *(Name)*				
N_2O											
Chemical											
	N2O	C		ENEA (Italy) *Penza, M., et al.*	*Functional characterization of carbon nanotube networked films functionalized with tuned loading of Au nanoclusters for gas sensing applications* [2009, Sensors and Actuators B. 140(1): 176-184]	Chemi-resistor	Gold functionalized CNTs	NO_2, NH_3, CO, N_2O, H_2S, SO_2	Sub-ppm: NO_2, H_2S and NH_3 200ppb NO_2 Negligible response for CO, N_2O, and SO_2		Operational temperature: 20-250 °C.
Octane											
Chemical											
	octane	C, SAW		Instituto de Fisica Aplicada, CSIC (Spain) and Fundacion Inasmet, Mikeletegi (Spain) *Sayago, I., et al (Spanish MEC)*	*Surface acoustic wave gas sensors based on polyisobutylene and carbon nanotube composites* [2011, Sensors and Actuators B, 1(10): 1-5]	SAW		Octane, toluene, H_2, CO, NO_2, NH_3 (selective for VOCs)		Response: 30 sec recovery: 30 sec	Sensor was tested in a controlled environment (temp 23°C, dry air, constant flow rate) and was reported to be reversible over the course of the 45 day continuous testing period. Addition of nanotubes in higher percentages was not seen to increase response, and made the response worse in most cases. Sensor response frequency was not reported to be modified by the presence of NO_2, NH_3, H_2, or CO, indicating a sensor selective for VOCs.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
Propanol											
Chemical											
	propanol	C		University of Massachusetts Lowell *Li, X., et al.* *(National Science Foundation)*	*Fabrication and integration of metal oxide nanowire sensors using dielectrophoretic assembly and improved post-assembly processing* [2010, Sensors and Actuators B. 148(2):404-412]	MOS nanowires	Metal oxide nanowires (indium, tin, and indium-tin). Dielectro-phoretic (DEP) assembly onto interdigitated micro-electrodes	Acetone, chloroform, ethanol, methanol, propanol, and benzene.	1 ppm (potentially ppb)	Response: 10 sec recovery: 8-10 min	Good repeatability, however, recovery time increases when exposed to greater concentrations of substance. No response to 1500 ppm was observed below 200°C; performance was enhanced when 440°C was reached. Determined that further optimization of ITO composition may improve sensitivity and selectivity of the sensors. Oxygenated organic compounds cause a higher response than aromatic or chlorinated compounds.
2-Propanol											
E-nose											
	2-propanol	e-nose		Saratov State Technical University (Russia), Southern Illinois University at Carbondale, Northeastern University *Sysoev, V.V., et al.* *(Funding: Fullbright scholarship and RFBR grant and NSF)*	*The electrical characterization of a multi-electrode odor detection sensor array based on the single SnO_2 nanowire* [2011, Thin Solid Films. 520(3):898-903]	e-nose	SnO2 wedge-like nanowire, multielectrode odor detection sensor array; functionalized by deposition of Pd nanoparticles	Acetone, 2-propanol, CO, and H_2			Fabricating metal oxide single crystals in shape of nanowires may be cost effective.

#	Sort Codes			Organization *Author* (Sponsor)	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
Sulfur dioxide											
Chemical											
	SO2	C		ENEA (Italy) *Penza, M., et al.*	*Functional characterization of carbon nanotube networked films functionalized with tuned loading of Au nanoclusters for gas sensing applications* [2009, Sensors and Actuators B. 140(1):176-184]	Chemi-resistor	Gold functionalized CNTs	NO_2, NH_3, CO, N_2O, H_2S, SO_2	Sub-ppm: NO_2, H_2S and NH_3 200 ppb NO_2 Negligible response for CO, N_2O, and SO_2		Operational temperature: 20-250 °C.
	SO2	C		JiLin University (China) *Liang, X., et al.* *(Natural Science Foundation of China)*	*Solid-state potentiometric SO_2 sensor combining NASICON with V_2O_5-doped TiO_2 electrode* [2008, Sensors and Actuators B. 134(1):25-30]	Potentio-metric	based on NASICON (sodium super ionic conductor) and V_2O_5-doped TiO_2 sensing electrode	SO_2	1-50 ppm at 200-400 C	Response: 10 sec recovery: 35 sec	A small amount of V_2O_5 doping may promote catalytic activity of sensing electrode and increases sensitivity (using more increased response time and decreased the catalytic ability, >10% weight). Appears to be selective against NO, NO_2, CH_4, CO, NH_3, and CO_2.
E-nose											
	NO2	e-nose		CNR-IMM-Istituto per la Microelettronica ed i Microsistemi, University Campus (Italy), ITC-irst – Microsystems Division, (Italy) *Francioso, L., et al.*	*Linear temperature microhotplate gas sensor array for automotive cabin air quality monitoring* [2008, Sensors and Actuators B. 134(2):660-665]	e-nose	MOS, MEMS	CO, NO_2, SO_2			Investigates a temperature gradient electronic nose for increasing sensitivity. Total power consumption below 130 mW with power supplied to voltage heater. Temperature was increased in a 100°C-wide temperature window. Sensor exhibited faster response times for higher temperatures (300-400°C) and higher gas concentrations. Signal was lost when sensor was operated below 280°C. Sensor was exposed to injected gas for 30 minutes, followed by 90 minutes of recovery in dry air. PCA was used to identify and analyze patterns in data.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
Tetrahydrofuran											
Chemical											
	THF	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al. (Shanghai Pujiang Program, State Key Laboratory of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, and the National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1):63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance recovery: begins 3-5 sec after injection of dry air	

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
Toluene											
Chemical											
	toluene	C		Donghua University (China), Leibniz Institute of Polymer Research Dresden (Germany) *Fan, Q., et al.* *(Shanghai Pujiang Program, State Key Laboratory of Chemical Fibers and Polymer Materials, Doctorate Innovation Foundation of Donghua University, and the National Natural Science Foundation for Distinguished Young Scholar of China)*	*Vapor sensing properties of thermoplastic polyurethane multifilament covered with carbon nanotube networks* [2011, Sensors and Actuators B. 156(1):63-70]	Nano-materials	Thermoplastic polyurethane multifilament – carbon nanotubes (TPU-CNTs) composite (conductive polymer)	VOCs, specifically benzene, toluene, $CHCl_3$, THF, ethanol, acetone, and methanol		Response: 10 sec to 50% max relative resistance recovery: begins 3-5 sec after injection of dry air	
	toluene	C		Ehime University (Japan), National Institute for Materials Science (Japan) *Mori, M., et al.* *(Japan Science and Technology Agency)*	*Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air* [2009, Sensors and Actuators B. 143(1):56-61]	Potentio-metric	Pt|YSZ|Pt structure	VOCs, specifically acetic acid, methyl ethyl ketone, ethanol, benzene, toluene, o- and p-xylene	Sub-ppm	Ethanol response: 4-204 sec (quickest for 0.5 ppm at 500°C) recovery: 190-480 sec (quickest for 1 ppm at 500°C)	400-500°C, highest response at 400°C. Increased temperatures decreased sensitivity but modified response and recovery times. Analysis of multidimensional plots of sensor output at various temperatures suggests possible selective sensing of different VOCs.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
	toluene	C, SAW		Instituto de Fisica Aplicada, CSIC (Spain) and Fundacion Inasmet, Mikeletegi (Spain) *Sayago, I., et al (Spanish MEC)*	*Surface acoustic wave gas sensors based on polyisobutylene and carbon nanotube composites* [2011, Sensors and Actuators B, 1(10):1-5]	SAW		Octane, toluene, H_2, CO, NO_2, NH_3 (selective for VOCs)		Response: 30 sec recovery: 30 sec	Sensor was tested in a controlled environment (temp 23°C, dry air, constant flow rate) and was reported to be reversible over the course of the 45-day continuous testing period. Addition of nanotubes in higher percentages was not reported to increase response, rather diminished the response in most cases. The sensor response frequency was not found to be modified by the presence of NO_2, NH_3, H_2, or CO, indicating a sensor selective for VOCs.
E-nose											
	toluene	enose		Chinese Academy of Sciences (China), Anhui Polytechnic University (China) *Meng, F.-L., et al. (Chinese Academy of Sciences, National Natural Science Foundation of China, National Basic Research Program of China, Anhui Provincial Natural Science Foundation)*	*Electronic chip based on self-oriented carbon nanotube microelectrode array to enhance the sensitivity of indoor air pollutants capacitive detection* [2011, Sensors and Actuators B. 153(1):103-109]	e-nose	Electronic chip with self-oriented CNT microelectrode array	Formaldehyde (best response), toluene (lowest response), ammonia		Response: "tens of seconds" recovery: slowest for toluene	Use of self-oriented CNTs reduces noise and less response to water (weak adsorption between CNTs and water molecules.

#	Sort Codes			Organization *Author (Sponsor)*	Abbreviated Citation	Sensor Technology		Pollutant/ Parameter	Reported Detection Capability	Response/ Recovery Time	Application and Operation Context
	P	T	A			Type	Description *(Name)*				
VOCs											
E-nose											
	VOCs	e-nose		University of Nevada, Reno *Je, C.-H., et al.*	*Development and application of a multi-channel monitoring system for near real-time VOC measurement in a hazardous waste management facility* [2007, Science of the Total Environment. 382(2-3):364-374]	e-nose	Array of PID sensors	VOCs		"Real time"	Setting: walk-in hood in a hazardous waste management facility. System consists of an array of PID sensors and a networked control program providing operational schematic diagrams, performs data analysis, and illustrates real-time graphical displays. Shows that real-time monitoring system may be effective for early warning detection of hazardous chemicals and for predicting the performance of adsorption filters used for VOC removal.
	VOCs	e-nose		University of Pune (India) *Botre, B.A., et al.*	*Embedded electronic nose and supporting software tool for its parameter optimization* [2010, Sensors and Actuators B. 146(2):453-459]	e-nose	MOS sensors by Figaro	VOCs	Resolution: 250 ppm; Alcohol ID = 100%, concentration estimation 98%, mixture analysis 95%		Supporting software extracts unique characteristics from sensor array response patterns to various odors and allows for easy identification. The data acquisition virtual instrument allows user to specify specific sensor parameters (e.g., heater, on/off period, odor pulse period, selection of number of gas sensors in the array, sampling rate, and data acquisition time). The VOCs tested in this study were alcohols, separately and mixed with water.
Xylenes											
Chemical											
	xylenes	C		Ehime University (Japan), National Institute for Materials Science (Japan) *Mori, M., et al.* *(Japan Science and Technology Agency)*	*Detection of sub-ppm level of VOCs based on a Pt/YSZ/Pt potentiometric oxygen sensor with reference air* [2009, Sensors and Actuators B. 143(1):56-61]	Potentio-metric	Pt|YSZ|Pt structure	VOCs, specifically acetic acid, methyl ethyl ketone, ethanol, benzene, toluene, o- and p-xylene	Sub-ppm	Ethanol response: 4-204 sec (quickest for 0.5 ppm at 500°C) recovery: 190-480 sec (quickest for 1 ppm at 500°C)	400-500°C, highest response at 400°C. Increased temperatures decreased sensitivity but modified response and recovery times. Analysis of multidimensional plots of sensor output at various temperatures suggests possible selective sensing of different VOCs.

[a] This table highlights sensor technologies/techniques reported in selected conference proceedings, poster abstracts, peer-reviewed journals, and university and other organization (e.g., company) web pages; at the time of the publications reviewed, these sensors were in the research and development stage. The publications reflected in this table were gathered as part of a later literature review conducted in early 2013 that specifically targeted chemical detection techniques and electronic noses (e-noses).

The table is organized by pollutant in alphabetical order with the targeted study subset shaded green and additional pollutants shaded grey. Sensors reported to detect more than one pollutant are repeated across the respective pollutant sections. The entries are further grouped by sensing technique, and then by research institution (in alphabetical order).

APPENDIX F:

OVERVIEW OF SENSING TECHNOLOGIES/TECHNIQUES

APPENDIX F:
OVERVIEW OF SENSING TECHNOLOGIES AND TECHNIQUES

Brief descriptions of selected sensing technologies and techniques discussed in this report are presented in this appendix, together with associated architecture/infrastructure approaches from the recent literature. These technologies and techniques are grouped according to three basic sensing principles: chemistry, ionization, and spectroscopy.

F.1 CHEMISTRY

Chemical sensors typically contain a sensing substrate, usually a metal or polymer film, that interacts with a pollutant to produce measurable changes in physical properties of the substrate (such as electrical resistivity or mass). Several types of chemical sensors are highlighted below.

F.1.1 Electrochemical Gas Sensors

Electrochemical sensors are typically composed of an electrochemical cell containing an electrolyte (solid or liquid) and electrodes, one referred to as the working electrode and the other as the reference or counter electrode. An incoming gas reacts at the working electrode and creates a measurable difference in electrical potential between the working and reference/counter electrodes proportional to the target gas concentration (Capone et al. 2003).

Recent research in this area includes the use of nanoscale materials. A common research focus is on improving sensitivity, selectivity, and cost efficiency of sensors by varying electrolyte or electrode composition.

Architecture and infrastructure approaches reported for these electrochemical sensors include fixed/semi-portable units and mountable sensors with micro- and miniature-scale platforms.

F.1.2 Metal Oxide Semiconductors (MOS)

These metal oxide sensors, also frequently referred to as chemiresistors, typically consist of an *n*-type or *p*-type oxide thick, thin or porous film, metal electrodes, and an internal heating device to increase the reaction rate. The incoming gas or pollutant adsorbs to the film, typically transition or heavy metal oxides such as SnO_2, WO_3, or ZnO (research summaries also note In_2O_3, $BaTiO_3$-CuO, TiO_2 and others) deposited on a thin layer of silicon, where it then undergoes catalytic oxidation. The oxidation produces a change in resistance of the sensing material, which is generally proportional to the concentration of the gas or pollutant present (Capone et al. 2003).

Recent research indicates active investigation of various *n*-type or *p*-type oxide film compositions, electrode composition, and internal heating temperature to create more sensitive, responsive and cost-effective sensing systems. Nanoscale materials represent an active research area, using wires, rods, particles, and carbon nanotubes (CNTs) with sensing substrates in order to increase reactive surface area, thus increasing sensitivity and decreasing reaction time. Room temperature operation is also being studied for MOS sensors (operational temperatures for these sensors have typically ranged from 200 to 500ºC).

Architecture and infrastructure approaches reported for MOS sensors include fixed/semi-portable sensor units, mountable sensors with micro- and miniature-scale platforms, and wearable sensors for participatory sensing.

F.1.3 Polymer Films *(organic and hybrid)*

Organic polymer films are being used as sensing materials, with thin-film polymers providing conductive or fluorescent surfaces that are often highly sensitive. Advantages of using organic films over inorganic films include the ability to operate at room temperature. Thin-film polymers identified from the review of recent sensor literature include poly(2-(acetoacetoxy)ethyl methacrylate) (PAAEMA), polyaniline (PANi), polypyrrole (PPy), and N,N'-(glycine t-butylester)-3,4,9,10-perylendediimide. These films are sometimes modified with nanomaterials such as single walled carbon nanotubes (SWCNTs) to increase sensitivity.

As grouped for this report, this category also includes hybrid films composed of inorganic oxides and organic materials. For these hybrids, the limited chemical reactivity of inorganic oxides is balanced by the high specific reactivity of the organic substances. Similarly, the limited thermal stability of the organic material is balanced by the thermally stable inorganic oxides. Hybrid films have many additional advantages, including ease of fabrication, controllable porosity and surface characteristics, high thermal stability, and good flexibility in sensor reactivity and specificity (Bescher 1999).

Architecture and infrastructure approaches reported for polymer film sensors include mountable sensors with micro- and miniature-scale platforms, fixed/semi-portable units, handheld devices, and visual sensing systems.

F.1.4 Surface Acoustic Wave

These sensors contain a chemical film that selectively adsorbs the gaseous analyte to produce a measurable change in mass, which is detected by change in surface propagating waves (Kryshtal and Medved 2002). Recent research for these piezoelectric-type sensors has focused on the use of various sensing materials and methods to reduce power consumption.

Architecture and infrastructure approaches reported for these sensors include mountable systems with micro- and miniature-scale platforms.

F.1.5 Nanotechnology-Based Sensors

While this category is cross-cutting, it is grouped here because many of the sensors that use nanotechnology involve chemical techniques.

Nanotechnology advances are prominent in recent sensor research, as nanocrystalline metal oxides, carbon nanotubes (CNTs), organic nanocomposites, and other nanomaterials and coatings are being used to develop increasingly small-scale sensors. Some nanoscale materials are being tapped as stand-alone sensing films, while others are incorporated into integrated systems to improve sensing characteristics via increased surface area.

A variety of architectures and approaches are reported for sensor systems using nanotechnology, as reflected in the other summaries within this appendix.

F.2 IONIZATION

These sensors have traditionally existed as fixed, non-portable sensors; however, some sensors such as the photoionization detector and mass spectrometer are being modified to

make them more portable and cost efficient. Research highlights relevant to portable systems in which ionization is a primary detection principle are presented below.

F.2.1 Mass Spectrometry

Mass spectrometers consist of an ion source, analyzer, detector, and data recorder. Several elements of these systems can be changed to address specific chemical species. Major ion formation techniques include electron impact ionization, chemical ionization, fast atom bombardment, electroscopy ionization, and matrix-assisted laser desorption ionization. Analyzers include magnetic, electrostatic, quadrupole, ion trap, time of flight, and Fourier transform ion cyclotron resonance. Detector components include secondary electron multipliers, photomultipliers, and multi-channel plates. Architecture and infrastructure approaches reported for sensors that use mass spectrometry include handheld and other portable devices.

F.2.2 Gas Chromatography

In traditional gas chromatography (GC) systems, the gas sample (pure or mixed) is injected into a chromatograph where it is selectively dissolved or absorbed in a solid or syrup-like substrate-lined flow column. The components of the gas sample interact with the absorbing agent at different rates as they travel through the column, allowing for selective separation. A computer chart is generated depicting the rate at which various components of the gas sample exit the column. The general rate peaks are associated with specific chemicals or chemical species. In systems that use GC for selective separation, photoionization and flame ionization detectors (PIDs and FIDs) and mass spectrometers are the detectors typically used.

Recent research relevant to portable sensors involves the addition of gas pre-concentrators to improve detection levels. Architecture and infrastructure approaches reported for gas chromatography detection techniques include handheld and larger portable systems.

F.2.3 Photoionization Detector (PID)

Photoionization detectors capitalize on substance-specific ionization potentials (IP). The core component of this system is an ultraviolet (UV) lamp which emits a specific light frequency (measured in electron volts, eV). Gases with IPs less than or equal to that of the lamp are detectable. Concentrations of these gases are measured based on the amount of ions (resulting from absorption of photons from the UV lamp) deposited on a collecting electrode. Nearly twenty years ago, PIDs were identified as 'go to' devices for detecting VOCs (EPA 1994). Note that costs can be relatively high (e.g., several thousand dollars).

Image source: http://www.intlsensor.com/pdf/photoionization.pdf.

F.2.4 Flame Ionization Detector (FID)

Flame ionization detectors are commonly part of gas chromatography systems. Incoming gas samples are mixed with hydrogen before being introduced to a flame, which causes the release of electrons. The electrons are collected at electrodes and converted into electrical output signals. Sensitivity is influenced by gas flow rates (before and after flame ionization), flame jet exit diameter, positioning of components, and detector temperature (Hinshaw 2005).

F.3 SPECTROSCOPY

Spectroscopic techniques involve examining the substance-specific emission and/or absorption spectra resulting from the interaction between molecules and an energy source, such as light. This technique operates on the principle that chemical substances absorb light at specific frequencies. This category includes, and is often referred to as, optical-based sensing techniques.

F.3.1 Broadband Molecular Absorption Spectroscopy

Molecular absorption spectroscopy techniques function on the principle that bonds of organic compounds absorb different frequencies of light. Currently in broadband molecular absorption spectroscopy, infrared, UV, and visible light sources can be used to selectively detect some specific chemicals. A light source is directed at the target gas sample and resulting light absorption patterns are observed. Absorption peak patterns are analyzed to identify of the compound, while the intensity of the peaks are analyzed to identify the concentration of the compound. Research in this area includes nanoscale technologies and multiple-line integrated absorption spectroscopy (MLIAS), a technique that combines many different spectroscopic readings to obtain a greater degree of sensitivity and accuracy.

Architecture and infrastructure approaches reported for sensors using absorption spectroscopy include fixed/semi-portable units, handheld sensors, mountable sensors with micro- and miniature-scale platforms, wearable sensors, and vehicle-mounted units.

F.3.2 Laser Absorption Spectroscopy

This method covers a variety of lasers, including quantum cascade lasers (QCLs), tunable diode lasers, and organic micro-lasers adjusted to operate at, or within, a specific light frequency range. Thus, pollutant-specific sensors can be fabricated based on the knowledge of corresponding light absorption spectra. Some devices using this technology may also include optical fibers, a detection path or cell, and a photodetector. One investigated component of these systems is the tuning fork. Efforts are focused on developing more responsive polymer coatings and polymer nanowires in order to increase sensitivity of sensors. Research is also focused on the development and optimization of laser systems, as well as increased portability of sensors. Specific techniques under further development include cavity enhanced absorption spectroscopy (CEAS) and tunable diode laser absorption spectroscopy (TDLAS).

Architecture and infrastructure approaches reported for sensors using laser absorption spectroscopy include fixed/semi-portable units, handheld devices, mountable sensors with micro- and miniature-scale platforms, remote sensor/monitoring units, wearable sensors, and wireless sensor networks.

F.3.3 Molecular and Atomic Emission Spectroscopy

Luminescence

Luminescence is a form of ‘cool body’ radiation, meaning reactions are not induced by a heat source. Emissions occur after a sample gas has absorbed energy from a source (such as radiation or chemical reaction), leaving it in an unstable excited state. As the substance undergoes the transition back to the preferred ground state, the absorbed energy is released as light. Because only a small percentage of reacting molecules emit light, these sensors can be

chemical specific. The techniques in this category include bioluminescence, cataluminescence, chemiluminescence, and fluorescence.

Architecture and infrastructure approaches reported for these sensors include fixed/semi-portable units, handheld devices, mountable sensor with micro- and miniature-scale platforms, and visual sensing systems.

Laser-Induced Breakdown Spectroscopy (LIBS)

This technique uses a high-power, pulsed laser beam to produce laser-induced plasma which then vaporizes, atomizes, and excites the atoms of the gas sample. The resulting emission intensities and frequencies are used to determine the identity and concentration of the substance.

Architecture and infrastructure approaches reported for LIBS sensors include fixed/semi-portable units, handheld units, and vehicle mounted units

F.3.4 Light Scattering (Nephelometry)

Light scattering or nephelometric techniques measure the irradiance of scattered light resulting from contact with particulates within a specified volume or area defined by an intersection of a light beam and the field of view of an optical detector. The resulting electrical signal is proportional to the concentration of particulates present. This technique is very responsive to rapid changes in particulate concentrations, but it is only responsive to substances with constant optical properties.

Architecture and infrastructure approaches reported for light-scattering sensors include fixed/semi-portable sensor systems.

F.3.5 Light Detection and Ranging (LIDAR)

This detection technique can be applied to multiple spectroscopy sensing systems, including laser absorption and fluorescence emission. A laser or other light source is used to illuminate the target gas sample. The backscattered light is recorded and analyzed to determine sample composition and concentration. Infrastructure requirements are substantial (and these translate to substantial costs).

Architecture and infrastructure approaches reported for LIDAR sensors include mounted sensors with micro- and miniature-scale platforms, remote sensing/monitoring, and vehicle mounted units.

SELECTED REFERENCES

Bescher, E., and J.D. Mackenzie. (1999). *Hybrid Organic-Inorganic Sensors*. Materials Science and Engineering*: C, 6 (2-3)*;
http://www.sciencedirect.com/science/article/pii/S0928493198000393
(last accessed May 22, 2013).

Capone, S., A. Forleo, L. Francioso, R. Rella, P. Siciliano, J. Spadavecchia, D.S. Presicce, and A.M. Taurino (2003). *Solid State Gas Sensors: State of the Art and Future Activities*. Journal of Optoelectronics and Advanced Materials, 5(5):1335-1348.

Chu, S., Graybeal, J.D., Hurst, G.S., and Stoner, J.O. (undated/2013). *Spectroscopy*. In Encyclopedia Britannica Online; http://www.britannica.com/EBchecked/topic/558901/spectroscopy *(last accessed May 22, 2013).*

Clark, J. (2000). *The Mass Spectrometer;* http://www.chemguide.co.uk/analysis/masspec/howitworks.html *(last accessed May 22, 2013).*

EPA (1994). *Photoionization Detector (PID) HNU*. SOP# 2114, Rev. 0.0; http://www.dem.ri.gov/pubs/sops/wmsr2114.pdf.

Goohs, K. (2011). *Thermo Scientific Hybrid PM CEMS Development Update*. White Paper AQIPMCEMS_05.11; http://stratusllc.com/uploads/PM_CEMS_White_Paper.pdf.

Gundermann, K.-D. (2013/undated). *Luminescence*. In Encyclopedia Britannica Online; http://www.britannica.com/EBchecked/topic/351229/luminescence *(last accessed May 22, 2013).*

Hinshaw, J.V. (2005). *The Flame Ionization Detector*. ; http://www.chromatographyonline.com/lcgc/GC/The-Flame-Ionization-Detector/ArticleStandard/Article/detail/254500 *(last accessed May 22, 2013).*

Honicky, R.E. (2011). *Towards a Societal Scale, Mobile Sensing System*; http://www.eecs.berkeley.edu/Pubs/TechRpts/2011/EECS-2011-9.pdf (UCB/EECS-2011-9).

Kryshtal, R.G., and A.V. Medved (2002). *New Surface Acoustic Wave Gas Sensor of the Mass-Sensitive Type Sensitive to the Thermal Properties of Gases*. In Sensors 2002. Proceedings of IEEE, 1:372-375; http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1037119.

Sheffield Hallam University (2013). *Chromatography Introductory Theory;* Department of Biosciences and Chemistry; http://teaching.shu.ac.uk/hwb/chemistry/tutorials/chrom/chrom1.htm *(last accessed May 22, 2013).*

Physical Sciences Inc. (2013). *About TDLAS: Overview*; http://www.tdlas.com/ *(last accessed May 22, 2013).*

Plodinec, J. (1998). *Technology Demonstration and Verification Research.* DE-FT26-98FT40395, Diagnostic Instrumentation and Analysis Laboratory prepared for the U.S. Department of Energy (Oct.)

UCLA (University of California Los Angeles). (2013). *Introduction to IR Spectra*; http://www.chem.ucla.edu/~webspectra/irintro.html *(last accessed May 22, 2013).*

APPENDIX G:

EVALUATION OF SELECTED AIR QUALITY APPS

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EVALUATION OF SELECTED AIR QUALITY APPS

Several organizational websites were reviewed to evaluate air quality resources available to the general public relevant to mobile phone apps and data representations. The objective was to assess gaps underlying existing apps, to frame potential opportunities for investments in this area. The online resources considered include:

- AIRNow, AirData, and Envirofacts (EPA)
- State of the Air (American Lung Association)
- Air Quality Forecast (National Weather Service, National Ocean and Atmospheric Administration (NOAA)
- The Weather Channel
- Power Plant Pollution Risk (Clean Air Task Force)

A number of free mobile phone apps compatible with Android smartphones were found. Of these, the AIRNow and State of the Air mobile phone apps were selected for a brief comparison. Screen captures were taken for both apps every morning for two weeks; examples are shown in Figures G-1 and G-2.

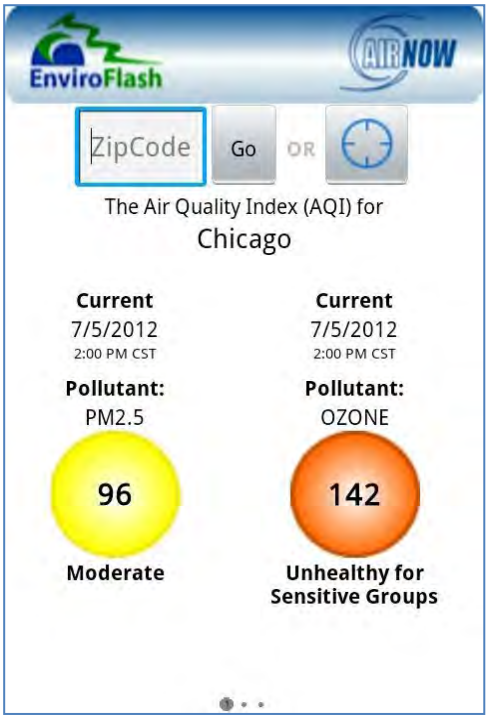

FIGURE G-1 AIRNow Mobile Phone App, Screen Capture for Chicago, 7-5-12
(Source: Temple 2012.)

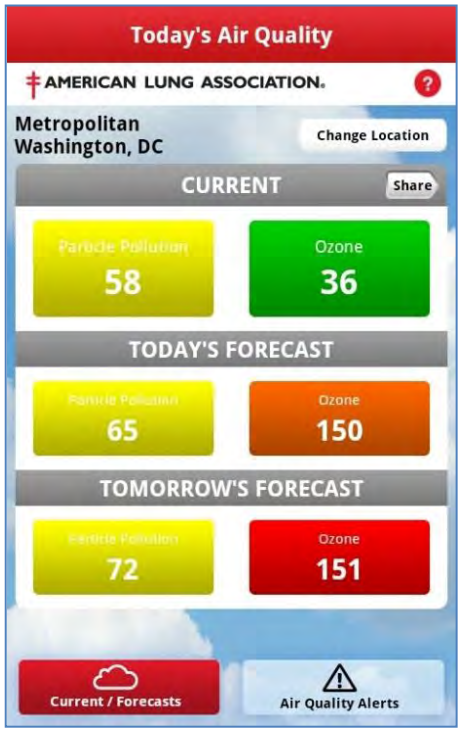

FIGURE G-2 State of the Air Mobile Phone App, Screen Capture for Washington DC, 7-6-12
(Source: Temple 2012.)

The average rating from 36 reviews posted online for the State of the Air App is 3.4. Twelve gave it 1 star, and seventeen gave it 5 stars, reflecting different expectations and indicating opportunities for improvement.

The air quality data collected from these two mobile phone applications were plotted to illustrate how conditions in Chicago and Washington, DC, could be compared. The $PM_{2.5}$ comparison is presented in Figure G-3, and the ground-level ozone comparison is presented in Figure G-4.

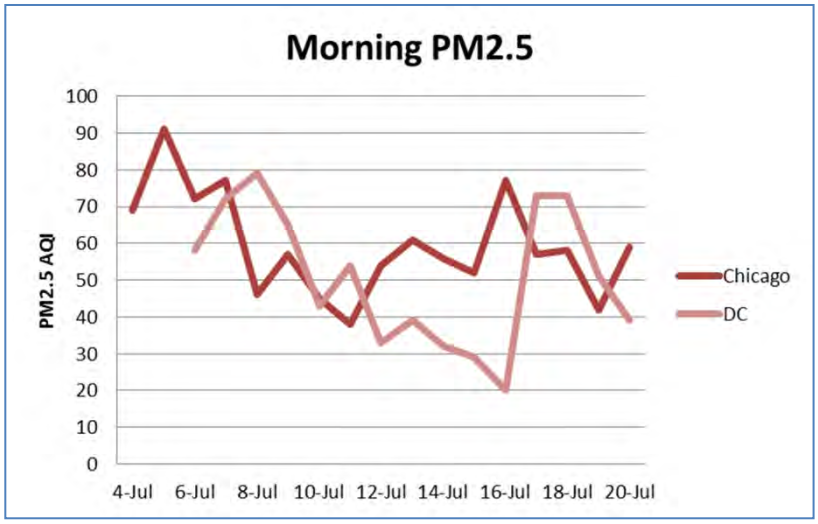

FIGURE G-3 Morning AQI Data for Ozone, 4-20 July 2012 *(Source: Temple 2012.)*

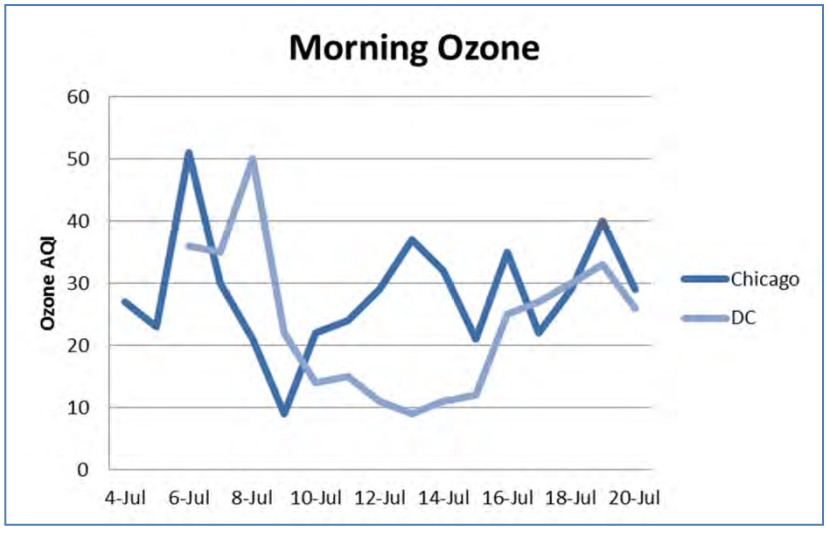

FIGURE G-4 Morning AQI Data forPM2.5, 4-20 July 2012 *(Source: Temple 2012.)*

A third mobile phone app, Air Quality by Aesthetikx, also provides information for these criteria pollutants. Data representations include color-coded overlays on geographic maps, as illustrated in Figure G-5. Note that the average rating from nine online reviewers was 3.2 out of 5, which indicates an opportunity for improvement. (Three reviewers gave this app 1 star and one reviewer gave it a rating of 2, while four gave it 5 stars and one person who gave it 4 stars. Only 5 reviews are available online; the reviewer who gave the 4-star rating indicated the map was "awesome" but they wished for more detailed descriptions.)

FIGURE G-5 Air Quality Mobile Phone App.
Screen Capture of U.S. AQI Map, 7-5-12
(Source: Temple 2012.)

A variety of air quality data and resources are available online. The EPA AirData website (EPA 2012) provides links to resources and data summaries, including daily AQI plots, time series concentration plots, an interactive map, and AQI reports. The link for "monitor values" (http://www.epa.gov/airdata/ad_rep_mon.html) provides access to a tool for user-selected reports for data from monitoring stations available in the user-selected area. Additional information resources available through AirData include educational materials for school children.

The findings of this focused review of air quality apps are highlighted as follows. Of ten air quality-related mobile apps initially identified, three provide relevant air quality monitoring data. Both EPA's AIRNow app and the American Lung Association's (ALA) State of the Air app supply hourly and forecasted AQI for $PM_{2.5}$ and ozone at the nearest urban center. The State of the Air app also provides air quality alerts as issued.

Gaps identified from the evaluation of selected mobile phone apps include the following.

- Data coverage

  Limited to a fixed monitoring station from the nearest urban center, and data are only available for major cities. Such data are clearly not representative across community, neighborhood, and individual scales.

- Pollutant coverage

  Essentially limited to just two: $PM_{2.5}$ and ground-level ozone. The AQI map application does not differentiate between the two. (Note in most cases, the air quality is represented by a number associated with the AQI.)

- Update frequency

  The frequency of AQI updates varied for certain areas and monitors. Forecasting is affected in those areas for which data are updated less frequently.

- User interface, and inconsistencies

  Air Quality by Aesthetikx supplies animated AQI maps of the U.S. and local areas. The animation characteristics depend on the data connection speed for the phone. Using a 3G Android smartphone with limited service in many areas led to restricted performance of the app. With limited data connection, the app provided an AQI map of the requested area taken many hours earlier (12:20 that morning). Presumably, this feature would work better with a 4G connection and/or greater data coverage. (This issue resulted in inconsistencies due to data access, coverage, and other limitations.)

Other user reviews for the three free apps evaluated here have been posted online. Comments and overall ratings that reflect inputs from more than 60 users are presented in Table G-1. (Note the inputs address progressive versions of the apps in some cases, so the comments are ordered within each main topic first in order of rating and then in order of date posted.) The comments are grouped by main category, and topical ratings are provided for those with multiple comments, per app. (Ratings are on a scale of 1 to 5, in order of increasing satisfaction.) Overall ratings were modest, ranging from 3.1 (AIRNow) to 3.4 (State of the Air).

Most users commented on the ALA State of the Air app – more than double the number commenting on EPA's AIRNow app, and four times the number commenting on the Air Quality app by Aesthetikx. High regard for the concept (collective rating of 4.5) affirms that mobile apps represent a clear opportunity area. The main gaps are associated with data coverage (collective rating of 1.4) and the user interface (collective rating of 2.3).

The data coverage limitations (locations and pollutants) reflect limitations in the data available, not in the apps themselves. That underlying data limitation represents one of the drivers for this initiative, toward facilitating participatory sensing that can contribute to the overall state of knowledge for air quality. The insights from existing free apps can help frame research and development investments toward future mobile apps that enhance citizen involvement.

TABLE G-1 Online User Reviews of Three Mobile Apps for Air Quality[a]

App / Issue	Online Reviewer Comments	Rating
Air Quality *(Aesthetikx)*	*(Overall rating from 9 user reviews; 5 available online)*	**3.2**
Concept value	**Awesome.** The map is awesome. I wish there were more detailed descriptions. *(V1.0, Motorola Droid X2; April 12, 2012)*	4
Data coverage	**Not helpful.** Only informative if you are looking for one of the major cities. The US map time laps goes too fast. Uninstalling, useless. *(HTC Thunderbolt; Aug. 9, 2012)*	1
User interface *(1.3)*	**No N.M. Radar.** It force-closes when you turn phone sideways. *(V1.0; June 2, 2012)*	2
	No map. Maps not showing, useless. Uninstalling. *(Samsung Galaxy S; July 15, 2012)*	1
	Lol. Closes if I turn my phone. *(Galaxy S2 Skyrocket; July 16, 2012)*	1
AIRNow *(EPA)*	*(Overall rating from 16 user reviews, 10 available online)*	**3.1**
Concept value	**Thank you!** Helps me monitor air in Nashville. *(V. 1.0; June 14, 2012)*	5
Data coverage *(1.8)*	**Nah.** Gives air quality for white plains, 30 minutes away, instead of the bronx, which is 2 blocks from my house. *(V1.0, HTC G2; June 13, 2012)*	3
	Needs more features. It's a decent app for finding out what air quality is like in areas around you but because of a lack of air quality reporting in many areas, the results are generally irrelevant. It would be better for the app to let the user know that there is little to no air quality information for their specific location and then show information for nearby areas. Searching by city name would also be nice to have. *(Galaxy S2 Skyrocket; Jan. 24, 2013)*	3
	Great idea. Needs more sources. push an air quality add on national Weather Service stations. *(V1.0, Samsung Galaxy S3; Sep. 27, 2012)*	2
	Won't locate. App can't display anything about my zipcodes or Geo location. *(V1.0, Samsung Galaxy Nexus; July 8, 2012)*	1
	Coverage sucks. Doesn't work in my area. *(Samsung Galaxy S; Sep. 25, 2012)*	1
	Vog. Nothing on vog on Oahu. *(Samsung Galaxy Nexus; Oct.4, 2012)*	1
User interface *(1.7)*	**Good but needs favorite locations!** This is more convenient than the website. It needs a favorites list to save time. A way to search by city would be great. *V1.0; July 8, 2012)*	3
	Worthless. I use web page all the time but can't get this to work for gsp area of sc which is a metro area..... *(HTC Thunderbolt; July 1, 2012)*	1
	Doesn't work. I have a droid and whenever I type in my zipcode it won't show me any results. Highly disappointed. *(Feb. 7, 2013)*	1

App / Issue	Online Reviewer Comments	Rating
State of the Air *(ALA)*	*(Overall rating from 36 user reviews, 26 available online)*	**3.4**
Concept value *(4.5)*	**Great.** Have little kids, air quality is essential. *(HTC Thunderbolt; June 20, 2012)*	5
	Love it! It's definitely the best air quality alert app out there. It helps give me an idea of whether I should run outside or hit the gym. *(V1.0, Motorola Droid X2; June 18, 2012)*	5
	Great app! Helps protect my kids. This is a very useful app to monitor air quality in my community. Helps me make sure I know if it's safe for my kids to go outside. *(V1.0, Motorola Droid X; June 18, 2012)*	5
	Works on Galaxy SII. Wonderful app I will use to schedule my outdoor activities. Adding an hourly forecast would raise this to 5 stars. *(Samsung Galaxy S2; June 23, 2012)*	4
	State of the air. Only app w air pollution forecast. Includes ozone. Needs to show alert time window. *(V1.3, Samsung Infuse 4G; Aug. 3, 2012)*	4
	Hi. It's good to be able to tell when to breath outside. *(V1.3, HTC Sensation 4G; Aug. 16, 2012)*	4
Consistency with other information *(4.0)*	**Does exactly what it says, accurately! Thank you!** I see a number of reviewers complaining about inaccurate information in this app. When I compare this app's data to actual readings in my community, they are dead on. You can get confused if you expect the apps real time readings to match the daily FORECAST - they don't. Real time readings are not the same as the forecast (much like the weather.) To see real time readings, I go into my state's Department of Environmental Quality site and go to the MONITORING page, NOT the forecast page. That shows me a map of several monitoring sites, some monitoring particulates (PM2.5), some monitoring ozone, and some monitoring carbon monoxide (CO). The readings vary slightly by site, but I have figured out which sites are the local sources of this app's readings, and IT IS VERY ACCURATE. Right now, the air quality forecast for today is 50 for PM2.5, but the reading at the monitoring site is only 28, which is exactly what is displayed on this app on my phone. Of course, it can only report data from WHERE THERE ARE MONITORING SITES. No sites, no data. Before you criticize this app for being inaccurate, educate yourself! This app does exactly what it claims. Those who say it doesn't are confused. *(V1.3, Sep. 7, 2012)*	5
	Spot on for Cincinnati's air quality. *(V1.3, HTC myTouch 4G; Dec. 8, 2012)*	5
	Not sure if this works. Just downloaded. live in slc we have lots of smog. Wanted to see what the air quality was right now because i wanted to go on a Bike ride. tons of smog probably half visibility but the app says its green and low pollution. Hard to trust that. *(V1.3, Motorola Droid RAZR; Sep. 17, 2012)*	2

App / Issue	Online Reviewer Comments	Rating
State of the Air *(Cont'd.)*		
Data coverage	**No data for my zipcode.** Lame. *(Samsung Galaxy Note; Aug. 29, 2012)*	2
	Uninstall. The app gives me data of a location that's 46 miles away. What good is that for me? *(V1.3, HTC Droid Incredible; June 21, 2012)*	1
(1.1)	**This app is useless. I live in Long Beach NOT South Coastal LA. Only ...** This app is useless. I live in Long Beach NOT South Coastal LA. Only gives you a general area that spans 50-100 miles and several climates. *(V1.1, HTC myTouch 3G Slide; June 21, 2012)*	1
	Data not available. I don't live near a big city so this is worthless. Neat idea but only ideal if you live in a major city. *(Droid Bionic; June 23, 2012)*	1
	Almost worthless. info given does not seem to be zip code specific but regional for a metro area. 30 miles away in the burbs same information. *(V1.1, HTC Evo 4G; June 24, 2012)*	1
	This is the worst! The app is not accurate. Asthmatics need to know what the air quality is each day. Having a mobile app that shows the air quality using GPS is a great idea. But the worst thing that could happen is an air quality app that says the air quality is Green when it is Yellow or some other color. I checked their website for my location and it shows the Ozone = Yellow but the app shows the Ozone = Green. How sad, how irresponsible. *(V1.3; July 9, 2012)*	1
	Doesn't locate. When i typed in my zip it put a city that's over four hours away. How can it say that's my areas air quality when it doesn't even locate my area within a reasonable distance. Also i know where i live has horrid air quality. I live in factory district. This app needs more pinpoint accuracy. *(LG Optimus One; Sep. 21, 2012)*	1
	Needs more coverage. Doesn't cover where I live. *(Samsung Galaxy S; Sep. 25, 2012)*	1
User interface	**Thank you!** This is so helpful and easy to use. *(V1.1, Samsung Galaxy S2; June 19, 2012)*	5
	Very useful app!! The air alerts and ability to contact Congress are great! *(June 19, 2012)*	5
(2.8)	**You Need This App.** I plan to use this app every morning as part of my daughter's asthma management plan. So glad the Lung Association has made this tool so easy to use. *(June 19, 2012)*	5
	Great. I downloaded the same app for my ipod and my android phone and it works great. *(June 29, 2012)*	5
	Doesn't work. After the opening screen, it goes blank/dark and does nothing. *(V1.1, HTC Rezound; June 20, 2012)*	1
	Doesn't Work for Me. It opens to a black screen and does nothing. *(HTC Rezound, June 20, 2012)*	1
	Disappointed Force closes at opening every time. Was excited about it too as my one yr old has severe lung disease, PH and BPD. *(V1.2, Samsung Sidekick 4G; June 22, 2012)*	1
	Force closes. Not working. Infuse. *(Samsung Infuse 4G; June 23, 2012)*	1
	Ergh. This app has never worked for me. Even after refreshing and reopening, still gives me nothing. *(V1.3, Samsung Galaxy S; Sep. 9, 2012)*	1

[a] Sources: Aesthetikx (2012), ALA (2013), EPA (2013). ALA = American Lung Association; "V" indicates the app version, where reported; the mobile device is also identified where reported. (A few comments reflect minor editing, e.g., for spelling.) Topical ratings are shown in column 1.

SELECTED REFERENCES

Aesthetikx (2012). *Air Quality, Android Application*; https://play.google.com/store/apps/details?id=com.aesthetikx.airquality&feature=search_result#?t=W251bGwsMSwxLDEsImNvbS5hZXN0aGV0aWt4LmFpcnF1YWxpdHkiXQ *(page indicated last update was Feb. 22, 2012; online reviews continued to later that year; last accessed April 4, 2013)*.

ALA (American Lung Association) (2012). *State of the Air, Android Application*; http://www.lung.org/healthy-air/outdoor/state-of-the-air/app.html; https://play.google.com/store/apps/details?id=com.reddeluxe.sota *(page indicated last update was Oct. 24, 2012; online reviews continued to later that year; last accessed May 22, 2013)*.

Temple, B. (2012). *Air Quality Monitoring: Citizen Sensing Initiative*. Prepared in fulfillment of the requirement of the Office of Science, Department of Energy's Science Undergraduate Laboratory Internship, Environmental Science Division, Argonne National Laboratory (Aug.).

U.S. EPA (U.S. Environmental Protection Agency) (2012). *Air Data*; http://www.epa.gov/airdata/ *(page last updated Sep. 27. 2012; last accessed May 22, 2013).*

EPA (2013). *AIRNow, Android Application*; https://play.google.com/store/apps/details?id=com.saic.airnow *(page indicated last update was March 23, 2012; most recent comment was posted in April 2013; last accessed May 22)*.