Journal of The Electrochemical Society

The Electrochemical Society
Advancing solid state & electrochemical science & technology

RESEARCH PAPER • **OPEN ACCESS**

Distributed Sensors for Wildfire Early Warnings

To cite this article: M. Findlay *et al* 2022 *J. Electrochem. Soc.* **169** 020553

Journal of The Electrochemical Society, 2022 **169** 020553

Distributed Sensors for Wildfire Early Warnings

M. Findlay,[1,z] D. Peaslee,[2,z] J. R. Stetter,[1,*,z] Scott Waller,[3,z] and Andrew Smallridge[3,z]

[1]*KWJ Engineering Inc., Newark, California 94560, United States of America*
[2]*SPEC-Sensors, LLC, Newark, California 94560, United States of America*
[3]*Thingy, LLC, dba Thingy IOT, Bellevue, Washington 98004, United States of America*

Wildfires cause immense damage and loss of life. They are exacerbated by climate change effects and will be getting worse each year for some time to come. One way to deal with them is to have better means of early detection. Fires produce significant changes in the physical and chemical makeup of the local atmosphere that, in practice, can be detected by air quality monitors. This paper describes a sensor array that measures trace levels of fire produced emissions that is coupled to computation and communication equipment that is low power and low cost. The emission arrays are calibrated and deployed in controlled fire detection situations. Evaluations illustrate some important characteristics of detecting fire emissions including: 1] sensing CO and Particulates together reduce ambiguity of signals; and 2] fire emission signatures for relatively close fires produce rapid spikes in concentrations of emissions. Most importantly, the details of this work indicate that an individual sensor node consisting of only a CO and particle detector can provide an early indication of a wildfire. Additionally, the low-cost CO and particle sensors used in this study show a correlation of greater than 0.9 R^2 with FRM reference monitors. The results are encouraging that very low-cost arrays could substantially contribute to an early warning system for detection of wildland fires thereby improving response times for mitigation measures.
 [DOI: 10.1149/1945-7111/ac5344]

Manuscript submitted September 22, 2021; revised manuscript received January 27, 2022. Published February 17, 2022.

Early detection of wildland fires could improve emergency response and limit and loss of lives and property damage caused by wildland fires that have been observed at increasing frequency and magnitude over the past decade. The wildfires in California and throughout the western USA have been devastating, especially over the past 3 years. And it is not just the USA that suffers fiery disasters but Europe, Asia, Australia, and Russia.[1–6] The magnitude is so great that notwithstanding loss of many lives and incredible property losses, fire is largely responsible for the bankruptcy of a giant utility with over $50B of debt. It is estimated that in the USA alone, the first half of 2021 has seen more than 4 M acres burned. Natural disasters cost the USA about $17 B/year a few decades ago, but last year natural disasters cost the USA > $180 B and costs are projected to increase rapidly.

Wildfire emissions contain numerous hazardous species—including but not limited to fine particulate, carbon monoxide, NOx and other strong oxidizers, and a variety of hazardous VOC compounds.[7,8] The levels of primary hazardous pollutants emitted include CO (150 g kg^{-1} biofuel burned), PM 10 (25 g kg^{-1}), NOx (2–5 g kg^{-1}), NH3 (0.5–10 g kg^{-1}), $S^{-1}O^{-2}$ (0.5 g kg^{-1}), and total NMOCs (50–100 g kg^{-1}), including acetic acid (2–10 g kg^{-1}), formaldehyde and acetaldehyde (1–5 g kg^{-1} among and numerous other species at lower emission rates. Actual atmospheric concentrations will of course depend on the size and duration of the fire as well as windspeed. Also, two of the primary greenhouse gases—CO_2 (1,500 g kg^{-1}) and methane (5–10 g kg^{-1})—are emitted during wildfire, further contributing to climate change in a self-reinforcing cycle. Early detection with response and containment of even one large fire could save lives and billions of dollars in property loss, and reduce hazards of prolonged breathing of polluted air. The pollutants from large wildfires are dispersed over very large areas, and thousands to millions of people are exposed to unhealthy levels of these pollutants for varying periods of time.[9–13]

Additionally, early detection of expansion of a fire, or change in direction, would be of great benefit to the firefighters working in the immediate vicinity of the fire.[14–18] There are standards guiding the protection of wildland firefighters and firefighters in general,[19,20] and protective equipment including respirators and multigas monitors is available. The reality of the situation, however, is that often the gear is uncomfortable, bulky, or gets in the way when working amongst trees and brush. These emergency responders are thus often exposed to potentially hazardous levels of pollutants,[21–26] in addition to the increasing risk of being trapped within the fire fronts as the fires become larger and more prone to rapid growth and change of direction.

Numerous reports have demonstrated that climate change and land use changes have led to increasing susceptibility to fires.[3,27–35] Climate change has increased the average air temperature, with earlier spring and later fall seasons drying the forests and making fuel more combustible. Wildfires have been started by Mother Nature in the form of lightning strikes, or by utility lines downed by wind or falling debris, by careless people, or even gender reveal party accidents. Even if we stopped greenhouse gas emission today, as global warming continues methods to deal with this reality are existential for many of us.

Current methods to detect these fires include patrol by local forest rangers, satellite imaging, local monitoring, the use of local temperature arrays, and public education (for example about climate change, citizen science, and behavior changes to limit fire risk). Since satellites can be obscured by weather, and do not have sufficient spatial or temporal resolution or sensitivity required to catch small startup fires quickly, improved methods are needed to proactively react to fire danger.

Since fires produce emissions including gases and particles that can change the local atmospheric air quality, as well as physical plumes and airborne embers,[14] then the detection of these "fire" signatures with a low cost distributed network of sufficiently sensitive low-cost sensors could provide early warning of potential fires. Such a network would enable rapid response and the early control of some fires.

In order to match a sensor to any application, one must understand the sensors and their performance as well have clear engineering requirements for the field application. While lab performance of a sensor is important, field data is required and often obtained through co-location data of the sensors with "standards" for the measurement of interest. The requirements on distributed sensor performance include: sensitivity, response time, selectivity, and stability in addition to logistical properties like uniform performance, long lifetime, low or no maintenance, small size, low power, communications capability, and of course low cost. It is equally important to understand the application's requirements. Such requirements include considerations of the density of spatial and temporal data needed for early warning for a sensor with a given

*Electrochemical Society Fellow.
[z]E-mail: mfindlay@kwjengineering.com; dpeaslee@spec-sensors.com; jrstetter@gmail.com; scott@thingy.com; andrew@smallridge.com.au

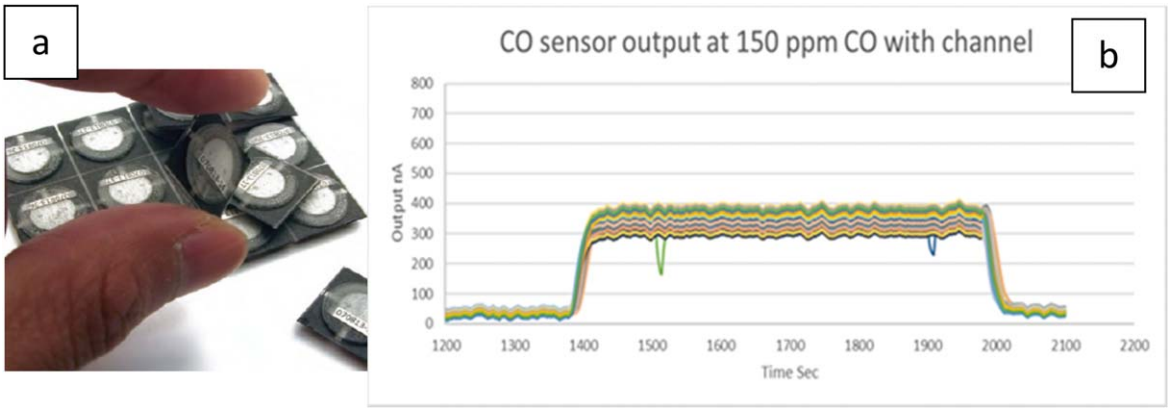

Figure 1. (a) SPEC Sensors printed electrochemical sensors, showing small dimensions of the standard package (15 × 15 × 2 mm [3 mm with selective filter]). (b) Response for 60 sensors for carbon monoxide, illustrating the uniform nature of the printed CO sensor.

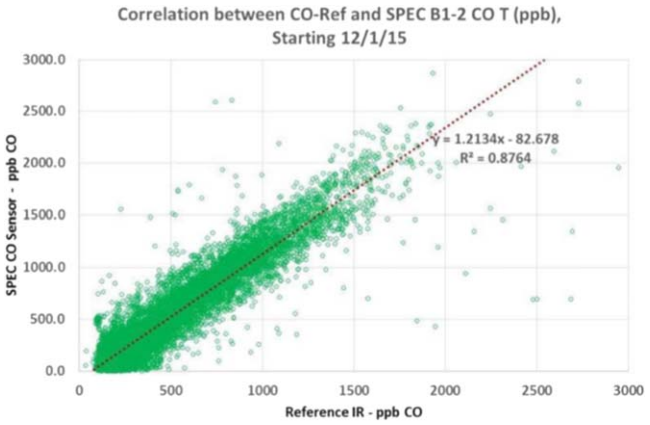

Figure 2. Correlation between SPEC CO sensor and EPA reference analyzer during AQ-SPEC testing of ambient outdoor air over several months in LA county during winter 2015–2016.

sensitivity, the range of AQ parameters needed for unambiguous detection, and the potentially changing matrix in which the early detection occurs. One of the challenges of deployed sensors noted by the citizen science community is the need to guide the placement of the sensors [e.g., not next to a local pollution source like a grille or auto tailpipe] so that the data reflect the general AQ variability. Sensors and systems must be evaluated in the lab and the field to be validated for practical applications and while environmental variables such as temperature, pressure, and humidity (T/P/Rh) can be easily controlled in lab testing, these variables are widely different around the globe in the wild and make intelligently and automatically compensated sensors a goal of such work.

Under SBIR projects being funded by the US EPA and the USDA, we are evaluating arrays of particle and gaseous pollutant sensors for utility in rugged, outdoor applications for both air quality monitoring in the areas impacted by wildfires (including remote rural and small-town areas tens to 100's of miles down-wind from fires), as well as monitors to protect the safety of firefighters in the immediate vicinity of emerging and growing fires.[15–18]

In this applied sensor paper, we discuss two important aspects: 1] the sensing, computation, and communication hardware for fire detection, and 2] application testing with a goal toward understanding the use (scenario) and implications for the sensor and vice versa. The sensing and networks discussed herein can have wider uses in rural, urban, and roadside air quality networks, and with a small form factor (and lower cost) can also be utilized as personal wearable protective equipment.

Experimental

Laboratory controlled tests and sensors.—An array of sensors was evaluated in earlier laboratory testing and reported to US EPA and USDA (funding/sponsors[16,18]) prior to this work. "Constant-potential" amperometric gas sensors (**AGS**)[36] for CO, Ozone, NO_2 and SO_2 (SPEC Sensors, Newark, CA) were compared to industry standard Alphasense (Essex, UK) amperometric gas sensors (A4 "air quality" series) for the same gases. Sensirion SPS30 and Plantower PMS 5003 sensors and Sensirion SCD30, Alphasense IRC-A1 and GSS CozIR-A CO_2 sensors were evaluated for inclusion in the array. The particulate sensors were compared to Alphasense OPC-N3 and Particles Plus 8306 particle monitors during measurements of wood smoke introduced into a small (25 l) chamber, and the CO2 sensors were evaluated for accuracy and response time in the same test. Since the sensors all provide a digital output, communication reliability was also tested.

SPS30 PM sensors and SCD30 CO2 sensors (Sensirion, AG, Switzerland) were chosen based on excellent combination of size, cost and performance. Performance was comparable to or exceeded the other low-cost sensors for calibrated optical sensors with digital output.

SPEC Sensors, LLC amperometric sensors were chosen because they are printed sensors manufactured in a scalable batch process for low cost, and have many of the features needed for deployable field sensors.[37–39] Figure 1a illustrates the small size.[19] Figure 1b shows the response for 60 sensors for carbon monoxide, illustrating the uniform nature of the printed CO sensor. The UL rating requires stability for months at extreme RH and the performance has been field tested at low CO levels (0–3 ppm) against the industry standard IR CO meters in outdoor air over several months in LA county in 2015[40] (see Fig. 2). Other features of the AGS include algorithms for temperature compensation to improve baseline stability, and for CO, selectivity is obtained with an internal carbon filter which scrubs most other reactive pollutants and VOCs. Further, the SPEC CO sensor is a UL approved part and has more than 3 years of lab testing to provide a MTBF that is measured in decades.

The AGS are mounted on digital potentiostat module (Digital SDK, SPEC Sensors), consisting of a configurable analog front end (AFE; LMP9100 Texas Instruments), a precision voltage reference, and a microcontroller with a 10 bit ADC (PIC24F16, Microchip). The AGS for ozone, NO2, and SO2 monitoring were individually calibrated at the time of deployment. The sensors were evaluated by gathering the field data and then performing individual post-compensation for temperature by using an exponential baseline correction algorithm provided by the vendor. In the tests described here, all gas sensors are sampling from an enclosure using simple diffusion into the enclosure through vents, while the particle sensors

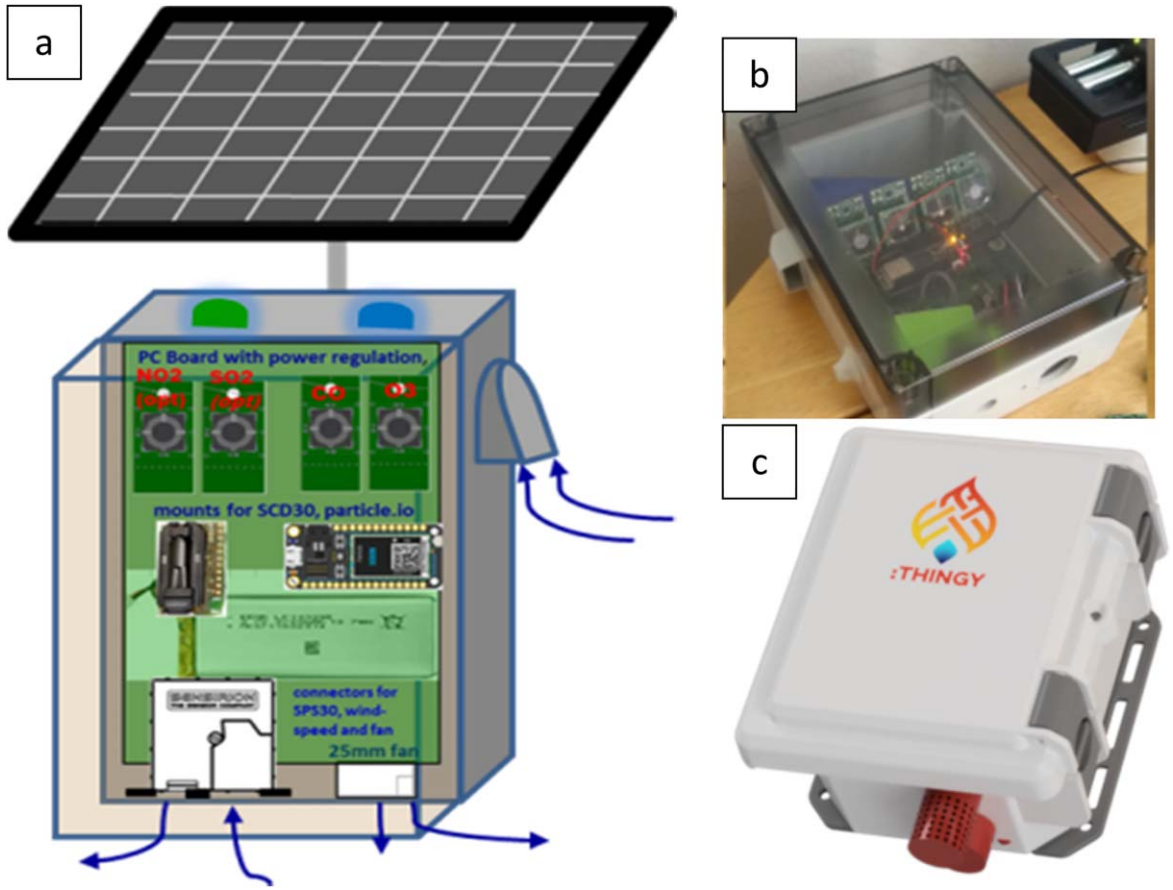

Figure 3. KWJ Prototype Wildfire Air Quality Monitors (WFAQM). (a) Concept layout with flow paths designated with arrows; (b)benchtop prototypes fabricated during 1st year evaluation; (c) *Thingy:AQ* outdoor air quality monitor, using SPEC printed gas sensors and Sensirion low-cost PM and CO_2 sensors.

are sampling through enclosure ports using integral fans to pump air into the optical sensing cavities.

A wildfire pollutant monitor concept was developed (Fig. 3a) and prototypes constructed (Fig. 3b) using the above sensors. Preliminary evaluation and selection criteria for sensors included in the monitor have been reported previously. These prototype monitors have been assembled and tested in the laboratory and under outdoor simulated fire conditions. The laboratory testing is being conducted to determine optimum temperature compensation and potential need for cross-sensitivity to gases other than the target analyte.

Additionally, we have been collaborating with Thingy, LLC (Bellevue, WA) to develop and validate a field rugged wildfire air pollutant monitor (Fig. 3c). This monitor has been tested by EPA at the Missoula, MT USFS Combustion Laboratory - *data analyzed and reported herein was collected in conjunction with EPA and USDA Phase II SBIR projects.*[16,18] The *Thingy:AQ* monitor uses a proprietary LoRa and LPWAN communication protocols to transmit the sensor data to a LoRa gateway. For testing purposes, the gateway is located within the test area. The data collected by each node is raw sensor module data, with the AGS sensor modules reporting temperature compensated gas concentrations.

Outdoor tests and simulated wildfires.—

1. A preliminary test was conducted outdoors with a small wood fire. All sensors were stabilized for several days so that a stable zero in air was assured. Then during field tests, the sensors we allowed to stabilize overnight before beginning data acquisition.
2. A second test was conducted in April, 2021 by EPA and USFS personnel at the Missoula, MT, Combustion Laboratory. This was a more detailed evaluation of a number of low-cost monitors, including several monitors built in a collaboration between KWJ and Thingy, LLC. These "Thingy:AQ" wildfire monitors utilize the set of SPEC AGS as well as the Sensirion SPS30 PM and SCD30 CO_2 sensors evaluated by KWJ in laboratory testing. A number of burns using various fuel compositions, loadings, and moisture content were conducted over a 2 week period, with data collected from the test devices as well as from a bank or reference analyzers.

Results

Preliminary test.—A "small" wood fire was ignited approximately 1 m upwind from the sensor array box, and burned for approximately 15 min. This first test incorporated the reference and benchmark sensors—a Particle Plus 8306 and Alphasense OPC for particles and Alphasense CO, SO_2, NO_2 and O_3 sensor for amperometric benchmark sensors. Outdoor ambient air was monitored for more than 24 h, to establish baseline signals and trends. A commercial AQ node, containing Alphasense 4-electrode "ppb-level" air quality sensors was located next to the KWJ prototype.

Data is summarized in the figures below.

Particulate.—The particulate concentration during a small outdoor woodfire was measured using the 8306 monitor and the Alphasense and Sensirion PM sensors. The results are shown in Fig. 4. Figure 4a is the PM1 and PM2.5 data from the Particles Plus Model 8306 Analyzer used as benchmark. 4.b is the data from the Sensirion SPS30 sensor. The Sensirion data for 1 and 2.5 μm tracks the reference very closely, though concentrations read about 1.5–2

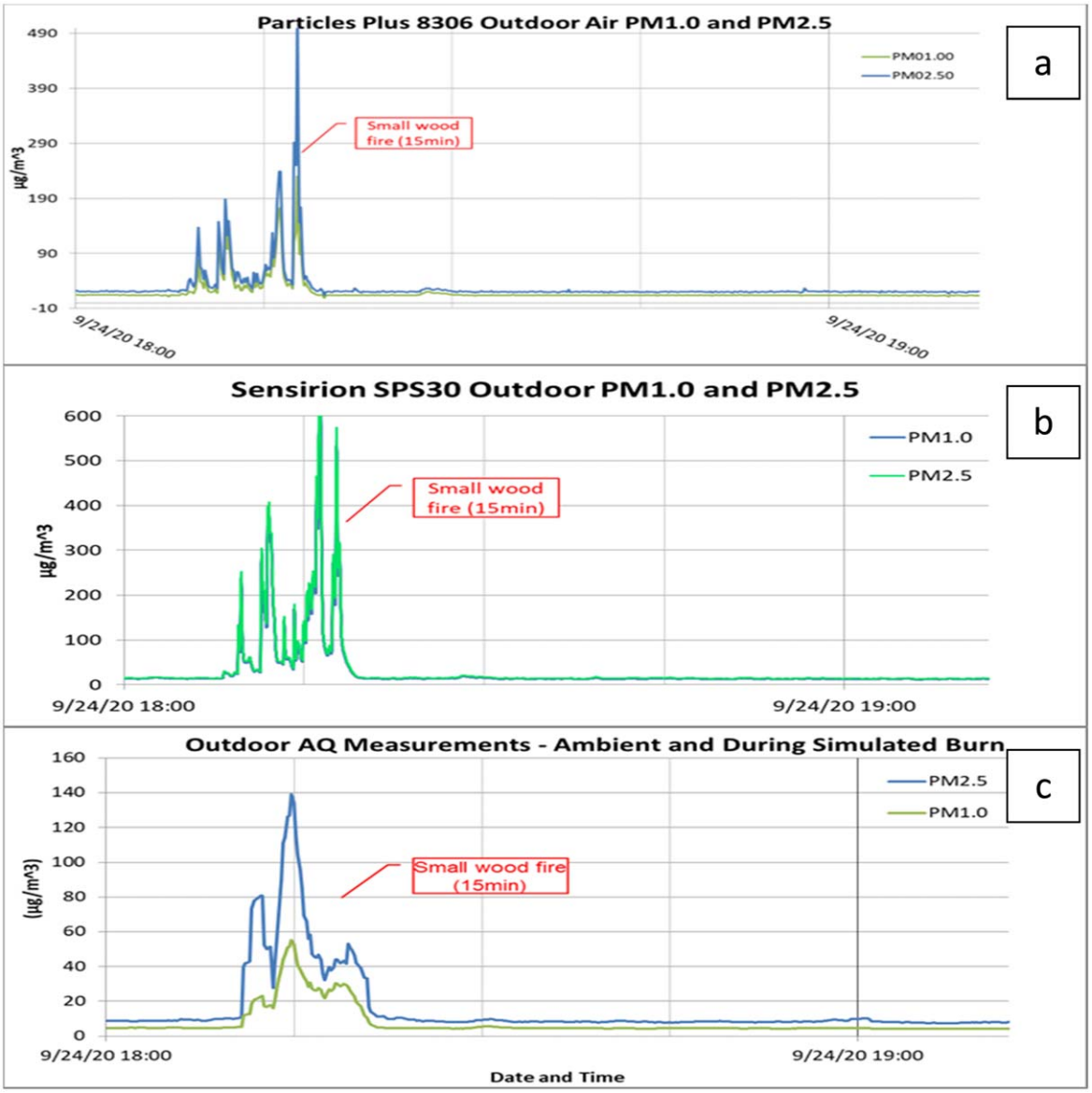

Figure 4. (a) PM1 and PM2.5 data from the Particles Plus Model 8306 Analyzer; (b): Data from the Sensirion SPS30 sensor; (c) Response from the Alphasense OPC-N3 sensor.

times high. Figure 4c shows the response from the Alphasense OPC-N3 sensor. The OPC data has a 5-min averaging routine to filter out rapid spikes and noise. The 5-min average data is OK for air quality applications, but dampens the rapid increases and fluctuations that may be indicative of an emerging fire. The OPC also shows a greater fraction of the particles are more than 1 μm, whereas the PPLus analyzer and SPS30 both indicate most particles are more than 1.0 μm.

The performance of the Sensirion SPS30 in this test made us comfortable choosing this sensor for inclusion in the field array going forward. Where the agreement with the analyzer varied substantially, it was uncertain if this was due to location (although they were close to each other steep gradients and narrow plumes can occur in field testing) or to accuracy and calibration differences among the sensors. In any case, both particle sensors can detect the fire event and provide correlation to the analyzer; the Sensirion device is much smaller and about 1/5 the cost.

Gaseous emissions.—To give us an indication of whether any of the gaseous components are detectable early enough to provide early warning of an emerging wildfire, we compared the responses from the different gas sensors with that of the particle concentrations as measured with the Particles Plus 8306. This preliminary correlation test was performed outdoors without trace gas reference analyzers, so comparison of concentrations was against the Alphasense benchmark sensors.

Carbon monoxide.—First the CO sensor is discussed, with Fig. 5a presenting response of the Alphasense CO sensor response, and Fig. 5b showing the SPEC CO response. In both plots, the measured CO is overlain on the PM1 data to illustrate the correlation between the measured CO and measured particulate. Clearly the particle sensor (green trace) and the CO sensor (blue trace) show comparable response indications when detecting the small fire from 1 m away. The CO levels are greatest in the later stage of the fires, when the flames had disappeared and the material was smoldering.

Ozone and NOx.—Both the Alphasense and SPEC ozone sensors, which in fact respond to nitrogen oxides as well as O_3, also provide a rapid response to the wood smoke, though at much lower concentrations. Figure 6 presents the data from the same small burn. Again, a very good qualitative correlation is observed,

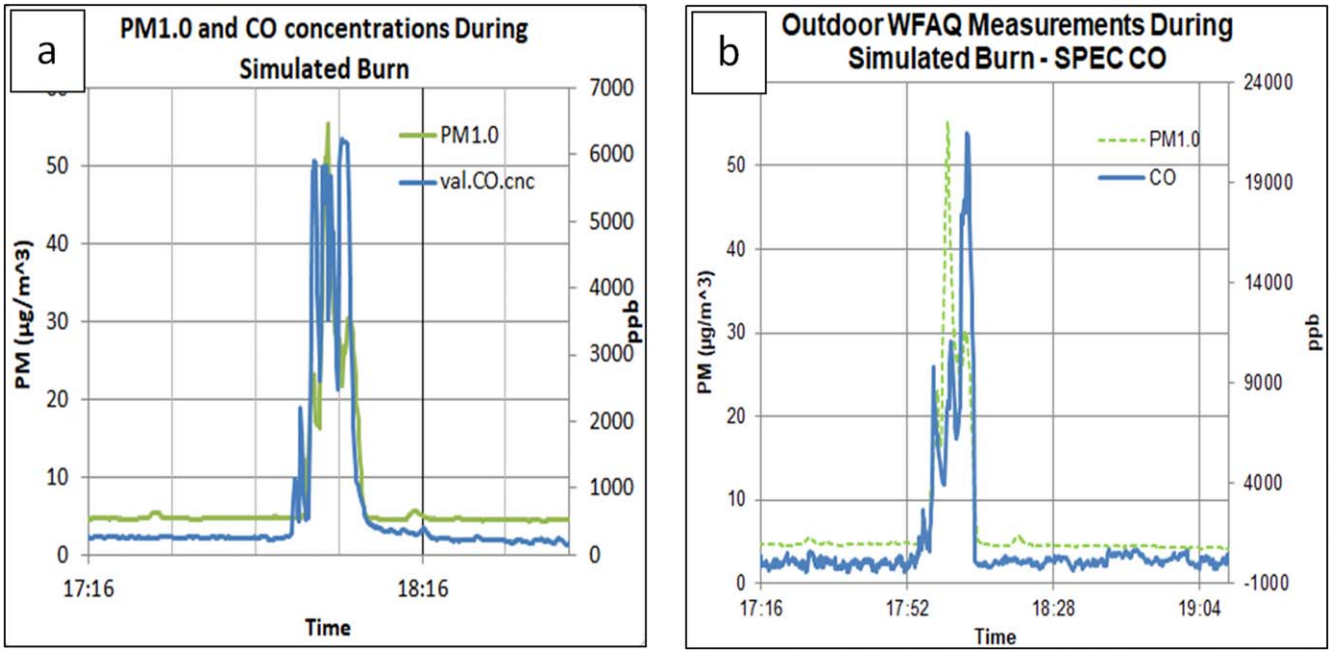

Figure 5. Measured CO concentration overlain on the PM1 data; (a) Response of the Alphasense CO sensor; (b) SPEC CO response.

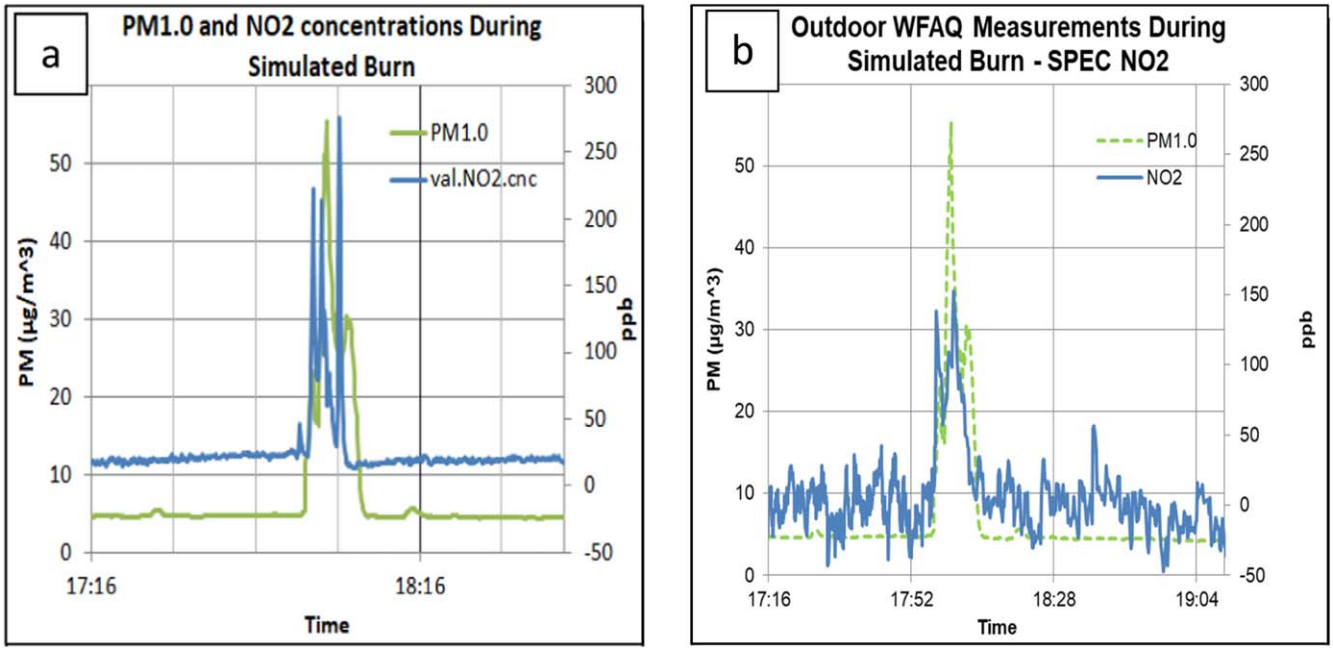

Figure 6. Measured NO_2 concentration overlain on the PM1 data. (a) Response of the Alphasense sensor; (b) SPEC sensor response.

although levels are much closer to the MDL, based on baseline noise and drift.

NO_2 and SO_2 also were measurable in this simulated wildfire, but at low concentrations (see Figs. 7 and 8). The Alphasense sensors responded with a signal well above the background noise. The SPEC sensors, while giving a definite response, were much lower relative to the baseline noise. 1-min averaging of the SPEC sensor signal reduces the high frequency noise, but also dampens the response to rapid concentration changes (Fig. 9), not appreciably improving S/N.

Figure 10 demonstrates one advantage of multi-parameter monitoring to improve reliability of indication of a fire. By overlaying the CO and PM sensor responses, it can be seen that when farm equipment drove by the rural test location, the particle sensor recorded the resulting dust cloud, but there was no response from the CO sensor. This combination of particle and CO sensors provides a one simple way to discriminate and reduce false alarms.

Simulated burns at missoula USFS combustion laboratory.— The second test involved putting the KWJ SPEC sensor array inside several *Thingy:AQ* air quality modules and testing at the USFS in Missoula, Montana where a variety of fires were tested over several weeks during April, 2021. The sensors were tested "as received," with initial baseline zero but no calibration throughout these tests.

Results are summarized below in representative plots for the pollutants measured by the Thingy:AQ monitor system over a

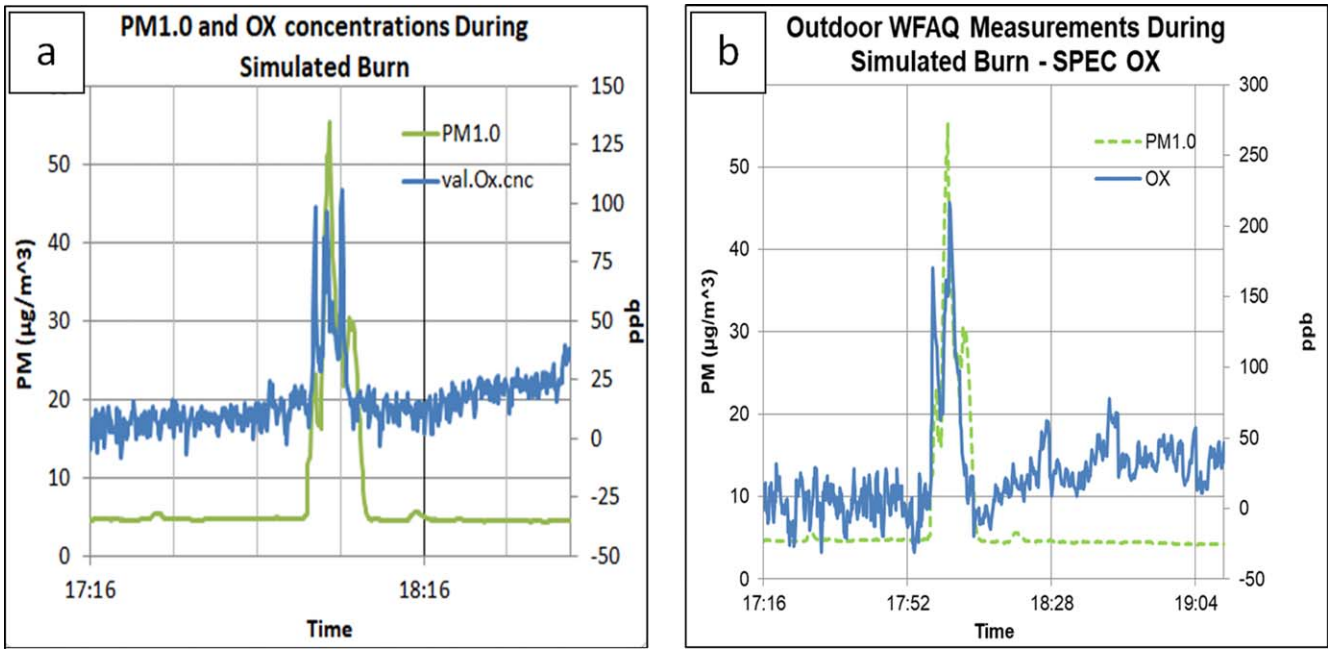

Figure 7. Measured O_3 + NOx concentration overlain on the PM1 data. (a) Response of the Alphasense sensor; (b) SPEC sensor response.

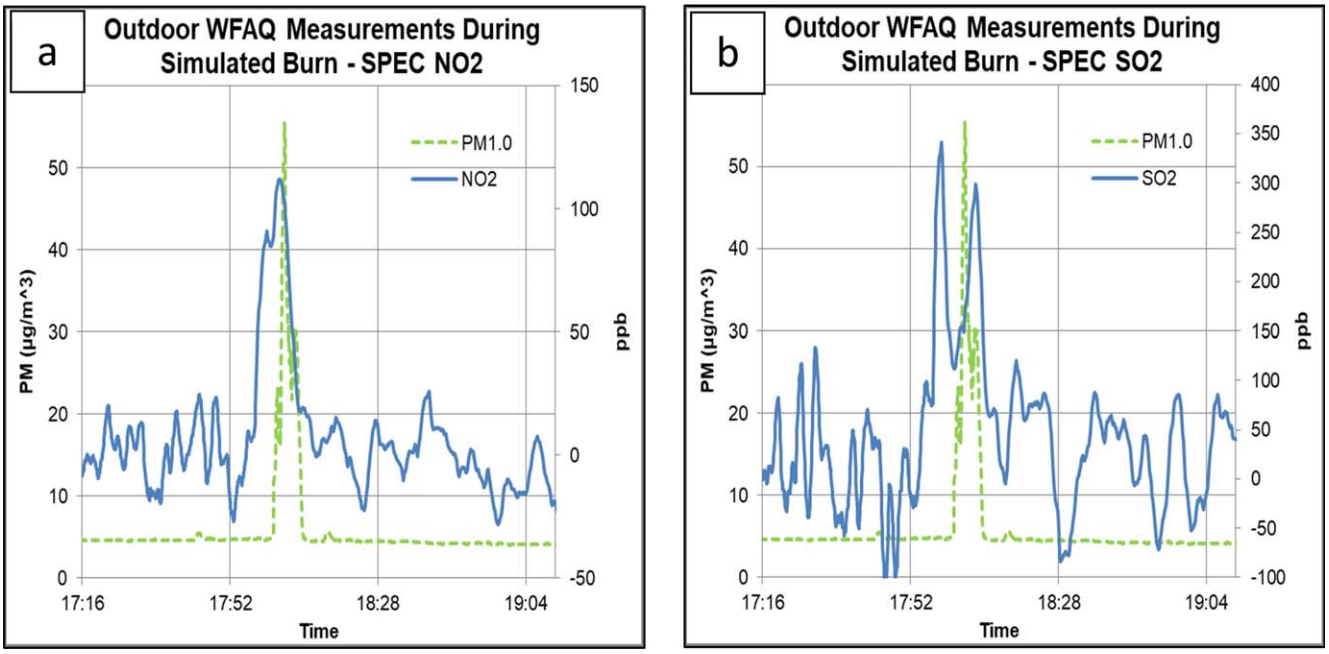

Figure 8. Measured NO_2 (a) and SO_2 (b) concentrations with 1-min averaging. Compare to unaveraged signals (7b and 8b).

two-week period. The picture of Fig. 11 shows the system as deployed in the test facility.

These first plots illustrate the sensitivity of the different sensors to the fire events, and, by overlaying each gaseous parameter with the PM2.5, give a strong visual indication of correlation of the measured gas with the particulate concentrations.

PM2.5 and CO.—Again, in Fig. 12 we see a strong correlation between the CO levels and PM2.5 concentration, across highly variable concentrations within the plume and reflecting similar rapid responses. The fires used a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18. Interesting observations confirm that the fire signature will have some unique features that include the temporal concentration variability.

CO_2 and PM2.5.—The CO_2 sensor tracks PM2.5 (Fig. 13), but shows a slower and less conclusive response than CO, primarily due to fact that the CO2 produced is being added to an existing background of $>$ 400 ppm. There were no burn tests on Sunday, 4/18, the variable CO2 level is likely due to people in the building and lack of rapid ventilation that is used between burns.

Temperature and RH profiles (Fig. 14).—While temperature does increase during the combustion period, it is smaller compared

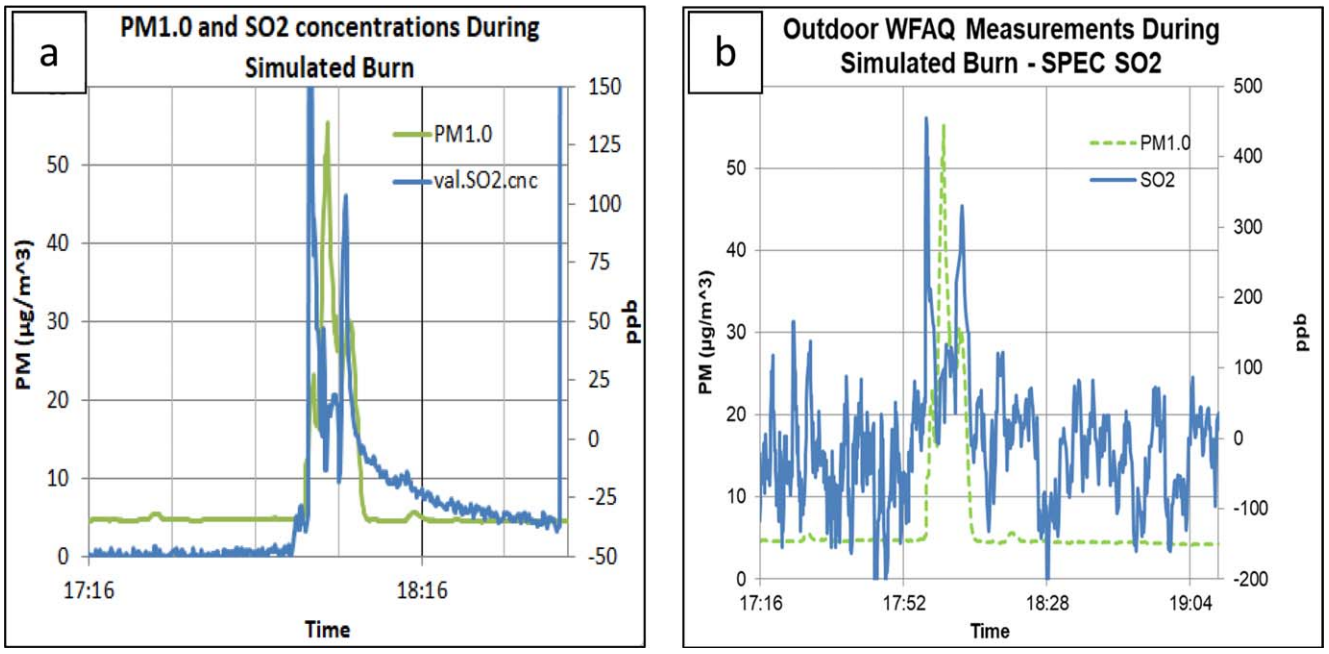

Figure 9. Measured SO_2 concentration overlain on the PM1 data. (a) Response of the Alphasense sensor; (b) SPEC sensor response.

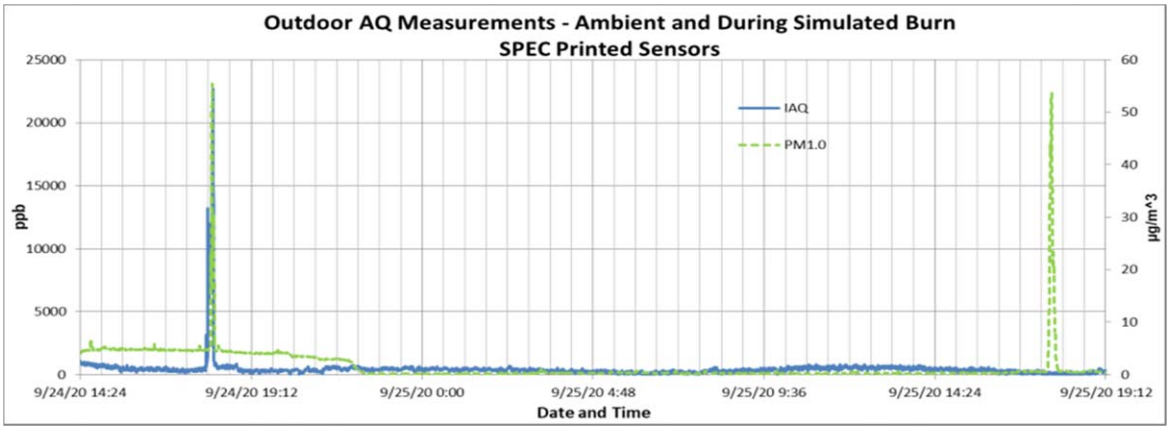

Figure 10. Plot of the CO and PM sensor responses overlain over a 24-h period deployed outdoors. The solid/blue trace is a SPEC CO sensor (AGS), while the dashed/green trace is the optical particle sensor.

to ambient fluctuations, and the response is much slower than that of particulate and CO concentrations .

PM2.5 and O_X (Fig. 15).—Total oxidizing gases ("OX," or NO_2 + O_3), though concentrations are much lower than CO, tracks PM2.5 well and the data illustrate that rapid increase in the two parameters together are a strong indicator of emerging fire .

PM2.5 and NO_2 (Fig. 16).—NO_2 tracks PM2.5; rapid increase in the two parameters together are strong indicator of emerging fire. However, the measured NO_2 is $<$ 5X the noise level, providing a less conclusive early response .

PM2.5 and SO2 (Fig. 17).—The SO_2 sensor tracks PM2.5, though not as strongly as CO in this test. There appears to be a significant difference in the SO2 emissions during the 2nd week compared to the first week. This may be due to fuel composition and this is being further investigated .

Responses can be highly varied depending on the fuel composition and the water content of the fuel. In general, the common character of the fire signature includes a variable and large response to CO compared to a smaller response to CO2 and other pollutants and temperature. A significant observation is that CO and particles are a good team for an inexpensive, rapid responding and reliable monitor to early warning of fires of widely variable wood fuel and moisture content.

Estimations of accuracy and reliability of the sensor arrays.—Multiple *Thingy:AQ* monitors were placed in the combustion lab space, alongside an array of EPA's FRM and FEM reference monitors for particulate and a suite of gaseous pollutants emitted by wildland materials during fires. Multiple burn events were conducted over a 2-week period, using a variety of fuels, loadings, and moisture contents.

The following plots illustrate the consistency of response between four *Thingy:AQ* systems, and correlation between the *Thingy:AQ* and Reference analyzers for several of the measured parameters. Accuracy is also indicated by the slope of the correlation plot (NOTE: the data presented is using the "as received" factory span of sensors, with a single onsite zero measurement).

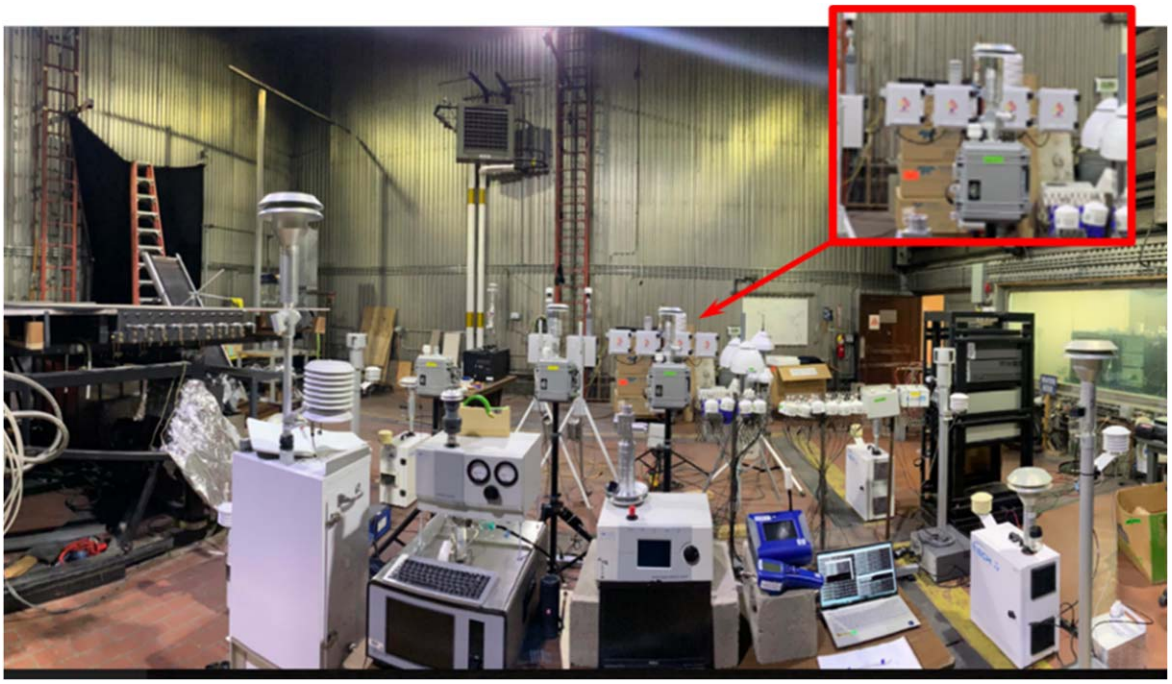

Figure 11. Thingy:AQ monitors with SPEC Sensor gas sensors and Sensirion PM and CO2 sensors, as specified by KWJ following laboratory evaluations.

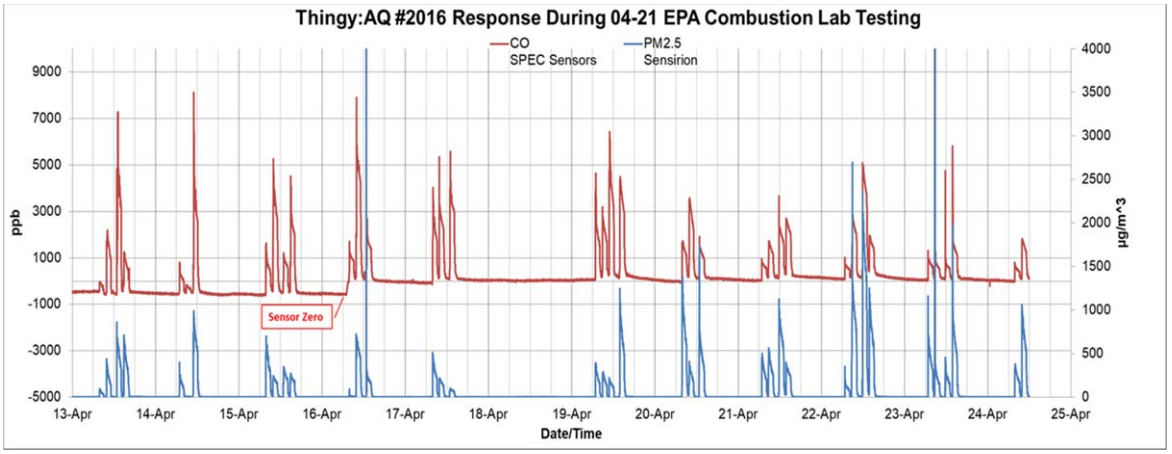

Figure 12. Measured CO and PM2.5 during combustion laboratory burns across a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18.

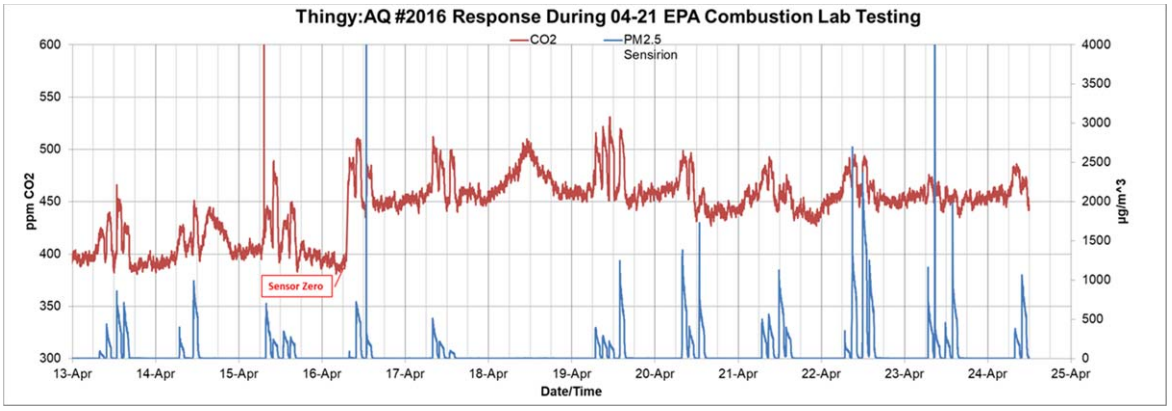

Figure 13. Measured CO_2 and PM2.5 during combustion laboratory burns across a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18.

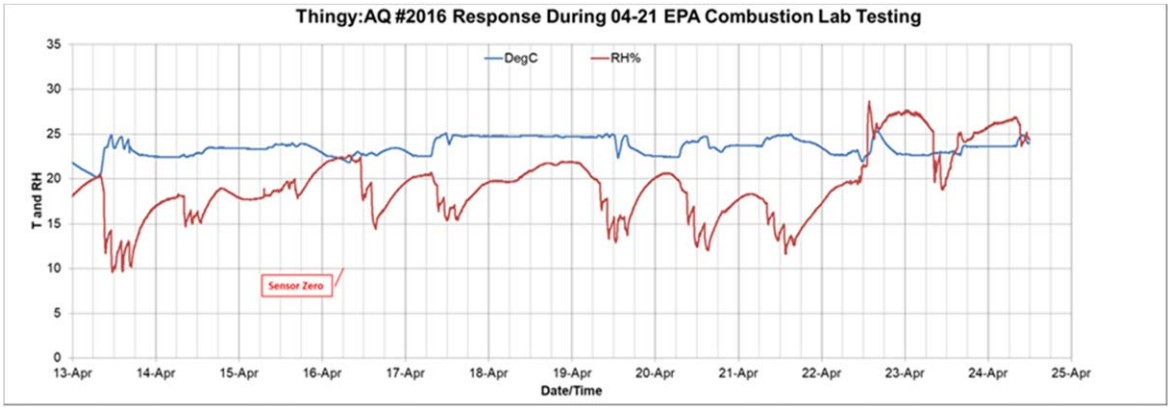

Figure 14. Measured temperature and RH during combustion laboratory burns across a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18.

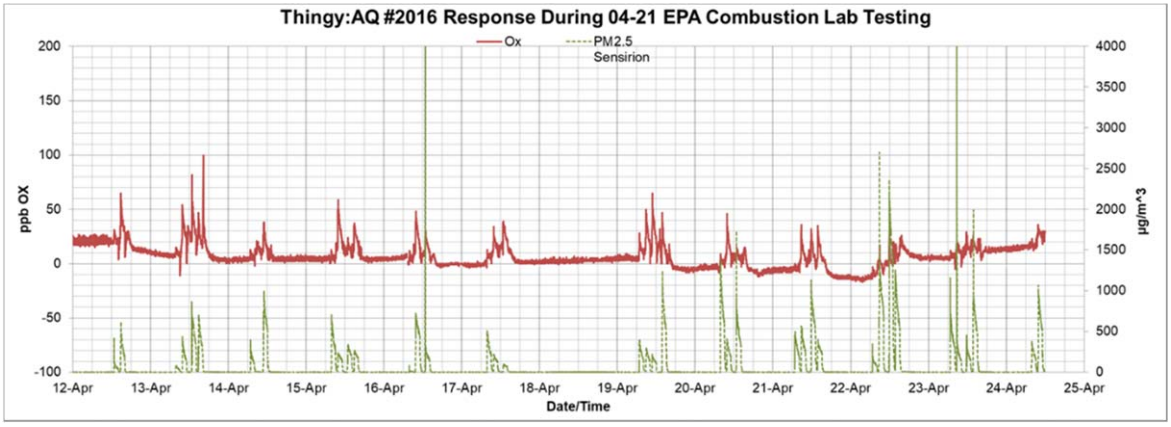

Figure 15. Measured oxidizers (O_3 + NOx) and PM2.5 during combustion laboratory burns across a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18.

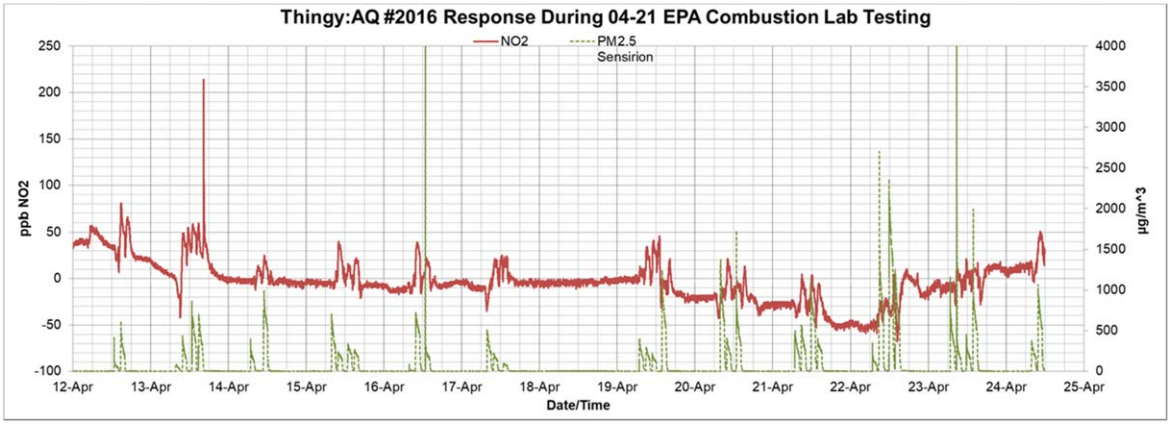

Figure 16. Measured NO2 during combustion laboratory burns across a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18.

Device-to-device uniformity of* thingy:AQ *monitors.— *PM2.5 (Fig. 18).*—The PM sensors exhibit excellent device-to-device uniformity of response, using the as-found calibration .

CO (Fig. 19).—The CO sensors exhibit excellent uniformity of response, following a field zero the morning of 4/13. (The CO sensors were zeroed against the EPA reference analyzer in the test chamber).

The consistency in performance for CO and PM measurement between the three monitors was excellent. We plan to gather additional data on a number of monitors with down-selected sensor arrays, monitoring response to repeated simulations, initially with new, freshly stabilized sensors.

Accuracy.—For health, safety and exposure assessment, the accuracy and stability of the sensors is also important, in addition to uniformity.

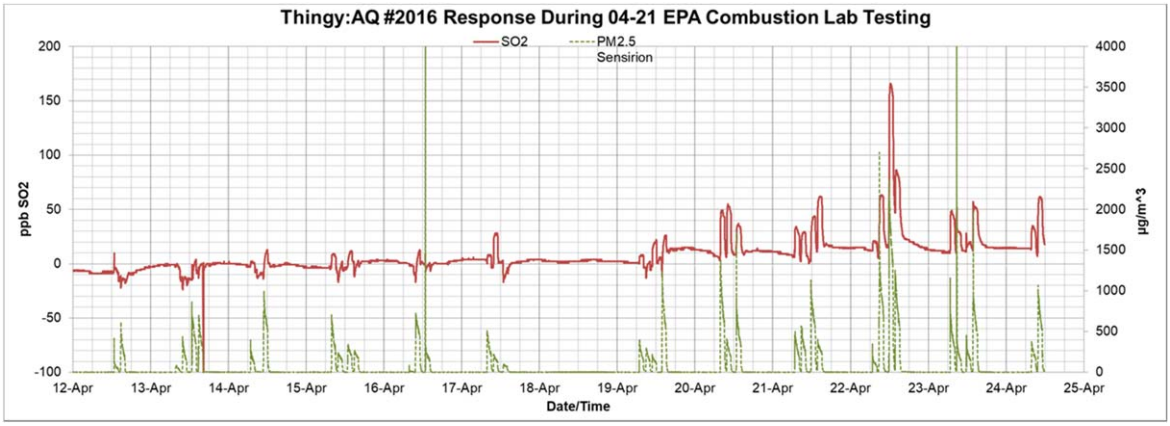

Figure 17. Measured SO2 and PM2.5 during combustion laboratory burns across a variety of fuels and moistures, and controlled burns were conducted every day except Sunday, 4/18.

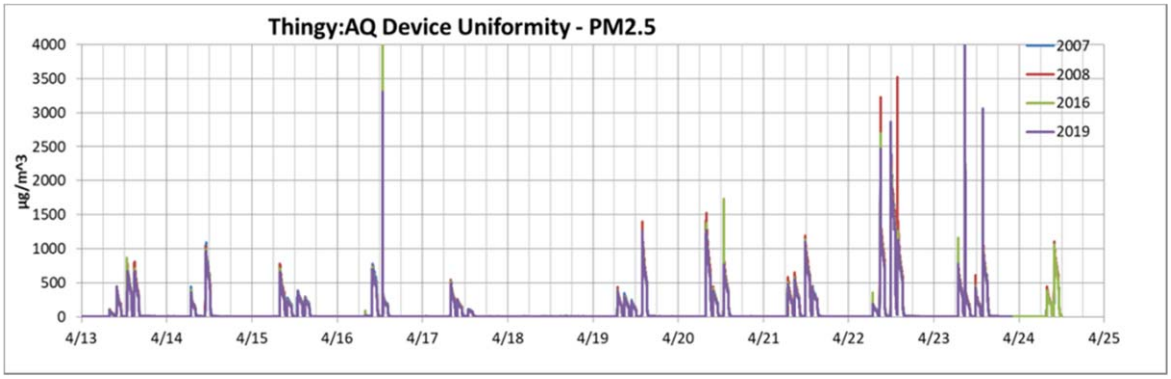

Figure 18. Device-to-Device uniformity of measured PM2.5 during EPA testing of 4 *Thingy:AQ* monitors.

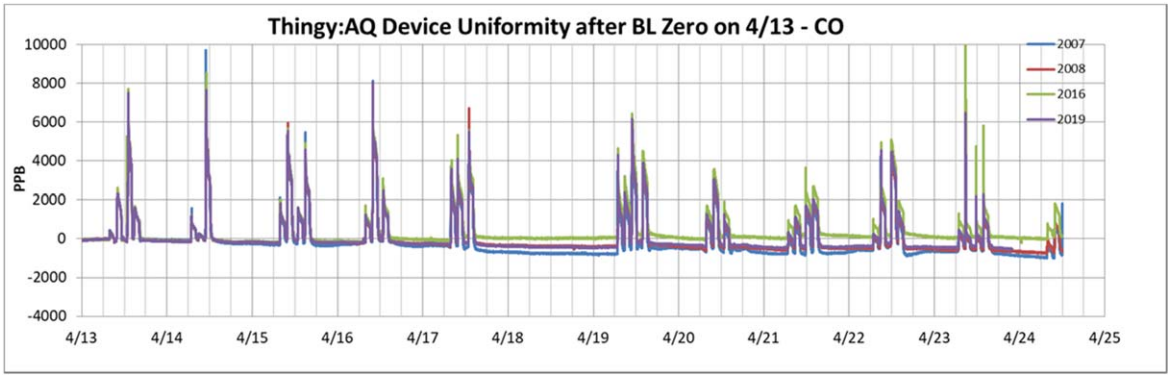

Figure 19. Device-to-Device uniformity of measured CO during EPA testing of 4 Thingy:AQ monitors.

The figures below show the response of the PM2.5 and CO sensors during tests 10 days apart, relative to the EPA qualified FRM analyzers. *[NOTE: The Thingy:AQ monitors were located ~1 m from the combusted material. The reference analyzers were drawing air from the chamber* via *sample lines. It is possible that the AQ monitors may have been exposed to higher levels, and possible transient levels during the initial phase of each burn event.]*

There is excellent correlation between inexpensive optical PM sensor and an FRM reference analyzer (T640 PM Mass Monitor, Teledyne) during the 4/13/21 and 4/23/21 burns (Fig. 20). There is also excellent ccorrelation between the inexpensive electrochemical AGS CO sensor and the EPA reference analyzer during the 4/13/21 and 4/23/21 burns (Fig. 21).

Concluding Remarks

There are several very important observations in the sensor data collected that are relevant to detection of wildfires. It should first be said that it is clear our hypothesis that AQ changes can be used to detect wildfires is exactly correct. But it is also clear that sensor placement, adequate sensitivity in the field, and remote communication needs to be more thoroughly evaluated. Major observations include:

(1) Response time: all the sensors show a very rapid response when detecting the plume. The sensor response time is rapid enough to see these variations and spike emissions can be a

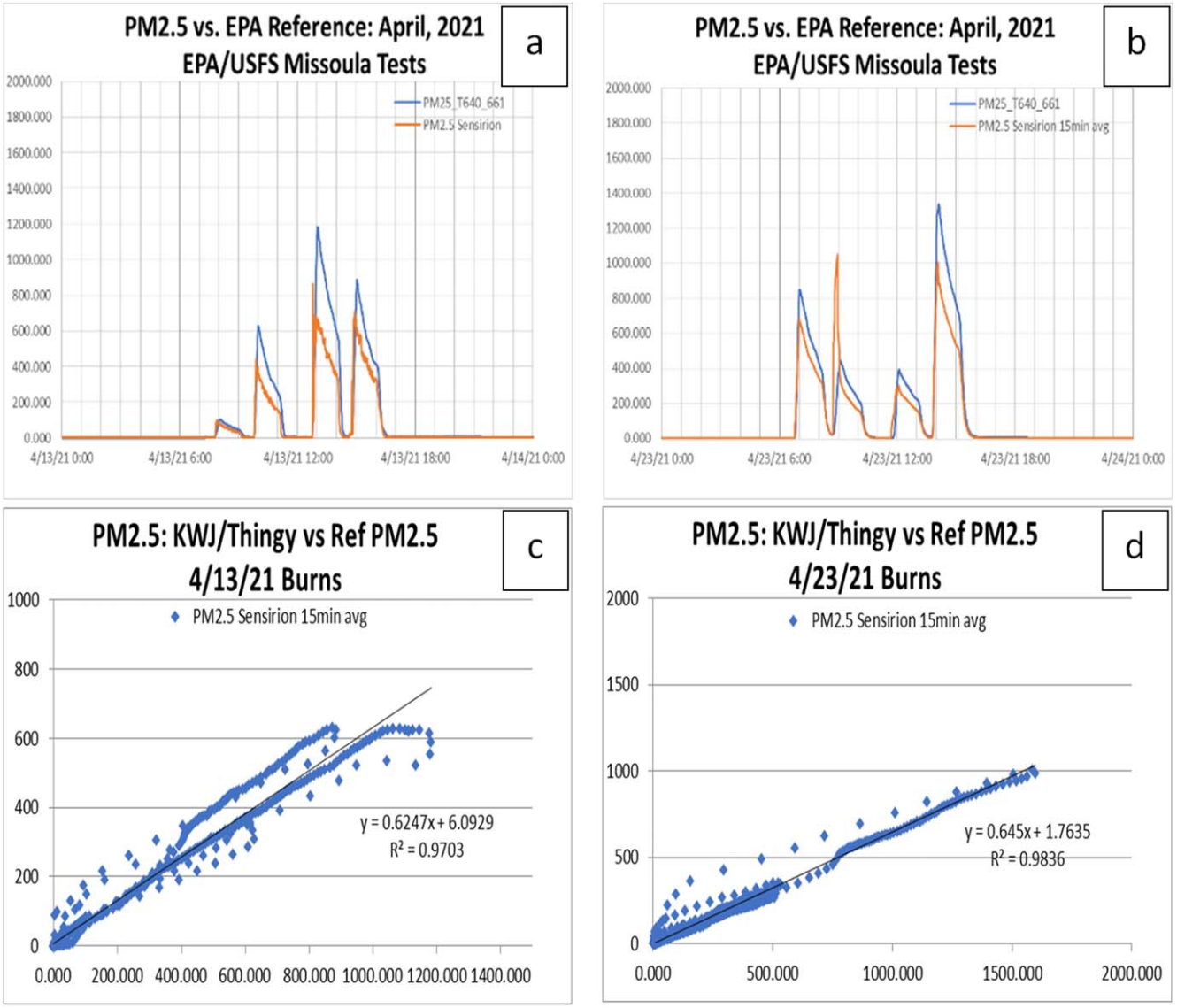

Figure 20. Correlation between inexpensive optical PM sensor and EPA reference analyzer during the 4/13/21 and 4/23/21 burns. (a) & (c) Response to four burns on 4/13/21; (b) & (d) Response to four burns on 4/23/21. For all four charts the units are in ug m^{-3}.

characteristic differentiator of a fire signature from a slow increase in background levels.

(2) A combination of only 1) CO and 2) particulate sensors can provide a mini-array without reduction of ambiguity.

(3) Low cost and low power sensors are feasible for deployment in distributed arrays with some confidence of reliability and repeatability.

(4) The principal question not addressed here is required lower level of detection, because we know the concentration will decrease rapidly as the distance from the fire increases. The dynamics in play are the distance from the fire, the emissions and air dilution of the plume and the distance apart the sensors are placed in the area to be monitored. These conditions are not yet modeled.

There are now practical sensors for deployment of large arrays. This work did not report on the communications requirements [LORA or cellphone or satellite wireless part of the system] but indications are that a heterogeneous system will be needed in today's world. That is a combination of simple low cost nodes with line of sight LoRa communication with interspersed "gateway" nodes that can upload data to cloud communication and alert and deploy first responders immediately. A combination of sensors will clearly reduce false positives and nuisance alarms and deployment around high value target areas like cities and high probability fire locations is yet to be designed.

One primary concern with the use of low-cost gas sensors is the anticipated drift and accuracy over time. The EPA testing in Missoula was only two weeks, but is being followed by a series of outdoor ambient studies conducted over the summer and fall at several of their laboratories in the west and northwest. These data will provide insight into the reliability of the sensors for monitoring background outdoor ambient levels, and, most importantly for our study, the ability to track and alert to increasing levels of pollutants that show strong correlation to an emerging fire.

We are planning additional deployments of sensor arrays wherein we can detect controlled burns in a local community around small and large areas. Using current printed sensor designs, a million CO sensors can be produced for several million dollars which would be a small price to save billions in assets and precious human life. It will take all of us to join forces to combat the effects of climate change and specifically the exacerbated effect of wildfires on our people. First responders, sensors and warning systems, better mitigation

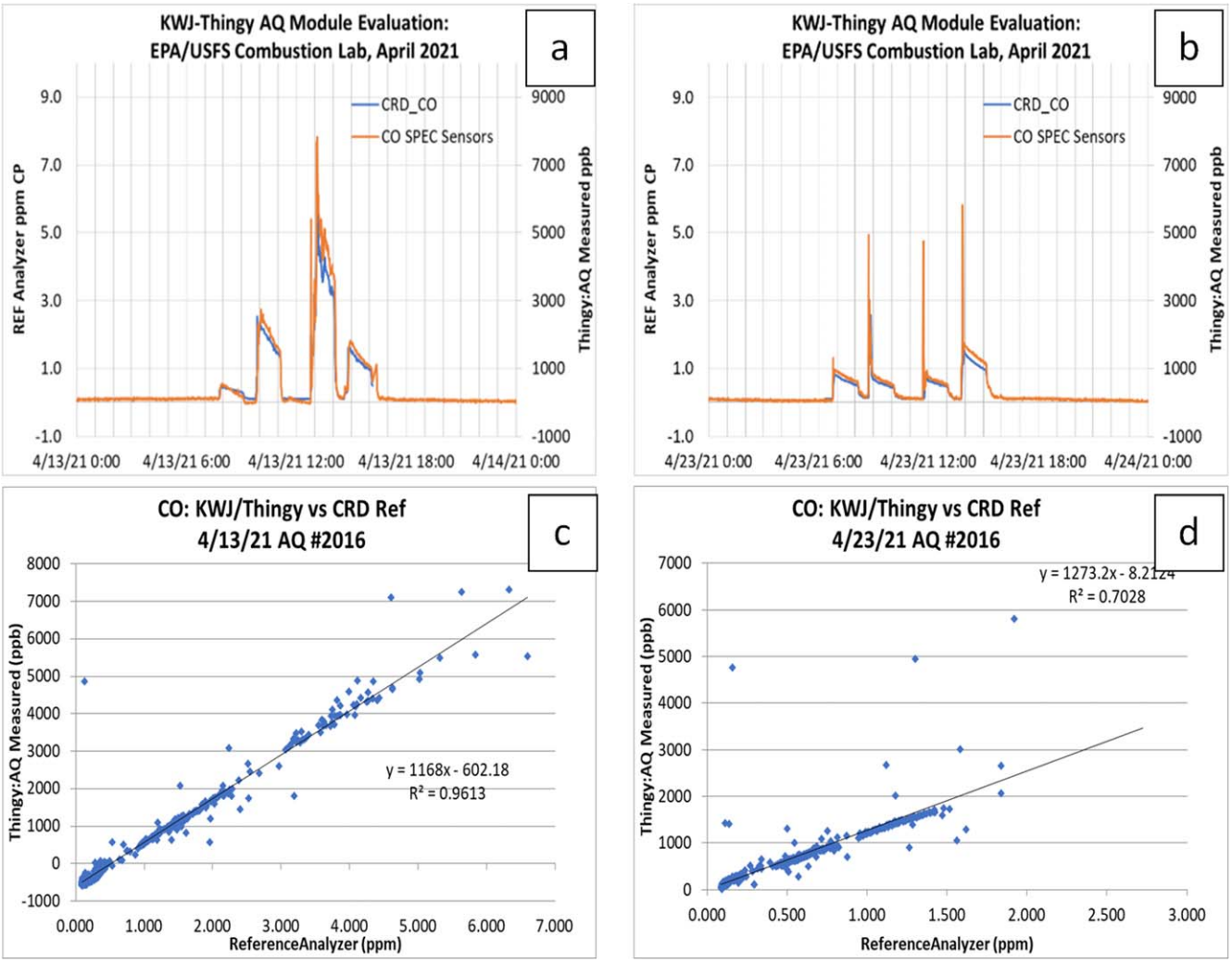

Figure 21. Correlation between amperometric CO sensor and EPA reference analyzer. (a) & (c) represent the data collected on 4/13/2021, while (b) & (c) represent the data collected on 4/23/2021. NOTE: If the three extreme outlier data points corresponding to transient CO spikes on 4/23 are excluded, $R^2 = > 0.9$. The *Thingy:AQ* monitor consists of low-cost electrochemical AGS CO sensors, and is reported in ppb, while the reference monitor is reported in ppm. The left and right axes in figure (a) & (b) are aligned for scale, while in (c) and (d) a linear fit with slope 1,000 represents a 1:1 corespondence.

strategies, and multi-dimensional large data array collection by citizen science, as well as partnerships of industry, and government will all contribute to a better world.

ORCID

J. R. Stetter https://orcid.org/0000-0002-7839-0980

References

1. Royal Society (2020), Global trends in wildfire and its impacts | Blog Post from The Royal Society, https://royalsociety.org/blog/2020/10/global-trends-wildfire/.
2. Jesse Roman, Angelo Verzoni, and Scott Sutherland (2020), NFPA Journal - THE WILDFIRE CRISIS, https://nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/November-December-2020/Features/Wildfire.
3. FutureEarth (2022), https://futureearth.org/publications/issue-briefs-2/global-fires/.
4. EarthSky (2021), Another Terrible Year For Wildfires And Smoke In The US In 2020https://earthsky.org/earth/us-2020-wildfire-season-record-bad/.
5. World Environment (2020), Wildfires, forest fires around world in 2020, https://aa.com.tr/en/environment/wildfires-forest-fires-around-world-in-2020/2088198.
6. Veronica Penney (2020), It's Not Just the West. These Places Are Also on Fire, https://nytimes.com/2020/09/16/climate/wildfires-globally.html.
7. S. K. Akagi et al., "Emission factors for open and domestic biomass burning." *Atmos. Chem. Phys.*, **11**, 4039 (2011).
8. S. P. Urbanski, W. Min Hao, and S. Baker, "Chemical Composition of Wildland Fire Emissions." *Developments in Environmental Science,*, ed. A. Bytnerowicz, M. Arbaugh, A. Riebau, and C. Andersen (Elsevier, USA) Developments in Environmental Science, 8 (2009), https://www.fs.fed.us/rm/pubs_other/rmrs_2009_urbanski_s001.pdf.
9. A. Melin, P. Obert, M. Rebocho, and P. Bonnet, "Cardiac morphology and function following long term exposure to carbon monoxide at high altitude in rats." *J. Toxicol. Environ. Health*, **65**, 1981 (2002).
10. C. L. Townsend and R. L. Maynard, "Effect on health of prolonged exposure to low concentrations of carbon monoxide." *Occup. Environ Med.*, **59**, 708 (2002).
11. Science Matters (2020), The Danger of Wildland Fire Smoke to Public Health, https://epa.gov/sciencematters/ danger-wildland-fire-smoke-public-health.
12. W. Cascio, "Wildland Fire Smoke and Human Health." *Science of the Total Environment* (Elsevier, USA) 624, 586 (2018).
13. J. Lelieveld, J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer, "The contribution of outdoor air pollution sources to premature mortality on a global scale." *Nature*, **525**, 367 (2015).
14. NIST (2021), NIST's Emberometer Could Gauge Threat of Wildfire-Spreading Embers, https://www.nist.gov/news-events/news/2021/08/nists-emberometer-could-gauge-threat-wildfire-spreading-embers.
15. EPA SBIR EPA Contract Number: 68HERD19C0020, 'Ultralow Power Sensor Package for Ground Level Air Pollution Levels from Wildland Fires', Phase I Final Report, Nov. 2019, Findlay, Stetter, et al.
16. EPA SBIR Phase II Project, Contract Number: 68HERD20C0020, 'Ultralow Power Sensor Package for Ground Level Air Pollution Levels from Wildland Fires', 6/2020-5/2022, Findlay, Stetter, et al.
17. Ultralow Power Sensors for Firefighter Safety and Monitoring of Surrounding Air Quality, Final Technical Report, USDA Phase I SBIR, Award #: 2019-33610-29747; July 1, 2019 - February 29, 2020.
18. Ultralow Power Sensors for Firefighter Safety and Monitoring of Surrounding Air Quality, USDA Phase II SBIR, Award #:2020-33530-32997; Sept 1 2020—August 31, 2022..
19. NIOSH workplace safety and health topics (2018), Fighting Wildfires, http://cdc.gov/niosh/topics/firefighting/.

20. NFPA, *Standard on Respirators for Wildland Fire Fighting Operations* 2016 ed. (1984), https://nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1984.
21. C. C. Austin and N. Goyer, "Respiratory Protection for Wildland Firefighters—Much ado about Nothing or Time to Revisit Accepted Thinking?" *Wildfire 2007*, Seville, Spain (2007).
22. G. Broyles, *Wildland Firefighter Smoke Exposure* (US Department of Agriculture) (2013).
23. E. P. Radford M.D. and M. S. Levine M.D., MPH, "Occupational Exposures to Carbon Monoxide in Baltimore Firefighters." *Journal of Occupational and Environmental Medicine*, **18**, 628 (1976).
24. F. Reisen, D. Hansen, and C. P. (Mick) Meyer, *Assessing firefighters' exposure to air toxics in bushfire smoke*, *TASSIE FIRE Conference Proceedings*, Hobart, Tasmania, Australia, 18–20 July 2007 (Wrest Point Conference Centre) (2007).
25. T. E. Reinhardt, R. D. Ottmar, and M. J. Hallett, (1990), Guide to Monitoring Smoke Exposure of Wildland Firefighters, United States Department of Agriculture Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-448.
26. T. E. Reinhardt1 and R. D. Ottmar, "Baseline Measurements of Smoke Exposure Among Wildland Firefighters." *Journal of Occupational and Environmental Hygiene*, **1**, 593 (2004). K. H. Dunn, I. Devaux, A. Stock, and L. P. Naeher, "Application of end-exhaled breath monitoring to assess carbon monoxide exposures of wildland firefighters at prescribed burns." *Inhalation Toxicology*, **21**, 55 (2009).
27. R. Dutta, A. Das, and J. Aryal, "Big data integration shows Australian bush-fire frequency is increasing significantly." *Royal Society Open Science*, **3**, 150241 (2016).
28. T. E. Lovejoy and C. Nobre, "Amazon tipping point." *Sci. Adv.*, **4**, eaat2340 (2018).
29. J. L. Pierce, G. A. Meyer, and A. T. Jull, "Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests." *Nature*, **432**, 87 (2004).
30. M. G. Turner, D. C. Donato, and W. H. Romme, "Consequences of spatial heterogeneity for ecosystem services in changing forest landscapes: priorities for future research." *Landscape Ecology*, **28**, 1081 (2013).
31. W. M. Jolly, M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and D. M. Bowman, "Climate-induced variations in global wildfire danger from 1979 to 2013." *Nat. Commun.*, **6**, 1 (2015).
32. S. Harris and C. Lucas, "Understanding the variability of Australian fire weather between 1973 and 2017." *PLoS One*, **14**, e0222328 (2019).
33. S. H. Doerr and C. Santín, "Global trends in wildfire and its impacts: perceptions vs realities in a changing world." *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**, 20150345 (2016).
34. A. L. Westerling, H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, "Warming and earlier spring increase western US forest wildfire activity." *Science*, **313**, 940 (2006).
35. R. B. Hammer, V. C. Radeloff, J. S. Fried, and S. I. Stewart, "Wildland–urban interface housing growth during the 1990s in California, Oregon, and Washington." *International Journal of Wildland Fire*, **16**, 255 (2007).
36. J. R. Stetter and J. Li, "In modern topics in chemical sensing: chapter 4, 'amperometric gas sensors—a review." *Chem. Rev.*, **108**, 352 (2008).
37. Sensor literature on commercial products, www.spec-sensors.com; www.kwjengineering.com.
38. M. T. Carter, J. R. Stetter, M. W. Findlay, and V. Patel, "Printed amperometric gas sensors." *ECS Trans.*, **50**, 211 (2012).
39. J. R. Stetter, A. G. Shirke, B. J. Meulendyk, V. Patel, G. O'Toole, and M. T. Carter, "Health and environmental applications of integrating low power sensors with wireless technology." *ECS Trans.*, **53**, 7 (2013).
40. South Coast Air Quality Management District, Field Evaluation SPEC Gaseous Sensors (Accessed 12/23/2021), http://aqmd.gov/docs/default-source/aq-spec/field-evaluations/spec-sensors—field-evaluation249fa8efc2b66f27bf6fff00004a91a9.pdf?sfvrsn=2.