

Current Issues Related to Combustion Byproducts & Human Health: A Summary of the 18th International PIC Congress

Julia E. Rager, Sarah L. Miller, Kate Hoffman, Yong Ho Kim, Brian Gullett, Toddi Steelman, Daniel Jaffe, Linda S. Birnbaum, Miriam M. Calkins, Marc Durno, and Heather M. Stapleton*



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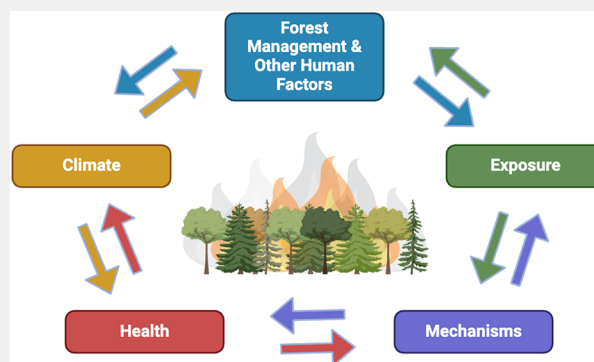
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ABSTRACT: The 18th International Congress on Combustion Byproducts and Human Health Effects (PIC2024) was held in Durham, North Carolina on May 20th–22nd, 2024. The overall goal of this conference, typically organized biannually, is to bring together scholars and researchers from diverse fields including chemistry, toxicology, engineering, epidemiology, and occupational and public health, and from various sectors (academia, government, and industry) to engage on new and emerging issues related to combustion processes, human exposure, and potential health risks. The theme of the 18th International Congress was “Fire Emissions & Community Impacts at the Wildland Urban Interface and Disaster Sites.” Specific focus and emphasis was placed on new research concerning wildland fires, climate change, firefighter exposures, and data collected following the East Palestine train derailment in Ohio. Plenary speakers included Drs. Toddi Steelman (Duke University), Daniel Jaffe (University of Washington), Miriam Calkins (NIOSH), Mark Durno (U.S. EPA), and Linda S. Birnbaum (NIEHS, retired). This report summarizes the primary research highlighted during the conference, major discussion points raised, and areas recommended for future research.

KEYWORDS: combustion byproducts, health, wildfire, climate, firefighter, PFAS, smoke, disaster response



HISTORY OF PIC CONFERENCE

Combustion-derived pollutants have long been recognized as one of the primary sources of environmental exposures with adverse impacts on human health. A recent article in the *Lancet Commission on Pollution and Health* estimated that 9 million premature deaths occurred in 2015 related to pollution, with air pollution identified as the leading culprit.¹ Combustion byproducts are a significant component of air pollution associated with many of these disease outcomes and affect both outdoor and indoor air. Climate conditions and at-risk infrastructure as potential ignition sources (e.g., power transmission, train tracks) are both contributing to increased risk of major fires and combustion emissions. The International Congress on Combustion Byproducts and Their Health Effects has provided a unique platform for discussion of the most pressing issues related to these combustion and combustion-associated health impacts for nearly 25 years.

Starting in 1990, the first Congress was held at the National Institutes of Health facility in Bethesda, MD, USA. Commonly referred to as the “PIC Congress” (Products of Incomplete Combustion), this meeting has typically been held in a biennial format alternating venues between North America, Europe, and Asia. The overall goal of the conference is to bring together scholars and researchers from diverse fields including

chemistry, toxicology, engineering, epidemiology, and occupational and public health, and from various sectors (academia, government, and industry) to discuss a variety of issues related to combustion and thermal processes. For this Congress, combustion was used in the broadest sense of the word and included all forms of thermal reactions, even those used to produce energy or remediate wastes. Thus, it also included discussions on the generation and health effects of toxic byproducts from other thermal reactions including energy recovery, materials recovery, and climate change aspects as it pertains to combustion emissions and environmental health. A goal of this Congress was to develop practical, scientific solutions to protect health, the environment, and communities by fostering interdisciplinary interactions that also help train and develop the next generation of scientists.

The theme of the 18th Congress was “Fire Emissions & Community Impacts at the Wildland Urban Interface and

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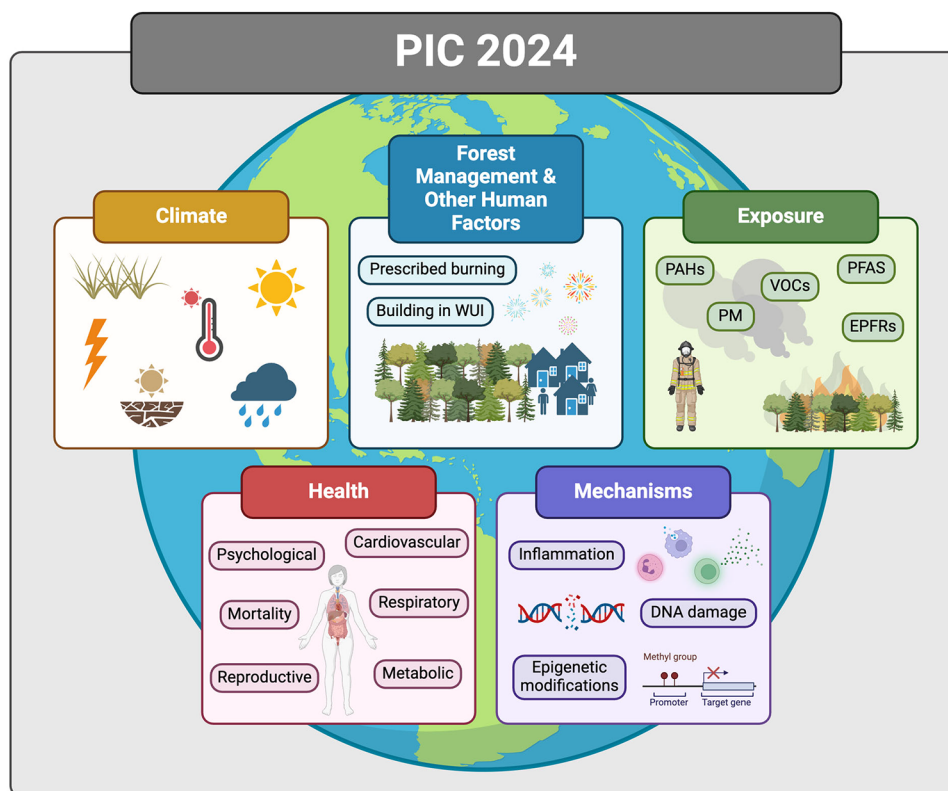


Figure 1. An overview of the common themes discussed at the 18th International Congress on Combustion Byproducts and Human Health held in 2024, also known as PIC2024.

Disaster Sites.” The Congress was grounded in five plenary presentations over 2.5 days that focused on the following topics: wildland fires and their impacts on air quality and health, chemical exposures in both wildland and structural firefighters, community health assessments following the East Palestine train derailment event, and new and emerging issues related to combustion byproducts and health (Figure 1). A copy of the presentations and titles associated with the conference can be found in the [Supporting Information](#). Here, we dive further into the new information presented at this Congress and some of the discussion points that were raised.

WILDLAND FIRES

Plenary lectures presented by Toddi Steelman (Duke University) and Dan Jaffe (University of Washington) discussed the increasing impact of wildland fires across the U.S. and globally, the factors that have contributed to this observed increase, along with solutions that can mitigate risks posed to communities by wildland fires. Wildland fires and the long-range, downwind smoke they produce do not obey bureaucratic borders, creating scenarios where a future inevitably plagued by additional fire will also pose additional geopolitical challenges as air quality and health are impacted by long-range, downwind smoke plumes. Smoke plume chemistry is highly complex and variable where fuel composition, temporal factors, and spatial factors play fundamental roles. Factors influencing emitted plume chemistries were discussed in detail in this session, along with growing impacts of wildfire events occurring at the wildland urban interface (WUI). Further discussions also highlighted public outreach, awareness, and community preparedness, as detailed below.

Preliminary data discussed at the workshop indicated total particulate matter (PM) mass is largely conserved during downwind transport; however, during this type of transport, there are often significant changes in PM species composition. Once in the atmosphere, PM can undergo various chemical and physical transformation processes, including oxidation.² For example, as PM transports downwind of smoke sources, its chemical properties often shift toward a more oxidized state dominated by secondary organic aerosol species due to photochemical aging.^{3,4} One distinguishing feature of wildland fire PM is the presence of incomplete combustion materials and thermal degradation products of cellulose and other biomass-relevant materials, which are commonly absent other PM emission sources (e.g., automobile exhaust).² Similar to smoke PM, gaseous phase components can also be photochemically converted during downwind transport, especially when the plume moves toward more urban environments where air has higher levels of oxidative species like ozone and nitrogen oxides (NO_x) as compared to wildland source air.⁵ These downwind plumes, also referred to as “aged” smoke, may potentially pose differential risk to downwind communities despite dilution given that the secondary organic aerosols formed during aging are associated with worse human health outcomes compared to primary pollutants like PM_{2.5}.^{6,7} In the past few decades, we have witnessed greater impacts on and consequences for humans when it comes to wildfire.^{8,9} We have observed increasing extreme wildfire weather which in turn is associated with extreme wildfire events^{10,11} and, in some places, increased wildfire intensity, severity and frequency^{12,13} along with human and ecological losses. These trends produce larger amounts of smoke, thereby potentially increasing the likelihood that said smoke will travel longer

distances, depending on complex atmospheric conditions and phenomena, and increase the likelihood of exposure to hazardous pollutants for downwind communities.^{14,15} Altogether, this may represent higher risk of exposure to downwind communities with aged smoke, countering reduced concentrations due to dilution.

Wildland fires require fuel, an ignition event, and oxygen. Climate change is creating fire-favorable conditions that alter these required factors and increase the likelihood of a fire igniting and burning more readily. Warming and drought from climate change are creating conditions that dry out vegetative fuel, making it more prone to ignition and faster burning rate. As a result, fires are more likely to start and spread over larger areas. Warming due to climate change is contributing to the lengthening of fire weather season, creating longer periods of weather conditions favorable to the ignition and spread of wildland fires. Regional trends in some boreal and midlatitude forests point to a longer wildfire season now^{11,13} and increasing over time globally.¹⁶ Extended periods of warming also put excess stress on trees and vegetation, which increases their susceptibility to pathogens, water loss, and other factors that ultimately render them more likely to burn.¹⁷ Warmer temperatures increase evapotranspiration and decrease fuel moisture and these together increase risk;¹⁸ decreasing relative humidity and increasing temperatures are linked to more extreme weather, which in turn drive regional extreme fire activity and risk;^{10,18} warmer temperatures will also lead to more lightning-based ignitions.^{19,20} Wildland fires are primarily ignited by lightning and human activities. Human activities accounted for 84% of wildland fire ignitions across the U.S. in an analysis of government wildfire records spanning 1992 to 2012.²¹ However, spatial distributions of lightning- versus human-caused ignitions demonstrated that wildland fires are somewhat more likely to be ignited by lightning in the western U.S. and more commonly by human activities in the eastern U.S.²¹ Human-ignited fires also tend to burn faster compared to lightning-ignited fires in the days immediately following ignition, leading to more devastating ecosystem effects.²² The overall number of human ignitions has increased, largely driven by increased populations living at the WUI.²³

Given that rates and severity of wildland fires are increasing, it is imperative that communities understand how to protect themselves. Official U.S. and state public health advice during heavy smoke days typically directs people to stay indoors, keep doors and windows closed, and avoid outdoor exercise.^{24,25} School and community events may even be canceled to conform with these public health advisories.²⁴ It is generally advised to wear a well-fitting mask or respirator, such as a NIOSH-certified N95 respirator, if activities must be performed outside for an extended period of time.^{24,26} If an N95 respirator is unavailable, surgical masks can provide some protection from exposure; however, degree of protection from any mask is largely based on mask fit and duration of wear.^{27,28} Additionally, masks and respirators protect the wearer from primarily particulate emissions as their filtration efficiencies for gaseous components of air pollution are much lower.²⁹ Notably, there are no N95 respirators certified in sizes suitable for children, leaving caretakers (e.g., parents, schools, daycares) to rely on other methods of exposure reduction.^{26,28} Masks or respirators, additionally, may not be suitable for those living with preexisting conditions that reduce their ability to breathe.²⁶ Ultimately, sheltering inside has been the most common advisory to protect against smoke exposure.²⁴

However, preliminary data presented at the 18th International Congress suggested that indoor environments may not be as inherently protective as previously assumed. During peak wildfire season on the western U.S. coast, air quality monitors stationed inside various buildings throughout Seattle measured PM_{2.5} (particles of aerodynamic diameter 2.5 μm) levels only marginally lower than readings that came from outside. These data suggest that not all buildings are created equal, and building age and infrastructure (e.g., seals on doors, windows, air vents, etc.) must be considered when determining risk of exposure. Data from these studies also supported the use of air purifiers to reduce indoor smoke exposure. For example, using a low-cost air filter (box fan with attached MERV 14 filter) dramatically reduced indoor PM_{2.5} measurements.³⁰ These data indicate that even low-cost air purifiers, which may be more accessible to socioeconomically disadvantaged populations, are effective at reducing indoor smoke exposure to levels that are more protective of human health.

Toddi Steelman urged in her plenary lecture to look toward the future with a “narrative of hope and possibility, not despair and apocalypse” combined with a focus on solutions. Fire suppression policies, land management practices, and climate change have all contributed to worsening trends in wildland fire incidence and size. Given this, Steelman commented that, in her opinion, changes in fire suppression strategies and climate change mitigation are imperative to change the trajectory of wildland fire incidence and severity in the future. Increasing the use of prescribed burning will help reduce fuel loads in wildfire-prone areas, and starve wildland fires of the fuel they need to become large, destructive mega-fires that threaten both people and infrastructure.³¹ However, prescribed burning may temporarily increase the exposure to smoke in rural and WUI communities located near and within these wildfire-prone areas, representing a trade-off with the risk of significant wildfires. Questions still persist regarding the public health costs of more chronic, low level exposure to biomass burning emissions due to prescribed burning compared to those of more acute, high level exposure characteristic of wildland fire events.³² Over 148 recommendations to address wildfire mitigation, management, and postfire rehabilitation and recovery were made by the Wildland Fire Mitigation and Management Commission in their 2023 report, some of which include the expansion of beneficial prescribed fire.³³ Additional recommendation themes include changes to governance and organizational response to wildfire, supporting collaboration across the wide range of entities involved in wildfire response, shifting from reactive to proactive approaches to wildfire response, supporting and expanding the wildfire response workforce, modernizing tools for informed decision-making, and investing in community resilience.³³ Ultimately, strategies to reduce fuel loads and greenhouse gas concentrations have been suggested as means to offset climate effects on wildland fire trends and are imperative to reduce the impacts of rising temperature and cascading consequences on drying vegetation in addition to increases in lightning-based ignitions both observed over recent decades in the U.S. and predicted over future decades globally.

■ FIREFIGHTER EXPOSURES AND HEALTH CONCERNS

Firefighters are among the populations most frequently exposed to elevated levels of combustion byproducts due to the nature of their work. Firefighting is also inherently

dangerous, requiring intense physical exertion, altered sleep schedules, and episodic exposure to hazardous chemicals, soot, and smoke. As such, firefighters may also experience mental health issues from combinations of these stressors; however, research in this area is under-studied.

During the Congress, several sessions highlighted new research assessing firefighters' exposures in wildland and WUI settings. The plenary speaker, Dr. Miriam Calkins from National Institute for Occupational Safety and Health (NIOSH), provided an overview on the state of the science. Clearly, firefighters face higher levels of exposure to combustion-derived pollutants found in the soot and smoke (e.g., hydrogen cyanide, polycyclic aromatic hydrocarbons (PAHs)) as well as synthetic chemicals released from the fuel source during fire events.^{34,35} For example, structural firefighters are often exposed to synthetic chemicals released from burning buildings and household materials, which can include plastic additives (e.g., phthalates), chemicals that provide flame resistance (e.g., polybrominated diphenyl ethers (PBDEs)), and chemicals used as water and grease repellents such as per- and polyfluoroalkyl substances (PFAS), among others.³⁶ In contrast, wildland firefighters are more likely to encounter organic fuel sources like wood, grass, and vegetation, resulting in exposure to different chemicals (e.g., PAHs, volatile organic compounds (VOCs), and aldehydes).^{37,38}

Several researchers presented new data on chemical exposures among firefighters in different scenarios and in different regions. These studies suggest that firefighters encounter coexposures to a variety of carcinogenic and noncarcinogenic contaminants, including volatile chemicals (e.g., benzene, formaldehyde), PAHs, flame retardants, and PFAS. In addition, they face unique challenges and exposures due to changes in building materials over time (resulting from changes in manufacturing), increasing transition to electric motors (e.g., vehicles, bikes, etc.), phase-out of some hazardous chemicals (e.g., PBDEs) and introduction of new chemicals in building materials.

Monitoring firefighters' exposure presents significant challenges due to the unpredictable and episodic nature of fire events, as well as the logistical difficulties of accessing firefighters in remote or hazardous locations. A variety of approaches have been used to assess exposure including air monitoring, wearable exposure technology and tools, and biological sampling. Data collected to date demonstrate that exposures among firefighters can also vary widely depending on their job tasks, even after a fire is over. For example, proximity to "hot" and "cold" areas during fire-clean up and investigations was highlighted as an important predictor of differences in exposure to particulate matter, acetaldehyde, and formaldehyde.³⁹ Similarly, PAH exposures monitored during wildland and prescribed fires were found to vary significantly based on the job task.³⁸ Several additional presentations at the conference highlighted exposure assessments in firefighters responding to wildland and WUI fires. For example, a presentation by Andrew Stafford (University of Arizona) summarized a new study that examined PAH exposures in firefighters responding to WUI, wildland, and prescribed fires. They found that while PAH exposures overall were elevated in postfire urine, the magnitude of exposure varied and appeared higher in WUI firefighters relative to firefighters responding to wildland or prescribed fires. This may be related to enhanced combustion and emissions from building materials.

To address some of the challenges encountered in assessing episodic exposures that occur during firefighting, silicone wristbands have been proposed as a novel tool for monitoring occupational exposure among firefighters.⁴⁰ Wristbands capture data on a wide range of exposures and offer several advantages over traditional exposure assessment tools. Notably, they are easy to deploy, even in remote areas, and do not interfere with firefighter effectiveness or safety. Wristbands can uniquely capture chemical information that can be useful in determining how different job tasks and fire conditions impact an individuals' exposure.

During the conference, Taylor Hoxie (Duke University) presented new data indicating that exposure to some PFAS, a group of chemicals present in both firefighting foam and in firefighter personal protective equipment (PPE), is prevalent among structural firefighters and may be related to the work duties performed. For example, Hoxie found that firefighters on active fire calls had higher exposure to some PFAS compounds, suggesting firefighting activities or the materials they use while working to suppress the fire are a potential source of exposure. Importantly, concentrations of certain PFAS detected on silicone wristbands have been shown to correlate with internal dose, suggesting they capture a significant exposure pathway.⁴¹ In addition to monitoring specific chemicals, wristbands can also support applications using nontargeted analyses, allowing for a more comprehensive evaluation of firefighters' overall exposure. A second presentation by Nicholas Herkert (Duke University) highlighted data from a nontargeted analysis of wristband samples which found that firefighters on active fire calls had exposure to a greater number of chemicals at greater magnitudes than those not responding to active fire calls. More research is needed to understand the complexities of these exposures and how they vary based on demographics and behaviors; however, the use of wristbands may help address this data gap.

Exposure variability is not restricted to the type of fire being fought, as it is also impacted by the type of PPE that is worn. Wildland firefighters often work in rural areas and face longer duration fire events and higher temperatures, with less access to advanced PPE. Limited access to advanced PPE is especially true for volunteer firefighters, who may need to respond to fires in a wildland environment. In addition, fire investigators and other fire professionals are also potentially exposed as they frequently enter fire scenes after suppression, where they encounter numerous environmental contaminants. Previous research has demonstrated that even different types of hoods worn by firefighters can impact penetration of combustion byproducts.⁴² Of particular note was a PIC2024 Congress presentation by Melissa Armstead (North Carolina State University) comparing different types of respiratory protection that could be available to wildland firefighters. Currently there is no requirement for wildland firefighters to wear respiratory protection, and many wear bandanas to provide protection from soot and smoke. Armstead's presentation demonstrated that there is a wide range in filtration efficiency for various respirators and protective devices. Advanced air purifying respirators performed much better than standard bandanas or face masks in removing chemical hazards; however, they also created more resistance to inhalation and potentially put more strain on a firefighter's ability to breathe. Consequently there are apparent trade-offs in selecting the appropriate respiratory protection in wildland firefighting.

Firefighting is associated with both short-term health issues, such as acute respiratory problems and skin irritation, and long-term diseases, including chronic respiratory conditions like chronic obstructive pulmonary disease, cardiovascular disease, and various cancers. Cancer mortality is 14% higher in firefighters than in the general U.S. population, with significant increases in lung, gastrointestinal, and kidney cancers as well as mesothelioma.⁴³ Due to these elevated risks, the International Agency for Research on Cancer (IARC) has classified firefighting as a Group 1 carcinogenic occupation.⁴⁴

To protect firefighters, there is a need to identify key biomarkers of toxicity that may be detectable before clinical disease develops. Early effect biomarkers could be especially valuable for detecting long-term health consequences from high-risk events (e.g., extreme wildfires, floods, explosions) that, although rare, can result in significant exposure. For example, on February 3, 2023, a train carrying various chemicals (e.g., vinyl chloride, butyl acrylate, and benzene) derailed and caught fire in East Palestine, Ohio. Preliminary data presented by Jackie Goodrich (University of Michigan) found that first responders in East Palestine had altered levels of multiple microRNAs in their blood, which have been linked to certain cancers and cardiovascular health outcomes in other studies. Identifying novel biomarkers for early disease detection in firefighters thus offers an opportunity for intervention to improve health outcomes.

■ PFAS RESULTING FROM COMBUSTION PROCESSES

PFAS have gained scientific attention over the last two decades; however, information is still lacking regarding the reaction mechanisms and breakdown pathways of their combustion byproducts. Jonathan Krug (U.S. EPA) described the EPA's efforts to characterize chemical breakdown components of PFAS known as products of incomplete combustions (PICs) and provided insights into mechanistic details of PFAS degradation. This work was mainly focused on measuring volatile, semivolatile, polar, and nonpolar PICs derived from the treatment of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) at combustion temperatures ranging from 810 to 1180 °C. This was accomplished using a U.S. EPA research combustor named the Rainbow Furnace.^{45,46} Results show that destruction efficiencies (DEs) for measured PFAS in aqueous film forming foam (e.g., firefighting foam) that was atomized through the combustor were 99.99% at temperatures above 1100 °C. However, high DE levels (99.99%) were also observed for some PFAS, e.g., PFOS, below 900 °C, yet these conditions resulted in significant PIC formation of nonpolar volatiles (e.g., fluoroalkanes and alkenes), polar volatiles (e.g., short-chain perfluoroalkyl carboxylic acids), and polar semivolatiles (e.g., long-chain perfluoroalkyl carboxylic acids) that are linked to a wide range of potential health impacts and environmental effects. This suggests that DE alone is not an adequate metric for determining effectiveness of treatment for PFAS. Thus, chemical analysis of combustion byproducts is critical to identify the complete breakdown of PFAS.

Breaking down PFAS into less harmful chemicals is challenging because breaking their C–F bonds can almost instantly form hydrogen fluoride (HF), which is a highly corrosive and extremely toxic gas. Brian Gullett, Johanna Aurell, and Ariel Wallace (U.S. EPA) investigated PFAS and HF emission from military ordnance detonations. Because

PFAS are used as binders in plastic-bonded explosives (PBX) and various military munitions,⁴⁷ there are growing concerns surrounding exposures to PFAS and their combustion byproducts (e.g., HF and tetrafluoromethane (CF₄)). Aerial emission sampling of combustion plumes from PBX detonation and magnesium-Teflon-Viton (MTV) flares was conducted using an uncrewed aircraft system (UAS, also known as a “drone”) equipped with a lightweight sensor-sampling system (“Kolibri”) for PFAS (sorber tube and evacuated canister) and HF (tunable diode laser and cassette). Results demonstrated that HF in the plume from the MTV flares was correlated with CO₂ and CO levels and were higher than that from the PBX detonation. CF₄ was detected in the plume from the PBX detonation but not from the MTV flares. Six organofluorine compounds were detected in both the MTV flares and PBX samples. This is believed to be the first study that used a drone-based sampling system to measure PFAS in air emissions. These results are important in understanding the fate of fluorinated components (PFAS byproducts) with military ordnance during use or disposal.

While combustion can degrade PFAS under certain conditions, it still poses significant challenges to human health because combustion byproducts from PFAS degradation often include short-chain PFAS (chemicals with fewer than 8 carbons). These short-chain PFAS are generally harder to breakdown and more mobile in the environment (e.g., water, soil and air), leading to increased risks of exposure and potential for health problems to develop.⁴⁸ Thus, it is critical to measure these combustion byproducts accurately, precisely, and consistently in various environmental media. The U.S. EPA has developed, validated, and released analytical methods to do that.⁴⁹ In terms of sample media, Methods 533/537.1/1633/1621 are intended to measure a variety of PFAS compounds from water and soils.^{50–53} Selected PFAS in air emissions are measured by Other Test Methods (OTM); for example, polar semivolatile PFAS compounds (OTM-45),⁵⁴ nonpolar volatile fluorocarbons,⁵⁵ and nonpolar semivolatile fluorocarbons (Methods 0010/3542/8270)^{56–58} can be detected from incomplete combustion or destruction of PFAS. A key element of these analytical methods is not just to identify PFAS compounds but to also quantify their concentrations and evaluate exposure levels for the human population. Thus, more robust and accurate analytical techniques are needed to (1) understand comprehensive source characterizations in the environment, (2) evaluate PFAS removal and destruction efficiencies, and (3) identify exposure pathways that may present potential risks to human health.

■ EMERGING HEALTH CONCERNS AND EFFECTS RELATED TO COMBUSTION BYPRODUCTS

Linda Birnbaum's (NIEHS, retired) plenary lecture explored emerging health concerns and effects related to combustion byproducts. Though there are well-documented associations between these exposures and adverse health outcomes across nearly all organs in the body, the nature of these specific health effects relies heavily upon the source of air pollution and subsequent chemical compositions of exposure. The life stage at which a person is exposed further impacts the type of resulting health effects and at what point these effects manifest across a person's life. Various windows of susceptibility to combustion byproduct exposure are noted in the literature, including preconception, pregnancy (effects on mother and/or

child), early childhood, and late adulthood; notably, though findings across many studies find positive associations between adverse outcomes and exposure to air pollution and, specifically, wildfire smoke, outcome-specific findings are sometimes mixed.^{28,59–61}

Understanding the relationships between combustion byproducts and the health effects that result from these different exposure scenarios is especially imperative given climate change factors are amplifying the frequency and severity of wildfire events across the world. As posited in the plenary, exposure to wildfire smoke may, in fact, be one of the largest public health consequences of climate change. An April 2024 working report by the U.S. National Bureau of Economic Research estimated that by 2050, economic costs due to lives lost from wildfire smoke will exceed \$240 billion.⁶² This cost is comparable to the sum of estimated economic costs from all other damages in the U.S.⁶² Compounding this increased risk of exposure, multiple talks (see [Supporting Information](#)) throughout the PIC2024 highlighted data that suggest indoor environments may not be as inherently protective from wildfire smoke as previously thought.

Combustion byproducts are grouped into primary air pollutants (e.g., gases, VOCs, hydrocarbons, etc.) and particulate matter (PM). PM_{2.5}, also considered a secondary pollutant due to downwind formation, represents particles of aerodynamic diameter 2.5 μm or less in size and can penetrate the lung epithelium.^{63,64} Studies have shown that mortality incidence increases across all age groups with increasing PM_{2.5} exposure, and PM_{2.5} specifically has been identified as the primary environmental risk factor for cardiovascular disease.^{62,65} Studies have found a monotonic relationship between PM_{2.5} exposure and risk of cardiovascular disease, suggesting that no safe threshold exists for cardiovascular health.^{65,66} Thus, even minute increases in PM exposure can result in deleterious cardiovascular effects.^{65,66} Additionally, naphthalene, the simplest of the polyaromatic hydrocarbons, is a ubiquitous environmental contaminant identified across ambient urban air, wildfire smoke, military burn pit model emissions, food products, groundwater, well water, and human breast milk.^{67–70} *In vitro* and *ex vivo* models had previously identified naphthalene's ability to adduct DNA;^{71,72} Sarrah Hannon (University of Arizona) and Morgan Domanico (University of California Davis) presented complementary data that identified naphthalene-induced DNA adducts in cigarette smokers, occupationally exposed firefighters, and mice exposed across multiple routes to naphthalene. These data importantly represent the first reported observations of naphthalene adducts occurring *in vivo*, and provide supporting mechanistic evidence underlying epidemiological findings that previously connected naphthalene exposure to cancer.

Mixtures of combustion byproducts pose unique risks because different components often synergize to magnify the toxicity of exposure compared to that of any single parent component. For example, combustion-derived PM has higher toxicity on and after high oz1 days due to ozone-mediated oxidation processes that change the particles' physiochemical characteristics.^{73,74} Additionally, though flame retardants used in household furniture delay the onset and slow the rate of foam burning during a house fire, they increase the toxicity of the resulting combustion byproducts when the flame retardant-foam mixture does eventually burn.⁷⁵ This increased toxicity is largely due to higher amounts of soot, smoke, carbon monoxide, hydrogen cyanide, dioxins, and furans that are

produced under these slower burn conditions.⁷⁵ Understanding mixture effects on combustion byproduct toxicity is especially imperative given that real-world exposure scenarios (e.g., air pollution, wildfires, house fires, etc.) never comprise single chemical components, and instead, predominantly include complex mixtures of various combustion byproduct components.

The study of life stages susceptible to combustion byproduct exposure has primarily focused on maternal exposures both before and during pregnancy in addition to childhood exposures. However, a window of susceptibility becoming increasingly appreciated is the period of paternal sperm maturation immediately preceding conception. Colette Miller (U.S. EPA) used a rat model to investigate the effects of paternal biomass smoke exposure during sperm maturation. These exposure designs were found to alter pubertal timing and later life estrous cyclicity via endocrine disruption in female F1 offspring, affect sperm motility and endocrine disruption in male F1 offspring, and increase levels of circulating pro-inflammatory markers in F1 offspring of both sexes. These data support the need to further investigate preconception paternal exposures to combustion byproducts and how they relate to subsequent changes in fertility and offspring development. These studies are particularly relevant for firefighters, an occupational group highlighted during PIC2024, given that 91% and 70% of U.S. firefighters in 2020 were male and of reproductive age (20–49 years old), respectively.⁷⁶

Collectively, there has been immense growth in health research applicable to combustion byproducts in recent years, particularly surrounding the identification of vulnerable populations and the diversity in target organs that can be influenced by these complex atmospheric exposures. Based upon presentations and discussions at PIC2024, it is evident that windows of susceptibility will continue to be explored, including trans-generational impacts, and further elucidation of substances and groups of substances within these mixtures that quantifiably impact health risks is needed. As an example, recent research has identified nitrogen dioxide, a gaseous combustion byproduct, as a contaminant that may pose greater health risks than previously known.⁷⁷ Gas and propane combustion as well as traffic-related pollution can be a source of nitrogen dioxide exposure.⁷⁷ Employing multiomic study designs to identify exposure-related dysregulation patterns at multiple levels will further inform which mechanistic pathways are at play. There is also a push within the field to better define the economic costs of health effects due to combustion byproduct exposure, especially losses like emotional pain, distress, and discomfort that are inherently difficult to quantify.

■ RESPONDING TO EMERGENCY EVENTS AND HEALTH CONSIDERATIONS: EAST PALESTINE

A major focus of PIC2024 was combustion emissions, soil contaminants, and health concerns from accidents, wildfires, and thermal treatment processes. This was highlighted by a plenary presentation on the train railcar accident in East Palestine, Ohio. Mark Durno (U.S. EPA) was one of the on-scene coordinators in East Palestine, and gave insights into U.S. EPA's response. Durno felt that the most important take home message from what became a major socio-political issue is to establish early communication with the public, engage with the community early and often, deal promptly with misinformation, and to have a well-trained, continuous staff

on-site and available to respond. Durno indicated that this accident had enormous public pressure that resulted in significant federal participation beyond typical responses. The decision by the train company to vent and burn the vinyl chloride from five railcars has been questioned by public groups, news outlets, and the National Transportation Safety Board (NTSB).⁷⁸ Durno indicated that the public and elected officials expressed concerns regarding resulting chemical emissions, including semivolatiles and chlorinated dioxins and furans, and the lack of assets in place to appropriately anticipate and monitor the combustion byproducts.

Assessments of soil samples and the presence of toxicity markers were conducted to gain a retrospective sense of the environmental releases from the East Palestine fire and smoke plume. Over 20 soil samples from the East Palestine area were collected and analyzed for environmentally persistent free radicals (EPFRs) by presenter Myron Lard (Louisiana State University). Preliminary results indicated a correlation with levels of chlorinated dibenzodioxins and dibenzofurans (CDD/CDF). A study of toxicity markers in firefighters by presenter Jackie Goodrich, was expanded to include roughly 1/3rd of the firefighters from East Palestine. Goodrich's study is examining exposures and persistent epigenetic markers—heritable changes in gene function without changes in the genes (e.g., noncoding RNA) and somatic markers themselves. A follow-up study is planned for 18–24 months. A similar study of community exposure to potential toxics, this from open burning and open detonation of hazardous waste, was conducted by presenter Jennifer Richmond-Bryant (North Carolina State University). Richmond-Bryant conducted open area sampling of PM_{2.5}, EPFRs, metals, and CDD/CDF to assess potential health effects of nearby community members.

Plumes from open burning incidents were discussed by Hendryk Czech (University of Rostock). Czech examined smoke samples from Nadym City, Russia coupled with photochemical aging chamber experiments to assess the type and level of pollutants from fires and how they disperse in the environment. Photochemical chamber studies were also conducted by Khushboo Fnu (University of South Carolina) to study the formation of EPFRs from VOCs. This effort examined the mechanisms of EPFR formation and their rate controlling factors in an effort to understand the role precursor VOC structures play in formation. Similarly, Lavrent Khachatryan (Louisiana State University) examined the role of biomass constituents (lignin, cellulose, and hemicellulose) to form EPFRs in an effort to understand formation mechanisms from wildland fires. Khachatryan was able to form stabilized radicals from hydrolytic lignin in a metal-free environment in his reactor, informing potential pollutant formation regimes during wildfires. Biomass combustion regimes and pollutant formation studies were also accomplished by Timothy Nurkiewicz (West Virginia University) and colleagues with their pellet combustor and an attached exposure chamber, allowing for versatile testing of fuel types and combustion conditions.

Sources of open, uncontrolled combustion can expose civilian populations and emergency responders to a variety of pollutants whose composition and concentration, by the nature of the event, are relatively unknown. Characterizing these pollutants is challenging due to the often impromptu nature of the source and the inability to bring appropriate sampling instruments to bear in a timely manner. The atmospheric reactions, chemical transformations, and environmental fate of

these pollutants require creative study to further understand the health and environmental consequences of these sources.

■ CONCLUDING REMARKS AND RESEARCH GAPS

The complex interactions among climate change, urbanization, and higher chemical burdens in our environment have all led to a significant increase in the type and amount of chemicals present during combustion events, thereby heightening exposure risks and potential health consequences. Wildfires in particular represent an important and growing challenge in terms of air quality, exposure, and health risks. The expansion of the WUI has positioned wildfires as a critical and growing source of pollutant exposure for a larger population. The permeability of wildfire smoke into indoor environments has challenged earlier assumptions of indoor protection, underscoring the need for improved indoor air filtration and treatment technologies. Understanding the health trade-offs associated with purposeful prescribed fires is urgent; while they can lead to short-term increases in the concentrations of some hazardous air pollutants, and particularly PM_{2.5}, they also offer a potential strategy to mitigate more intense wildfires that result in severe health impacts and billions of dollars in damage over larger regions.

On top of concerns related to the combustion byproducts themselves, additional chemical contaminants may co-occur and lead to complex exposures in impacted communities. For example, PFAS may be present in burning materials (e.g., lithium batteries, building components), contributing to additional combustion byproducts. In other cases, PFAS may be introduced during fire suppression activities, such as through the use of aqueous film-forming foam (AFFF). This is further complicated by the influence of atmospheric transformations on pollutant fate and transport, which can affect their toxicity. Firefighters, both structural and wildland, face significant occupational exposure risks, highlighting the need for targeted policies and protections for these high-risk groups. Emerging health concerns related to combustion byproducts, particularly the varied heat effects and complex biological responses, could benefit from further multiomic investigations to fully understand underlying mechanisms. And last, accurately assessing exposure risk from combustion, especially during unpredictable and highly variable events like wildfires, or emergency responses to disasters that include fires (e.g., the East Palestine rail derailment), may be hindered by limitations in our ability to adequately and quickly respond to these events, and/or have data available that describes concentration levels before the event (e.g., baseline data). In particular, it can be challenging to deploy fully resourced response teams into an affected area in a timely manner as well as establish a clear and open line of communication with the local community and local and regional first responders.

Discussions from this conference stress the importance of multifaceted and more holistic approaches to help address health risks associated with combustion. Importantly, every fire and fuel source may contain different materials and chemicals that produce distinctive emissions and, thus, approaches are needed that fully characterize chemical emissions and exposure and subsequent risk for different fire scenarios (e.g., PFAS emissions from lithium ion batteries). The increasing use of -omics and nontargeted chemical analytical approaches may help address these shortcomings. More research to improve performance, and in some cases availability, of PPE may also help firefighters reduce their exposures associated with

combustion byproducts and reduce health risks. We also recognize that some populations may be more vulnerable than others, and thereby recommend further research on regional differences in health effects from wildfire smoke. And finally, climate change links to increased wildfires suggest that more prescribed burns may be called for to mitigate impacts at the residential and community levels, and to reduce the damages and loss of life associated with wildfires. To repeat plenary speaker Toddi Steelman's take-home message, our actions can create a "narrative of hope and possibility, not despair and apocalypse" as we move forward to address these challenges.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/envhealth.5c00246>.

The conference program with the agenda and list of speakers and titles (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Heather M. Stapleton — *Nicholas School of the Environment, Duke University, Durham, North Carolina 27708, United States*; orcid.org/0000-0002-9995-6517; Phone: (919) 613-8717; Email: heather.stapleton@duke.edu

Authors

Julia E. Rager — *Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, United States*

Sarah L. Miller — *Curriculum in Toxicology and Environmental Medicine, School of Medicine, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, United States*; orcid.org/0000-0002-1441-4015

Kate Hoffman — *Nicholas School of the Environment, Duke University, Durham, North Carolina 27708, United States*; orcid.org/0000-0001-8029-7710

Yong Ho Kim — *Center for Public Health and Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711, United States*; orcid.org/0000-0001-7527-0134

Brian Gullett — *Center for Environmental Measurements and Modeling, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711, United States*; orcid.org/0000-0003-4547-4026

Toddi Steelman — *Nicholas School of the Environment, Duke University, Durham, North Carolina 27708, United States*; orcid.org/0000-0001-7492-8635

Daniel Jaffe — *School of Science, Technology, Engineering and Mathematics, University of Washington Bothell, Bothell, Washington 98011, United States*; *Department of Atmospheric Sciences, University of Washington Seattle, Seattle, Washington 98195, United States*; orcid.org/0000-0003-1965-9051

Linda S. Birnbaum — *Retired, National Institute of Environmental Health Sciences, Research Triangle Park, North Carolina 27709, United States*; orcid.org/0000-0001-5429-5658

Miriam M. Calkins — *National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Cincinnati, Ohio 45226, United States*
Marc Durno — *U.S. Environmental Protection Agency Region 5, Emergency Response Branch, Westlake, Ohio 44145, United States*

Complete contact information is available at:
<https://pubs.acs.org/10.1021/envhealth.5c00246>

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Notes

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Biography



Heather M. Stapleton, Ronie-Richelle Garcia-Johnson Distinguished Professor, Nicholas School of the Environment, Duke University, Durham, NC USA. Professor Heather Stapleton is an environmental chemist and exposure scientist in the Nicholas School of the Environment at Duke University. Her research interests focus on identification of halogenated and organophosphate chemicals in building materials, furnishings and consumer products, and estimation of human exposure, particularly in vulnerable populations such as pregnant women, children and firefighters. She currently serves as the Director for the Duke Superfund Research Center, and Director of the North Carolina Firefighter Cancer Cohort Study.

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