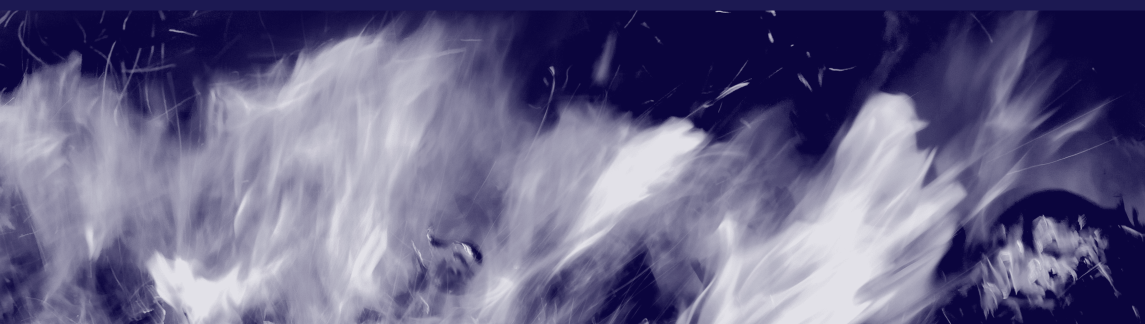
AIHA® Technical Guide for Wildfire Impact Assessments for the OEHS Professional

2nd edition



A practical guide for OEHS professionals and practitioners conducting wildfire impact assessments.

Edited by Enrique Medina, MS, CIH, CSP, FAIHA

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2nd edition

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Table of Contents

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Preface

The second edition of the *AIHA® Technical Guide for Wildfire Impact Assessments for the OEHS Professional* ("Technical Guide") updates and expands on the first edition published in 2018.

The impetus for the original Technical Guide started at the 2016 American Industrial Hygiene Conference and Exposition (AIHce) held in May in Baltimore, Maryland. The conference took place during the active phase of the Ft. McMurray wildfire in Alberta, Canada that burned 1,958 structures and more than 1.4 million acres (589,000 hectares) at a cost of CA$8.9 billion dollars. Fortunately, there were no human lives lost.

Coincidentally, a small group of industrial hygienists and laboratory experts presented a technical session on wildfire impact assessments. The positive response to the session reflected the profession's need for information and guidance on this subject. The group decided to form the "Wildfire Team" under the auspices of the Environmental Affairs Committee. Two years later, a team of 19 authors, editors, and contributors and five subject matter expert peer reviewers from the United States and Canada produced the first edition of the Technical Guide published by AIHA.

The Technical Guide is intended for use by industrial hygienists, analytical laboratories, restoration industry professionals and associations, insurance adjusters, government agencies, and law firms to address wildfire impacts. At the same time, the state of the practice has evolved in parallel with the experience of investigators, analysts, risk assessors, and restorers. Research on wildfire chemistry and atmospheric transport of air pollution has increased as global warming predicts more frequent and larger wildfires.

The second edition of the Technical Guide makes extensive use of the current published scientific research and established methods, protocols, and guidance found in AIHA publications, including *A Strategy for Assessing and Managing Occupational Exposures*; *The Occupational Environment: Its Evaluation, Control and Management*; *Recognition, Evaluation, and Control of Indoor Mold*; *The IAQ Investigator's Guide*; *Odor Thresholds for Chemicals*; *Principles of Good Practice,* and articles from *The Synergist*.

As in any emerging discipline, there are gaps in the peer-reviewed literature. The authors want the reader to know that the content of the Technical Guide represents the professional judgment, opinions, and advice of the expert authors based on current research, extensive firsthand practical experience, lessons learned, and good practice, in accordance with the AIHA *Principles of Good Practice Version* 5, October 2024. As with the first edition, the second edition of the Technical Guide has greatly benefitted from independent external peer review.

The Technical Guide was written by a multidisciplinary team of subject matter experts and practitioners in the areas of wildfire and structural fire assessments, industrial hygiene, medicine, toxicology, risk assessment, optical and organic laboratory science, professional restoration, statistics, and exposure assessment with literally hundreds of years of combined directly relevant experience and expertise. The updated Technical Guide is intended to serve as a practical guide for OEHS professionals and other practitioners on conducting evidence-based wildfire impact assessments.

Enrique Medina, MS, CIH, CSP, FAIHA
Editor and author
February 20, 2025

Executive Summary

The second edition of the *AIHA® Technical Guide for Wildfire Impact Assessments for the OEHS Professional* presents the current understanding of wildfire combustion processes and the chemical transformations that generate particulates, organic compounds, and metal residues.

The scope of this updated Technical Guide is on homes, buildings, and structures that were outside of the burn zone or survived a wildfire or a wildland-urban interface (WUI) fire and can be restored and reoccupied. The Technical Guide may be applied to wildfires that expand into conflagrations. However, caution is required to understand the myriad chemical and physical hazards that may exist in an extensive urban firestorm. Structure fires that consume buildings and property are outside the scope of the Technical Guide. They are only addressed when similar methods and techniques can be used to assess their level of impact. The primary purpose of the Technical Guide is to help occupational and environmental health and safety (OEHS) professionals and other investigators design and conduct wildfire impact assessments for exposure evaluations, forensic origin and cause investigations, or both.

Following the anticipate, recognize, evaluate, control, and confirm (ARECC) model used by OEHS professionals, forensic investigations of wildfire impacts on structures fit into the anticipate, recognize, and evaluate categories, whereas exposure assessment expands on the evaluation phase by characterizing human health hazards and risk. Forensic investigations are performed to assess the level of impact to the structure, evaluate contents from the wildfire residue, and develop a restoration plan. Exposure assessments seek to evaluate health risks to building occupants from infiltration and deposition of wildfire contaminants into a structure. Once damage or hazards are characterized, control and confirmation measures can be applied to restore property and/or protect the health of the occupants.

Whether the scope is a forensic investigation, a health exposure assessment, or both, the Technical Guide presents a framework for selecting a sampling strategy, choosing the appropriate sampling media and analytical methods, interpreting collected data to reach evidence-based conclusions, and preparing restoration specifications. This approach helps the OEHS professional and wildfire impact investigator work collaboratively with owners and restorers to determine the most appropriate approach for returning the structure as closely as possible to pre-loss conditions and controlling exposures.

Wildfires in the WUI burn homes, vehicles, and other structures in addition to vegetation. WUI fires generate a complex mixture of particulates, vapors and gases containing metals, volatile and semi-volatile organic compounds (VOCs and SVOCs), polycyclic aromatic hydrocarbons (PAHs), dioxins, furans, and other inorganic and organic compounds. These compounds can affect the indoor environment when they infiltrate a structure. The Technical Guide references studies from recent major wildfires to describe the factors that contribute to wildfire impact, whether from purely vegetation fires or mixed burns in the WUI. Many of the concepts, methods, and practices described in the Technical Guide may also apply to structure fires in a WUI fire.

The interrelated concepts of "time and distance" from the fire event are critical aspects that determine the fate and transport of particulates, organic chemicals, and metal constituents of wildfire residue. The Technical Guide describes how the effects of temperature, pressurization, and near-field and far-field distance from the fire perimeter determine the types, composition, and concentration of wildfire residue. The length of time elapsed after the fire significantly impacts the reactive chemistry, gas-to-particle partitioning, and decay rate of wildfire residue. Understanding the interplay between these factors is essential to defining the scope of the investigation.

The Technical Guide follows the investigative sequence, starting with a qualitative description of the initial exterior and interior site assessment, visual inspection, odor characterization, semi-quantitative and quantitative in-field testing, and assignment of preliminary impact levels. Criteria to evaluate when additional sampling may be required are presented. The sampling chapter explains how to develop a sampling strategy and sampling plan and describes the preferred sampling techniques, methods, and media for collecting particulates, organic compounds, and metals that will work for the intended analytical method. The chapter also introduces the uses of portable direct-reading instruments in wildfire impact investigations.

The chapter on microscopical and analytical chemistry methods explains how to select the most appropriate primary and secondary analytical methods to identify and quantify particulates associated with wildfire residue. A unique collection of optical and electron microscopy images illustrates the analysis of char, ash, soot, and signature fire-indicator particles using specific instrumentation to determine the origin and cause of the fire event. Organic and inorganic analytical methods are described for identifying organic indicator compounds associated with wildfire residue, identifying inorganic corrosive salts, or distinguishing similar organic and inorganic compounds unrelated to the wildfire that are present at background or typical levels in most structures.

Wildfire impact assessments often have practical and cost limitations on the numbers of locations and samples that can be collected and analyzed, which can constrain the statistical treatment of the data. Distribution of settled combustion particulates following a wildfire often deviates substantially from the "bell-shaped" normal or log-normal distribution used in classic exposure-based industrial hygiene statistics. This guide describes the application of the “permutation/randomization” or P/R model, a parallel inference model suited for wildfire data analysis and interpretation in forensic investigations. Some advantages of the P/R model are that it is not dependent on the mean or random sampling techniques. Examples of its application for wildfire impact assessments are described step by step in the Appendix section of the Technical Guide.

After characterizing the site, sampling and analyzing possible wildfire residue, and evaluating the resulting data for health exposure or forensic impact, the OEHS professional may be tasked with developing specifications for the restoration work plan. The Technical Guide explains how to develop prescriptive or performance-based specifications for those performing the restoration work, including the post-restoration verification conducted by the OEHS professional to confirm successful completion of the restoration goals.

The updated Technical Guide is intended to provide OEHS professionals, industrial hygienists, forensic investigators, laboratory analysts, restoration industry practitioners, and all other users with the knowledge, tools, and professional judgment to conduct wildfire impact assessments in order to help people who experience a wildfire return to a safe and healthy indoor environment.

1 Overview of the Potential Impact of Wildfires

WILDFIRES DIRECTLY AFFECT the property and environment in the immediate vicinity of the fire and can have regional or even international impacts (U.S. EPA, 2019). These impacts ultimately create potential exposures that could affect the health of building occupants and the public.

Wildfire impact investigations of structures that survived a wildfire and can be reoccupied involve professionals in a wide range of disciplines (e.g., OEHS professionals, forensic investigators, laboratory analysts, and restorers). Although the Technical Guide is primarily intended for OEHS professionals, the term "investigator" is used to refer to these professionals as a group.

The driving force behind the investigation is the impact from wildfire residues, which include not only particulate matter but also organic and inorganic chemical compounds. Time and distance from the fire event affect plume temperature and the chemistry of these compounds.

Impact-related concerns may include insurance claims, health and safety matters, legal items, or reoccupancy issues. These investigations can take place from days to months or longer after a fire. Most investigative, sampling, and analytical techniques are primarily intended for quantitative and qualitative analysis as well as source attribution to assist in determining the scope and degree of impact.

1.1. Types of Wildfire Impact Assessments

Wildfire impact assessments can be performed for a) forensic investigations, which are intended to confirm the presence or absence of wildfire residue and attribute the source, and b) exposure assessments to evaluate and control potential health hazards. Wildfire assessments can combine both goals.

The major difference is that a forensic investigation concentrates on whether the detected materials have an origin from the fire in question, whereas the goal of an exposure assessment is to assess the effects of the detected materials on human health to determine if the home or building is safe to occupy. These two goals are complementary.

Forensic investigations and exposure assessments are similar in their methods. Both must first define what the question is and develop a hypothesis to test it. Then, both must produce a sampling plan, select the appropriate statistical and inferential analysis for quantitative data, follow established quality assurance procedures, document data limitations, address confounders and uncertainties, and state evidence-based and supportable conclusions.

1.1.1. Impact Assessments for Exposure Evaluation

According to AIHA's *A Strategy for Assessing and Managing Occupational Exposures,* 4th edition, "exposure assessment is the process of defining exposure profiles and judging the acceptability of workplace exposures to environmental agents" (Jahn et al., 2015). Exposure assessment represents the evaluation portion of the fundamental industrial hygiene tenets of anticipation, recognition, evaluation, control, and confirmation (ARECC). In combination with hazard assessment and risk characterization, exposure assessment is an integral part of the risk assessment process. The ARECC concept can be adapted to wildfire impact investigations. Using this structured process, the OEHS professional is able to reach a conclusion on the acceptability of the exposure determination based on applicable criteria of human health risk and professional judgment (Jahn et al., 2015).

1.1.2. Forensic Impact Assessments

Forensic investigation is conducted when the presence, origin, and/or cause of combustion-associated materials in a building is uncertain. It describes the use of deductive reasoning to determine the level of wildfire impact to a building outside of the burn zone. This Technical Guide provides a framework for categorizing forensic impact on a continuum from Level 1 (Background) to Level 4 (Heavy).

In many cases, the overall inquiry may be less complex and not require a full forensic investigation. This may include investigation of a structure that was either visibly affected by a wildfire or exposed to contaminants generated by the wildfire (e.g., smoke). The initial assessment by the OEHS professional may be straightforward and not require items such as an origin and cause assessment. There are few unknown questions to answer, and the project may proceed using standard test methods (e.g., heavy metals, asbestos, char and ash concentration, etc.).

For example, to accurately address whether a structure has been impacted by a wildfire, an OEHS professional may have to determine whether materials found within the structure are consistent with the materials from the suspected point of origin. In the case of char and ash, the materials must be examined to determine whether the pyrolyzed materials detected are consistent with pyrolyzed materials from within the burn zone (i.e., fire perimeter). The OEHS professional must also take into account confounding factors that may influence the interpretation of their observed results. This would include accounting for other sources of combustion products that are similar to wildfire combustion products, such as fireplace ash, barbeque residue, smoking products, etc.

1.2. Wildfire Combustion Chemistry and Temperatures

A wildfire is a rapidly moving and uncontrolled fire that consumes specific parts of plants and other combustible materials in its path. Pyrolyzed and oxidized (burned) fragments and other products associated with the combustion of source fuels are distributed into the environment as components of the plume. Pyrolysis is the decomposition of a material into one or more other substances due to exposure to energy—typically driven by high temperatures—without oxidation (Larrañaga et al., 2016).

Wildfire fuels accumulate from the development of vegetation over time. Fuels are characterized by the establishment, growth, phenology, and mortality of the vegetation. The biomass on the ground, or necromass, becomes surface and ground fuel and is decomposed by microbes and soil macrofauna (e.g., worms, insects, slugs) over time. The development and decomposition processes continuously interact such that wildfire fuel properties and their distributions are a cumulative result of the vegetative development/decomposition cycle in space and time (Pritchard et al., 2022). Wildfire fuels exist in vertical layers defined as canopy, surface, and ground fuels. Canopy fuels are biomass above the surface fuel layer at approximately over two meters high; surface fuels typically include biomass from ground level to two meters high; and ground fuels are the necromass and vegetation on and below the ground (Pritchard et al., 2022).

Examples of ground fuels include partially decayed vegetation, tree roots, dead leaves, and fine deadwood. Surface fuels include downed logs, stumps, large limbs, low brush, grass, and seedlings. Canopy fuels include tree branches and crowns, dead trees, tree moss, and high brush.

During combustion, vegetative matter is decomposed due to the chemical reaction of fire, which is the rapid oxidation of organic material producing carbon dioxide, water, heat, and other components of smoke. During the incipient stages of the fire, pyrolysis begins, which dehydrates and converts fuel into combustible vapors and gases, providing fuel to the fire and allowing the fire to grow.

Flaming combustion follows pyrolysis, which burns the generated gases and vapors and increases the intensity of the fire. The fire will continue to grow due to convective or radiative energy, and flames will preheat and pyrolyze nearby fuels to generate gases and vapors available for burning and fire growth.

Flaming and smoldering combustion occur both sequentially and simultaneously as a fire front moves across a landscape, with smoldering combustion sometimes continuing for extended periods (weeks to months) after flaming combustion ceases (Pritchard et al., 2022). Smoldering combustion tends to occur in densely packed and highly lignified fuels in the necromass [e.g., organic soils, deep ground fuels (roots), peat, and decayed vegetation] due to fuel geometry that prevents oxygen from reaching the fuel in concentrations that support flaming combustion. In northern or southern subarctic ecosystems in the Northern Hemisphere, approximately 90% of wildfire emissions can be attributed to smoldering combustion of deep necromass (Pritchard et al., 2022).

Smoldering fires produce higher yields of some constituents (e.g., particulate matter, gases, and vapors, etc.) than flaming fires, where the yield is defined as mass of constituent per mass of fuel consumed. These types of fires have a lower mass loss rate. Although the yield is higher, the overall concentrations of constituents may not be significantly different from those produced by a flaming fire, which has lower yield but higher mass loss rate.

1.3. Composition and Distribution of Wildfire Smoke

Wildfire smoke contains a mixture of chemicals from the combustion of vegetative matter, including gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), corrosive inorganic chemical compounds, and metals (CARB, 2021). Additional chemicals from the combustion of manufactured materials, such as chlorinated compounds like dioxins and furans, may also be present in smoke from WUI fires where structures and vehicles are burned.

VOCs and SVOCs are carried in the smoke plume. Soot forms from the agglomeration of polycyclic aromatic hydrocarbons (PAHs), a group of SVOCs. Particulates in the smoke plume, such as char, adsorb some of the organic compounds. Metals and other inorganic compounds from burned soil, vegetation, fire retardants, and structures concentrate in the wildfire ash (Kohl et al., 2019; Schammel et al., 2024). As the number of electric vehicles is expected to increase, metals in the batteries (e.g., lithium, cobalt) may be found in WUI fire ash.

Wildfire smoke production and composition is dependent on several variables, including fuel type, the moisture content of the fuel, fire temperature, the size of the fire, and weather-related influences. The composition of smoke during each fire event is constantly evolving as the fire moves through the fuel source and the fire temperature changes downwind from the fire (Simms et al., 2021). Smoke from a wildfire can travel great distances depending on weather conditions (EPA SA, 2018). As the fire travels downwind, heat and convection currents created by the fire can disturb and uplift soil particles, which can contain naturally occurring minerals and metals. Components of wildfire smoke (e.g., particulate matter, or PM) can deposit on surfaces (EPA SA, 2018).

1.4. Fate and Transport of Wildfire Residue

Fate and transport address the likelihood of a contaminant spreading beyond its source area. This includes “how the nature of contaminants might change (chemically, physically, or biologically) and where they go as they move through the environment” (ATSDR, 2022). The concepts of fate and transport help with understanding the temporal and spatial effects of a wildfire or WUI fire on air quality and are referred to in the Technical Guide as time and distance effects.

A detailed discussion of the fate and transport processes is beyond the scope of the Technical Guide. A simplified conceptual model summarizing the fate and transport of wildfire smoke is presented based on a review of the literature on wildfire impacts on air quality (Britt, 2002; Dresser et al., 2024; Heilman et al., 2013; Jaffe et al., 2020; Juncosa Calahorrano et al., 2020; Liang et al., 2023; NASEM, 2022a, 2022c; Palma et al., 2020; Sekimoto et al., 2023; Selimovic et al., 2020; Yokelson et al., 2008). The conceptual dispersion model is described in four stages: emission and uplift, transport, mixing, and plume deposition, as illustrated in Figure 1.1.

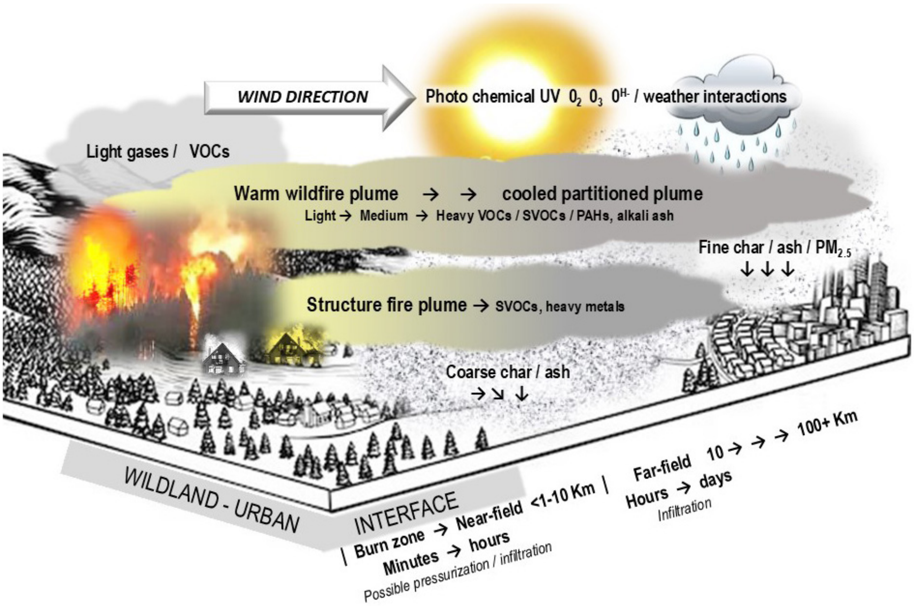


Figure 1.1: Wildfire and wildland-urban interface (WUI) fire conceptual model showing time and distance effects. PAHs, polycyclic aromatic hydrocarbons; $PM_{2.5}$, particulate matter equal to or smaller than 2.5 μm, SVOCs, semi-volatile organic compounds; UV, ultraviolet; VOCs, volatile organic compounds.

Wildfires impact air quality in three domains: a) in the troposphere and stratosphere, b) at the surface level, and c) in the indoor environment. For wildfire impact assessment, the spatial scale is divided into near-field and far-field zones (NASEM, 2022a).

Combustion of biomass produces particulate matter consisting of black carbon, organic carbon, brown carbon, and mineral dust. The primary chemical aerosols produced include VOCs, carbon monoxide, nitrogen oxides (NOx), sulfur dioxide (SO_2), and PAHs. Levoglucosan, a wildfire indicator compound marker, is produced from cellulose combustion. Short-lived, tracer transformation products of nitrogen-containing compounds include acetonitrile, hydrogen cyanide, and ammonia. Chemical and photochemical reactions in the plume can oxidize these tracer compounds to nitrogen and NOx.

The firestorm plume uplifts wildfire smoke to the troposphere, the lowest layer of earth's atmosphere, which is most influenced by topography, temperature, pressure, water content, and winds. Depending on these variables, wildfire smoke can be trapped at the troposphere's boundary layer at approximately 10 miles or 16 kilometers from the ground surface in the mid-latitudes, resulting in high ground-level pollution. Under a different set of variables, wildfire smoke is injected above the boundary layer. Here, wind shear can transport the wildfire smoke hundreds of miles from the source (regional) and up to transcontinental distances measured in thousands of miles. In some cases, wildfire smoke can cross into the stratosphere 10–30 miles (16–48 km) above earth's surface, resulting in global transport of wildfire aerosols.

The mixing of wildfire aerosols takes place within all of the atmospheric layers. Reactions of NOx and VOCs lead to ozone formation. Complex chemical reactions promoted by sunlight transform the primary organic aerosols (POAs) into secondary organic aerosols (SOAs), including formaldehyde, acetaldehyde, acrolein, glyoxal, and methylglyoxal. The atmospheric lifetimes of various SOAs can range from minutes to months. In the process, SOAs undergo oxidation, coagulation, condensation and/or evaporation, and partition between the gas and particulate phases. Plume dynamics and dry or wet deposition eventually drive particulate matter and SOAs back to surface level in the far-field zone downwind from the wildfire source. As a result of these processes, the composition of wildfire smoke that returns to surface level is different from its original composition.

The ground- or surface-level domain is characterized by high temperatures and turbulent mixing of combustion products in the burn zone, which is the area immediately impacted by flames and thermal energy from the fire. The hot ground-level plume may include corrosive or toxic particulates, vapors, or gases carried by the wildfire. Organic chemicals carried by the hot plume can condense and form particulate matter from the chemical itself, such as soot particles formed from PAHs (Shao et al., 2023), or they can adsorb onto other solid particles. The areas outside the burn zone are divided into near-field and far-field zones that are impacted by the smoke plume. The near- and far-field impact zones can be different for gaseous phase compounds than for particulate phase compounds due to differences in chemical composition and partitioning properties. The near-field and far-field zones are determined by the deposition pattern of the fire-related debris plume and its adsorbed gaseous components. These can vary with the size and intensity of the fire, firestorm wind velocity and direction, post-fire meteorological conditions, terrain, whether it is a wildland or WUI fire, and the specific chemical or particulate of interest.

The near field has been defined conceptually as ranging from 1–10 km (0.62–6.20 miles) beyond the fire perimeter [<1 km (<0.62 miles) from the burn zone] based on effects associated with smoke plume transport, deposition, and atmospheric transformation (NASEM, 2022a). The far field was further subdivided into order-of-magnitude conceptual scales with a local scale from 10–100 km (6.2–62.0 miles), a regional scale from 100–1,000 km (62–625 miles), and a continental scale greater than 1,000 km (or 625 miles) (NASEM, 2022a). The spatial and temporal scales are influenced by meteorological and topographical factors, which, in turn, result in different chemical and physical processes that affect smoke composition. Assigning specific distance boundaries outside the burn zone is subject to high degrees of variability. Factors such as the nature of the combusted materials, proximity to the burn zone, atmospheric conditions during the course of the fire, and topography can all play major roles in dynamic wildfires and WUI fire conditions. Studies of several wildfires have defined near-field zones ranging from 0.4–24.0 km (0.25–15 miles) and far-field zones from 1.6–240 km (1–150 miles) based on historical incidents in Texas and California (CARB, 2021; Wade et al., 2013).

For the purpose of the Technical Guide, the main area of interest is the effect of wildfire smoke on indoor air quality resulting from infiltration of particulates, vapors, and gases. Thermal impact and pressurization on structures in the burn zone of a WUI fire can drive wildfire smoke into buildings and vehicles through infiltration points, such as doors, windows, attic vents, and gaps in the building envelope. Infiltrated smoke particles settle on surfaces.

In the indoor environment, the fate and transport of the residual contaminants carried by wildfire are partially dependent on the chemicals' partition coefficients, ventilation, and cleaning activities to remove deposited dust from wildfire smoke infiltration. Vapor-phase smoke contaminants are diluted by passive or active ventilation, which can overtake the adsorption-desorption equilibria controlling the air concentration (Li et al., 2023). SVOCs attached to particles deposited onto solid surfaces, including some HVAC units and ductwork, and vapor-phase SVOCs can be absorbed into materials, such as carpets, floors, walls, and furnishings (Whitehead et al., 2011). The larger-sized fractions of settled dust are removed by cleaning, whereas the respirable-sized particulates may remain entrained longer in the absence of HEPA filtration.

Adsorbed SVOCs may off-gas following their gas-solid-phase equilibrium kinetics for days, weeks, and even months. Vapor-phase VOCs and SVOCs can adsorb onto building components and contents or partition into the solid phase. Both the settled particulates and VOCs and SVOCs off-gassing from surfaces and contents can cause odors associated with wildfire smoke. When occupants return days or weeks after the fire, the potential health risk from the wildfire residuals is more likely to be from exposure to particulates (mostly char and ash deposited by the smoke) and SVOCs (primarily PAHs and dioxins) and furans that adsorbed onto the fire particulates and surfaces. In the far field, where the cooled plume has returned to the surface level and VOCs have become diluted, particulate infiltration is the main impact to indoor air quality. At certain concentrations, these chemicals may present a health hazard to returning occupants.

The OEHS professional needs to consider the temporal scale when planning the investigation's goals and methods. In some cases, VOCs and SVOCs adsorbed onto particulates, materials, and surfaces can continue to emit over time based on their decay half-lives and partition coefficients. Secondary infiltration or re-entrainment is possible due to the tracking of outdoor settled wildfire residue back into the structure and resuspension of outside dust entering the structure through windows and doors. Re-entrainment can occur weeks or months after the fire event and after cleaning and restoration have been completed.

Table 1.1 presents a summary of the wildfire fate and transport conceptual model parameters for characterizing near-field and far-field zones based on the sources cited (Britt, 2002; Dresser et al., 2024; Heilman et al., 2013; Jaffe et al., 2020; Juncosa Calahorrano et al., 2020; Liang et al., 2023; NASEM, 2022a, 2022c; Palma et al., 2020; Sekimoto et al., 2023; Selimovic et al., 2020; Yokelson et al., 2008).

Table 1.1: Wildfire Fate and Transport Conceptual Model Parameters for Near-Field and Far-Field Zones

Parameters	Near-Field Zone	Far-Field Zone
Distance from fire front or burn zone	<1–10 km (0.62–6.20 miles)	>10 to >1,000 km (6.2–625 miles)
Plume temperature	Hot plume	Cooling to ambient
Transport	Horizontal surface-level transport; plume rise from hundreds to thousands of meters	Long range; atmospheric circulation patterns in thousands to tens of thousands of meters
Mixing	Turbulence and buoyancy driven; high mixing rate	Mixing with ambient air; complex chemistry
Major air quality effects	Surface level (outdoors); indoors	Troposphere and stratosphere 16–48 km (10–30 miles) above ground-surface level from plume deposition
Particle and volatile and semi-volatile organic compound (VOC/SVOC) generation	Primary organic aerosols (POA); some initial secondary organic aerosols (SOAs)	POA, SOA, and ozone
Particle and VOC/SVOC concentration	Higher concentrations with some dilution at longer distance due to mixing with ambient air	Lower concentrations from dilution, dispersion, and transformation over long distance
Particle types	Char and ash (and some soot), especially in wildland-urban interface (WUI) fires	Char, ash, and aged soot from PAHs
Particle size distribution	Wide range of particle sizes; $>PM_{10}$ to $<PM_{2.5}$	Predominant fine particulates $\leq PM_{2.5}$
VOC/SVOC transformation chemistry	Photooxidation (daytime); oxidation; reactive intermediates; initial aging; gas-particle partitioning	Oxidation, coagulation, condensation, evaporation, aging; gas-particle partitioning
VOC/SVOC partition and time scale	Outdoors: gas-phase predominant; indoors solid-phase predominant; time scale minutes to hours	Gas-solid phase in dynamic equilibrium; time scale of hours to days
Plume deposition	Predominantly high-volume dry deposition	Dry and wet deposition

1.4.1. Time and Distance Effects of VOCs and SVOCs

Until recently, few studies have looked at the persistence of wildfire-generated contaminants in indoor environments after a fire event. The fire chemistry in which an organic compound exists determines its potential for infiltration and residence time in the indoor environment. There are significant chemical differences between a low-oxygen interior structure fire, the infiltration impact of a warm smoke plume in the burn zone, and the infiltration of a cooled and a partitioned plume outside and downwind of the burn zone.

During the Camp Fire of 2018, wildfire-generated VOCs dissipated and became diluted or chemically transformed as the plume mixed with ambient air. Outdoor concentrations of benzene, toluene, and xylene were measured at three to four times the non-fire background levels in urban settings more than 100 miles from the source. The outdoor concentrations were below health-based reference exposure levels and returned to background levels weeks after the wildfire event (Wang et al., 2024). In the outdoor environment, VOCs undergo chemical reactions with oxidizers such as ozone. A VOC source apportionment study of the Marshall Fire in Colorado reported that indoor benzene levels in one home declined sharply from a mixing ratio in parts per billion by volume (ppbv) of 3 ppbv to <1 ppbv within 15 days after the fire. The rate of decrease slowed down before returning to more regular indoor levels after 35 days. Biomass burning accounted for the largest portion of the indoor concentrations during the study period (Dresser et al., 2024).

Evaluation of the potential impact of a specific PAH, as well as all VOCs and SVOCs associated with a specific fire event, needs to consider the known compound chemical properties (e.g., molecular weight, gas-phase to particle partitioning rate with temperature, equilibrium adsorption and desorption rates, transitional decay potential, and residence time) and the site-specific conditions of the structure.

Basic chemistry concepts of VOC and SVOC half-lives and air-to-solid partition coefficients as well as the authors' extensive professional experience in wildfire investigations suggest a set of common processes that consistently occur in wildfires. These processes reflect the effects of time and distance on the presence of VOCs/SVOCs in the indoor environment, as shown in Figure 1.2.

Time and distance factors that need to be considered by the OEHS professional investigator are summarized in the sections that follow:

Light and Medium VOCs. Most VOCs (molar mass of less than ~200) generated during a wildfire have short gas-phase to particle half-lives of seconds to hours (Li et al, 2023). Light molecular weight compounds such as acrolein (NASEM, 2022a) and formaldehyde can be rapidly diluted and have detectable residence times and desorption equilibrium/decay rates of only hours to days. For example, acrolein is unlikely to be detected in the residues and attributed to wildfire more than several weeks after a fire event. SVOCs partition from a gas-phase to a particle or adsorb to other particles. Their subsequent desorption equilibrium and decay rate is based on the compound chemistry (e.g., molecular weight, boiling point, decay half-life) and environmental conditions (e.g., available oxygen, media or substrate, sunlight exposure).

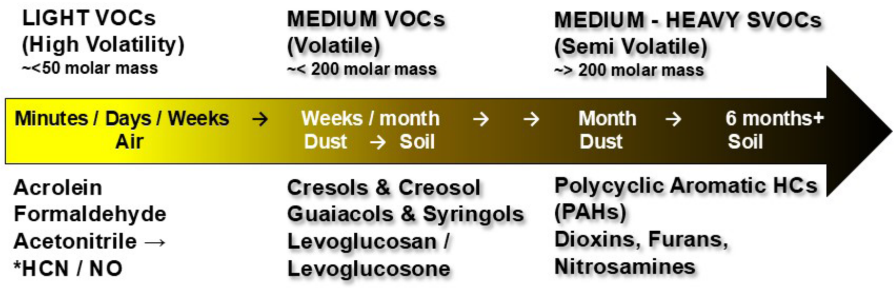


Figure 1.2: Decay rates of light, medium, and heavy volatile organic compounds (VOCs). HCN, hydrogen cyanide; HCs, hydrocarbons; SVOCs, semi-volatile organic compounds; NO, nitrogen oxide.

Medium to Heavy SVOCs. SVOCs and PAHs (molar mass > 200) generated during a wildfire have longer gas-phase to particle half-lives and desorption equilibrium/decay rates of days to less than two months depending on environmental conditions. These include compounds such as creosol, levoglucosan, and a range of PAHs (e.g., anthracene fluoranthene, pyrene, chrysene, benzopyrenes) (Wilson et al., 2021).

Longer Half-Life VOCs and Gases. Certain compounds such as benzene, acetonitrile, and hydrogen cyanide (HCN) have longer half-lives that are oxygen and ozone dependent. The atmospheric half-life and equilibrium/decay rates can range from two months to a year (Li et al., 2000). Particularly in the conversion from acetonitrile to HCN versus acetonitrile to nitrogen oxide, this range is dependent on whether the compound was generated in an oxygen-rich or oxygen-starved environment or whether the particulate reservoir environment was household dust or soil (Britt, 2002).

Partition. Airborne VOCs and SVOCs decay or adsorb onto particulates. The half-life of many of these chemical compounds in the environment and the temperature of combustion in wildfires, in addition to the decrease in concentration by dispersion, limit the ability of these chemicals to migrate much beyond the near field or local far field from the immediate combustion source (Ragothaman and Anderson, 2017; WHO, 2001). Partitioning studies of PAHs show that they have a strong affinity for organic matter and charcoal. This means that much of the mass of these nonpolar compounds adsorbs and partitions from a gas-phase to building materials and furnishings, such as carpet, gypsum wallboard, and even stainless steel, and can slowly desorb (i.e., off-gas) for time periods ranging from hours to weeks or months (Kohl et al., 2019; Li et al., 2023; Wang et al., 2017). As a result, PAHs are commonly found as a component of household dust. Infiltrated organic compounds primarily reside in the particulate phase (Dresser et al., 2024).

1.4.2. Background VOC and SVOC Levels

Wildfires produce a wide range of organic chemicals, including aliphatic and aromatic hydrocarbons, PAHs, and oxygenated compounds, such as aldehydes, acids, esters, and alcohols. Many of these compounds have also been identified inside homes as part of the chemical background. VOCs, including formaldehyde and toluene, are found in common household cleaning products and building materials. VOCs and SVOCs are constituents of many consumer products, furnishings, and construction materials. (NASEM, 2022b).

Benzene is a component of gasoline and may be found as a trace contaminant in some solvents and personal care consumer products, including hand sanitizers and suncare products (NTP, 2021). It is also found in outdoor air.

PAHs are produced from all types of combustion. Background sources of PAHs in urban outdoor air and in homes not affected by wildfires include smoke from fireplaces and cigarettes, asphalt pavement sealers containing coal tar, and vehicle exhaust (Whitehead et al., 2011). Grilling, charbroiling, and frying meat products are sources of $PM_{2.5}$ and ultrafine particulates and PAHs (Isaxon et al., 2015; McDonald et al., 2003).

The OEHS professional must consider background sources of VOCs, SVOCs, and PAHs that may be part of the normal environment. Background sources can be confounding variables that complicate the interpretation of sampling results.

1.5. Wildland-Urban Interface Fire Zone Considerations

The WUI is defined as the line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels (Interagency Working Group, 2001). Wildfires in the WUI can involve destruction of some structures and their contents, such as appliances, furniture, and household chemicals and often internal combustion and electric vehicles in addition to vegetative matter. These are referred to as mixed-burn or WUI fires. The materials that are consumed, dispersed by the firestorm, and ultimately infiltrate into the adjacent and nearby structures are different from simply burned vegetative matter and soil. Combustion products of many manufactured goods include particulates, VOCs, SVOCs, halogenated compounds, and metals, some of which are different from those in vegetative fires (NASEM, 2022a).

Mixed-burn and WUI fires represent an additional potential impact to the surviving structures and an increased risk of exposure to toxins for investigators and returning occupants (Dresser et al., 2024). Mixed-burn and WUI fire impact assessments more closely resemble a structural fire and an indoor air quality (IAQ) investigation, where identifying the origin and cause is relevant to assessing impact and potential health hazards. However, trying to distinguish the origin of the WUI fire residuals from background sources that are normally found in occupied structures requires a more elaborate investigative approach. The OEHS professional needs to consider and address the unique circumstances of WUI fires when designing the scope of work and selecting the tools and methods of investigation.

1.6. Wildfire Particulates

Wildfires generate particulate matter in a wide range of sizes. Particles from wildfire smoke typically range in aerodynamic diameter from 10 micrometers (µm), referred to as PM_{10}, to particles equal to or smaller than 2.5 µm, referred to as $PM_{2.5}$. Submicron-sized particles, referred to as ultrafine particulates, are also emitted. $PM_{2.5}$ is commonly measured in research studies and regulated by the U.S. Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (U.S. EPA, 2025a). The larger particles make up the majority of the mass while the smaller particles, particularly $PM_{2.5}$, are the most numerous. The size distribution of infiltrated wildfire particulates inside structures is often substantially different from the outside size distribution (Liu and Nazaroff, 2003; Long et al., 2001; Shrestha et al., 2019).

Time and distance considerations have significant impact on the size distribution of particulates, especially in the near field from the fire perimeter at an active wildfire versus the far field at greater distances from the fire. The length of time that transpires after the fire is extinguished at the combustion site also has significant impact on the types, concentration, and size distribution of particulate matter.

1.6.1. Combustion Byproducts

Wildfire particulate residue is generally divided into three morphological and compositional categories: char, ash, and soot (Albert et al., 1999; Babayemi et al., 2010; Baxter et al., 2022; Bodí et al., 2011; Conedera et al., 2009; Frenklach, 2002; Han, 2016; Han et al., 2018; Tumolva et al., 2010). These are defined as follows:

- Char is the carbon-enriched residue of a solid fuel following pyrolysis and incomplete combustion that retains morphological features of the solid fuel precursor (e.g., trees, shrubs, bushes, herbs, flowers, grasses, plant litter peat, lichen, etc.). Its size ranges from a few micrometers to centimeters.
- Ash is the inorganic residue of complete combustion. Particles consist of the residual metals, metalloids, and soluble components that were contained in the plants as macro- and micronutrients as well as the scorched grains of metal and metalloid minerals contained in the soil of the wildland that burned. In biomass fires, phytoliths of diagnostic morphology are common. Ash ranges in size from 2–500 µm. The phytolith residues range in size from a few micrometers to about 100 µm.
- Soot is produced by the uncontrolled pyrolysis and gas-to-particle conversion. It is formed in a four-step process by the homogeneous nucleation of elemental carbon, particle coagulation, particle surface reactions, and agglomeration. Agglomeration includes the condensation of precursor gas phases that are not combusted as well as VOCs and SVOCs that partition from gas to particle phase as the wildfire smoke plume cools. PAHs are precursors of soot. Particle

morphology is the result of combustion conditions and not the morphology of pyrolyzed solid fuels. Particle sizes range from about four nanometers to millimeters in aerodynamic diameter.

The burned biomass that remains on the ground after a wildfire has burned out or been extinguished is commonly called "ash." Different scientific disciplines define ash in different ways. When referring to wildfire residues in soil, the term can be used for a mixture of mineral and organic constituents. Research on the composition, properties, and effects of ash on the burned ecosystem has been conducted on material collected in the field after wildland and prescribed fires as well as on material produced in the laboratory. At low combustion completeness, typically below 842°F (450°C), ash is organic-rich, with organic carbon as the main component. At high combustion completeness (above 450°C), most organic carbon is volatized, and the remaining mineral ash has elevated pH when in solution. It is composed mainly of calcium, magnesium, sodium, potassium, silicon, and phosphorous in the form of inorganic carbonates; at 1,076°F (580°C), the most common forms are oxides and oxalates. Ash produced under lower combustion completeness is usually darker, coarser, and less dense and has a higher saturated hydraulic conductivity than ash with higher combustion completeness, although physical reactions with carbon dioxide and when moistened produce further changes in ash characteristics (Babayemi et al., 2010; Bodí et al., 2010).

1.6.2. Settling and Resuspension of Wildfire Particulates

Wildfire particulates enter a structure and deposit on surfaces (e.g., floors, carpets, counters, furniture, and other contents) over preexisting background dust, creating a multilayer effect on a surface. Particle deposits on surfaces can vary in composition, loading and particle size distribution, and from one location to another in a structure and from one structure to another. Some surfaces, such as carpets, can become reservoirs for settled particulates. Agglomerated particles may be resuspended if the surface is not cleaned or if a particulate reservoir is disturbed by cleaning. Dust loading can vary over several orders of magnitude and influence the level of resuspension of settled dust within a structure (Boor et al., 2013).

Resuspension of settled particulate deposits on surfaces is dependent on several factors within the indoor environment. Resuspension occurs from occupant activities and air velocity over the surface covered with settled dust, such as dry dusting, sweeping, and vacuuming without high-efficiency particulate air (HEPA) filtration. Other factors that contribute to the level of resuspension include particle adhesion, particle aggregation, deposit structure, and porosity of settled particulates (Boor et al., 2013).

1.6.3. Exposure to Wildfire Smoke Particulates

Acute and chronic adverse health effects from exposure to wildfire smoke and residue can be a matter of concern to people returning to work or home following a wildfire event. This is particularly true for sensitive or susceptible populations.

The primary air pollutant of health concern in wildfire smoke for the general population is particulate matter. Of particular concern are PM_{10}, which can penetrate into the bronchial region of the respiratory system, and $PM_{2.5}$, which can reach the alveoli—the gas-exchange region of the lungs—and cause short-term and long-term effects (Durán, 2014; Wettstein et al., 2018). Particulate matter also acts as the physical vector for exposure to metals and adsorbed chemicals.

Health effects associated with exposure to particulate matter at sufficient concentrations can cause eye and respiratory tract irritation, reduced lung function, pulmonary inflammation, bronchitis, exacerbation of asthma and other lung diseases, exacerbation of cardiovascular diseases, and even premature death (U.S. EPA, 2019, 2025b). Particulate matter in the atmosphere is also generated from a variety of other industrial and natural sources. It is well established that short-term effects such as eye and respiratory irritation, exacerbation of asthma, and other respiratory effects can be associated with wildfire smoke exposures. However, there is limited evidence of the cumulative, long-term health effects from exposure to wildfire particulates outside of the fire service cohort (U.S. EPA, 2019, 2025b).

Direct exposure to wood smoke generated during residential cooking and heating activities using wood as a fuel can result in both acute and chronic health effects. Acute effects include upper respiratory tract irritation, asthma aggravation, immune system suppression, and changes in lung function. Chronic illnesses, such as bronchitis, obstructive pulmonary disease, cardiac disease, and cancers of the lung, skin, and bladder have been considered as potential long-term effects (Zelikoff et al., 2002). Similar results have been reported from cooking with coal (Kim et al., 2016).

1.7. Volatile and Semi-Volatile Compounds

A complex mixture of VOCs and SVOCs is generated during the burning of biomass. The second-largest source of atmospheric VOC pollutants is attributed to biomass burning. Wildfires accounted for 45% and 10% of VOC emissions during the 2018 and 2019 Western U.S. wildfire seasons, respectively (Jin et al., 2023; NOAA, 2023). Heating and cooking with wood are estimated to be the primary source of VOCs worldwide (Yokelson et al., 2008). VOCs emitted by an active wildfire may include formaldehyde, acetaldehyde, acrolein, benzene, toluene, ethylbenzene, xylenes, styrene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, naphthalene, PAHs, SVOCs, and complex mixtures of VOCs (NASEM, 2022a; Wang et al., 2024).

1.7.1. Potential Human Health Risks of Volatile and Semi-Volatile Organic Compounds

Smoke from a burning fire is a complex mixture of gases, vapors, and particulate matter that can be distributed over a wide area. For the most part, smaller particles (PM_{10} and $PM_{2.5}$) are transported by wind and air currents, become diluted, and eventually settle to the ground. Gases, VOCs, and SVOCs carried by the plume will dissipate after the fire has been exhausted and natural weather conditions are reestablished (Wang et al., 2024). After the wildfire, settled particulates are deposited on surfaces both outside and inside of a structure depending on site-specific conditions. These particulates primarily contain ash, char, some soot, metals, PAHs, and other SVOCs. These represent potential sources of exposure.

Wildfire impact investigators must consider potentially exposed populations (in the context of this document, primarily building occupants returning after the fire)—namely, people of all ages and health status, including susceptible individuals. Exposure pathways include inhalation, skin and eye contact, inadvertent ingestion, and, particularly in the case of children, ingestion by hand-to-mouth behavior. Known health effects of specific VOCs include cancer, reproductive and developmental toxicity, neurotoxicity, respiratory irritation, liver and kidney toxicity, and skin disorders (NASEM, 2022a, 2022b). However, detection of a chemical or particulate in a sample does not mean that there is an elevated health risk or that a health effect will occur as a result of exposure. A thorough risk assessment that takes into account exposure and dose can be used to predict theoretical risk of cancer and non-cancer endpoints using recognized health-based toxicity values to fully characterize the risk.

Although the health effects of poor air quality from high levels of $PM_{2.5}$ pollution during wildfire events have been established (Reid et al., 2016a, 2016b), the human health effects of wildfire residues after a fire have not been thoroughly studied. However, studies from non-wildfire sources have shown evidence of health effects from exposure to some of the same constituents of wildfire residue that are found in the indoor environment, such as PAHs from fireplaces, cigarettes, asphalt pavement sealers, and diesel-powered vehicle exhaust (Maertens et al., 2004; Whitehead et al., 2011). Exposure to PAHs has been found to cause oxidative stress and is suggested to induce asthma symptoms in children and adults through immune system mediation (Wang et al., 2017). Additionally, some PAHs are also known genotoxins and Group 1 carcinogens (ATSDR, 1995).

1.8. Metals

Metals are natural constituents of plant matter and vary in composition based on the underlying geology, soil type, geography, plant community, and whether the plants are annual or perennial. Some metals such as arsenic, lead, nickel, zinc, and manganese are constituents of rocks and soil and are found as trace elements in living plants. Studies of ash from prescribed and uncontrolled U.S. and Canadian wildland fires report concentrations of several metals, including arsenic at 880 parts per million (ppm); lead (2–44 ppm); manganese (1,000–6,000 ppm); nickel (20–3,120 ppm); and zinc (55–172 ppm) (Bodí et al., 2010; Kohl et al., 2019; Sánchez-García et al., 2023).

The metal composition of ash differs between wildfires and WUI fires where nonvegetative sources, including structures, cars, manufactured products, electronics, and other household items, are consumed in addition to plant matter. The metals detected are dependent on fuel sources. Kohl et al. (2019) reported 8 ppm of arsenic and 15–20 ppm of lead in house dust in homes located in the near field from burned structures of the 2016 Horse River Fire in Ft. McMurray, Alberta. Ash from urban neighborhoods where homes burned had trace metal levels up to 100 times higher than house dust from homes in the same urban neighborhoods. Arsenic and vanadium levels were higher in homes located in highly affected areas where nearby homes were destroyed compared to those located in less affected areas subjected mainly to vegetative fire smoke. Metal concentrations in house dust from Ft. McMurray homes were lower than background levels found in other Canadian cities.

Chromium VI was detected in soil and ash in the burn zone of the 2019 Kincade Fire, which burned approximately 78,000 acres of wildland, 174 residences, and 11 commercial properties in the Sonoma, California area. High heat transformed naturally occurring chromium III into chromium VI. Repeat sampling showed significant concentrations of chromium VI in the wildfire burn zone soil and smoke ash as long as 10 months after the wildfire extinguished (Lopez et al., 2023).

According to the United States *Geological Survey's Geochemical and Mineralogical Maps for Soils of the Conterminous United States* (Figure 1.3), the

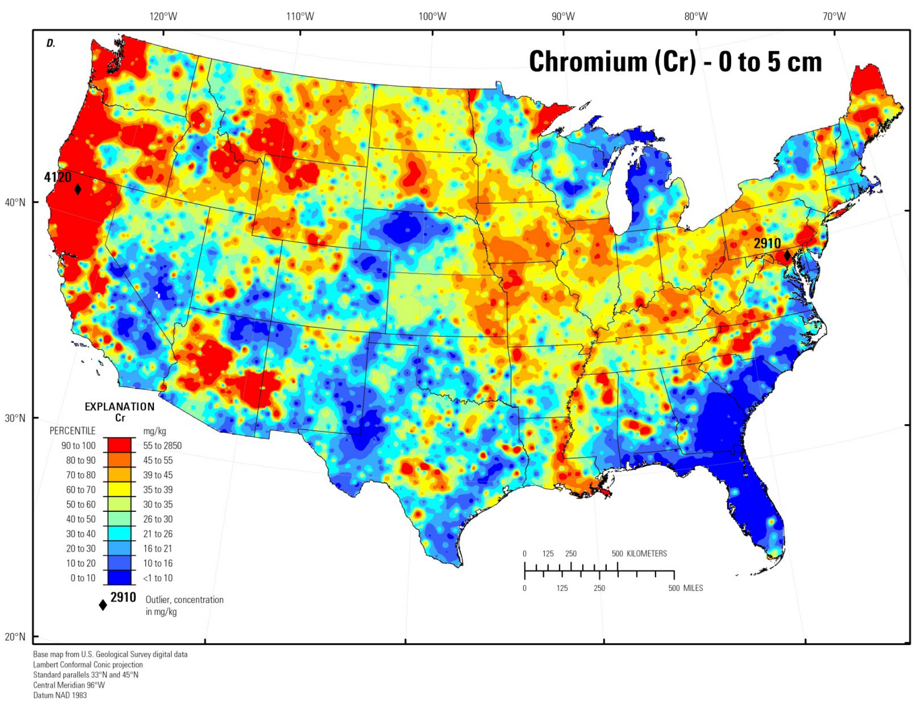


Figure 1.3: Geochemical and mineralogical maps for soils of the conterminous United States. [Source: Smith et al., 2014, Open-File Report 2014-1082. In public domain.].

Sonoma, California area where the Kincade Fire occurred has some of the highest levels of naturally occurring chromium in surface soils in the United States (Smith et al., 2014).

Although most studies of the metal content of wildfire ash are conducted on bulk samples collected from soil or house dust, elevated concentrations of airborne metals have been reported during wildfires. The California Air Resources Board studied four major 2018 wildfires (CARB, 2021), including the Camp Fire that burned 150,000 acres and almost 19,000 structures in the town of Paradise. The study found that during this wildfire, airborne lead and manganese concentrations were, respectively, 4 times and 50 times above average for one day in Chico, California, 15 miles away. Zinc was detected at 20 times the average ambient level in Modesto, California, 150 miles from Paradise. These results reflect the effects of WUI fires on the fate and transport of wildfire residue.

1.9. Confounders and Uncertainty Analysis

To minimize the effect of potential confounding variables, OEHS professionals should account for these factors in the study design and hypothesis formulation. Methods and techniques to account for confounders include testing for the presence or absence of background sources; collecting blank samples or pre- and post-sampling, if possible; comparing samples from different zones or areas; analyzing surface samples for contextual assemblage; or adjusting for their effects statistically.

Confounding variables are factors that may not be readily apparent and, if not accounted for, can skew testing results and distort the determination of actual impact. In wildfire impact assessments, they can be sources of microscopic particles and chemicals not from the wildfire event. Background sources can be confounding variables when they cannot be isolated from the wildfire-associated sources. Examples of background sources are anthropogenic combustion particles from fireplaces, candles, smoking, and cooking typically found indoors in homes and buildings. Background sources of potential health concern include VOCs, SVOCs, and PAHs commonly found in building materials, furniture, and consumer goods; generated from cooking meats; or infiltrated from outdoor sources. Accelerants and materials that might cause interferences in the analysis, such as metal content of wildfire suppressants, are another source of confounders.

Measuring background levels of combustion particulates is an essential aspect of the sampling strategy and hypothesis testing in wildfire impact assessments. For exposure evaluation, measuring background concentrations of particulates, VOCs, SVOCs, metals, and organic and inorganic acids of health concern helps identify the source(s) and their contribution to the indoor environment. This information is key to developing and recommending control measures to reduce the exposure to acceptable levels.

In the case of forensic investigations, background testing helps establish the level of anthropogenic sources of combustion particles that existed prior to and are not related to impact from the wildfire in question. This information can help determine both the relative impact of a known wildfire event and the appropriate level of restoration and cleanup needed.

OEHS professionals should also understand the sources of uncertainty in the investigation and report the degree of uncertainty in the results. Uncertainty from natural variability in the distribution of the target compounds in the sampled areas, sampling and analytical error, and site-specific variables is quantifiable and can be addressed through statistical treatment of the data (refer to Chapter 5). Uncertainty also arises from the use of reference levels as protective benchmarks rather than precise indicators of where adverse effects are expected. These levels incorporate extrapolated health data and safety factors to minimize risk to the most susceptible populations. In addition, reference toxicity values for individual compounds do not account for mixture effects. Experience, knowledge of impact assessment methods and procedures, and professional judgment form the basis for arriving at an evidence-based decision. The OEHS professional should assess the degree of uncertainty in the findings and conclusions of the assessment and convey it clearly when describing the analysis of any test data. AIHA's *A Strategy for Assessing and Managing Occupational Exposures* (Jahn et al., 2015) describes uncertainty rating models and numerical analysis methods that may be adapted to nonoccupational settings for wildfire impact exposure assessments.

1.10. Special Concerns for Susceptible and Vulnerable Populations

There is some uncertainty as to the acute or chronic health effects of exposure to wildfire residue. In the absence of definitive information and out of an abundance of caution, individuals who have preexisting health conditions that are related to or may be exacerbated by exposure to wildfire particles or their chemical constituents should try to avoid or minimize contact as much as possible. Based on research on the health effects of exposure to wildfire smoke, the following groups may be considered more susceptible than the general population (Reid et al., 2016a):

- Infants and young children, due to underdeveloped respiratory systems and immune systems.
- Individuals with chronic or preexisting respiratory medical conditions, including but not limited to asthma, chronic pulmonary obstructive disease (COPD), emphysema, or chronic bronchitis.
- Pregnant people.
- Those with immunocompromised conditions.
- Socioeconomically under-resourced groups, including Indigenous, poor, and rural residents who develop chronic health conditions due to lack of access to proper healthcare.

Individuals who experience symptoms or exacerbation of symptoms related to respiratory problems or other health conditions after exposure to wildfire residue should contact their healthcare provider.

Members of more susceptible and vulnerable populations present in buildings and settings impacted by wildfire residue should take sensible precautions to minimize exposure. Examples of these types of buildings and locations include but are not limited to daycare centers, hospitals, schools, nursing homes and assisted living units, senior centers, shelters, substandard housing, and areas with inadequate urban infrastructure.

Members of these vulnerable groups may have limited capacity to adapt to and mitigate the effects of a wildfire event. This might include lacking access to portable room air filters or community clean-air rooms during the wildfire, healthcare services, qualified exposure assessment expertise, and professional restoration resources in the aftermath.

1.11. Exposure Assessment and Characterization

The process of conducting a human health risk assessment is beyond the scope of the Technical Guide. The U.S. EPA has developed guidance, handbooks, frameworks, and general standard operating procedures to conduct risk assessments based on sound science (U.S. EPA, 2025c). For the OEHS professional conducting an exposure assessment, AIHA provides exposure risk assessment and management guidance as well as free online software tools to evaluate exposures and determine if they are acceptable or not acceptable or whether more data are needed (AIHA, n.d.).

The exposure assessment and characterization process must be conducted on a case-by-case basis. Conducting an exposure assessment for building occupants where settled wildfire deposits are present may not be necessary for cases in which the primary goal of the investigation is to prescribe basic restoration or cleaning measures, as the human health risks in this context are low or *de minimus*. However, in areas where hazardous debris and chemicals may be present, such as the mixed-burn zone or near-field WUI, evaluating potential health exposures and risk may be relevant, particularly for cleanup and restoration personnel.

The list of chemicals generated by wildfires and WUI fires is extensive. Many of these chemicals infiltrate buildings and can be detected in indoor air in wildfire impact investigations (Jin et al., 2023; Li, 2023; NASEM, 2022a, 2022b; NIOSH, 2024; NOAA, 2023; Simms et al., 2021; U.S. EPA, 2019). However, not all chemicals generated by wildfires or WUI fires have health-based acute and chronic exposure limits or no-effect thresholds. It is therefore important to select chemicals with established levels of health concern to compare them against detected concentrations under high-risk circumstances.

Published chemical-specific toxicity values are available to assist with exposure assessment, such as the inhalation reference concentrations (RfCs) and oral reference doses (RfDs) in the U.S. EPA's Integrated Risk Information System (IRIS) database (U.S. EPA, 2025d) and the California Office of Environmental Health Hazard Assessment's (OEHHA) Toxicity Criteria database (OEHHA, 2019). Such resources are commonly used to assess potential non-cancer health risks in regulatory frameworks. For carcinogens, public health agencies have developed potency factors, such as the U.S. EPA's inhalation unit risk, to estimate upper-bound incremental theoretical lifetime cancer risks.

The U.S. EPA uses these values to establish Regional Screening Levels (RSLs) for air, soil, and water remediation at residential and industrial sites (U.S. EPA, 2024a). RSLs are tools that describe cancer and non-cancer endpoints. They must be applied and interpreted by competent users who understand the default assumptions that underpin the RSLs for a given exposure group (U.S. EPA, 2024b). Exposure concentrations exceeding an RSL do not necessarily indicate that cleanup is required; rather, further evaluation is needed to apply the appropriate response action.

Indoor air exposure values for the general population include the *Indoor Air Quality Guidelines* (IAQGs) published by the French Agence Nationale de Sécurité Sanitaire de L'alimentation, de L'environnement et de la Santé au Travail (ANSES) (ANSES, 2013) and the World Health Organization's (WHO) *Guidelines for Indoor Air Quality: Selected Pollutants* (WHO, 2010). These guidelines are specific to the general population's exposure to a number of chemicals commonly present in indoor air in concentrations that are concerning to health.

Chemical-specific toxicity values are designed to be protective of public health, including susceptible populations. They are set below levels where adverse effects are observed and do not represent thresholds for adverse effects or predict the occurrence of disease (U.S. EPA, 1986). For many agents, they are based on lifetime risk (U.S. EPA, 2025d; OEHHA, 2019). Exposure above reference toxicity values does not establish that an adverse health effect has occurred. When a health guideline is exceeded, the first step in understanding the public health significance is reviewing and understanding the basis for that guideline. Understanding the applicability and strength of the study data will be a primary tool in evaluating whether site exposures are expected to cause harm. The goal of the analysis is to determine where site-specific doses lie in relation to the observed effect levels reported in the studies of interest. Then, it can be determined whether differences between study data and the exposure scenario being evaluated make health effects more or less likely (ATSDR, 2022).

Wildfire residue presents a unique challenge as it comprises a complex mixture of chemicals, particulates, and combustion byproducts. This is particularly relevant in the WUI, where wildfires interact with human-made structures. Evaluating the health significance of exposure to wildfire residue requires a comprehensive assessment of all potential agents involved. Public health agencies provide guidance on how to incorporate individual specific toxicity values into mixtures for assessing health risks (U.S. EPA, 2025d).

Wildfire Impact Assessment

2

WILDFIRE IMPACT ASSESSMENTS are typically performed for a) forensic investigations, which are intended to confirm the presence or absence of wildfire residue and attribute the source, b) exposure assessments to evaluate and control potential health hazards, or c) a combination of both. A comprehensive wildfire impact assessment should include a relevant history of events, general construction basics of the property of concern, and detailed sensory observations (e.g., odor evaluation, visible and physical impact) supplemented by sampling as needed. Knowledge of mechanical building ventilation and air movement inside a structure (especially during the fire event) can be helpful in anticipating particle deposition patterns and subsequently identifying sampling locations. The investigation should include interior and exterior spaces and surfaces where accumulations of combustion byproducts are likely.

2.1. Impact Evaluation

The primary role of the OEHS professional conducting a wildfire impact assessment is determining what has been impacted (and to what level) and establishing the source, origin, and cause of that impact.

If the evaluation is conducted for exposure assessment, the OEHS professional should follow the ARECC model of anticipation, recognition, evaluation, control, and confirmation. The OEHS professional should be able to select the appropriate site inspection, monitoring, sampling, and analytical methods to establish the presence and concentration of potentially hazardous agents.

In forensic investigations, the level of impact to properties is dependent on the location of the property relative to the wildfire, wind direction during the fire event and shortly thereafter, and opportunities for the wildfire residue to infiltrate into the structure.

The exterior surfaces of a structure generally sustain the most direct impact of wildfire residue and heat depending on the structure's location within the burn zone, near field, or far field from the fire perimeter. Exterior building components provide essential information on the level of impact. Wildfire particles can infiltrate buildings through visible penetrations as well as unperceived gaps in the building envelope and deposit and settle on proximal surfaces (Kovar et al., 2015).

The OEHS professional should understand that impact and damage are not synonymous terms. Evidence of wildfire residue impact to the environment does not necessarily mean that damage has occurred. "Impact" is a general term that indicates that the structure's condition, or portions thereof, is different than the background conditions that existed before the wildfire. "Damage" is generally defined as the alteration of appearance, utility, or value (Kovar et al., 2015). Although a change in appearance (e.g., a dirty window) indicates impact that requires cleaning, it is not considered damage by itself. It is not the role of the OEHS professional to determine or measure damage or ascribe a value to impacted structures and contents.

2.2. Pre-Entry Safety Considerations

OEHS professionals and other materially interested parties (MIPs) conducting an initial building inspection should exercise adequate caution to prevent exposure to potential health and safety hazards. The location of the structure and the time elapsed since the fire are important considerations. Structures located in the near field or a WUI fire area pose a greater risk of exposure than buildings located in the far field. At a minimum, foot covers should be worn when entering a building that has already been cleaned, ventilated, reoccupied, and returned to normal operations.

Initial inspections performed before the building or home is reoccupied or has been cleaned merit additional precautions. Personal protection equipment such as gloves and disposable coveralls may be recommended. N-95 masks are also advisable when accessing attics and crawlspaces or unoccupied spaces, such as sheds and warehouses. Upgrade to tight-fitting air-purifying respirators with N-95 and organic vapor cartridges may be necessary if volatile organic compounds (VOCs) or semi-volatile organic compounds (SVOCs) are detected or suspected.

Although not considered typical for a wildfire residue impact assessment, fire-impacted structural members may compromise the structural integrity of roofs, floors, walls, and foundations. In these cases, evaluation by a qualified engineer or building official is warranted prior to entry.

Other safety hazards to consider before entering a building regardless of its distance from the fire perimeter can also include fire risk, falling trees, electrical hazards, gas leaks, animals and uneven terrain, water damage, and mold, among others.

2.3. Information Gathering/Occupant Interviews

The collection of relevant data prior to or during the investigation is a fundamental component of wildfire residue impact investigations. Data collected should include the following:

- Details of the subject wildfire, including date(s) of wildfire occurrence, name, size of wildfire, location and proximity of wildfire relative to the property, prevalent wind direction(s), occupant observations during the wildfire, ambient air quality monitoring station data (e.g., $PM_{2.5}$, PM_{10}), relevant information from reliable sources (e.g., fire department, news media outlets, satellite imagery, video, etc.), cleaning or restoration performed to date, and building and site characterization and stabilization, if needed.

- Controls for confounding variables (e.g., sources of microscopic impact and chemicals other than from the wildfire that may skew testing results, such as smoking or fireplace use). The operating status of the building during the fire event (e.g., HVAC on or off, windows closed or open, water suppression system operating, etc.) will affect the level of impact and the fate, transport, and depositional patterns of wildfire residue.

2.4. Visual Inspection

Visual inspection of the subject property is the most important part of any impact investigation. Prior to arriving on site, the OEHS professional should have a clear and specific purpose and set objectives for the investigation. A comprehensive written inspection checklist is essential for accurately documenting the initial conditions observed. The checklist should be preserved as part of the permanent record. Appendix B presents example forms for exterior, interior, garage, attic/crawlspace, and HVAC system inspections.

In the immediate aftermath of a fire event, determining the level of impact at a structure located adjacent to the fire perimeter may not be difficult due to

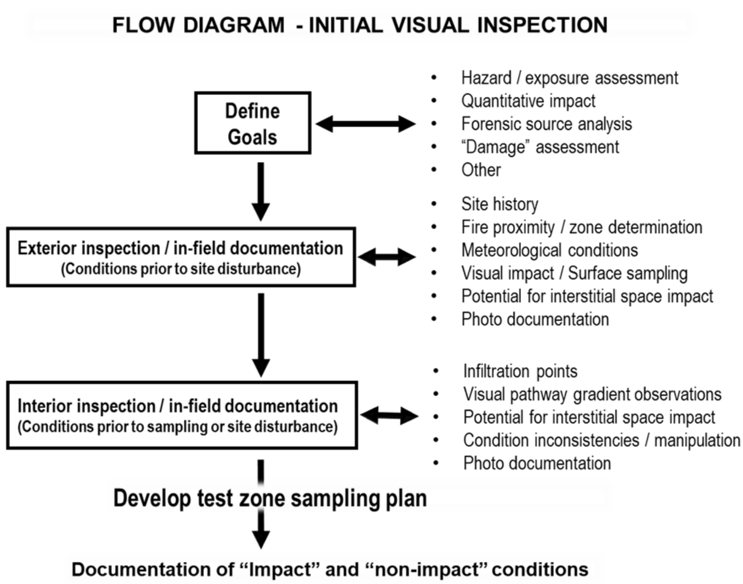


Figure 2.1: Forensic wildfire inspection flowchart.

the presence of burned vegetation adjacent to the structure, deformed exterior features, or visibly identifiable combustion particles (e.g., char and ash). Surface particles found at properties located farther away from the wildfire or investigated after a significant period of time has elapsed may be difficult to assign to wildfire impact because they may be confused with other particles typically found in household dust (Kovar et al., 2015). Figure 2.1 illustrates a suggested flowchart for conducting the visual inspection.

Wildfire residue produces distinct visual cues of impact, which include the following (King and Kovar, 2014):

- **Selective Deposition/Accumulation of Combustion-Related Particles**. Wind-driven wildfire-related particles can settle on exterior and interior surfaces of a structure. Typically, they accumulate at points of entry (e.g., windows, doors, attic vents) and potentially move toward the interior based on the routes of entry and characteristics of the surface (i.e., polarity). The products of combustion are not all black or even dark. Often, most black particles in a structure are not from a wildfire even when that structure has been demonstrably exposed to residue from a wildfire event. When all the carbon is consumed, the result is generally a white, yellow, or red ash. These particles still retain structure and optical characteristics sufficient to be identified as ash.

Although not typically associated with wildfires, other distinct residual cues may be present. These are described in the sections that follow. Example images from structural fires are shown for illustrative purposes.

- **Electrophoresis**. This is a condition caused by the localized accumulation of airborne particles due to electrical attraction, commonly known as "ghosting" (Figure 2.2). During an investigation, ghosting appears as a visible pattern on a surface outlining the borders of an object. In a building fire, ghosting is often caused by charged particles and gases that move to materials such as cloth, metal, ceramics, glass, plastic, and cooler surfaces. Further investigation may identify underlying carbonized soot conditions from candles or the lack of or inadequate ventilation of wood-burning fireplace, furnaces, water heaters, cigarette smoking, cooking, and automobile exhaust.
- **Thermophoresis**. In a fire, thermophoresis is a force network of warmer suspended particles and gases migrating toward cooler surfaces. Examples include vertical stripes on the interior side of exterior walls when structural members or locations with insufficient insulation provide a thermal bridge between the exterior sheathing and interior drywall. Visual findings of thermophoresis may resemble mold or rust but are typically accumulations of household dust, which may include combustion particles (Figure 2.3) (Barbour et al., 1994; Batchelor and Shen, 1985; Millette, 2007).

Figure 2.2: Example of electrophoresis (ghosting). [Image Courtesy of Safeguard EnviroGroup].

- **Filtration Marks/Threshold Streaks.** Filtration marks are the discoloration caused by air-driven particles impacting and collecting on the material due to pressure differentials between spaces. These marks can be visually seen as dark streaks, splotches, or dark lines and are commonly observed below doors (Figure 2.4) (NAHB, 2000).
- **Smoke Webs and Smoke Chains/Smoke Tags**. Spider webs are common occurrences in all types of buildings, especially in areas that are not frequently accessed, such as the ceiling corners of confined spaces like attics. Carbon particles and other fire-related byproducts of incomplete combustion are produced in smoldering wood fires and the burning of petroleum-based materials. Smoke tags, webs, and swirls start as individual microscopic combustion particles, which become attached to spider webs. Over time this material can completely coat the spider webs, causing them to appear black (Figure 2.5).
- It is important to note that individual strands of spider silk are extremely strong, having up to five times the tensile strength of steel, and are also heat resistant. This imparts the strength to support the weight of the soot particles and still retain the web structure. The individual spider silk strands can be extremely small, with diameters as small as 1 µm. This can make finding the individual strands difficult, as they may be completely coated with particulate. For detecting the individual strands, polarized light microscopy with cross-polarized light and first-order compensation is strongly recommended, along with an appropriate refractive index mounting medium.

Figure 2.3: Example of thermophoresis. [Image courtesy of Safeguard EnviroGroup].

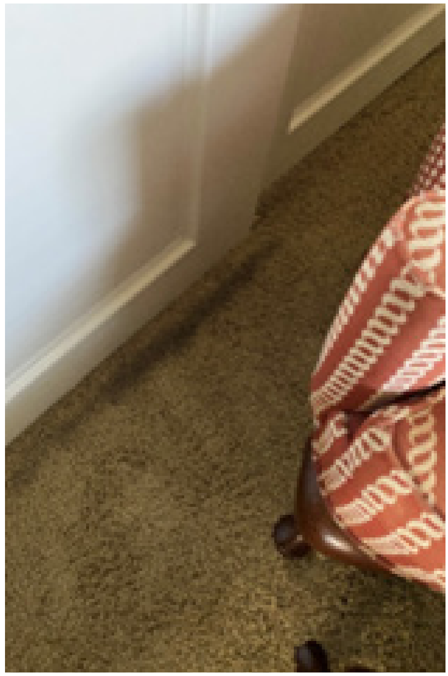


Figure 2.4: Example of threshold streaks. [Image courtesy of Forensic Analytical Consulting Services, Inc.].

Figure 2.5: Example of smoke webs. [Image courtesy of Safeguard EnviroGroup].

Spider silk has refractive indices in the 1.54–1.58 range; therefore, a mounting medium with a high refractive index (RI = 1.662) is recommended). Upon microscopical examination, it may be observed that many other types of particles are attached to the strands in addition to the soot (Huby et al., 2013; Little and Kane, 2011).

- **Corrosion**. The corrosivity of wildfire residue depends on the fuel source and distance from the fire. Corrosion is caused by the generation of corrosive gases and particles. Metal items exposed to corrosive gases and/or particles may begin to oxidize or rust relatively quickly in a matter of days. Visual cues of corrosion are pitting, yellowing, and grooving (Larrañaga et al., 2016). The high pH and solubility of wildfire ash (Bodí et al., 2014) can result in cation corrosion on metals, such as zinc and aluminum, which are contained in electronic components in the presence of moisture (Otani et al., 2014).

2.5. Odor Perception

Addressing the characteristic "smoke" odor from a wildfire is one of the greatest challenges in a post-wildfire assessment. The complexity of combustion chemistry and the hundreds of possible chemical compounds as well as the wide range of odor characteristics make determining what to test for difficult. Even though no single wildfire residue odor exists, a general "burnt" odor similar to a fireplace or wood fire, while subjective, is an indicator of wildfire residue's impact to an occupiable structure. The smoke odors may emanate from the structure, building contents, and residual burned material in the exterior environment. Depending on wind directions and proximity to the fire perimeter, occupants may notice varying degrees of wildfire residue odors both inside and outside of the structure.

Odor perception can vary by orders of magnitude between individuals. Laboratory experiments were used initially to determine a set of target compounds that comprise the "burnt smell." These include acetophenone, benzyl alcohol, 4-ethyl-2-methoxyphenol, 2-hydroxybenzaldehyde, 2-hydroxy-5-methylbenzaldehyde, 2-methoxyphenol, 2-methoxy-4-methylphenol, 2-methylphenol, 3-methylphenol, 4-methylphenol, and naphthalene (Heitmann et al., 2009). Subsequent studies confirmed that these target compounds represented the characteristic smoke odor in both laboratory and field sites and for a variety of fuels, including several types of wood, polymers, resins, and fabrics (Heitmann et al., 2011; Wichmann et al., 2012).

It can be difficult to differentiate indoor odors from external conditions. In the mixed-burn zone or WUI, the characteristic odors may be more varied and complex from the combination of burned vegetative matter, building materials, contents, and other items.

Although abundant information is available on how humans process odors, such as published odor threshold ranges for both detection and recognition

(Lehocky et al., 2024; Leonardos et al., 1969; U.S. EPA, 1992), research has yet to show how an individual will interpret and respond to a particular odor.

Clear and unambiguous odor perception and recognition that is not influenced by existing outside odors is an important factor for evaluating potential impact. However, trained odor perception panels and similar methods used in research settings are not suited to field applications.

Investigators in wildfire cases have developed practical field techniques for qualitative odor perception that have not been formally and independently validated. One common technique involves wrapping a sample suspect material or item in aluminum foil to concentrate the odors and smelling the air inside the wrapper after some period of time. Another technique for post-restoration evaluation involves placing previously cleaned contents in a plastic bag or wrapping large items, such as sofas, in plastic for several hours and then smelling the headspace. A variation of this technique is to heat the item or air and then smell the item. Some investigators smell coffee beans prior to and between odor tests to "clear" the olfactory sense. These techniques are subject to confounding factors and uncertainties when interpreting the results. Quantitative sampling of headspace air for some smoke-associated odor compounds can be performed in the field or conducted in a laboratory test chamber by drawing samples using thermal desorption-gas chromatography-mass spectrometry (TD-GC-MS) for analysis by EPA Method TO-17 and ISO Method 16000-6.

Valuable guidance and additional resources are presented in AIHA's *Odor Thresholds for Chemicals*, 4th edition (Lehocky et al., 2024). OEHS professionals should understand that the subjective nature of odors means that qualitative odor perception should only be used in conjunction with other lines of evidence to establish wildfire impacts.

2.6. In-Field Evaluation Methods

In-field evaluation methods are used for preliminary or initial determination of the condition of the structure and contents with respect to potential impact from wildfire residue. These may involve nondestructive or destructive testing techniques. Quantitative sampling and analytical methods are not typically applied at this stage of the investigation. Figure 2.6 illustrates a suggested flowchart for conducting sampling as part of a forensic investigation.

A nondestructive, qualitative in-field evaluation can be conducted as part of the initial walkthrough visual inspection of the building's exterior and interior. These techniques may include noting the presence or absence and location of characteristic odors, recording unaided visual observations, and using visual aids (e.g., white glove method, cellulose sponges, white cosmetic sponges or similar media) to test the presence or absence and extent of settled dust accumulation, which may be associated with wildfire residue intrusion.

Wipe testing involves lightly or gently wiping representative horizontal surfaces with a white glove or cellulose sponge to visually detect the presence

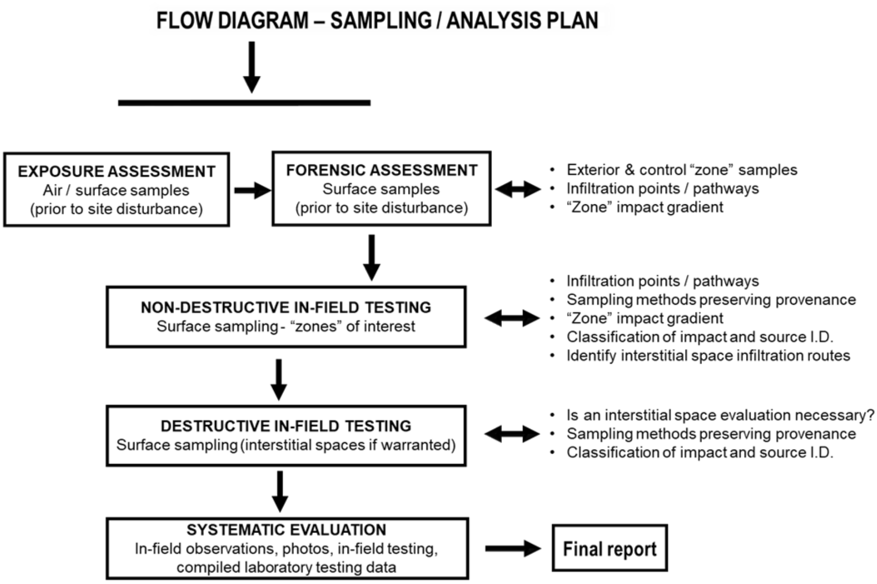


Figure 2.6: Forensic wildfire investigation sampling plan flowchart.

of black, brown, or gray settled dust on the wipe media. Interior and exterior surface locations near possible entry points of outside air, such as windowsills, floors near doorways, or furnishings near entry points should be sampled along with surfaces in interior spaces for comparison. Care should be taken not to use abrasive methods, which may remove the substrate material and lead to erroneous results.

Intrusive or destructive in-field evaluation techniques may include bulk sampling of exterior building components or removing fixtures, electrical cover plates, or acoustic ceiling panels to access interstitial spaces and wall cavities.

The findings and observations of the in-field evaluation should not be interpreted as definitive or confirmatory evidence of wildfire impact at this stage. These qualitative methods are helpful in identifying possible entry points of wildfire residue and differential levels of impact between areas of the building. They are also a valuable tool for documenting and obtaining evidence of the condition of the structure and contents prior to undertaking any restoration activities. In addition, they indicate the level of cleanup and restoration that may be required.

In some cases, a visual walkthrough inspection may be sufficient to establish impact. Sampling is always secondary to the visual assessment process. Based on the initial results, a comprehensive sampling plan including sampling and analysis of microscopical particles, organic and inorganic chemicals, or metals using appropriate methods may be warranted to confirm and assess wildfire impact.

2.7. Assessment of Attics and Crawlspaces

The potential for wildfire residue to infiltrate into attics and crawlspaces should be evaluated where appropriate. Attics often have points of infiltration into occupied spaces, such as stairways, ladderways, and mechanical, electrical, and plumbing penetrations. Wildfire residue may impact loose attic insulation (e.g., rock wool, mineral wool, fiberglass, cellulose).

2.8. Assessment of Heating, Ventilation, and Air Conditioning Systems

Heating, ventilation, and air conditioning (HVAC) systems should be inspected and evaluated, including cooling coils, supply and return plenums, and the air conveyance network (i.e., ductwork). Note that central HVAC supply air plenums located in the attic represent a significant pathway for wildfire residue to enter the occupied space through direct air exchange. Collecting information on the operating status of the HVAC system during the fire is important in evaluating potential impact.

2.9. Assessment of Interstitial Spaces

Interstitial structure spaces can include enclosed and nonoccupied spaces such as wall cavities, soffits, recessed lighting, and other confined areas. Wildfire residue can infiltrate into these interstitial spaces primarily from the exterior environment into structures located in the burn zone or near-field distance from the fire perimeter. The potential for exterior or interior structure infiltration into interstitial spaces is determined by the presence and degree of temperature and pressure differentials. Interstitial space infiltration from the exterior is primarily due to heating and directional firestorm winds that produce a high-pressure differential between the windward and leeward sides or the interior of a structure. Internal pressurization between the occupied interior environment and interstitial spaces can occur indirectly through large external penetrations such as attic vents, exhaust vents, fireplace chimneys, or windows that may have been left open during a fire event. Pressurization within a structure can either be outward in structures with full or partial combustion or inward from wind-blown impacts. Noting these differences is important to better understand the thermodynamics and aerodynamics and the possible secondary impacts on the building and contents. Figure 2.7 illustrates instances of visual markers of smoke pressurization within the interstitial space of walls or ceilings typically observed when the structure burns. The external gradient pattern of dark staining around the peripheries of switch or outlet plates and fixtures strongly suggests the release of pressurized smoke into areas of lower pressure.

Both external and internal infiltration into interstitial spaces occurs through penetrations, such as plumbing or HVAC penetrations, exhaust vents, electrical

Figure 2.7: Examples of evidence of interstitial pressurization (from structure fires). [Image courtesy of Safeguard EnviroGroup].

outlets, and cracks or gaps in walls, floors, or ceilings. Active, thermally or pressure-driven infiltration is less likely to be a concern outside the burn area. The potential for a significant infiltration into the interstitial space related to a fire event can typically be detected by visual examination or testing for particle deposition patterns surrounding the penetration margins in the suspect source area. In most instances, the source area would be an impacted, formerly occupied living space, with suspect infiltration into wall cavities, attic space, and crawlspace(s). However, the attic may be considered a potential source area for infiltration into the occupied space(s), in which case particle deposition patterns on "attic side" surfaces at penetration points would be relevant. The presence or absence of visual deposition patterns and testing can be used as indicators to determine whether destructive testing of the interstitial space may actually be warranted.

Passive infiltration of outdoor wildfire residues can continue into the occupied spaces by the occupant after cleaning or restoration has been completed. Active infiltration occurs by tracking settled dust in through doors or airborne through open windows. Infiltration into interstitial spaces has not been extensively studied. Given that pressure difference is one of many factors that drives particle movement in buildings, it is likely not significant (Chun and Zhao, 2011).

2.10. Preliminary Wildfire Smoke Impact Levels

The findings of the initial assessment are used to assign a preliminary degree of impact from wildfire residue on a structure as a whole or to individual parts of the structure's interior, exterior, and contents. Impact levels range from Level 1 (Background) to Level 4 (Heavy). These preliminary impact levels serve to direct sampling strategies to further refine and complete the impact assessment. They can also help define the scope of subsequent restoration efforts. These levels represent a continuum or gradation—a level does not codify a specific set of restoration activities but rather a general set that can be expanded depending on the specific case. Preliminary smoke impact levels must be assigned on a case-by-case basis. Contents should be evaluated independently from structural elements and may be assigned different levels than the room or area they occupy.

The initial criteria for assigning preliminary impact levels are based on the findings of the visual inspection, in-field testing, and odor perception and recognition. The levels can be adjusted up or down as additional data become available from quantitative sampling and analysis. Based on the assessment objectives, additional parameters can be incorporated into the criteria. Examples include source apportionment in the form of wildfire indicators and assemblage analysis for forensic evaluations and background levels and health-based exposure limits for exposure assessments.

The impact levels provide a guide for OEHS professionals to weigh the broad range of qualitative information. They do not necessarily describe fixed criteria for every circumstance. There may be instances of overlap across impact levels. The OEHS professional needs to evaluate the weight of evidence derived from the site characterization and testing when establishing and adjusting preliminary wildfire smoke impact levels.

The evaluation criteria may be expanded or modified in the case of mixed-burn zone or WUI fires or if sampling and analytical data are available. The spectrum of particles from these sources are distinctly different than the profile of typical wildfire particles and are part of an expanded combustion particle analysis as an addition to a wildfire particle analysis. They require a more detailed analysis and should be quantified separately.

The impact levels are defined as follows:

Level 1 (Background):

- No visible evidence of wildfire heat, smoke, or particulate residues;
- No perception of wildfire odors;
- Evaluation accounts for interior particles or odor sources unrelated to wildfires (i.e., fireplace, wood-burning stove, candles, etc.);
- Structure not located in a mixed-burn zone or near field to a WUI fire;
- No evidence of mixed-burn or WUI fire effects in multiple areas (if applicable).

Level 2 (Light):

- Discrete evidence of wildfire heat, smoke, or particulate residues;
- Evidence limited to points of entry (e.g., windowsills/tracks, door thresholds, proximate flooring, etc.);
- Faint or intermittent or discrete perception of wildfire odors;

- Evaluation accounts for interior particles or odor sources unrelated to wildfires (i.e., fireplace, wood-burning stove, candles, etc.);
- Structure may or may not be located in the WUI or near field to a WUI fire;
- Limited evidence of mixed-burn or WUI fire effects in discrete areas (if applicable).

Level 3 (Moderate):

- Noticeable evidence of wildfire heat, smoke, or particulate residues present on multiple interior surfaces and spaces;
- Noticeable perception of wildfire odors in designated areas;
- Evaluation accounts for interior particles or odor sources unrelated to wildfires (i.e., fireplace, wood-burning stove, candles, etc.);
- Structure located in a mixed-burn zone or near field to a WUI fire;
- Noticeable evidence of mixed-burn or WUI fire effects in multiple areas (if applicable).

Level 4 (Heavy):

- Confirmed and widespread evidence of wildfire heat, smoke, or particulate residue;
- Thermal impact to the exterior and/or interior surfaces may be present;
- Noticeable and irritating perception of wildfire odors throughout the affected area;
- Evaluation accounts for interior particles or odor sources unrelated to wildfires (i.e., fireplace, wood-burning stove, candles, etc.);
- Structure located in a mixed-burn zone or near field to a WUI fire;
- Generalized evidence of mixed-burn or WUI fire effects throughout the affected area (if applicable).

2.11. Report Elements

The OEHS professional's report of findings should reflect the specific project goals and objectives of the investigation. The report's format and organization should be compatible with the purpose of the assessment. The industrial hygiene ARECC principles of anticipation, recognition, evaluation, control, and confirmation (Anna, 2011) can serve as guidance to OEHS professionals in preparing the report. The wildfire impact assessment report should, at a minimum, include the following elements:

- An introduction describing the scope of work, background, and objectives of the investigation.
- A detailed worksite description.
- Sampling procedures and laboratory analysis naming the corresponding reference methods.
- Field data, including visual and olfactory observations, and measurements of field parameters (e.g., temperature, relative humidity, moisture content, particle count) collected during the investigation. A sample field form may be included in the appendix.
- A summary of the investigative and laboratory findings and their basis and relevance to the investigation.
- Conclusions and recommendations based on established industry guidelines and best practices.
- Study limitations, complexities, complications, confounding factors, and uncertainties.
- Appendices, including relevant photographs, laboratory reports, chain-of-custodies, and layout drawings marking sampling locations, if applicable.
- A Restoration Specifications appendix, if applicable to the scope of work.
- An appendix cover sheet listing other documentation relevant to the project preceding the section.

If the investigation objectives encompassed an exposure assessment after a wildfire, the following elements should be incorporated into the report:

- Identification of potential hazards.
- Exposure assessment monitoring data.
- Summary of findings.
- Comparison to established exposure levels.
- Conclusions and recommendations for control measures.
- A list of action items and suggested timelines(this may be appropriate if the report is intended for follow-up and verification by other parties).

3 Sampling

THIS CHAPTER DESCRIBES two instances where sampling may be performed as part of a wildfire investigation: impact assessment and post-restoration verification. In a wildfire or structure fire, forensic investigation sample collection typically has two related goals. The first goal is to determine whether the particle types or concentrations, or the ratio of combustion-generated residues, indicate an atypical impact above background. If analysis shows that the particles in residues are greater than background, the second goal comes into play: to determine whether the impact defined by the assemblage of particles found is more likely to be associated with a specific fire event or with a site-specific background condition identified by the OEHS professional.

The project goal must consider time and distance from the wildfire event when selecting sampling methods. For structures located in the burn zone or wildland-urban interface (WUI), the sampling goals may focus on infiltration pathways, penetration, impact, and potential for corrosive and hazardous materials found in the particulate fraction (e.g., char, ash, soot, and firestorm residue) and from gas-phase chemical penetration and adsorption. Heat impact and potential pressurization into interstitial spaces may also become an important consideration in the burn zone or in structures subjected to firestorm winds in the near-field zone. Sampling and laboratory analysis methods in the far field of the WUI may require additional forensic procedures that address both the impact and origin differentiating fire event-related impact from background combustion sources.

3.1. Sampling Strategies

A well-designed sampling and analysis strategy is essential for providing data that enable a trained OEHS professional to test a hypothesis. A sampling objective may be to test a primary hypothesis intended to confirm or discount the presence of combustion-generated particulate matter accumulation. Another sampling objective may be to test a second hypothesis to confirm whether particle accumulation and associated organic compounds or metals were generated by a wildfire in a nearby wildland or were due to a different combustion source. A third hypothesis may be to determine whether the accumulation is at levels above background or a recognized health-based exposure level.

Considerations for hypothesis testing include determining the types, locations, and number of samples to collect and whether the decision analysis will utilize statistical hypothesis testing methods or nonstatistical qualitative weight-of-evidence methods based on professional judgment and experience. The OEHS professional must consider the size of the subject property, points of entry, and layout of the structure when developing hypotheses to confirm or deny the presence of combustion products or associated volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), dioxins, furans, or metals.

In forensic investigations, sampling may be recommended when the qualitative data collection and visual inspection are inconclusive or when a more quantitative evaluation of the property's condition is required or requested. Sampling is necessary for exposure assessments to identify potential health risk. The value of sample data is entirely dependent on the quality and reliability of the collection method and sampling procedure used.

OEHS professionals should conduct a thorough wildfire impact assessment before declaring that a building is impacted by wildfire.

3.2. Sampling Plan

The sampling plan implements the goals and objectives of the sampling strategy. It ensures that the data obtained in both volume and quality are sufficient to test the stated hypothesis of the investigation. The sampling plan describes the number of samples, sample locations, sampling time, and collection and handling procedures. The plan specifies the standardized analytical methods to be used and a laboratory that can produce limits of quantitation or reporting limits below the target exposure limits. The statistical analysis, data quality objectives, and quality assurance procedures to support evidence-based conclusions are part of the sampling plan. Resources to help OEHS professionals prepare and execute a sampling plan are available from AIHA, OSHA, NIOSH, and the U.S. EPA and included in the reference section (Anna, 2011; NIOSH, 1994; OSHA, 1999; U.S. EPA, 2025e). AIHA's *A Strategy for Assessing and Managing Occupational Exposures*, 4th edition (Jahn et al., 2015) has an excellent section on data quality.

Before beginning sampling operations, the OEHS professional must know what type of materials they are sampling for and why, as this will make a large difference in the selection of sampling techniques, media, and laboratory analysis.

The OEHS professional should collect a sufficient number of samples to support the purpose of the investigation and establish an accurate representation of the conditions in the building. For surface samples, a sampling plan should be representative of sampling zones, identified by functional spaces or areas where the accumulation of particles and combustion products exist or is suspected. Various types of materials, such as hard horizontal surfaces; porous materials; fabrics; curtains; carpet; and heating, ventilation, and air conditioning (HVAC) filters, can also be factored into the identification of a sampling zone to help document wildfire debris impact. It may also be necessary to sample locations where wildfire impact is not present for comparative purposes.

When necessary, exterior surface sampling may be useful for establishing the presence of wildfire impact. This is most likely to occur in close proximity to the burn zone and near-field distance. In this case, the locations sampled should be representative of where the impact may have occurred or where infiltration and pressurization into the indoor environment through penetrations leading to confined or interstitial spaces would most likely occur. Examples of these locations can include exterior windowsills or ledges, covered porch areas, attic spaces near vents, HVAC and other openings, or other surfaces. Outdoor surfaces protected from moisture may generally be more suitable for retaining evidence of impact. Surfaces protected from the weather, such as a porch or awning, may be good locations for sampling. Depending on the specific hypothesis tested, exterior surface sampling would therefore be one or more of the sampling zones in the sampling plan.

Indoor sample locations should address the gradient and extent of potential impact from points of entry to interior areas, including the potential for infiltration and airflow from attics and crawlspaces, where relevant. Any impact identified can then be used to determine the scope of restoration attributable to the particular fire.

In WUI fires, mixed-burn zones, or near-field locations where nearby structures are significantly impacted or consumed by wildfire, the sampling plan should consider the potential for the impact from additional combustion products that may have a different or similar composition than wildfire smoke.

After consultation with the laboratory, the OEHS professional should request the type of analysis that meets the objectives of the investigation.

3.3. Sampling Techniques

Sampling and laboratory analyses are key to assessing environmental quality, determining potential wildfire-related combustion residue impact, and identifying potential health risk.

The particles of greatest interest are usually the products of incomplete combustion of plant matter resulting from a wildfire (to include anthropogenic materials such as timber from burned structures) and are defined and classified as char, ash, and soot. These are used as surrogates for the quantitative and qualitative impact and chemistry transformations occurring in the combustion process.

Sampling for VOCs and SVOCs is essential in post-wildfire exposure assessment investigations to evaluate potential health risk. Particle sampling and analysis for forensic evaluations complements the exposure assessment by providing data to identify possible sources and reservoirs of SVOCs in the home or building.

3.4. Sampling Methods and Media

A primary concern in assessing and choosing a sampling and analytical method is that the method must be efficient and effective at collecting a representative sample of the analytes of interest. The method must have the appropriate limit of quantitation for meaningful interpretation to allow for comparing the results to health-based criteria.

Sampling for combustion particulate should consider both the potential source and the point or points of accumulation. Samples that represent exposure history are an important aspect of sampling representative particles. Cleaning the environment prior to sampling may remove these particles. Therefore, it is often helpful to conduct sampling representative of uncleaned areas or surfaces representing longer-term accumulation of particles at the site to provide a historical perspective.

Particles settled on surfaces are a critical part of the sampling plan. Factors affecting the sampling design include collection efficiency, collection efficacy, medium suitable for analysis, point sources, and representation of particulate deposition as an indicator of potential exposure (Crutcher et al., 2007).

Surface sampling techniques are intended to collect materials so that they may be accurately identified, categorized, and quantified. The sampling technique should be matched to the intended application, such as testing for asbestos, lead, combustion products, SVOCs, or any number of materials.

There are several main types of sampling techniques and media used in settled dust sampling for combustion products. These include tape lifts, dry and wet wipes, micro-vacuum, and bulk sampling. NIOSH has developed detailed guidance on different types of surface sampling methods (Broadwater et al., 2022).

Tape lift sampling is appropriate for surfaces containing particulate material that requires both morphological and positional data for interpretation. This technique is suitable for the identification of individual particles. The sampling retains both morphology and positional data without altering the individual particles. A disadvantage is the relatively small area sampled, as the tape is pressed to the surface only once. At the time of writing, there were several different laboratory procedures requiring different types of tape (e.g., matte, gloss surface). Organizations such as ASTM International have parallel tape lift sampling methods: D7910 for surface fungal material (ASTM 2014b) and E1216 for general particulate (ASTM, 2016). Consult the laboratory for sampling requirements for specific investigations.

Dry wipe sampling is generally used for presumptive testing such as testing for soot. Because many materials have the same morphology and color, further confirmatory testing is required. Dry wipes are also an inefficient collection medium, meaning that quantitation is not possible. In addition, positional data are lost on collection, and individual particles may be altered by the mechanical action of the collection.

Wet wipe sampling is an extremely valuable technique for the collection of materials that can be quantified by laboratory analysis when the sample area is known. Specific marked and measured surface areas must be sampled as the area is a part of the quantitation (e.g., micrograms/square inch). The sampling medium and all the material it has collected are processed in a manner that extracts all of the intended analyte into solution. The technique is not ideal for analysis of particulate populations involving particle identification, as the collected analyte(s) are usually altered by the sampling and subsequent sample processing. Most wipes on the market used for combustion product testing are 70% isopropyl alcohol and 30% water. This creates solubility issues for both polar and nonpolar soluble materials, making them incompatible with particulate sampling. This method is ideal for metals like lead, for which standardized methods of sample collection, laboratory analysis, and interpretation guidance are available.

Micro-vacuum sampling uses a filter cartridge to collect samples using a vacuum pump. This technique is useful for difficult-to-reach sampling areas or non-smooth surfaces, such as carpets. Although the technique is useful, its utility is limited due to both the inefficiency of the sampler on an unknown surface and the amount of sample that may be collected, which may range from none to several grams. Thus, sampling may provide adequate qualitative characterization but is only semi-quantitative.

Collecting bulk samples has the same constraints on quantitation that apply to micro-vacuum sampling. Bulk sampling is a very effective method for collecting exemplars of a known surface or material for comparison with samples from unknown surfaces. However, it is not effective for quantification purposes.

For microscopical analysis, tape lifts are reported in units of visual area estimation percentage (VAE ratio %) or counts per square millimeter (cts/mm^2). Wipes, micro-vacuums, and bulk samples for microscopical analysis can only be reported as estimates of VAE ratio %.

3.4.1. Tape Lifts

A tape lift sample uses adhesive tape to collect settled dust. Tape lifts have proven to be an effective sampling method for collecting particles from surfaces with typical dust loading. Tape lift samples are preferred for evaluating char, ash, soot, and other signature particles—the primary indicators of wildfire debris impact. The tape lift technique acts as a "fingerprint" by preserving the relative position, density, size, and shape of all the particles on the original surface as well as the population per unit area.

The type of tape (clear or frosted) and tape size are functions of the analytical method used and laboratory preference. Other suitable tape sampling methods are available, and new ones are coming into the market. The essential elements of appropriate tape lift media are high-quality cellophane tape that allows light microscopy analysis; samples that can be individually collected and stored; the elimination of cross-contamination; and a sample that does not degrade under the use of refractive index oils or stains. It is critical to consult with the laboratory for media preferences and sample storage and delivery requirements before sampling.

Sample collection begins the same way for all types of adhesive tapes. The tape is pulled free from its storage position, placed on the surface to be sampled, then affixed to a transport carrier that minimizes contamination (e.g., a clean plastic bag, microscope slide, etc.). The tape lift should not be affixed to paper products or nontransparent surfaces. Also, the tape lift must be placed flat on the surface (i.e., not folded over). The transport container is labeled with the information required, as detailed in the sampling and analysis plan. This often includes the sample position, date and time, and the sampler's initials or name. Further sampling details can be found in ASTM International standards D7910-14 (ASTM, 2014b), E1216-11 (ASTM, 2016), and IESO/RIA 6001 (2012).

If the tape is removed from its storage position too rapidly, it can build a static charge due to tribostatic (friction charging) differences between the adhesive and the surface from which it is being pulled (Crutcher et al., 2007). This static charge can collect particles from the air, hand, clothing, or surface to be sampled, and it can draw particles from the edge of the roll of tape onto the main body of the adhesive. When using rolls of tape, a good precaution is to start by cleaning the edges of tape before beginning to collect samples. To do so, simply pull off some of the tape and use it to clean the edges of the roll of tape or outer carrier. Once that is done, pull the tape gently from its storage surface or roll to minimize the generation of static electricity and apply the tape to the surface to be sampled.

Light pressure—only enough to affix the tape briefly to the surface—is required. Any overapplication of pressure or successive sampling using the same tape on multiple surfaces (composite method) can obscure or damage the char and ash particles, overload the tape surface, or remove material from the sampled substrate.

Advantages of tape lift sampling include:

- Good collection efficiency for particles with typical dust loading.
- Defined sample area for analysis.
- Particle integrity maintained during collection.
- Minimum preparation.
- Little to no damage to captured particles.
- Variety of light microscopy methods available, including standard light microscopy; transmitted light (brightfield, darkfield, oblique, linear polarized, circular polarized, crossed linear polarized, crossed circular polarized, off-crossed polarized, and other optical crystallographic methods); and reflected light (darkfield is critical for the analysis of combustion products in environmental samples), including epifluorescence, polarized reflected or transmitted light analysis, and Raman spectroscopy.
- Allows for direct analysis using chemical microscopy, micro-laser emission spectroscopy, and scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDS or EDX) after coating, as well as elemental analysis.

Disadvantages of tape lift-sampling include:

- Limited sampling area per tape lift compared to other media types.
- Rough surface finishes result in low removal efficiencies.
- Large agglomerations and heavy dust accumulations may not be correctly identified due to particle overlapping.
- Some analytical techniques are limited due to the fixed refractive index medium (adhesive).
- Analyzing the edge of the tape is not recommended to limit effects from handling.

3.4.2. Wipes

Wipe sampling is one of the primary sampling methods to be used for the chemical analysis of organic compounds associated with the wildfire deposits. Because of the inherent disruption of particulate matter in terms of location relative to the original surface sampled, poor collection efficiency for small particles, and the morphological changes to the particulate matter, the sampling of particles using a wipe is less reliable than tape lift samples. Wipes typically require removing the particles and transferring them from one media to another media during processing at a laboratory. These processes and the number of transferences can result in a loss of information, limiting the value of quantification.

Wet wiping is more efficient than dry wiping in removing and collecting particles on surfaces. That follows as a result of the reduction of electrostatic, Van der Waals, and capillary forces holding the particles on the surface.

Advantages of wet wipe sampling include:

- Established standardized sampling methods
- Able to sample relatively large areas (e.g., 100 cm^2).
- Efficient for relatively smooth, nonporous surfaces with heavy loading.
- Qualitative analysis can be performed using optical microscopy methods and electron microscopy.
- Quantitative analysis can be performed for metals.
- Chemical analysis of organic compounds associated with wildfire residues (e.g., lead, SVOCs, PAHs).

Disadvantages of wet wipe sampling include:

- Not appropriate for porous surfaces.
- Not quantitative for particle analysis due to unknown release efficiency from sampling media.
- Often results in physical separation of particles collected as agglomerates.
- Can leave traces of liquid agents behind, along with particles in the liquid agent.
- Liquid agents may degrade or solubilize the particles, introducing sampling bias.
- Alcohol can remove finishes (e.g., paint), affecting analytical results.
- Can induce some damage to brittle particles (i.e., change the appearance and detectability of fragile fire residue particles such as char and ash) and can result from particle dispersion preparation procedures and ultrasonication.
- Does not preserve relative positions of particles on original surface and the population per unit area.
- Limitation if agglomerate size and distribution over the collection surface is of interest.
- Limited references for health-based limit values.

3.4.3. Micro-Vacuuming

The techniques for collecting particles from surfaces discussed so far do so through the direct application of force. Vacuuming uses an indirect force. A vacuum creates a low-pressure area and draws air onto a particle-trapping device. This is less efficient than the methods described previously (Crutcher et al., 2007).

Advantages of micro-vacuum sampling include:

- Allows collection of bulk particle material, often of many different sizes.
- Easy preparation at a laboratory for a variety of analytical methods.
- Effective for collecting particles from porous and uneven surfaces with medium and heavy loading.
- Collects a larger sample volume than tape lifts.
- A variety of optical microcopy methods can be used in identification analysis similar to analysis of particles on tape lifts and wipes.
- SEM/EDX analysis for particle identification is easily applicable.
- Permits the confirmatory identification of soot by transmission electron microscopy (TEM) analysis, where soot is an analyte of interest.
- Permits the spectrometric and/or chromatographic extraction preparation of collected material.
- Allows for pH analysis.

Disadvantages of micro-vacuum sampling include:

- Ineffective for collecting particles under 45 µm from relatively smooth, nonporous surfaces with low loading.
- Does not preserve relative positions of particles on the original surface or population per unit area.
- Can induce damage to delicate structures or agglomerates such as char and ash.
- Inconsistent sample collection may result in misleading interpretation.

3.4.4. Bulk Sampling

Bulk sampling is the commonly used term for removing a piece or portion of a solid material, such as soil, concrete, wallboard, fabric, carpet, or insulation, for subsequent analysis. Grab, wipe, or micro-vacuum sampling are also types of bulk sampling, as they are indirect techniques where the sampled material is collected in its original substrate or onto a collection device or medium and transferred to a different medium for manipulation and analysis. These secondary sampling methods are suitable for microscopical or chemical analysis of particles, fibers, pH, inorganic cations and anions, VOCs, SVOCs, and metals. They are appropriate methods when it is not necessary to preserve and maintain the spatial integrity, original particle morphology, or relative depositional pattern of the sampled material in order to identify it, establish its origin, determine elemental composition, or perform numerical estimation or quantitation (ASTM, 2014a).

3.4.5. Organic Compound Sampling Methods

The location and specific conditions of the wildfire event result in wide variability in the composition and concentrations of wildfire residuals. Combustion produces most types of chemical compounds, including small reactive compounds (CO, CO_2, methane, NOx, etc.), simple hydrocarbons, aromatics, including polycyclic aromatic hydrocarbons (PAHs), furans, phenols, methoxyphenols, aldehydes, ketones, nitriles, etc. (Heitmann et al., 2009; Urbanski et al., 2009). Fuel type and amount, ambient temperature, relative humidity, atmospheric mixing, and other environmental conditions (Urbanski et al., 2009) vary too widely in wildfires to use only one chemical fire indicator. Also, many of the chemical compounds produced during the fire as well as through subsequent chemical reactions can be found in indoor environments. Therefore, a panel or assemblage of fire indicators that can account for fuel material, temperature, and other factors is the best mechanism to determine the presence of fire contaminants from the fire event.

Sampling and analyzing the airborne VOCs and SVOCs soon after a fire event (i.e., days to weeks) may help locate and characterize sources of wildfire residue odors and evaluate potential health hazards to occupants from exposure to wildfire residuals.

Organic compounds may not be in a form that is identifiable using optical or electron microscopy methods. However, they are readily identifiable using methods that require specific instrumentation, such as mass spectrometry.

Wipe sampling is an effective surface sampling method for analysis of SVOCs. The main advantage of this method is the ability to quantitate specific analytes to a high degree of accuracy and precision. For wipe sampling, specific areas are collected. The entire wipe is placed in solution of known volume and either fully digested or allowed to solubilize. The solution is then analyzed by the appropriate instrumentation (refer to Section 4.4.1: Organic Chemical Analysis Methods).

For micro-vacuum samples, a specific area is sampled. A 100 cm^2 template is standard. Larger areas may be needed to achieve the desired limit of quantitation. The material within the cassette is removed from the cassette and directly weighed. The particulate is then placed into solution for subsequent analysis by the appropriate instrumentation, similar to wet wipe methods. Note that this type of instrumental testing is usually for a specific analyte or class of analytes. For example, furans and dioxins must be sampled and analyzed separately. A single wipe generally cannot be used for analysis of more than a single class of materials.

Many VOCs and SVOCs change over time. Consult the laboratory for the proper sample container, sample holding time, and handling requirements (i.e., cool to <4°C). This potentially influences ultimate data interpretation. Similarly, potential losses during sample shipment due to relative humidity and temperature need to be considered.

Reporting units for organic compound analysis are nanograms per gram (ng/g) for bulk samples, nanograms per wipe (ng/wipe) when using the standard

100 cm^2 wipe or nanograms per square centimeter (ng/cm^2) for different size wipes, and either micrograms per cubic meter ($\mu g/m^3$) or nanograms per liter (ng/L) for air samples.

3.4.6. Metals Sampling Methods

Several sample types may be used to assess the presence of metals. These include micro-vacuum, bulk, and wipe sample types. Micro-vacuum sampling, which is best used for light dust loading surfaces, may be used to collect samples for metals analysis. However, some analytical methods require larger amounts of material, making bulk sampling a preferable collection method. Bulk sampling techniques can be used to sample surfaces for metals, such as arsenic, beryllium, cadmium, chromium, lead, and others that are transported and deposited with wildfire or mixed-burn area residues. Wipe media used to directly extract sample material from a surface are also best used for surfaces with relatively light dust loading. These media may include moistened paper towelettes, digestible polyvinyl alcohol wipes, or cellulose ester membrane filters treated with deionized water or dry. Reference methods include ASTM International Standard E1792 (ASTM, 2020) and *NIOSH Manual of Analytical Methods* (NMAM), 4th edition (NIOSH, 1994), using Method 9102 as a complement to NIOSH 7300 for analysis by inductively coupled argon plasma, atomic emission spectroscopy (ICP-AES). Metal analyses are reported in milligrams per cubic meter (mg/m^3) or micrograms per cubic meter ($\mu g/m^3$) for air samples and micrograms per square centimeter ($\mu g/cm^2$) for wipes. Solid samples, such as soil or bulk samples, are reported as milligrams per kilogram (mg/kg), which is equivalent to parts per million (ppm). Consult with the laboratory for the proper sample container, preservation requirements (i.e., nitric acid), holding times, and shipping requirements.

3.5. Real-Time Sampling and Detection Methods

Portable direct-reading instruments (PDRIs) are designed to provide real-time measurement of airborne particulate, gas, and vapor concentrations. They can be useful survey tools for source detection. The types of available field instruments include photoionization detectors (PIDs) and flame ionization detectors (FIDs) that can measure total VOC concentrations in air down to the ppb range. Additionally, Fourier-transform infrared (FTIR) detectors (are capable of detecting and measuring specific airborne gases and vapors at ppm to ppb concentrations.

Proton-transfer-reaction time-of-flight mass spectrometry (PTR-TOF-MS) is a real-time technology typically used in atmospheric air pollution research (Sekimoto et al., 2023) that has been used to measure gas and particle-phase VOCs in indoor air in homes affected by wildfire (Dresser et al., 2024). The instrument's size, weight, cost, and complex calibration and operating procedures places it out of range of most wildfire impact assessment applications at this time.

Particulate meters include optical particle counters (OPCs) measuring in the range of 0.3–10 μm, laser particle counters (LPCs), which are OPCs that use a laser beam for more precise measurements down to sub-micron size ranges, and condensation nuclei counters (CNCs) for ultrafine particles (UFPs) ranging from 0.002–1 μm. X-ray fluorescence (XRF) analyzers can identify and measure metal concentrations on surface and subsurface layers in the ppm range (Anna, 2011).

PDRIs that read real-time total VOC concentrations in air are valuable for initial screening in the preliminary investigation phase days to weeks after a fire event. They are useful to OEHS professionals during initial entry to a structure fire or building in the near-field zone of a WUI fire. PDRIs can help the OEHS professional assess whether airborne particulates, chemicals, or both are present at levels above occupational exposure limits or at concentrations considered immediately dangerous to life or health (IDLH) (Barsan, 2007). PDRI readings can help inform professionals about what type of personal protective equipment (PPE) may be necessary for safe entry. PDRIs are most useful shortly after the WUI fire to assess whether smoke from nearby burned buildings or vehicles has infiltrated into the subject structure.

The main advantage of PDRIs in all applications is that they do not require sampling media and laboratory sample analysis. These qualities translate into savings in the time and expense required to collect and ship the samples to the analytical laboratory and get results back to help make decisions on how to proceed with the investigation.

The main limitation of PDRIs for wildfire impact assessments is that LPCs, OPCs, and CNCs cannot identify specific particle types or distinguish between airborne particles of char, ash, and soot from the wildfire event and anthropogenic particles typically found in buildings. Direct-reading PIDs and FIDs that measure total VOCs are not able to identify specific compounds, determine the source, or apportion the results to a particular wildfire event. However, they could be used as a nonselective measure of cleaning effectiveness in post-restoration verification.

PDRI readings can be followed or complemented by more precise analytical laboratory methods to identify specific airborne contaminants. Applicable analytical methods for integrated samples are described in Section 4.4.1: Organic Chemical Analysis Methods.

Air sampling for VOCs and SVOCs has unique challenges due to the effects of dilution through ventilation, the amount of time these chemicals persist, the chemical reactions that they undergo, and the constantly changing nature of the air. PAHs condense into soot aerosols. Other SVOCs adsorb to particles and certain porous surface materials, such as fabrics, and, depending on the half-life of a particular compound, may be detected in trace amounts even months after the initial exposure.

VOCs and SVOCs are present at background levels from a variety of common sources found in the built environment (e.g., formaldehyde in laminates and manufactured framing materials, PAHs in diesel fuel, etc.). This makes their characterization relative to the actual source very difficult in post-fire investigations. Because of these complications, OEHS professionals sampling for VOCs and SVOCs must follow a carefully designed sampling plan and have specific goals or benchmarks to interpret the results.

Assessments of wildfire residue impacts can take place days, weeks, months, and even years after a wildfire has been extinguished and occupants reenter the building. Infiltrated gases, VOCs, and SVOCs potentially present in wildfire smoke become diluted through mechanical and natural ventilation, degraded by chemical reactions, or adsorbed onto interior surfaces (building materials, furnishings, clothing, drapes, settled dust, etc.). OEHS professionals should keep in mind that residual airborne concentrations of VOCs and SVOCs potentially associated with infiltrated wildfire residue may be below the detection limits of PDRIs or indistinguishable from background airborne concentrations typically found in buildings.

As with other applications of PDRIs, it is important to consider how the advantages of obtaining real-time monitoring results balance the limitations of PDRIs for wildfire impact assessment. As stated in the AIHA's *The Occupational Environment: Its Evaluation, Control and Management*, 3rd edition:

> ...direct-reading instruments all require the user to and conditions that can affect performance and calibration understand the limitations, and also to understand maintenance requirements and (interpretation of) results. Measurements of gases and vapors can be adversely affected by interferences from other contaminants; therefore, the occupational hygienist needs to be aware of the sampling environment before selecting an instrument (Anna, 2011).

The AIHA *Technical Framework: Guidance on Use of Direct Reading Instruments* (Bolstad-Johnson et al., 2022) provides excellent guidance on the appropriate use and challenges of PDRIs for OEHS professionals.

Important factors to consider when opting to use PDRIs include:

- The physical and chemical properties of the target wildfire residue;
- The persistence in the air of target compounds in wildfire-impacted buildings; and
- The PDRI's target compound detection limits.
- Important limitations of PDRIs to consider include:
- All PDRIs are subject to false positives, false negatives, and positive-negative biases;
- The accuracy and reliability of PDRIs for detecting and measuring only the target wildfire residue without other potential interferences;
- Typical background concentrations of target airborne particulates, VOCs, and SVOCs commonly found in buildings that can also be found in wildfire residue; and
- Potential PDRI interferences by other airborne substances commonly found in background concentrations in buildings, which can cause false-positive, false-negative, positive, and negative biases in target wildfire residue readings.

Careful consideration must be used in evaluating PDRI data for reliability before reaching conclusions on the existence and extent of wildfire impacts. OEHS professionals should conduct confirmatory integrated industrial hygiene air sampling for any significantly elevated PDRI air monitoring results. Any comparison of a PDRI reading to a health-based exposure limit should account for the exposure scenario, exposed population, basis for the limit, representativeness of the monitoring data, and confounding factors.

3.6. Post-Restoration Evaluation

The restorer typically performs the post-restoration evaluation (PRE), with participation from the client, owner, or other interested parties to determine if the structure and contents encompassed in the restoration work plan have been returned as close as possible to a background condition. The process documents that the restoration was performed according to current industry standards and meets the criteria of acceptability established in the contract. A third-party with demonstrated competence in restoration may conduct the evaluation in cases when there is disagreement between the parties or to resolve a particular concern. The evaluation involves visual inspection, in-field evaluation, and smoke odor detection in all interior and exterior areas of the structure as well as for contents that underwent cleaning or restoration. If visual and olfactory evaluations are accepted by all parties, wildfire smoke residues may be deemed restored based on visual and olfactory criteria. The PRE does not include sampling for quantitative laboratory analysis.

3.7. Post-Restoration Verification

Although not required by law, code, or statute, post-restoration verification (PRV) of the effectiveness of cleaning or restoration is an established best practice followed in other evaluations of remedial effectiveness such as mold (Hung et al., 2020). The property owner, affected party, or insurance carrier may also request it. In wildfire and WUI fire impact cases, an optional PRV may be performed following the PRE to determine whether the concentrations of wildfire-associated residues have been reduced to background levels or are still elevated and require further restoration. The PRV may be recommended when the parties do not agree with the PRE findings.

A PRV should be conducted for restorations performed following exposure assessments to confirm that the identified exposures have been controlled to within preestablished acceptable health risk tolerance. The PRV should be performed by an independent third-party OEHS professional. The PRV involves similar steps as the PRE, plus collection of representative samples for laboratory analysis. The methods for quantitative PRVs are the same as those applied in the assessment phase to characterize the level of impact or exposure. Criteria for interpretation of quantitative laboratory data may involve comparing the PRV sample results to the initial impact assessment tests, preestablished restoration acceptance criteria, established guidelines of background levels, or recognized health-based exposure levels (in the case of exposure assessments).

PRV or clearance should include the following activities:

1. Review and verify that the restoration scope of work, estimates, and/or work plan were implemented and that all proposed work has been completed.
2. Verify the efficacy of cleaning/restoration activities. Conduct a visual inspection of the structure, HVAC systems, and contents for evidence of fire impact, staining, and noticeable odors. No stains, sealers, or encapsulants should be applied to building materials that may prevent thorough visual inspection and surface testing. If appropriate, they should be applied after the visual inspection to verify that the cleaning is effective.
3. Systematically inspect all accessible surfaces to verify that there are no smoke stains or dust accumulations on surfaces that should have been cleaned.
4. Close all doors in restored areas and evaluate odors in one space at a time with the HVAC off. Repeat with HVAC on.
5. Use white glove test on representative surfaces to verify wildfire residue removal
6. Perform a qualitative odor test of the area or material for residual wildfire smoke. There should be a consensus agreement that no noticeable odors beyond those associated with the evaluated materials are detected.
7. Perform surface sampling following the appropriate method(s) described in the initial assessment phase.
8. Conduct data interpretation analysis of quantitative laboratory data to confirm clearance criteria have been met.
9. Reclean items and areas where inspection and testing results reveal deficiencies
10. Conduct a subsequent round of PRV if required to meet restoration acceptance criteria.
11. Note that infiltration and tracking of outdoor wildfire residues into the occupied spaces due to occupant activities that occur after cleaning or restoration may cause odors or result in exceeding the restoration acceptance criteria.

Microscopical and Analytical Chemical Methods

4

4.1. Overview

As WITH THE SELECTION OF SAMPLING METHODS, the OEHS professional needs to select the appropriate analytical laboratory to perform forensic microscopy or analytical chemistry. Both particle and chemical fire residues are too complex to measure in their entirety. Therefore, suitable surrogates must be selected to support the project scope, which typically encompasses physical impact on structures, potential health risk of occupants, or both.

These laboratories must be capable of performing the appropriate analysis to test the desired hypothesis. This includes conducting forensic source and particle pathway identification using optical microscopy as well as organic and inorganic analyte testing for exposure assessment. The OEHS professional should also ensure the sampling methods used are compatible with the required analysis method.

Forensic analysis methods involving the origin, cause, and spread of the fire event may not be adequately defined by existing ASTM, U.S. EPA, NIOSH, or other analytical methods, which were originally designed for exposure assessment purposes. Standardized testing methods or accreditation programs do not encompass the full scope of these specific forensic laboratory requirements. In many cases, the existing methods may require modifications. The laboratory should be able to provide internal standard operating procedures (SOPs) specifically written for these particular purposes. By consensus, the Technical Guide authors developed a suggested analysis method framework for wildfire particulates , which is provided in Table 4.1 and Figure 4.6 (in SECTION 4.2.4). The guidelines are consistent with industry-accepted method formats for all analytical methods. They also provide minimum requirements for the laboratory to develop and use an internal laboratory SOP and test method.

The methods to be used include both primary and secondary methods. Primary methods are established consensus procedures relied on to provide both qualitative and quantitative impact evaluation and origin determination. Secondary methods are additional procedures that can be implemented to provide specific additional particulate, chemical, and elemental data to help resolve interferences. They may also be used in instances where the primary method(s) provides incomplete or inconclusive data for a specific investigative goal. Secondary methods may be based on experiential or experimental data, unpublished or in-house methods, or modification of an established method. Any deviation from a standard test method should be noted, and the OEHS professional should understand the deviation on the reported results.

4.2. Optical Microscopy

Optical microscopy is the primary method used to identify and quantify the surface impact from wildfire combustion residues. Optical microscopy of tape lift samples is used to address infiltration, pathway penetration, gas-phase particle deposition, and settling. The resulting particle assemblage is then used to help differentiate a wildfire-related impact from background sources. An advantage of light microscopy is that many thousands of particles can be quickly scanned, the combustion particles isolated and identified, and the source often characterized by the assemblage of identified particles. Optical microscopy can be used as a screening or surrogate method to determine if other chemical organic and inorganic testing and analytical methods may be required.

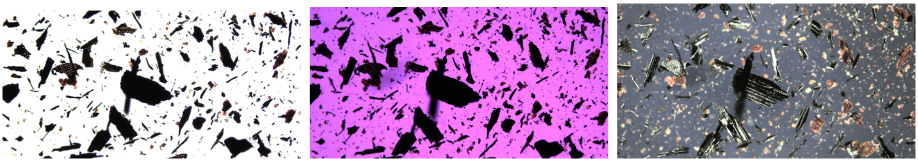
4.2.1. Optical Microscopy Transmitted and Reflected Light Illumination Method Requirements

Particle combustion residues carry the signature of the fuels consumed. Many of these products are opaque and characterized optically by their reflectivity and morphology using reflected light darkfield illumination. Some are transparent, optically active, and have characteristic morphology. Initial examination by low-magnification reflected light microscopy (50–100×) is first performed to help define and report the macroscopic texture and color of the sample. It is also used initially to determine the absence or presence of large fire residue particles and deposition patterns observed in the sample (char, suspect ash, or uniformly deposited soot clusters).

The high magnification (50–500×) quantitative portion of the light microscopy analysis is performed by examining each field of particles using both reflected and transmitted light illumination sources, specifically using brightfield, polarized light, and darkfield reflected illumination as a minimum capability. Differentiating between the optically "opaque" vegetative combustion char, decayed biomass, and other opaque debris such as commonly encountered corrosion particles (e.g., galvanized metals, iron oxide) within the same microscopic field of view requires both confirmation and quantification by the use of reflected light darkfield illumination. This minimum instrumental requirement to simultaneously differentiate between optically opaque "burned" particles and the most commonly encountered opaque environmental particles is illustrated in Figures 4.1 to 4.4.

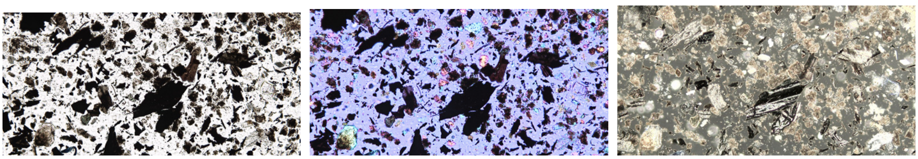
4.2.2. Optical Microscopy: Analysis of Char, Ash, Soot, and Fire-Indicator Signature Particles

The comprehensive analysis of wildfire particles encompassing the identification, origin, and distribution of indicator signature particles is best achieved by preserving the spatial distribution of settled particles using tape lift sampling for direct microscopical analysis. Indirect procedures such as wipes, solvents, and ultrasonication should be avoided where possible. Pyrolyzed vegetation char is



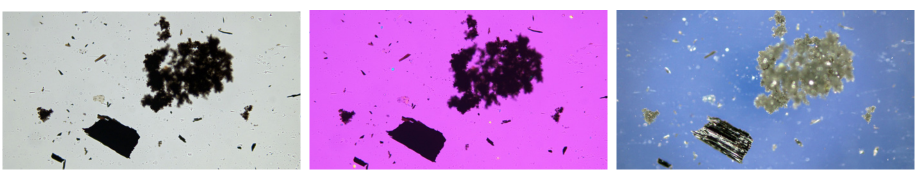
(A) Transmitted light brightfield (B) Transmitted polarized light (C) Reflected light darkfield

Figure 4.1: Mixed iron oxide corrosion particles and wildfire char. Images provided by Environmental Analysis Associates shown in (A) transmitted light brightfield, (B) polarized light with a full wave plate inserted, and (C) reflected light darkfield (RLDF) illumination in refractive index oil 1.550. For a reference point, the particles in the center are vegetation char particles and the orange iron oxide corrosion particles can only be differentiated in the RLDF illumination mode. Note the shiny black "reflective" surface of the char particles is visible in RLDF. All micrographs were collected at approximately 200×.



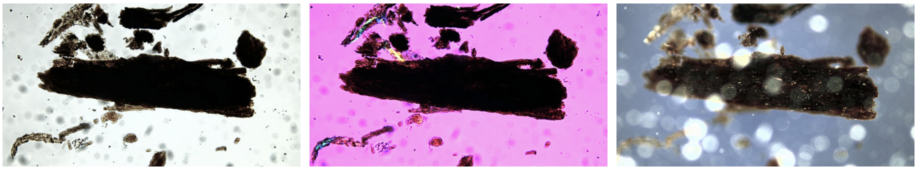
(A) Transmitted light brightfield (B) Transmitted polarized light (C) Reflected light darkfield

Figure 4.2: Mixed galvanized HVAC duct corrosion particles and wildfire char. Images provided by Environmental Analysis Associates shown in (A) transmitted light bright field, (B) polarized light with a full wave plate inserted, and (C) reflected light dark field illumination in refractive index oil 1.550. For a reference point, the large particles in the center of the micrograph are vegetation char. Galvanized metal particles (aluminum and zinc oxide) are the primary background particles and are highly reflective, showing a white-silver to light yellow-orange color in contrast to the shiny black and "reflective" surface of the char particles in reflected light darkfield. All micrographs were collected at approximately 200×.



(A) Transmitted light brightfield (B) Transmitted polarized light (full wave plate) (C) Reflected light darkfield

Figure 4.3: Mixed tire wear rubber and wildfire twig/leaf char. Images provided by Environmental Analysis Associates shown in (A) transmitted light brightfield, (B) polarized light with a full wave plate inserted, and (C) reflected light dark field illumination in refractive index oil 1.550. The reflective color of the silica matrix in the tire rubber allows immediate differentiation in reflected light (darkfield) illumination. The micrographs were collected at approximately 200×.



(A) Transmitted light brightfield (B) Transmitted polarized light (C) Reflected light darkfield

Figure 4.4: Decayed vegetation particle in Miracle Gro® potting soil Images provided by Environmental Analysis Associates shown in (A) transmitted light brightfield, (B) transmitted polarized light with a full wave plate inserted, and (C) reflected light darkfield illumination in refractive index oil 1.550. Decayed vegetation biomass is differentiated from "burned" vegetation by its absence of reflectivity observed in reflected light darkfield. All micrographs were collected at approximately 400×.

identified by its surface morphology, fracture pattern, light reflectivity, and color using optical microscopy with reflected light darkfield illumination as described in SECTION 4.2.1. These parameters are all required to differentiate burned vegetation char particles from decayed biomass and other lookalike opaque particles, primarily corrosion. Long experience among professional microscopists indicates that supervised practical microscopy training on the minimum microscopy requirements described in this chapter enables analysts to easily distinguish char from other classes of particles. Although char is brittle and will easily fracture, it is more robust than ash and will not degrade at the same rate. It does not solubilize in water, alcohol, or standard microscopy mounting media. The presence of larger and intact char particles may also help determine the vegetation source. The presence or absence of ash when char is detected and initially examined dry may also assist in determining the origin of detected combustion particles.

Ash particles can appear similar to other types of mineral debris and are strongly affected by sampling methods and sample preparation techniques. Ash particles can be broken up when sampling methods that require the transfer of particles from one media to another (e.g., bulk, wipe, liquid transfer, and especially the use of ultrasonication) are used. These procedures may partially dissolve and disassociate ash in stains, water, alcohol, and refractive index oils. When prepared dry, the range of ash particles can be differentiated by chemistry (EDX) and micro-texture observable using scanning electron microscopy (SEM) at magnifications above approximately (~)2000×. Because these particles (primarily sodium, magnesium, potassium, and calcium salts) are very fragile and soluble, the use of dry mounting procedures for examination by scanning or transmission electron microscopy (SEM/TEM) is required. SEM is the preferred method for this examination because dry tape lifts (or bulk samples transferred to adhesive mounts) can be placed directly into the SEM without any alteration to the particles through the use of water or solvents. This allows for the rapid analysis of a wide size range of indicator particles (0.5–1,000 µm), including plant phytoliths, char, and other ash particles, without altering their actual morphology, particle size, or chemistry. Microchemical techniques may also be used to determine the pH of individual particle clusters as small as 50 µm. The high pH of ash particles (~9–12) may be used as a test for the potential presence of soluble wildfire ash-related chemistry (primarily potassium hydroxide).

Wildfire debris contains minimal soot. Soot is more important for residential and industrial fires, depending on the fuel. Although the most common soot agglomerates and the fingerprint pattern associated with fires are easily visualized using optical microscopy at magnifications of 100–400×, sub-micron-sized, grape cluster-shaped soot-like particles cannot routinely be identified or quantified. Additional electron microscopy analysis may be warranted and helpful in determining the chemistry of soot clusters or fine individual combustion particles when their composition is part of the goal or scope of investigation.

4.2.3. Optical Microscopy: Assemblage Analysis

One method or procedure used in source identification of combustion particles is assemblage analysis, a centuries-old process that is widely applied in many disciplines where the purpose of the investigation is to identify the source of a material. For combustion particles, assemblage analysis is based on the distribution of contextual indicator particles, which are defined as a group of objects or features that in combination establish a fact or context not established by any individual feature or object. Fire events create their own specific assemblages of combustion particles that indicate the source of those particles. For example, in the case of a wildfire, the assemblage consists of charred wood/plant indigenous to the area where the fire took place, fire retardant, carbon/soot-coated quartz or mineral grains, burned or heat-altered clay minerals from the soil, and pyrolyzed calcium oxalate or silica phytoliths from the bark and leaves of the various plants and trees (Bodí et al., 2010; Crutcher and Crutcher, 2020; Horn and Underwood, 2014; Paulssen, 1964; Piperno, 2006). Assemblage analysis will detect the characteristic particle signature and unique assemblage of particles created by a specific fire event (Crutcher et al., 2007, Kovar et al., 2016). Examples of common indicator or signature particles that can form an assemblage are shown in Figure 4.5.

This method of quantification is independent of the other particles in the background. A surface that was cleaned just before the combustion product exposure and one not cleaned for some time before the exposure would show the same impact of exposure. Similarly, a surface contaminated after the wildfire residue exposure by some unrelated activity will show the same exposure as another surface that is not contaminated. This method is not based on estimated percentage coverage; it is based simply on the recognition of a few different particle types in a field of view or in a scan across a tape lift sample.

Familiarity with unique wildfire assemblage particles is critical in performing a complete analysis of indoor impact associated with wildfire residue. The wildfire assemblage is typically very different from that of a fireplace, backyard firepit, or other relatively controlled fires. Microscopic features of common indoor particulate matter and environmentally generated combustion particles are distinctly different than wildfire-generated particulate matter. Assessment of the impact of wildfire residue on settled surfaces indoors is diluted by normal buildup over time.

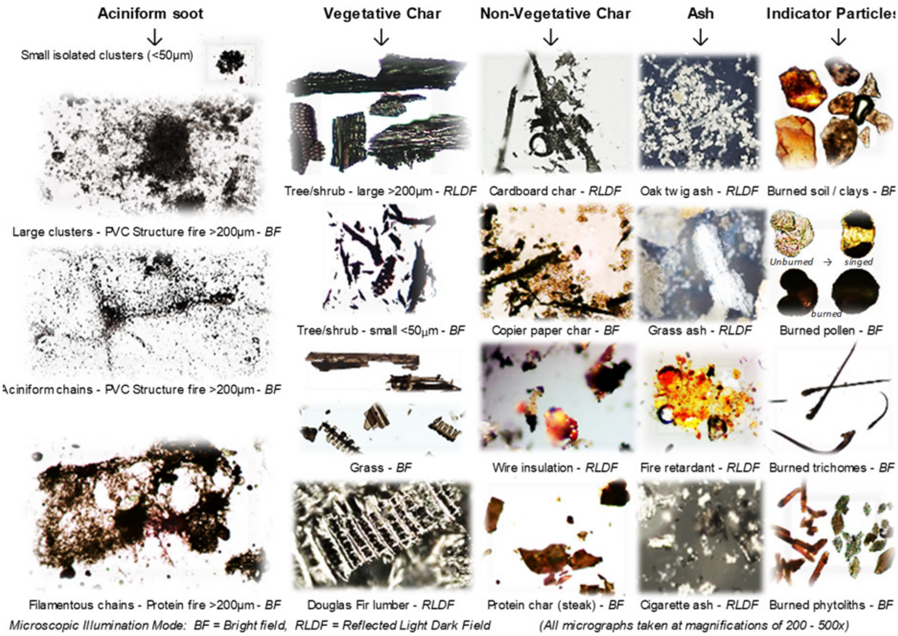


Figure 4.5: Examples of common wildfire and structure fire particles using optical microscopy. [Images provided by Environmental Analysis Associates].

4.2.4. Optical Microscopy: Quantitative Analysis Procedures

Currently, there are no available standards or directly applicable accreditations for the quantification of fire/combustion particles using microscopy methods. However, there is extensive literature going back more than a century showing the use of microscopy methods in forensic, archeological, anthracological (the study of extant charcoal fire remains), and micropaleontological investigations. Because the composition of burned vegetation results in a wide variety of residues and particle assemblages, a simple quantitative analysis is not always an accurate representation of impact, composition, and source alone. To understand or interpret the microscopical results requires a multiparameter approach to the varied assemblage of quantifiable properties.

Two approaches are typically used for quantification of combustion particles: numerical or percent ratio analysis by visual area estimation (VAE) ratio analysis and surface concentration per unit area in counts per square millimeter (cts/mm^2). The term "percent ratio analysis" is used to be inclusive for all counting methods, including numerical particle ratio counting and "point" counting. Numerical and percent ratio calculations by default are a ratio analysis method that compares the percentages of fire residue particles to other dust in the sample. The surface

Table 4.1: Summary Method Guidelines for Optical Microscopy Analysis of Combustion Particle Emissions Gvenerated from Wildfires, Controlled Burns, and Structure Fires

Overview: The summary guidelines described in this table provide a brief outline of the industry-accepted format and content required for a forensic combustion particle analysis method specific to wildfires, controlled burns, and structure fires. The framework is based on ASTM, OSHA, EPA, and ISO/IEC 17025 standard method requirements and addresses the current lack of industry-accepted published test methods. The guidelines provide minimum requirements for an internal laboratory standard operating procedure (SOP) and test method to be developed and used by the laboratory.	
Scope	Define sampling and testing for distinguishing combustion-related emissions (soot, char, ash, and fire-event indicator particles) from decayed biomass, corrosion, and other combustion particle interferences. The methodology also covers the quantitative and qualitative analysis using visual area estimation (VAE) ratio %, surface deposition density (counts per unit area), and source and fire origin of combustion particles.
Reference Documents	Provide reference methods and publications directly applicable to the specific analysis of wildfires, controlled burns, and structure fires.
Terminology	Provide precise definitions, terminology, and metrics specific to soot, char, ash, and indicator particles from fires (wildfires, controlled burns, and structure fires).
Summary of Practice	Provide light microscopy practices specific to identifying the classes of combustion particle residues consistent or inconsistent with the different types of fire sources.
Significance and Use	Specify the significance and application of the procedures in the method to distinguish and quantify char, ash, and soot from decayed biomass and other environmental particles. This section should also address the usefulness and forensic approach to differentiate fire event-related combustion particles from other anthropogenic sources.

density concentration (cts/mm^2) procedure for quantifying fire combustion particles is independent of other accumulated dust particle concentrations. This method can only be performed from tape lift or filter samples where the sampled surface area is known and a known area of the sampled media is analyzed. This procedure can provide a more representative assessment of combustion particle concentrations when the background dust levels are very high, very low, or contain a significantly dissimilar particle size distribution.

The suggestions for quantitative analysis do not directly address the reporting of assemblage particles that may be critical to determining the potential source of the fire. It is suggested that the presence and/or absence of assemblage particles (i.e., plant phytoliths, carbon/soot-coated quartz or mineral grains, burned or

Table 4.1: Summary Method Guidelines for Optical Microscopy Analysis of Combustion Particle Emissions Generated from Wildfires, Controlled Burns, and Structure Fires (*Continued*)

Sampling Methods	Provide precise descriptions of the sampling methods and media and areas representative of impact areas or test zones to be sampled. Define the primary and secondary collection techniques: sticky tape and vacuum dust cassettes or bulk dust scrapings, respectively.
Summary Light Microscopy Examination Method	Provide an outline of the light microscopy analysis method using the simultaneous application of both transmitted light and reflected light (darkfield) illumination. A flow diagram illustrating the suggested analysis steps used by the laboratory is provided in Figure 4.6.
Analytical Procedures, Calibration, and Calculations	Provide detailed descriptions of the appropriate sampling media, collection, preparation, and microscopical analysis method. Also describe the calculations and use of different metrics provided (e.g., VAE ratio % numerical particle density or counts per area of the tape analyzed).
Report	The report should consist of chain-of-custody records, observations, quantitative results, and statistical reporting parameters that would satisfy an industry-accepted certificate of analysis as defined by ISO/IEC 17025 guidelines.

heat-altered clay minerals from the soil, fire retardant, etc.) should also be systematically quantified in the analysis report. Additionally, their frequency of detection and concentration should be considered as part of the impact evaluation.

In the absence of an existing standard light microscopy method specific to wildfires and structure fires, Table 4.1 and Figure 4.6 present the information from this chapter in a suggested analysis method framework. This suggested approach follows industry-accepted method formats (e.g., ASTM, OSHA, EPA, ISO/IEC 17025) for all analytical methods. These guidelines are provided as a basis for the OEHS professional to understand basic microscopy laboratory requirements for forensic combustion particle analysis and for the laboratory to provide industry-accepted SOPs. The same guidelines may apply to other primary and secondary microscopy methods for combustion particle analysis as appropriate.

4.3. Electron Microscopy and Energy-Dispersive X-Ray Spectrometry

Electron microscopy and energy-dispersive X-ray spectrometry can be implemented as secondary methods to provide further analysis of the surface morphology and elemental composition of resilient particles (i.e., particles that are not soluble, heat-resistant, or contain semi-volatile compounds) when interferences

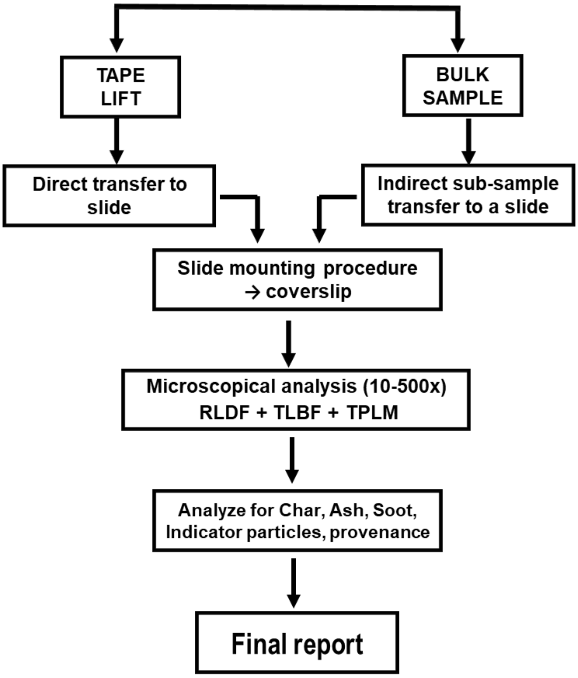


Figure 4.6: Flow diagram for the analysis of combustion particles using light microscopy. Light microscopy illumination modes are described as reflected light darkfield (RLDF), transmitted brightfield (TLBF), and transmitted and polarized light (TPLM).

are present and quantification cannot be fully resolved by optical microscopy alone. These particle interferences can include fine paint pigments, metal corrosion, and some manufactured carbonaceous particles. Quantitation is typically less reliable than optical microscopy and is not routinely recommended for this purpose.

Electron microscopy (i.e., SEM and TEM) can provide higher magnifications than optical microscopy as well as individual particle identification using dispersive X-ray analysis (EDS). However, the visual identification of pyrolysis (burning) is precluded by a black and white electron contrast image. Example comparisons between optical microscopy reflected light darkfield illumination and SEM are shown in Figures 4.7 and 4.8.

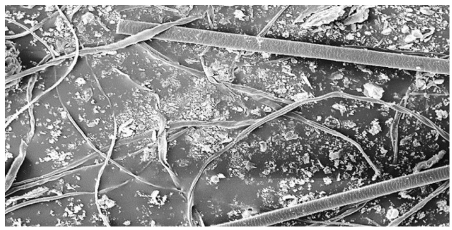
In addition to the visual identification limitations of a black-and-white (electron contrast) image described previously, electron microscopy preparation and analysis procedures limit the analysis reliability for char particles and especially the semi-volatile or semi-soluble soot particles. The soot particles typically generated by wildland or structure fires are not carbon black (i.e., elemental carbon) and are not always resilient (Baxter et al., 2022; Long et al., 2013). This problem is even more pronounced in indoor protein and plastics fires where the soot particles are highly soluble and unstable. Semi-volatile soot particles can dissolve during preparation using water, alcohol, solvents, or ultrasonication. Some types of soot particles can further evaporate or sublimate when placed under the low vacuum ranges

(A) Partially charred (burned) vegetation (RLDF)

(B) Partially charred (burned) vegetation (SEM)

Figure 4.7: Partially charred vegetation fragment. Images provided by Environmental Analysis Associates observed in (A) reflected light darkfield (RLDF) microscopy and (B) the exact same area in scanning electron microscopy(SEM). The charred area of the vegetation fragment is invisible in the black-and-white image generated by the SEM. Both images were collected at a magnification of 100×.

(A) Structure fire soot deposition (RLDF)



(B) Structure fire soot deposition (SEM)

Figure 4.8: Soot depositional patterns on the same tape lift sample. The images provided by Environmental Analysis Associates show the exact same area of soot depositional patterns collected on a tape lift sample from a structure fire using (A) optical microscopy and (B) scanning electron microscopy (SEM). Two human hairs were placed in a cross-wise position to show the location and relative size of the deposited soot patterns. The black soot deposition patterns observed in the reflected light darkfield (RLDF) optical microscopy image are invisible in the electron contrast image provided by the SEM. Both images were collected at a magnification of 100×.

required to perform the electron microscopy analysis. The high temperatures of the electron beam (200–1,000°F) can also burn and volatilize the lower temperature soot particles (Holmes et al., 2000; Liao, 2006; Starley et al., 2016; Wang et al., 2019). The remaining resilient soot clusters typically found in fire residues can be identified using high-resolution SEM and EDX. However, the identification of individual nonvolatile soot particles requires magnifications ranging from 20,000–100,000×, which is only achievable using TEM. Consult the laboratory to determine if the TEM soot analysis is useful or applicable to your project and type of fire. It is important to note that soot particles are ubiquitous in the environment due to the presence of not only natural sources of combustion such as wildfires, but also from a very large number of anthropogenic sources (e.g., automobiles, power generation, aircraft, barbecues, fireplaces, candles, cigarettes, etc.). Although volatile and semi-volatile analysis methods may provide information on the source of the sampled soot, only limited information can be obtained by SEM or TEM analysis of individual soot

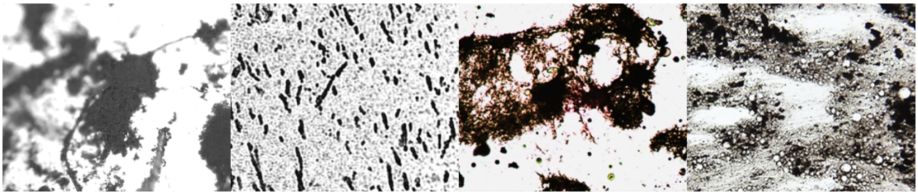


Figure 4.9: Soot agglomerate patterns from various types of fuels as observed by optical microscopy and tape lift sampling. Image A was collected using reflected light dark field illumination. Images B, C, and D used transmitted light brightfield illumination. Confirmation of particle type may also require reflected light darkfield illumination. All images were collected at approximately 400×. [Images provided by Environmental Analysis Associates].

particles (this excludes carbon black, which is a specifically manufactured product with testable properties on a sub-microscopic scale). Based on these concerns, soot should be treated as a secondary indicator only and primarily in the burn zone. Caution should be exercised with the understanding that electron microscopy analysis cannot be used to confirm the absence of the lower temperature soot generated in uncontrolled fires. Furthermore, the origin of surface soot deposition associated with a fire event is best indicated and observed by the depositional patterns seen using optical microscopy of collected tape lift samples (refer to Figure 4.9).

Although soot is not a primary constituent of wildfire infiltration residues, the depositional soot patterns characteristic of gas-phase to particle partitioning associated with a direct fire impact event (i.e., condensation of soot clusters and chains to ~5–1,000 µm agglomerates) can be typically identified and quantified using a combination of reflected and transmitted light optical microscopy. These patterns can be found when the structure itself is involved in the fire, preserved, and subsequently identified on tape lift samples. Examples of soot partitioning and surface deposition patterns from various types of fuels are shown in Figure 4.9.

Electron microscopy and EDS analysis may be useful in determining the individual chemistry of resilient soot nodules or small aggregates and the presence, but not the absence, of fine combustion soot. Semi-volatile and semi-soluble soot particles may not be readily observed due to potential losses from solvent preparation, the required transfer from multiple collection media, or the vacuum and electron beam temperatures required to obtain an image.

4.4. Volatile and Semi-Volatile Organic Compound Selection

Before specific strategies of testing for organic compounds can be determined, the purpose(s) of the assessment must be clear. An exposure assessment prioritizes the heavier chemical compounds, primarily PAHs and dioxins. An odor assessment focuses on the mid-weight VOCs, primarily methoxy phenols and methyl phenols (Heitmann et al., 2009, 2011). Forensic source apportionment may involve testing for wildfire trace indicator molecules like levoglucosan and products of lignin combustion.

Organic chemical analysis is primarily useful in the near field close to the burn zone or the WUI. This is where the hot plume of the wildfire or WUI fire may either infiltrate or adsorb directly into the structure or partition into the particulate phase of the firestorm debris that is in close proximity to the structure.

The sampling and analytical method for VOC and SVOC detection should be readily available, broad-based to detect different types of chemical compounds, and sensitive at the sub-ppb detection limits. The investigation must also be able to consider other possible sources of similar compounds unrelated to the wildfire and differentiate for the presence of background or typical levels of these compounds.

Wildfires primarily involve biomass—trees, grasses, shrubs, and ground debris. The primary components of plant cell walls are cellulose, a plant polysaccharide made of linked D-glucose units, and lignin, which is composed of cross-linked phenolic polymers that lend rigidity and are mostly found in woody plants. When subject to wildfire temperatures exceeding 350°C, the pyrolysis of cellulose produces levoglucosan, a universal indicator of biomass burning, as well as furans, pyrans, and light oxygenates. Lignin pyrolysis primarily forms methoxy-substituted phenols, specifically guaiacols and syringols (NASEM, 2022a). The exact compositions change with species and can be used as a distinguishing characteristic tied to a specific wildfire event and location.

4.4.1. Organic Chemical Analysis Methods

Organic chemistry methods may include gas chromatography-mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy. Thermal desorption-GC analysis (TD-GC-MS) should be a first consideration because it represents the best mechanism for identifying residual combustion compounds by EPA TO-17 analysis, vacuum canister for EPA TO-15, or solid-phase microextraction (SPME). These techniques differ in the media used to collect samples, but all use GC-MS for analysis.

Other methods focused on different analytical areas, such as XAD™ nonionic polymeric adsorbent resins for SVOCs, use different analysis technology. Some of these methods test for a relatively small range of compounds, which limits their breadth of coverage in wildfire events that produce hundreds of chemical compounds. However, they can be used to detect and measure surrogate or representative indicator analytes generated in a wildfire or WUI fire.

Most standard methods, such as TO-15 and TO-17, use a preselected list of chemical analytes. These lists do not typically include the most distinct VOCs produced by fires and therefore provide only limited information. As a result, just as with particle measurements, the standard techniques may need to be modified to measure fire-related VOCs and SVOCs.

Most of these analytical methods are used for determining the relative loading and organic chemical composition of char, ash, and soot particles. These methods are useful in distinguishing alternative sources of combustion particles, accelerants, and materials that might cause interferences in the analysis. No published standards exist at this time for assessing visual and other impacts of settled combustion particles or chemical residues. The OEHS professional should consult with the laboratory to define the most appropriate sampling and analytical method that complements the PDRI capabilities.

4.5. Inorganic Chemical Methods

Infiltrated wildfire residues can be analyzed for corrosion properties (pH, conductivity, and cation/anion analysis) and heavy metal content generated by nearby burned structures in WUI fires or concentrated trace elements in wildfire ash from burned plant matter and soil in the burn zone and near-field zone (Peacock et al., 2012).

4.5.1. pH, Conductivity, Corrosion Potential, and Cation/Anion Analysis

Performing pH and conductivity analysis on bulk dust samples is the best way to determine the potential presence or absence of active "corrosive wildfire ash." ASTM method D4972-01 (ASTM, 2017b) is a soil analysis method for measuring pH and conductivity and can be easily modified for use as a positive/negative indicator (Baxter, 2019) of wildfire ash. The pH of fresh wildfire ash can be significantly elevated due to the residual soluble potassium, magnesium, and calcium salts and oxides in the ash (Baxter, 2019; Ovington and Madgwick, 1958; Sánchez-García et al., 2023). The typical pH range of normal indoor settled dust is ~6.5–7.8 (Baxter, 2019). Dust collected from coastal marine locations or in proximity to carbonate-rich geology may increase the normal range up to a pH of 8.0 (Baxter, 2019). Fresh and concentrated ash from burned vegetation can range in pH from 10–13 (Baxter 2019; Bodí et al., 2014; Zhang, 2017). Modifications to the ASTM soil method are required to address the restricted collection of the small amounts of indoor dust typically collected using micro-vacuuming (i.e., 0.001–0.1 g). Indoor dust inherently has a different material composition, a much lower dry density (i.e., specific gravity of 1.0 or less), higher porosity, void volume, and a much higher water holding capacity (WHC). Using a threshold pH of 9.0 (in this weight range of dust samples) has been demonstrated to be a good indicator of potassium hydroxide/oxalate impact from infiltrated wildfire ash. Structure fires generate different synthetic residues and are primarily acidic from the formation of hydrochloric and sulfuric acids in the 3–6 pH range.

WHC is defined as the maximum measured water volume that can be added to a known weight of dry dust until the sample is thoroughly saturated and no excess water is visibly present or released (A&L Canada Laboratories, 2013; ASTM, 2017a; Jones, 2003; National Soil Survey Center, 1998]. This saturation condition also represents the maximum potential for corrosion impact from wildfire ash in a dust sample. The saturation condition or WHC can be used to standardize and compare samples prepared with differing dust weight to water volume levels. For example, typical soils have WHC values of ~3 g mL, whereas household dust samples have estimated WHC values empirically determined to be ~0.5 g/mL (A&L Canada Laboratories, 2013; Baxter, 2019). Developing a serial dilution curve and line equation can then be used to standardize the maximum pH and conductivity corrosion impact potential to their WHC equivalent values.

The liquid remaining after filtration removes the particulate phase from the pH and conductivity analysis can also be evaporated and analyzed by SEM/EDS elemental analysis to determine the soluble elemental cation/anion composition of the dust sample. This information can be important to determine the presence or absence of potential surface corrosion conditions for various materials and metals such as HVAC components, electronic circuits, or other materials.

Although the same pH and conductivity procedures can be used for structure fires, the residues are typically acidic from the production of hydrochloric or sulfuric acid fumes generated from synthetic materials. They may also include some cellulosic or wood materials that can affect the usefulness of pH measurements alone.

4.5.2. Metals Analysis

Established analytical methods for the identification and quantitation of metal elements in wildfire ash include inductively coupled plasma mass spectroscopy (ICP-MS), atomic absorption spectrophotometry (AAS), and X-ray fluorescence (XRF). ICP-MS and AAS can also detect metal isotopes. Preferred sampling media include bulk samples and wet wipes. The basic metals panel for wildfires includes arsenic, cadmium, chromium, cobalt, copper, lead, nickel, silver, vanadium, and zinc. Depending on circumstances, particularly for WUI fire events, additional metals may be needed to evaluate the extent of fire residue present. Test methods for metals include EPA 6010 for solid and waste samples, EPA 6020 for wipes, and NIOSH 7303 for air and wipe samples.

5 Data Interpretation

5.1. Introduction

INTERPRETATION OF TESTING DATA generated as part of wildfire impact assessments may involve different goals depending on the hypotheses to be tested. Assessments generally target either a health hazard (e.g., exposure assessment) or forensic evaluation relative to source identification and extent of impact. In both cases, the goals include post-restoration verification.

With some limited exceptions (e.g., lead in dust in child-occupied facilities), there are generally no fixed numerical levels of settled combustion particulates that are universally associated with an unacceptable condition or unequivocally denote impact from a wildfire. The same holds for combustion-related airborne chemicals that may be detected at trace levels (i.e., near the limits of detection) and well below recognized health-based standards.

Impact and health hazard conditions may be readily observable within all or part of structures inside the boundaries of the burn zone. For purposes of site investigation and data interpretation as discussed herein, the "burn zone" is that area where wildland vegetation—or in the case of WUI fires, where manufactured structures and items in addition to vegetation—have combusted. Conditions can vary widely on the margins and in the near field outside of the "burn" zone, and more so in the far-field distance where impact may not be obvious. At this point, the testing goal becomes primarily a forensic assessment of the source, origin, and cause of the combustion particles found rather than an exposure assessment.

The inherent differences in the testing goals are primarily determined by the distance from the burn zone and elapsed time between the fire event and the investigation. As a part of these challenges, the OEHS professional is also faced with practical and cost limitations on the number of locations, samples, and zones that can be collected and evaluated. These limitations also affect the statistical inference models that can be applied for data interpretation within the context of the sampling and testing goals.

Preserving both the quantitative impact and forensic origin and cause via qualitative or quantitative descriptors relies primarily on tape lift sampling. In contrast, chemical analyses using airborne or bulk sample collection are primarily, but not exclusively, used to assess organic and inorganic contaminants within the burn zone and near-field distance.

Exposure assessment and forensic impact evaluation often require different statistical frameworks or inference models for data interpretation. That is, the appropriate inference model within the statistical concept of identifying meaningful differences of a measured quantity is determined by the goals within the hypotheses being tested, laboratory analytical variability, distribution of the data collected, sample size, and the background absence or presence of testing targets.

Distribution of settled combustion particulate data following a fire, as well as other particulates including but not limited to metals, often deviates substantially from the "bell-shaped" normal distribution. This frequently makes evaluation of the laboratory-provided numerical levels misleading when trying to delineate impact from a fire. Differences in comparative combustion particulate data (e.g., zone to zone or zone to background) are better identified by evaluating differences in distribution rather than differences in mean values. This is described in detail in Appendix A: Data Interpretation.

Chapters 3 and 4 describe optical microscopy and chemical methods used as the primary and initial surrogate methods to evaluate residual wildfire surface impact. Optical microscopy is utilized as the initial and primary surrogate impact method because it is the only method that can simultaneously estimate the quantitative impact and origin of source particulate debris on surfaces months to potentially even years after a wildfire event.

Although other chemical airborne and surface methods may be beneficial within the burn zone and at the near-field distance in mixed-burn fires, infiltrated particulates remain a primary reservoir for organic and inorganic residue, which can therefore be inferred from microscopical data.

Chemical analysis of settled particulates relies predominantly on bulk sampling methods (e.g., bulk, micro-vacuum, and wipes). As a result, data analysis and interpretation may require different approaches.

5.2. Statistical Inference and Data Interpretation

Customary practice within the occupational and environmental health, medical sciences, and engineering disciplines has by historical convention deferred to traditional parametric or nonparametric statistical methods, denoted as "negative hypothesis significance testing" or NHST.

The common occurrence of the normal distribution in conjunction with its symmetrical (bell-shaped) nature has resulted in the mean (average) becoming the most common metric for data interpretation and the normal model by which to recognize a parameter as greater or lesser in the quantitative sense. The associated statistical terms of variance, standard deviation, coefficient of variation (CV), confidence intervals, outliers, etc. are several of the standard concepts derived with NHST.

Data derived from occupational and environmental hygiene exposure monitoring generally fit into the normal or log-normal distribution, as the sampling/analytical and resulting exposure standards are derived from large data sets to generate universal reference distributions. However, data distributions that deviate substantially from "normal" (particularly with relatively small sample sizes) often make NHST based on the mean unsuitable for deriving valid statistical inference (in absence of a well-established criteria such as a permissible exposure limit, or PEL). R.A. Fisher developed a parallel inference model to NHST, sometimes referred to as the permutation/randomization or P/R model (used interchangeably with Fisher). This model is not dependent on the mean and requires only representative sampling, not necessarily random sampling. Additionally, Type I (or Type II) errors, *a priori* significance of $\alpha = 0.05$, and confidence intervals, etc. are not applicable.

Probability and significance within the P/R model are not rigid decision criteria by which to reject the null hypothesis and therefore accept an alternative. Rather, Fisher probability is a directly calculated measure of similarity or difference in comparative distributions from proportions derived from the data at hand in a given investigation. Some problems clearly fit and are best evaluated within the classical normal distribution model, whereas others driven primarily by distributions and sample sizes are more of a probability problem handled through P/R. Refer to Appendix A: Data Interpretation for further relevant discussion and references.

5.3. Microscopical Data Evaluation

Microscopical analysis methods specifically using both reflected and transmitted light illumination sources, equipped with brightfield, polarized light, and darkfield reflected illumination as a minimum capability, are described in Sections 4.2: Optical Microscopy and 4.3: Electron Microscopy and Energy-Dispersive X-ray Spectrometry. Data interpretation should be derived from statistical inference, incorporating both quantitative metrics (i.e., concentration and/or loading of combustion particulates) and qualitative information, including the origin or source of combustion debris. The latter requires identification and quantification of wildfire assemblage or forensic indicator particles described in Section 5.3.1. This is especially important when the impacted or suspect structures are in the far field significantly downwind from the fire event and the source of combustion particles may not be readily apparent and/or in question.

Use of the P/R inference model allows an OEHS professional to determine by direct calculation if both quantitative and qualitative comparative data of interest exhibit a significant difference in the frequency of detection relative to a critical reference value (CRV). This is particularly relevant in post-wildfire investigations given that the absence of numerical criteria to a standardized reference drives the need to identify relative differences within a statistical/probabilistic framework between building(s) or zone(s) within a building and/or relative to background. Multiple CRVs, which can incorporate different metrics [i.e., concentration as percent visual area estimation (%VAE) or loading as counts/mm^2], and presence of assemblage/indicator particles may be utilized to evaluate the data from several different perspectives or goals.

The key point is that the particular CRV chosen is used as a cut point for comparative data (similar to selecting a confidence %), around which difference in detection and a probability value (p) can be calculated. The calculated $p \geq 0.90$ that infers a significant difference in distributions is conservative, as it favors identification of a difference on what is generally considered a marginal probability value.

Deriving a probability of a difference in comparative distributions prevents much of the subjectivity of investigator opinion, which is often based on "eyeballing" data. It also avoids classical statistics, such as particulate mean levels, which may result in misidentification of relative impact when the data deviate substantially from normal (Modarres et al., 2005; Spicer, 2020, 2024; Spicer and Gangloff, 2016).

Implicit in this approach is that the OEHS professional should specify and, if necessary, justify the CRV applied as well as collect several samples within given target zone(s).

5.3.1. Critical Reference Values for Microscopical Data Evaluation

Examples of some useful CRVs for microscopical data evaluation are described in the following section and explained in detail in Appendix A:

a) Single minimum metric CRV (e.g., 1% char VAE, 1 particle/mm^2; 100 particles/cm^2).

b) Multiple metric CRV (e.g., 1%, 3%, 10% VAE, counts/mm^2 or cm^2) total combustion, char, and/or soot.

c) Integrated CRV criterion (e.g., minimum threshold metric with presence of assemblage fire indicators; or maximum total combustion particle metric irrespective of assemblage indicators).

d) Common metric CRV such as the combined median (50th percentile) of the samples from comparative zones and the combined percentile value resulting in the greatest difference in frequency distribution (Δf_d) (e.g., 62nd, 75th, 90th percentiles) for total combustion, char, soot, or both.

5.3.2. Critical Reference Values and Statistical Inference

The more direct CRVs are the single minimum metric and multiple metric (a and b, respectively), as a minimum background or reference metric is based on an assumed laboratory analytical limit (e.g., LOD or LOQ as delineated by the OEHS professional).

The more versatile and most widely applicable integrated CRV (c) uses an assumed minimum background of reference detection criterion. This is satisfied by both a minimum quantitative metric and then affirmed by the presence or assemblage of indicator particles (e.g., surface vegetative deposition patterns of burned char, phytoliths, druses, clays, and firestorm debris).

The common indicator particles or spatial properties defining a characteristic wildfire source assemblage in a sample may include but are not limited to:

- Detection of char from burned vegetation particles above the limit of quantitation (LOQ) characteristic of grasses, twigs, bark, leaves, pollen, or other vegetation-derived particles;
- Detection of vegetation ash particles above the LOQ (including but not limited to burned phytoliths, druses, and potential soluble ash components);
- Presence of a homogenous depositional pattern of a specific category of indicator particles throughout the tape lift sample (i.e., soot agglomerates throughout the deposited area);
- Detection of large vegetative char or ash particles exceeding 100 µm in diameter (indicative of close proximity to the fire event); and
- Detection of burned soil clay and quartz grains potentially associated with firestorm winds (indicative of close proximity to the fire event).

For statistical inference purposes, laboratory reporting of the presence of a characteristic assemblage in a sample as a qualitative feature equates to "1," and absence equates to "0". When this combination is satisfied, the sample can then be assigned as a "positive" detection indicative of an impact.

The common metric CRV (d) is applicable to identifying differences in relative impact with no assumption of background. This approach is particularly applicable to larger buildings or zones of interest and/or when most of the data are values that are multiples of trace background and may vary by orders of magnitude. Therefore, an OEHS professional may also derive a CRV from the site data, which involves samples actually collected/analyzed from a comparative or control zone (CZ) and the test zone(s) (TZ). The common metric CRV incorporates relevant aspects of the other CRVs described but is the most data intensive. That is, the quantitative value that produces the greatest Δf_d. for the given target particulate (soot, char, total combustion particulate, etc.) from the data across two comparative zones establishes the greatest probability of a difference and becomes the quantitative component of the CRV. The best "first pass" quantitative CRV is the combined median (50th percentile) of two comparative zones. However, the combined median does not always reflect a probabilistic difference in Δf_d; thus, other useful combined percentile values for the CRV may be used (e.g., the 62nd, 70th, 75th, and 90th). Determining the CRV requires inspection of the comparative ordered data to visualize the greatest Δf_d (further discussed in the following sections). Once the most appropriate common CRV is identified, the significant occurrences of Δf_d around the numerical CRV identified from the sampled data are determined.

The flowchart in Figure 5.1 summarizes the logic applied for settled combustion particulate data using the probability model based on differences in detection frequency when no actual background/comparison data are collected, as in CRV examples (a), (b), or (c).

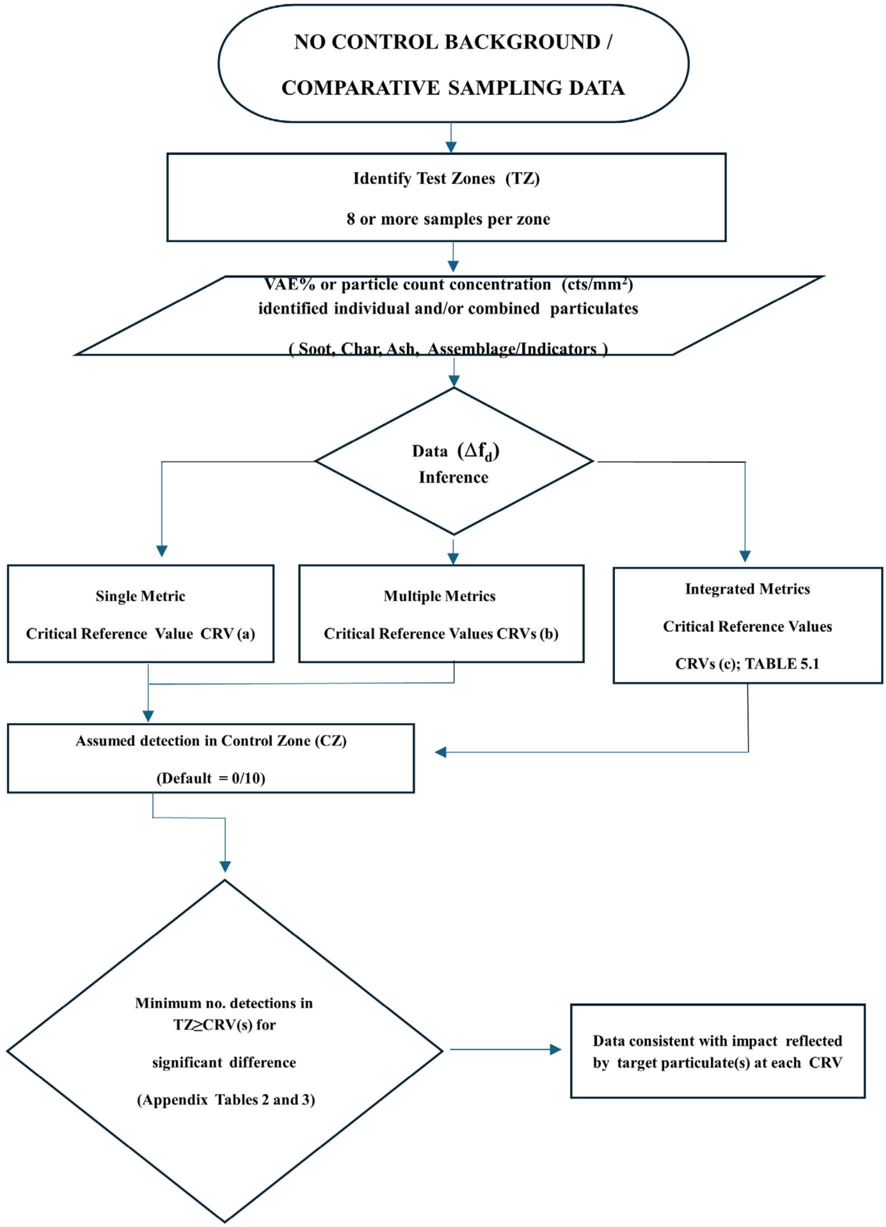


Figure 5.1: Flowchart of zone comparisons of settled combustion particulate data using the probability model with no actual background data.

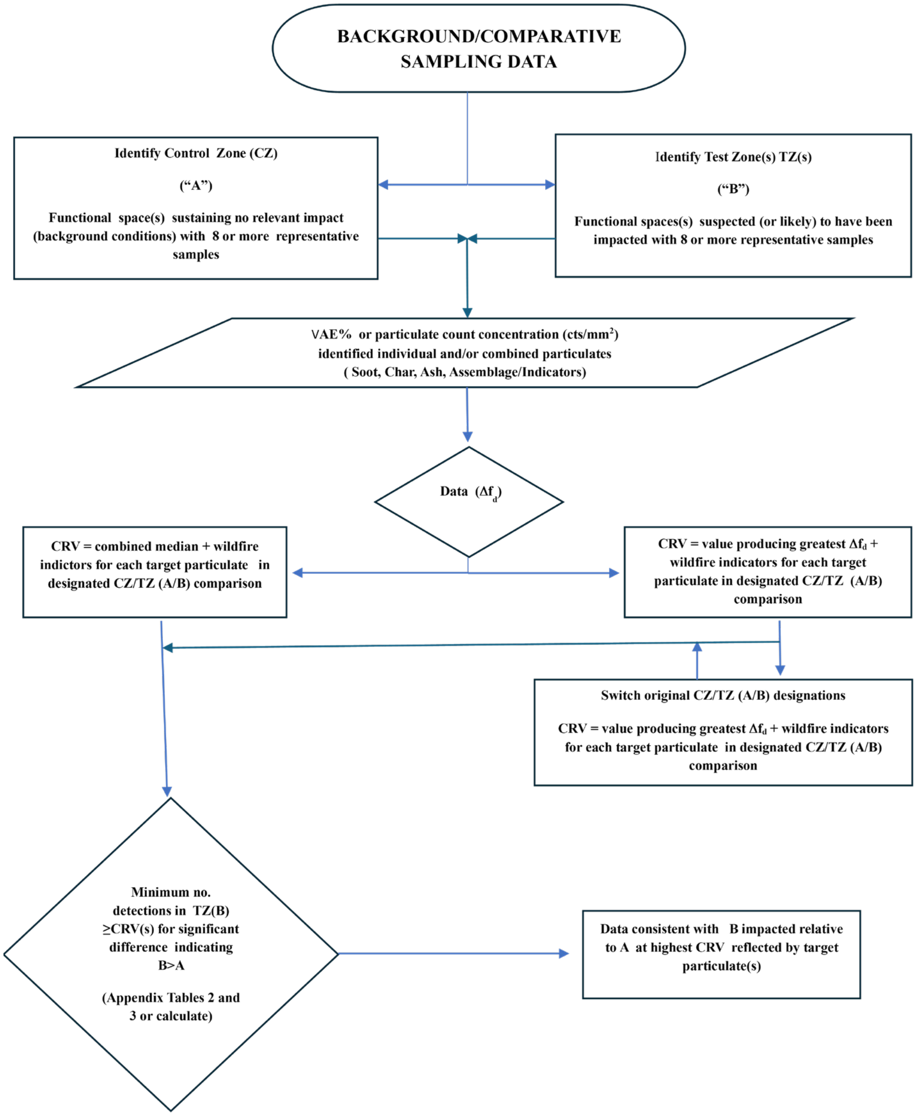


Figure 5.2: Flowchart of zone comparisons of settled combustion particulate data using the probability model with actual background data.

The flowchart in Figure 5.2 summarizes the logic applied for settled combustion particulate data when using the probability model based on differences in detection frequency when actual background comparison data are collected, as in CRV example (d).

While the discussion on sampling and interpretation has focused on post-fire assessment purposes, the same sampling and inference model is also applicable for post-restoration verification (PRV) if the ultimate goal is to render an impacted space to background conditions. This may be determined to be appropriate, for example, if there was a significant time interval between the completion of restoration and the collection of PRV samples where general background combustion particulate settling unrelated to the specific event could potentially affect results. As an example, as described in the Figure 5.1 flowchart, two samples at 2% combustion particulate out of ten samples in a particular zone are not significantly different from an assumed background of zero detection out of ten samples (refer to Appendix A). Thus, the sampling data support an acceptable restoration under the goal of rendering the space to background conditions. However, an OEHS professional may choose to assume that sampling conditions following restoration drive a non-detect PRV criterion under the stipulation that a complete remediation under the particular circumstance should render no detectable combustion particulate. In this case, zero out of ten would be necessary. However, more generally, the specific PRV sampling and criterion as well as visual/olfactory conditions for acceptability chosen by the OEHS professional should be specified and understood by all interested parties as part of the remediation work plan.

In broad view, OEHS professionals should recognize that tape lift sampling for wildfires (as well as structural fires) produces individual data points that represent very limited surface area. These points do not directly represent exposure in the traditional occupational and environmental hygiene sense, for which numerical occupational/environmental exposure can be referenced. Several samples from similar surfaces from each comparative zone are necessary to be representative of conditions. Also, the OEHS professional should evaluate particulate levels from zones of interest within an appropriate inference model rather than simply "eyeball" the data. Similarly, the traditional NHST inference based on the mean should be used with caution. This inference is applicable only when the data do not deviate substantially from normal and there is a sufficiently large reference/background data set. For example, a standard deviation greater than the mean is an indicator that NHST comparison of means will likely result in mischaracterization of the data. Thus, the P/R inference model as described in detail in Appendix A is recommended as a refinement over the traditional approaches.

Note that VAE is currently the most common reporting metric. Actual particle count (per square millimeter or centimeter) for soot, char, and/or total particulate may also be reported as an absolute measure of surface impact and may be preferred (e.g., IESO/RIA method). However, particle counts are dependent on particle size, which—particularly in the case of soot—can lead to wide disparity in the assessment of impact between VAE and soot count metrics. It is recommended that OEHS professionals contact the analytical laboratory regarding the standard operating procedures for reporting and quantification. If the laboratory provides quantification using both concentration (%VAE) and loading (e.g., counts/mm^2), data should be evaluated using each. Interpretation based on reaching the significance threshold chosen (e.g., ≥ 0.90) by either should be considered, factoring in all other site information. As a final note, OEHS professionals should consult literature references as necessary to ensure they are handling their data appropriately.

5.4. Organic and Inorganic Chemical Data Evaluation

Due to the dynamics of smoke dispersion and settling and the chemistry involved in the partitioning and adsorption of organic compounds onto combustion particulates, testing for the latter also serves as a potential surrogate indicator for impact. The direct evaluation and interpretation of organic and inorganic compounds potentially present in smoke as specific targets on surfaces outside the burn zone may be used as secondary testing for the determination of impact. However, circumstances may demand characterization of the difference in deposition of specific target compounds (e.g., potentially hazardous, property damaging, caustic, corrosive, etc.).

Data interpretation should be driven by surface testing and statistical inference consistent with that as described for the microscopical analysis. However, different assemblage parameters (if used) will be different, as reflected in Section 5.4.1. These assemblage parameters parallel CRVs as previously described for soot/char/ash and characteristic wildfire indicators.

5.4.1. Critical Reference Values for Organic and Inorganic Chemical Data Evaluation

Useful CRVs for organic and inorganic chemical data mirror those for combustion particulate data, as shown in the list that follows. Examples are provided in Appendix A.

a) Single minimum metric CRV [e.g., singular organic or inorganic compounds used as an indicating metric, which should be mass per area (e.g., mg/cm^2)].

b) Multiple metric CRV (e.g., mg/cm^2) and the presence of specific elemental or compound assemblages.

c) Integrated CRV criterion (e.g., minimum threshold metric with presence of assemblage fire-indicating compounds; or maximum total combustion compound metric irrespective of assemblage indicators).

d) Common metric CRV, such as the combined median (50th percentile) and the combined percentile value resulting in the greatest Δf_d (e.g., traditional choices have been 62nd, 75th, and 90th percentiles) for target compounds.

5.4.2. Critical Reference Values and Statistical Inference

The more direct CRVs are the single minimum metric and multiple metric (a and b), as a minimum background or reference metric is based on an assumed laboratory analytical limit.

The more versatile and most widely applicable integrated CRV (c) uses an assumed minimum background or reference "detection" criteria that is satisfied by both a minimum quantitative metric and then affirmed by "assemblage" particle detection qualifier (e.g., "vegetative" or synthetic combination of compounds). The common chemical indicator properties defining a characteristic wildfire or mixed structure source assemblage may include but not be limited to the following:

- Detection of an assemblage of metalloids, organic compounds, or other inorganic chemical indicators (pH, conductivity) associated with an altered chemistry characteristic of a wildfire or structure fire (in the burn zone
- Detection of an assemblage of organic combustion compounds characteristic of a wildfire or structure fire (in the burn zone).
- As with analysis for particulate indicators, a common metric CRV is applicable when a background value cannot be assumed for target compounds and/or data values are multiples of trace background and vary by orders of magnitude.

Cations and anions should be evaluated differently than surface combustion particulate because of the potential for localized property damage (e.g., electrical component malfunction). Specialized assistance from individuals with expertise in electronics should be solicited in these instances.

Restoration Project Specifications 6

WILDFIRE SMOKE RESTORATION may involve cleaning, demolition, repair, or replacement of building components or environments, depending on the severity of impact established during the investigation. If the building is located within the wildland-urban interface (WUI) or near a burned structure, professional wildfire residue cleaning and restoration will likely be necessary to repair materials impacted by wildfire energy, eliminate accumulated particles, clean smoke-affected materials, and treat surfaces to mitigate the risk of persistent odors.

In addition to infiltrated wildfire residue in the form of particulates, metals, polycyclic aromatic hydrocarbons (PAHs), and semi-volatile organic compounds (SVOCs), the structure's building components and contents may contain polychlorinated biphenyls (PCBs), asbestos, lead, and other chemical hazards at concentrations that could pose a health risk to workers and subsequent building occupants.

The OEHS professional is generally responsible for drafting the restoration project specifications or protocol as part of the impact investigation report. The protocol forms part of the final project specifications or contract documents prepared by the restorer. Project specifications convey the OEHS professional's expectations for the work's performance to the restoration contractor and materially interested parties (MIPs), such as the owner or occupant, insurance adjuster, and local building code agencies. The restorer's team that is responsible for the job must comprehend the specifications.

This chapter discusses two types of project specifications: prescriptive or detailed specifications and performance-based specifications. Prescriptive specifications instruct the restoration contractor on the actions to undertake and their order, detailing the required methods, materials, and equipment. They specify the requisite training and experience for people doing the activities. Prescriptive specifications guide the restorer's actions and make it easier for restorers to submit bids or proposals for the project.

Performance-based specifications state requirements in terms of results and include criteria for verifying compliance but do not define the methods for achieving the required results. Performance-based requirements provide restorers with the most rudimentary guidance on achieving the specified project objectives.

Most projects will involve a combination of performance-based and prescriptive specifications. When selecting between performance-based specifications and prescriptive specifications, the OEHS professional should evaluate the degree of flexibility to be afforded to the restorer. Performance-based specifications grant the restorer greater autonomy in method selection for achieving the desired results. Prescriptive specifications should be chosen when stringent control over methods and procedures is required. Fundamentally, performance-based specifications emphasize "what must be accomplished," whereas prescriptive specifications delineate "how it must be executed."

6.1. Prescriptive or Detailed Specifications

Prescriptive specifications detail the required procedures and the preferred methods for performing the work. Specifications should not explain the reasons for specific requirements. Precise language and technical definitions must be used to prevent confusion and misunderstanding about the meaning of words in common usage. Colloquialisms and slang terms must be eliminated from specifications. If an appropriate technical term effectively conveys the concept to the restorer, it should be applied consistently and exclusively. Specifications must avoid using synonyms for stylistic purposes. For instance, use "excavate" in place of "cut," "dig," or "bulldoze."

The specifications should distinctly identify the responsible party. The use of terms like "as directed by the restorer," "to the satisfaction of the restorer," or "satisfactory to the restorer" should be restricted, as such language does not convey a measurable standard. Redundant phrasing may lead to uncertainty. Requirements should be stated once to prevent potential disputes.

The objective of a specification is to be precise. Concise specifications are crucial for attaining quality and efficiency in smoke impact restoration. Use the active over the passive voice whenever possible to clearly articulate crucial instructions and procedures.

6.2. Performance-Based Specifications

Performance-based specifications describe the desired outcomes of a project rather than the step-by-step methods used to achieve them. The following is an example of a performance-based specification for a wildfire smoke impact project:

> The interior, exterior, systems, and contents of the subject property must be clean, dry, and dust-free and exhibit no visible or evidential effects from wildfire heat, smoke, or particulates (beyond background levels), and no odors related to the wildfire should be detectable within the habitable areas.

The goal is to draft performance-based specifications including objectively quantifiable criteria so that the appropriate party can determine whether these have been met. No single approach to cleaning fits all wildfire impact situations.

When performance-based specifications are used, the OEHS professional must explicitly indicate that the requirements are to be construed to provide the restorer with considerable flexibility in achieving the performance goals. The following is an example:

> The specifications outlined above are to be regarded as "Performance-Based Specifications" and are intended solely to describe the criteria by which the work completed by the restorer shall necessarily comply. Unless explicitly stated otherwise, the methods, procedures, equipment utilized or installed, and all other facets of the job are solely at the restorer's discretion and responsibility.

When drafting performance-based specifications, it is essential that the restorer, owner, and MIPs easily comprehend each component. OEHS professionals should write clearly and use appropriate industry terminology, when necessary. They should also convey their availability to address inquiries.

6.3. Common Restoration Practices and Procedures

The objective of wildfire smoke impact restoration is to restore the property and/or its contents as close as possible to pre-fire conditions. Due to hidden factors and the varying efficacy of restoration efforts, the OEHS professional must recognize that wildfire restoration is a fluid process with considerable potential for divergence from the original scope of work. There is no definitive formula for success. The OEHS professional should consider including the following elements in the restoration specifications or protocol based on the severity of assessed impact and the recognized health and safety hazards.

6.3.1. Restoration Approach

When preparing a restoration specification, the OEHS professional should consider a methodical approach that moves from the least aggressive to the most aggressive cleaning methods and procedures. The intensity and complexity of the cleaning methods are unlikely to be uniform throughout an impacted structure. For most areas of the structure, residue removal may be limited to basic surface cleaning. For heavier accumulation or residue that is more persistent or more difficult to access, cleaning can be expected to require more detailed efforts or more specialized services. WUI fires can inflict thermal impact to structures and property, leading to burn marks and scorching that are often permanent. Suspect structural impact should be evaluated by a qualified structural engineer and promptly disclosed to the client.

6.3.2. Restorer Experience, Training, and Licensing

Restorers should be proficient in investigating, identifying, and restoring wildfire and smoke-related impact. Proficiency is obtained through specialized education, training, and field experience, including but not limited to wildfire and smoke impact investigation, decontamination cleaning methods, contractual and legal requirements, improving indoor environmental quality, and smoke odor management. Restorers acquire requisite restoration skills through industry technical training programs, certification programs, experience, and continuing education, including but not limited to current technical literature in the field. It is recommended that restorers be familiar with current and past construction methods, materials, and building assemblies. Education and training on fire-related residue and identification, investigation, and removal techniques are available through internationally recognized certification and training bodies such as the following:

- Institute of Inspection, Cleaning, and Restoration Certification (IICRC);
- Restoration Industry Association (RIA);
- Indoor Air Quality Association (IAQA);
- American Council for Accredited Certification (ACAC); and
- American Industrial Hygiene Association (AIHA).

The restorer should be appropriately licensed and insured as required. In addition, the restorer shall comply with all jurisdictional health and safety regulations.

6.3.3. Structural Issues

The first step in evaluating wildfire impact is ensuring the structure is safe to enter. The structural system includes those elements required to stabilize a building during weather events such as wind, earthquake, and snow as well as protect against the effects of gravity. Structural elements typically include wood or metal studs, beams, posts, steel members, and concrete or masonry walls. Structures outside the fire area are unlikely to have been affected by direct flame impingement or exposure to energy generated by the fire. However, windblown firebrands or embers can cause localized or concealed degradation by heating or burning building materials.

Look for signs of potential collapse or compromised support structures. A qualified structural engineer or licensed contractor should be consulted when evidence suggests that structural members, electrical systems, glazing, or other building components have been impacted by heat or fire.

6.3.4. Work Area Isolation and Personal Protective Equipment

Separate and isolate work areas with polyethylene sheeting to prevent the spread of wildfire particles during cleaning. A sufficient number of high-efficiency particulate air (HEPA)-filtered negative air machines should be installed and operational during cleaning. When work areas are isolated, negative air machines should be used to maintain a negative pressure differential within work areas compared to adjacent areas. Heating, ventilation, and air conditioning (HVAC) supply and return openings should be sealed during the cleaning process.

Based on the impact assessment, determine the level of personal protective equipment required. This may include respirators with appropriate filter cartridges, gloves, hard hats, puncture-resistant footwear protection, eye protection, and coveralls. OEHS professionals and restorers should consult NIOSH guidance on selecting air-purifier respirators (Cichowicz et al., 2018).

Individuals conducting testing or restoration after WUI fires should be aware of the potential chemical and physical hazards associated with this type of cleanup and the possibility of exposure to toxic debris by inhalation and skin contact. In cases where the property is a total loss and needs to be demolished, there are hazardous waste considerations for cleanup and remediation that may require a formal health and safety plan and exposure control procedures that are beyond the scope of this document. OSHA's *Hazardous Waste Operations and Emergency Response* standard 1910.120 should be consulted.

6.3.5. Cleaning Practices

Surface cleaning is required for all walls, ceilings, and other similar painted surfaces. Use HEPA vacuuming first and then damp methods, such as mild detergent and water or other appropriate methods and media for cleaning after a fire.

Clean all flooring, followed by the subfloor. Use HEPA vacuuming and clean all flooring such as carpeting, hardwood, tile, linoleum, and similar items according to the manufacturer's recommended cleaning guidelines. Pre-treat carpets by vacuuming, powder cleaning, and applying solvent or detergent spray-wipe and bonnet cleaning. More intensive procedures such as rotary shampooing and hot water extraction should be performed when needed. Procedures may be combined or repeated as the situation requires. Floors may have to be evaluated to determine the cost of cleaning versus replacement. Extensive fire- and smoke-impacted carpet may need to be fully replaced, which includes replacing the carpet pad and cleaning the subfloor.

Where appropriate, ceilings, walls, and exposed framing may need to be sealed and repainted to eliminate the smoke residue's visual and odor impact. Before applying sealant, remove fire residues and neutralize smoke acids by cleaning with alkaline detergents and water. When appropriate, a sealer or encapsulant can be applied by brush, roller, or sprayer before painting.

Combustion particles and residues on wood framing members should be removed by HEPA vacuuming. This is followed by damp wiping, wire brushing, sanding, or other appropriate method while using HEPA vacuuming or performing removal within the capture zone of an air filtration device, along with other appropriate controls.

Seal the building materials to eliminate the potential for smoke contaminants to become entrained into the occupied space.

6.3.6. Contents and Personal Property

Options to restore or replace contents and personal property depend on the nature of the material and degree of apparent impact and may involve several steps. Some examples include the following:

Nonporous Hard Surfaces. Use HEPA vacuuming and damp methods, such as applying mild detergent and water, or other appropriate cleaning method after a fire. Clean nonporous hard surfaces, such as ceramic tile or other hard surface counters, finished wood cabinets, hard furniture, picture frames, knick-knacks, and similar items.

Unfinished Wood. Purely mechanical removal is often the most effective remedy and may use a variety of moisture-free cleaners and abrasives, such as steel wool or sandpaper. Water stains may be treated with acetic acid or bleaches. Desorbent odor counteractants containing alcohol can often volatilize absorbed odors. Sealing is sometimes required.

Finished Wood. Begin with the removal of loose residues, progressing to the application of detergents, solvents, cleaning creams, and oils. Penetrating lacquers and various restorative treatments for finishes may be applied as an alternative to refinishing. Partial refinishing, recoating, and, when cost-effective, full stripping and refinishing may be necessary.

Upholstered Furniture. Begin by removing fire residues to prevent their absorption. Cleaning may involve several steps, from initial vacuuming and brushing to the use of absorbent sponges or terry towels. More intensive procedures include powder cleaning, spray and wipe techniques using dry or wet solvents, foam cleaning, bonnet cleaning, shampooing, hot water extraction, and solvent extraction. When restorative cleaning cannot return upholstery to an acceptable appearance, reupholstering is an option if the value warrants the cost.

6.3.7. Removal and Replacement

The decision to restore or replace building components and contents depends on the nature of the material and degree of apparent impact. Building materials and flooring impacted beyond restoration and repair will require removal and replacement. Any existing fiberglass insulation should be removed, disposed of, and replaced.

Wood Framing. Charring to a depth of 0.25 inches is often permitted on framing, but the treatment of any significant loss of surface should be approved by local building inspectors or a qualified structural engineer. The same inspection approval process should be followed for any impact that adversely affects the structure and integrity of framing members. Depending on the material and nature of the impact, restoration options include a full range of cleaning procedures, from removal of loose residues to highly aggressive grit blasting and progressing through deodorization, repair, and replacement. Charring that does not adversely impact the structural integrity of framing members should be scraped or abraded down to clear wood, deodorized, and sealed before reinforcements are attached.

Flooring. Depending on the impact and nature of the surface, restoration options can include a full range of cleaning procedures, from mild mechanical removal of surface residues or use of aggressive detergents or acid cleaners with pressure washing to full removal of flooring material. When fire exposure suggests that heat, thermal shock, or other fire-related effects may have compromised structural materials, the restorer should obtain approval from a structural engineer prior to conducting repairs.

6.3.8. Attics and Heating, Ventilation, and Air Conditioning Systems

Clean attic space surfaces, such as HVAC ducting and equipment surfaces, wood framing, plywood flooring, and other affected surfaces using methods appropriate for attic spaces. Follow manufacturer recommendations, such as HEPA vacuuming and wet wiping with mild detergent and water.

Depending on the type of attic insulation material, remove and replace blown-in or rolled insulation materials; foam-in-place insulation materials may need to be encapsulated.

Clean the HVAC system thoroughly and effectively to eliminate the detected smoke residue. During the emergency service phase, if visual and olfactory evidence indicates that the system is affected, restorers may recommend replacing the system filter(s) and having similar filter media installed on return and supply HVAC diffusers until such time that a qualified HVAC assessor can inspect the system. If HVAC system airside surfaces require detailed assessment and cleaning, only a qualified HVAC assessor should perform this work.

The OEHS professional should evaluate the use of deodorizers and odor-control chemicals for possible irritant and acute and chronic toxic effects prior to their application. Gas-phase deodorization for odor control using ozone or hydroxyl generators has been used by restorers usually in structure fires with extensive odor issues (RIA, 2007). The EPA has issued precautions for the use of air cleaners that emit ozone in indoor environments (U.S. EPA, 2024c). The restorer should consider the effects of deodorization methods on building material or content compatibility, including corrosive effects on sensitive electronic components. During restoration, odor-treatment devices and techniques should only be used when residents are not present. Additionally, these devices should only be used by experienced restorers and workers trained in their uses, limitations, and appropriate personal protective equipment.

6.3.9. Post-Restoration Evaluation and Verification

Following the final cleaning stage of restoration and before reoccupancy, a post-restoration evaluation (PRE) should be conducted by the restorer and the client, as described in Section 3.5.

A post-restoration verification (PRV) for clearance should be performed by an independent, third-party OEHS professional in cases where health risk clearance criteria from wildfire or WUI fire residue infiltration are part of the restoration work plan. The objective of the PRV is to verify the successful restoration and return of the structure, systems, or contents to a pre-loss condition as well as resolution of all recognized health and safety hazards. This is best accomplished by incorporating a PRV sampling plan with pre-established clearance criteria into the restoration specifications to demonstrate and confirm cleaning effectiveness. The scope and criteria for PRV clearance is described in SECTION 3.6.

Appendix A. Data Interpretation

A.1. Hypothesis Testing and Statistical Inference

As the two fundamental approaches to statistical inference, traditional negative hypothesis significance testing (NHST) under Neyman/Pearson (N/P) decision logic and Fisher's permutation/randomization (P/R) model have been the subject of intense controversy and debate for several decades. The differences, limitations, and applicability of each have only recently begun to be recognized outside the statistical community (Biau et al., 2010; Bradley and Brand, 2016; Hubbard and Bayarri, 2003; Hurlbert and Lombardi, 2009; Gliner et al., 2002; Sterne, 2002; Szucs and Ioannidis, 2017). Some clarity has been provided by Bradley and Brand (2016) in their view that the two primary statistical inference models can best be conceptualized as defining a continuum. That is, some problems clearly fit and are best evaluated within the N/P logic, whereas others (driven primarily by the lack of a global reference "standard," non-normal data distributions, and small sample sizes) are more of a "Fisher" problem handled through P/R. Between these two boundary approaches are problems that derive essentially the same probabilistic inference using either classical N/P or P/R, in which the "statistics" deriving inference and interpretation will vary or overlap depending on the particular problem.

The statistical inference comparison of the traditional NHST approach and P/R is graphically presented in Figure A1. This is adapted from Bradley and Brand (2016).

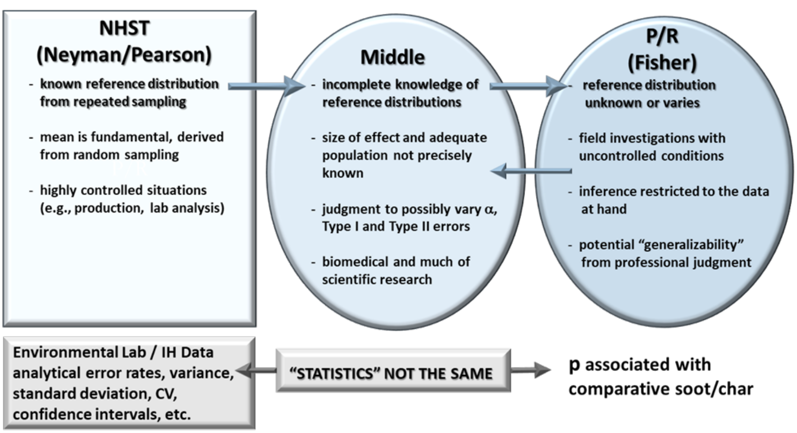


Figure A1: Comparison of traditional negative hypothesis significance testing (NHST) and permutation/randomization (P/R) statistical inference. CV, coefficient of variation; IH, industrial hygiene. [Source: Bradley and Brand, 2016].

It should be apparent that the conditions under which post-fire combustion particulate data are collected and utilized more closely fit the Fisher P/R inference model than traditional NHST parametric and non-parametric "statistics" routinely applied by occupational and environmental health and safety (OEHS) practitioners.

A.2. Calculating p Δf_d Using Fisher P/R Inference

Table A1 displays data as an example of applying a tiered **integrated critical reference value (CRV)** for a sample set consisting of 14 tape lift samples from surfaces believed to have been impacted (by either a wildfire or structure fire) and for which there are no actual comparative data. To determine whether an individual sample is characteristic of impact and in the wildfire situation where there are no known background sources, a CRV criterion is chosen by an investigator. As an example, an individual sample (data point) to represent impact must indicate total combustion particulate ≥ 1% visual area estimation (VAE) with characteristic wildfire indicators OR total combustion particulate (regardless of wildfire indicators) ≥ 10% VAE to reach the threshold for "impact" as denoted in the last column of Table A1.

In this case, the number of detections satisfying the CRV criteria in the test zone (TZ; the tally of "Y's" in the last column) produces a detection frequency (f_d) of 5 out of 14 samples. Because the only data come from a suspect TZ and there are no

Table A1: CRV and Impact Determination

Sample ID	VAE %	≥ 1% Criterion	WF Indicator	≥ 10% Criterion	Impact
T-01	12	Y	Y	Y	Y
T-02	<1				
T-03	5	Y	Y		Y
T-04	<1				
T-05	3	Y	Y		Y
T-06	<1				
T-07	3	Y			Y
T-08	<1				
T-09	2	Y			
T-10	<1				
T-11	<1		Y		
T-12	3	Y	Y		Y
T-13	<1				
T-14	3	Y			

CRV, critical reference value; VAE, visual area estimation; WF, wildfire.

actual data from an unimpacted area, a theoretical background may be assumed. For simplicity, an investigator may decide to assume that an unimpacted or "clean" background (control zone; CZ) would be represented by 10 samples, none of which would exhibit a positive detection ("impact") as defined above—that is, no samples ≥ 1% VAE with wildfire indicators and/or ≥10% VAE total combustion particulate regardless of indicator. Thus, the f_d in this *assumed* background = 0/10 (0.00). The minimum number of detections in a 14-sample TZ in comparison to no detections in the background (0/10) to exhibit a probability (p) ≥ 0.90 of impact is 3.

This is derived by the fact that there are a finite number of detections (occurrences) defined by the number of samples in two comparative zones, indicated in the orange axes in Figure A2 (matrix).

Occurs	TZ	→	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CZ	Rel Freq	→	0.000	0.071	0.143	0.214	0.286	0.357	0.429	0.500	0.571	0.643	0.714	0.786	0.857	0.929	1.000
↓	↓	Probability	0.154	0.308	0.286	0.164	0.064	0.018	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0	0.000	0.263	--	--	--	*0.043*	*0.017*	*0.005*	*0.001*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
1	0.100	0.376	--	--	--	--	--	*0.007*	*0.001*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
2	0.200	0.242	--	--	--	--	--	--	*0.001*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
3	0.300	0.092	--	--	--	--	--	--	--	--	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
4	0.400	0.023	--	--	--	--	--	--	--	--	--	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
5	0.500	0.004	--	--	--	--	--	--	--	--	--	--	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
6	0.600	0.000	--	--	--	--	--	--	--	--	--	--	--	--	*0.000*	*0.000*	*0.000*
7	0.700	0.000	--	--	--	--	--	--	--	--	--	--	--	--	--	*0.000*	*0.000*
8	0.800	0.000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
9	0.900	0.000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
10	1.000	0.000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Figure A2: Matrix displaying probability calculation for 3/14 in the test zone (TZ) and 0/10 in an assumed "clean" control zone (CZ). [Adapted from Spicer and Gangloff, 2016; Spicer, 2024].

The possible occurrences are 0/14, 1/14, 2/14, 3/14. . . .14/14 for the TZ and 0/10, 1/10, 2/10, 3/10 . . . 10/10 for the assumed CZ. Each occurrence has a decimal equivalent as indicated in the (clear) vertical and horizontal axes, respectively. In turn, each f_d in each comparative zone has an associated exact probability calculated by the binomial random mass function (RMF), as shown in the grey axes. The probability (p) for each occurrence in the CZ and TZ is determined by Equation 1:

$$p = {}_{n}C_{x}\,(P^{x})(Q^{n-x}) \qquad \text{(Eq. 1)}$$

where:

p = probability of x sample outcomes out of n samples meeting detection (impact) criteria

P = estimate of f_d meeting detection (impact) *criteria combining data from both comparative zones*; 0/10 + 3/14 = 3/24 (0.125)

Q = estimate of f_d not meeting detection (impact) criteria; Q = 1 – P = 0.875

n = total number of samples in each zone; n = 10 for (assumed) CZ, n = 14 for the actual data from the TZ

x = number of sample outcomes meeting detection (impact) criteria

C = possible number of combinations of x outcomes in n samples meeting the detection (impact) criteria; C = n!/[(n–x)!x!].

For example, in the case of 3 occurrences in the 14-sample TZ, $p = 0.16365$ (rounded to 0.164) and is displayed in the bordered cell on the horizontal grey axis, corresponding to the relative frequency of 0.214 (3/14) in the cell directly above. With the appropriate substitutions into the formula, this is calculated as (14!/3!*11!)* (0.125)3 * (0.875)11. The other occurrences (0/14, 1/14, 2/14, etc. in the TZ and 0/10, 1/10, etc. in the CZ) similarly can be determined with the appropriate RMF substitutions. Examples of derivations for the CZ occurrences are:

p for 0/10 = $(10!/0!*10!) * (0.125)^0 * (0.875)^{10} = 0.263$ (rounded from 0.26308)
p for 1/10 = $(10!/1!*9!) * (0.125)^1 * (0.875)^9 = 0.376$ (rounded from 0.37582)
p for 2/10 = $(10!/2!*8!) * (0.125)^2 * (0.875)^8 = 0.242$ (rounded from 0.24160)
etc. (all displayed in the vertical grey axis)

The total probability associated with the observed Δf_d of 0.21429 (3/14 – 0/10) is produced from the products of the probability for each of the underlying f_ds greater than or equal to that exhibited in the data. This is shown as the sum of the italicized values in the body of the matrix, or 0.07582 (rounded to 0.076). This is analogous to one-tailed α in traditional NHST following N/P inference. For Fisher-based P/R (as shown here), this is applied in a parallel inference to $1{-}\alpha$ to derive 0.92, interpreted as 0.92 probability (rounded) that the TZ represents greater impact than the assumed CZ.

If there were only 2 detections in the TZ under the specified CRV criteria, the appropriate substitutions in the RMF would result in a probability of 0.83 that the TZ was impacted. Thus, 3/14 in the TZ is the minimum number of detections resulting in a significant difference ($p \geq 0.90$) relative to 0/10 in an assumed CZ. In the Table A1 example where 5 occurrences reached the CRV criteria in the TZ, the appropriate substitutions in the RMF result in a probability of 0.98 that the TZ is impacted relative to the hypothetical "clean" CZ. Were TZ sample T-003 (5% VAE) to exhibit no wildfire indicators, the number of samples meeting the integrated CRV criterion would be 4. Appropriate substitution into the RMF in this case results in $p = 0.97$. Therefore, 4/12 (TZ) versus 0/10 (CZ) would still represent a $p \geq 0.90$ for a difference in the respective distribution consistent with impact.

Table A2 is a summary/consolidation of the calculated probability under the Fisher P/R inference model for a 10-sample CZ and various comparative TZ sample schemes (each derived by a two-dimensional matrix with the associated substitutions into the RMF as above). The ~~yellow~~ highlighted row displays minimum detection in the respective TZ for which there are 0/10 detections (occurrences) in the CZ. An investigator may decide to assume this for comparative purposes in the absence of actual CZ samples. As indicated, a suspect TZ consisting of 9–16 samples would have to exhibit at least 3 "positive" detections as defined by the investigator's CRV criterion to infer a "statistical" difference under Fisher P/R logic. (For more than 8/10 detections in the CZ, at least 36 samples in the TZ with all reaching the CRV criteria would be necessary to represent an impact $p \geq 0.90$.)

Note that individual sample impact determination to identify difference in detection frequency may vary depending on the CRV approach chosen by an

Table A2: Example of the Calculated Probability Under the Fisher P/R Inference Model

Control Zone	Test Zone Minimum detection relative to CRV resulting in probability ≥ 0.90 TZ> CZ							
N_{TOTAL}= 10	N_{TOTAL}= 8	N_{TOTAL}= 9	N_{TOTAL}= 10	N_{TOTAL}= 11	N_{TOTAL}= 12	N_{TOTAL}= 13	N_{TOTAL}= 14	N_{TOTAL}= 15
N ≥CRV	N ≥ CRV	N ≥ CRV	N ≥ CRV	N ≥CRV	N≥ CRV	N ≥ CRV	N≥ CRV	N≥ CRV
0	2	3	3	3	3	3	3	3
1	4	4	4	4	5	5	5	5
2	5	5	6	6	6	7	7	8
3	5	6	7	7	8	8	9	9
4	6	7	8	8	9	9	10	10
5	7	8	9	9	10	11	11	11
6	8	8	9	10	11	12	12	12
7	8	9	10	11	12	13	13	14
8					12	13	14	15
Control Zone	Test Zone Minimum detection relative to CRV resulting in probability ≥ 0.90 TZ> CZ							
N_{TOTAL}= 10	N_{TOTAL}= 16	N_{TOTAL}= 17	N_{TOTAL}= 18	N_{TOTAL}= 19	N_{TOTAL}= 20	N_{TOTAL}= 21	N_{TOTAL}= 22	N_{TOTAL}= 23
N ≥CRV	N ≥CRV	N ≥ CRV	N≥ CRV	N≥ CRV	N≥ CRV	N ≥ CRV	N ≥ CRV	N ≥ CRV
0	3	4	4	4	4	4	4	4
1	6	6	6	7	7	7	8	8
2	8	8	9	9	10	10	10	11
3	10	10	11	11	12	12	13	13
4	11	12	12	13	14	14	15	15
5	13	13	14	15	16	16	17	17
6	14	15	16	16	17	18	19	19
7	15	16	17	18	19	19	20	21
8	16	17	18	19	20	21	22	23

Detection frequencies defined by an investigator's chosen critical reference value (CRV) that would produce a detection frequency (Δf_d) resulting in a p ≥ 0.90 of a difference (i.e., impact) between a 10-sample control zone (CZ) and various test zone (TZ) sample schemes.

investigator, such as the **single** or **multiple minimum metric** CRV. Additionally, in the case of a structure fire, a wildfire indicator may or may not be relevant depending on the hypothesis tested and possible confounder of mixed structure fire and wildfire contributory effects. Therefore, the investigator should clearly describe the CRV being utilized in the analysis.

The **common metric CRV** is applicable to identifying differences in relative impact *with no assumption of absolute background*. This approach is the most accurate in the sense that background is actually determined from onsite data rather than assumptions of detection frequency for background. Additionally, the **common metric CRV** is particularly applicable to larger buildings or zones of interest and/or when most of the data values are multiples of trace background that may vary by orders of magnitude. The common metric CRV incorporates relevant aspects of the other CRVs described but is the most data intensive. That is, the quantitative value that produces the greatest Δf_d. for the given target particulate (soot, char, total combustion particulate, etc.) from the data across two comparative zones establishes the greatest probability of a difference in the distributions of the comparative data and becomes the quantitative component of the CRV. The best "first pass" quantitative CRV is the combined median (50th percentile) of two comparative zones. However, the combined median does not always reflect a probabilistic difference in Δf_d; other useful combined percentile values for the CRV may be, for example, the 62nd, 70th, 75th, and 90th. Determining the CRV requires inspection of the comparative ordered data to visualize the greatest Δf_d (further discussed in the following section). Once identified, the significant occurrences of Δf_d around the numerical CRV *identified from the sampled data* is determined as previously described.

The following example for settled char data (counts/mm^2) demonstrates the use of a common metric CRV for two comparative zones in a building following a fire, consisting of 15 samples in one zone (in this case designated the CZ; "A") and 15 samples in a comparative zone (designated TZ; "B").

Zone A (Control)

Sample	1	2	3	4	5	6	7	8	9
Char count/mm^2	7.7	9.9	102.4	275	27.4	8.2	18.7	6.0	8.2

Sample	10	11	12	13	14	15	Mean	Std Dev	Combined Median (A+B)
Char count/mm^2	365.2	15.9	64.9	1.6	0.8	10.4	61.5	109.8	23.8

Zone B (Test)

Sample	1	2	3	4	5	6	7	8	9
Char count/mm^2	23.1	73.5	24.5	11.5	23.1	27.4	200.4	80.7	33.2

Sample	10	11	12	13	14	15	Mean	Std Dev	Combined Median (A+B)
Char count/mm^2	233.4	40.4	46.1	8.6	28.8	7.2	57.5	68.3	23.8

Table A3: Consolidated Detection Frequencies for Various Sample Sizes

Control Zone	Test Zone Minimum detection relative to CRV resulting in probability ≥ 0.90 TZ> CZ							
N_{TOTAL} = 15	N_{TOTAL}= 10	N_{TOTAL}= 11	N_{TOTAL}= 12	N_{TOTAL}= 13	N_{TOTAL}= 14	N_{TOTAL}= 15	N_{TOTAL}= 16	N_{TOTAL}= 17
N ≥CRV	N ≥ CRV	N ≥ CRV	N ≥ CRV	N ≥CRV	N≥ CRV	N ≥ CRV	N≥ CRV	N≥ CRV
0	2	2	2	3	3	3	3	3
1	3	3	4	4	4	5	4	5
2	4	5	5	5	5	6	6	6
3	5	5	6	6	7	7	7	8
4	6	6	7	7	8	8	8	9
5	7	7	8	8	9	9	10	10
6	7	8	8	9	10	10	11	11
7	8	9	9	10	10	11	12	12
8	9	9	10	11	11	12	13	13
9	9	10	11	11	12	13	14	14
10	10	10	11	12	13	14	14	15
11	10	11	12	13	13	15	15	16
12	10	11	12	13	14	15	16	17
13								

Control Zone	Test Zone Minimum detection relative to CRV resulting in probability ≥ 0.90 TZ> CZ							
N_{TOTAL} = 15	N_{TOTAL}= 18	N_{TOTAL}= 19	N_{TOTAL}= 20	N_{TOTAL}= 21	N_{TOTAL}= 22	N_{TOTAL}= 23	N_{TOTAL}= 24	N_{TOTAL}= 25
N ≥CRV	N ≥CRV	N ≥ CRV	N≥ CRV	N≥ CRV	N≥ CRV	N ≥ CRV	N ≥ CRV	N ≥ CRV
0	3	3	3	3	3	3	3	4
1	5	5	5	5	6	6	6	6
2	7	7	7	7	8	8	8	9
3	8	8	9	9	9	10	10	11
4	9	10	10	11	11	12	12	12
5	11	11	12	12	13	13	14	14
6	12	12	13	14	14	15	15	16
7	13	14	14	15	16	16	17	18
8	14	15	16	16	17	18	18	19
9	15	16	17	17	18	19	20	20
10	16	17	18	18	19	20	21	22
11	17	18	19	20	20	21	22	23
12	18	19	20	20	21	22	23	24
13			20	21	22	23	24	25

Consolidation of the necessary detection frequencies to reach p ≥ 0.90 for various test zone (TZ; Zone B) sample sizes relative to a control zone (CZ; Zone A) of 15 samples. CRV, critical reference value.

It is clear that the quantitative values of, for example, 1–5 counts/mm^2 as might be considered background (e.g., single, multiple, and integrated metric CRVs) would not be useful as CRVs for differentiation of impact. The mean (average) char "level" in Zone A is 61.5 (rounded), while the mean count in Zone B is 57.5 (rounded). Comparing the mean count data using traditional NHST ("t" statistic for difference in means) indicates there is no statistical difference. In fact, the average char count in Zone A is slightly greater than in zone B, and the common practice of "eyeballing" the data indicates that, if anything, Zone B appears to represent "greater" impact. However, the combined median (50th percentile; 23.8 counts) from the two comparative data sets can be used as a CRV. Zone A exhibited 5 out of the 15 data points greater than or equal to the combined median of 23.8 counts, while Zone B exhibited 10 of 15 samples greater than or equal to the combined median. Table A3 consolidates the necessary detection frequencies for various TZ (Zone B) sample sizes relative to a CZ (Zone A). For example, the highlighted cell at the intersection of 15 samples in the Test Zone (bordered cell) and 5 samples greater or equal to the CRV in the 15-sample Control Zone (bordered cell) indicates the minimum detections in the TZ (B) to represent a $p \geq 0.90$ probability of a "greater" impact than the CZ (Zone A) under the 15 by 15 sample scheme applied.

The data point providing the highest Δf_d to generate a CRV across the two comparative zones can be determined by first sorting the data in each zone from lowest to highest. (This should not be confused with non-parametric "rank order analysis" such as Spearman's rank correlation or Wilcoxon rank sum test.)

Zone A ordered data becomes:

0.8	1.6	6.0	7.7	8.2	8.2	9.9	10.4	15.9	18.7	27.4	64.9	102.4	275	365.2

Zone B ordered data becomes:

7.2	8.6	11.5	23.1	23.1	24.5	27.4	28.8	33.2	40.4	46.1	73.5	80.7	200.4	233.4

By first assigning the lowest value in Zone B (7.2) as the CRV, it is immediately apparent that there are 15/15 detections in Zone B and 12/15 in Zone A equating to a $\Delta f_d = 0.2$ (calculated as 15/15 – 12/15). The next ordered value is 8.6, and as the CRV, it results in 14/15 detections in Zone B and 9/15 in Zone A ($\Delta f_d = 0.33$, calculated as 14/15 – 9/15). By continuing to tabulate the difference in number of values across the two comparative zones (Δf_d) by sequential inspection, the maximum Δf_d occurs at 23.1 cts/mm^2. Shown as the highlighted cell, as 23.1 produces a $\Delta f_d = 0.467$ (12/15 – 5/15). (This actually equates to a probability of 0.99 that Zone B represents greater char contamination than Zone A, despite there being no significant difference in the overall mean "levels" via conventional NHST).

Another aspect of this type of data that can be obscured by simply calculating difference in (mean) "levels" reported by the laboratory is the asymmetry or lack of "balance" in the distributions. That is, it is possible that each zone represents a significant difference relative to the other but at a different CRV. The check for this is to inspect "backwards" in Zone A, starting at the highest value (extreme right of the ordered data) and similarly tabulating the difference in detection sequentially. The higher CRV resulting in a significant difference therefore identifies whether Zone A (CZ) > Zone B (TZ) or Zone B (TZ) > Zone A (CZ), which is unknown prior to the site investigation. In this example, 275 cts/mm^2 (the second highest value in Zone A) set as the CRV results in 2/15 detections in Zone A and 0/15 detections in Zone B. While this suggests that Zone A represents greater impact than Zone B, the Δf_d of 0.133 (2/15 – 0/15) generates Fisher P/R $p = 0.88$, which is not generally regarded as sufficient for significance. However, if the value reported as 102.4 cts/mm^2 in the Zone A data were actually 1,024 cts/mm^2, as might occur through a laboratory transcriptional/typographical error, there would be 3/15 detections in Zone A and 0/15 in Zone B at a CRV of 275 cts/mm^2. Thus, the inference would be a greater impact in Zone A because $p \geq 0.90$ at 275 cts/mm^2, despite Zone B representing greater impact at the lower CRV of 23.1 cts/mm^2.

Appendix B. Wildfire Impact Site Investigation Forms

WILDFIRE INSPECTION - (General Property / Exterior Geographical Impact Conditions)

Page ______ *of* ______

Inspection

Project #

Client Project #

Project Name

Address

Date(s) of subject fire event?

Days since fire event

Question Codes (U) Unknown (Y) Yes (N) No

Home in / near burn zone of fire (Y / N / U) ? →		Distance (miles) ______ Wind gusts ______
Home downwind of fire (Y / N / U) ? →		Distance (miles) ______ Wind gusts ______
Exterior pressurization (Y / N / U) ? →		Describe
Interior pressurization (Y / N / U) ? →		Describe
Windows open during fire (Y / N / U) ? →		Describe
HVAC operating during fire (Y / N / U) ? →		Describe
Cleaning post-fire (Y / N / U) ? →		Describe
Firefighter property activity (Y / N / U) ? →		Describe
Electronic issues post-fire (Y / N / U) ? →		Describe
Vehicles impacted by fire (Y / N / U) ? →		Describe
Homeowner photos (Y / N / U) ? →		Describe
Inspection photos collected (Y / N / U) ? →		Describe
Previous exterior fires (Y / N / U) ? →		Describe
Pre-existing conditions (Y / N / U) ? →		Describe

	Construction type				Age (if known) →	25
Construction	Single fam	Duplex	Townhome	Condo	High-rise	Other
Type/floors	1	1	1	1	1	1
	2 3	2 3	2 3	2 3	2 3	2 3
Foundation	Slab	Crawl	Pillar/stilt	Mid-floor	Other	
Siding	Wood	Stucco	Brick	Masonry	Other	
Roofing	Asphalt	Wood	Stone	Tile	Cement	

	Blank	Not addressed by inspection
Inspection	u	Unknown / Inconclusive
Conditions	y	Condition present
	n	Condition not present

Main Structure orientation			Ext. Fire Impact Level (0-3)					Ext. Garage Fire Impact Level (0-3)					Describe impacted landscaping features
Orientation	(N S E W)	Comments	Overall Impact	Vegetation	Wall	Window	Roof	Overall Impact	Vegetation	Wall	Window	Roof	Overall Impact
Front (entrance)	S												
Left side	W												
Right side	E												
Back entry	N												

	Blank	Not addressed by inspection
FIRE	0	Inspected - No visual or other / impact
IMPACT	1	Light fire residue impact
LEVELS	2	Moderate fire residue impact
	3	Heavy fire

Other Structure / ADU / Out-building		Other Structure - Fire Impact Level				
Orientation	Comments	Impact	Vegetation	Wall	Window	Roof
Front (entrance)						
Left side						
Right side						
Back entry						

Comments

Inspector______________________ Inspection Date______________

Figure B1: Example in-field investigation form to illustrate parameters for a systematic exterior evaluation applicable to wildfire and structure fire impact conditions.

INTERIOR FIRE INSPECTION - 1 (Main Living Spaces) Page___ of___

Floor/Level →		Proj. #		Client Project #	Description:	Address:

Room Description	Room Component	Orientation (N S E W)	Protential Impact Location				Visual potential fire-related impact observations (rated from 0 - 3)										Bkg. Combustion Sources		Bkg. Dust
							Fire Odor	Spot-like deposition	Ghosting	Fine Char / ash	Coarse Char / ash	Heat / Melting	Warping / Crackling	Corrosion	Mold / Moisture	Sample #	**Description** Fireplace, Cooking, Candles, Vehicular, Industrial, Other	Bkg. Fire Impact Level	Occupant related activities (0-3)
ENTRY	Ceiling		Perimeter	Center	Fixture	Other											Room / Zone →		
# of Windows	Windows		Operable	Fixed	Ledge	Track	Room / Zone ↑												
	Walls		Base	Center	Upper														
Photo #s	Flooring		Carpet	Tile	Wood	Laminate													
	Contents		Perimeter	Center	Closet		Furniture	Cabinets	Pictures	Electric	Soft gds	Utilities	Other →						
LIVING ROOM	Ceiling		Perimeter	Center	Fixture	Other											Room / Zone →		
# of Windows	Windows / sliders		Operable	Fixed	Ledge	Track	Room / Zone ↑												
	Walls		Base	Center	Upper	Fireplace													
Photo #s	Flooring		Carpet	Tile	Wood	Laminate													
	Contents		Perimeter	Center	Closet		Furniture	Cabinets	Pictures	Electric	Soft gds	Utilities	Other →						
FAMILY ROOM	Ceiling		Perimeter	Center	Fixture	Other											Room / Zone →		
# of Windows	Windows / sliders		Operable	Fixed	Ledge	Track	Room / Zone ↑												
	Walls		Base	Center	Upper														
Photo #s	Flooring		Carpet	Tile	Wood	Laminate													
	Contents		Perimeter	Center	Closet		Furniture	Cabinets	Pictures	Electric	Soft gds	Utilities	Other →						
KITCHEN	Ceiling		Perimeter	Center	Fixture	Other											Room / Zone →		
# of Windows	Windows / sliders		Operable	Fixed	Ledge	Track	Room / Zone ↑												
	Walls		Base	Center	Upper														
Photo #s	Flooring		Carpet	Tile	Wood	Laminate													
	Contents		Perimeter	Center	Closet		Furniture	Cabinets	Pictures	Electric	Soft gds	Utilities	Other →						

	Codes	Fire Impact Levels	Bkg. Dust Levels	Additional Comments
	Blank	Not addressed by inspection	Not addressed / relevant	
FIRE	0	Inspected - No visual or other / impact	Low / recently cleaned	
IMPACT	1	Light fire residue impact	Light - moderate	
LEVELS	2	Moderate fire residue impact	Moderate	
	3	Heavy fire residue and/or heat impact	Heavy (rarely cleaned)	

Figure B2: Example in-field investigation form to illustrate parameters for a systematic interior evaluation applicable to wildfire and structure fire impact conditions.

INTERIOR FIRE INSPECTION - 5 (Garage, Attics / Crawl Spaces, HVAC) Page___ of___

Proj. # Jan-04 Client Project # Description: Address:

Room Description	Room Component	Orientation (N S E W)	Protential Impact Location				Visual potential fire-related impact observations (rated from 0 - 3)										Bkg. Combustion Sources		Bkg. Dust
							Fire Odor	Spot-like deposition	Ghosting	Fine Char / ash	Coarse Char / ash	Heat / Melting	Warping / Crackling	Corrosion	Mold / Moisture	Sample #	Description Fireplace, Cooking, Candles, Vehicular, Industrial, Other	Bkg. Fire Impact Level	Occupant related activities (0-3)
GARAGE	Ceiling		Drywalled	Wood joist	Fixture	Other											Room / Zone →		
# of Windows	Windows		Operable	Fixed	Ledge	Track	Room / Zone ↑												
	Walls		Drywall	Stud	Bld paper	Other													
Photo #s	Flooring		Cement	Coated	Other	Laminate													
	Contents		Perimeter	Center	Closet		Furniture	Cabinets	Pictures	Electric	Soft gds	Utilities	Other →						
ATTIC SPACE	Roof		Joists	sheathing	Insulation												Room / Zone →		
	Soffet vents		Perimeter	Oth. Vents			Room / Zone ↑												
	Access		Home side	Attic side															
Photo #s	Joists		Perimeter	Center															
	Deck Insulation		Perimeter	Center															
CRAWL SPACE (if present)	Sub-floor		Perimeter	Center	Slab on grade												Room / Zone →		
	Posts		Perimeter	Center			Room / Zone ↑												
	Foundation Wall		Perimeter	Center															
Photo #s	Insulation		Perimeter	Center															
	Vent / Other		Perimeter	Center															
HVAC EVALUATION	Location →	Hall closet	Atic	Crawl	Above ceiling												Room / Zone →		
	Fan unit / coils →						Room / Zone ↑												
	Supply locations →																		
Photo #s	Return / filter →																		
	Duct locations →		add water heater																

	Codes	Fire Impact Levels	Bkg. Dust Levels
	Blank	Not addressed by inspection	Not addressed / relevant
FIRE	0	Inspected - No visual or other / impact	Low / recently cleaned
IMPACT	1	Light fire residue impact	Light - moderate
LEVELS	2	Moderate fire residue impact	Moderate
	3	Heavy fire residue and/or heat impact	Heavy (rarely cleaned)

Additional Comments

Figure B3: Example in-field investigation form to illustrate parameters for a systematic evaluation of non-living spaces and utilities (garage, attic, crawlspaces, HVAC) applicable to wildfire and structure fire impact conditions.

Appendix B References

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Acronym List

Δf_d: difference in frequency distribution
µm: micrometers
AAS: atomic absorption spectrophotometry
ACAC: American Council for Accredited Certification
AIHA: American Industrial Hygiene Association
AIHce: American Industrial Hygiene Conference and Exposition (now AIHA Connect)
ANSI: American National Standards Institute
ARECC: Anticipation, recognition, evaluation, control, confirmation
ASTM: American Society for Testing and Materials
ATSDR: Agency for Toxic Substances and Disease Registry
CNCs: condensation nuclei counters
CO: carbon monoxide
CO_2: carbon dioxide
COPD: chronic pulmonary obstructive disease
CPCs: condensation particle counters
CRV: critical reference value
cts/mm^2: counts per square millimeter
CV: coefficient of variation
CZ: control zone
EAA: Environmental Analysis Associates
EDS or EDX: energy dispersive X-ray (analysis)
EPA: Environmental Protection Agency
ESAM: Environmental Sampling and Analytical Methods
FEMA: Federal Emergency Management Administration
FIDs: flame ionization detectors
FTIRs: Fourier-transform infrared detectors
GC/MS: gas chromatography/mass spectrometry
HEPA: high-efficiency particulate air (filtration)
HPLC: high-performance liquid chromatography
HUD: (Department of) Housing and Urban Development
HVAC: heating, ventilation, and air conditioning
IAQ: indoor air quality
IAQA: Indoor Air Quality Association
IARC: International Agency for Research on Cancer
ICP M/S: Inductively coupled plasma mass spectrometry
ICP-AES: inductively coupled plasma-atomic absorption spectrometry

IDLH: immediately dangerous to life or health
IICRC: Institute of Inspection, Cleaning, and Restoration and Certification
ISO/IEC: International Organization for Standardization and the International Electrotechnical Commission
IUR: inhalation unit risk (U.S. EPA IRIS database)
LOQ: limit of quantitation
LPCs: laser particle counters
mg/cm²: milligrams per square centimeter (of surface)
mg/cm³: milligrams per cubic centimeter (of air)
mg/kg: milligrams per kilogram (of bulk material)
MIPs: materially interested parties
NADCA: National Air Duct Cleaners Association
NASEM: National Academies of Sciences, Engineering, and Medicine
NESHAP: National Emission Standards for Hazardous Air Pollutants
NFPA: National Fire Protection Agency
ng/cm²: nanograms per square centimeter (of surface)
ng/g: nanograms per gram (of bulk material)
ng/L: nanograms per liter (of air)
ng/wipe: nanograms per wipe
NHST: null hypothesis significance test (statistical method for testing a hypothesis against an observation)
NIOSH: National Institute for Occupational Safety and Health
NMAM: NIOSH Manual of Analytical Methods
NOAA: National Oceanic and Atmospheric Administration
NOx: nitrogen oxides
NRC: Nuclear Regulatory Commission
NTP: National Toxicology Program
OEHHA: Office of Environmental Health Hazard Assessment (CA)
OEHS: Occupational and Environmental Health and Safety
OPCs: optical particle counters
P/R model: permutation/randomization
PAHs: polycyclic aromatic compounds
PDRIs: portable direct-reading instruments
pH: potential of hydrogen (measure of acidity or basicity)
PIC: products of incomplete combustion
PIDs: photoionization detectors
PM: particulate matter
$PM_{2.5}$: particulate matter, 2.5 µm
PM_{10}: particulate matter, 10 µm
POAs: primary organic aerosols
ppbv: parts per billion by volume
PPE: personal protective equipment
ppm: parts per million
PRE: post-restoration evaluation
PRV: post-restoration verification

PTR-TOF-MS: proton-transfer-reaction time-of-flight mass spectrometry
RfD: reference dose (inhalation, U.S. EPA IRIS database)
RI: refractive index
RIA: Restoration Industry Association
RLDF: reflected light darkfield
RSLs: regional screening levels (U.S. EPA)
RWP: restoration work plan
SEM: scanning electron microscopy
SO_2: sulfur dioxide
SOAs: secondary organic aerosols
SOPs: standard operating procedures
SPME: solid-phase microextractions
SVOCs: semi-volatile organic compounds
TD-GC-MS: thermal desorption-gas chromatography-mass spectrometry
TEM: transmission electron microscopy
TLBF: transmitted light brightfield
TO-15: Toxic Organics method number 15
TO-17: Toxic Organics method number 17
TPLM: transmitted and polarized light microscopy
TZ: test zone
UFPs: ultrafine particles or ultrafine particulates
$\mu m/m^3$: microgram per cubic meter (of air)
USDA: United States Department of Agriculture
U.S. DOI: United States Department of the Interior
U.S. EPA: United States Environmental Protection Agency
VAE: visual area estimation
VOCs: volatile organic compounds
WUI: wildland-urban interface
XAD™: trade name for a hydrophobic organic porous polymer sorbent
XRF: X-ray fluorescence

Glossary

Aciniform: Shaped like a cluster of grapes.

Ash: Particles of wildland biomass that are pyrolyzed and decarbonized and therefore consist of the residual metals and metalloids as well as soluble components that were contained in the plants (as macro- and micronutrients) and scorched grains of metal and metalloid minerals contained in the soil of the wildland that burned. Ash ranges from 2–500 micrometers (μm).

Assemblage Analysis: Analytical method based on the concept of the distribution of contextual indicator particles. A contextual assemblage is defined as a group of objects or features that in combination establish a fact or context not established by any individual feature or object. Assemblage analysis will detect the characteristic particle signature and unique assemblage of particles created by a specific fire event.

Background Conditions: The presence of non-fire-event related chemical or particulate combustion residues. Chemicals and particulate combustion residues may be present at some levels depending on background or non-fire conditions.

Bulk Sampling: The commonly used term for removing a piece or portion of a solid material, such as soil, concrete, wallboard, fabric, carpet, insulation, etc., for subsequent analysis. Grab, wipe, or micro-vacuum sampling are also types of bulk sampling.

Burn Zone: Area or footprint of a wildland fire where vegetation has burned or, in the case of a wildland-urban interface (WUI) fire, where structures and items have also burned.

Cellulose: A plant polysaccharide made of linked D-glucose units. Pyrolysis of cellulose produces levoglucosan, a universal indicator of biomass burning.

Char: Particles of partially burned wildland biomass [trees, shrubs, bushes, herbs, flowers, grasses, plant litter (necromass), peat, lichen, etc.] that still retain some of the original plant's morphological structure. Char is greater than 2 micrometers (μm) in size.

Collection Efficacy: The sampling method or procedure that encompasses all particle types that may induce the complaint and is capable of yielding the intended outcome.

Collection Efficiency: The chosen sample method or procedures that effectively collect particles in a representative manner.

Competent Professional: An individual who A) possesses a relevant degree, certification, or professional standing in occupational/environmental health and safety (OEHS), industrial hygiene (IH), or related science/engineering/public health and a minimum of two years' relevant experience or B) through demonstrated formal training and extensive knowledge in the subject matter and a minimum of five years' experience, has the ability to recognize, evaluate, and solve problems relating to the work or the project.

Contamination: In a wildfire, contamination refers to the presence of combustion particulate and associated volatile and semi-volatile organic substances and residues from burnt and unburnt organic matter deposited indoors. Contamination can also refer to substances that enter indoors from nearby burnt buildings that contain asbestos, lead, and heavy metals. The presence and quantities of these contaminants can complicate the restoration and cleanup process and may render a given indoor environment unsuitable for its intended use or pose risks to human health, the environment, and property.

Corrosion: Corrosion is caused by the generation of corrosive gases and particles. Metal items exposed to corrosive gases and/or particles may begin to oxidize or rust relatively quickly in a matter of days. Visual cues of corrosion are pitting, yellowing, and grooving. The corrosivity of wildfire residue depends on the fuel source and distance from the fire.

Critical Reference Value (CRV): A particular metric used as a cut point for comparative data, around which a probability value can be calculated. CRVs may be single, multiple, integrated, or common reference metrics.

Damage: Damage is generally defined as the alteration in appearance, utility, or functionality of the space, contents, or equipment due to fire event-related combustion impact. Damage is subjective and must be defined by the materially interested parties.

Decay Half-Life: The time it takes for half of the initial amount of the substance to undergo decay, transformation, or elimination.

Desorption Half-Life: The time it takes the compound to dissipate from a substrate to which it has been absorbed.

Druses: A group of crystals of calcium oxalate, silicates, or carbonates present in plants.

Electrophoresis: A condition caused by the localized accumulation of airborne particles due to electrical attraction, commonly known as "ghosting."

Equilibrium Half-Life: The time it takes for the absorption and desorption process to reach a steady state. A dynamic equilibrium is the balance between continuing processes when the forward and reverse processes occur at the same rate.

Exposure Assessment: Investigation to evaluate the potential health effects of inhalation and dermal exposure to wildfire or structural fire-produced residual contaminants.

Far-Field Distance: The far-field area downwind of the burn zone where the plume has cooled to near-ambient temperatures and infiltration of particulates is the main impact to a structure.

Filtration Marks/Threshold Streaks: Filtration marks are the discolorations caused by air-driven particles impacting and collecting on the material due to pressure differentials between spaces. These marks can be visually seen as dark streaks, splotches, or dark lines, commonly observed below doors.

Fire: The rapid oxidation of organic material producing carbon dioxide, water, heat, and other components of smoke.

Fire Perimeter: The boundary between burned and unburned areas of a wildfire or wildland-urban interface (WUI) fire. In an active fire, the fire perimeter is constantly changing.

Firestorm: A firestorm occurs when heat from a wildfire creates its own wind system. This phenomenon can lead to very strange weather effects. A wildfire, or multiple wildfires in the same area, can cause a firestorm.

Forensic Investigations: Evaluation and procedures intended to confirm the presence or absence of wildfire residue associated with a specific origin or source.

Impact: (1) Alteration to the indoor environmental surfaces and/or contents resulting from the presence of fire event-related combustion particulates and/or chemical compounds and associated odors. (2) Impact is a general term that indicates that the structure's condition, or portions thereof, is different than the background conditions that existed before the wildfire.

Indicator Signature Particles: A unique assemblage of particles created by a specific fire event.

Inference: A conclusion reached on the basis of evidence and reasoning.

In-Field Evaluation: Qualitative method used for preliminary or initial determination of the condition of the structure and contents with respect to potential impact from wildfire residue.

Lignin: Plant material composed of cross-linked phenolic polymers that lend rigidity and are mostly found in woody plants. Lignin pyrolysis primarily forms methoxy substituted phenols, specifically guaiacols and syringols, which are indicator compounds of biomass combustion.

Micro-vacuum Sampling: A sampling method that uses a filter cartridge to collect samples using a vacuum pump.

Mixed-Burn Zone: The area in a wildland-urban interface fire that involves destruction of some structures in addition to vegetative matter and represents an additional potential impact to the surviving structures.

Near-Field Distance: The near-distance area downwind from the burn zone where the effects of the hot plume may include potential impact from particulates, vapors, or gases carried by the firestorm that can infiltrate the structure and cause wildfire odors as well as direct heat impact and pressurization on the structure.

Necromass: Dead biomass on the ground (e.g., organic soils, deep roots, peat, and decayed vegetation).

Optical Microscopy: Light microscopy analysis using both reflected and transmitted light illumination sources, specifically using brightfield, polarized light, and darkfield reflected illumination.

Oxidation: (1) A reaction in which oxygen combines chemically with another substance. (2) Any reaction in which electrons are transferred. Oxidation and reduction always occur simultaneously. Dehydrogenation is a form of oxidation.

Partitioning: Partitioning refers to the distribution of chemicals among phases or compartments. At the state of thermodynamic equilibrium, partitioning determines the concentration of a chemical in air, on surfaces, and elsewhere. Partitioning can also refer to the process of molecular exchange between phases, such as a solid and a gaseous phase.

Permutation/Randomization Model (P/R): A statistical inference (also referred to as the Fisher model) that is based on determining all possible outcomes in an experiment modeled as unordered permutations. Directly calculated proportions for each possible outcome then generate the respective probability. For purposes of settled contaminants such as combustion particulate, the P/R inference model allows an investigator to determine significant differences for both quantitative and qualitative comparative data of interest relative to a critical reference value.

Phytoliths: Microscopic plant-derived inorganic structures forming within cells, between cells, or on the surface of cells.

$PM_{2.5}$: Particles from smoke that are typically very small with an aerodynamic diameter of 2.5 micrometers (μm) or less.

Portable Direct-Reading Instruments (PDRIs): Instruments designed to provide real-time measurement of airborne particulate, gas, and vapor concentrations.

Post-Restoration Evaluation (PRE): A post-restoration evaluation conducted by the restorer to ensure that cleaning or restoration activities have successfully removed fire damage and odors from structures, contents, electronics, and textiles.

Post-Restoration Verification (PRV): Clearance inspection and testing conducted by an independent third party following the completion of the work plan to verify whether the cleaning or restoration process was effective.

Pressurization: Due to temperature and pressure differentials, interstitial pressurization can occur through penetrations, cracks, or gaps in exterior and interior walls, floors, and ceilings. It can typically be detected by examining the visual cues that are present or by testing.

Pyrolysis: Decomposition of a material into one or more other substances due to exposure to energy, typically driven by high temperatures, without oxidation.

Restoration Work Plan: A residue cleanup or restoration scope of work aiming to return the property and/or contents as close as possible to a pre-fire condition. At a molecular level, buildings and contents impacted by combustion byproducts generated in a wildfire event may never be totally restored to a pre-loss condition.

Smoke Chains: See “smoke tags” and “smoke webs.”

Smoke Tags: Webs and swirls that start as individual microscopic combustion particles and become attached to spider webs. Over time, this material can completely coat the spider webs, causing them to appear black.

Smoke Webs: Carbon particles and other fire-related byproducts of incomplete combustion produced in smoldering wood fires and from the burning of petroleum-based materials found commonly in all types of buildings, especially in areas that are not frequently accessed, such as ceiling corners of confined spaces (e.g., attics).

Smoke: Combustion of vegetative matter by the rapid oxidation of organic material producing carbon dioxide, water, heat, and other components. Wildfire smoke contains a mixture of chemicals including gases, volatile and semi-volatile organic compounds, dioxins/furans, corrosive inorganic chemicals, and metals.

Soot: Organic carbon that partitions from gas to particle phase as the wildfire smoke plume cools during combustion of wildland biomass or, in the case of the mixed-burn zone in the wildland-urban interface (WUI), from manufactured products in structures and their contents. Individual soot particles are submicron in size while soot "aciniform" deposition patterns range between 2 and 5,000 µm.

Statistical Inference: Probability-based informed judgment regarding similarities and/or differences in distributional properties of data.

Surface Density Concentration: A procedure for quantifying fire combustion particles in counts per square millimeter (cts/mm^2) that is independent of the concentration of other accumulated dust particle concentrations.

Tape Lift: A sampling technique that uses adhesive tape to collect settled dust. Tape lifts have proven to be an effective sampling method for collecting particles from surfaces with typical dust loading.

Thermal Damage: Damage caused by heat itself, without ignition. Thermal damage to wood may appear as buckling, twisting, shrinkage, and cupping. Thermal damage also commonly impacts cementitious substrates, including brick and masonry, by spalling or cracking.

Thermophoresis: In a fire, thermophoresis is a force network of warmer suspended particles and gases migrating toward cooler surfaces. Visual findings of thermophoresis may resemble mold or rust but are typically accumulations of household dust, which may include combustion particles.

Ultrafine Particles: Particulate matter with an aerodynamic diameter in the submicron range between 0.1 to 0.3 microns.

VAE Ratio %: A numerical or percentage ratio analysis method that compares the percentages of fire residue particles to other dust in the sample.

Water Holding Capacity (WHC): The maximum measured water volume that can be added to a known weight of dry dust until the sample is thoroughly saturated and no excess water is visibly present or released.

Wildland-Urban Interface (WUI): The zone of transition between unoccupied land and human development. It is the line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels.

Wildland-Urban Interface (WUI) Fire: A wildfire that reaches the WUI and burns property, structures, vehicles, and other items in addition to wildland vegetation. Also called the mixed-burn zone.

Wipes: A sampling method that involves wiping a collection medium on a surface and typically requires the removal and transfer of the particles from one media to another media during processing at a laboratory. Wet wiping is more efficient than dry wiping in removing and collecting particles on surfaces. Dry wiping is typically used for a bulk sample.

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