July 4, 2012

Mr. Jeremy Sternlicht
Public Adjustor
Loss Recovery Services, LLC
990 Highland Drive, Suite 203
Solana Beach, CA 92075

Subject: The Impact of Forest Fire Smoke on the Indoor Environment

Dear Mr. Sternlicht,

I am providing this letter to summarize my findings into the issues you inquired about in regards to indoor environments impacted by forest fire smoke. Below is a discussion of each of the topics:

Composition of Forest Fire Smoke

Forest fire smoke is composed of a complex mixture of air pollutants in both particulate and gas-phases. Of the thousands of chemicals identified, many have well-documented adverse human health effects. Smoke constituents include those pollutants that are regulated by the United States Environmental Protection Agency (EPA) through National Ambient Air Quality Standards (NAAQS), including particles less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$), carbon monoxide (CO), ozone (O_3), and nitrogen oxides (NOx). Forest fire smoke is also composed of a number of toxic or carcinogenic compounds, including free radicals, polycyclic aromatic hydrocarbons (PAHs), and aldehydes (Pryor, 1992; Leonard et al., 2000; Schauer et al., 2001). Other ciliatoxic respiratory irritants such as phenols, cresols, acrolein, and acetaldehyde; carcinogenic organic compounds such as benzene, formaldehyde, and 1,3 butadiene; and carcinogenic cyclic compounds are often measured in wood smoke through chemical analyses. Further, forest fire smoke components include at least five chemical groups classified as known human carcinogens by the International Agency for Research on Cancer (IARC), others categorized by IARC as probable or possible human carcinogens, and at least 26 chemicals listed by the EPA as hazardous air pollutants (Naeher et al., 2007).

$PM_{2.5}$ is comprised of a complex mixture of soot, tars, and volatile organic substances (Ryan and McMahon, 1976), and is the most prominent pollutant found in forest fire smoke in relation to existing air quality standards (Naeher et al., 2007). The properties of $PM_{2.5}$ vary, and are largely determined by fuel properties and combustion conditions (Reid et al., 2005). Wood smoke particles are generally smaller than 1 μm, with a peak in the size distribution between 0.15 and 0.4 μm (Kleeman et al., 1999; Hays et al., 2002). Although approximately 5–20% of wood smoke particulate mass consists of elemental carbon (EC), the composition of the organic carbon (OC) fraction varies dramatically with the specific fuel being burned and with the combustion conditions. Nearly 200 distinct organic compounds have been measured through detailed analyses of organic wood smoke aerosol, many of them derivatives of wood polymers and resins (Rogge et al., 1998).

Wildland forest fires also emit a large number of semi-volatile organic compounds (SVOCs) including PAHs that are partitioned between the gaseous and liquid or solid phase at ambient temperatures. PAHs, some of which are carcinogenic, can condense or be adsorbed onto the surface of fine particles. They are assembled from carbon fragments into larger structures in low-oxygen environments, such as occurs inside the flame envelope in the fuel-rich region of the flame structure (Ward, 1997). Using scanning electron microscopy

(SEM), a study by Chakrabarty et al. (2006) studied the properties of particulate matter emitted by fires, including the size, morphology, and microstructure of particles emitted from the combustion of eight different wildland fuels (i.e., sagebrush, poplar wood, ponderosa pine wood, ponderosa pine needles, white pine needles, tundra cores, and two grasses). SEM analyses of individual particles revealed the presence of tar balls with diameters ranging to >600 nm. Although tar balls have been observed previously during biomass smoke events, agglomeration of tar balls into small and large clusters had not been reported. SEM analysis of individual particles emitted from the combustion of the dry fuels revealed the presence of mostly sooty chains (Chakrabarty et al., 2006).

The gas-phase component of forest fire smoke includes a large variety of trace gases and volatile organic compounds (VOCs). Following $PM_{2.5}$, CO is second in abundance to carbon dioxide (CO_2) and water vapor (Ward et al., 1993). Hydrocarbons, including ethylene, alkynes, aldehydes, furans, and carboxylic acids can all be products of incomplete combustion. Oxygenated species, such as formaldehyde (CH_2O), methanol (CH_3OH), acetic acid (CH_3COOH), formic acid (HCOOH), hydroxyacetaldehyde ($HOCH_2CHO$), and phenol (C_6H_5OH) have been measured by Fourier transform infrared (FTIR) spectroscopy (Griffith et al., 1991; Yokelson et al., 1996a; Yokelson, 1996b; Yokelson, 1997; Yokelson, 1999; Goode et al., 1999; Goode et al., 2000). Consistent with the broad range of materials, conditions, and scales of origin and impact, both the gas- and particle-phase composition of emissions are complex and highly dynamic, so that these characteristics need to be considered when assessing the risk from exposure to biomass smoke (McKendry et al, 2004; Oanh et al., 2005; Buzcu et al., 2006; Gorin et al., 2006; Niemi et al., 2006; Zheng et al., 2006; Subramanian et al., 2007).

Health Risks Resulting From Exposure to Forest Fire Smoke

As summarized in several review manuscripts (Ezzati and Kammen, 2002; Zelikoff et al., 2002; Lewtas, 2007; Naeher et al., 2007), there is a growing body of evidence from human and animal studies that suggest that exposure to wood smoke poses a risk to human health at environmentally relevant concentrations. These adverse health effects range from irritancy to serious respiratory diseases, including chronic obstructive airway disease and lung cancer. Some types of effects reported to be associated with wood smoke are not unlike those of mixed, urban ambient particulate matter for both cancer and non-cancer endpoints (Mishra et al., 2004; LeVan et al., 2006; Gerlofs-Nijland et al., 2007; Morandi and Ward, 2010).

Exposure concentrations are expected to vary significantly depending on specific scenarios and human receptors (Fine et al., 2004; Olsson et al., 2004; Hannigan et al., 2005; Kocbach et al., 2005; Molnar et al., 2005; Larson et al., 2007; Nopmongcol et al., 2007; Oliveira et al., 2007; Saksena et al., 2007; Ward et al., 2007; Barn et al., 2008; Gimbutaite and Venckus, 2008; Kim and Hopke, 2008a,b; Kleeman et al., 2008; Ward et al., 2008; Zhang et al, 2008). These exposures can range from the elevated, close-to-source inhalation of forest fire smoke, to the lower level exposure to primarily emitted and secondarily formed air pollutants in ambient and indoor air due to long range transport of forest fire smoke. Exposures to communities located immediately downwind from wildland forest fires can be of low frequency and predictability, but can also result in episodes of highly elevated concentrations of smoke-related $PM_{2.5}$ over short and multiple-day (and sometimes weeks) time periods.

A number of studies have found associations between wildfire smoke and emergency room visits for both upper and lower respiratory tract illnesses (including asthma), respiratory symptoms, and decreased lung function (Duclos et al., 1990; Copper et al., 1994; Chew et al., 1995; Smith et al., 1996; Brauer, 1998; Hisham-Hashim et al., 1998; Leech et al., 1998; Sorenson et al., 1999; Emmanuel, 2000; Jalaludin et al., 2000; Tan et al., 2000; Johnston et

al., 2002; Kunii et al., 2002; Mott et al., 2002; Mott et al., 2005; Sutherland et al., 2005; Chen et al., 2006; Moore et al., 2006). With the exception of three Australian bushfire investigations, all of which have significant structural limitations, epidemiologic studies of indoor and community exposure to biomass smoke indicate a generally consistent relationship between exposure and increased respiratory symptoms, increased risk of respiratory illness, including hospital admissions and emergency room visits, and decreased lung function. Several studies suggest that asthmatics are a particularly susceptible subpopulation with respect to smoke exposure (Naeher et al., 2007).

Indoor Air During Forest Fire Smoke Events

Sampling programs have shown that biomass combustion emissions can be transported over hundreds of kilometers, such that local air quality is degraded even at great distances from forest fire locations (Gillies et al., 1996; Sapkota et al., 2005). Much of the increase in particulate matter concentrations during these episodes is primarily due to $PM_{2.5}$. It has been established that larger particles (those >10 μm in aerodynamic diameter) tend to settle closer to their source due to gravitational settling, while ultrafine particles (those < 100 nm) tend to coagulate, leading to loss of particles in that size fraction (Hinds, 1982; Zhu et al., 2002). $PM_{2.5}$ is preferentially transported over long distances because these particles are too small to settle by gravity, and too large to coagulate (Wilson and Spangler, 1996).

During forest fire events, smoke from the ambient air can penetrate into the indoor environment, resulting in elevated, prolonged exposures. Penetration of $PM_{2.5}$ into the indoor environment is determined by a combination of particle type and size, as well as building and ventilation characteristics (Riley et al., 2002). To date, several studies have documented the impact of forest fire smoke on indoor environments. Henderson et al. (2005) found that indoor $PM_{2.5}$ concentrations were 58–100% of the concentrations measured outdoors during one prescribed burn and three wildfires during the 2002 Colorado fire season. Phuleria et al. (2005) measured the impacts of the October 2003 wildfire episode on pollutant levels in the Los Angeles Basin. Their findings showed that particle number distributions downwind of the fires displayed number modes with diameters between 100 and 200 nm, with the particles able to penetrate effectively indoors. In a study conducted during the 2002 Canadian forest fires, Sapkota et al. (2005) found that penetration of ambient $PM_{2.5}$ indoors during a smoke event was efficient (median indoor-to-outdoor ratio 0.91), such that the high ambient levels were similarly experienced indoors. In another study, Barn et al. (2008) measured infiltration rates in homes in British Columbia affected by summer forest fire smoke, concluding that remaining indoors provided little protection from outdoor smoke. Finally, during the 2007 summer forest fire season in Missoula, Montana, $PM_{2.5}$ measurements were made using a TSI DustTrak inside a building impacted by forest fire smoke. During a 24-hour sampling period, $PM_{2.5}$ concentrations inside the building averaged 102 $\mu g/m^3$ (note that this is nearly three times the 24-hour NAAQS for $PM_{2.5}$), with the maximum $PM_{2.5}$ concentration measured during this period 177 $\mu g/m^3$. Ambient levels were measured over 150 $\mu g/m^3$ during this same time period (Ward, unpublished data).

Fate of Forest Fire Smoke Particles Inside the Home

When wildfire smoke particles enter an indoor environment, the particles will eventually settle out of the air, often depositing on horizontal surfaces. Soot is attracted to cooler surfaces due to thermophoresis, a process in which particles migrate under the influence of forces created by temperature and moisture (Moffett, 2008). Suspended particles can penetrate upholstery, drapes, and insulation, and can also electrostatically adhere to electronic components or other charged surfaces (including plastic products such as vertical blinds, TVs and computers), as well as impact on surfaces in the path of air currents. The dry air and

static charge developed by wind conditions contribute to soiling of interior ceilings and wall surfaces more so than on exterior walls (Moffett, 2008). Importantly, $PM_{2.5}$ that has settled indoors can be re-entrained into the air by even small disturbances, leading to continued exposures within the home until the home is cleaned.

The chemical makeup (including acidity) of the forest fire smoke particles (soot) facilitates damage to the contents of the home, causing discoloration, corrosion, and overall damage. In *Soot Particles: A Procedural Guide for Containing and Removing Wildfire-Caused Soot in Buildings*, Patrick Moffett lists a general timeline on the effects of fire and smoke that can damage a home and its contents:

Within Minutes: Acid soot residues can cause some plastic contents and building materials to yellow; small appliances located close to the source of combustion may discolor; highly porous materials consisting of marble and alabaster can experience discoloration (sometimes permanent); and air quality is affected.

Within Hours: Collectibles and antiques that have a natural patina can become damaged; acid residues stain grout in bathrooms; fiberglass bath fixtures turn yellow; metals tarnish and some types of counter tops may yellow; finishes on appliances, particularly refrigerators that extend into the heat line may yellow, including white rubberized gaskets and door seals; furniture finishes can discolor and become tarnished and pitted.

Within Days (Over a Few Days to a Week Or So): Acid residues cause painted walls to yellow permanently; metal corrodes, pits and rusts; wood furniture requires refinishing; wallpaper yellows; vinyl flooring may require refinishing or replacement; clothing becomes soot stained, especially when they are on hangers; upholstery may stain permanently.

Within Weeks: Cleaning and restoration costs can escalate tremendously; synthetic carpet fibers may yellow or discolor permanently; silver plating can be permanently corroded; glass, crystal, and china may require replacement due to severe etching and pitting caused by prolonged exposure to acid soot residues; caulking around doors and windows, base and crown molding yellows.

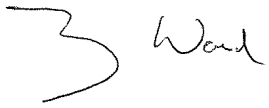
Conclusions

Although forest fires are a large source of $PM_{2.5}$ and other pollutants to the ambient environment, the impact on the indoor environment is often overlooked and misunderstood. This is concerning, in that most people spend ~95% of their time indoors (Fishbein and Henry, 1991; Jenkins et al., 1992). Many research studies have shown that there is compelling evidence that emissions from biomass burning are linked to adverse health effects, including increased respiratory symptoms, increased risk of respiratory illness, increased hospital admissions and emergency room visits, and decreased lung function (Naeher et al., 2007). Other studies have shown that homes downwind from forest fires (even hundreds of kilometers away from a fire) can be impacted by smoke, with particles entering the indoor environment. The procedural guide authored by Moffett (2008) details the damaging impact that forest fire soot can have on the contents within a home. In addition to the corrosive properties of wood smoke, odors from forest fire smoke can also persist long after the smoke has cleared, causing an ongoing nuisance problem. In homes impacted by smoke, there is also a concern about secondary and ongoing exposures within the home. Perhaps understated in previous reports, $PM_{2.5}$ that has settled indoors can be re-entrained into the air by even small disturbances, leading to continued exposures inside the home until the home is cleaned.

All of these supporting data lead me to believe that homes subjected to forest fire smoke, and that test positive for forest fire smoke contamination, should be properly remediated by outside professionals. This includes cleanup, deodorization, sanitizing and any repair work as covered under the homeowner's policy. I am less clear about at what level of contamination is needed (as determined by sampling and analyses) before cleanup is conducted. From what I understand, there are currently no widely accepted health-based standards, guidelines, or thresholds to determine/establish forest fire smoke contamination (or combustion by-products contamination) within a home (though a Limit of Quantitation (LoQ) of 1% or above is frequently used in requesting remediation).

By definition, the LoQ is the lowest concentration at which the analyte cannot only be reliably detected, but at which some predefined goals for bias and imprecision are met (Armbruster and Pry, 2008). During the routine operation of a wood stove, loading and stoking activities can release wood smoke particles inside the home (Ward et al., 2008). These residential wood smoke particles may be similar to those deposited (and subsequently measured) within the home during forest fire smoke events. Perhaps to eliminate any biases from wood stove use or other biomass burning sources within the homes that may skew analytical results, sampling should be conducted in a control group of homes not impacted by the forest fire smoke for comparison. Results from their measurements should be investigated to determine "background" contamination. It is my opinion that in addition to this 1% LoQ, the background contamination of the control group should be considered when determining cleanup.

Please let me know if you have any questions about this summary. Respectfully,



Tony J. Ward, Ph.D.
406-243-4092
tony.ward@umontana.edu

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