Research Proposal: Wood-Smoke Quantification along the Wasatch Front
Prepared by: Nancy Daher, Air Monitoring Section-DAQ

Problem Statement

Utah is often susceptible, during winter-time inversions, to elevated levels of fine particulate matter ($PM_{2.5}$) along the Wasatch Front. High-pressure weather systems during winter lead to cold-air pools that periodically trap air pollutants in the mountain valleys, resulting in pollution levels occasionally exceeding the federal National Ambient Air Quality Standards (NAAQS). Kerry et al.[1] recently showed, using positive matrix factorization (PMF), that wood-smoke and cooking fumes contribute to about 45% of primary fine PM in Salt Lake City on winter days when $PM_{2.5}$ concentration exceeded 20 μg/m^3. The individual contribution of wood-smoke to total $PM_{2.5}$ was, however, unclear. Further research is therefore needed to quantify wood combustion emissions and their contribution to $PM_{2.5}$ in non-attainment areas along the Wasatch Front during winter-time inversions.

Specific Tasks

Wood-smoke quantification using PMF receptor-modeling

To determine source contributions of wood-smoke, as well as other major sources, to $PM_{2.5}$, a source apportionment analysis will be conducted using PMF receptor modeling. EPA PMF model (v5.0.13) will be applied for this purpose. Year-long 24-hr $PM_{2.5}$ speciation data collected once every three days during 2015 at Hawthorne site in Salt Lake City will be used for this analysis. Inorganic ions (nitrate, sulfate, ammonium, chloride, potassium), metals, trace elements, levoglucosan as well as elemental and organic carbon (EC, OC, respectively) will be used as input variables. While potassium is conventionally used in PMF analysis to estimate wood-smoke emissions, the use of K (or K+) as a tracer for wood burning does not always allow one to effectively and unambiguously resolve the wood-smoke source. This is because potassium is emitted by a mix of sources, which include soil and meat cooking in addition to wood burning[2]. Levoglucosan, on the other hand, is a unique tracer for biomass burning[3]. Including levoglucosan in the PMF analysis will therefore allow for a more accurate quantification of wood-smoke emissions. Results from this analysis will help determine the contribution of wood-smoke to $PM_{2.5}$, particularly during high PM episodes. Findings will also help assess the contributions of other major sources, including, but not limited to, mobile sources, soil, secondary inorganic aerosol-rich sources and possibly industrial sources. Results will also be

[1] K. Kelly, R. Kotchenruther, R. Kuprov and G. D. Silcox. Receptor model source attributions for Utah's Salt Lake City airshed and the impacts of wintertime secondary ammonium nitrate and ammonium chloride aerosol, JAWMA, 63(5):575–590, 2013.
[2] Y. Cheng, G. Engling, K.-B. He, F.-K. Duan, Y.-L. Ma, Z.-Y. Du, J.-M. Liu, M. Zheng and R. J. Weber. Biomass burning contribution to Beijing aerosol, ACP, 13, 7765–7781, 2013.
[3] Simoneit BRT, Schauer JJ, Nolte CG, Oros DR, Elias VO, Fraser MP, Rogge WF, Cass GR, 1999. Levoglucosan, a tracer for cellulose in biomass burning and atmospheric particles. AE, 33:173–82.

complemented by a conditional probability function (CPF) analysis to identify probable geographical locations associated with high source concentrations.

Chemical analysis

24-hr Teflon samples will be collected at Hawthorne site throughout January 2016. Samples collection is already in progress. Samples are being collected on a daily basis in parallel with the speciation samples at this site. A total of about 122 filters, corresponding to the period January 2015-January 2016, will be used for determining levoglucosan levels. Levoglucosan will be measured using Ion Chromatography coupled with Pulsed Amperometric Detection (IC-PAD), following water-extraction of the filter samples.

Derivation of levoglucosan-to-$PM_{2.5}$/OC emission ratio

Resulting PMF factor profiles will be used to derive levoglucosan-to-$PM_{2.5}$ or levoglucosan-to-OC emission ratios specific to wood combustion in Utah. The derived ratios can then be used along with measurements of levoglucosan to estimate wood-smoke contributions at different locations in future studies. The contribution of wood smoke can be determined by multiplying the measured concentration of levoglucosan by the PMF-resolved emission ratio, following equation 1 or 2 below:

$$PM_{2.5,woodsmoke} = \frac{PM_{2.5}}{levoglucosan} \times levoglucosan_{measured} \tag{1}$$

$$OC_{woodsmoke} = \frac{OC}{levoglucosan} \times levoglucosan_{measured} \tag{2}$$

Noteworthy is that this approach assumes that the emission ratio used to convert the concentration of levoglucosan in $PM_{2.5}$ to that of wood-smoke is representative of wood smoke emissions in the entire state. While emission factors vary depending on the type of combustion appliance, wood type and burning conditions, the PMF-derived factor is not expected to substantially vary in the suggested analysis where the same geographical area is considered, ambient measurements are used to derive the factor and similar appliances are used across the state. This is supported by results of a survey conducted by ICF International under contract with the Utah Division of Air Quality, which showed that fireplaces, followed by inserts and wood-stoves, are the most popular wood-burning devices in all seven northern counties considered in the survey.

Comparison of PMF-derived estimates to modeling estimates

Wood-smoke PMF-derived estimates will be compared to modeling estimates, determined using the Community Multiscale Air Quality (CMAQ) model. The model uses county-specific emission inventory estimates, compiled by UDAQ. The inventory comprises emissions from residential wood combustion sources, including fireplaces, fireplace inserts as well as wood stoves (certified and non-certified). The estimates are based on population census numbers, the percentage of occupied housing units for a given appliance category and U.S. EPA emission factors. To ensure a robust comparison between location-specific PMF and domain-wide modeling estimates for wood-smoke, model simulations will be run at a high spatial resolution (~ 1 km).

Impact of EPA-certified wood-stove emissions on PM levels

To evaluate the impact of low-emission wood-burning devices on total $PM_{2.5}$ levels, a sensitivity analysis will be conducted. The reduction in wood-smoke emissions based upon the use of low-emission wood-burning appliances will be estimated by considering a hypothetical scenario where all existing wood-burning devices (conventional wood-stoves, fireplaces...) are replaced by low-emission wood-burning appliances. The change in emissions will then be estimated as the difference between baseline $PM_{2.5}$ emission levels and post-change-out $PM_{2.5}$ levels (i.e. after replacement of all wood-burning devices by low-emission units).

1. **Baseline wood-smoke emissions:**

Baseline $PM_{2.5}$ wood-smoke emissions (tons/year) will be determined by summing the emissions from all existing wood-burning devices, where wood-smoke emissions from a given device are estimated using the amount of wood use (i.e. cords use × wood density), emission factors (EF) and the number of wood-burning devices (equations 3 and 4). For a given county, the latter is determined as the product of the number of occupied housing units (P) and the percentage of occupied housing units that own a given wood combustion appliance and utilized it in the past 12 months (AP).

$$E_{baseline} = \sum E_i;\ i\ corresponds\ to\ a\ given\ wood - burning\ device\ (e.g\ fireplace..) \quad (3)$$

where,

$$E_i = cords\ use_i\ \times\ wood\ density\ \times\ EF_i \times P\ \times AP_i \quad (4)$$

Residential wood combustion appliances, including fireplaces, fireplace inserts (non-EPA certified, EPA-certified non-catalytic and catalytic) and woodstoves (freestanding non-EPA certified, EPA certified non-catalytic and catalytic), will be considered in this analysis. Table 1 below lists the appliance types, their Source Classification Codes (SCC) and emission factors (tons of primary $PM_{2.5}$/tons of wood burned). These were acquired from AP-42 air pollutants emission factors' compilation.

A wood density of 1.017 tons/cord will be used for the emissions calculation. This value, which corresponds to the density of oven dried wood, was obtained from the U.S. Forest Service for various wood species and for Salt Lake County (2005 timber products output fuel wood consumption). The density of oven dried wood was selected because emission factors developed by EPA are based on oven dried wood mass units.

Table 1. Appliance types, Source Category Codes (SCC) and emission factors (EF) for residential wood combustion sources.

Source Classification Code (SCC)	Appliance Type	EF (tons of primary $PM_{2.5}$/tons of wood burned)
2104008100	Fireplace, general	0.0118
2104008210	Woodstove: fireplace inserts; non-EPA certified	0.0153
2104008220	Woodstove: fireplace inserts; EPA certified; non-catalytic	0.0098
2104008230	Woodstove: fireplace inserts; EPA certified; catalytic	0.0102
2104008310	Woodstove: freestanding, non-EPA certified	0.0153
2104008320	Woodstove: freestanding, EPA certified, non-catalytic	0.0098
2104008330	Woodstove: freestanding, EPA certified, catalytic	0.0102

The number of occupied housing units and percentage of occupied units utilizing a given wood combustion appliance will be acquired from survey results conducted for the "Hawthorne" area by ICF International under contract with UDAQ. The "Hawthorne" area corresponds to a sub-county area within Salt Lake County, defined by a subset of census tracts. The use of appliances for main and secondary heating as well as pleasure purposes will be considered in the analysis. Moreover, the percentage of occupied housing units will only include the proportion of housing units that actually used the appliance for burning in the past 12 months. The proportion of housing units that own a burning device but did not use it within the past 12 months will not be considered in the analysis.

The amount of cords burned per appliance type (cords/appliance/year) will be acquired from the survey results and compared to those obtained using the EPA tool. Furthermore, given that firelogs and pellet stoves were grouped along with other appliances (e.g. cordwood central furnace...) into the same wood combustion category in the survey, they will not be considered in the analysis. These only accounted for 2% of households.

2. **Post-change-out wood-smoke emissions:**

Wood-smoke emissions following the hypothetical change-out program will be determined by assuming that all existing wood-burning devices, N_i, are replaced by EPA-certified appliances:

$$E_{cert.} = \sum cords\ use_i \times\ wood\ density\ \times \frac{\varepsilon_i}{\varepsilon_{cert.}} \times EF_{cert.} \times N_i \qquad (5)$$

$where\ i\ corresponds\ to\ a\ given\ wood - burning\ device\ (e.g\ fireplace..)$

This equation takes into account the net efficiency of the wood-burning devices, ε, to correct for the amount of wood burned using EPA-certified appliances. The latter are more efficient than high-emission devices and therefore use less wood (thus produce less emissions) for the same heating demand. Tables 2 and 3 list the various wood combustion source categories, their respective low-emission replacement devices and corresponding efficiencies. Different scenarios, using various combinations of low-emission devices, will be considered in this analysis. The efficiencies were obtained from a report prepared by OMNI Environmental Services, Inc. for the Mid-Atlantic Regional Air Management Association[4].

Table 2. List of existing wood combustion source categories and their alternative replacement devices.

Existing cordwood device	Alternative device
Uncertified freestanding cordwood stove	Certified NSPS non-catalytic cordwood stove
	Certified NSPS catalytic cordwood stove
	Pellet stove
Uncertified cordwood fireplace insert	Certified NSPS non-catalytic cordwood insert
	Certified NSPS catalytic cordwood insert
	Pellet insert
Cordwood fireplace without insert	Certified NSPS non-catalytic cordwood insert
	Certified NSPS catalytic cordwood insert
	Pellet insert

Table 3. List of efficiencies (%) for residential wood combustion sources. Data acquired from "Control Analysis and Documentation for Residential Wood Combustion in the MANE-VU Region" prepared for the Mid-Atlantic Regional Air Management Association by OMNI Environmental Services, Inc. (and references therein).

Appliance type	Efficiency (%)
Uncertified freestanding cordwood stove	54
Certified non-catalytic cordwood stove	65
Certified catalytic cordwood stove	70
Pellet Stove	75
Uncertified cordwood fireplace insert	49
Certified non-catalytic cordwood insert	60
Certified catalytic cordwood insert	65
Pellet insert	70
Cordwood fireplace	18

[4] Houck, J.E.; Eagle, B.N., "Control Analysis and Documentation for Residential Wood Combustion in the MANE-VU Region," prepared for the Mid-Atlantic Regional Air Management Association by OMNI Environmental Services, Inc., 2006.

Each of the resulting emissions will be input into CMAQ to determine baseline $PM_{2.5}$ concentrations and $PM_{2.5}$ levels following the hypothetical replacement of all non-certified wood-burning devices by EPA-certified ones. The potential reduction in emissions will hereafter be estimated as the difference between baseline $PM_{2.5}$ emission levels and post-change-out $PM_{2.5}$ levels.
While this method is associated with uncertainty related to 1) emission factors, 2) net efficiency and 3) activity data estimates, it provides insight on the degree of variation in wood-smoke contribution to $PM_{2.5}$ using low-emission wood-burning devices as compared to non-EPA certified units.

Deliverables and Policy Implications

In summary, the proposed project involves the following tasks:

1. Levoglucosan analysis of $PM_{2.5}$ speciation filters collected at Hawthorne during January 2015-January 2016
2. Estimation of wood-smoke source contribution using PMF
3. Derivation of levoglucosan-to-$PM_{2.5}$ emission ratio for use in future studies to estimate wood-smoke contribution at different locations in Utah
4. Comparison of PMF-derived estimates to modeling estimates
5. Performance of a sensitivity analysis to assess the impact of EPA-certified wood-burning emissions on total $PM_{2.5}$ levels.

Findings from this study will primarily help:

- Determine wood-smoke contribution to $PM_{2.5}$
- Determine the contribution of other major sources to $PM_{2.5}$, such as motor vehicles, secondary inorganic aerosol and soil.
- Provide insight on the impact of EPA-certified wood-stove emissions on PM levels.

These findings will help UDAQ determine the importance and significance of wood-smoke emissions contribution to $PM_{2.5}$, particularly during PM exceedance days. Results will also ultimately help UDAQ establish more effective and rationally-targeted control regulations for reducing source contributions to elevated $PM_{2.5}$ levels.