Adverse Health Effects, Exposure Threats, Outdoor Wood Boilers and

by Philip R.S. Johnson

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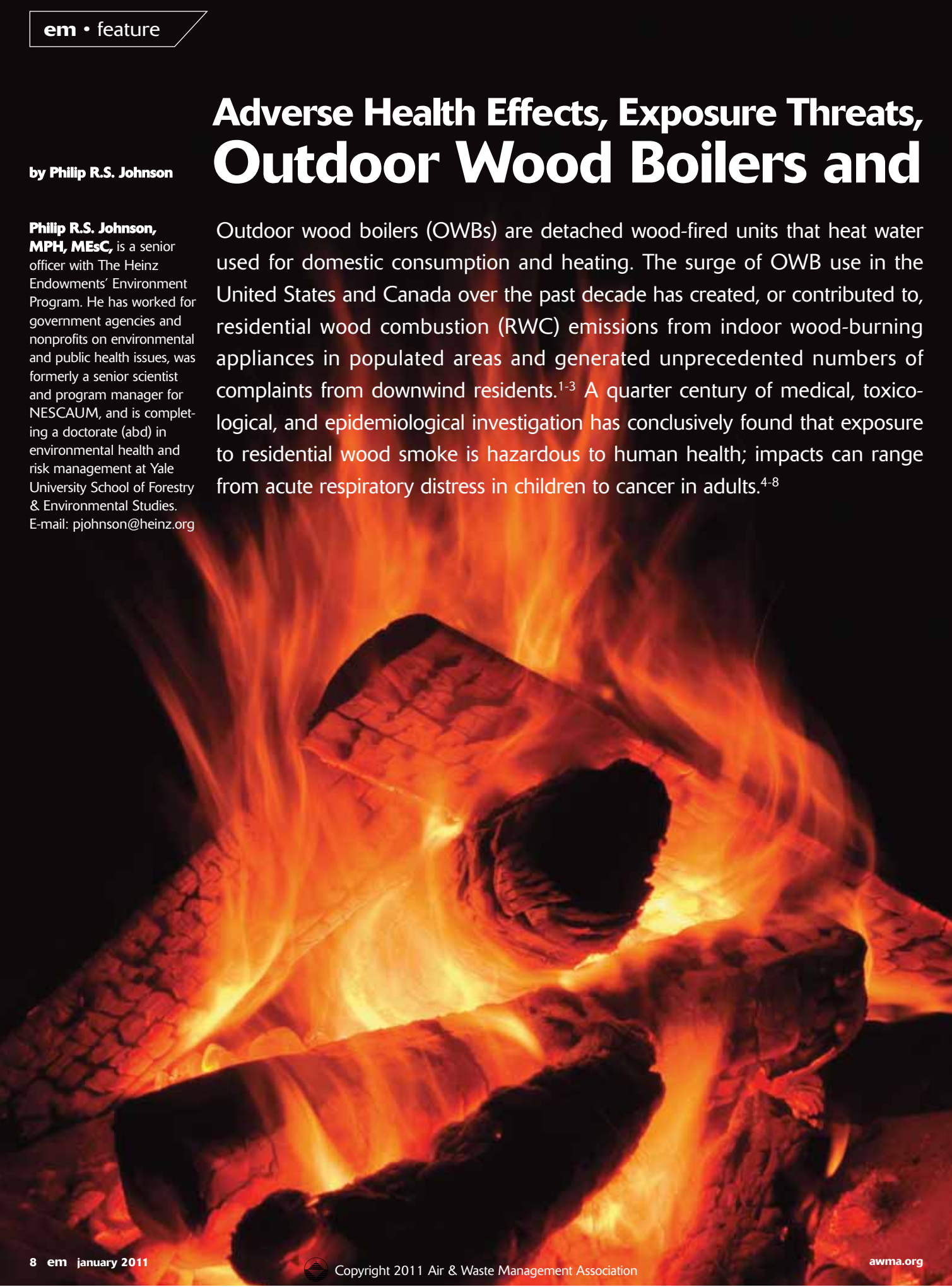
Outdoor wood boilers (OWBs) are detached wood-fired units that heat water used for domestic consumption and heating. The surge of OWB use in the United States and Canada over the past decade has created, or contributed to, residential wood combustion (RWC) emissions from indoor wood-burning appliances in populated areas and generated unprecedented numbers of complaints from downwind residents.[1-3] A quarter century of medical, toxicological, and epidemiological investigation has conclusively found that exposure to residential wood smoke is hazardous to human health; impacts can range from acute respiratory distress in children to cancer in adults.[4-8]



and Regulatory Challenges Relating to Residential Wood Combustion

The magnitude of exposure estimates to populations in wood-burning regions can be significant.[9,10] Three common regulatory approaches used to minimize harmful levels of OWB emissions—federal particulate matter (PM) standards, technology-forcing rules decoupled from effective measures to replace the existing operating fleet, and device location distance setbacks based on incomplete dispersion modeling—do not adequately protect all affected populations. Washington State standards and a growing number of community OWB bans across North America have effectively achieved adequate public health protection by means of eliminating exposures.[2,11,12]

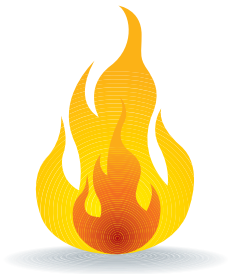
Health Effects and Exposure

Airborne emissions from traditional indoor RWC sources are composed of hundreds of compounds. Fine particulate matter ($PM_{2.5}$) is generally considered to be the surrogate marker for RWC emissions. Wood smoke particulates are dominated by the submicron fraction of $PM_{2.5}$ and characterized mainly by their rich carbonaceous content.[9,13,14] This physiochemical composition facilitates the conveyance of toxic organics into the human deep lung region. Tiny particles bypass upper pulmonary tracheal defenses and instead deposit exogenous materials into alveolar tissue where gas exchange occurs, one of the most vulnerable portals of the body.[15] In addition to $PM_{2.5}$, hundreds of gaseous compounds—some with mutagenic or carcinogenic properties—are found in wood smoke emissions, including acrolein, carbon monoxide, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs; e.g., benzene and formaldehyde) and other toxic combustion products.[16-18]

Any current review of RWC health effects is to some extent repetitive—the basics of the health threat have been understood for more than 25 years notwithstanding current research questions. This knowledge contrasts to long-held sociocultural dynamics that perceive wood smoke as harmless.[5,19] Increased use of residential wood-burning devices in the early 1980s prompted scientists to develop core knowledge that continues to be refined. Then, as now, it was found that short- and long-term exposure to RWC emissions can lead to a suite of acute and chronic adverse health effects. Known associations include irritation of eyes, triggering of headaches, and allergies; aggravation of asthma, emphysema, pneumonia, and bronchitis; visits to emergency departments and hospitalizations; decreases in lung function; contribution to development of emphysema, chronic bronchitis, and arteriosclerosis; nasal, throat, lung, blood, and lymph system cancers; and mortality.[6,20,21]

Boman et al.'s review of wood smoke epidemiology literature found that relative risks in areas where wood smoke was a major source of particulates were stronger in comparison to areas dominated by other PM sources.[22] Brown et al. recently estimated OWB wood smoke PAH cancer risks to represent a range of 7-fold increase to 2 orders of magnitude above acceptable cancer risk levels, using an emissions rate adjustment of 6.9 times a non-catalytic-certified indoor wood stove.[23] A 2009 health consultation prepared by the Michigan Department of Community Health with the Agency of Toxic Substances and Disease Registry concluded that the operation of an OWB in a residential neighborhood presented an "urgent public health hazard."[12]

The increasing use of continuous $PM_{2.5}$ monitoring over the past decade has led to findings of health associations at time scales of less than 24-hour averages. Several studies show acute cardiac and pulmonary adverse effects from exposures at mean and maximum hourly metrics, sometimes with greater significance than traditional daily averages.[24-27] A recent study in New York City found that peak $PM_{2.5}$ exposures (one-hour maximum average) had more robust health impacts than 24-hour average exposures.[28] Downwind in-field mean hourly and peak hourly $PM_{2.5}$ concentrations of an OWB in Upstate New York were found to be considerably higher than similar $PM_{2.5}$ metrics



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reported in recent urban studies showing acute cardiac and pulmonary adverse health outcomes.[29] A 2007 OWB risk assessment concluded that the 24-hour average $PM_{2.5}$ standard metric is not a sensitive measure of the relationships between dose and response for acute wood smoke effects from these devices.[23]

Susceptible populations at greater risk of experiencing health effects from inhalation of $PM_{2.5}$ emissions and other air pollutants commonly measured in wood smoke comprise a large fraction of the general population, including pregnant women, infant, children, and elderly subgroups; persons of any age group with preexisting respiratory, cardiac, and diabetes disease; and persons experiencing high exposures. In the Northeast United States, for example, the young and old comprise 38% of the total population, 4–18% of adults have cardiopulmonary or diabetes health conditions and 12–15% of children have respiratory allergies or lifetime allergies.[30]

Exposure studies in residential wood-burning regions worldwide point to a menacing problem of potentially broad magnitude and public health implications. In North America, RWC is one of the largest sources of $PM_{2.5}$ emissions and hazardous air pollutants (HAPs).[31-33] In both non-urban and urban areas of the United States, for example, RWC emissions can comprise the majority of ambient concentrations of $PM_{2.5}$, carbonaceous $PM_{2.5}$, and VOCs.[9,34-38]

Diurnal and multi-day atmospheric inversions that trap pollutants beneath a low boundary layer can give rise to elevated ground-level emissions over sustained periods.[39-40] The potential for large-scale exposures during these events occurs wherever high densities of humans dwell and burn wood in geographic catchment areas, such as river basins, valleys, and mountainous terrain in both non-urban and urban settings. Under these conditions a small number of RWC devices can contaminate an entire airshed.[41] Because wood combustion aerosols readily infiltrate through building envelopes, ambient RWC emissions, including OWBs, are an indoor air quality threat.[42-45] Indoor exposures to ambient-derived wood smoke have been associated with adverse health effects.[46-47]

In addition to terrain and meteorology effects on plume dispersion and pollution loading, conventional RWC devices, including OWBs, can create worst-case exposure scenarios because of fuel and operator variability, production of non-buoyant plumes and low stack height relative to ground-level receptors.[5,16,48] Unique attributes of OWBs can serve to exacerbate the exposure dynamic. These include short stack exit heights capable of fumigating and impinging at the ground-level, generation of exceptionally high criteria pollutant (e.g., PM) and HAP emission concentrations, intermittent oxygen-starved operating modes conducive to the formation of high molecular weight organic compounds, large firebox capacities to accommodate trash burning, as well as other undesirable fuels, and continuous 24-hour and four-season use.[49-50]

Regulatory Challenges

Conventional regulatory problem-solving tools have not uniformly addressed the risk to public health posed by traditional RWC and the more recent OWB phenomenon. First, the use of the National Ambient Air Quality Standards (NAAQS) $PM_{2.5}$ 24-hr averaging metric (35 $\mu g/m^3$) to establish a bright-line test is problematic. Studies have demonstrated that in some circumstances the standard metric does not adequately protect against sub-daily peaking at hourly concentrations associated with adverse health effects.[23,29,51] A recent spatial analysis of wood smoke in the Adirondack Mountains of New York State, for example, found the presence of elevated transient concentrations of public health concern. The study concluded that current air quality standards mask these episodic peaks through daily averaging.[10]

Current evidence suggests that the $PM_{2.5}$ NAAQS is not an effective means to protect populations from peaking wood smoke exposures, especially vulnerable subgroups, including asthmatics, children, and the elderly. In addition, the current $PM_{2.5}$ monitoring network is sparse in non-urban rural areas where wood burning occurs, in contrast to federal efforts to quantify exposure risks in urban areas to inform the current $PM_{2.5}$ NAAQS review.[52] This constrains regulatory understanding of the frequency and level of impacts to populations exposed to RWC.

Second, technology-forcing measures such as the U.S. Environmental Protection Agency's 1988

Standards of Performance for New Residential Wood Heaters demonstrate the need to implement companion regulations that can rapidly remove pre-existing devices from operation.[53] The assumption that newer units would somehow phase out older units was incorrect.[5] Upwards of 80% of indoor residential wood stoves manufactured before 1990 continue to operate without efficient combustion designs or pollution control devices.[54] There is no historical basis for assuming that regulatory efforts to improve OWB emissions technologies will hasten the removal of the current fleet.[55] Regulations designed to implement technological innovation have practical value prospectively, but will not maximize public health protection unless coupled with non-voluntary regulations to remove outmoded technologies.[56]

Third, efforts to prescribe OWB setback distances as a means of protecting downwind populations generally fail to account for real-world conditions and variability. Model-based determinations, while ambitious, are rarely able to consider all significant sources of variance that can include: multiple devices and other background source contributions to total concentrations; the sub-daily peaking character of emissions; the full range of meteorological parameters, including all wind speed and boundary layer conditions; complex terrain effects; operator behavior, including fuel selection and device control; and emissions rate variation.[57-59]

Successful efforts to describe and account for real-world variability include NESCAUM's source characterization of OWBs,[60] NYSERDA's Adirondack wood smoke field campaign quantifying population exposures,[10] Environment and Human Health Inc.'s report providing self-guidance to residents coping with significant exposure threats from OWBs,[44] and the State of Maine's OWB rules that provide redress for complainants who live outside of prescribed setback distances, but who experience nuisance conditions.[61] **em**

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