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ASHRAE Position Document on

COMBUSTION OF SOLID FUELS AND INDOOR AIR QUALITY IN PRIMARILY DEVELOPING COUNTRIES

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COMMITTEE ROSTER

The ASHRAE Position Document on "Combustion of Solid Fuels and Indoor Air Quality in Primarily Developing Countries" was developed by the Society's Combustion of Solid Fuels and Indoor Air Quality in Primarily Developing Countries Position Document Committee formed on September 16, 2013 with Paul Francisco as its chair.

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HISTORY

of

REVISION / REAFFIRMATION / WITHDRAWAL DATES

The following summarizes the revision, reaffirmation or withdrawal dates

10/03/2016 —BOD approves Position Document titled *Combustion of Solid Fuels and Indoor Air Quality in Primarily Developing Countries*

6/26/2019—Technology Council approves reaffirmation of Position Document titled *Combustion of Solid Fuels and Indoor Air Quality in Primarily Developing Countries*

Note: Technology Council and the cognizant committee recommend revision, reaffirmation or withdrawal every 30 months.

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ASHRAE Position Document on

"Combustion of Solid Fuels and Indoor Air Quality in Primarily Developing Countries"

ABSTRACT
Household solid fuel (biomass and coal) combustion for cooking and heating is one of the most significant contributors to the global burden of disease, especially in low- and middle-income countries (LMICs). As an organization with a focus on the standards and practice that impacts indoor air quality, ASHRAE is concerned with this issue. However, although indoor air quality is clearly within ASHRAE's purview, ASHRAE has not historically focused on LMICs and to date has not made commitments in this area. Addressing this issue requires the expertise of a broad range of fields other than ASHRAE's, making collaboration key. The recently published WHO Indoor Air Quality Guidelines describes the breadth of this issue. ASHRAE's expertise in ventilation and air cleaning technologies can be an important contributor to the ongoing efforts to solve problems related to household solid fuel combustion. ASHRAE should support other organizations through research and standards, especially related to ventilation and air exchange measurement and technologies.

EXECUTIVE SUMMARY

Based on the Disability Adjusted Life Years (DALYs) approach, which includes both years lived with illness or injury and years of life lost due to premature mortality, household air pollution from solid cookfuels was found to be the largest environmental health risk and the third greatest risk factor overall for the global burden of disease, with 4.3% of global DALYs (Lim et al. 2012; Smith et al. 2014). The largest impacts are in South Asia and Sub-Saharan Africa where household air pollution from solid cookfuels is among the top risk factors of any type regionally. In Southeast and East Asia, it is within the top five risk factors. In recent years, there has been a rapid rise in scientific research and national policies have focused on the impact of more efficient stoves and cooking fuels. Global and local modeling studies have estimated the impact of household solid fuel combustion on outdoor air, which can be significant in some countries. Other efforts to address the issue include making cleaner fuels available and managing the air primarily through ventilation.

ASHRAE is not in a position to be the primary leader in this area; however, ASHRAE's knowledge base provides the opportunity to play an important supportive role with leadership in key areas.

ASHRAE's positions at present are:

- ASHRAE is committed to partnering with clean-energy organizations and initiatives to provide expertise on home ventilation strategies.
- ASHRAE is committed to supporting research on ventilation/air change measurement and air cleaning options that are feasible in locations where common equipment and supplies are not available or easily accessible.
- ASHRAE is committed to developing standard methods of test for measurements of air change that are feasible in settings where common measurement equipment and supplies are not available or easily accessible.
- ASHRAE is committed to developing guidelines for proper design to achieve effective natural ventilation.
- ASHRAE is committed to pursuing strategic alliances, through mechanisms such as MOUs, with other organizations for all activities, including technical assistance and leveraging of research funding, in order to bring knowledge of local infrastructure, cultural norms, and regional/climatic challenges.

1. THE ISSUE

Household air pollution (HAP) from solid fuel combustion results in serious pollution and is a major component to the global burden of disease. Efforts to address the issue include improving stoves, making cleaner fuels available, and managing the air primarily through ventilation.

2. BACKGROUND

Household solid fuel (coal or biomass) combustion for cooking and space heating is a widespread source of air pollution exposure. In high-income countries, households use solid fuels primarily for space heating. In other areas solid fuels are used solely for cooking, while in others, for both cooking and heating, sometimes using the same stove. Over 40% of the world's population (about 3 billion) uses solid fuel for cooking in this decade (Bonjour et al., 2013), and many of these people (approximately 1.3 billion) also live without access to electricity (UNDP).

Based on the Disability Adjusted Life Years (DALYs) approach, which includes both years lived with illness or injury and years of life lost due to premature mortality, household air pollution from solid cookfuels was found to be the largest environmental risk factor and the third greatest risk factor overall for the global burden of disease, with 4.3% of global DALYs (95% confidence interval of 3.4-5.3%) from this source (Lim et al. 2012; Smith et al. 2014). The global distribution is far from uniform, however. The largest impacts are in South Asia and Sub-Saharan Africa where household air pollution from solid cookfuels is among the top risk factors of any type regionally. In Southeast and East Asia, it is within the top five risk factors. In other developing regions it is still important, but not so large compared with other risk factors. In contrast, there are so few people cooking with coal or biomass in North America and Western Europe that the disease burden is too low to quantify. (See http://www.healthdata.org/data-visualization/gbd-compare). In recent years, there has been a rapid rise in scientific research and national policies have focused on the impact of more efficient stoves and cooking fuels (for example the relatively recent shift in research priorities of the NIH, the development of cookstove standards by ISO, and the national cookstove programs of India, Nepal, and Peru). Wood-fired heating has been studied mainly in North America – with a focus on Native American populations – and Europe, but is also of research and policy interest in temperate regions with access to forests. Updated wood heating stoves standards, for example, are being promulgated by the US EPA. Global modeling studies have estimated the impact of household solid fuel combustion on outdoor air, which can be significant in some countries.

Studies of air pollution exposure and household concentrations have shown that the most critical mitigation strategy is to improve the quality of the combustion process itself, as it is difficult to sufficiently reduce exposures with just a chimney or general ventilation. In fact, even outdoor cooking over an open fire will create unhealthy exposures. The recent WHO Indoor Air Quality Guidelines (http://www.who.int/indoorair/guidelines/hhfc/en/) specifies Emissions Rate Targets for PM2.5 and CO that are necessary for cookstoves to meet health protective air quality guidelines (http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/). These were calculated in a probabilistic manner based on several factors including the measured distribution of air change rates in typical village households. However, there will be significant benefits from ventilation in some locations, depending on outdoor air pollution, climate, technology, infrastructure, incomes, and cultural norms.

Key Considerations:

- Reducing emissions is the most important factor for achieving good indoor air quality.
- The most serious impacts from household solid fuel combustion are in LMICs where cooking with solid fuels in unvented stoves is common.
- Impacts of space heating in LMICs are less well-characterized, but are coming to be better understood in developed countries which commonly use vented stoves.
- Improved combustion through modern biomass stoves is being promoted by a number of agencies
- There are many organizations working on improving combustion in these regions, and ASHRAE is not well-suited to enter this space.
- Solutions are not only technical, but also must take into consideration cultural and economic aspects.
- Clean fuels such as gas (liquefied petroleum gas and natural gas) and electricity, which already provide cooking energy to the richest 60% of the world, are starting to be provided to more of the poorest 40% and probably provide the best long-term solution for all.
- Biogas and bioethanol offer ways to obtain the clean-burning characteristics of gas using local renewable biomass sources in some areas. Biomass pellets made locally can also be burned more cleanly that loose biomass.
- Solar cookstoves can be used effectively for certain cooking tasks in some geographic areas and are often effective in institutional settings.
- Improved combustion venting, and home ventilation, can be beneficial in some locations.
- The contribution of solid fuel combustion to outdoor air pollution must be taken into account when ventilation is considered as a strategy for improving indoor air quality.

3. RECOMMENDATIONS

ASHRAE's positions at present are:

- ASHRAE is committed to partnering with clean-energy organizations and initiatives to provide expertise on home ventilation strategies.
- ASHRAE is committed to supporting research on ventilation/air change measurement and air cleaning options that are feasible in locations in which common equipment and supplies are not available or easily accessible.
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Appendix A – TECHNICAL REVIEW

A.1 Overview

It is thought that humanity began cooking with wood nearly 2 million years ago at the time we moved from the trees to living on the ground. Indeed, control of fire is probably the best transition point to indicate the change from pre-human to human state (Wrangham 2009). Today, in spite of much progress globally, about 40% of the world's population still cooks with solid fuels, with wood being joined by agricultural residues as well as coal in a few areas.[1] Although 60% of households now use modern fuels – gas and/or electricity – to cook, the increase has not kept up with population growth. Indeed, today, at a worldwide population of three billion, the number of people using solid cookfuels is probably greater than at any time in human history (Bonjour et al. 2013).[2]

Much of this solid fuel is burned in simple stoves – often just a pit, three rocks, or a U-shaped volume in a block of clay. Locally produced metal stoves, which are also common around the world, rarely have designs that improve combustion or are made of durable materials. Although most cooking is done indoors, there are hundreds of millions who cook outdoors in courtyards or other semi-enclosed arrangements, often seasonally. Indoors or outdoors, the vast majority of such cooking is done without flues, chimneys, or other venting arrangements to remove smoke from the living environment. Given that even outdoor cooking produces unhealthy exposures to pollution in household environments, the preferred term for this risk factor is now household air pollution (HAP), not indoor air pollution (Smith et al. 2014).

The simple design of traditional biomass cookstoves combined with extreme heterogeneity of natural biomass typically results in both poor combustion efficiency (conversion of fuel chemical energy to heat and radiation) and poor thermal transfer efficiency (transfer of this released energy into the cooking vessel) and, therefore, low overall energy efficiency. Burning biomass in such conditions produces a vast range of organic and inorganic compounds mainly as incomplete combustion products. These products – here termed "smoke" – cause of most of the ill-health associated with biomass burning.

A.2 Health Effects

The health effects produced by cookstove smoke have been extensively reviewed by several international expert groups (Lim et al. 2012, WHO 2014a, WHO 2014b, GBD 2015, Smith et al. 2014). Household air pollution from cooking with solid fuels is estimated to be the largest single environmental risk factor globally, exceeding poor water, inadequate sanitation, and ambient air pollution in its burden of ill-health. Globally, evaluations by different groups estimate that between 3.5-4 million premature

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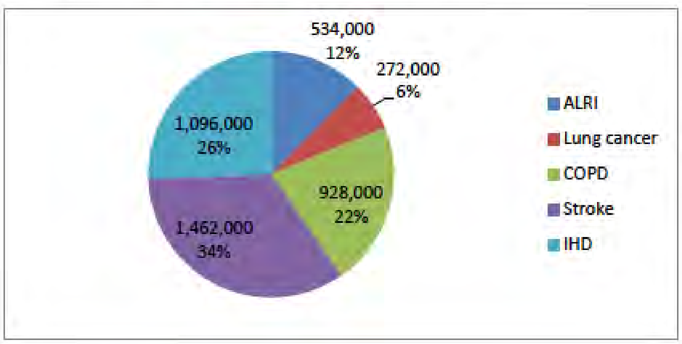
[1] Although sharing many issues with biomass fuels, coal poses additional challenges due to the great variety of coals in different areas sometimes with quite different compositions, including in some cases toxic contaminants such as sulphur, arsenic, fluorine, lead, mercury, etc. This report does not address these additional hazards of coal, but readers are referred to the review in WHO, 2014b.

[2] Most research that has been done on the topic of residential solid fuel use has been in the cooking context and so that is the primary focus of this discussion. Readers are referred to Chafe et al. , 2015 for further discussion.

deaths annually are attributable to HAP, with individual estimates overlapping in terms of their uncertainty bounds (see Figure 1). In a number of poor countries, HAP is the greatest risk of all, exceeding the risks of smoking, malnutrition, and blood pressure, but in nearly all poor countries it is among the top 4 risk factors, even including unsafe sex or risks for malaria.[3] These estimates are based on reviews of the global epidemiological literature indicating that significant proportions of six major diseases can be attributed to household air pollution: pneumonia in young children and, in adults, chronic obstructive pulmonary disease (COPD), heart disease, stroke, cataracts, and lung cancer. There is substantial additional evidence of other effects as well, including other cancers, still birth, low birth weight, birth defects, prematurity, tuberculosis and cognitive impairment. As these are well-established already as health impacts of smoking, it is likely that with more research they will be firmly associated with HAP as well since those now linked to HAP are also largely the most important impacts from smoking. Appendix B briefly summarizes the evidence supporting an association between HAP and a number of adverse health impacts in children and adults.

***Figure 3**. Deaths attributable to HAP in 2012, by disease*



Percentage represents percent of total HAP burden (add up to 100%).
HAP: Household air pollution; ALRI: Acute lower respiratory disease; COPD: Chronic obstructive pulmonary disease; IHD: Ischaemic heart disease.

Figure A1. Deaths Attributable to HAP in 2012, by Disease. (*Source - WHO - Burden of disease from Household Air Pollution for 2012* (WHO 2014a))

Among the thousands of chemicals found in woodsmoke, hundreds are hazardous including organic compounds known to be mutagens, immune system suppressants, inflammation agents, central nervous system depressants, cilia toxins, endocrine disrupters, and neurotoxins. Several others are firmly established as human carcinogens, including benzene, formaldehyde, poly-aromatic hydrocarbons, and dioxin (Naeher et al. 2007). In addition, there are toxic inorganic pollutants such as carbon monoxide and nitrogen oxides. Minus nicotine, woodsmoke is much like that from burning tobacco and, as noted in Appendix B, the health impacts are quite similar in type, if not in quantity.

As in studies of the health impacts of tobacco smoke, the best single indicator of the health risks of HAP is thought to be $PM_{2.5}$, particles under 2.5 micron in size, which penetrate deep into the lung. Second in importance for health is probably carbon monoxide. In general, the two pollutants are thought to

[3] Institute of Health Metrics and Evaluation, Global Burden of Disease website: http://www.healthdata.org/results/country-profiles

produce different health effects. As measured in woodsmoke, however, it should always be recognized that they are just indicators of a large range of other health-threatening pollutants that are in the smoke.

Because of the vast array of traditional biomass fuel types and stove characteristics, not to mention size, shape, and moisture contents in fuels used across the world in different seasons, there is not good characterization of "average" traditional stove emissions. Nevertheless, measurements show that typical wood-fired traditional cookstoves release $PM_{2.5}$ equivalent to 300-500 cigarettes being smoked per hour.

The vast majority of all cooking in the world is done by women, who also are nearly always the primary caregivers for infants (children before walking age). As a result, these two groups receive the highest exposure to cookstove smoke, although older children and men are also exposed. As a result, a perfect storm of risk is created: a highly polluting activity, done multiple times daily, at times and places when the most vulnerable people in the world are present – poor women and their youngest children.

A.3 Outdoor Air Considerations

It is now recognized that in many countries, household solid fuels are a major source of ambient particle pollution as well as exposure to particulate matter by people in the immediate household environment. Merely exhausting the smoke to outside does not eliminate its hazard. It comes back into the house, goes next door, pollutes the village air, and travels downwind to become part of the background pollution that can affect vast areas in some countries. For example, in India, household biomass use has been estimated to be responsible for 25-50% of all ambient particle pollution in the country in recent studies (Lelieveld et al. 2015). In Northern China, similar percentages have been estimated (Lelieveld et al. 2015, Liu et al. 2016). Table 1 shows examples of measured outdoor winter-time $PM_{2.5}$ levels from six studies in five countries. This table shows that average winter-time outdoor $PM_{2.5}$ levels have been measured as high as 250-450 $\mu g/m^3$, in Ulaanbaatar, Mongolia, and that outdoor levels are often very high in other locations. These high levels are in contrast to those found in other locations such as Kocaeli City, Turkey, with a measured average of about 22 $\mu g/m^3$, or New York City, with a measured average of about 17 $\mu g/m^3$.

The very high levels of $PM_{2.5}$ in some locations during winter is heavily influenced by heating, showing that there are significant climate considerations regarding the impacts of solid fuel use on outdoor air. Annual levels may be much lower, especially in locations where heating is needed less. Brauer. et al (2016) reports that the rural and urban mean annual concentrations of PM2.5 in Uganda is 18 $\mu g/m^3$, in Rwanda is 17 $\mu g/m^3$, in Mexico is 12 $\mu g/m^3$, and in Sri Lanka is 17 $\mu g/m^3$. Biomass burning from cooking has been shown to contribute 2.8 $\mu g/m^3$ in southern sub-Saharan Africa. South Asia showed the highest regional concentration of outdoor PM2.5 from household cooking (8.6 $\mu g/m^3$) (Chafe et al. 2014).

Clearly, when outdoor levels are extremely high, ventilation will be of little value since the makeup air will also be heavily polluted. Since the outdoor levels are often largely due to the use of the stoves of interest, solving the outdoor problem requires making the stoves much cleaner which in turn would mean that there would be less pollution that ventilation would need to remove and therefore ventilation would be less necessary.

Table A1. Measured outdoor $PM_{2.5}$ concentrations in various locations around the world.

Location	Sample	Time period	Range or average, µg/m^3
Ulaanbaatar, Mongolia (Ochir et al. 2014)	Four locations	Jan. 22 – Mar. 2, 2013	280-450
Shaanxi province, China (Zhu et al. 2010)	Three rural sites	Winter, 2007-2008	268
Agra, India (Massey et al. 2012)	At five urban roadside homes	Winter, 2007-08 and 2008-09	212
	At five urban homes		157
Guangzhou City, China (Huang et al. 2007)	Nine sites	Winter, 2004-2005	124
Koaceli City, Turkey (Pekey et al. 2010)	At 15 homes	Dec. 16, 2006 – Jan. 20, 2007	22
New York City, NY, USA (Kendall et al. 2002)	At 8 homes	12 days in winter	17

The community effect of household air pollution has several major implications. First, it indicates that simple venting is not a widespread solution in that it just moves the smoke from one place to another instead of eliminating it. Second, it indicates that community solutions should be sought – just providing clean fuels to a few homes in a village may not have much health benefit if they are receiving smoke exposures from their neighbors. Third, it indicates that cleaning up household combustion must be part of any strategy to address the severe ambient pollution that plagues countries like India and China.

A.4 Technological Approaches/Stove Design

There are three major approaches to reducing the health impacts of HAP globally. As use of solid fuels is a problem primarily of poverty, the first approach is just to hope that development will take care of it. Unfortunately, although the number of people using modern clean fuels has steadily risen with development, the total using solid fuels has not fallen overall for decades, although it is improving in some areas such as China. This approach is thus not working.

The second major approach is to attempt to burn biomass fuels more cleanly, to "Make the Available Clean" (Smith and Sagar 2014). Everything else remaining the same, better energy efficiency means less fuel burned and thus less smoke. Designing and disseminating more efficient stoves is one approach. Improving fuel efficiency is almost always beneficial and has other benefits beyond reducing pollution such as reducing impacts on forests and fuel gathering time for women, and, where fuels are purchased, saving money. Unfortunately, however, the needed reduction in smoke emissions to bring $PM_{2.5}$ down to acceptable levels is an order of magnitude, or more, greater than what can be achieved by simple improvements in fuel efficiency. Thus, what is needed is redesign of stoves to improve combustion efficiency (the percent of fuel chemical energy that is converted to heat and radiation during combustion)[4] – perhaps well above 99% as is common with gas and liquid fuels. Although much progress has been made, such efficiency improvements have been an insurmountable challenge using unprocessed biomass available easily via gathering. Even the best available unvented loose-biomass stoves produce $PM_{2.5}$ at rates that are higher in lab tests than are allowable to protect health according to the WHO, never mind in real households (WHO 2014b). Nevertheless, the attraction of using local biomass as fuel continues to drive innovation in this arena. The best available loose-biomass stoves vented with chimneys have been able to meet the WHO Intermediate Indoor Air standard for $PM_{2.5}$ (see Appendix C for a description of stove technologies and Appendix D for a discussion of WHO activities) in lab conditions (Still et al. 2015a), though field testing has yet to be completed to determine whether the stoves can be successful in real world conditions.

As with fuel efficiency in automobiles, there is typically a large gap between expectations from lab results and those achieved under conditions of actual use (Carter et al, 2014). Bridging this gap – making stoves sufficiently robust and improving testing protocols such that field performance more closely matches lab results – is another urgent need.

The third major approach is to accelerate the historical trend for households to move to clean fuels over time, i.e., to gas and electricity, i.e., to "Make the Clean Available" (Smith and Sagar 2014). Due to the lack of contaminants, uniformity of composition, and ease of premixing with air, nearly any gaseous fuel can be burned quite cleanly with inexpensive stoves. Liquefied petroleum gas (LPG) and natural gas are the primary modern gaseous fuels that today provide clean cooking worldwide. There are financial and infrastructure barriers to making them available for a larger proportion of the world's poor, but the health advantages of doing so are substantial. In addition, electric induction stoves have brought the efficiency of electric cooking into a range that they are now being promoted in poor populations with access to electricity in some countries.

In the interstices of the two large-scale approaches are a range of technical innovations that can play roles in reducing exposures from fuels. Gas fuel from local sources is one such approach. Primary among these is biogas made from anaerobic digestion of animal dung to produce a methane-rich fuel. This has made some impact in India and China and shows promise for further expansion. Less well developed to date, but also showing progress, is bio-ethanol from fermentation of cassava, sugar cane, or other plantation crops. Ethanol has been shown to burn quite cleanly in household stoves, but the main concern is how competition from other sectors would affect its price to households. Finally, processing biomass into pellets provides a fuel that can be burned much more cleanly than loose biomass due to being uniform in size, shape, composition, and moisture and thereby allowing optimization of stove design for combustion efficiency. To rely on biomass pellets, however, would require development of local fuels cycles including central collection of biomass.

Solar energy shows promise for some cooking needs, but is hampered at present by lack of affordable energy storage to enable cooking when the sun is low or at night, which is the primary need in most

[4] Often approximated by the fraction of fuel carbon converted to CO_2,- i.e., modified combustion efficiency (Jetter et al., 2012)

households globally.   Institutional cooking with solar energy using steam or hot oil storage, however, is practical in many areas.

One major research need in the field of solid fuel stoves is estimation of *in-situ* air change rates, especially when seeking to quantify improvements due to clean energy interventions. The highly weather-dependent nature of natural infiltration makes *in-situ* air exchange estimation necessary and critical to interpretation of results; however, standard methods used in the developed world are often impractical in the developing world due to lack of equipment and infrastructure. Developing accepted methods and standards for air exchange estimation in these environments would be a valuable contribution.

A.5 Ventilation

When discussing ventilation it is vital to distinguish between whole-dwelling ventilation and stove venting. Stove venting is neatly always beneficial, but is often not sufficient to provide healthy indoor environments. Whole-dwelling ventilation will only be of value in some situations.

A.5.1 Ventilation strategy in high ambient air pollution areas

Clearly, when outdoor pollution levels are extremely high, ventilation will be of little value since the makeup air will also be heavily polluted. Since stoves themselves are often a major contributor to outdoor pollutant levels, solving the outdoor problem requires making the stoves much cleaner – in which case the ventilation would be less necessary. However, there are situations when the outdoor air pollution is caused by outdoor activities not necessarily linked to the use of stoves and, in many instances, caused by trans-boundary haze that can be attributed to industries, coal-fired power plants, forest fires and slash-and-burn activities leading to unintended adverse consequences. In such situations, ventilating the indoor environments for household air pollution can only be effective if the ambient or make-up air used for dilution is filtered for $PM_{2.5}$. This would typically require a MERV 11 or higher rated filter that would inevitably add cost to the process of keeping the indoor environment reasonably clean and reduce the burden of diseases due to household air pollution. It would, therefore, be prudent to explore innovative, simple and cost-effective technological solutions in the form of fan-filter units. As it would be ideal to achieve a certain level of airtightness of such indoor environments for ventilation strategies coupled with filtration to be effective, simple refurbishment of the facades of these indoor environments to achieve improved airtightness – to the extent possible – may be necessary.

A.5.2 Ventilation strategy due to household air pollution in relatively clean ambient air areas

In relatively clean ambient air regions/zones, ventilation using outdoor air for diluting indoor contaminants generated by solid fuel combustion can be quite effective. There will also not be a need to clean the outdoor air when it is within acceptable threshold limits. In its basic concept, the provision of openings on the façade to enhance general cross ventilation should be explored. As a particular configuration, drawing of relatively cooler outdoor air through the lower levels (such as doors/windows) coupled with a chimney directly above the solid fuel combustion zone (i.e. the cooking plane) could prove beneficial. It is apparent that these natural ventilation strategies described will be dependent on wind conditions, both in terms of direction and intensity. When infrastructure allows, an enhancement could be considered by providing a simple cost-effective exhaust strategy (either an exhaust fan upstream of the chimney and close to the cooking zone or a downstream self-activated roof turbine fan at the chimney end).

A.6 Social Considerations

Finally, as with any household behavior that is intimately connected with daily life, there are cultural and social aspects of cooking patterns that are often slow to change even when more convenient and healthful alternatives become available. As with any new technologies, there tends to be a period of overlap between the old and new, which for cooking is called "stacking", i.e. both old and new devices are used, but usually for different cooking tasks. Means are needed to shorten this period in order to maximize the health and other benefits of improved stoves and fuels. In addition, new cooking stove and/or fuel also can pose significant cost to the poorest families who rely mostly on biomass. Thus innovative ways to enhance affordability is required for large-scale dissemination to the poor. Indeed, the global challenge from a public health standpoint could be summarized as finding ways to move poor people into healthier behaviors and living conditions before they become wealthy by promoting, in this case, the best cooking technology in the world by applying modern financial, behavior, and information science in doing so. This is how to enhance health for the bottom billions.

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Appendix B – Health Effects associated with Residential Solid Fuel Use

Glossary:

Meta-analysis – a statistical approach to combine the results of multiple studies into a single risk estimate and confidence interval by weighting the contribution of separate studies according to quality criteria.

Odds Ratio (OR) – measure of association between exposure and outcome; a confidence interval above 1.0 indicates a statistically significant increase in risk. An odds ratio of 1.5, for example, means that there is a 50% greater likelihood of the outcome occurring than if the exposure had not been present. Odds ratios or the similar term, relative risks (RRs), are commonly reported along with a confidence interval (CI) indicating the range within which there is a 95% chance that the true effect lies. The usual convention is that if the CI does not include 1.0, the effect found is considered statistically significant.

Pregnancy and birth outcomes. The fetal, neonatal, and infant periods are considered to be very critical periods of maturation during which adverse environmental effects like exposure to air pollution may have permanent consequences. The small number of studies that have evaluated the relationship between solid fuel use and outcomes related to pregnancy and birth including low birth weight, stillbirth, pre-term birth, and miscarriage have been reviewed in detail by Pope et al (2010), Misra et al (2012), and Amegah et al (2014), and are briefly summarized here. A recent systematic review and meta-analysis found that the increased risk of low birth weight associated with solid fuel use (compared with clean-burning stoves) was OR=1.38 (95% CI: 1.25, 1.52) and an associated mean reduction of 96.6 g (95% CI: 68.5, 124.7) in birth weight; the increased risk of stillbirth was OR=1.51 (95% CI: 1.23, 1.85) (Pope, 2010), with other reviews finding similar results. In one case-control study that measured miscarriage and ascertained neural tube defect and provided a case definition, the researchers found an increased risk of second trimester miscarriage (OR: 3.83, 95% CI: 1.50, 9.90) associated with use of solid fuels among Indian women, after controlling for period of gestation.

Respiratory outcomes and infections in children and adults. There is strong and consistent evidence of a causal association between HAP exposure and acute lower respiratory infections in children, which are the leading causes of death in young children in developing countries. A review and meta-analysis from the WHO found that children exposed to HAP were at an increased risk of acute lower respiratory infection, or ALRI (pooled OR=1.56, 95% CI: 1.33, 1.83). For severe ALRI, as determined by physician diagnosis or low oxygen saturation, the risk of ALRI was nearly two-fold among children exposure to HAP (pooled OR=2.04, 95% CI: 1.33, 3.14). Among adults, a number of studies have assessed the association between HAP from solid fuels and chronic obstructive pulmonary disease, or COPD. COPD was estimated to be responsible for 2.9 million deaths in 2010, and was the third leading cause of death globally after cardiovascular diseases. The WHO-led meta-analysis found an almost two-fold risk of ALRI among adults exposed to HAP (pooled OR=1.94, 95% CI: 1.62, 2.33) though there was significant heterogeneity of the studies and evidence of publication bias (WHO 2014b). There is nonetheless strong overall evidence suggesting a causal relationship between HAP exposure and COPD, particularly in light of the very strong evidence linking smoke and COPD.

Cardiovascular diseases. Cardiovascular diseases are the leading causes of death globally and increasing in most developing countries (Lim et al. 2012). A large body of literature on smoking and ambient air pollution demonstrates a causal association with the development of cardiovascular disease and the incidence of cardiovascular events, and with longer-term exposure being associated with even greater risk (Brook et al. 2010; Lim et al. 2012). In contrast, no studies of household air pollution have been long or large enough to assess a possible causal association between solid fuel use and the development of clinical cardiovascular disease. Thus, the hypotheses that associate HAP with cardiovascular diseases are based almost entirely on inferences from exposures to outdoor air pollution and smoking (active and secondhand) (Burnett et al., 2014).

Cancer. There is strong and consistent epidemiologic evidence that demonstrates a causal relationship between cooking and heating with coal and lung cancer. In a systematic review and meta-analysis conducted by Hosgood et al., household coal use for cooking and heating was strongly associated with an increased risk of lung cancer when evaluating all studies (pooled OR=2.15, 95% CI: 1.61, 2.89) (Hosgood et al., 2011), and it was classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC) (Straif et al., 2006). Exposure to biomass smoke was classified as 'probably carcinogenic' (Group 2A), in large part due to less epidemiologic evidence. A meta-analysis conducted for the WHO Guideline group found an increased risk of lung cancer from biomass cooking for both men (pooled OR=1.17, 95% CI: 1.05, 1.31) and women (pooled OR=1.20, 95% CI: 0.97, 1.49), with some heterogeneity between studies (WHO 2014b). Though studies of smoking (active and secondhand) further support the hypothesis of a link between HAP and other types of cancers (WHO 2014b), further research in this area is needed.

Cataracts. There is consistent epidemiologic evidence suggesting HAP exposure is associated with severe lens opacification, or cataract (Lim et al. 2012), a relationship which is further supported by strong evidence linking smoking with cataract and age-related macular degeneration (Cong, 2008; Chakravarthy et al. 2010). The pooled relative risk for seven studies comparing cataracts among biomass versus cleaner-burning fuel users using a random effects model was 2.46 (1.74, 3.50) (Lim et al. 2012).

Exposure-response relationships. The exposure-response relationship between $PM_{2.5}$ and lung cancer is approximately linear, meaning that the relative benefit achieved with a given intervention does not depend on the baseline exposure (Pope et al. 2011). In contrast, the observed exposure-response between biomass smoke exposure and ALRI in children from the RESPIRE study and extrapolated exposure-response relationships between $PM_{2.5}$ and ischemic heart disease and stroke in adults are strongly suggestive of 'supralinear' exposure-response relationships, meaning that the relative risk of disease is very steep at low levels of exposure and then flattens off at the highest exposure levels (Burnett et al. 2014, Pope et al. 2009, Smith et al. 2011). The supra-linear relationship has important implications for the health benefits from clean energy technologies since it suggests that exposures likely need to be very low to observe a measurable population health benefit for many important outcomes. In light of this evidence, for example, it is unlikely that ventilation of a biomass cookstove on its own is sufficient for reducing $PM_{2.5}$ to a sufficiently low level. Further, the use of traditional stoves in conjunction with cleaner-burning stoves and fuels (i.e., stove stacking, discussed in detail in the following section) may largely negate any potential health benefits of the intervention (Johnson and Chiang 2015).

Appendix C – Stove Technologies and Emissions

This appendix provides information regarding performance of different stoves from multiple sources, as well as discussing ongoing ISO efforts to develop stove testing standards.

Figure xx shows results from stove evaluations done in a test kitchen. This figure shows three common stove types: the Three Stone Fire (TSF), the Rocket stove, and the Top-Lit Updraft stove (TLUD).

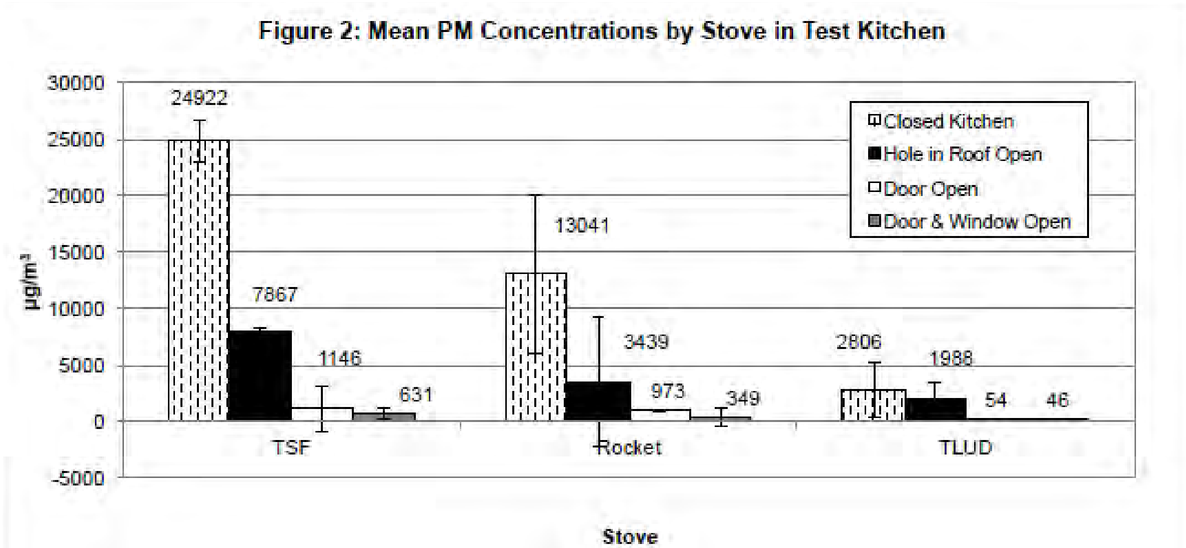

Figure 2. Mean $PM_{2.5}$ Concentrations by Stove in Test Kitchen. (Source: Grabow et al. 2013)

The following is a partial summary from *Clean Burning Biomass Cookstoves* (Still et al., 2015b) (note: Tier 4 is the designation for the least-polluting stoves):

- A large range of stoves achieved over 40% thermal efficiency when tested at medium power with a 6mm pot skirt.
- Cleaner burning wood stoves easily achieve Tier 4 on measures of Carbon Monoxide.
- Unfortunately, even the best unvented stoves (in lab tests) emitted more $PM_{2.5}$ than permitted by the new WHO indoor air guidelines (WHO 2014b) and the similar International Workshop Agreements (IWA) Indoor Air Tier 4 metric.
- A charcoal burning stove scored in the Tier 4 range on all nine ISO/IWA metrics. When charcoal is well made (the wood is completely burnt out) the charcoal does not make appreciable amounts of smoke. The auto-ignition temperature of CO can quickly be reached when the stove is well insulated. Natural draft jets of secondary air also seem to help to combust the CO.
- It must be kept in mind that real world tests of stoves have consistently shown higher levels of CO and $PM_{2.5}$ compared to lab test results. The next step is to test clean burning stoves in use as one part of an effort to design interventions that might protect health. The effective intervention is certainly a lot more than just the stove.

Studies of modern biomass cookstoves have found that in laboratory Water Boiling Tests forced air stoves with chimneys can emit less than the WHO vented stove Intermediate Emission rate $PM_{2.5}$ target (Still et al. 2015a) (see Appendix D). As with any other results, these need to be verified in the field under conditions of actual use.

Appendix D – Activities of World Health Organization (WHO) and International Standards Organization (ISO)

World Health Organization Indoor Air Quality Guidelines (WHO IAQGs)

In 2014, the WHO published its Indoor Air Quality Guidelines for Household Fuel Combustion, which was the result of nearly three years of work of a large international expert group that extensively reviewed the world literature on emissions, exposures, health effects, technologies for control, economics, climate, safety, and other aspects of fuels and appliances used for household cooking and lighting, with heaviest emphasis on solid fuels for cooking in developing countries. This work was extensively peer reviewed and then revised, again reviewed and revised, and then separately reviewed and revised according to the rigorous internal protocols that WHO now uses to evaluate and approve all recommendation and guideline documents. The entire process was subject to extensive scrutiny of potential conflicts of interest among the expert group members and reviewers. A common set of methods was developed and published for assessing and judging evidence and, as much as possible, applied across all aspects of the review. The extended Summary is available in hard copy (WHO 2014) but the eleven chapters presenting the main evidence reviews are only available on the WHO website[5].

Four groups of recommendation were made:

1 – Emission rate targets: limits to emissions indoors and via flues that can be considered health protective based on the previously published WHO Air Quality Guidelines (WHO 2006)
2 – Policy during transition: recommend moving to clean fuels as rapidly as possible and promote lower emission stoves in the interim for populations not soon able to adopt clean fuels
3 – Household use of coal: recommend prohibition of any unprocessed coal use in households and caution about use of so-called "clean coals"
4 – Household use of kerosene: recommend no expansion of use and caution about any use

Of most relevance to this ASHRAE document are the quantitative Emission Rate Targets (ERTs) for PM2.5 and CO for household cookstoves, which are reproduced below from the Summary. Note that separate ERTs are provided for vented and unvented stoves and that intermediate ERTs are provided to allow for benchmarking of stoves that have lower emissions than traditional stoves, but still do not reach the final recommended ERTs. Also note that the ERTs are framed in a probabilistic manner because there are wide ranges in the household conditions (hours of use per day, household volume, and air exchange rates) that affect the relationship between emissions and indoor concentration. The ranges were taken from literature describing the situation in India, which has one-quarter of the world's solid fuel cookstoves and where the most studies on pollution from cookstoves have been done. Monte Carlo modeling was conducted to repeatedly sample within those ranges to derive the final values. Importantly, the ERTs do not claim to represent emissions that would protect every household no matter how small and poorly ventilated from exceeding the AQGs, but rather what would be needed to protect 60%, 90%, etc.

[5] http://www.who.int/indoorair/guidelines/hhfc/en/

Also of particular relevance to this document is an appendix section on Testing facilities and protocol development.

WHO. 2006. WHO *Air quality guidelines global update 2005: particulate matter, ozone, nitrogen dioxide and sulfur dioxide.* Copenhagen: World Health Organization Regional Office for Europe, 484 pp.

WHO. 2014. WHO *Indoor air quality guidelines: household fuel combustion,* Summary, Geneva: World Health Organization, Geneva, 152 pp.

Table R1.2: Emission rate targets (ERT) for meeting WHO AQGs for $PM_{2.5}$

ERT	Emission rate (mg/min)	Percentage of kitchens meeting AQG (10 μg/m³)	Percentage of kitchens meeting AQG IT-1 (35 μg/m³)
Unvented			
Intermediate ERT	1.75	6	60
ERT	0.23	90	100
Vented			
Intermediate ERT	7.15	9	60
ERT	0.80	90	100

Table R1.3: Emission rate targets (ERT) for meeting WHO AQGs for CO

ERT	Emission rate (g/min)	Percentage of kitchens meeting 24-hour. AQG
Unvented		
Intermediate ERT	0.35	60
ERT	0.16	90
Vented		
Intermediate ERT	1.45	60
ERT	0.59	90

Figure D.1. WHO Emission Rate Targets

International Standards Organization (ISO) Standards Efforts[6]

As of this writing, there is an ISO effort (ISO TC 285) underway to standardize evaluation of solid fuel stoves. This effort has the largest representation of developing world countries of any ISO standard. The intent of TC 285 is to harmonize evaluation of stove and fuel emissions, efficiency, safety, and

[6] http://www.iso.org/iso/iso_technical_committee?commid=4857971

durability, including performance in field conditions and social impacts. There are several working groups within the committee:

- Working Group 1 is tasked with providing guidance regarding the applicability of a test protocol to a given situation. This effort recognizes that no single test is appropriate for all situations.
- Working Group 2 is tasked with harmonizing **laboratory** test methods, for a variety of issues (emissions, fuel efficiency, safety, durability), and includes recommendations for ways to harmonize and customize stove and fuel operation for international comparability and regional relevance.
- Working Group 3 is tasked with harmonizing **field** test methods, including consideration of aspects that cannot be adequately captured in the lab such as user practices.
- Working Group 4 is tasked with providing guidance regarding social impacts.

There are also two task groups, one tasked with reviewing existing standards on fuels and one with ensuring good communication with all stakeholders throughout the process.

It is expected that the earliest date that this process will be completed is in 2016.