A Research Road Map:
Improved Cook Stove Development and Deployment for
Climate Change Mitigation and Women’s and Children’s Health
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REPORT TO THE U.S. STATE DEPARTMENT FROM THE
ASEAN-U.S. NEXT-GENERATION COOK STOVE WORKSHOP (NOV 2009)

“If user demand were the sole driver of innovation, the biomass cooking stove would be one of the most sophisticated devices in the world.”

“The cost of providing such fuel efficient stoves to every family on earth now using biomass fuels for cooking would be less than a typical 1GW nuclear power plant, yet save some 10-20 times as much energy each year as the reactor would produce during its entire lifetime.”

“Each megajoule of energy produced by a traditional biomass-burning cook stove produces more than 100 megajoules of atmospheric warming due to solar heating of the resultant cook stove emissions.”

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Executive Summary

This report summarizes ASEAN-US Next Generation Cook Stove Workshop held at the Asian Institute of Technology in November 2009. Three billion people use biomass or coal-burning cook stoves that are responsible for more health problems than any other category of energy use globally and are the most greenhouse-intensive fuel systems in the world, per unit energy delivered. Thus, there is an urgent need to develop and deploy effective and efficient solid fuel stoves on a global scale. The Workshop produced recommendations for the development of a systematic short-term program to improve and verify the performance of cook stoves in ways that will permit them to be produced on the scale necessary to meet the global requirements.

Research to improve cook stove performance and acceptance suggested herein must be seen in the larger context of household energy systems. For most of the three billion cook stove users, their stove also provides lighting and space heating. The recommendations from this Workshop also impact those other two domestic energy functions.

Recommendations

One size fits some (not all) – It is important to first identify groupings of users with similar cooking preferences, fuel, availability of electricity, etc., and to determine the number of users in each grouping, thus defining a “cook stove user space”. The largest user groupings can be targeted and several sets of specifications, one for each grouping, can be created. To see the best return on research investment, the development focus should be on large groupings and developing basic principles for stove design that can be adapted to a variety of user needs.

“You don’t get what you expect, you get what you inspect.”16 – The ability to test a stoves’ performance in the lab and in the field is essential. Improvements in sensor technology, computerized data acquisition, and networks need to be applied to the cook stove problem. Cook stoves present special challenges because of the mixture of air, combustion products, and moisture that are present in their emissions. Automated in situ measurements and data logging (i.e., not monitoring that relies exclusively upon user logs) can establish actual use patterns and quantify reductions in emitted products of incomplete combustion (PIC) and exposure under actual operating conditions. In a program this large, carefully planned and documented statistical sampling will be required. Such data can be used to justify further investment, motivate field staff, and provide useful feedback to make mid-course corrections, while documenting household conditions that can provide input to future household energy initiatives.
Combustion Science and Fuels – There has been considerable study of solid fuel combustion systems for medium (40 kW) and larger systems, but no systematic study of combustion at the scale needed for home cooking and small scale heating (3 to 6 kW) for the three general categories of stove operation: (i) fuel metered, (ii) air metered, and (iii) restricted air (gasifiers). For cook stoves, a quantitative understanding of the combustion process is a particularly difficult challenge because of the variety of fuels and the fact that even the same fuel might vary with season, moisture content, etc.

Forced-air injection has already been demonstrated to improve efficiency, reduce cooking time, provide a mechanism to control cooking power (also known as “turn-down ratio”), while producing dramatic reductions in the cook stove emissions that impact both health and global warming. Thus far, those performance improvements have been achieved by empirical methods without the aid of scientific analysis based on controlled experiments with adequate instrumentation. Stove developers experiment with air-flow rates, pre-heating, steam augmentation, pitch of the injection duct (for swirl control), and injection location, without any fundamental understanding of the individual effects or their mutual interactions that could lead to better and more robust designs.

Materials – The options for technology development are always enabled (or constrained!) by the availability of materials and their cost of acquisition and fabrication. The materials used in the combustor (walls and insulation) are obvious targets for improvement through use of improved metallic alloys or ceramics and glasses, if they can be mass-produced cheaply while retaining good dimensional tolerances and consistent material properties. Other material development areas are important, but far less obvious. One area that is particularly important for development of fan stoves are the materials associated with waste-heat co-generation strategies such as affordable and robust thermoelectric (TE) materials and materials used for thermoacoustic “stacks” or Stirling-cycle regenerators.

Design Tool Development – A comprehensive, open-source software package should be developed to translate science-based stove design results into a form that can be used to design optimally-engineered cook stoves for the variety of “operating points” in the “cook stove user space”. As important as the design, simulation, and analysis capabilities of the software will be, it is even more important that the software also define a unifying “language” for the expression and incorporation of existing engineering knowledge and new research results. An initial package can be developed based on the best science and engineering knowledge currently available, but in a flexible manner, so it will be easy to incorporate new findings that would arise from the research on materials, combustion, and fuels outlined in the previous sections.
Additional (and/or Compensatory) Functionality – An improved stove will probably eliminate a primary source of lighting for the 1.6 billion cook stove users who have no access to electricity. It is possible to generate electricity from the stove’s waste heat and use that electricity to power a fan to reduce emissions with excesses generating capacity available to power high-efficiency lighting (e.g., fluorescent or LED) or charge a small appliance (e.g., cell ‘phones). When stoves are used for space heating, all of the stove’s high-quality (i.e., high temperature) heat is available to produce electricity. Since the space heating application requires only modest temperatures, the stove could be considered an electrical generator with its “waste heat” warming the room.4 Although there are several co-generation techniques currently under investigation that were reported at the Workshop (e.g., thermoelectric in the US, thermoacoustic in the UK, and steam engines in Brazil), there are many ways to implement such small-scale co-generation technologies that warrant further experimentation and evaluation.

Paths to Scale-Up – The large-scale deployment of improved cook stoves cannot follow the traditional path of most mass-marketed, technologically-intensive consumer goods that evolved from limited high-margin markets (e.g., automobiles, mobile telephones, and computers) to commoditized mass-market products. Subsidies will be required to stimulate the development of businesses that provide today’s better stoves. The distribution channels and marketing strategies of those businesses should be closely monitored to determine the most successful approaches during the time when further improvements and user-requirement-driven customization are being pursued. In addition to direct government subsidies for research and dissemination efforts, the establishment of internationally-sanctioned CO2 equivalence ratios for non-CO2 climate forcers will be enabling. This will provide a mechanism for improved cook stoves to earn the “carbon credits” that correspond to the warming reductions they produce when they replace traditional cook stoves and open fires.

Because subsidized stove programs can disrupt and skew markets, strategic subsidies of stoves should be programmatic, not product oriented. An exception is the provision of subsidized components to stove producers (e.g., fans, thermoelectric modules, rechargeable batteries, improved pots and pot rests).

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Research Funding and Management Structure

A $100 million, 10-year program is described which provides funding to a US Government Agency that should act as the “Lead Institution” for a combined short-term (4-year) effort followed by a long-term (6-year) program. Following a series of briefings in FY2010, Q3 and Q4, an agency should be chosen to administer Congressionally-mandated funds. Core Institutions should be selected to head each TASK Area, to initiate a research programs at their institutions in FY2011, and to contribute members to an Evaluation Committee and a Steering Committee. Those committees should create a Call-for-Proposals that will be used to select an additional Affiliated Institution to conduct research in each TASK Area.

Both Committees that also include representatives of the Lead Institution, should meet quarterly during the Short-Term Program to track research results, identify research TASKS that are not making satisfactory progress based on the Evaluation Committee reports, and to identify new TASKS or expansion of existing TASK descriptions to address unforeseen problems or to exploit other technologies that might provide advantages for the next generation of cook stoves.

In addition to the research funding for the Lead Agency and the Core and Affiliated Institutions, the budget should includes funding for outreach activities (e.g., engineering student capstone projects and competitions), collaboration with Non-US research institutions, capital equipment purchases, and a climate change mitigation consultant who will work with the Committees.
THE ASEAN-US NEXT-GENERATION COOK STOVE WORKSHOP

This Research Road Map is the primary product of a Workshop organized and funded by the Bureau of East Asian and Pacific Affairs\(^5\) of the U.S. Department of State (State) with the co-operation of The Pennsylvania State University, Clarkson University, the University of California (Berkeley), and the Asian Institute of Technology. The Workshop was held at the Asian Institute of Technology (AIT) Conference Center, near Bangkok, Thailand, from 16-20 November 2009. In addition to the funding provided by State that supported participation of experts from ASEAN and other countries (including the US), the U.S. National Science Foundation provided a grant to support travel and lodging for some of the Workshop participants who came from the US, and the Air Force Office of Scientific Research provided a grant directly to AIT to cover local administrative expenses and to support participation of students from several ASEAN countries\(^6\) including Cambodia, Laos, Thailand, and Viet Nam.

Workshop participants included academic researchers from most ASEAN countries, the US, Africa, Australia, Egypt, and India; cook stove developers and manufacturers from the US, India, Brazil, and Cambodia; and representatives of US Government agencies including State (EAP/RSP, OES, and INR/EER), the US Agency for International Development (USAID), the US Environmental Protection Agency (EPA), the US Department of Energy (Headquarters, Ames Laboratory, Lawrence Berkeley Laboratory, and the Los Alamos National Laboratory), and the US Air Force. A complete list of participants and the list of presentations are included as appendices to this report.

Background – Health & Climate

Although traditional cook stoves do not comprise a large part of global energy demand, they are responsible for more health problems than any other category of energy use globally - far exceeding that from vehicles and power plants combined. These adverse health effects are created by the combination of highly inefficient combustion, producing unhealthy emissions of products of incomplete combustion (PICs), and high exposure per unit emissions because of the proximity of the users to the source. It should be recognized that the societal and economic costs of treating these stove-related illnesses is also significant.

\(^5\) Office of Regional and Security Policy Affairs.

\(^6\) Brunei, Burma, Cambodia, Indonesia, Laos, Malaysia, the Philippines, Singapore, Thailand, and Viet Nam.
In addition, many of these same products of incomplete combustion, which include methane, ozone-precursors, and black carbon (soot), are important greenhouse pollutants, thus making traditional biomass-burning cook stoves the most greenhouse-intensive fuel systems in the world per unit energy delivered. The poor combustion and poor heat-transfer of traditional cooking technologies also leads to unnecessary waste of the primary fuel supplies, largely wood and crop residues.

Figure 1. Comparison of the health and climate mitigation cost-effectiveness of household, transport, and power sector interventions. Area of circles denotes the total social benefit in international dollars from the combined value of carbon offsets (valued at 10$/tCO₂e) and averted DALYs [$7,450/DALY is representative of valuing each DALY at the average world GDP (PPP) per capita]. The more cost-effective the interventions are closer to the origin of the graph.
Biomass-burning cook stove improvement has been shown to be more cost effective in both improving health and reducing contributions to global warming than nuclear, wind, or solar power.\footnote{P. Wilkinson, et al., “Public health benefits of strategies to reduce greenhouse-gas emissions: household energy”, The Lancet \textbf{374}\{9705\}1917-1929 (2009); Published Online, November 25, 2009; DOI:10.1016/S0140-6736(09)61713-X; \url{www.thelancet.com}.} Figure 1 plots the relative return-on-investment for various interventions in terms of reduction in equivalent tonnes of carbon dioxide emission (tCO$_2$e) on the y-axis and health improvement measured in the reduction of Disability Adjusted Life Years (DALY).

**Current State-of-the-Art**

There has been significant progress in the development of stoves and testing protocols over the past few years. Many of these developments were highlighted at the Workshop. There are now several types of stoves in commercial production at modest scale ($\geq 100,000$ units/year) that have been shown to provide fuel savings of 40% to 50% and emissions reductions of similar magnitude.

![Figure 2. Grams of CO$_2$ equivalent per liter of water boiled and simmered for 30 minutes for five different stoves. The black carbon (soot) warms the atmosphere and the organic carbon has an atmospheric cooling effect. The fan stove also reduced the time to reach boiling. This graph is adapted from a report on measurements made at the Aprovecho Research Center 2007.\footnote{K. R. Smith and E. Haigler, “Co-Benefits of Climate Mitigation and Health Protection in Energy Systems: Scoping Methods,” Annu. Rev. Public Health \textbf{29}, 11–25 (2008).} The conclusions have been confirmed and expanded in a series of tests performed by the US Environmental Protection Agency in 2009.\footnote{N. MacCarty, et al., “Laboratory Comparisons of the Global-Warming Potential of Six Categories of Biomass Cooking Stoves”, Aprovecho Research Center, (then) Creswell (now Cottage Grove), OR 97426 (Sept. 2007).} It should be noted that this figure does not include production of carbon monoxide (CO) emissions which are very significant for the charcoal stove and ignores the emissions from the production of the charcoal.}

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\begin{itemize}
\item \footnote{P. Wilkinson, et al., “Public health benefits of strategies to reduce greenhouse-gas emissions: household energy”, The Lancet \textbf{374}\{9705\}1917-1929 (2009); Published Online, November 25, 2009; DOI:10.1016/S0140-6736(09)61713-X; \url{www.thelancet.com}.}
\item \footnote{N. MacCarty, et al., “Laboratory Comparisons of the Global-Warming Potential of Six Categories of Biomass Cooking Stoves”, Aprovecho Research Center, (then) Creswell (now Cottage Grove), OR 97426 (Sept. 2007).}
\end{itemize}
For example, the mass-produced ceramic combustion chamber stoves used by StoveTec™ and Envirofit™ can provide approximately 40% reductions in fuel use in lab tests due in large part to improved heat transfer to the pot. Field studies in East Africa by Dr. Vijay Modi found an average fuel reduction of 38% using the StoveTec™ stove. The new Envirofit™ B-3300 stove, which incorporates a metal combustion chamber, has reported higher efficiencies, but independent measurements of its performance have not yet been completed. Dr. Modi reported a 32% average fuel use reduction with the G-3300 in Tanzania.

The FirstEnergy “Oorja™” stove, originally developed by BP, has similar fuel efficiencies but requires pelletized fuel and electrical power for its fan. In urban areas, where people already buy fuel and have access to an electrical grid, such a stove may be practical, but in rural areas where fuel is free, the use of fuels that are inappropriate for the Oorja™ would be more likely, even if the users had access to electricity. FirstEnergy™ reported having sold over 480,000 Oorja™ units to date.

Another fan stove, being piloted in India by Philips, uses a much smaller fan with lower electrical power demand (<2 watts) and incorporates a back-up rechargeable battery. Jetter\(^{10}\) has reported that the Philips Woodstove™ uses 50% less fuel with a substantial reduction in emissions. The Philips stove is top-loading and requires that the wood fuel be cut into small pieces before use but does not require a supply of wood pellets.

The portable Vesto™ stove, manufactured by New Dawn Engineering,\(^{11}\) is a durable, mostly stainless steel, natural draft stove that can burn a wide range of biomass fuels. It saves about 35% of fuel compared to an open fire and won three design awards since 2004. Independent testing shows significant CO and particulate reductions. It retails for $29, a figure that can be significantly reduced if the production were to be mechanized.

Beyond the stoves currently in commercial production, there are a number of attractive new approaches, particularly those using forced air. A combined effort by Aprovecho Research Center and BioLite™ has produced a prototype fan stove, shown in Figure 3 that provides electrical power to the fan with a thermoelectric generator.

In laboratory tests, this fan stove produced a fuel savings of 42% and emissions reductions of greater than 90% in PM and CO. Aprovecho believes that they can bring this stove to the market at a wholesale price of $18/each.


\(^{11}\) Crispin Pemberton-Piggot, [www.newdawnengineering.com/website/stove/singlестove/vesto/](http://www.newdawnengineering.com/website/stove/singlестove/vesto/)
Figure 3. A StoveTec™ stove with a ceramic combustion chamber is shown (Left) with a thermoelectrically-power fan (orange enclosure) that had its debut at the Workshop. The orange enclosure contains a fan that draws air over an aluminum heat exchanger before injecting the pre-heated air into the combustion chamber. A copper “probe” extracts some heat from combustion and reduces its temperature before applying the heat to one side of a thermoelectric module (TEM) that generates about one watt of electrical power for the fan. (Right) The arrangement is shown schematically by the cartoon that depicts the individual components making up this co-generation prototype.

An important technical improvement that has become commercially available is a field deployable system for the measurement of emissions during fuel consumption tests. The Portable Emissions Monitoring System (PEMS) developed by Aprovecho Research Center fits in a briefcase and provides real-time measurements of CO, CO₂, and particulate matter (PM) that can provide a good initial indicator of stove emission performance. The system can provide the technology needed by regional organizations such as the Asia Regional Cook Stove Program (ARECOP), based in Yogyakarta, Indonesia, to provide independent evaluations of stove performance. ARECOP recently purchased two PEMS and has already found that there remain many “improved” stoves on the market in various Southeast Asian locations that show little or no improvement over traditional stoves or open fires and may be significantly (in some cases ten or one-hundred times) worse than conventional cooking approaches, especially in the production of PM per megajoule. The ARECOP testing capability has demonstrated that the local improved stoves were not providing the improvements that were claimed by their vendors.

12 The PEMS does not provide particulate size distribution information.

13 http://www.arecop.org/.
There are significant concerns regarding the standard methods currently used to test both stove efficiency\textsuperscript{14} and emissions. For particulate matter (PM), the commonly used instrument employs light scattering to measure particle numbers from which PM mass is inferred. However, light is not effectively scattered from particles with sizes below 250 nm. Work by Balakrishnan and Dhaniyala, presented at the Workshop, showed that there can be a large fraction of the PM mass in sizes that cannot be observed using these light scattering systems. As stoves’ combustion improves, the emitted particle size decreases and the overall mass of emissions can decrease. Much of the reported decrease may be due to the movement of the particles out of the detection capability of the light scattering instruments. This could lead to an overestimation of the comparative PM reductions obtained by improved stoves.

A Comprehensive Strategy.

There have been many attempts to address the health issues related to indoor air pollution produced by the use of biomass- and coal-burning cook stoves. With the exception of the Chinese effort (1983-1998) that resulted in the distribution of 183 million stoves, most of those efforts resulted in distributions that were well below the necessary saturation levels.

The recent recognition of the impact of the cook stove emissions on global climate change has highlighted the urgency of this problem by focusing on the production of short-lived climate forcers (SLFs) by household combustors. Interest now goes beyond the direct health consequences for the user which was the original reason to improve cook stove performance by reducing emission for more than two decades. Now that improved cook stoves may also provide a means for mitigating climate change in the short-term, so that “tipping points” could be averted and some time could be “bought” to develop the technologies necessary to mitigate the global warming contributions of carbon dioxide, there is a possibility that funds will be made available to the cook stove community to improve both the product and its distribution channels.\textsuperscript{15}

\textsuperscript{14} Several protocols based on the “Water Boiling Test” (WBT), and two other metrics introduced by Baldwin\textsuperscript{2}, are currently under revision in the hope that an internationally acceptable testing standard can be developed. An alternative set of protocols presented at the Workshop were devised by the SeTAR Centre at the University of Johannesburg.

\textsuperscript{15} Shortly after the Workshop (02 Dec 09), the Indian Ministry of New and Renewable Energy announced their “National Biomass Cook Stove Initiative” that will include a series of pilot-scale projects using several existing commercially-available cook stoves and different grades of processed biomass fuels as well as “a series of activities that are designed to develop the next-generation of household cook stoves, biomass-processing technologies, and deployment models”.
A robust community of researchers and technologists exists that serves the needs of large-scale energy producers (e.g., turbines, vehicles, power plants, fuel processing, standards, etc.). The industrial and academic research community has had the benefit of long-term investment in both talent and infrastructure development. Unfortunately, the results of those investigations do not directly support the needs of the small-scale household (<10 kW) and institutional (<100 kW) energy producers that dominate (numerically) worldwide, although their established techniques and laboratory facilities could serve that purpose. This document seeks to provide a road map for the research activities that could create that household energy community based on the best engineering practices and scientific practices.

This Research Road Map suggests that a coordinated multi-disciplinary approach, similar to that which has served the power and transportation industries, must be pursued so that the results become available to the stove community in a usable form to support the development of improved stove and to the in situ evaluation of the performance and usage patterns of those stoves. One advantage of doing so now is the availability of computerized analytical tools and advanced sensors and networks. The disadvantage is that this capability must be mobilized in only one or two years, rather than the two centuries (starting with Carnot in 1822) of research and analysis that grew to its current state of sophistication in the service of the large-scale energy producers and transportation systems.
THE RESEARCH ROAD MAP

Given the number of attempts to introduce sustainable improved biomass-burning cook stoves that have been unsuccessful in the past, nobody today claims that this is a simple problem with a single obvious solution. Although cooking food seems like a fairly mundane task, the development and dissemination of a fuel-efficient stove that can prepare food quickly, without negative health effects for the cook and others in the kitchen (mostly children), and without significant emissions that contribute to global warming, is a very difficult challenge.

What gives us confidence that we may now be able to address those challenges successfully in a short time? The high-level answers are (i) the power of the scientific method, (ii) improved tools to execute scientific and engineering analyses, and (iii) more robust technologies, manufacturing infrastructure, and materials to create affordable solutions at the enormous scale required. At steady-state, between 100 and 125 million stoves need to be produced and distributed each year.

The following sections of this report describe the necessary components of a scientifically-motivated approach. The urgency of producing and distributing a number of improved cook stoves that could make a significant impact on health and climate change mitigation requires that these components be pursued in parallel.

Task 1: User-Based Performance Specifications (“The Cook Stove User Space”)

“One size fits some.”

The first step in any systematic design process is the clear definition of the specifications that the product will be required to meet or exceed. Because there are potentially more than three billion people that need to be served by improved cook stoves, it is essential to determine common stove-relevant factors for groups that are large enough to produce significant climate impacts if their cook stoves were improved and used to displace their traditional cooking methods. These potential users represent a diversity of locations, cultural preferences, use patterns (e.g., cooking or cooking and space heating), and available fuels. Some users have access to centrally-generated electricity (although frequently without reliable 24-hour access), but roughly 1.6 billion do not have any access and will not be connected to any electrical distribution grid on the time scale of interest for global climate mitigation.
We would like to think of the users as being characterized by their “location” in a multi-dimensional user space. One axis could represent cooking requirements. Some cooks use pots to cook starches while others cook beans that require much longer cooking times. Some also require a flat cooking surface (e.g., tortillas in Latin America and Ingera in Ethiopia). Another axis represents fuel: green wood, dry wood, processed biomass, animal dung, and a variety of crop residues (e.g., corn cobs, oil palm parts, rice husks). Other axes include availability of electricity; dwelling in cities, villages, or camps for Internally Displaced Persons (IDP) or refugees; proximity to transportation routes, etc.

Careful analysis is required to first determine the smallest number of axes and entries on those axes that provide sufficient boundaries between different use cases and their impact on the choice of appropriate stove technologies. Then it will be necessary to determine where users are located in this “user space” and how many users occupy a volume of that space that could be served by a particular combination of stove technologies. For example, there are many users in Asia who have free access to rice husks that require a fan to gasify the husks for efficient and clean combustion, but they have no access to electricity to run a fan.

The “impact weighting” must also be considered. For instance, there could be one use case with a relatively small number of users, but their present impact on black carbon and/or CO₂ might be huge due to their current cooking practices. This could increase the “ranking” of a seemingly less important use case. There are communities that burn coal (ancient carbon) for both cooking and heating from 4 to 24 hours each day, seven days a week, and do so in very bad stoves. One classic example would be Ulaanbaatar, Mongolia. Although there may not be many of these users, their aggregated impact would be significant.

Most of the data required to create the “cook stove user space” exists, having been gathered by the World Health Organization, the World Bank, and other Non-Governmental Organizations (NGOs), but it has not been amalgamated in a way that would clearly identify the number of people with common cooking needs. The design requirements of the largest dozen or so classes should be the target for the first improved designs and for placement of testing centers to service those areas to certify the quality of the stoves under those use conditions and monitor the stove performance to track degradation with age or identify improper use.
Task 2: Performance Characterization

“You don’t get what you expect, you get what you inspect.”

The recent affordability of appropriate sensors, signal-conditioning electronics, and automated data acquisition systems are central to the premise that we can monitor significant numbers of improved cook stoves, particularly in the area of emission reductions that affect both health and global warming. One demonstration of this new era is the PEMS system developed by Aprovecho Research Center to monitor the production (but not size distribution) of particulate matter (PM), carbon dioxide (CO₂), and carbon monoxide (CO) produced by the stoves they were developing in their laboratory. Quantitative measurements are essential during the stove development process to determine if a particular design modification is actually an improvement.

At their own expense, Aprovecho packaged an optical PM sensor (of their own design using parts from a smoke detector), along with CO and CO₂ sensors, in a small briefcase-sized package and provided an interface to a laptop computer to acquire, display (in real-time), analyze, and record emission data. Intended for use in a laboratory environment, the PEMS is combined with a “collection hood” that incorporates a suction fan and an airflow sensor. Aprovecho has sold twenty units for $10,000/each to stove developers, and to testing labs in Latin America, Asia, and most recently in Africa. This was an extremely significant first step, especially considering that they received no outside funding for the effort.

With our new understanding of the variety of emissions that have significant atmospheric effects (e.g., methane and ozone precursors), other emission sensors should be included. The need for a low-level methane sensor is high on that list. As stoves improve, better sensitivity will be required and calibration protocols will have to be established so that uniform international cook stove performance standards can be developed and updated as our understanding improves.

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17 A more complete laboratory system might include a Dusttrack™ DRX with filters and a microgram scale ($20,000) which provides size, count, and total mass, or an instrument like a GRIMM Aerosol Monitor and a dilution system ($50,000 plus supporting instrumentation). A conventional combustion analyzer and a DRX can provide meaningful stove evaluations for a total of $40,000.
The following are several specific examples of research challenges in sensor development:

- Gas concentration sensors for the following gases and vapors with the required dynamic range (ppm or %) that are inexpensive and can operate for 8 hours continuously: \( \text{O}_2 \) (25%), \( \text{CO} \) (10%), \( \text{CO}_2 \) (20%), \( \text{SO}_2 \) (0.1%), \( \text{NO} \) (0.1%), \( \text{NO}_x \) (500 ppm), \( \text{H}_2 \) (2%), \( \text{H}_2\text{O} \) (15%), \( \text{H}_2\text{S} \) (0.1%).

- Robust, inexpensive scales for weighing filter samples (< 5 \( \mu \text{gm} \)) and for weighing fuel (< 15 kg ± 0.1 gm), with USB interface capability.

- Inexpensive high-temperature (~700 °C) measure of \( \text{H}_2\text{O} \) content in chimney gas.

- Particle measurement and counting system for particles between 10 nanometers and 10 microns with a dynamic range of \( 10^9 \) particles/cm\(^3\).

- Inexpensive sensor for light absorbing carbon particles.

- Automated fuel characterization system to measure moisture, ash, sulfur, hydrogen, carbon, oxygen, and nitrogen quickly (\( \lesssim 10 \) minutes) in solid fuel samples and determine the fuel's total heat content (HHV).

A similar modernization of field measurement has progressed, again championed by a single research group at UC Berkeley under the direction of Prof. Kirk Smith. They have developed a low-cost (< $500) particulate measurement device and an ultrasonic transducers to track kitchen occupancy by mothers and children, personal dosimeters, and inexpensive data loggers recording thermocouple readings to establish stove use patterns. Again, this effort could be far more successful if resources were available to provide better sensors, data acquisition systems, and networks. There is no technical reason why users should need to keep logs of their behavior (which are notoriously inaccurate) in an era of radio frequency tags and satellite data burst networks whose costs have dropped dramatically.

Without good laboratory and field sensing, it will be difficult to achieve the emission reduction goals and impossible to monitor (and justify) the investment in better cook stoves. The development of international performance-based standards will encourage stove developers who want to enter the market while reducing the liability exposure of existing manufacturers. Standards, and their enforcement, will provide a means to suppress the dissemination of inferior imitations (“knock-offs”) that have already started to appear in markets served by manufacturers of truly improved cook stoves.

Finally, more data needs to be acquired and analyzed to determine the correlation between laboratory and field performance (emission and fuel efficiency) measurements. Ultimately, testing procedures need to be improved in both venues to harmonize these two critically important measurement requirements.
Task 3: Combustion and Fuels

Most of the modern energy conversion technologies rely on standardized fuels. We do not care whether the gasoline we put in our cars’ tanks came from oil fields in Texas, Nigeria, Alaska, the North Sea, Canada, Mexico, or the Middle East. We promulgate standards that petroleum refineries must maintain to sell their product to the energy consumer. These stringent chemical requirements apply to all liquid, solid, and gaseous fossil fuels used in developed countries. Their uniformity guarantees that the engines which burn those fuels can be effectively optimized for both energy efficiency and emission reduction. This is not the case for biomass-burning cook stoves.

The variety of fuels used by the three billion people who burn biomass for cooking can be overwhelming; both in type and condition. The energy yield of even one “class” of fuel, such as wood, will depend on the species of wood and on its moisture content. It will vary with location and season. Certain potential fuels (many that are considered agricultural waste) can become efficient and safe cooking fuels, but may require special processing and/or fuel-specific combustion strategies.

One such example, demonstrated at the Workshop, was the Rice Husk Stove developed by Prof. Alexis Belonio, from the Philippines. Two million metric tonnes of rice husks each year are available as a byproduct of rice milling in the Philippines alone. An 18 watt fan is currently required to gasify the rice husks in Belonio’s stove, but that gas produces a very low emission (clean) “blue flame” for cooking that is nearly indistinguishable from the flame of stoves that burn liquefied petroleum gas (LPG) or natural gas (methane) as shown in Figure 4.

Similar opportunities exist for many other forms of agricultural “waste” (e.g., oil palm husks, sugar cane bagasse), as well as fast-growing plants cultivated specifically as sources fuel (e.g., switchgrass, Miscanthus giganteus, jatropha beans) and municipal waste. Based on the opportunities identified by the “cook stove user space” analysis, there could be many other successful utilization strategies. Although some agricultural materials can be

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19 A. T. Belonio, Rice Husk Gas Stove Handbook, Appropriate Technology Center, Department of Agricultural Engineering and Environmental Management, College of Agriculture, Central Philippine University, Iloilo City, Philippines (2005):
http://www.bioenergylists.org/stovesdoc/Belonio/Belonio_gasifier.pdf

20 It is disconcerting to note that rice husk are burned in open fields (producing copious quantities of black carbon!) in Egypt every year, simply to dispose of large quantities of this “waste” without any use made of the thermal energy released by the combustion.
converted to liquid fuels for transportation applications, it has been shown that burning the materials is twice as energy-efficient as converting to liquid and then burning.\textsuperscript{21}

Figure 4. The very low emission blue flame is the product of gasification of rice husks in Belonio’s stove\textsuperscript{19} that is made possible for forced-air convection using an electrically-power fan that consumes 18 watts of grid-supplied electrical power. The burnt husks can be used as a soil amendment (\textit{i.e.}, fertilizer) or mixed with other materials to produce bricks, once the burnt husks are removed from the stove.

Another dimension that has to be considered in fuel choice is the prospect for centralized or local processing. The Oorja™ cook stove, developed by BP and distributed by FirstEnergy™ in India, is intended to burn pelletized biomass exclusively. The densification and moisture control facilitated by the pelletizing of biomass is essential to the proper operation of the Oorja™. Since the target markets for the Oorja™ are urban families who already purchase fuel, distribution of the fuel is simplified and sale of the stove can be justified from the fuel cost savings. The use of other materials as fuel in the Oorja™ can lead to inferior performance and much greater emissions unless it matches the qualities of the wood or grass pellets.

These two examples are provided to demonstrate that the study of cook stove combustion cannot be separated from an understanding of the fuel. A complete combustion analysis must incorporate the intended fuel and the cooking vessel, as well as the options provided by use of “raw” biomass vs. processed biomass, and must examine the economics of fuel delivery if it is processed at central locations or can be modified at the village level by developing and providing simple human-powered machinery.

Modeling programs using computational fluid dynamics (CFD) to simulate combustion under the conditions of low gas flow and relatively low temperatures (with respect to gas turbines) for specific fuels could provide insight that might result in correlations that could be incorporated in the Design Tools discussed in the following section, again with the stipulation that meticulous experimental validation be routinely required.

It should be noted, specifically in the consideration of combustion research supporting cook stove improvement, that forced-air injection has already been demonstrated to be the best strategy for improvement in efficiency, reduction of cooking time, user adjustment of cooking power (also known as “turn-down ratio”), and dramatic reduction in the cook stove emissions that impact both health and global warming. Thus far, the performance improvements demonstrated by the addition of a fan have been achieved by empirical methods without the aid of scientific analysis based on controlled experiments with adequate instrumentation. Stove developers experiment with air-flow rates, pre-heating, steam augmentation, pitch of the injection duct (for swirl control), and injection location or the addition of a chimney, without any fundamental understanding of the individual effects or their mutual interactions.

It is imperative that the air-injection effects be understood and that understanding be translated into engineering guidance that can be used to optimize the parameters of the air injection process. Those results can also be used to properly engineer a chimney or the fan and minimize the fan’s electrical power requirements.

Finally, a better understanding of the combustion process and the mechanisms that result in the known advantages of forced-air injection could possibly lead to the development of passive (i.e., natural draft) mechanisms that would eliminate the need for a fan and could make biomass-burning “as clean as propane” for those without access to electricity or without the need for electrical co-generation that utilizes some stove heat to provide electrical power for a fan (e.g., see Fig. 3).
To summarize, the current state of our understanding of biomass combustion in small domestic (<10 kW\textsubscript{thermal}) and medium institutional-sized cook stoves (<100 kW\textsubscript{thermal}) is inadequate to answer the following fundamental questions:

- How is the combustion rate determined?
- How is soot formed and how are the emissions generated?
- What is the relationship between stove performance and the size of particles produced?
- What is the impact of fuel moisture and fuel type?
- What effect do different cooking vessels have on the system performance?\textsuperscript{22}
- What effect do operator actions have on stove performance?
- How do we quantify the overall effectiveness of a “cooking system”?\textsuperscript{22}

Our understanding of the heat transfer from the stove to the pot or \textit{plancha}\textsuperscript{23} is better than our understanding of the combustion process that provides the heat, but ultimately all of the elements of the “cooking system” must be co-optimized as discussed in the following section on Design Tools and Research Coordination.

**Task 4: Materials**

The options for technology development are always enabled (or constrained) by the availability of materials and their cost of acquisition and fabrication. One need only think about the role of silicon in electronics, pre-stressed concrete in civil engineering structures, or plastics and metal alloys in transportation systems. Cook stoves provide a particularly harsh combination of extreme temperatures and corrosive gases that dominate this applications environment. The materials used in the combustor (walls and insulation) are obvious targets for improvement through use of improved metallic alloys or ceramics and glasses, if they can be mass-produced cheaply while retaining good dimensional tolerances and consistent material properties. Some work has been done in this area, but many promising directions remain unexplored (particularly, glasses and ceramics).

\textsuperscript{22} Options need to include pot improvements, possibly through enhanced heat transfer surfaces (\textit{e.g.}, fins), pot skirts, lids, etc.

\textsuperscript{23} A \textit{plancha} is a metal plate (griddle) used for grilling, particularly tortillas in Latin America, Ingera in Ethiopia, or crepes in France.
Other material development areas are important, but far less obvious. One area that is particularly important for development of fan stoves are materials associated with waste-heat co-generation strategies such as thermoelectric (TE) materials and the technique used to bond the multiple p-n junctions required for fabrication of the TE modules.\(^{24}\) Materials used for thermoacoustic “stacks” or Stirling-cycle regenerators,\(^{25}\) as well as the heat exchangers for either thermoacoustic or TE systems, are dependent upon both their availability and of affordable means of high-volume production and assembly. Materials performance issues for cook stove applications include the typical engineering properties of the materials, but must also include considerations of cost, weight (to minimize shipping costs), processing costs and times, local availability, repairability and recyclability.

The following are several specific examples of potential research challenges in materials development:

- Transparent glass or ceramic materials that can be used to make stove combustion chambers and/or stove bodies that transmit light from the fire into the room while retaining the heat in the combustion chamber (i.e., the “good” greenhouse effect).

- Castable materials for making stove components that have very low thermal expansion and very high temperature shock resistance and may be either insulating or heat conducting, depending on the required function.

- Surface coatings for stove components that will give off light when the stove is in use or warm (e.g., a thermally-activated photo-luminescent glaze for ceramics).

- A thermoelectric (i.e., Seebeck effect) generator (TEG) that works up to 750 °C and can be produced in modules that can produce as much as 20 watts of electrical power.\(^{26}\) In addition to the relatively “high tech” thermoelectric module, there is a need for a cheaper, lighter substitute for copper as the heat conduction path from the combustion chamber to the module’s hot side.

- A coating for mild steel (e.g., paint) that will protect sheet metal to a temperature above 750 °C and does not require expensive surface preparation.

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\(^{24}\) One TE module used to provide electrical power for a fan stove demonstrated at the Workshop produced slightly over one watt but included 127 p-n segments requiring 254 solder joints. Since the junctions are electrically in series (but thermally in parallel), failure of only one of the 254 joints makes the module useless.


\(^{26}\) The availability of off-grid electrical power in villages could be the most transformative technology in developing countries.
Task 5: Design Tools and Research Co-Ordination

The first systematic attempt to apply the principles of combustion and heat transfer engineering to the improvement of biomass-burning cook stoves used in developing countries was Baldwin’s report entitled *Biomass Stoves: Engineering Design, Development and Dissemination*, prepared for the Volunteers in Technical Assistance (VITA), and published in 1987. At the time of its publication, computers were not widely available to apply the engineering formulæ to specific cases and many stove developers lacked sufficient mathematical and/or technical sophistication to apply design equations. To make some of Baldwin’s general results accessible to artisanal cook stove builders, Dr. Larry Winiarski promulgated a list of ten “Rules of Thumb” to improve heat transfer and make cook stove combustion more efficient using a natural draft “rocket stove” design template. Although Winiarski’s rules were better than no guidance at all, his “one size fits all” compromise is inadequate to guide design of stoves that are both more fuel efficient and produce far less emissions that both create global warming and are responsible for detrimental health effects. Unfortunately, Winiarski made no attempt to extend the “rules” to stoves used for space heating.

To start, there needs to be a clear understanding of the transient (i.e., start-up) and steady-state performance, as well as their relative importance under a “typical” cooking and/or space-heating scenario. It is likely that the time-integrated emissions will be dominated by the steady-state behavior, but there may be conditions, particularly with an “improved” stove that has low steady-state emissions, where the start-up might be a significant source (if not the largest source) of emissions. The analytical techniques for those two cases will probably differ.

For the steady-state case, a comprehensive, open-source software package should be developed to translate science-based stove design results into a form that can be used to design optimally-engineered cook stoves for the variety of points in the “cook stove user space” using appropriate materials. Based on extensive experience with a very successful product developed over the past twenty years at Los Alamos National Laboratories for a somewhat similar (thermoacoustic) heat engine and refrigeration application (DELTAEC), the cook stove software could also be structured as a sequence of “segments” that represent stove components (e.g., combustor, fuel, grill, pot, pot skirt, etc.). The physics and engineering performance relevant to each segment would be calculated within the

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27 Available in English, French, German, Italian, Portuguese, and Spanish at http://sleekfreak.ath.cx:81/3wdev/VITAHTML/SUBLEV/EN1/BIOSTOV.HTM

segment and continuity of mass flow, energy flow, and species at segment interfaces would guarantee that the effect of each segment would be “handed off” to the subsequent segment. Figure 5 provides a segment of DeltaEC code and an apparatus schematic to illustrate the concept.

The combustion of a gas mixture is necessarily accompanied by motion of the gas. The process of combustion is therefore not only a chemical phenomenon, but also one of gas dynamics. In general, the nature of the combustion process has to be determined by solution of simultaneous equations which include both the chemical kinetics for the reaction and those of gas dynamics for the mixture concerned. These process are contained in the combustion chamber so that the material properties (e.g., heat capacity, thermal expansion, thermal conductivity, etc.) also need to be incorporated into the design.

As with DeltaEC, segment properties should be specified in MKS units and the calculation of material properties for the solids and gases (e.g., density, heat capacity, thermal conductivity, viscosity, Prandtl number, polytropic coefficient, species concentration, etc.) that characterize each segment would be calculated automatically for the conditions of temperature and pressure within each segment. The progression of the coupled segments would be controlled by a differential equation solver to integrate the differential equations, while providing the flexibility to specify properties that are treated as optimization variables (i.e., “guesses”) and as performance goals (i.e., “targets”). Again, like DeltaEC, the software must include utilities for incrementing variables and producing tables and plots of the variations. Indigenous plotting of stove variables throughout the system should also be incorporated (e.g., temperature vs. axial position).

As important as the design, simulation, and analysis capabilities of the software will be, it is even more important that the software will also define a unifying “language” for the expression and incorporation of existing engineering knowledge and new research results. The information required to improve stove performance will be generated by many different techniques whose output will be dictated by the both the specific problem and by the researchers’ methodology. Whether better understanding is obtained from computer simulations (e.g., finite-element analysis) or experimentally-motivated correlations, the results can only be applied efficiently, and validated experimentally, if they can be expressed in a format that can be applied by the stove designers and can predict outcomes. The existence of such software allows quantitative predictions based on a stove’s construction that can be compared to measurements made in the laboratory.

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**Figure 5.** The Dynamic Environment for Low-Amplitude ThermoAcoustic Energy Conversion (DELTAEC)\textsuperscript{28} was developed at the Los Alamos National Laboratory for design and analysis of thermoacoustic engines and refrigerators. The above example includes Segments #3 through Segment #14 of a model of a thermoacoustic heat engine that is intended to produce electrical power. Physical properties of each segment are specified in the left column and calculated quantities are provided in the right column. The continuity of pressure, volume flow rate, and energy are preserved between each segment and the differential equation “solver” allows the user to specify “targets” (\texttt{Targ}) and the variable “guesses” (\texttt{Gues}) that the program can adjust to meet those targeted variables. Below the segments is a scaled diagram that indicates the location and interconnection of the segments in the physical system. The software can produce a variety of graphical outputs including plots of the variables vs. position within the system and plots of performance vs. incremented variables. A design and analysis tool for cook stoves that is similar to DELTAEC is an essential component in the proposed research program.
Improved Cook Stove Research Road Map

It cannot be emphasized frequently enough that experimental validation of both the physical and chemical equations used by the software, as well as validation of the software itself, will be a critical component of this endeavor.

One requirement for research funding to pursue the goals in this Research Road Map should be participation in regular web-based meetings to ensure that the software structure and variables accommodate the application and that the funded research results be compatible with the agreed software structure (e.g., variables and segment joining conditions). Although open-literature publication of research results will be encouraged, the urgency of the mission requires that a more efficient and interactive structure be available. Fortunately, the Internet can provide such a responsive mechanism that transcends the collaborative diasporas.

Task 6: Additional (and/or Compensatory) Functionality

“It’s a floor wax and a dessert topping.”

For a very significant fraction (>40%) of the Earth’s population, the cooking stove represents the largest source of power for the household, providing typically 2 to 6 kilowatts (kW) of thermal power produced by burning biomass or coal (i.e., ancient biomass). Depending on the users’ demographics, the same stoves that are used for cooking might also serve as heaters for living spaces in colder climates. More than half of that population does not have access to centrally-generated electrical power and will not have access for the foreseeable future.

One consensus reached at the Workshop is that fan-forced convection will probably be required to reach the PIC emission levels that are necessary for both user health and climate change mitigation. By clever use of a small fraction of the cook stove heat, it is possible to generate enough electricity to operate a small fan (see Fig. 3). Although more research is needed to investigate the conversion of heat to electricity at such small scales, and at a cost that is no more than the cost of the stove itself, it could be very useful to consider electrical generation and storage mechanisms that would allow excess electrical power to be generated for purposes beyond providing power for the fan.

30 Saturday Night Live.

31 There were examples of natural draft stoves presented at the Workshop that burned as cleanly as the forced-air (fan) stoves under certain circumstances.
Improved Cook Stove Research Road Map

In addition to the alleviation of “energy poverty”, the motivation for such research is that the “improvements” a better cook stove provides to health and climate may not be appreciated by the stove’s user and therefore adoption may be less than enthusiastic. For example, the improvement in cook stove energy efficiency (i.e., both combustion efficiency and heat transfer efficiency) requires:

(i) that the stove, fuel, and pot be considered as related elements of a single system;

(ii) that the combustion chamber be insulated to reduce heat loss to the surroundings and raise combustion temperature or the heat must be captured and used to pre-heat the air before heading to the fuel;

(iii) that the flame be contained to complete combustion;

(iv) that the hot combustion products be routed beneath and around the pot;

(v) and that power regulation is an important part of fuel savings (i.e., turn-down ratio) as otherwise efficient stove are invariably used in a wasteful manner if the power output is unregulated.

These guidelines also mean that the lighting produced by the flame in a three-stone fire is no longer available to the cook or the family. Successful adoption will probably require that the lighting function of the stove also be replaced.

The cost of electricity is similarly an issue for off-grid cook stove users. In Cambodia, for example, the effective cost of electricity that is purchased by bringing a lead-acid storage battery (e.g., 12 V, 40 Amp-hr) to a merchant with a diesel generator is $2/kWh. In the US, we typically pay under $0.20/kWh, inclusive of the transmission costs. The ability to generate small amounts of electricity at home, in the course of preparing meals or warming the living spaces, could be a very attractive motivation for improved cook stove adoption. It has also been shown that even small amounts of electricity can make significant improvements in lifestyle, education, and generation of disposable income from cottage industry.

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32 The price of electricity produced by dry cell batteries has remained constant at about $50/kW-hr for the past several decades.

33 The production of electricity could lead to increased stove usage beyond cooking requirements, thus increasing fuel consumption, but access to modern energy is also an important development goal.

A few projects with the goal of co-generation of electricity from cook stove combustion have been attempted,\textsuperscript{35,36,37,38} but as yet, only one has reached a stage that justified scale-up. The BMG LUX\textsuperscript{®} Bio Micro Generator\textsuperscript{39} uses a small piston-driven steam engine (similar to a very small locomotive) and a gear-coupled permanent magnet alternator to generate electricity that charges a battery (see Fig. 6). The integrated stove and electrical system includes sophisticated switch-mode electronic power controls for battery charging and load management and can produce a peak power output in excess of 100 watts. In typical use for four hours per day, the system delivers 435 W-hr/day, providing lighting and powering several small appliances, typically including a television. The stove-generator combination mass is 120 kg ($\cong 265$ lbs) and the overall electrical system efficiency is only about 1%.

At present, about four-hundred BMGLUX\textsuperscript{TM} units have been manufactured in a dedicated facility and installed in homes in the Amazon jungle at the cost of $3,200/each, including transportation, set-up, and user training. Financial support was provided under a program created by the Brazilian government to provide rural electrification in villages that are not going to be serviced by a centralized electrical grid. The initial installations were made in Chico Mendes Rubber Tree Reserve, Xapuri, Acre State. The choice of a national park that forbids tree cutting as the first location was made to emphasize the fact that the stoves were powered by fallen branches and did not lead to deforestation. The test families received their stoves for free and the testimonials of the users were uniformly positive, with praise for the improvement in quality-of-life (particularly entertainment available on the television), connection to events outside their village, and improvement in educational opportunities for the children.


\textsuperscript{39} \texttt{www.damp.com.br} and \texttt{www.bancobmg.com.br}. 
Figure 6. Schematic rendering of the BMG LUX® Bio Micro Generator cook stove\textsuperscript{39} that burns forest waste in the Amazon and uses heat to create low-pressure steam that powers a single-cylinder double-acting piston engine that is coupled by a gearing system to an electric alternator. Visible in the diagram is the steam pressure gauge, the piston engine, the exterior of the fire box, and the flywheel. The gearing system is behind the flywheel. Not shown is the switch-mode electronic load controller and storage battery. The system weighs 120 kg (\( \approx 265 \) lbs), costs $3,200 (including delivery, set-up, and user training), and produces about 435 W-hr/day if it is used for cooking three hours each day.
**TASK 7: Paths to Scale-Up**

*“It is not a question of numbers, but of steady-state production capacity”*⁴⁰

The traditional cook stove, known as the “three-stone fire”, will be difficult to displace since the components are readily available, no special skills or tools are required for its assembly, it can burn a wide variety of types and sizes of fuel, and *it is free*. Add to those features that a significant impact can only be achieved if 500,000,000 traditional stoves or open fires are replaced by improved stoves and the magnitude of the scale-up problem comes glaringly into focus. Since the improved stoves that are being mass-produced today have a typical lifetime of $3 \pm 1$ years,⁴¹ at steady-state, the required annual production capacities would be between 100 and 150 million stoves per year worldwide.

A simplistic calculation that assumes that the cost of an improved stove might be $30 suggests that “only” $15 billion would be required to replace 500,000,000 traditional stoves and open fires. It is thus argued that the cost is small when compared to other energy-related climate mitigation strategies (see Fig. 1). For example, that same expenditure would support construction of 8 modern nuclear power plants, each capable of generating 1.15 GWₑ.⁴² Eight such nuclear power plants, operating 24 hours/day, 365 days/year, would avoid placing just under 60,000 kilotonnes of CO₂ into the atmosphere each year⁴³, corresponding to total reduction cost of $250/tonneCO₂, or an annual cost of $10/tonneCO₂/year, assuming a 30 year power plant life.

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⁴¹ The stove lifetime has been limited primarily by the degradation of the combustion chamber that is subjected to the intense heat and corrosive gases. It is possible that improved materials could extend stove life, but there are advantages to the limited service life. It means that a sustainable business can be created to supply the stoves, provide user training and service, stock spare parts, and sell new stoves to satisfied customers. The limited lifetime provides the opportunity to introduce upgrades and additional functionality. This pattern has been successful with other modern products with similar service lifetimes such as computers and cell ‘phones.


⁴³ This calculation incorporates the US power generation average CO₂ production of 0.674 kgCO₂/kW-hr.
A similar calculation that takes into account the global warming impact of the stove emissions\textsuperscript{44} indicates that $5 \times 10^8$ wood-burning fan stoves would produce nearly a 1,000,000 tonneCO$_2$ reduction each year, or over 2,000,000 tonneCO$_2$ reductions each year if the fan stove burns pelletized fuel. Even the lower (wood-burning) figure corresponds to the total CO$_2$ emissions from Japan or 3.5\% of the world’s annual CO$_2$ emissions.\textsuperscript{45}

Unfortunately, such a simplistic calculation does not recognize that the acquisition cost of the stove is not the most significant obstacle to achievement of either health improvement or climate mitigation. The problem is that the designs for the improved stoves that can replace traditional stoves and open fires, while producing those emission reductions for 500,000,000 families, \textbf{do not exist}. Even if such stoves were created tomorrow, the necessary marketing, manufacturing, distribution, sales, financing, parts and service channels to sustain deployment do not exist. It’s not really about purchase price yet!

\textit{“This is not your father’s Oldsmobile.”}

The production scale-up and distribution of improved cook stoves presents a challenge that is unique in the history of consumer product development. Almost every mass-marketed, technologically-intensive consumer product began as a very expensive item available only to specialized consumers (\textit{e.g.}, businesses or wealthy individuals). Automobiles, computers, and mobile telephones are obvious examples of manufactured goods that started out selling into a small market but over time, using the cash flow generated by high-margin sales into that limited market, “improved” their way into the mass market.\textsuperscript{46} Improved cook stoves for the poor cannot evolve by this path. There is neither the high-end market nor sufficient time.

The nearly unanimous consensus of those at the Workshop was that only manufactured stoves would be able to maintain the quality control necessary to achieve the required efficiency and emission reductions at the required scale and guarantee that level of performance for a minimum time period to allow emissions reductions to be “certified”.

\textsuperscript{44} Based on unpublished calculations by Prof. T. Bond (May, 2009) that assign an atmospheric lifetime and 20-year global warming (or cooling) potential equivalence (life/GWP) to CO$_2$ (century/1.00), N$_2$O (century/275), CH$_4$ (decade/62), CO (month/10), NMVOC (days/4.9), black carbon (days/2,000), organic carbon (days/-250), and SO$_2$ (days/-150).

\textsuperscript{45} This comparison is based on the 2006 data collected by Carbon Dioxide Information Analysis Center within the US Department of Energy for the United Nations.

\textsuperscript{46} C. Christensen, \textit{The Innovator’s Dilemma} (Harper, 2003); ISBN 978-0060521998.
Although most participants felt that an entirely pre-fabricated product would be acceptable, there were many who felt that high-quality stoves could combine factory production of major parts with local assembly, thus possibly achieve some savings in shipping costs and stimulating local business growth.

The fundamental difficulty with “business” as a dissemination strategy is that most of the three billion people who cook with biomass are impoverished. Most do not have the disposable income to pay full price for a manufactured stove that includes materials and manufacturing costs, transportation, and sales costs (e.g., distribution, marketing, and profit). It is fairly clear that subsidies will be required. One potential source of subsidy presented at the Workshop was carbon credits that could be earned by verifiable fuel reduction. The Ugastove™, now being sold in Uganda, has already qualified for credits brokered through Morgan Stanley in a trade that allocates the carbon credits to offset sales of new Land Rover™ vehicles.

There was considerable skepticism among Workshop participants regarding the long-term reliability of carbon credit financing for improved stoves. It was also generally acknowledged that the absence of a carbon dioxide emission equivalent (CO$_2$e), sanctioned by the Intergovernmental Panel on Climate Change (IPCC), for the cook stove emissions such as black carbon (BC), makes the improvement of cook stoves less attractive in the “carbon market.” This oversight may be corrected since the Senate version of the climate bill contains a requirement for setting a CO$_2$e for BC. The House version (HR 2454) does not contain the CO$_2$e requirement for BC, but calls for the distribution of 20,000,000 improved stoves within five years of passage.

“Better is the enemy of good enough.” 47

There are several business-based improved cook stove projects that have reached the scale of 10,000 to 50,000 units/month. Although they do not yet achieve the necessary scale, those efforts should be encouraged and closely monitored. The stoves are clearly improvements over the traditional units they are intended to displace, although none achieve the desired long-term emission reductions. These pioneering businesses are important because they test the business model and establish distribution networks that can be used for sales of better stoves when research leads to production of stoves that incorporate further improvements.

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The same “dissemination laboratory” mentality can be used for improved cook stoves that are provided to people in refugee camps and camps for internally displaced persons (IDPs). Recent studies conducted by USAID in Uganda\(^{48}\) and Darfur\(^{49}\) demonstrated that most of the cook stoves distributed in the camps by NGOs were no better (and sometimes worse) than cooking on the three-stove fire. Because these camps are controlled environments, they can provide useful data on stove performance, usage, and the validity of the test protocols.

As long as the target market for improved stoves is the base of the “economic pyramid”, distribution will require subsidies to make the stoves affordable. There is significant evidence that even if the subsidies make complete stoves free to the user or critical components free to the manufacturers, they will not be adopted if they do not perform as well as the technique they replace.\(^{50}\)

> “I automatically reject any business plan for sales in developing countries that does not spend 80% of start-up funds on advertising.” \(^{51}\)

In concluding this section, it is worth mentioning that adoption depends upon several factors including customer education (i.e., advertising), aspirations for a more modern kitchen, etc. There have been studies that attempt to identify and weight the factors that drive adoption of a new product or technology which have to be considered thoughtfully.

Any plan that does not pay careful attention to indoctrination that raises awareness (i.e., health benefits, user convenience, and fuel conservation) and training the end user, as well as those along the supply chain, is doomed to failure. This is particularly true for a product that is intended to displace an appliance which is essentially free. This educational effort must employ multiple delivery vehicles, many of which have long vanished from developed countries.\(^{52}\) (When was the last time you saw a “medicine


\(^{50}\) Anything given for free in large numbers often ends up being sold. A general rule (which does not apply in refugee or internally displaced persons camps) is not to sell anything at less than twice the item’s salvage value, placing a lower limit on the price of an improved cook stove.


\(^{52}\) The Monitor Group has conducted several studies of marketing strategies for introduction of consumer products in developing countries; http://www.monitor.com/.
show” roll into your neighborhood?) Integrated dissemination tactics are critical; when a woman receives a pre-natal exam, she should be told about the damage to herself and her baby from the smoke produced by traditional cook stoves. At the exam, she should be offered an improved (subsidized?) stove and training that will make her comfortable and skilled operating the new appliance before her first baby is born.

**Task 8: Research Resources and Management Structure**

The American model of research support for individual investigators and small research groups in both academic institutions and national laboratories has led to the creation of the world’s most technologically advanced society during the 20th century. A similar approach will be required to execute this improved cook stove effort, although the urgency of the required climate change mitigation will require a management structure that can distribute research funds and amalgamate research results much more quickly than the typical proposal solicitation, review, and award cycle that is characteristic of traditional research funding agencies like the National Science Foundation and the National Institutes of Health.

A structure that is similar to research sponsorship by military agencies like DARPA, the Office of Naval Research, or the Air Force Office of Scientific Research would be more appropriate to the “national security” nature of this proposed effort. Fortunately, the existence of the Internet and the lack of security classification (i.e., weapons related) restrictions suggests that a “Manhattan Project” centralization (i.e., research at Los Alamos, enrichment at Oak Ridge) will not required.

It must also be recognized that there should be two research structures that correspond to shorter-term (4-year) developmental research and longer-term (10-year) foundational research. Both are equal in importance but different in execution and focus. In the short-term, there must be a focus on user characterization (the “cook stove user space”) and performance specification, monitoring, standards, production scale-up and dissemination models. The short-term effort will “set the stage” for the introduction and certification of the next generation of ultra-low emission products. The longer-term research effort will need to provide the scientific and engineering basis for detailed and robust design principles that will lead to the next generation of mass-produced biomass-burning cook stoves that will burn biomass “as cleanly as propane”.

The management of these efforts needs to utilize all available intellectual and infrastructural resources: government laboratories, universities, business, and philanthropic organizations. Each channel has different funding requirements to
guarantee their serious commitment to the effort. In all cases, the potential unreliability of year-by-year funding decisions will not fulfill any of those requirements.

The urgency imposed by current efforts to produce international climate change mitigation treaties dictates that the required management structure be able to initiate funded research efforts this year among “Core Institutions” and to evaluate responses to targeted proposal solicitations and have funding in place to support research at the competitively selected “Affiliated Institutions” starting in FY2011.

It is expected that there will be several funding sources that will support the development and deployment of improved cook stoves. Although this Research Road Map is focused on recommendations for US Government support, there are several non-governmental organizations (NGOs) that have already invested in this effort and possibly others that may be expected to provide financial support for both research and deployment efforts in 2010.

For this Road Map to lead to the required emission reductions, hence large-scale deployment, there must be Congressionally-mandated funding. That funding must be administered by a single US Government (USG) agency.

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53 In the area of cook stove improvement by NGOs, the following are the most visibly active:

- Shell Foundation [Simon.Bishop@shell.com] has provided $25M to fund deployment of Envirofit stoves in India and some earlier activities of the Aprovecho Research Center. An earlier Shell cook stove investment of equal magnitude was distributed equally to stove programs on five continents.

- Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH [Otto.Gomm@gtz.de] primarily through €11.1M (=$16M) spent in their Programme for Biomass Energy Conservation (ProBEC) in the Southern Africa Development Community (SADC) and their Sustainable Energy for Development (SED) in Bangladesh. ProBEC received €3M (=$4.3M) for 2010 and will be replaced by a new 10-year stove program in 2011.

- World Bank Energy Sector Management and Assistance Program (ESMAP) [Rogério Carniero de Miranda; rmiranda@worldbank.org] recently funded (~$2M) a dozen pilot projects that demonstrate new approaches to modernizing biomass energy in Sub-Saharan Africa by trying to enable market conditions for sale of improved stoves, modernization of the charcoal industry, as well as biofuels and bioelectricity.

- The Millennium Challenge Corporation has committed $15M to the Ulaanbaatar Clean Air Project which is managed by the World Bank.

54 For example, the UN Foundation is currently seeking partners for the initial phase of a clean cook stoves campaign designed to provide 50 million clean cook stoves in ten key developing countries by 2015 [Leslie Cordes; LCordes@unfoundation.org].
**Lead Agency.** In addition to managing contracts and allocating funding to Core and Affiliated Institutions, the USG Lead Agency would be responsible soliciting research proposals and convening the Evaluation Committee and Steering Committee on a quarterly basis. These quarterly committee meetings will be held at the Lead Agency and at the Core Institutions on a rotating basis to allow all of the committee members to familiarize themselves with the research efforts and infrastructure at the Lead Agency and Core Institutions. To encourage coherence between the short- and long-term programs, those Committees would consider both.

**Evaluation and Steering Committees.** The Evaluation Committee would have responsibility for *(i)* evaluation of proposals from potential “Affiliated Institutions”, *(ii)* monitoring the progress of Core Institutions and the Affiliated Institutions once they were selected and funded, *(iii)* tracking expenditure and encumbrance of research funds, and *(iv)* reporting on the progress of each Core Institution’s and Affiliated Institution’s research efforts to the Steering Committee. The Steering Committee would have responsibility for *(i)* initiating the Call for Proposals in support of each TASK, *(ii)* identifying research TASKS that are not making satisfactory progress based on the Evaluation Committee reports and recommending remedial actions, and for *(iii)* identifying new TASKS or expanding existing TASK Descriptions to address unforeseen problems or to exploit other technologies that might provide advantages for the next generation of cook stoves.

**Core Institutions.** One “Core Institution” will be selected to provide leadership and expertise for each of the TASKS. Like the “Affiliated Institutions” that will be selected by a competitive proposal process, each Core Institution will be expected to conduct research of the same quality as an Affiliated Institution, but would have additional responsibilities associated with their special status. These responsibilities would include designation of one of their researchers as a Steering Committee Member and one as an Evaluation Committee Member, as well as a back-up person for each committee assignment. Since the Committees meet quarterly during the first four years, 8 additional man-weeks would be added to their research budget. During years 5 through 10 (the long-term research period), the Committees would meet only twice each year. Also, each Core Institution would be expected to host Committee Meetings at their institution on a rotating basis.

**Affiliated Institutions.** Selection of these institutions will be based on their response to the Call-for-Proposals. In addition to the proposed research, each Affiliated Institution would be required to provide a researcher as a judge for student cook stove competitions held at their institution or at other universities in their vicinity.
Non-US Collaborating Institution. Although this Research Road Map is intended to guide US investment in improvement of cook stove technology, and it is expected that there will be non-USG funding for both research and deployment efforts, it will be useful to involve academic institutions in the developing countries, both for capacity building within those countries and as a channel of acquisition for user feedback. Non-US Collaborating Institutions would not be funded directly, but would be funded through the Core or Affiliated Institution that would be collaborating with the Non-US Institution. The Core or Affiliated Institution would be responsible for monitoring performance of the Non-US Institution and reporting that performance to the Evaluation Committee as part of Core or Affiliate’s evaluation process. No support for Non-US collaborators is included in the long-term research program.
The Execution Road Map

The estimated cost to the US Government to support the research necessary to contribute to the goal of manufacturing and selling 125,000,000 ultra-low emission biomass-burning cook stoves each year by 2020 is estimated to be approximately $100M spread over 10 years. This section of the Research Road Map will justify that amount by describing the programs that would be supported by that funding level.

Although that level of research expenditure is large when considered as an absolute number, it is extremely modest by comparison to research expenditures for other mass-marketed products with a significant technological component. If we again use the simplistic model that assumes the sale of $5 \times 10^8$ stoves that cost $30/each, the total expenditure is $15 billion making the $100M research program roughly 0.7% of sales. As shown in Table I, typical numbers for R&D expenditures in the home appliance industry as a percentage of sales during the past five years has ranged between 1.0% and 2.7% of sales for total annual sales of $20 to $25 billion/year for these three companies alone.

<table>
<thead>
<tr>
<th>Year</th>
<th>Electrolux AB</th>
<th>Maytag Corp.</th>
<th>Whirlpool Corp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R&amp;D (k$)</td>
<td>Sales (k$)</td>
<td>R&amp;D (k$)</td>
</tr>
<tr>
<td>2004</td>
<td>126,539</td>
<td>9,584,176</td>
<td>62,609</td>
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<td>2006</td>
<td>130,514</td>
<td>12,249,495</td>
<td>75,955</td>
</tr>
<tr>
<td>2008</td>
<td>163,614</td>
<td>10,937,388</td>
<td>60,892</td>
</tr>
</tbody>
</table>

Table I. Research and development budgets vs. sales for three appliance manufactures over the past five years. \(^{55}\) Total sales for those three appliance companies range from $20.4 to $24.9 billion/year during this most recent 5-year interval.

Possibly a more relevant comparison is the expenditure made by Trane Corp. to modify their air conditioning products to comply with the ban on CFC refrigerants that was imposed by the Montreal Protocol on Ozone-Depleting Substances.\textsuperscript{56} In the span of only two years of intensive effort, Trane spent $100M to modify the components (\textit{e.g.}, heat exchangers, valves, lubricants, etc.) in their existing product lines to allow use of the HFCs substitute refrigerants. That figure does not include the expenditure required to make modification to the compressors used in Trane products but procured from a different manufacturer.

It should be understood that the proposed 10-year research budget represents only the investment of the US Government. It is likely that other governments, as well as NGOs, should also be providing funding for improved cook stove research and deployment.

The following paragraphs describe the proposed programmatic structure and expenditure timeline:

\textit{Agency Briefings (FY2010, Q3 and Q4)}: During this period symposia will be held at USG Agencies that could potentially become the “Lead Agency” for the proposed research effort.

\textit{Lead Agency and Core Institution Program Launch (FY2011)}: Research programs at the Core Institutions are funded and the quarterly Committee meetings are held to review the research plan and produce the Call-for-Proposals that will solicit participation by the Affiliated Institutions.

\textit{Initiate 3-Year (Short-Term) Research Effort (FY2012-FY2014)}: The Core and Affiliated Institutions begin their research directed toward (\textit{i}) establishing performance specifications for groups of stove users (\textit{Task 1}), (\textit{ii}) utilizing on-going deployment efforts to test models for scale-up and dissemination (\textit{Task 7}), (\textit{iii}) developing and testing sensor suites while establishing laboratory- and field-testing stations and protocols (\textit{Task 2}), and (\textit{iv}) initiating research to enhance stove performance directed toward improvement of existing stove that are currently capable of mass-production (\textit{Tasks 3-6}).

\textit{Initiate 6-Year (Long-Term) Research Effort (FY2015-FY2020)}: The Core and Affiliated Institutions expand their research effort toward creation of the next generation of ultra-low emission cook stoves informed by the lessons learned during the Short-Term effort but that will be unconstrained by the choices that were dictated by improvement of the existing products.

Acknowledgements

This road map is based on the presentations and break-out session discussions at the ASEAN-US Next-Generation Cook Stove Workshop. Valuable comments on several drafts of this report were provided by Scott Backhaus, Mark Bryden, Alex King, Matthew Poese, and Ray Wakeland. The post-Workshop comments and suggestions from Paul Anderson, Samuel Baldwin, Tami Bond, Dean Still, Bryan Willson, and Catherine Witherspoon provided useful guidance. The authors are particularly grateful to Crispin Pemberton-Piggot for his thorough reading and insightful comments based on decades of stove development efforts in Africa and Asia.

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Resource Links

Workshop Presentations will be posted on the Partnership for Clean Indoor Air (PCIA) website “Proceedings” page: www.pciaonline.org/proceedings

Association of South East Asian Nations (ASEAN): www.asean.org

U.S. State Department:

Bureau of East Asia and Pacific Affairs: www.state.gov/p/eap/
Oceans and International Environmental and Scientific Affairs: www.state.gov/g/oes/
Population, Refugees and Migration: www.state.gov/g/prm/

National Science Foundation (NSF): www.nsf.gov/


U.S. Environmental Protection Agency: www.epa.gov/cop15/

U.S. National Institutes of Health: www.niehs.nih.gov/
APPENDIX A – WORKSHOP AGENDA

ASEAN-US NEXT-GENERATION COOK STOVE WORKSHOP

Asian Institute of Technology, Bangkok, Thailand (16 – 20 Nov 2009)

Session 0 - Arrival and Reception

2:30 – 4:30 pm  Participant registration and hotel check-in

5:00 – 6:00  Opening Ceremony
   Welcome and Opening Remarks
      Local Organizer – Professor Kim Oanh
      AIT Dean - School of Environment, Resources and Development
      Opening speech by AIT President
      Welcome from ASEAN Representative
      Welcome from US Government Representative (Tanya Anderson)

6:15 – 7:30  Dinner
7:30 – 8:30  Participant self-introductions with comments on key interests/opportunities
8:30 – 8:40  Presentation of Day 2 (Tuesday) schedule, breakfast arrangements, etc.

Day 2 (Tuesday Morning) 57

7:00 – 8:00 am  Breakfast

Session 1 – Current State-of-the-Art

8:00 – 8:05 am  Session introduction (S. Garrett)
8:05 – 8:35  History of stove development (D. Still)
8:40 – 9:10  Current state-of-the-art (B. Willson)
9:15 – 9:30  The Berkeley Darfur stove (A. Gadgil)
9:35 – 9:50  The EcoFagão stove (C. do Canto Muniz)

9:50 – 10:00  Break
10:00 – 10:15  The Rice Husk (gasifier) stove (A. Belonio)
10:20 – 10:35  The FirstEnergy (formerly BP-Oorja) stove (M. Yagnaraman)
10:40 – 10:55  The Prakti stove (T. Drouin)
11:00 – 11:15  The Envirofit stove (N. Lorenz)
11:20 – 11:35  The GERES New Lao stove (D. Beritault)

11:40 – 12:30  Stove demonstrations

12:30 – 1:30  Lunch  (AITCC Dining Room)

57 Time gaps between talks are for questions and answers.
Day 2 (Tuesday Afternoon)

Session 2 – Stove Characterization and Testing

1:30 – 1:45 pm  Introduction to performance tests (M. Bryden)
1:45 – 2:05   Revised water boiling test (T. Bond)
2:10 – 2:30   Solid fuel cook stoves: Characterization of performance and emissions (J. Jetter)
2:35 – 2:55   Stove emission testing and the PEMS (D. Still)
2:55 – 3:15   Emission field testing (K. Balakrishnan)
3:15 – 3:35   New approaches in stove performance testing (R. Edwards)
3:35 – 3:55   Stove evaluations in South Africa (C. Pemberton-Pigott)
4:00 – 4:20   Field evaluations in East Africa (V. Modi)

4:25 – 4:40   Break

4:40 – 6:15   Break-Out Sessions on Testing Needs - 3 groups
6:15 – 6:35   Testing Break-Out Group Reports

6:40 – 8:20   Dinner
7:45 – 8:30   Partnership for Clean Indoor Air (PCIA) Update (J. Mitchell)

Day 3 (Wednesday Morning)

7:00 – 8:20 am  Breakfast

Session 3 – Combustion and Fuels

8:30 – 8:55 am  State-of-the-art (M. Bryden)
9:00 – 9:20   Issues in solid fuel combustion (M. A. Wahid)
9:50 – 10:10   Processed biomass fuels (M. Yagnaraman)
10:15 – 10:25  Summary of key open issues in combustion (V. Modi)

10:25 – 10:40   Break

10:40 – 11:40  Break-Out Sessions on Research Needs for Improved Combustion
11:45 – 12:00  Combustion Break-Out Group Reports

12:00 – 1:00   Lunch
Day 3 (Wednesday Afternoon)

Session 4 – Utilizing Stove Heat for Co-Generation

1:00 – 1:10 pm  Concept introduction (S. Garrett)
1:10 – 1:30  Thermoelectric stove (B. Willson)
1:35 – 1:55  Thermoelectric stove (C. Lertsatitthanakorn)
2:00 – 2:20  Thermoelectric fan stove (J. Ceder)

2:25 – 2:40  Break

2:40 – 3:10  Thermoacoustic cogeneration applied to advanced cook stoves (S. Backhaus)
3:15 – 3:35  SCORE Project thermoacoustic co-generator (C. Lawn)
3:40 – 4:00  Steam electrical co-generation (C. do Cunto Muniz)

4:05 – 5:45  Break-Out Sessions on Research Needs for Co-Generation
5:45 – 6:00  Co-Generation Break-Out Group Reports

6:10 – 7:45  Dinner
7:45 – 8:30  National Science Foundation Programs (M. McAuliffe & P. Mazumder)

Day 4 (Thursday Morning)

7:00 – 8:20 am  Breakfast

Session 5 – Sensor Needs

8:30 – 8:40 am  Introduction (K. Smith)
8:40 – 9:00  Particles and PM (P. Hopke)
9:05 – 9:25  Black carbon (T. Hansen)
9:30 – 9:50  Use sensors (R. Edwards)

10:00 – 10:20  Break

Session 6 – Basis for Scale-Up

10:20 – 10:30  Introduction (W. Behn)
10:30 – 10:55  Improved understanding of health implications (K. Smith)
11:00 – 11:15  Climate implications of improved stoves (T. Bond & P. Hopke)
11:20 – 11:40  Air quality and climate co-benefits in Asia (K. Oanh)
11:45 – 12:05  Cook stoves and the carbon market (E. Haigler)

12:15 – 1:25  Lunch
Day 4 (Thursday Afternoon)

Session 7 – Design for Large Scale Deployment

1:30 – 1:45 pm  Introduction (P. Hopke)
1:45 – 2:15  Challenges and opportunities for different cook stove use models (W. Behn)
2:15 – 3:45  Break-Out Sessions for Different Cook Stove Use Models
   Cook stove design from a systems perspective
   Build consensus on key challenges/opportunities for different use models
3:45 – 4:00  Break-Out Session Reports
4:00 – 4:15  Break
4:15 – 5:45  Break-Out Sessions to Refine Design Opportunities
   Identify possible international collaborations
   Plans-of-action, ways to start
5:45 – 6:00  Break-Out Session Reports

Keynote Session

6:15 – 7:35 pm  Dinner
7:35 – 8:10  Keynote Speech – Global Initiatives (K. Smith)
8:15 – 8:25  Preparations for Day 5 Sessions and Departure Transportation

Day 5 (Friday Morning)

7:00 – 8:15 am  Breakfast (AITCC hotel check-out)

Session 8 – Scale-Up Issues

8:30 – 8:40 am  Introduction (W. Behn)
8:40 – 9:00  Issues in large-scale production (B. Willson)
9:05 – 9:25  Scale-up issues in SE Asia (C. Aristanti)
9:30 – 9:50  Scale-up issues for displaced persons (A. Gadgil)
9:55 – 10:15  Scale-up opportunities for assistance programs (E. Dimpl & K. Zaman)
10:20 – 10:40  Funding scale-up in a market that includes black carbon and CO limits (E. Haigler)
10:45 – 11:10  Break (AITCC hotel check-out)
Session 9 – Wrap Up

11:10 – 12:25  Wrap-Up and Next Steps (Panel)
12:30 – 1:30  Lunch
1:45 – 5:00 pm  Departures for airport

Summary Report (Workshop Co-Organizers Only)

Day 5 (Friday Afternoon)

3:00 – 6:00 pm  Report writing

Day 6 (Saturday)

9:00 – 4:00  Report writing
# APPENDIX B – LIST OF PARTICIPANTS

<table>
<thead>
<tr>
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