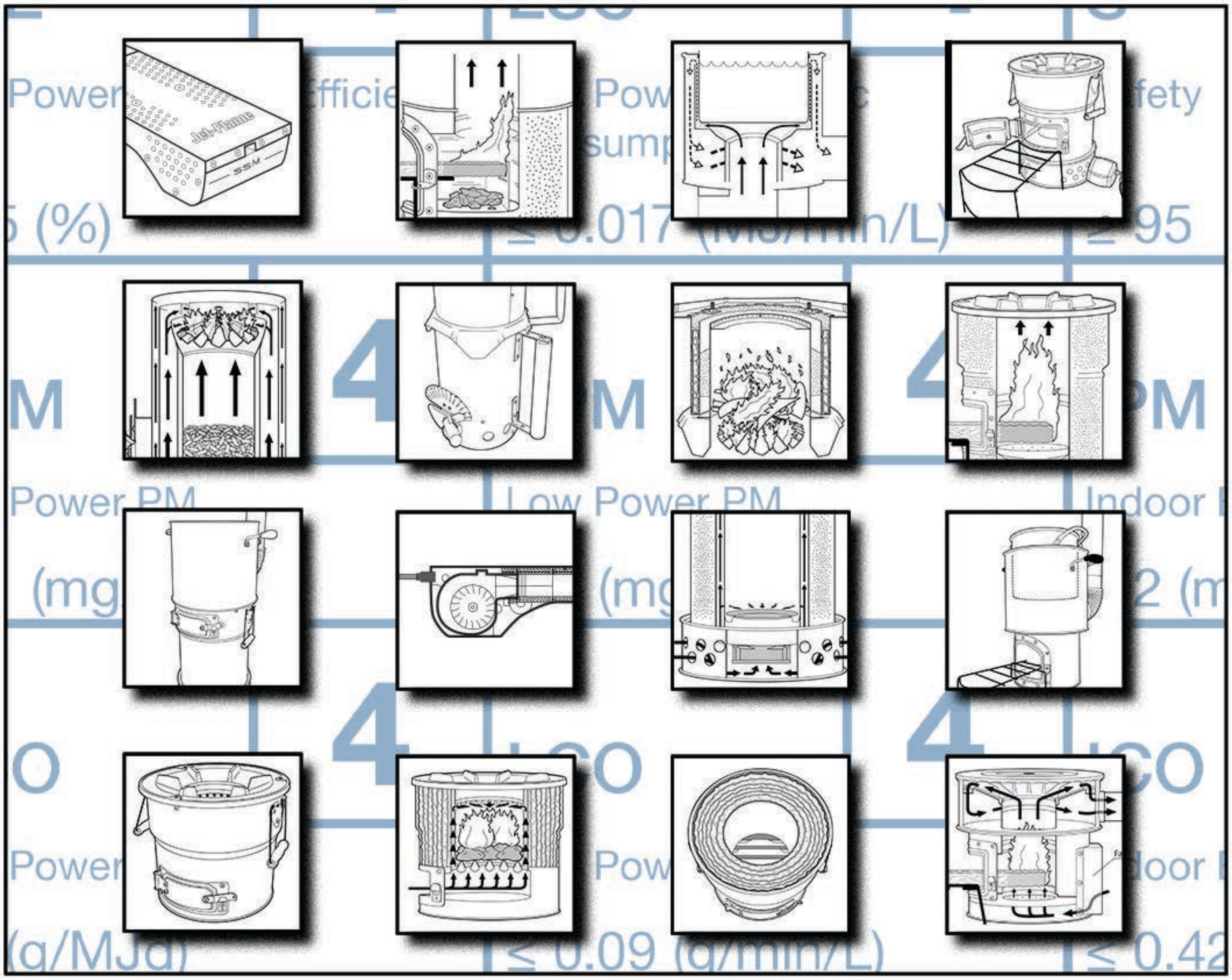
Clean Burning Biomass Cookstoves 2nd Edition 2021



Dean Still, Samuel Bentson, Richard H. Lawrence, Jr., CFA,
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Aprovecho Research Center

Household Energy and Clean Air
United States Environmental Protection Agency

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Aprovecho Research Center gratefully acknowledges support of the first edition under grant number EE0006285 from the United States Department of Energy. The journal articles "Results of Laboratory Testing of 15 Cookstove Designs in Accordance with the ISO/IWA Tiers of Performance" Still, Bentson, Li, EcoHealth (2014) 12:12-24, and "Fuel Use And Emissions Performance Of Fifty Cooking Stoves In The Laboratory And Related Benchmarks Of Performance" MacCarty, Still, Ogle, Energy for Sustainable Development (2010) 14(3):161-171, add to the survey of household stove performance described here.

Aprovecho Research Center is a non-profit 501(c) 3 organization that was founded in 1976. ARC provides various services involved with biomass stoves including:

- Design or re-design of biomass stoves to achieve improved heat transfer and combustion efficiency. Working in the field with users to assure the effectiveness and market viability of the new stove.
- Manufacturing and sales of the Laboratory Emissions Monitoring System (LEMS) to measure $PM_{2.5}$, CO, CO_2, and black carbon emitted from biomass stoves.
- Training of laboratory and field staff to set up and operate the LEMS to test and improve stove performance. Testing of stoves using the Water Boiling Test and Controlled Cooking Test with the LEMS emissions hood in the lab and field.
- Working with factories to build the new generation of clean burning stoves.
- Conducting open source research to improve the technical understanding of stoves.
- Informing the stove community

For more information or help with any of these stove designs, please contact us via www.aprovecho.org

This book is dedicated to Huiyang Shen and Meirong Mo, who turned these ideas into beautiful, affordable stoves.

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Foreword

I first made the 300-mile drive from Seattle to Aprovecho in the fall of 2001. I had encountered Dean Still through some on-line discussion fora on cooking stoves, where he had gently scoffed at my naïve ideas about perfectly-designed technology and precision measurements. His concerns had the ring of truth and hard-won knowledge, so I headed down to Cottage Grove for a little Jedi Master treatment. Hospitality was boundless; I toured their stove laboratory and organic gardens and ate lunch in their straw-bale dormitory. I met their dedicated, some would say obsessed, cast of characters: Larry Winiarski, who implemented Rocket Stove principles in everything from stoves to Guatemalan trash incinerators; Ken Goyer, driven to simplify stove construction so that fewer babies would die; and Damon Ogle, who contemplated materials from his background of road construction. As my car backed down the dirt road, Dean yodeled in farewell, "Let's change the world, Tami!"

Little cooking stoves were originally crafted by Aprovecho and other humanitarian organizations to replace rudimentary cooking fires. The resulting fuel savings could be helpful when users had a limited supply or when demands were putting pressure on forests. What we didn't know during those makeshift lab days of the new millennium was that emissions from cooking stoves, in addition to fuel savings, were about to break into international awareness.

Hundreds of millions of women with coughs and watering eyes knew that the fires they used to feed their families were vexing their health. Kirk Smith had been working for many years to raise awareness of the health effects of solid fuel burning; there should be a market for first editions of his 1987 book "Biofuels, Air Pollution, and Health." In the early 2000s, a confluence of observations raised the political awareness of smoke. Veerabhadran Ramanathan led a major atmospheric measurement campaign near India. The airplane, shipboard, and island measurements showed that haze was not just an urban phenomenon—it spread over continents, and the Indian Ocean particles were darker than those in other places. Jim Hansen and Mark Jacobson pointed out that black carbon particles were climate warmers and could be quickly removed from the atmosphere. I was busy adding up global emissions, and it turns out that household solid-fuel burning produces about a quarter of those particles. Meanwhile, the Global Burden of Disease calculations, launched in the early 1990s, came to fruition in 2012 and confirmed that one of the top ten global causes of lost life-years was breathing cooking smoke.

All these reports accentuated two things about cooking with fire. First, solid-fuel emissions are bad for people, bad for outdoor air pollution, and either bad or just weird for climate. Second, understanding the current situation and proposed alternatives is pretty darned important. Throughout the lively discussions, Aprovecho and some other small, dedicated developers had been quietly plugging away. Now with emission-testing equipment in their laboratory, and in labs around the world, they continued exploring, modifying, and rating stoves in the quest to clean up cooking. The principles in this book represent what they learned by observing, watching, experimenting, measuring, talking to cooks, and designing stoves for mass manufacturing.

As I write, many issues remain in order to clean up cooking and reduce its major impacts. We need to understand better what cooks want, what they will use, and how to make stoves so they burn just as cleanly with local fuels and practices as they do in the laboratory. For some households, the solution should be providing clean-burning fuels rather than clean stoves; perhaps in a just and future world everyone will have that access. The trajectory between today's Earth and that future world is certain to include hundreds of millions of men, women and children who arise, work, care for farms, learn to read, start businesses, and aspire to improvement, all surrounded by the cooking smoke that defined the transition to humanity. Until the air is clear for them, summaries like Clean Burning Biomass Cookstoves—based on observation and measurement, on conveying design principles, and on plausible construction— can lift some of the haze.

-Tami Bond, November 2018

Preface

How much investigation and subsequent refinement of a technology should precede manufacturing and distribution? The practical answer probably revolves around the capitalization of the project, the time needed to create a truly improved product, the receptivity of the market, and a host of other factors. An organization like Aprovecho Research Center (ARC), which began by making a very public mistake, may naturally lean towards the "It's time well spent" perspective.

When Dean Still came to Aprovecho in 1989, Dr. Larry Winiarski asked him to compare how much wood was used to boil and simmer water using the Lorena stove and the Three Stone Fire. The test revealed a problem for the ARC staff when the Lorena used three times more fuel than the open fire! Half of the staff, who had written books about the Lorena and taught thousands of people about their invention, were never convinced that the problem existed. The other half were embarrassed but became fervent believers in Dr. Kirk Smith's famous saying that "You get what you inspect, not what you expect."

Making a public mistake pushed ARC to go a bit more slowly, to challenge speculation, and to try to depend on reliable data. A lot of local knowledge is required to take prototypes to market. The analysis of infield performance and emissions, learning from cooks, distributors, retailers, manufacturers, and all stakeholders is needed to create successful products. All of this information really should precede manufacturing, but inventors' pride is hard to resist. We try to confront it with a slogan: "The lab is the field! The field is the lab!"

Fire has fascinated mankind for thousands of generations. The complete combustion of biomass opens up sustainable and carbon neutral applications for all passengers on Earth.

What a great and empowering challenge!

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Introduction

Adding chapters and re-writing “Clean Burning Biomass Cookstoves” has reminded the Aprovecho staff how much has been accomplished from 2015 to 2020 and how much remains to be accomplished. On the plus side, the TLUD and Rocket biomass stoves are much improved. In the last five years, stove technologies have moved closer to being able to protect health by reducing harmful emissions. How to save fuel by increasing heat transfer efficiency has been understood for years, while increasing combustion efficiency in user friendly and affordable stoves has been the continuing challenge.

The stove movement that started so vigorously in the 1970s with the goal of saving fuel has been challenged by the health community to show that stoves can be a viable intervention. Unfortunately, most available stoves are either not designed to achieve good combustion efficiency or, stoves that show promising results in the lab have not been as successful when operated by cooks in the field. The popular press has repeatedly pointed out that expectations have not been met.

At the same time, the science-oriented segment of the stove world has generated information to guide data driven decision making. The ISO 19867:2018 standard for laboratory testing of cookstoves and the preceding ISO IWA 11:2012 have improved how stoves are tested. The Clean Cooking Alliance has been very active in publishing results of field testing that have shown shortcomings. The ISO 19869:2019 standard for field testing provides methods to evaluate cooking system performance in real-world conditions.

Jim Jetter, U.S. Environmental Protection Agency, and co-authors have published several journal articles comparing emissions and performance, and describing the limited effectiveness of biomass fueled stoves. Aprovecho published two recent papers describing similar results. The multiple World Health Organization and USAID publications have plainly shown that biomass stoves have to be improved before interventions that protect health can be fully successful. As in many fields, scientific writings have not been effective in communicating to the general public that under-achievement in the field has been predictable.

While the Department of Energy and the Environmental Protection Agency have supported technological progress, the amount of funding has diminished in the last five years. At the same time, a core group of colleagues in government and from non-governmental organizations, as well as individuals, have been hard at work trying to assist the millions of biomass users in the world. Progress in the last five years is a result of their continued work and perspicacity.

1 HTE **4** High Power Thermal Efficiency ≥ 45 (%)	2 LSC **4** Low Power Specific Consumption Rate ≤ 0.017 (MJ/min/L)	3 S **4** Safety ≥ 95
4 HPM **4** High Power PM ≤ 41 (mg/MJd)	5 LPM **4** Low Power PM ≤ 1 (mg/min/L)	5 IPM **4** Indoor Emissions PM ≤ 2 (mg/min)
7 HCO **4** High Power CO ≤ 8 (g/MJd)	8 LCO **4** Low Power CO ≤ 0.09 (g/min/L)	9 ICO **4** Indoor Emissions CO ≤ 0.42 (g/min)

The ratings on nine IWA measures provide a multi-dimensional representation of stove performance.

The Top Lit Up Draft (TLUD) Stove

First generation, natural-draft TLUDs were not as clean burning as desired, especially when burning found fuels. Although forced-draft TLUDS were very clean burning at high power, they did not, as a rule, achieve adequate turn-down ratios to enable good performance at lower power. A significant advancement is the Kirk Harris Natural Draft TLUD that accomplishes adjustable firepower by moving a lever controlling the amount of primary air entering the combustion chamber. Static mixers and pressure differences more effectively achieve close to complete combustion efficiency. The Kirk Harris TLUD, when burning wood fuel pellets, emitted 0.7mg/minute of $PM_{2.5}$ when tested at the Lawrence Berkeley National Laboratory. Unfortunately, burning found fuels cleanly is more difficult to achieve. The WHO Intermediate Emission Rate Targets for $PM_{2.5}$ is 1.75 mg/min for unvented stoves and 7.15 mg/min for stoves with chimneys (see Chapter 13).

The Rocket Stove

Many variations of the Rocket stove can be found worldwide including single-pot stoves, griddle (plancha) stoves, institutional stoves, multiple-pot stoves, and mud/sand versions that partially reflect the Rocket stove design principles. Unfortunately, even low-mass, insulated Rocket stoves when operated at high power emit about as much smoke as a carefully operated open fire. The typical natural-draft Rocket stove has been shown to be cleaner burning at medium power, around 2.5 kW firepower. Even modern Rocket stoves do not provide adequately efficient combustion to lower emissions of $PM_{2.5}$ at high power.

Recently however, studies have shown that forced-draft Rocket stoves can be much cleaner burning. A device developed by ARC called the SSM Jet-Flame provides forced-air from the bottom of open fires and stoves. In the ARC lab, burning sticks of wood in a high mass sand/clay Rocket stove with the SSM Jet-Flame, emitted an average of 1.8mg/minute for $PM_{2.5}$ during the hot-start, high-power test phase. Adding forced draft to a vented Rocket stove provides higher combustion temperatures, and better mixing of air and combustion gases needed for improved performance (see Chapter 13).

Charcoal

Surprisingly, a charcoal stove achieved all Tier 4 scores for total emissions, indoor emissions, and efficiency – the highest tier level defined by the ISO IWA 11:2012 guidelines. When charcoal has the wood burned out of it, it can combust very cleanly, emitting almost no appreciable amounts of smoke. Even the CO can meet the Tier 4 metric when temperatures are hot enough. Charcoal can be a clean burning prepared fuel like propane or alcohol. However, it is difficult to recommend charcoal because: (1) 5/8ths of the energy is lost when changing wood into charcoal, (2) a lot of smoke is produced during manufacturing, and (3) lighting charcoal often results in emissions of $PM_{2.5}$ (see Chapter 16).

It needs to be remembered that the WHO emission rate targets are based on actual emissions in the field that are more variable than emissions measured in the lab, and field emissions have typically been, on average, about three times higher than lab emissions. As a rule of thumb, ARC estimates that a stove with a chimney has to emit around 2.38 mg/min in the lab (7.5 mg/min. divided by 3) to have a chance of meeting the Intermediate Target. The Harris TLUD burning wood pellets, the Charcoal Stove, and the Forced-Draft Rocket burning sticks of dry wood, all with added chimneys, meet this target. Adding a chimney to a very clean burning stove is necessary to meet the WHO Intermediate Emission Rate Targets for $PM_{2.5}$.

Interventions

ARC has learned a lot about effective health oriented interventions by doing experiments in a 30 cubic meter Test Kitchen that has adjustable air exchanges rates. PM sensors are located in the Test Kitchen and stoves are operated at various firepower levels while interventions are tested. The stove with chimney has been shown to essentially remove all emissions from the home in the same way as space-heating stoves commonly do in many countries. Chimneys are highly recommended.

Increasing the air exchange rate is also a very effective intervention. When the air exchange rate is doubled in the Test Kitchen, the concentrations of $PM_{2.5}$ are cut in half. Chapter 5 explores the various interventions that assist the improved stove to protect health. An EPA model of indoor air pollution has been used to predict concentrations of $PM_{2.5}$ caused by cooking with various types of biomass stoves in homes. Post combustion techniques, commonly used in industry, are also effective in reducing emissions and seem to have possible applications in households (see Chapter 8).

Appropriate Technology

Since its inception, the stove movement has consistently maintained that the users and local stakeholders must be the drivers of innovation. The German development agency, GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), and many other organizations, have made it clear that successful stove solutions come from the users. In 1987, Dr. Samuel Baldwin outlined how stoves should be evolved by design committees comprised of cooks, retailers, distributors, manufacturers, engineers, and funders who interact together to create an appropriate technology. Along with technologies that are capable of reducing harmful emissions and increasing efficient heat transfer to reduce fuel use, the local evolution of practical, market viable stoves that are also great at cooking continues to be a necessity.

A Decade of Discovery

In January, 2011, the Department of Energy (DOE) convened a large, two-day meeting of experts to determine what types of research and development were needed to create very clean burning and fuel efficient stoves. Later that year, the DOE began to fund various organizations with the goal of super clean burning cookstoves being designed and manufactured. The staff at Aprovecho, with funding from DOE, spent three years (2013-2015) working on the problem. In laboratory tests, five stoves described in this book met most of the criteria for top tier ratings specified in the International Organization for Standardization (ISO) International Workshop Agreement (IWA) 11:2012, "Guidelines for Evaluating Cookstove Performance" (ISO, 2012). This 2021 second edition also includes test results using the newer ISO 19867-1 laboratory testing protocols. Descriptions of the design process for the five stoves can be found in Chapters 12-16. CAD drawings provide descriptions of how the stoves were constructed.

Aprovecho Research Center manufactures the Laboratory Emissions Monitoring System (LEMS), a hood system designed to quantify the amounts of CO, CO2, $PM_{2.5}$ and Black Carbon emitted from cookstoves. The cleaner burning stoves were evolved with an iterative development and modeling process using the Version 4.2.3 Water Boiling Test and the IWA Tier ranking system. On average, more than one hundred test iterations and design cycles were required for each stove to achieve improved performance.

The stove prototypes then moved into field testing phases in India, China, Nepal, Peru, Kenya, and Ghana. Groups of cooks in the various countries worked with the top-tier prototype stoves preparing local meals. The stoves were changed using feedback from the cooks to meet their requirements. ARC engineers were responsible for designing stoves with improved combustion and improved heat transfer while users created the cooking functions of the stoves. The redesigned stoves were rebuilt in China at Shengzhou Stove Manufacturer and went through a subsequent round of field testing to help evolve market viable prototypes. Market testing repeatedly showed that local stoves were inexpensive, and that to achieve a significant market share, the new product would be most successful at a retail price of around $10.

In 2015, the World Health Organization published a book that included intermediate and next step emission rate guidelines for vented and unvented biomass cooking stoves (WHO, 2015). Their strong recommendation is to advocate only technologies and fuels that are proven to protect health. The WHO advised implementers that cookstoves should not exceed the following air pollutant emission rates in actual use:

WHO *Intermediate* Emission Rate Targets	
Unvented stove	***Vented stove***
$PM_{2.5}$ 1.75 mg/min	$PM_{2.5}$ 7.15 mg/min
CO 0.35 g/min	*CO* 1.45 g/min

Stoves have to be exceptionally clean burning and include a chimney to meet the intermediate target for vented stoves. The final WHO indoor air guidelines are significantly lower. The Emission Rate $PM_{2.5}$ Targets, as seen below, are dramatically harder to meet. The vented Emission Rate Target for $PM_{2.5}$ is almost ten times lower than the Intermediate Target.

2015 WHO Emission Rate targets	
Unvented stove	***Vented stove***
$PM_{2.5}$ 0.23 mg/min	$PM_{2.5}$ 0.80 mg/min
CO 0.16 g/min	*CO* 0.59 g/min

The WHO guidelines helped ARC stove designers make the decision to add chimneys to the stoves. Adding chimneys makes them more costly, but ARC designers are relieved to have a "line drawn in the sand" by the WHO that helps to define the research and development task. Engineers appreciate clear goals.

In 2018, the WHO published another book that recommends methods for protecting health by limiting exposure to smoke (WHO, 2018a). The WHO suggests five 'prescriptions' to clean the air and protect health:

(1) Use only clean household energy for cooking, heating, and lighting.

(2) While waiting for cleaner energy to be available, use technologies and fuels that reduce exposure such as low-emission biomass cookstoves.

(3) Minimize the time children spend around smoky fires.

(4) Increase ventilation.

(5) Install a chimney.

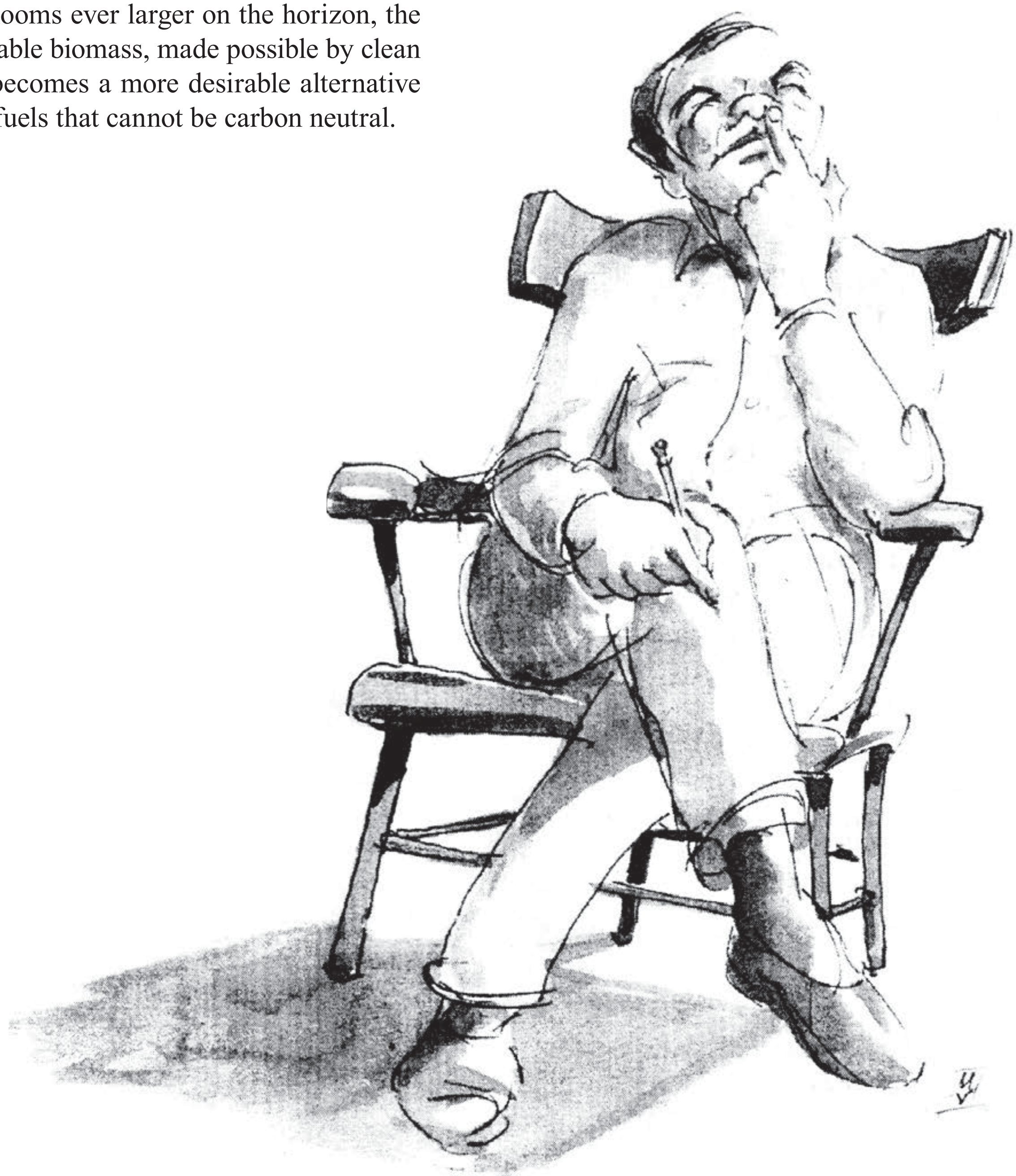
Obviously, protecting health by reducing exposure is important. It should be remembered however, that better wood burning stoves can improve life in many ways besides lowering emissions. Saving firewood benefits the user who either pays for the fuel or has to collect it. A functional chimney makes a tremendous difference by sending harmful smoke and gases out of the kitchen. The interior walls of the home stay cleaner, and eyes may no longer sting. The kitchen can become a more pleasant environment. Improving the smoky mud stove to use less fuel is not a complete cure by any means, but it can be helpful. Making any stove safer can result in fewer injuries. The list of additional improvements includes increasing the number of air exchanges per hour in the kitchen, using a better cooking pot, a retained heat cooker, a solar cooker, etc. As Confucius said, "Better a diamond with a flaw than a pebble without."

The US Department of State was farsighted to organize a multi-agency effort, linked with the Clean Cooking Alliance, to address the stove challenge. The effort included investigation of combustion and heat transfer, stove testing, emissions, health impacts, deployment, and field testing. ARC very much appreciated the opportunity to work on creating better biomass cookstoves with DOE funding. Stoves that save fuel and protect health become possible as discoveries in the laboratory move into use.

Since 2015, ARC and ASAT (the for-profit arm of ARC that sells stoves) have been funded by the EPA SBIR program and the Gates-funded Global Health Laboratories to further explore how solid fuels can be used sustainably. The work resulted in several new products including the SSM Jet-Flame. Our understanding of solid-fuel combustion has been substantially expanded, and the newer learnings are described in this book.

As with many problems, practical solutions are varied. Fire is used for so many things! Cooking with fire is a complicated task that changes from one place to another. Making the best tortilla is very different than preparing the perfect omelet or using a wok for high-temperature flash frying to make delicious Chinese food. The cooks are the experts who know how the stove must function. ARC engineers can help with the technical aspects, but designing a stove is a perfect example of a group collaboration.

We have learned that the most useful health interventions are situation dependent. In one place it makes most sense to change the stove, in another to add a chimney, and in the next to change fuels, or add ventilation, or to cook outside. The field informs the open mind of the funder, engineer, or program manager how to be helpful. And, as climate change looms ever larger on the horizon, the use of sustainable biomass, made possible by clean combustion, becomes a more desirable alternative to petroleum fuels that cannot be carbon neutral.

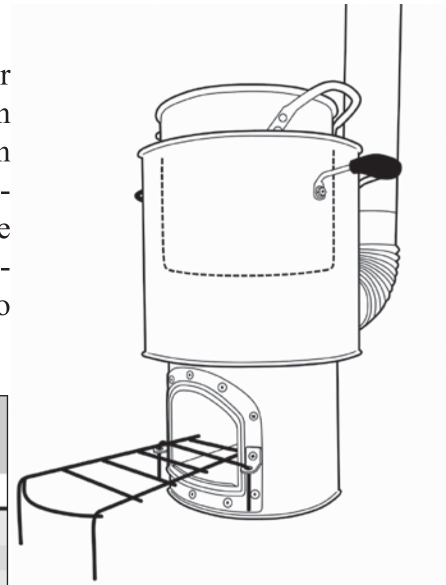


Six Stoves

Natural Draft Sunken Pot Rocket Stove (pp. 67-74)

(pp. 67-74)

($PM_{2.5}$: 11.8mg/min. at high power)

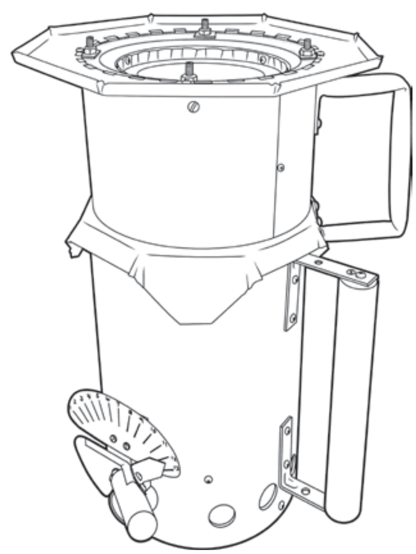


The depth of the low mass, well-insulated Rocket combustion chamber was reduced to burn 8cm of the tips of the wood sticks. The sunken pot stove was designed to be operated at a high power of 2.5kW with a channel gap around the pot of 6mm. A chimney helps to reduce fugitive emissions while an automatic damper directs emissions up the chimney when the pot is removed. This stove serves ARC as a benchmark for a cleanest burning, natural draft Rocket stove with close to optimal thermal efficiency.

Stove type/model		Sunken Pot Rocket		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	49.7%	4%	4
Low Power Specific Consumption	MJ/min/L	0.020	19%	3
High Power CO	g/MJd	2.22	38%	4
Low Power CO	g/min/L	0.05	42%	4
High Power PM	mg/MJd	152.2	53%	3
Low Power PM	mg/min/L	1.73	58%	3
Indoor Emissions CO	g/min	0.25	41%	4
Indoor Emissions PM	mg/min	11.8	46%	2

Kirk Harris Natural Draft Top Lit Up Draft Stove (TLUD) (pp. 75-81)

($PM_{2.5}$: 0.7mg/min at high power)



ARC developed a natural draft TLUD stove that was a top performer in EPA tests (Jetter et al., 2012). An initial survey of best performing stoves (Chapter 9) showed that batch loaded TLUDs were not generally able to turn down the firepower effectively and used too much fuel when simmering. Mr. Kirk Harris developed this TLUD version. It has a superior turn-down ratio created by controlling the amount of primary air supplied into the batch of fuel. A secondary combustion unit on top of the primary combustion chamber includes static mixers with pressure differences that mix the fuel, flame, and air, and swirl the mixture to reduce emissions and increase dwell time. This is a great stove!

Stove type/model		Natural Draft TLUD		Average
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	45.2%	4%	4
Low Power Specific Consumption	MJ/min/L	0.023	10%	3
High Power CO	g/MJd	0.01	1004%	4
Low Power CO	g/min/L	0.01	33%	4
High Power PM	mg/MJd	8.0	16%	4
Low Power PM	mg/min/L	0.10	52%	4
Indoor Emissions CO	g/min	0.001	1041%	4
Indoor Emissions PM	mg/min	0.73	17%	4

Side Feed Bottom Air Forced Draft Rocket Stove (pp. 82-85)

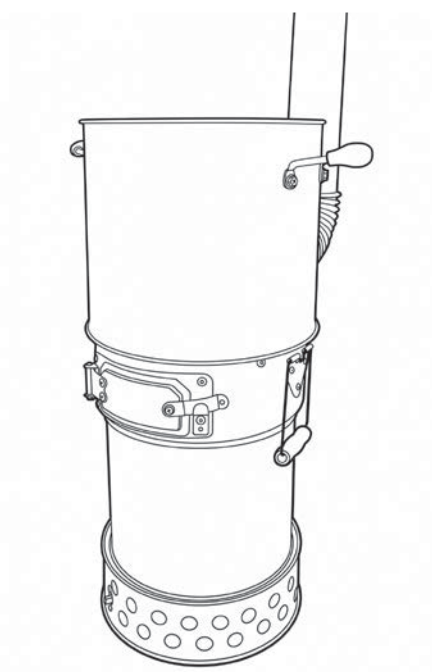
($PM_{2.5}$: 4.5 mg/min at high power)

Sticks of wood are pushed into the side fed stove in the same manner as in an open fire. ARC researchers did not have great success reducing emissions with jets of secondary air aimed into the side of or above the fire. After many experiments, forceful jets of air were placed under the fuel blowing air up into the sticks, charcoal, and fire. The resulting mixing of air/fire/gas/smoke resulted in lowered emissions and the bottom air approach is fairly simple and affordable to manufacture. The SSM Jet-Flame accessory evolved from this stove.

Stove type/model		Side Feed Forced Draft		Average Tier
Location		Average	COV	
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.1%	4%	4
Low Power Specific Consumption	MJ/min/L	0.010	8%	4
High Power CO	g/MJ_d	1.76	30%	4
Low Power CO	g/min/L	0.01	24%	4
High Power PM	mg/MJ_d	47.2	53%	3
Low Power PM	mg/min/L	0.47	48%	4
Indoor Emissions CO	g/min	0.16	22%	4
Indoor Emissions PM	mg/min	4.5	57%	3

Top Lit Forced Draft Stove (TLUD) (pp. 86-89)

($PM_{2.5}$: 3.9 mg/min at high power)



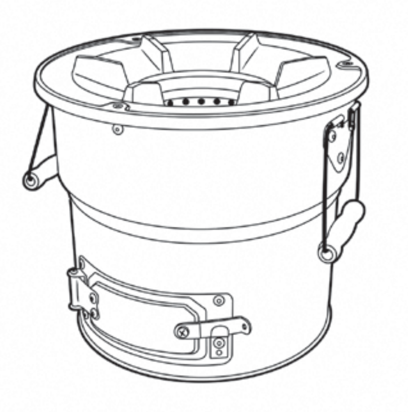
Dr. Tom Reed invented the low emission Top Lit forced draft (TLUD) stove in 1985 with help from Dr. Ron Larson (Reed and Larson, 1996). Many stoves have been manufactured that are patterned after the Reed forced draft WoodGas TLUD. While the Reed stove is very clean burning at high power, reducing the firepower to simmer requires metering chunks of wood into the combustion chamber or using the made charcoal to simmer during the low power phase. ARC added a fuel door under the pot to facilitate adding fuel into the combustion chamber. The velocity of the secondary air jets was increased. The primary air was also increased to facilitate using the made charcoal for simmering.

Stove type/model		Top Loaded Forced Draft		Average Tier
Location		Average	COV	
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	42.7%	9%	3
Low Power Specific Consumption	MJ/min/L	0.010	25%	4
High Power CO	g/MJ_d	0.35	34%	4
Low Power CO	g/min/L	0.04	4%	4
High Power PM	mg/MJ_d	37.4	26%	4
Low Power PM	mg/min/L	0.06	104%	4
Indoor Emissions CO	g/min	0.22	5%	4
Indoor Emissions PM	mg/min	3.9	25%	3

Charcoal Stove (pp. 90-94)

($PM_{2.5}$: 1.8 mg/min. at high power)

Well-made charcoal that has no wood remaining in it burns without making appreciable amounts of smoke. ARC has been studying charcoal burning for many years. Ryan Thompson and Sam Bentson, ARC General Manager, worked on the charcoal stove for two years. It is surprising that a charcoal stove was one of the best performing stoves, achieving all nine IWA Tier 4 scores. While pure charcoal doesn't smoke, it often makes a lot of carbon monoxide (CO). The ARC team super-insulated the combustion chamber resulting in temperatures above 620°C (the auto-ignition temperature of CO) about four minutes after ignition. Secondary air jets, just above the fuel bed, also assist the combustion of CO. A large airtight door is used to increase firepower for boiling when fully open and reduces firepower for simmering when the door is almost completely closed.

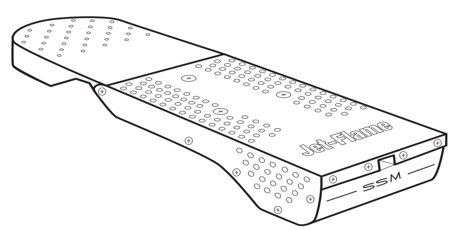


Stove type/model		Charcoal		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.0%	4%	4
Low Power Specific Consumption	MJ/min/L	0.002	10%	4
High Power CO	g/MJ_d	6.35	19%	4
Low Power CO	g/min/L	0.01	11%	4
High Power PM	mg/MJ_d	28.2	54%	4
Low Power PM	mg/min/L	0.01	6%	4
Indoor Emissions CO	g/min	0.41	25%	4
Indoor Emissions PM	mg/min	1.8	58%	4

SSM Jet-Flame (pp. 95-102)

($PM_{2.5}$: 2.4 mg/min. at high power)

When designing a clean stove ARC starts the iteration process by optimizing thermal efficiency, metering the fuel, and attempting to create about 40% excess air at 900°C or higher for 0.2 seconds of time in the combustion zone (see Chapter 7). The 2 Watt cast iron and stainless steel Jet-Flame blows air jets up into the fire/charcoal, elevating temperatures and creating molecular mixing. The penetration depth of the jets and velocity/volume of the air have been adjusted to improve performance and emissions.



Stove type/model		Jet-Flame		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	40.6%	2%	3
Low Power Specific Consumption	MJ/min/L	0.032	4%	2
High Power CO	g/MJ_d	2.82	9%	4
Low Power CO	g/min/L	0.09	12%	4
High Power PM	mg/MJ_d	26.6	24%	4
Low Power PM	mg/min/L	1.13	22%	3
Indoor Emissions CO	g/min	0.39	11%	4
Indoor Emissions PM	mg/min	5.0	20%	3

Clean Burning Biomass Cookstoves: A Quick Summary

- The combustion zone is as hot as possible. At high temperatures, above 900°C, the combustion and heat transfer efficiency are increased.
- The heat transfer efficiency is close to optimal resulting in 40% to 50% thermal efficiency. One successful technique is to combine moderate firepower with very small channel gaps (6mm) around the pot. Burning less wood results in fewer emissions.
- Emissions are reduced by increasing combustion efficiency. An appropriate amount of wood gas is made. The rate of reactions is controlled by adjusting the primary air in a TLUD or by metering the fuel in a Rocket stove.
- A zone of mixing of air, gases, smoke, and flame is created using static mixers or jets of air. The secondary air can be powered by natural draft in a Top Lit Up Draft stove or by forced draft in both Rocket and TLUD stoves.
- The cooling effect of the secondary air jets is not allowed to decrease thermal efficiency below 40%.
- Primary air jets blow up into the burning charcoal and generally raise temperatures in the combustion chamber.
- The metering of flame, air, and woodgas entering the zone of mixing is adjusted until close to optimal combustion efficiency is obtained.
- Removing the emissions from a living space with a chimney is mandatory in the United States. The ARC stoves have chimneys to comply with new WHO guidelines.
- The prototype stove moves through an iterative development process by testing one change at a time under the LEMS emissions hood. The Water Boiling Test and the Controlled Cooking Test are used to evolve a stove that is clean burning, fuel efficient, and cooks as well or better than the traditional model.
- The cooking function of the stove is designed by local users. The emissions equipment is set up in the field, producing data for the team as the design evolves. The market viability of the product is determined by field testing involving stakeholders such as distributors, manufacturers, funders, consumers, etc. Market testing precedes and informs manufacturing (Baldwin, 1987).
- Reducing adverse health effects requires the new stove to be a successful intervention. The intervention involves many infield factors that influence the effectiveness of the whole package. Identifying these factors begins the process of creating the successful intervention.

Chapter 1

Fire: Today and Yesterday

Humanity has been using fire for about one million years. Around 300,000 years ago, people were habitually making cooking fires in caves in what is now Israel. Combustion still powers almost every facet of modern civilization. Burning continues to be an essential technology of organized human life providing the needed energy for transportation, electrical generation, cooking, heating, and illumination. Frequently, burning provides the electricity for computers that store information in the "cloud."

Many foods have to be cooked to become edible and cooked food can be safer to eat. Water often has to be boiled to become potable. In large part, burning oil and gas, a very old energy source that has been stored in the ground, powers perhaps half of humanity while combusting much newer biomass serves the same function for the other half of us who probably have less money.

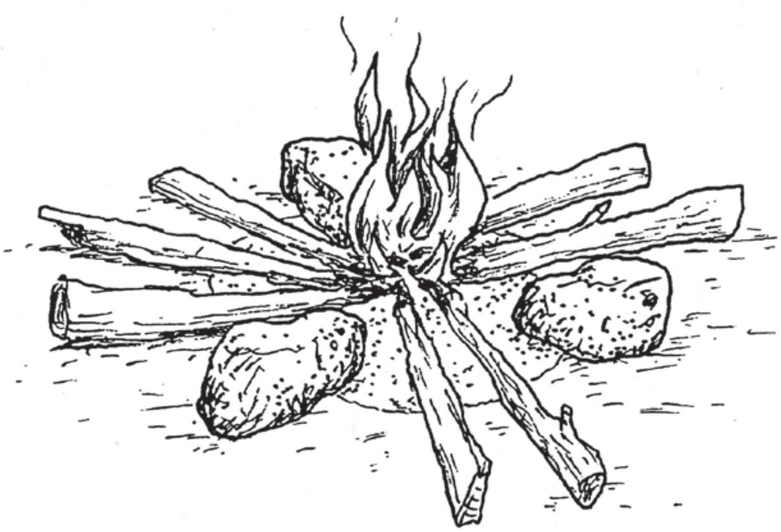
Aprovecho Research Center (ARC) has been investigating fire since 1976. We have discovered that some of our better "inventions" have been in use for hundreds of years in other cultures and we wonder how much learning is being rediscovered, perhaps time and again. Studying fire is one of the problems that intrigued the ancients and continues to motivate modern researchers searching for sustainability. Can biomass become a carbon neutral energy source replacing the oil and gas that have added so much carbon dioxide (CO_2) into the ecosystem?

The smoke that accompanies solid fuel combustion connects tribe members sitting next to their Three Stone Fire with modern residents of Beijing, New Delhi and many other places where the air is polluted with smoke from incomplete combustion. Upper class urbanites suffer from the accompanying respiratory illnesses just like the folks who are dependent on the fire on the floor of their kitchens.

Although solid fuel combustion is not yet mathematically described, fire is a well-known and much appreciated practical companion. In colder climates, life becomes more amenable with a warming fire in the house. A fire makes the house an inviting refuge, a place of civilization. One small firelight at night protects inhabitants from dangers that are no longer hidden. With illumination, books can be read, tools and clothing made and repaired, while animation enlivens stories. Fire can be the night time sun.

Unfortunately, when buried oil and natural gas are extracted and burned, the stored CO_2 is added to the atmosphere. Combustion continues to power automobiles, factories, and spaceships. Since the advent of the Industrial Revolution, there has been so much burning that the concentration of CO_2 in the atmosphere has been steadily rising. In 1959, there were 315 parts per million (ppm) of CO_2 in the atmosphere which rose to an average of 385 ppm by 2008 (Keeling et al., 2008). As of July, 2020 the monthly global average concentration of this greenhouse gas has now surpassed 418 parts per million (www.co2.earth).

Current projections, depending on the amount of emissions humans create, are for concentrations of CO_2 to rise to 500–1000 ppm by the year 2100 (IPCC, 2007). The resulting climate change will,



of course, have greater or lesser effects depending on the multitude of consequences. Will combustion that elevates CO_2 burning, that is not carbon neutral, eventually be prohibited? Perhaps it now seems inevitable? Several European countries are planning to ban cars with internal combustion engines by 2035, as is the state of California.

Like CO_2, smoke has recently been found to be hazardous in new ways. Many of the pollutants from cookstoves add to the warming potential in the atmosphere. Carbon Monoxide (CO) has a climate warming potential many times greater than CO_2 and the black carbon in smoke has been estimated to cause approximately seven hundred times more warming compared to CO_2 by weight. The lightweight smoke particles rise into the upper atmosphere and warm quickly like a black blanket, especially when they fall to earth and snow turns darker (Bond et al., 2013).

Reflections on climate change, caused in some part by burning biomass, have added new perspectives to the concept of an “energy ladder.” The original ladder paradigm had biomass near the bottom, up which cooks climbed as they rose towards the use of electricity and natural gas. Whether a fuel adds CO_2 or other climate forcers to the atmosphere is a new factor that may be changing the order of fuel placement on a ladder. Traditionally, the energy ladder is climbed by economic improvement. If oil and gas are replaced by renewable energy sources what rung will biomass occupy? Will biomass be used more or less in the foreseeable future?

The European Commission has concluded that the clean burning of biomass could reduce Europe’s greenhouse gas emissions by 20% and estimates that using sustainably harvested biomass for heat and power applications would reduce emissions by 55% to 98% (European Commission, 2010). It is conceivable that the clean burning of sustainably harvested biomass may emerge as one of the preferred carbon neutral cooking methods, as well.

Burning natural gas or cooking with coal generated electricity adds thousands of tons of CO_2 to the atmosphere. The possibility that the very clean burning of sustainably harvested wood will be carbon neutral has reinforced recent efforts to modernize the use of biomass, the traditional energy source. Of course the question is: Can humanity learn how to burn sustainably harvested wood very cleanly in heating, cooking, and electric generating applications without making smoke? Then, can we manufacture and sell improved products at affordable retail prices to generate widespread use?

Wood is surprisingly energy rich. Over generations, trees concentrate sunlight into a dense energy source. From time immemorial, steam has been made from pots of water suspended over biomass fires. Civilizations became industrialized when they learned to harness and make profit from steam. Will industry again be powered by cleanly combusted, sustainably harvested biomass? Will some team invent cold fusion or something equally wonderful? Can the world learn to conserve? It’s a fascinating question and challenge.

Direct or Indirect Use of Solar Energy

Direct use of the sun’s energy has alternate advantages. Sunlight is abundant. Every day about 200 times more energy than is used yearly in the United States pours down onto our planet (Merrill et al., 1974). Using sunlight is also an inherently cleaner energy source. When the sun is shining, the free energy can generate electricity, cook food, heat houses, and power engines.

While burning wood makes smoke and can harm individual and planetary health, the photovoltaics on a neighbor’s roof are silent and clean. It is, after all, the lovely, natural light from the sun that makes all activity possible on our blue sphere.

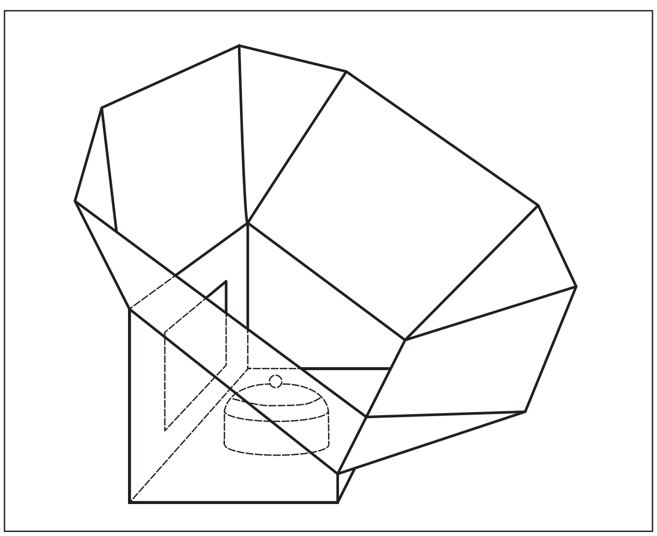
The light from the sun is a gentle warming influence because direct solar energy is diffuse. One square foot of hot sunlight per hour only has about 1/35th the energy contained in a pound of wood. For this reason, solar applications like cookers, ovens, water heaters and photovoltaic panels have to be large and efficient to accomplish even relatively small amounts of work.

As a rule of thumb, a square meter of strong direct sunlight delivers energy at the rate of about 1kW per hour. Many biomass cookstoves have a minimum firepower of about 3kW. If the heat transfer efficiency in a solar cooker is the same as in a wood burning stove (say 33%) the solar cooker has to intercept about 3 square meters of sunlight to cook food in similar times.

That's a pretty big oven, but once it is built clean and quick cooking is possible whenever the sun shines. Cooking no longer makes smoke, and the pots, the cook, and the kitchen aren't blackened by soot. A well-built solar cooker can last for decades. It's easy to imagine that the cost of the cooker will be forgotten, or at least compensated for, by all of the delicious food that it produces.

However, nothing is perfect. Solar cooking does not work at night, at dawn, or dusk. Solar cooking takes place outside of the home and the cook is now outside in the hot sun. In the winter, at least in Oregon, we may not see the sun for weeks at a time. When it is raining, cooking inside the kitchen with wood is a lot more comfortable.

Aprovecho has two rural campuses near Cottage Grove, Oregon, a 40 acre farm/forest and a 5 acre cookstove research center. Interns live at the farm studying farming, forestry, sustainable living skills, and appropriate technology. Large solar cookers are used at both campuses during the summer. Cooking with 3 square meters of intercepted full sunlight creates ovens that stay around 190°C during the peak solar hours. The Telkes solar ovens cook large amounts of food with only a minimal amount of attention. We love solar ovens! They make cooking so easy especially when coupled with a retained heat cooker. See "Capturing Heat" at aprovecho.org/publications-3 (Still and Kness, no date).



A Maria Telkes Solar Oven.

Emissions from Wood

Sometime in October, the staff and interns have to revert to cooking with wood when the seven-month-long winter rains return. The average woodlot production from the 40-acre ARC farm campus is about 10 tons of wood per acre per year. A not-so-great Rocket stove uses approximately two pounds of wood per hour to cook food. If the stove is used 5 hours a day then food can be cooked for 2,000 days without diminishing the biomass resource from one good Oregon acre of trees. Theoretically, five small families could cook food without overdrawing from a one-acre "energy bank account." However, smoke is a lot worse for climate change by weight compared to carbon dioxide! Only really clean burning stoves have a place in a carbon neutral future.

Wood is often used at the rate of growth in Oregon. But it is easy to see clear cuts without any trees left standing and lots of un-combusted smoke escaping from chimneys. As the WHO points out, even small amounts of smoke can become hazardous to health. Winter smoke alerts prohibit wood burning in Oregon valleys when air inversions occur.

About 4 million deaths per year and something like 21%-25% of black carbon emissions are caused by wood fires, used mostly for cooking food by nearly 2.4 billion people worldwide (Bond et al., 2013; International Energy Agency, 2010; Lim et al., 2012). The WHO 24-hour mean concentration air quality guideline for particulate matter 2.5 microns or less in diameter ($PM_{2.5}$) is 25 μg/m^3 (micrograms per cubic meter) and the yearly value is 10 μg/m^3 (WHO, 2006).

Unfortunately, there are many cities in the world where the $PM_{2.5}$ concentration in the outside air is much higher. The average PM_{10} level in a study of 1600 cities was 71 μg/m^3 (WHO, 2018b). The causes are numerous but cooking food with wood fires is a part of the problem. Obviously, in these cities, stoves and other combustion fueled technologies should not add to the already dangerously high levels of pollution. The potentially beneficial dilution effect of the open air has been negated by the existing levels of emissions.

Almost all societies pollute their environments to one extent or another. Reducing the amounts of emissions so that only safe levels of pollution exist in air, water, and earth is a constant challenge, especially where mitigation is costly or socially difficult to enact. In many developing nations, industry manufactures a large percentage of the world's goods, and the resulting pollution has become an evident and worrisome by-product of economic success.

The improved cookstove designer cannot always depend on dilution to protect health by lowering the outdoor concentrations of smoke. In the US clean outdoor air generally does dilute wood smoke to acceptable levels but some large cities have banned wood burning heating stoves. Generally, the combustion efficiency of the stove should improve as the outdoor concentrations of $PM_{2.5}$ increase. Burning up the CO and $PM_{2.5}$ in the stove becomes more important in places where the outside air is already somewhat dangerous to breathe. Clean combustion, which is commonplace with natural gas and other liquid fuels, becomes a necessity if new biomass stoves are to protect personal and planetary health.

How to improve combustion efficiency is becoming better understood. Combining fuel metering with the molecular mixing of woodgas, air, and fire at high temperatures (above 900°C) for a sufficiently long time (experiments at ARC in cookstoves indicate at least 0.2 seconds) results in close to complete combustion in industrial applications. Moving these techniques into affordable, practical wood burning cookstoves is the next challenge. For billions of biomass users, from Oregon to Africa, the results are important.

Chapter 2

The Laboratory Emissions Monitoring System (LEMS)

An accurate mathematical model of a wood burning stove has not yet been developed. Experiments are needed to build the experience base for predictive stove development and subsequent computer modeling. Since most effective biomass stove development must be done experimentally, collection of accurate emissions data is essential. ARC developed, and continues to improve the Laboratory Emissions Monitoring System (LEMS) to assist in accurate data gathering.

Creating a Baseline for Stove Development

The DOE funded studies on improving cookstoves at ARC began with a survey of the cleanest burning cookstoves then available. Many stoves were tested under the LEMS hood with the International Working Agreement (IWA) 4.2.3 Water Boiling Test (WBT).

The survey results were used to begin the developmental process by starting with and then further improving the best performing stoves. One change at a time, an iteration, was made in a stove. Each stove iteration was tested three times for fuel use and emission rates under the LEMS hood. Over a couple of months, fuel use and levels of emissions were improved and the experimental data pointed out how each particular stove, and stoves in general, could be improved. We now test stoves from seven to nine times to achieve statistical significance.

Developing the Laboratory Emissions Monitoring System

Work on developing the LEMS began in 2004 when Dr. Tami Bond, Damon Ogle, and Dr. Dale Andreatta assisted Dr. Nordica MacCarty in constructing the first emissions hood at Aprovecho. Without the hood we were only guessing about the level of emissions. To make a clean burning stove, ARC had to develop a method of quantifying the emissions. Our colleagues helped to push the ARC lab forward and started a long process of testing stoves and improving the LEMS system.

In 2012, the ISO International Working Agreement specified that the measurement of $PM_{2.5}$ had to be done with a gravimetric pump and filter system. Sam Bentson, ARC General Manager, incorporated an affordable gravimetric system into the LEMS. The 2018 ISO 19867 Standard for biomass cookstoves required more than ten further improvements to the LEMS. NextLeaf, Inc. developed a black carbon photographic technique that works with the PM filters used in the LEMS. ARC continues to update the system to provide Regional Testing and Knowledge Centers, university labs, NGOs, and others with accurate and affordable testing capabilities.

Dr. Jim Jetter of the US Environmental Protection Agency (EPA) has helped to improve the LEMS and it has been run side by side with his equipment. He published a paper showing general agreement

Sam Bentson, ARC General Manager, invented the gravimetric system used in the LEMS. The IWA guidelines mandated the use of gravimetric (pump and filter) for measurement of $PM_{2.5}$. Sam used a large filter to reduce the cost and complication of weighing the filters.

between the LEMS and EPA test results (Jetter and Kariher, 2009). The first sale was to Zamorano University in Honduras in 2007. Since then ARC has sold more than 60 emission hood systems to testing centers around the world. ARC staff have helped to set up and train the staff at most of the new labs. It's a great way to make friends and colleagues around the world.

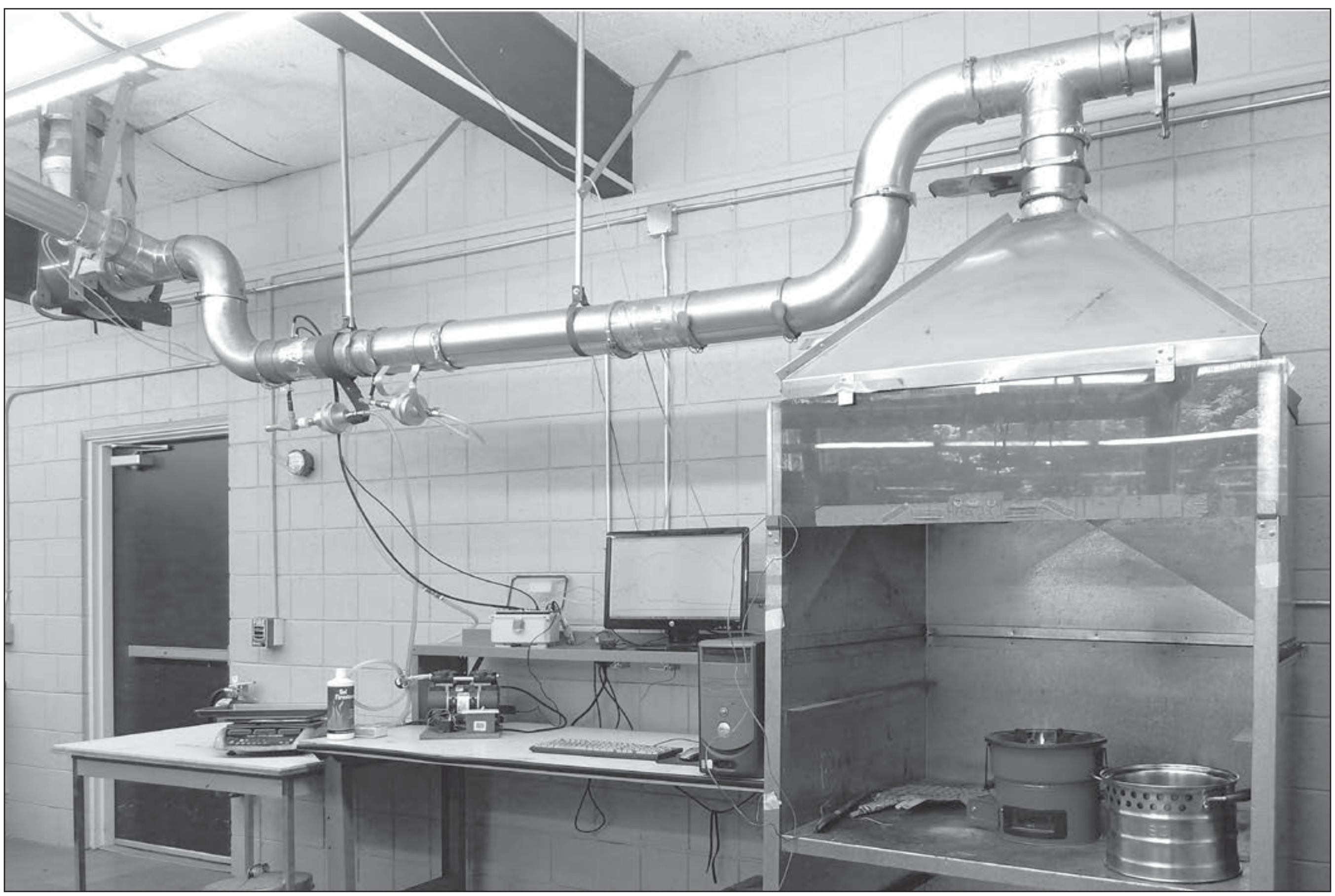
How the LEMS Works

Without the LEMS hood, the ARC iterative development process wouldn't be possible. CO is invisible, and the very low levels of $PM_{2.5}$ that affect health are just as hard to identify. The LEMS pulls smoke through a white filter that is pre-weighed, and then post-weighed, using various test protocols. The test is repeated until a 90% confidence interval at one third the distance between tiers of performance is attained. In recent tests, seven to nine repetitions were needed to achieve statistical confidence.

The LEMS measures the CO, CO_2, and $PM_{2.5}$ produced during the simulated cooking event of heating, boiling, and simmering water, known as the Water Boiling Test (WBT), the Water Heating Test (WHT), or the more realistic Controlled Cooking Test (CCT) (see Chapter 3). The stove is used under the hood which collects all of the emissions. The flow rate and temperature are measured in the exhaust tube. A fraction of the flow through the system is drawn by a suction pump through a sample line to the sensors.

Separately, a thermocouple measurement of the temperature of the water in the pot(s) is logged. A computer displays and records the temperatures, flow of exhaust gas, and concentrations of gases and $PM_{2.5}$ in real-time. The tester processes the recorded data using provided software to report the performance of the stove based on the mass of emissions measured.

The CO sensor is an electrochemical cell. Conductivity between two electrodes in the cell is proportional to the concentration of CO present. This cell has a reference terminal as well and requires a po-



The Laboratory Emissions Monitoring System (LEMS) set up in the stove lab.

tentiostatic controller. The CO_2 sensor uses non-dispersive infrared (NDIR) to measure CO_2 concentration and outputs voltage. It is self-calibrating, with pure nitrogen gas used for a zero reference.

The LEMS has two $PM_{2.5}$ sensors. The scattering photometer has a laser and a light receiver. When smoke enters the sensing chamber, particles of smoke scatter the laser light into the receiver. More light reaching the receiver indicates less smoke in the chamber. The amount of scattered light is calibrated with a laboratory-standard nephelometer. A constant is applied to the output to estimate the mass concentration of smoke particles. This is integrated into the data processing spreadsheets.

The gravimetric system gives a direct and more accurate measurement of total $PM_{2.5}$ using filter sampling. Laser based measurement is known to miss smaller particles. A vacuum pump pulls emissions through the sample line and the critical orifice, which holds the flow at a steady 16.7 L/ min. A cyclone particle separator is used so that the $PM_{2.5}$ is collected on a glass fiber filter while the pump is on. The filter is pre- and post-weighed to calculate the total $PM_{2.5}$ mass.

The flow is measured by a pressure transducer which outputs a signal based on the pressure drop measured across the flow grid. The flow grid is an amplified pitot tube that provides a low pressure drop through the system and a strong differential pressure signal, averaged across the entire duct cross-section. Exhaust gas velocity, volume, and mass flow rate within the duct are calculated based on pressure drop recorded using the Magnesense®.

Analogue pressure measurement is provided by the Magnehelic® sensor. Measuring in parallel to the pressure transducer mentioned above, the Magnehelic sensor provides a calibration to the Magnesense for each test. The Magnehelic sensor can also be used to balance the pressure from calibration tanks with the suction pressure of the sensor box pump. Higher flows within the duct are represented by higher values on the Magnehelic, reported in inches of water.

The temperature of the exhaust gas is measured by the sensor in real-time. The data are required to calculate the density of exhaust air in order to know the mass flow of emissions. A thermocouple temperature sensor is used to record the water temperature of the pot. The thermocouple temperature output is linear and the probe provided with the LEMS is rated for temperatures up to 250°C.

Why Test Cookstoves?

ARC has many good reasons to look to testing as a method for improving performance. As mentioned, the first ARC stove, the Lorena, used a lot more wood to boil and simmer a pot of water than a Three Stone Fire. Only testing, after the Lorena stove was famous, revealed that unfortunate characteristic. Our misguided stove designers had been sure that their stove was great and with utter conviction went around the world explaining the wonders of their invention. The exaggerations of truth were, for the most part, unintentional.

Damon Ogle, who was the Research Director at ARC for ten years, is a great believer in experimentation. His motto “Speculation is worthless!” is mounted on the wall in the lab. Damon would kindly remind folks who were talking about a stove in the lab that actually getting to work and testing it might be a better use of time. Inventor’s pride is a strong influence and is known throughout history to have misguided great human beings.

“Of course, it’s perfect!”

Chapter 3

Testing Cookstoves

Successful cookstove development and improvement requires evaluating data from a variety of tests and other sources. The task of testing cookstoves has traditionally been split into three categories:

Laboratory testing – a standardized Water Boiling Test (WBT) or Water Heating Test (WHT).

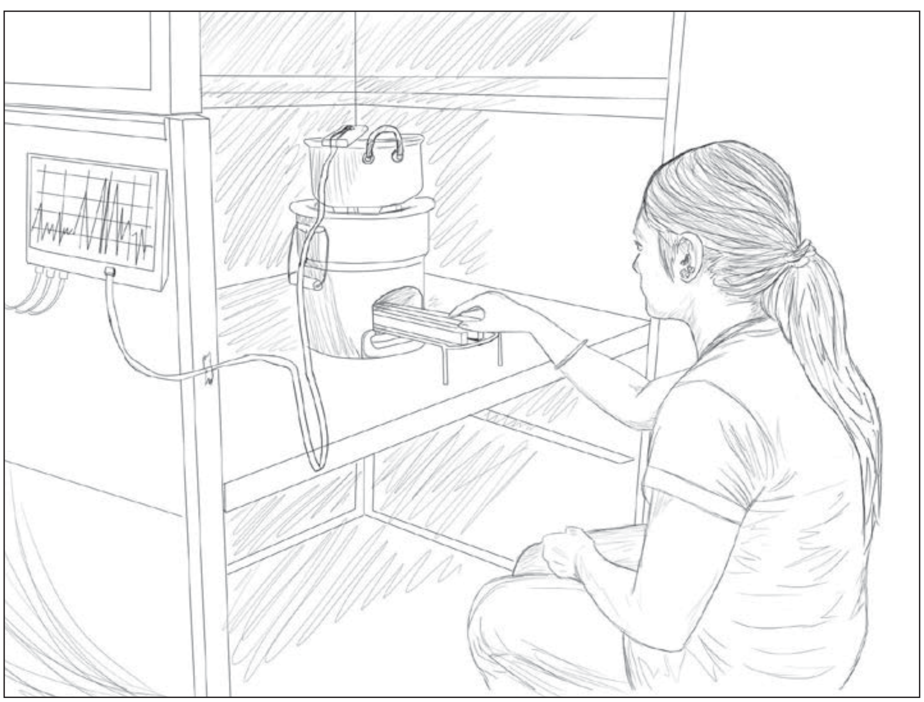
Field testing – a Controlled Cooking Test (CCT) where local cooks, rather than lab technicians, make a specific common food using their wood, pots, etc.

Field surveys – the Kitchen Performance Test (KPT) where cooks use a stove in their own kitchen to perform usual cooking tasks.

In the WBT and the CCT, fuel use and emissions can be measured using a total capture emissions hood like the LEMS that sends samples to a sensor that logs the data. When emissions are measured in homes (KPT), the emissions equipment takes samples from the room air using small independent sensors or a partial capture device. Testing can be designed to provide reliable data on many variables including fuel use, emissions, safety, price point, user satisfaction, durability, etc. Each kind of test generates data that is used for different purposes. Dr Samuel Baldwin describes the process of stove design using these tests in his seminal book "Biomass Stoves: Engineering Design, Development, and Dissemination." ARC has tried to follow the procedures for decades and we pass Chapter 5 around to design team members as a first step in a project (Baldwin, 1987).

Water Boiling Tests

Unfortunately, international benchmarks and standards are often based on results from the lab based WBT. Cooking in the field can be different in many ways. "In addition to the limitations arising from differences from real-world performance, laboratory test metrics (efficiency, emissions, safety, and durability) do not inform other factors that are critical to the impacts a product, program, or intervention may achieve. These factors include, but are not limited to geographic/cultural suitability, price-affordability, acceptability to the target user group, and other socio-economic factors." (ISO, 2018). The WBT is great at showing how combustion and heat transfer can be improved, but the cooking function of the stove has to be designed by experts, starting with the cooks.



Reshma Chowdary Manukonda tests the performance of a Rocket stove that is boiling and simmering a pot of water.

ARC began testing with the WBT first published by VITA and then revised over the years by many experts (VITA, 1985). The VITA WBT has been continually revised. The IWA WBT 4.2.3 has recently been replaced by ISO 19867. The IWA WBT 4.2.3 that was used by ARC for the DOE stove research and development project is based on bringing the water to boil twice, starting with a cold stove and then again with the stove hot. After the hot start to boil phase is completed, the remaining water is simmered for 45 minutes. The newer ISO 19867 test heats water at high, medium, and low fire power for 30 minutes in each phase. The Chinese and Indian WBT protocols only include a cold start high power phase.

The ISO 19867 test can be adapted to how users are cooking with a particular stove. For instance, in China low power and simmering are not needed as much as high power, as high firepower is generally used to stir fry food. In Honduras, many pots are simmered for long hours and the slow fire may stay lit all day. In the ISO test the wood used, the firepower of the stove, time to boil, pot(s) used, etc., can be adapted to reflect real use.

Obviously a Water Boiling Test cannot be relied upon to predict regional performance, especially when the cooking task is not boiling or simmering water. Making Mexican tortillas or Indian roti are very different tasks compared to boiling rice or beans. The 1987 VITA WBT was designed to get a first impression of how a stove boils water, how well it combusts the biomass fuel, and how to estimate the actual emissions, real world fuel use, and other factors. Experiments under the hood using the WBT provide data about whether a series of iterative changes in a stove improve performance and emissions. Only field tests can come close to predicting actual performance and if a stove will be useful or purchased.

The Benefits of Field Testing

The WBT researcher is investigating, out of the context of actual use, how fuel use and emissions can be reduced. The lab test data then needs to be supplemented by field tests that generate vital information required to make an actual cooking stove. The information generated by the field tests informs the project team, including the researcher, engineer, funder, user, manufacturer, retailer, and distributor, how the stove has to perform to meet the requirements of all stakeholders. Is health protected? Will consumers buy the product? Will they understand how to start and use the new stove? Can food be easily prepared? These are questions that need to be answered by field testing before the stove is manufactured and marketed.

A good cook knows how the stove needs to function to prepare local foods. Cooking is a complicated and delicate task. The local retailer and distributor know how to sell the stove. The competent manufacturer knows how to make the stove. The funder has distinct knowledge as well and may require that the stove protect health. The various field tests are designed to bring accurate data, so necessary for predictive decision making, to the distinctly different project team members who may have varying perspectives and requirements. Reliable data informs accurate decision making.

Controlled Cooking Tests

The Controlled Cooking Test yields results that are directly related to actual stove use while still offering a high degree of repeatability. The CCT compares the traditional and new stove on multiple measures, creating percentage differences. ARC depends heavily on the CCT to estimate the actual emissions, real world fuel use, and other factors that determine whether a stove is ready for production. Lots of needed information can be gathered from a CCT including how the stove cooks food, acceptable cost, preferences, best height, firepower, and the list goes on and on.

Local cooks can be brought into a home or lab in which the LEMS is disguised. At ARC there is often a pleasant test kitchen in which both WBTs and CCTs can be performed with pictures on the walls, rugs on the floor, and a rocking chair in the corner. The cooks prepare food in as natural a setting as possible while accurate emissions data is being generated. Usually three cooks and three repetitions each of standardized cooking events are needed to create statistically significant information. The test kitchen lab often smells like good food. We all get to eat well for lunch and dinner. The CCT can usually be completed in about two weeks.

Safety Testing

A frequently used safety test is based on Nathan

Johnson's thesis from Iowa State University (Johnson, 2005). The protocol contains 10 different tests to characterize stove safety. The tests are: sharp edges and points, tipping, containment of fuel, obstructions near cooking surface, surface temperature, heat transfer to surroundings, temperature of operational construction, chimney shielding, flames surrounding cookpot, and flames/fuel exiting fuel chamber. The safely test was developed for immobile, continuously fed wood stoves. It has been updated by the Clean Cooking Alliance to include more types of stoves and is included in the ISO 19867 protocols.

Durability Testing

Durability testing can be time consuming. The most accurate tests examine the stove before and after years of use. The new ISO protocol includes several different tests that evaluate aspects of stove durability. They are: the extended run test, the external impact test, the internal impact test, the corrosion test, the coating adhesion test, the quenching test, and a test for material failure temperature.

Durability is very important to users. Determining the temperature inside the combustion chamber can be used to predict the lifespan of materials. ARC maintains a continual testing regimen that consists of three one hour burns per day at Shengzhou Stove Manufacturer in China. The stoves are also monitored when used in Chinese homes near the factory. Quarterly visits to homes in the project area seem to be an accurate method for determining durability and service life. Weighing the parts of the prototype stove after each quarter of use provides the project manager with information on expected product life. Start durability testing as soon as possible! Things break!

More Input, More Tests, Greater Success

As mentioned, it is important to keep in mind that cooks, engineers, and the various stakeholders have equally important roles when designing a new cookstove. All of the project members have distinct expertise. When the retailer and distributor push for a price point they think will determine the market share, the team should be listening. ARC has experienced time and again that local knowledge can be the key to creating success or failure. Unfortunately, as in most endeavors, especially in business, it is easier to fail and harder to succeed.

Our advice is that a lot of testing needs to precede production. Testing the stove after it is for sale, puts the cart before the horse. Fixing mistakes as early as possible is obviously most cost effective. When the stove is being sold, the need for changes can be experienced as failure and change becomes a disagreeable option for personal as well as financial reasons. Our team was very resistant to admit that the Lorena stove had serious problems. More than half of the team quit. It's more efficient to let the user and local team evolve the cooking and market functions of a new stove, and to try to make sure of success before starting manufacturing! Making sure that the funder is on board as decisions are made requires effort, but the distance between field and town does create differences in perspective.

To the extent possible, everybody involved in the stove project should jump in the pool together and share the same experiences.

The WBT, CCT, KPT (and others) can be found at: cleancookstoves.org/technology-and-fuels/testing/protocols.html.

Chapter 4

What is an Improved Cookstove?

Creating standards that define an improved biomass cookstove can be productive on many levels by assuring funders, project managers, and the cooks themselves that the stoves they use are fuel efficient, safe, emit fewer harmful emissions, and are a good value. Testing a stove provides standardized information that can move a stove project closer to the real life performance that fulfills intentions and meets project goals. In 2020, funders are likely to request test results that include the emissions of CO and $PM_{2.5}$ as measured on a standardized test. Market testing leading to a business plan is essential.

Creating Standards and Benchmarks

In 2006, two meetings were held in Bonn, Germany concerning standards for biomass cookstoves. Ms. Caroline Okwiri opened the session with a presentation on the Shell Foundation's motivation for developing a set of stove standards. She listed the following benefits:

- Promote innovation.
- Validate stove potential in the lab.
- Compare stoves from around the world.
- Understand and transfer design features.
- Objective evaluation and comparison of technologies leading to certification against a quality standard.
- Quantify performance.
- Institutionalize a world-wide standard.
- Define an "improved stove" for funders and consumers based on verifiable data.
- Standards ensure the safety and durability of cooking stoves.

In 2010, ARC published a paper detailing the Water Boiling Test performance of fifty cookstoves (MacCarty et al., 2010). The stoves were tested using the WBT 4.2.1, by which the emissions of CO, $PM_{2.5}$, and the fuel used to boil and simmer water were compared to benchmarks of performance that ARC had developed for the Shell Foundation. A later paper shared results of testing fifteen stoves with the IWA 4.2.3 WBT (Still et al., 2014). Both papers showed that there were big differences in stove performance and identified how stoves could be improved.

The Shell benchmarks were created by drawing lines on graphs of lab performance data, separating stoves into top half and bottom half performers. These benchmarks helped the Shell Foundation and other organizations begin the process of defining an improved cookstove. The Shell Foundation benchmarks are:

Fuel use: Using the International Testing Pot, a wood burning cookstove without a chimney should use less than 850 grams (15,000 kJ) of wood to bring to boil 5 liters of 25°C water and then simmer it for 45 minutes during the University of California at Berkeley (UCB) revised WBT.

Emissions of CO: The wood burning cookstove without a chimney should produce less than 20 grams of CO to boil 5 liters of 25°C water and then simmer it for 45 minutes during the UCB revised WBT.

Emissions of $PM_{2.5}$: The wood burning cookstove without a chimney should produce less than 1500 milligrams of $PM_{2.5}$ to boil 5 liters of 25°C water and then simmer it for 45 minutes during the UCB revised WBT.

Chimney Stoves: Wood burning cookstoves with chimneys are exempt from the above standard if the stove does not allow more than an average of 50 ppm of CO to pollute the air anywhere within 30cm of the stove. A wood burning stove with chimney should use less than 1500 grams (30,000 kJ) of wood to bring to boil 5 liters of 25°C water and then simmer it for 45 minutes during the UCB revised WBT.

The ISO International Working Agreement (IWA) Tier Rating System

The Shell Foundation benchmarks were designed to be straightforward: either the stove met or did not meet the level of performance. The low and high power metrics were combined, so if a stove did poorly at one power level it affected the entire rating. Changing the analysis to look at high and low power performance separately occurred in the 2012 IWA standards.

Since 2012, the Clean Cooking Alliance worked closely with the International Organization for Standardization (ISO) to create an international cookstove standard. The resulting International Working Agreement (IWA) included a tier rating system based on the World Health Organization (WHO) health standards. The tiers were organized as follows:

Description of IWA Tiers	
Tier	**Description**
0	No Improvement over the Open Fire/ Baseline
1	Measureable Improvement over Baseline
2	Substantial Improvement over Baseline
3	Currently Achievable Technology for Biomass Stoves
4	Stretch Goals for Targeting Ambitious Health and Environmental Outcomes

In the IWA, performance is evaluated in various ways. High power thermal efficiency is the fraction of energy transferred to the pot. The low power metrics are based on specific consumption, the energy required per liter per minute to maintain a simmer. The fuel use Tier metrics are influenced by the amount of water and shape of the pot and, for this reason, the pot has to be standardized for comparative purposes.

The third category is the rate of emissions produced that can pollute the indoor (and outdoor) environment. The indoor emissions are predictions of the CO and $PM_{2.5}$ concentration based on a model of an average kitchen. These rates were calculated using the health based WHO air quality guidelines. Of course, stoves with well-functioning chimneys and close to zero fugitive emissions, as with heating stoves in the USA, can remove essentially all produced emissions from a room. But the emissions can contaminate the outside air and both $PM_{2.5}$ and CO influence health and climate change (see Chapter 5).

Perhaps the most important innovation in the IWA was a repeatability standard that brought needed rigor to stove testing. Stove testing has been characterized by a general lack of acceptable statistical significance when reporting results. The IWA proposed that the results should be repeatable to within one third of the distance between tiers.

To meet this level of precision, the ARC staff performed the tests carefully with as few differences in procedure as possible. ARC also had to increase the number of tests of each stove. In 2020, our well-trained testing staff needed an average of seven to nine repetitions to achieve acceptable statistical confidence.

The Gold Standard carbon credit foundation proposed a testing repeatability standard called the 90/30 rule. To satisfy the rule, the 90% confidence interval of either the emissions or fuel measurement had to be less than or equal to 70% and 130% of the mean. If the rule is not met, a project may still be certified if the lower value of the confidence interval is used to portray the savings. The German agency Gesellschaft für Internationale Zusammenarbeit (GIZ) is the largest developer of stove projects worldwide. A stove is considered to be improved by GIZ if it achieves a 40% improvement over a local baseline. It is statistically easier to show that two stoves perform differently compared to meeting the repeatability standard of the IWA.

The World Health Organization published “Indoor Air Quality Guidelines: Household Fuel Combustion,” (WHO, 2015). In the publication, the WHO introduced a simplified benchmark designed to protect health based on the metric of indoor emissions (mg/min for $PM_{2.5}$ and g/min for CO). The guideline levels are different for vented or unvented stoves. The estimates were based on 4 hours of cooking per day, in a 30 square meter house with 15 air exchanges per hour. The vented guidelines estimate that only 75% of the pollution exits the room up the chimney out of the indoor environment.

There are a few stoves that have achieved acceptable WHO $PM_{2.5}$ emission rates in lab tests. For example, the Harris Natural Draft TLUD was tested in 2016 at Lawrence Berkeley National Laboratory and scored 0.73 mg/min at high power (5Kw) burning wood pellets (see page 75). The Mimi Moto pellet stove emitted 1.3 mg/min $PM_{2.5}$ in lab tests conducted by Colorado State University, and during cooking tests in Rwanda, scored 3.3 mg/min for $PM_{2.5}$ (Champion and Grieshop, 2019). Recently, the Jet-Flame in the earthen brick C Quest Capital stove emitted 1.8mg/min $PM_{2.5}$ at 4kW when tested in a hot start phase. If the results were multiplied by three in an attempt to predict field conditions, the Mimi Moto, the Harris TLUD stove, or the Jet-Flame C-Quest Capital stove, when connected to chimneys, might be expected to meet the WHO Intermediate Vented Stove $PM_{2.5}$ Standard of 7.1 mg/min. But even these very clean burning cookstoves do not come close to meeting the unvented Intermediate target of 1.75mg/min for $PM_{2.5}$. For this reason, ARC has been guided by the WHO targets to include chimneys on stoves when possible. To protect health, we highly recommend that chimneys be attached to stoves.

It should be remembered that metrics based on mg/min for $PM_{2.5}$ and g/min for CO can be misleading. When a stove is operated at a lower firepower, it burns less wood per minute and emits less $PM_{2.5}$ and CO. Since the WHO emission rate metrics don't include firepower the metrics favor lower firepower stoves. Be sure to compare emission rates from stoves only when the firepower is the same.

The 2018 ISO 19867 standard for laboratory testing of cookstoves protocols addresses this problem by testing stoves at high, medium, and low power. Comparing emission rates at the same firepower results in a more accurate comparison of performance especially when the same pot and firewood are used. The ISO 19867 Tier metrics for emissions are now measured in terms of mass of pollutants per useful cooking energy delivered, not in terms of mg/min or g/min as used in the older IWA.

Improved stoves work by increasing both sides of the combustion and heat transfer equation. As a rule of thumb, a combination of metering fuel, intense heat, sufficient residence time of smoke and gas in the flame, and molecular mixing combine to reduce emissions. Increasing heat transfer efficiency also reduces the amount of pollution. Both dynamics are combined in the ISO 19867 metric of mass of pollutants per useful cooking energy.

The ISO 19867 protocols include new Tiers based on calculations of effects on health derived from the laboratory emissions data. The emission rate based Tiers use theoretical calculations to estimate the concentrations of CO and $PM_{2.5}$ in a 30 square meter building with 15 air exchanges per hour in which food is cooked on a biomass stove for four hours per day. The emissions are calculated as if they are equally distributed in room air, which is known to be an oversimplification. Tier 5, reflecting the lowest amounts of CO and $PM_{2.5}$ emitted, would protect health almost completely while Tiers 4 to 1 result in increasing amounts of ill health caused by exposure.

There are several observations based on our experience with ISO 19867 that have resulted from experience:

ISO 19867 Voluntary Performance Targets – Default Values

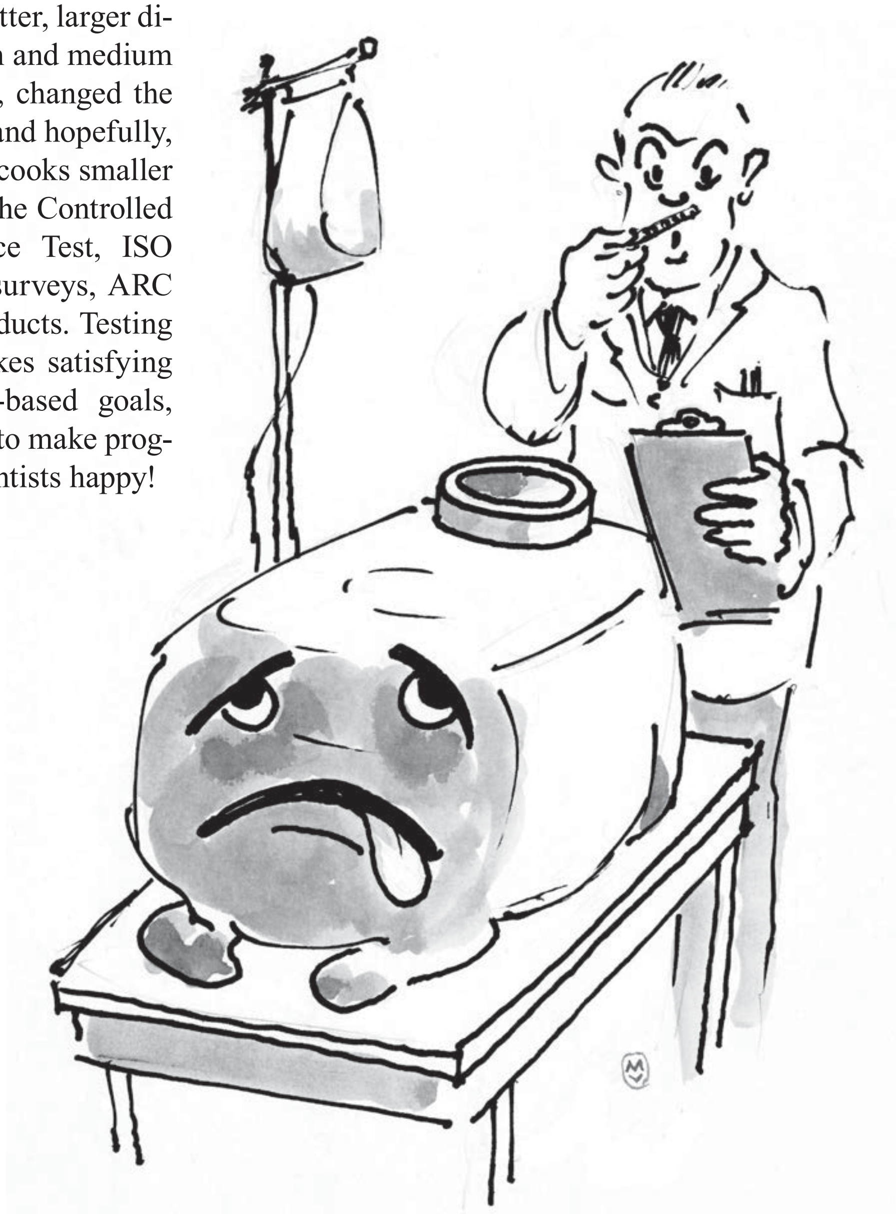
Tier	Thermal Efficiency %)	CO Emissions (gram/megajoule delivered)	$PM_{2.5}$ Emissions (milligram/megajoule delivered)	Safety (score)	Durability (score)
5	≥50	≤3.0	≤5	≥95	<10
4	≥40	≤4.4	≤62	≥86	<15
3	≥30	≤7.2	≤218	≥77	<20
2	≥20	≤11.5	≤481	≥68	<25
1	≥10	≤18.3	≤1031	≥60	<35
0	<10	>18.3	>1031	<60	>35

- Particulate matter is known to stratify vertically and therefore personal exposure to the cook and others in the kitchen is not predicted accurately by a single-zone model. A test kitchen with the fixed ventilation rate and dimensions used in the WHO calculations was built at ARC and fitted with thirty HAPEx PM Sensors that were evenly distributed at 4 different heights within the kitchen. Seventy modified water boiling tests were performed with a common Rocket stove operating at known firepower and emissions rates in two testing phases at 10, 15 and 20 air exchanges per hour. Results showed that stratification was less pronounced with increasing ventilation and with decreasing firepower. Measured concentrations at 15 ACH were compared to the predicted value from the single-zone model, showing equilibrium at a height of approximately 1.6 m. The box model over-predicted concentration at heights lower than this, including a 23% to 63% excess at 1.3 meters height above the floor. This implies that the current emission rate targets, and the Tier rankings based on the targets, may be overly conservative when cooks are breathing at lower levels and especially when sitting on the floor while cooking (MacCarty et al., 2020).
- ARC has completed more than two thousand Water Boiling Tests (WBT) with gravimetric measured emissions since 2012. Only the escaping fugitive emissions from stoves are measured in ISO 19867 so most stoves with close to 100% functional chimneys, when tested in the lab, score in the Tier 4 to 5 range. A simple way to score in the highest Tiers is to include a chimney on the stove because emissions inside the chimney are not reflected in the score.
- It is well known that emissions are much higher when measured in actual use. For this reason, ARC multiplies emission rates from lab tests by a factor of 3 when attempting to estimate actual minimum concentrations in houses. It is a well-known mistake to assume that lab results can predict field conditions. The Tiers can only be used to compare stoves as tested in the lab. This book includes a closer look at the Tiers and predictions of how the emissions from various stoves effect the concentrations of $PM_{2.5}$ in indoor and outdoor air (see Chapter 5).
- It is necessary to make sure that the same pot, fuel, operating procedures, etc. are used when comparing ISO 19867 test results. These variables change the performance and emissions from stoves, so testing reports must be carefully read and differences taken into account.

A lot of human energy has gone into the WBT. Although moving into the project area and working with users, and testing to analyze success or failure is known to be helpful, field testing does not seem to be as popular as lab testing. All WBT test protocols continue to include warnings that results cannot be used to predict what happens with real use. The 19867 ISO Standard states that performance metrics cannot “serve as the sole basis for decisions about which technologies/fuels to promote for a given setting, since the performance of a given technology will likely differ under real-use conditions. The best way to assess real-world impacts of a stove intervention or program is through field studies. In addition to the limitations arising from differences from real-word performance, laboratory test metrics (efficiency, emissions, safety, and durability) do not inform the stove project about the many other factors that are critical to the impacts a product, program, or an intervention may achieve. These factors include, but are not limited to geographic/cultural suitability, price-affordability, market viability to the target user group, and other socio-economic factors.” (ISO, 2018)

At the same time, ARC uses ISO 19867 almost every day in the lab, and we value the test. By testing iterative changes in each series and generating statistically significant data, ARC learns what works better and how to improve heat transfer and combustion efficiency in stoves. After so much time, we feel that stove testing with water heating has matured. ISO 19867 has also improved the reliability of the emissions hood itself. These changes elevated the quality of LEMS data that is now ISO compliant. Both hardware and software have been improved.

ISO 19867 encourages the use of pots, fuels, and cooking techniques from the project area with the intention of getting closer to producing helpful results. ARC has just completed a series of tests to determine the most effective Jet-Flame velocity settings for high, medium, and low power. The lab tests were informed by as much local information from Malawi as possible. Burning wetter, larger diameter sticks of wood, mostly at high and medium power, as indicated by field surveys, changed the results on several important metrics and hopefully, when the settings are tested by local cooks smaller changes will be necessary. Without the Controlled Cooking Test, Kitchen Performance Test, ISO 19867, the LEMS, and commercial surveys, ARC would be unable to create useful products. Testing with these complimentary tools makes satisfying customers, while achieving health-based goals, mostly a matter of effort. The ability to make progress, even deliberate, makes eco-scientists happy!



Chapter 5

Protecting Health

Cooking with an unvented biomass cookstove usually means breathing a lot of harmful smoke (including $PM_{2.5}$). Smoke and harmful gases are also created in many other ways, such as smoking cigarettes, burning trash, and fields. Cooks often try to move away from smoke and since smoke rises along with hot air, sitting as low as possible when cooking is a good idea. Encouraging children to play outside may help to protect their health. However, it is frequently not possible for a cook to reduce the time spent near a smoky stove. Without a chimney the smoke is flowing near to or into the face of the cook. Health is generally protected by (1) venting smoke up a chimney or hood, (2) burning more of the smoke in the stove, and (3) increasing the amount of fresh air entering into the kitchen to dilute the smoke and gases.

In 2015, when the first edition of this book was published, the WHO issued Emission Rate Targets for cookstoves that were mathematically generated using a single zone box model to predict the concentration of smoke in a 30 cubic meter room in which the air is exchanged 15 times per hour (WHO, 2015). The model assumed that pollutants are equally present in all spaces in the room. When the Emission Rate targets, generated by the model, are met it was estimated that health will be protected. The 2015 emission rates are in milligrams per minute for $PM_{2.5}$ and in grams per minute for CO. Since the targets are based on protecting health it is more difficult for wood burning cookstoves to meet the $PM_{2.5}$ targets. CO is better tolerated by human beings and larger amounts are not as unhealthy.

The vented stove targets are based on 75% of the $PM_{2.5}$ and CO exiting the room out of a chimney or hood. 25% of the emissions are then leaking into the room. Fully functional chimneys take essentially 100% of the smoke and gases outside of the house. But in real life a chimney may leak, the stove may not be air tight, and when pots are removed smoke can pour into the kitchen.

The emission targets did not include the firepower of the stove. Burning more wood per minute usually creates more smoke. Stove designers are often trying to make clean burning, higher power stoves as often desired by cooks. The WHO targets, based on the effects of smoke and gas on health, are based on amount of pollutant per unit of time. Lower firepower stoves are more likely to meet the published standards.

2015 WHO Emission Rate targets	
Unvented stove	***Vented stove***
$PM_{2.5}$ 0.23 mg/min	$PM_{2.5}$ 0.80 mg/min
CO 0.16 g/min	*CO* 0.59 g/min

WHO *Intermediate* Emission Rate Targets	
Unvented stove	***Vented stove***
$PM_{2.5}$ 1.75 mg/min	$PM_{2.5}$ 7.15 mg/min
CO 0.35 g/min	*CO* 1.45 g/min

Exposure can be reduced by (1) using an air tight, vented cookstove (2) that makes the least amount of smoke (3) in a kitchen that has the most air exchanges per hour. Using a functional chimney can prevent almost all of the smoke from entering the kitchen. When the outside air is clean, increasing the air exchange rate dilutes dirty indoor air and, in this way, reduces exposure. Unfortunately, when the outside air is already polluted it is not as effective at reducing the concentrations in the indoor air.

$PM_{2.5}$ Tier 4 stoves and the WHO model: Indoor Air

Recently, various types of biomass cookstoves have been tested in laboratories that achieve the 2015 Tier 4 ratings for Indoor Emissions of $PM_{2.5}$. The WHO Intermediate Guideline for $PM_{2.5}$ is 35µg/m^3. When the single zone box model, used to create the 2015 WHO Emission Rate Targets, is applied to Tier 4 stoves, they are predicted to reach the Intermediate guidelines when used in an "average" kitchen. Again, an average low and middle income kitchen was estimated by the WHO to have an air exchange rate of 15 per hour. The time spent cooking used in the calculations was 4 hours per day, and the kitchen volume was 30 cubic meters.

Unfortunately, moderate amounts of smoke seem to damage health almost as much as higher concentrations. The air in a kitchen has to be very clean to protect women and children from multiple diseases. Unvented Rocket stoves, and other moderately clean burning stoves, emit too much smoke and gas to protect health in houses. As exposure rises from zero, the chance that a child will get pneumonia increases sharply and then levels off so that indoor air with 200µg/m^3 $PM_{2.5}$ is almost as dangerous as air at 400µg/m^3 (Burnett et al., 2014).

To predict indoor air quality using the single zone box model it is necessary to know (1) the air exchange rate, (2) the volume of the room, (3) the duration of cooking, (4) the outdoor air pollution concentration, and (5) the amount of smoke produced by the stove that enters the room.

Table 1 shows results from an ARC implementation of the WHO model with the Side Feed Bottom Air Forced Draft Rocket Stove and the Natural Draft Sunken Pot Rocket Stove using the WHO standard kitchen volume, air exchange rate, and cooking time, but with variable outdoor air pollution concentrations. Stoves are closer to protecting health when background levels of $PM_{2.5}$ are low. The outdoor concentration is effectively added to the indoor concentrations that are produced by the stove. An ARC air pollution model that predicts how clean burning the stove must be to protect health in cities worldwide, with varying amounts of pollution in the outside air, is available at aprovecho.org under project planning.

Table 2 shows results from an ARC use of the WHO model for the Side Feed Bottom Air Forced

Stove	High Power Emissions Rate (mg/min) avg. for 2 hours	Low Power Emissions Rate (mg/min) avg. for 2 hours	Background Concentration µg/m^3	Predicted 24-hour Avg. Kitchen Concentration µg/m^3
Side Feed Forced Draft	4.5	3.8	24	116
Side Feed Forced Draft	4.5	3.8	7	99
Side Feed Forced Draft	4.5	3.8	0	92
Sunken Pot Rocket	11.7	7.7	24	239
Sunken Pot Rocket	11.7	7.7	7	222
Sunken Pot Rocket	11.7	7.7	0	215

Table 1 Using the single zone box model to predict IAQ with various background pollutant concentrations.

Stove	Background Concentration µg/m^3	Air Exchange Rate 1/hr	Predicted 24-hour Avg. Kitchen Concentration µg/m^3
Side Feed Forced Draft	0	15	92.2
Side Feed Forced Draft	0	30	46.1
Side Feed Forced Draft	0	60	23.1
Sunken Pot Rocket	0	15	215.4
Sunken Pot Rocket	0	30	107.7
Sunken Pot Rocket	0	60	53.9

Table 2 Using the box model to predict the effect of changing air exchange rate. Doubling the air exchange rate halves the kitchen concentrations when the background concentration is zero.

Draft Rocket Stove and the Natural Draft Sunken Pot Rocket Stove using the WHO standard kitchen volume, cooking time, and an outdoor air pollution concentration of 0 µg/m3, but with variable air exchange rates in the kitchen. It can be seen that when the air exchange rate is doubled, the indoor air pollution is halved when the outdoor concentration is zero. The air exchange rate and the outdoor concentration of $PM_{2.5}$ have a substantial effect on how much bad air is breathed in the home.

Side Feed Bottom Air Forced Draft Rocket Stove: Based on lab test results the WHO model predicts that the 24-hour Average Kitchen Concentration for the Side Feed Bottom Air Forced Draft Rocket Stove will be 92.2 µg/m3 when the air exchange rate is 15 times per hour. When the air exchange rate is doubled to 30 times per hour the predicted 24-hour Average Kitchen Concentration fell to 46.1 µg/m3. Again, doubling the air exchange rate halves the predicted 24-hour concentrations.

The Natural Draft Sunken Pot Rocket Stove: The WHO model predicts that, as tested in the lab, when this low mass, sunken pot, natural draft Rocket stove (without the chimney) is used to cook it will result in an indoor concentration of $PM_{2.5}$ of 215.4µg/m3 when the air is exchanged 15 times per hour. At 30 air exchanges the predicted 24-hour Average Kitchen Concentration is 107.7ug/m3. It requires 60 air exchanges per hour to lower the concentration to 53.9µg/m3. Cooking under a veranda, placing the stove outside of the home, introducing cross ventilation in the kitchen, etc. are methods to increase the rate at which clean outdoor air can be predicted to decrease human exposure. Increasing the air exchange rate seems to be an effective intervention. The most effective intervention was to use a chimney with the stove that, in lab tests, reduced emissions below the measurable threshold.

Table 3 reminds us that outdoor air pollution is added to the indoor air concentration which decreases the effectiveness of increased air exchanges intended to protect health.

Improved Stoves and Indoor Air Quality

What happens when newer, cleaner burning stoves are used in the calculations? Table 4 (next page) details the estimates for stoves with better combustion efficiencies. When the WHO model is applied to lab generated, gravimetric $PM_{2.5}$ emission rates from (1) the forced draft Mimi Moto TLUD stove burning pellets, (2) the Harris natural draft TLUD stove burning pellets, and (3) the insulated ARC charcoal burning stove, the predicted 24-hour Average Kitchen Concentrations are less than the Intermediate Indoor Air Quality WHO guideline of 35 µg/m3. The three stoves were able to meet the guideline by emitting reduced amounts of PM at high and low power. The calculations include a $PM_{2.5}$ background concentration of 7µg/m3. The

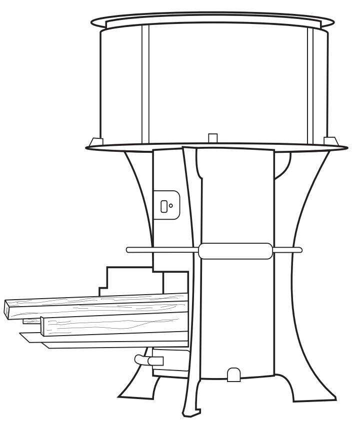
Stove	Background Concentration µg/m3	Air Exchange Rate 1/hr	Predicted 24-hour Avg. Kitchen Concentration µg/m3
Side Feed Forced Draft	7	15	92.2
Side Feed Forced Draft	7	30	53.1
Side Feed Forced Draft	7	60	30.1
Sunken Pot Rocket	7	15	222.4
Sunken Pot Rocket	7	30	114.7
Sunken Pot Rocket	7	60	60.9

Table 3 Adding outdoor air pollution to indoor air pollution.

Stove	High Power Emissions Rate (mg/min) avg. for 2 hours	Low Power Emissions Rate (mg/min) avg. for 2 hours	Background Concentration μg/m3	Air Exchange Rate 1/hr	Predicted 24-hour Avg. Kitchen Concentration μg/m3
Mimi Moto (TLUD)	1.4	0.9	7	15	28
ND TLUD (Kirk Harris)	0.75	0.23	7	15	18
Charcoal (ARC)	1.8	0.1	7	15	28
Sunken Pot Rocket (ARC)	11.7	7.7	7	15	222
Side Feed Forced Draft (ARC)	4.5	3.8	7	15	99
ND Rocket (UW)	1.9	1	7	15	39

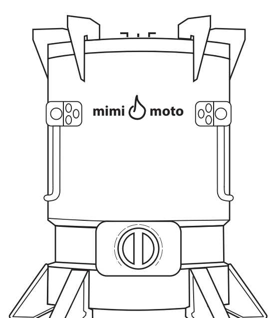
Table 4 The indoor air quality for lab results of clean burning stoves, as predicted by the box model with an air exchange rate of 15μg/m3.

Sunken Pot Rocket, the Side Feed Forced Draft, and the University of Washington Natural Draft Rocket stove scored higher than 35μg/m3.

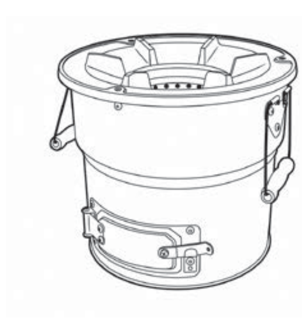


The Natural Draft Rocket Stove designed by the Posner Research Group at the University of Washington showed that, when tested in the lab, Tier 4 scores for Indoor $PM_{2.5}$ could be achieved by a natural draft stick fed stove. Their Rocket stove is remarkably clean burning. In a 30 m3 room with 15 air exchanges per hour, the WHO model estimates that when cooking for 4 hours per day ,the 24-hour Average Room Concentration of $PM_{2.5}$ would be 39μg/m3, which is close to meeting the WHO Intermediate Guideline of 35μg/m3. With a background concentration of 0 μg/m3 the stove would meet the guideline.

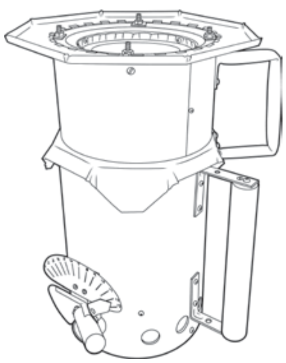
The Mimi Moto, Charcoal (ARC), and Harris Natural Draft TLUD did meet the WHO Intermediate $PM_{2.5}$ Guideline when baseline concentrations started at 7μg/m3. The TLUD and charcoal stoves both use prepared fuels: pellets made from compressed sawdust and well-made charcoal without remaining wood in it. The prepared fuels help the stoves to burn more cleanly. Also, both TLUD and charcoal stoves are top lit.



The Mimi Moto forced draft stove blows jets of air into the flames resulting in molecular mixing of woodgas, air, and flame. Using air jets works well in a TLUD when the air jets completely cover the space above the batch of fuel. The rising smoke and gas cannot escape unmixed. Most TLUDs attempt to reduce firepower by decreasing the primary air entering into the combustion chamber. A 2015 survey of clean burning stoves (Chapter 9) showed that merely decreasing primary air did not successfully reduce firepower in most TLUD stoves. Kirk Harris solved that problem, as described in Chapter 13. The Mimi Moto uses a larger and smaller combustion chamber for higher and lower firepower. Using the smaller combustion chamber resulted in better low power $PM_{2.5}$ emissions in the Mimi Moto.



The ARC Charcoal Stove was carefully lit using alcohol and only well-made charcoal was burned resulting in emissions of $PM_{2.5}$ that were lower than the Mimi Moto. Like pellets made from compressed sawdust, charcoal is a prepared fuel that decreases the emissions of $PM_{2.5}$. The WHO model estimated that the ARC Charcoal Stove, when operated carefully in the lab, resulted in a predicted 24-hour $PM_{2.5}$ Average Kitchen Concentration of 28µg/m3. Even when untrained participants at two ARC Stove Camps tested many different charcoal stoves the $PM_{2.5}$ emissions were consistently low. Lighting charcoal can make a lot of smoke but once it is lit, well-made charcoal is remarkably smoke free.



The Harris Natural Draft TLUD was the cleanest burning stove that made the least amount of $PM_{2.5}$. The stove was tested at Lawrence Berkeley National Laboratory at their Department of Energy funded wood stove lab. The Harris TLUD controls the rate at which wood is turned into burnable gas and then mixes the air, woodgas, and smoke into the fire so well that almost complete combustion occurs. A lever on the front of the stove quickly turns the power up and down. Unlike previous TLUDs, the Harris stove achieves a high turn-down ratio by controlling the amount of primary air entering the combustion chamber. In a 30 cubic meter kitchen with 15 air exchanges per hour when the Harris Natural Draft TLUD is burning pellets for an average of 4 hours, the predicted 24-hour Average Kitchen Concentration, from lab data, would be 18µg/m3 which is about half of the Intermediate Indoor Air Quality WHO guideline of 35 µg/m3.

Lab Test vs. Field Tests

It is important to remember that all of these tests were done in the lab. Field tests have shown that cooking stoves in houses usually emit at least 2 to 3 times more $PM_{2.5}$ compared to lab tests (Bailis et al., 2007; Berrueta et al., 2008; Johnson et al., 2011; Johnson et al., 2008; Roden et al., 2006; Roden et al., 2009; Zhang et al., 2000). The wood fuel is wetter and fires can be less carefully tended. Cooks often have lots of tasks to perform simultaneously in a kitchen. Cooks have been known to politely

Stove	High Power Emissions Rate (mg/min) avg. for 2 hours	Low Power Emissions Rate (mg/min) avg. for 2 hours	Background Concentration µg/m3	Air Exchange Rate 1/hr	Predicted 24-hour Avg. Kitchen Concentration µg/m3
Mimi Moto (TLUD) x 3	4.2	2.7	7	15	84
Charcoal (ARC) x 3	5.4	0.3	7	15	69
ND TLUD (Kirk Harris) x 3	2.25	0.69	7	15	40

Table 5 Box model results when the laboratory measured emissions rates are multiplied by a factor of 3.

Stove with Chimney	High Power Emissions Rate (mg/min) avg. for 2 hours	Low Power Emissions Rate (mg/min) avg. for 2 hours	Background Concentration µg/m3	Chimney Removal Efficiency	Predicted 24-hour Avg. Kitchen Concentration µg/m3
Sunken Pot Rocket (ARC)	11.7	7.7	7	75%	61
Side Feed Forced Draft (ARC)	4.5	3.8	7	75%	30
ND Rocket (UW)	1.9	1	7	75%	15
Mimi Moto (TLUD)	1.4	0.9	7	75%	13
Charcoal (ARC)	1.8	0.1	7	75%	12
ND TLUD (Kirk Harris)	0.75	0.23	7	75%	10

Table 6 Using the box model to predict the indoor air pollution when a chimney removes 75% of the stove emissions.

giggle when watching how lab staff very carefully manage their fires. ARC has decided to multiply the emission results generated by lab testing by a factor of 3 in an attempt to predict what might actually happen in real life use. The last line of Table 5 shows that even the Kirk Harris TLUD wouldn't achieve the Intermediate IAQ if its emissions rate was multiplied by three, although it would make it if the background concentration was zero.

Given that stoves in the field are known to emit a lot more $PM_{2.5}$ than when they are tested in the lab, it is likely that added interventions, such as chimneys and increased air exchanges, are needed to protect health. Even at 75% efficiency chimneys can effectively remove indoor air pollution from the room as seen in Table 6.

Perhaps the use of biomass pellets would tend to equalize scores from lab and field? If the pellet fuel is lit in the same way in the lab and in houses it may be possible that the emissions will be more similar than when burning sticks. The amount of smoke made when burning sticks is highly dependent on the operator. Further testing in the field is needed to determine whether the use of pellets can address this problem. A car started and run in the city or country can be expected to make approximately the same amount of smoke. Can pellet stoves achieve the same type of performance?

Tier 4 Stoves and Outdoor Air Quality

Modeling outdoor air quality can also be accomplished with a box model, but the volume of the "box" and the air exchange rate are often not known. An outside air emissions model was built by The Lane Regional Air Pollution Authority (LRAPA) to estimate the air pollution that the small town of Oakridge, Oregon would experience if residential heating stoves were less polluting. LRAPA is the local government organization that monitors and protects air quality in Lane County, Oregon. ARC used their computer model to estimate how the outdoor air quality in Oakridge would change if biomass burning cookstoves were venting various amounts of $PM_{2.5}$ into the outside air. Oakridge is one small town with distinct air quality, but it is hoped that the estimates based on Oakridge lead to an understanding of how the effects of outdoor air pollution can be mitigated.

Oakridge is located in Oregon about 50 miles from Aprovecho Research Center. The LRAPA mathematical model estimating air quality was constructed because the smoke from wood burning residential heating stoves was causing health problems in the town. As in many places in the United States, Oakridge homeowners use wood to stay warm in the winter. Although it's a bit more trouble to burn, wood is less expensive than gas and it can be gathered for free. Approximately 30 million people in the United States live in a home where wood burning is used for heating (Noonan et al., 2015).

In 2008, Oakridge had a population of 3,200 people. 88% of the $PM_{2.5}$ in the town air was determined to have come from wood fired heating stoves. LRAPA measured 24-hour average $PM_{2.5}$ concentrations of 40 μg/m³ in the outside air. It was found that an average of 552 pounds per day of $PM_{2.5}$ was released into the air above Oakridge, and that 486 of those pounds were by emissions from wood burning heating stoves. The 1,006 wood burning heating stoves in Oakridge all had chimneys.

The wood burning heating stoves in Oakridge tended to be highly polluting. Large logs were placed in a metal box with limited air and the results were quite smoky. The average measured emission rate of $PM_{2.5}$ for each of the stoves was 152 mg/min during the 24-hour day. That's a lot more than many cooking stoves!

Table 7 shows that Oakridge would theoretically experience a substantial reduction in emissions of $PM_{2.5}$, from 40 μg/m³ to 13.1 μg/m³, if all of the 1,006 wood burning heating stoves met the proposed 2020 US EPA residential wood heating stove emissions rate target of 36mg/minute. The third line in Table 7 shows that the outdoor air concentration would only be increased by a small amount, from 13.1 μg/m³ to 13.3 μg/m³, if all of the households in Oakridge used Side Feed Bottom Air Forced Draft Rocket Stoves with chimneys for cooking alongside their wood burning heating stoves for four hours each day. The increase is very small because the cooking stoves emit much less

$PM_{2.5}$ than the heating stoves over the course of a day (2 lb/day vs. 115 lb/day). Even using the Three Stone Fire would theoretically add 3.6 µg/m³ of $PM_{2.5}$ to concentrations in the outdoor air if everyone used it for cooking.

Oakridge is a small rural town and it has a low population density of 511 people per square kilometer. Chittagong, Bangladesh, on the other hand, is a fairly densely populated city with 4,063 people per square kilometer who regularly use wood fired heating stoves. The more stoves there are in the city, the more $PM_{2.5}$ is released into the city air.

In order to appreciate the small impact on outdoor air quality that the LRAPA model estimates modern cookstoves will have, let us assume that the population density of Oakridge is increased to that of Chittagong. Instead of 512 people per square kilometer there are now 4,063 people living in each square kilometer of Oakridge.

The calculations in Table 8 assume that the residents are cooking with the Side Feed Bottom Air Forced Draft Rocket Stove with chimney for 4 hours per day (4.1mg/min $PM_{2.5}$) and are also heating their houses with wood stoves that emit 36mg/min. of $PM_{2.5}$ for 24-hours per day. The increase in the outdoor air concentration in Oakridge caused by the addition of the modern cookstoves is estimated to only be a 1.1 µg/m³ increase in $PM_{2.5}$ in the outside air. Multiplying the lab generated number by a factor of three increases the theoretical concentration to 3.3 µg/m³. As seen in Table 8, truly improved stoves would not add very much pollution to the outdoor air but cooking with the Three Stone Fire is problematic.

The tables in this chapter attempt to provide comparisons to get a feeling for the effect of $PM_{2.5}$ made by wood burning cookstoves on the quality of indoor and outdoor air. It is important to remem-

Location	Event	Population Density people/km²	# of Cooking Stoves	Individual Cooking Stove 4-hr Avg. Emissions Rate mg/min	All Sources Total PM2.5 Emissions Rate into Inventory Area lb/day	Concentration of $PM_{2.5}$ in the Inventory Area µg/m³
Oakridge, OR	**Measured** worse case day of all sources in the valley	512	0	0	522	40
Oakridge, OR	**Hypothetical** TSF cooking, no other sources	512	1006	93.8	50	3.6
Oakridge, OR	**Hypothetical** Side Feed Force Draft Stove, no other sources	512	1006	4.15	2	0.2

Table 7 Predicting outdoor air quality in Oakridge, Oregon using the LRAPA emissions inventory model if only biomass cookstoves are emitting $PM_{2.5}$ into the surrounding valley.

Location	Event	Population Density people/km²	# of Cooking Stoves	Individual Cooking Stove 4-hr Avg. Emissions Rate mg/min	All Sources Total PM2.5 Emissions Rate into Inventory Area lb/day	Concentration of $PM_{2.5}$ in the Inventory Area µg/m³
Oakridge, OR	**Hypothetical** TSF cooking, no other sources, at Chittagong Population Density	4063	7983	93.8	396	29
Oakridge, OR	**Hypothetical** Side Feed Force Draft Stove, no other sources, at Chittagong Population Density	4063	7983	4.15	18	1.3

Table 8 Population density increase in Oakridge, Oregon (very simplified).

ber that the mathematical models, based on the assumption that all spaces within the house or the air in the town have the same amounts of $PM_{2.5}$ and CO in them, are not precise and may even be misleading. However, it is hoped that their predictions help to familiarize users with the relationships within the assumptions.

Problems Inside Houses and In The Outside Air

As suggested by Roden and others (Bailis et al., 2007; Berrueta et al., 2008; Johnson et al., 2008; Johnson et al., 2011; Roden et al., 2006; Roden et al., 2009; Zhang et al., 2000), lab test results are something like 3 times lower than actual emission rates in real world cooking. To get closer to a predictive estimate of outdoor air quality in Oakridge, Oregon, when cookstoves are added in a hypothetical example, the emissions rates of the Side Feed Bottom Air Forced Draft Stove have been multiplied by 3 (Table 9). In this case, the outdoor air $PM_{2.5}$ concentration in Oakridge (at a high population density with no additional heating stoves or background sources beyond those of the original population) would be 16.9 µg/m3, which is still lower than the WHO intermediate IAQ guideline of 35 µg/m3. On the other hand, adding 75% effective chimneys and substantially increased air exchanges to very clean burning stoves could theoretically produce safe conditions in a kitchen but much less easily. Improving chimneys to operate more effectively, as in the United States and Europe, could transport all emissions into outside air. Creating safe conditions in indoor air seems to be a lot more difficult compared to protecting health in outdoor air. The interior of a house is a lot smaller than the "box' of air above a town or city.

Location	Event	Population Density people/km^2	# of Cooking Stoves	Individual Cooking Stove 4-hr Avg. Emissions Rate mg/min	All sources Total PM2.5 Emissions Rate into Inventory Area lb/day	Concentration of $PM_{2.5}$ in the Inventory Area µg/m^3
Oakridge, OR	**Hypothetical** TSF cooking x 3, no other sources	512	1006	281	150	11
Oakridge, OR	**Hypothetical** Side Feed Forced Draft Cookstove x 3, no other sources	512	1006	12	7	0.5
Oakridge, OR	**Hypothetical** TSF cooking x 3, no other sources, at Chittagong Population Density	4063	7983	281	1189	86
Oakridge, OR	**Hypothetical** Side Feed Force Draft Cookstove x 3, no other sources, at Chittagong Population Density	4063	7983	12	53	3.8

Table 9 The outdoor air $PM_{2.5}$ concentration in Oakridge with a conservative estimate of cookstove emissions rate.

Chapter 6

Improving Heat Transfer Efficiency

While it is relatively difficult to improve combustion efficiency, how to use less fuel to cook is well understood. Getting more of the heat from a fire into the pot or griddle can often be accomplished without adding cost to the stove. Here are a few important design principles that are known to improve heat transfer in cooking stoves.

Insulation

Increasing the temperature of the hot gases has been shown to be the most effective way to increase heat transfer efficiency. High mass stoves frequently use more fuel than a Three Stone Fire in large part because of losses of heat due to conduction. Heat passes through materials by exciting molecules. The heat that is absorbed into the closely packed molecules in uninsulated stove walls diverts heat that could have gone into cooking food. The stove loses the least energy when the entire flow path of the hot gases is insulated. Earth and mud are examples of thermal mass, not insulation. Insulation is very light and consists of isolated air spaces.

Making the stove of light, highly insulative materials that contain the heat effectively can be accomplished by making the stove interior of an insulative, abrasion resistant ceramic, say .7g/cc or less, or by making the combustion chamber from refractory sheet metal and then surrounding the metal with insulation. Unfortunately, insulating sheet metal makes the gases hotter and better grades of refractory metal are required. FeCrAl or FeCrSi are preferred choices.

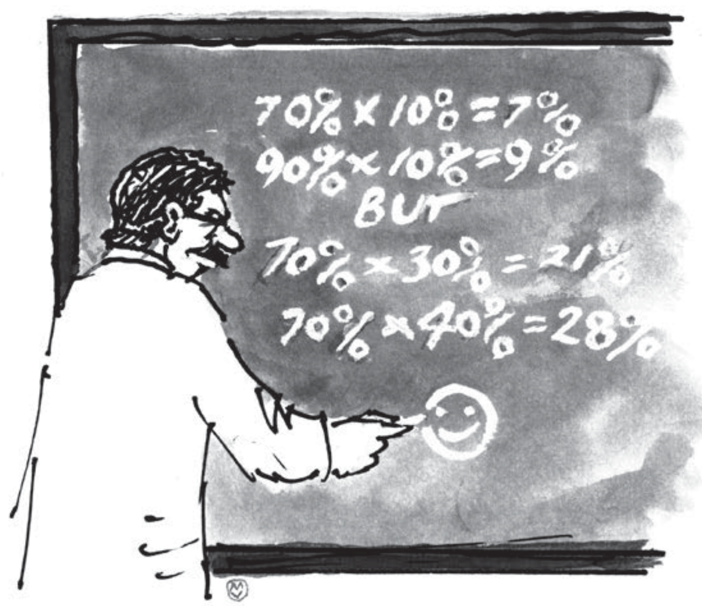
Examples of loose fill insulation include ceramic fiber, rock wool, pumice, vermiculite, or wood ash. Stoves with insulated combustion chambers are easier to light, and combustion is easier to maintain. Several of the new prototype stoves in this book use parallel sheets of shiny, stainless steel that do not touch each other as insulation. The air gaps between the sheets are great insulation. The shiny surfaces do not emit well and reduce losses by radiation.

Many newer Rocket stoves remove insulation to increase the durability of the stove since temperatures are lower. The still air within the stove body is now the insulation. Some stoves even encourage cold air to flow against the outer walls of the combustion chamber to preserve the material. When only sheet metal is available, even 304 stainless steel will not last for a long time if insulated. Light weight refractory ceramic is more durable but it can be hard to locate. We had to find Shengzhou Stove Manufacturer in China to secure a supplier of high quality, low cost refractory ceramic for Rocket combustion chambers. See www.ssmstoves.com.

Fast Moving Hot Gases

Transferring heat from the fire to the food can be thought of as a three step process. In the first step, heat is transferred to the outside of the pot or griddle. In the second step it travels through the metal or clay walls of the pot, and in the final step it travels from the inside of the pot to the food. The first part is the most difficult.

The key to designing a fuel efficient stove is to make the first step as effective as possible. It’s less helpful



When analyzing a system, try to improve the least efficient part first.

to improve the second and third steps, since the first step is the limiting factor. A layer of still air insulates the outside of the metal or clay walls of the pot and limits how much of the hot gases from the fire touch the wall. Thinning the boundary layer of air is important. The hottest gases, passing as fast and as close as possible to the pot or griddle, achieve the best heat transfer efficiency. The layer of still air next to the pot is thinned by the gases pushing against it and the fast moving, as-hot-as possible molecules in the gas warm the pot more effectively. A hot, fast moving molecule bangs into a slow moving cold molecule next to the outside of the pot and transfers energy. The cold molecules are knocked into the stream of gases flowing past the pot and replaced.

It is important to remember that there are three ways to transfer heat: conduction, convection, and radiation. Conduction is transferring heat through a solid, liquid, or gas without the heat transfer medium moving. Convection is like conduction, but it involves the liquid or gaseous medium moving. In conduction the hot molecules transfer heat to the cooler molecules, but with convection this process is aided by the hot molecules moving around to places where they can conduct heat more rapidly.

Radiation is completely different. Hot molecules, mostly from charcoal in the combustion chamber, emit radiation of various wavelengths. This radiation passes through the gases and is absorbed by cooler molecules in the exposed surfaces of the pot or griddle.

Well-insulated stoves can easily achieve a thermal efficiency above 40%. Even stoves with poor combustion efficiency are turning more than 95% of the chemical energy in the woodgas into heat. The limiting factor is not in releasing the heat from the fuel. Instead, what mostly limits heat transfer is transferring the heat into the pot. Well-known techniques, such as appropriately sized channel gaps under and next to the pot, can force more of the heat from hot gases into the pot.

Channel Gaps and Pot Skirts

Smaller fires are often cleaner burning compared to larger fires, and higher heat transfer efficiencies allow the use of smaller fires while the time to boil stays acceptable. ARC designers self-impose a limit of 25 minutes to boil five liters of water when designing a stove because cooks often do not like a slower stove. A stove that boils 5 liters of water in 15 minutes can be appealing to cooks. Using a tight pot skirt around the pot really speeds up time to boil.

In a Rocket stove, after the woodgas and flame rise together in the short chimney above the fire, the moderately clean hot gases are forced through narrow channel gaps next to the surface to be heated (pot, griddle, wok etc.). Dr. Larry Winiarski recommends that the channel gap is made as narrow as possible without reducing the velocity of the flue gases.

Like Dr. Samuel Baldwin, Dr. Winiarski realized that using a pot skirt which creates a narrow channel gap reduces fuel use and time to boil. Pot skirts improve heat transfer efficiency through a variety of mechanisms. The inside of the skirt gets hot, and heat radiates from the inside of the skirt to the pot independent of convection. The inside of the skirt is hottest when the outside of the skirt is insulated, although even an uninsulated skirt works well. Pot skirts that sit on the stove top are also effective in blocking wind.

Dr. Baldwin writes, "…The convective heat transfer coefficient should be increased. This can be done by increasing the velocity of the hot gas as it flows past the pot… In convective heat transfer, the primary resistance to heat flow is not within the solid object (unless it is a very good insulator), nor within the flowing hot gas. Instead, the primary resistance is in the 'surface boundary layer' of very slowly moving gas immediately adjacent to a wall… It is this surface boundary layer of stagnant gas that primarily limits heat transfer from the flowing hot gas to the pot… To improve the thermal efficiency of a stove, the thermal resistance of this boundary layer must be reduced. This can be accomplished by (among others) increasing the flow velocity of the hot gas over the surface boundary layer and, thinner, the boundary layer of stagnant gas then offers less resistance to conductive heat transfer across it to the pot…" (Baldwin, 1987).

In many Rocket type stoves, the fuel door is large and the draft from the fire pulls in a lot of excess air which cools the gases and decreases both combustion and heat transfer efficiency. The narrow channel gaps in pot skirts can be used to limit this excess air, leading to hotter combustion gases and better heat transfer to all parts of the pot. It is possible, however, to limit the amount of air too much, leading to smoky combustion, and even back drafting, especially at high power. In experiments in the ARC lab, a 6mm channel gap in a 10cm high pot skirt reduced the excess air to around 40% which increased performance.

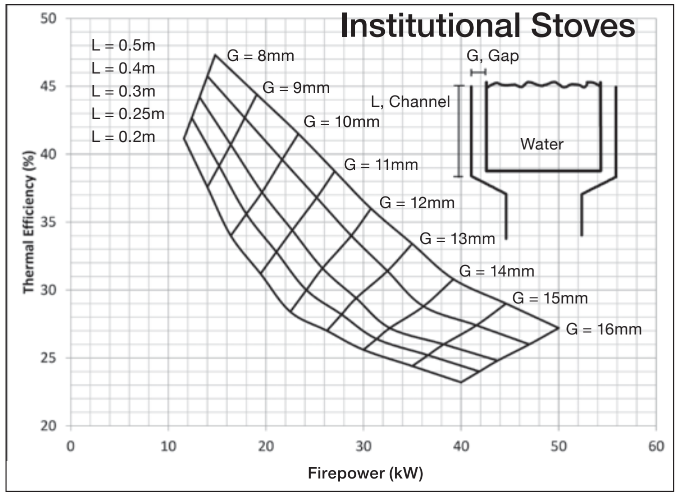
Dr. Baldwin describes in detail how heat transfer can be improved in his stove design book (Baldwin, 1987). Three chapters describe heat transfer by convection, conduction, and radiation in cooking stoves. We highly recommend his book as important reading for stove designers and project managers.

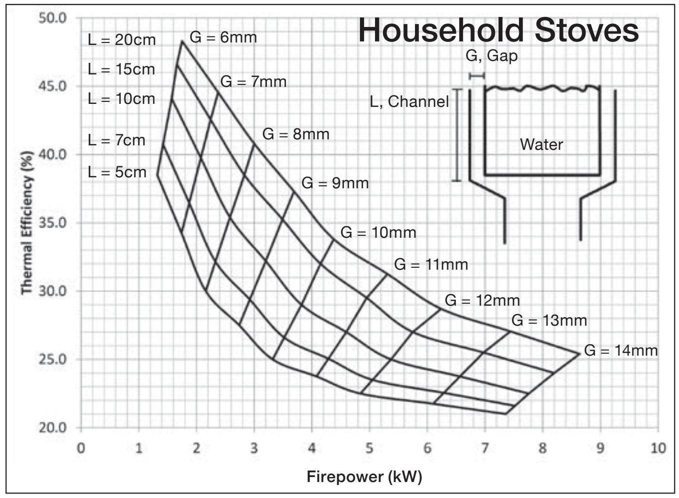
The charts from Dr. Baldwin's book depict the relationship of channel gap and length to thermal efficiency. Combining a channel gap of 6mm with a length of 15cm and a firepower of 2.5kW resulted in many different kinds of household stoves achieving over 40% thermal efficiency in WBT 4.2.3 tests (see Chapter 9).

When the firepower of a stove rises, the amount of gases passing through the narrow channel gap also increases. Channel gaps need to be widened. When too much gas tries to pass through a channel that is too narrow the velocity of the gas is decreased. On the other hand, as the channel gap widens, there are diminished beneficial effects. The hot molecules in the gases tend to flow up the middle of the channel and fewer hot molecules contact and replace the cold molecules close to the pot.

ARC experiments have generally confirmed the computer generated estimations in Dr. Baldwin's graphs although we think that even looser fitting skirts can be somewhat effective and that increasing the height of the skirt may not be as advantageous as predicted. Further studies will be conducted.

Low kilowatt firepower and fast flowing hot gases combined with narrow channel gaps (down to





Charts for sizing channel gaps, from Dr. Samuel Baldwin's "Biomass Stoves: Engineering Design, Development, and Dissemination." (Baldwin, 1987)

6mm) have resulted in over 50% thermal efficiency in ARC lab tests. A 7 liter family sized pot has a relatively small external surface area which limits effective heat transfer. On the other hand, the larger exposed surface area in institutional stove pots can be successfully matched with larger sized fires. ARC determines the optimum gap size by closing the gap until the velocity of the gases begins to decrease.

Constant Cross Sectional Area

Dr. Winiarski estimates that it is a useful rule of thumb to maintain constant cross sectional area in the flow path of the hot gases when beginning to design a stove (Bryden et al., 2006). ARC designers start by creating constant cross sectional area throughout the entire stove, including the chimney, and then experimentally reduce the flow path area next to the surface to be heated until optimal performance is seen. We conduct the experiments under the LEMS hood to include emissions. When the gases are hot, reducing the constant cross sectional area channel gaps by 0.7 seems to work well.

Tuning the stove to achieve both the lowest possible fuel use and the lowest emissions of CO and $PM_{2.5}$ is the goal. The iterative development method is based on making one change at a time in a prototype stove and testing it with either the WBT or CCT (or both) under the LEMS emission hood. Again, starting with the CCT in the project area saves effort and time (and it's more fun). Having the cooks test and help to evolve the finished stove product makes more sense than spending the same amount of time doing WBTs in Oregon. The lab is in the field! This is where the product must succeed.

TLUD Design Principles

Over the years, Top Lit Up Draft (TLUD) influenced heat transfer design principles have evolved to supplement Dr. Winiarski's Rocket stove principles. We start the stove design process by applying Dr. Winiarski's ten design principles (see pp. 69-71).

The following TLUD derived principles are cross linked with Dr. Winiarski's original approach. Design principles are intended to be accurate and easy to teach. They help stove makers to need the least number of iterations and experiments to optimize performance. Testing the prototype and moving towards improvement through the iterative testing process under the emissions hood is always necessary. Starting with design principles (that are predictive) shortens the process.

The TLUD derived heat transfer supplemental principles used by ARC designers are:

TARP-V

T: The *temperature* of the hot gas contacting the pot or griddle should be as high as possible.

A: Expose as much of the surface *area* of the pot or griddle to the hot gases as practical.

R: Increasing heat transfer by *radiation* is important. Move the zone of combustion as close as possible to the surface to be heated without increasing harmful emissions.

P: Optimize the *proximity* of the hot gases to the pot or griddle by narrowing the channel gap without reducing the velocity of the gases. Decrease the thermal resistance with appropriately sized channel gaps under and up the sides of the pot. Match the firepower to the channel gap and the size of the pot or griddle.

V: In convective heat transfer, the primary resistance is in the surface boundary layer of very slowly moving gas immediately adjacent to a wall. Increase the *velocity* of the hot gas as it flows past the pot without reducing the temperature of the gases. As a rule of thumb, heat transfer efficiency can double when the velocity of the hot gases also doubles (MacCarty et al., 2015).

Turn-down Ratio

It should be noted that there is a difference between heat transfer efficiency and fuel use. Fuel use is based on the amount of biomass needed to complete a cooking task. Heat transfer efficiency is the ratio of the heat released when the fuel burns to the heat that ends up in the food. Typically, fuel use is what we are really interested in, and increasing the heat transfer efficiency is a method for decreasing the fuel use.

There are exceptions, however. When the food is simmering, if you cannot turn down the size of the fire the pot will continue to boil, wasting energy and quite possibly burning the food. At full boil the food doesn't cook any faster than if the water is gently simmering at around 97°C. To efficiently boil and simmer food, the stove must have an adequate turn-down ratio.

In other words, the stove should be able to operate at both high and low power. To boil 5 liters of water in less than 25 minutes (uncovered pot), low mass stoves with tight pot skirts typically need a high power between 3kW and 2.5kW and a low power of around 1kW. But firepower is often a lot higher when cooks are trying to get food on the table in a hurry. In our experience, 5kW is preferred by many cooks.

Experiments at ARC have shown that with a lid on the 5 to 7 liter family size pot it takes only about 0.4 kW to maintain a 97°C simmering temperature. But cooking requirements vary from country to country. Chinese cookstoves tend to have very high power (around 10-15kW) and generally don't use simmering to cook food. On the other hand, the village cooks in the Southern India Shell Foundation project used many small (3 liter) pots and often didn't need to bring the water to a full boil.

Dr. K. K. Prasad has proposed, "…an ideal burner design with the power output ranging from 2.64 kW to 0.44 kW… fuel economy is dependent on three factors, namely, the efficiency (as a function of power output), the maximum power output, and the ratio of maximum to minimum power outputs." (Prasad and Sangen, 1983, pp. 108-109)

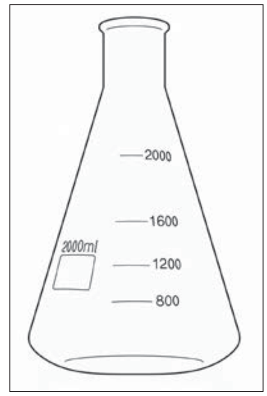
Dr. Baldwin adds, "One of the most important factors determining field performance of a stove is the firepower it is run at during the simmering phase. Because simmering times tend to be long, quite modest increases in firepower above the minimum needed can greatly increase fuel consumption." (Baldwin, 1987)

The Pot as Heat Exchanger

The pot is the heat exchanger and the shape of the pot, the area of the surface of the water in the pot, etc., have a large effect on the amount of fuel used to cook at both high and low power. Using a lid on the pot of simmering water quickly brings the relative humidity of the air above the water to 100% which slows the creation of steam. Since most of the energy needed while simmering goes into making steam, the use of a tight fitting lid can drastically reduce the needed energy input. Because so little energy is needed to simmer with a lid, the charcoal made at high power in both Rocket and TLUD stoves can be used to simmer food to completion.

The surface area of the water exposed to the air in the pot influences how much energy is needed to raise the temperature of the water when steam is being made. Each square centimeter of water surface area makes steam, so the energy loss due to steam making is related to the exposed surface area. Increasing surface area also increases convective and radiative heat losses. Reducing the area of the top water surface in a pot reduces the energy needed to bring water to boil and to simmer. Many rounded pots used in India feature reduced water surface area.

The Erlenmeyer flask is an example of an efficient pot shape although it is not practical for cooking. The large bottom is optimized for receiving heat and the reduced water surface area diminishes steam losses. While at simmering temperatures, a pot with 5 liters of water and a pot with 9 liters of water, but with equal water surface areas, will produce steam at approximately the same rate. The 9 liter pot will lose proportionally less water from making steam which increases the success on measures based on specific consumption.



The Erlenmeyer flask.

The pot is often ignored as an important part of the cooking system. Typically people talk about more efficient stoves, but not as much about more efficient pots. It is the combination of many factors that result in an improved cooking system. The entire cooking system, consisting of stove, pot, fuel and operator are working together.

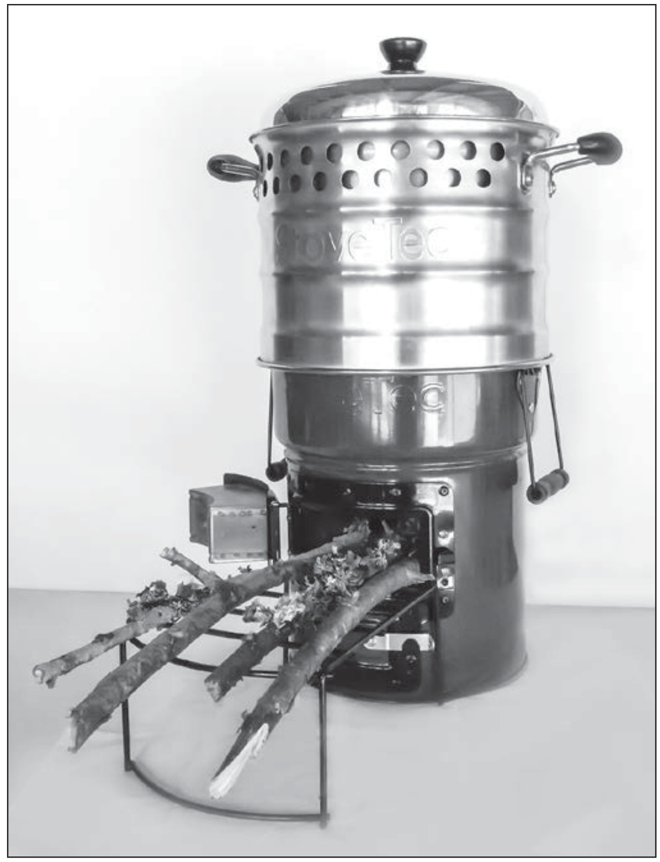
A stove that functions well with one type of fuel may work poorly using another type of fuel. Larger pots with lids are better heat exchangers compared to smaller pots, making the stove appear more efficient. A careful operator can be hampered by a high mass stove and by wet wood. On the other hand, another careful cook can achieve over 30% thermal efficiency using an open fire, as Dr. Tami Bond did in her laboratory at the University of Illinois as we watched in amazement.

It is not meaningful to talk about the efficiency of a stove without including the details of the operator, the pot, and fuel. This is why comparative stove tests have strict controls on the fuel and the pot that are used. However, how the stove is being operated is often the most important variable. ARC testers have to concentrate and precisely control fuel feeding to get statistically acceptable results with small differences between test scores.

Up to a point, bigger pots are better heat exchangers. Having more heat transfer area, especially on the bottom of the pot, is helpful. Even with a skirt, a large part of the heat transfer happens on the bottom. The temperatures of the hot gases have not been cooled as much as they have been when flowing past the sides of the pot.

However, if the bigger pot has more exposed water surface area, it will make boiling water harder to achieve and, during the simmering phase, bigger pots can lose more heat when they don't have a lid. Achieving full boil can be quite difficult when the open surface area of water in a pot is large and no lid is being used.

Various attempts have been made to redesign the pot for better heat transfer. ARC designers added a permanent skirt to a pot which has the added advantage of keeping the soot inside the channel gap. The outside of the pot stays shiny. The skirted pot can be used on various stoves or on the open fire. We find that the skirted pot can often be a more effective intervention compared to the improved stove. We might go so far as recommending better pots first! How about making a Super Pot with local manufacturers?



Multi-Fuel Rocket Stove with Super Pot.

Shengzhou Stove Manufacturer Super Pot.

Chapter 7

Improving Combustion Efficiency

Even three stone fires can be relatively smoke free when the smoke enters the hot flame and is mixed into it for a long enough period of time to burn, but they are especially clean burning when the wood has been changed into charcoal. Pure charcoal does not make appreciable amounts of smoke. Experiments at the ARC lab have shown that creating these two conditions in an open fire or in a cookstove result in reduced emissions of particulate matter ($PM_{2.5}$).

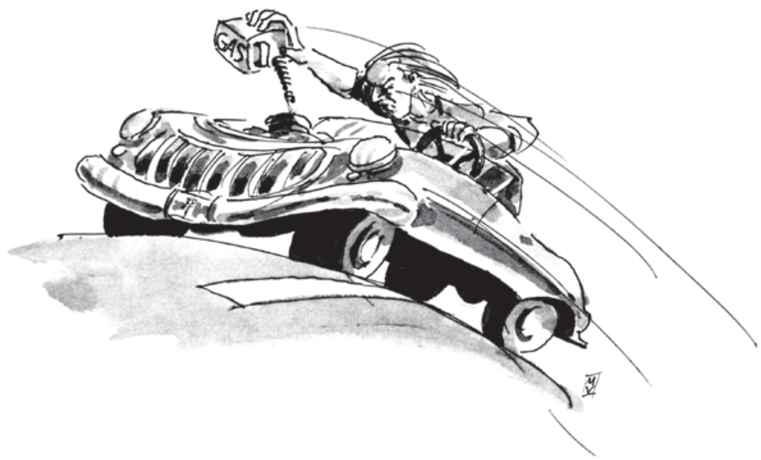
Slowly metering the fuel into a large fire also creates almost smoke free burning, but introducing even a small amount of excess fuel overwhelms the ability of the fire to fully combust the biomass, and the excess woodgas (that includes smoke) escapes into the air. Adding natural or forced draft mixing reinforces the ability of the fire to interact with the smoke and to burn it up. The goal of molecular mixing is to create a homogeneous zone where air, fire, gases, and smoke are in an optimized state to achieve complete combustion.

Carbon Monoxide (CO)

Wood burning does not usually produce elevated levels of CO. However, when not completely covered by flame, the made charcoal in a wood fire immediately starts to emit high levels of CO. The relationship between wood and the made charcoal in a fire is complex. After hundreds of hours observing how biomass fire works under the emissions hood it seems, as a rule of thumb, that wood burning emits a lot more $PM_{2.5}$ while charcoal burning makes a lot more CO. Also, when watching fires it is common to see that the combustion of wood makes an appreciable amount of flame and charcoal tends to make less.

When wood burning creates large flames above the fuel, the CO released from the made charcoal is fairly easily combusted, but when wood is made into charcoal the flames frequently subside and the CO can escape unburnt. A cleaner burning stove usually maintains a large amount of flame above the fuel bed so that greater percentages of both $PM_{2.5}$ and CO are combusted.

Metering the fuel is an essential part of the clean burning process in a biomass cookstove. A car also smokes if too much fuel is pushed into the carburetor and the optimal mixing of air, fire, gases, and smoke are disturbed. Metering the correct amount of woodgas into the zone of mixing is an important first step for clean burning.



Clean Burning is Fuel Dependent

Found fuels need to be prepared in order to burn well. Studies at ARC have found that overly dry or overly wet wood increased emissions of CO and $PM_{2.5}$ (Tangang Yuntenwi, 2008). When wood is too wet it will not burn at all. Boiling off the moisture in wood lowers the amount of energy that can be used for cooking. Wood at around 10% to 15% moisture content tends to burn at an even pace making the steady metering of gaseous fuel into the combustion zone more likely. Overly dry wood can burn too quickly, resulting in too much woodgas being made and more subsequent emissions.

Bark, sap, and certain oily woods are very smoky. When wood remains in charcoal the bits of wood make smoke. The recipe for wood pellets is important, as too much bark or sap or oily wood can make pellets smoky. In the same way, Chinese honey-comb coal briquettes can burn without making as much smoke while lump coal is dirtier (Zhi at al., 2008).

When ARC researchers test stoves, they inspect the Douglas fir sticks to make sure that they do not contain veins of sap that smoke uncontrollably. On multiple trips to Baja California Sur, Mexico, Dean Still and Dr. Winiarski found that one of the first signs of wood depletion was when ranchers were forced to burn second grade woods that were smelly and smoky. A fire made with palo fierro (iron wood) was much more comfortable to sit next to since it did not emit much smoke at all.

Well-Made Charcoal as a Clean and Convenient Fuel

Sam Bentson (ARC General Manager) and Ryan Thompson (Researcher) spent about one year testing fifteen charcoal stoves and are now more confident about designing improved models. The resulting charcoal stove included in this book (Chapter 16) boiled five liters of water quickly and used around 300 grams of charcoal to boil and then simmer water for forty-five minutes. Because the stove was super insulated, the temperatures in the combustion chamber quickly rose above 620°C, the auto-ignition temperature of CO. Their charcoal stove achieved all Tier 4 ratings including for emissions of CO and $PM_{2.5}$.

Testing charcoal stoves is a pleasant change from burning wood in a Rocket stove that requires constant tending. Cooks may prefer batch fed stoves, such as charcoal, coal, and TLUD stoves, because they are easier to use. The batch fed cooking process is similar to cooking with LPG. You light the fuel that makes a constant supply of gas and flame, and the cooking continues without much adjustment. How great!

However, the convenience of charcoal comes with a considerable energy price tag. Turning wood into charcoal wastes approximately 5/8ths or more of the energy in the wood (Aprovecho, 1984a). Wasting that much energy is hard to rationalize when thinking about fuel efficiency. On the other hand, after the stove is lit, well-made charcoal emits a lot less smoke compared to wood fires. Dr. Rob Bailis suggested that using charcoal could protect health by reducing exposure to $PM_{2.5}$ by 90% (Bailis, 2005).

The well-made charcoal that was used in the DOE tests did not contain left over remains of the original wood. For this reason, the prototype charcoal burning stove achieved a perfect all Tier 4 score on the IWA measures. The fuel is an important part of the clean burning process that includes the good stove, careful operator, good pot, and maintenance.

The use of cleaner burning fuels is an important consideration in improving cookstoves. The fuel and stove work together in combination. Even clean, dry sticks of wood that contain sap can make a lot of smoke in most stoves. Pellets made from grasses tend to make metal clinkers in the combustion chamber. On the other hand, well-made charcoal, pellets in TLUD stoves, and cleaner burning species of wood are more likely to combust with lower emissions of CO and $PM_{2.5}$.

Burning Biomass

A simple explanation of the combustion of wood involves:

Drying: The water inside the wood boils off.

Pyrolysis and Gasification: Burnable gases and smoke are emitted from the hot wood.

Wood combustion: The gases and smoke mix with flame and air and burn.

Charcoal combustion: The wood that has been changed into charcoal also burns.

These processes occur in both Rocket and TLUD stoves. Pyrolysis and gasification are processes that convert solid biomass into gaseous fuels. Exposing wood to the high temperatures in flame creates woodgas, which is then burnt. In a Rocket stove the flame burns directly above the sticks of fuel, whereas in the TLUD the production of the woodgas can occur at a greater distance from the flame. The secondary air jets positioned above the fuel bed in the TLUD supply air that supports the flame, and create a zone of mixing and secondary combustion.

ARC stove designers use overlapping design principles when attempting to improve performance in both types of stoves. The design principles assist staff to imagine changes to be made in prototype stoves that are then tested under the emissions hood. Many iterations are usually needed to evolve a truly improved stove. Luckily, whether 20 or 100 iterations are needed, the end result is the same. The stove has been improved.

Can a stove be improved without an emission hood? Yes! Kirk Harris, who invented the super clean burning TLUD in this book, puts a white piece of paper in the smoke stream above the stove for a certain amount of time and knows that the stove is burning well when the paper remains white. One of these days, ARC will try to develop an emission hood based on this technique.

Clean Combustion

Combustion involves complex physical and chemical interactions. Describing the interactions involved in burning biomass is difficult in part because wood changes into charcoal, which combusts quite differently. ARC stove designers have evolved "rules of thumb" that help to create better experiments which move the prototype stove more quickly towards optimized performance. Although a complete understanding of solid fuel combustion is difficult, the following design principles and descriptions have proven to be useful.

Use Clean Burning Fuel

Start with a biomass fuel that is as clean burning as possible. Like the rancheros in Mexico, try to use better kinds of wood. Dry stick-like fuels are usually burned in a Rocket stove, while pellets, chipped wood, or agricultural waste products can be batch loaded into a TLUD.

Meter the Fuel: Control the Rate of Reactions

Improving combustion efficiency is often described by applying the "Three T's:" Time, Temperature, and Turbulence. However, controlling the rate of reactions, i.e., how fast the biomass generated woodgas enters the combustion chamber is as important. The Winiarski Rocket Design Principles include "metering the fuel" and "burning the tips of the sticks" in an attempt to allow only the amount of air rich fuel that will cleanly combust into the combustion zone. In both Rocket stoves and TLUDs, controlling the rate of reactions is very important for smoke free combustion.

Sticks of fuel are metered into the fire in the Rocket stove or a batch of fuel is burned at a controlled rate in the TLUD. In both cases, there is flame above the fuel. The hot biomass creates the gaseous fuel that flows into the flame. In a well-designed TLUD all of the woodgas is directed to flow into a layer of hot charcoal then into flame, creating a cleaner burning technique.

In the natural draft Rocket stove, metering the fuel (creating only the amount of gaseous fuel that can be consumed in the flame) is accomplished by burning the tips of the wood sticks. Dr. Winiarski points out the importance of metering as follows: "Heat only the fuel that is burning (and not too much). Burn the tips of sticks as they enter the combustion chamber, for example. The object is not to produce more gases or charcoal than can be cleanly burned at the power level desired" (Bryden et al., 2006). However, even in improved Rocket stoves, the flame only partially fills the space above the fuel, resulting in less complete combustion. Some of the gaseous fuel rises into open spaces where there is no flame and escapes. The layer of charcoal is below the flame and cannot help to combust the woodgas.

Dr. Kirk Smith has commented on the importance of metering. "Evidence indicates that emissions are lowest with small charges… The reason for this effect is that with smaller charges there is less fuel in the combustion chamber and thus a lower amount of pyrolysis in that part of the fuel not directly in the combustion zone. Much of the fuel in a large charge will be near enough to the combustion zone to undergo extensive pre-burning pyrolysis and thus release materials into a region where space and char burning has not yet commenced. In addition, quenching by cold fuel is less likely with a small fuel charge… traditional cooking stoves are generally fueled by frequent additions of small amounts of fuel, a factor favorable to low emissions." (Smith, 1987, pg. 286)

Add Jets of Air for Mixing

Adding jets of forced air to the Rocket stove can result in the molecular mixing needed to reduce smoke. In the agitated combustion zone, the air, gas, smoke, and flame are intermixed resulting in greater combustion efficiency. On the other hand, the natural draft Harris TLUD with static mixing is as clean burning as forced draft TLUDs. Adding jets of air to the TLUD reduces the required residence time and the height of the stove can be reduced, but forced draft does not seem to be required for close to complete combustion as it does in a Rocket Stove.

Lefebre, Vanormelingen, and Udesen examined secondary air jets in cylindrical combustion chambers and describe the most successful patterns of penetration depth. Jet penetration lengths approaching the middle of a cylindrical combustion chamber resulted in a maximum reduction of $PM_{2.5}$ emissions. An increase in the number of jets created more thorough mixing. It is important to have the jets meet in the middle but with minimal necessary force to ensure highest temperatures and highest velocity of hot gases to the pot.

Jets of air aimed horizontally into the flame most efficiently create mixing, but even when aimed upwards slow the draft by creating a high pressure front. The jets create a "roof" made from fast moving air in the combustion chamber. Regardless of the velocity of secondary air, flow rates, or the angle at which air is injected into the combustion chamber, supplying secondary air tends to also lower the temperature of gases. For this reason, using a minimal amount of air to achieve thorough mixing seems to be preferable. There is a balance resulting in optimized mixing, draft, residence time, and temperature (Lefebvre and Ballal, 2010; Udesen, 2019; Vanormelingen and Van den Bulck, 1999).

One obvious difference between Rocket stoves and TLUDs is the large fuel door in the side of the cylindrical Rocket stove. In a Rocket stove horizontal sticks are pushed into the fuel door in the side of the cylinder. A TLUD is batch fed by dropping the fuel into an open topped cylinder with a very small primary air opening below the packed fuel bed. Introducing secondary air jets into the sides of the flames in a Rocket stove is problematic because the high pressure front caused by the air jets can create a backdraft that sends smoke out of the fuel door. This does not occur in the sealed cylindrical TLUD.

Metering, Temperature, Mixing, and Time

In some ways, what happens in the combustion chambers of the Rocket and TLUD is similar. In both stoves, the wood is lit with kindling or an accelerant and gaseous fuels are released from the hot wood. The volatile gases (mostly carbon monoxide, hydrogen, and methane) flow into the fire above the fuel. Charcoal forms as the wood is burned. When the right amount of gases and air are very well mixed into the flame at a hot enough temperature and reside there for a long enough period of time, almost complete combustion can occur.

The forced draft Jet-Flame Rocket and the forced draft TLUD can be very clean burning without much residence time. Higher gas temperatures and thorough mixing are able to achieve close to complete combustion. Longer residence times are found in the taller, clean burning natural draft TLUDs.

Sufficient time during which flammable gas and smoke are mixed with oxygen at the required reaction temperature is required for complete combustion (Hroncová et al., 2016). Higher temperatures are achieved by insulating the combustion chamber and by limiting the amount of injected air that cools the process. Preheating primary and secondary air helps to maintain sufficiently high temperatures. 4.58 pounds of air is needed for the complete burning of one pound of zero percent moisture content biomass. The typical excess air needed for combustion efficiency in biomass applications is in the range of 5% to 50%, depending on the fuel and the design. Tests at ARC have determined that the Jet-Flame is cleanest burning with approximately 40% excess air at around 5kW of firepower.

Experiments have shown that elevated temperatures shorten the combustion time for CO and $PM_{2.5}$. The combustion time required for complete combustion of biomass particles at 900°C is less than half that at 700°C (Li, 2016). At 900°C, a residence period of 0.5 seconds resulted in close to complete combustion of well mixed CO and $PM_{2.5}$ (Grieco and Baldi, 2011; Lu et al., 2008; Yang et al., 2008). Boman reports that high temperatures above 850°C in a 5kW combustion zone combined with air rich and well mixed conditions for 0.5 seconds in the post combustion zone resulted in an almost complete depletion of particulate matter (Boman et al., 2005). Shorter residence times are seen in clean burning forced draft TLUD stoves. The combustion zone is thin, right below the pot. The Jet-Flame/C-Quest Rocket stove has less than 0.2 seconds of residence time while achieving around 2 mg/min of $PM_{2.5}$ at high power. Cooking stoves are generally short and combustion time is limited. As a rule of thumb, ARC designers try for 0.2 seconds of residence time which is frequently hard to achieve in the shorter stoves preferred by cooks. Measured velocities in various natural draft stoves at ARC were generally in the range of one meter per second.

The use of insulation in Rocket stoves can create a combustion zone with temperatures of over 1,000°C. Forced draft TLUDs can generate similar temperatures in the secondary air mixing zone above the fuel bed. Interestingly, when temperatures are around 900°C the near complete combustion of well-mixed CO and particulate matter requires only short residence times. During such conditions, the residence time in the post-combustion zone seems to be of minor importance for minimizing the emissions of products of incomplete combustion.

Dr. Winiarski points out that only turbulence that results in molecular mixing helps to decrease emissions. Swirling the flame, for example, does not necessarily result in beneficial mixing of air, flame, and woodgas when the three components are moving together in the same direction but are not forcibly interacting. Forced draft mixing with preheated primary and secondary air reduced emissions of $PM_{2.5}$ by 90% in the stove tests included in this book (Chapter 9). Especially with forced draft, it is important to preheat the mixing jets as much as possible to avoid lowering temperatures in the combustion zone. Iterative experimentation under the emissions hood while monitoring temperatures and emissions will determine the optimum relationships and add to the state of knowledge.

Learning from Industrial Combustion

"The Handbook of Biomass Combustion and Co-firing" (Loo et al., 2012) lists the following conditions that result in the incomplete combustion of biomass:

- Insufficient mixing of flame, air and gaseous fuel.
- Overly rich fuel/air ratio.
- Not enough oxygen.
- Combustion temperatures that are too low.
- Residence times in flame that are too short.
- Too little gaseous fuel to sustain combustion.
- Low temperatures that diminish gaseous fuel production.

A Review of Combustion Techniques

1.) Optimize heat transfer

Iterate changes in the stove until achieving between 40% to 50% thermal efficiency. Using less fuel to cook reduces the amount of emissions.

Increase:

- The temperature of the gases contacting the pot.
- The area contacted by the hot gases.
- The radiation heating the pot.
- The proximity of hot gases contacting the pot.
- The velocity of the hot gases.

2.) Control the rate of reactions

Fuel mixtures that are too rich make smoke. ARC attempts to burn only 8cm of the sticks in Rocket stoves. A lever controls the primary air in the Harris TLUD.

Both techniques control the rate of reactions: How much woodgas is being made from the solid fuel.

Controlling the rate at which woodgas is made is necessary for clean burning.

When the stove starts to make smoke, ARC slows the rate of reactions by burning less of the stick in the Rocket and by reducing the primary air in the TLUD.

3.) Achieve molecular mixing

The woodgas, air, and flame must mix together on a molecular level.

In a Rocket stove, forced draft jets of air are required. Aim the jets into the bottom or side of the flame, not above the flame.

In the Harris natural draft TLUD, static mixers achieve sufficient mixing. Small differences in pressure help to push the woodgas and air together. The enhanced pressure difference, combined with contact over a large surface area, mixes the woodgas, flame, and air.

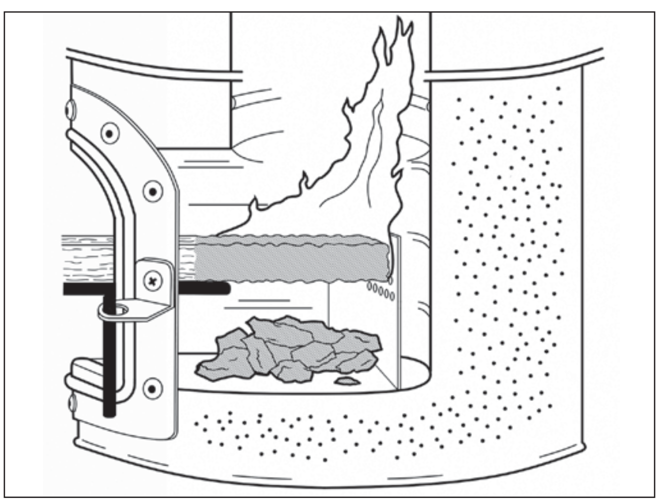
Forced draft can be added to a TLUD very successfully reducing the height and required residence time.

4.) Higher temperatures are helpful

To combust CO and $PM_{2.5}$, ARC designers try to achieve a minimum of 900°C in the combustion zone.

Higher temperatures are obtained by insulating the combustion zone, reducing the excess air ratio, and preheating the primary and secondary air.

Temperature is one of the most important factors in combustion and heat transfer efficiency.



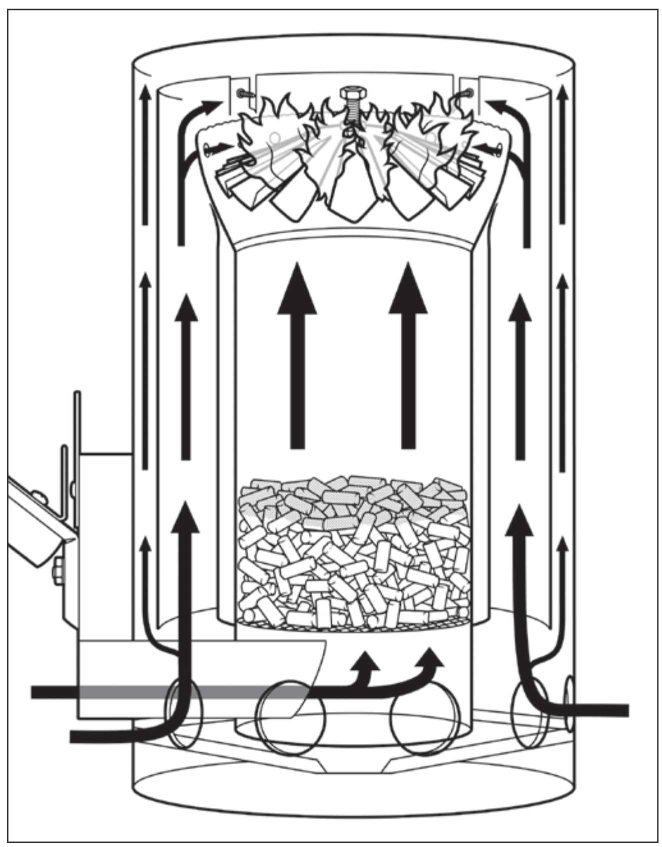
A fence in the combustion chamber of a Rocket stove limits the burning area of the sticks to 8cm.

5.) Residence time

When temperatures are 900°C, the near complete combustion of well-mixed CO and $PM_{2.5}$ requires short residence times.

Without high temperatures, longer residence times are needed.

At 900°C the combustion time required for complete combustion of biomass particles is less than half that required at 700°C (Li et al., 2016).



Static mixers at the top of the Harris TLUD help mix woodgas, flame, and air for improved combustion.

Chapter 8

Post Combustion Reduction of $PM_{2.5}$

Post combustion reduction of $PM_{2.5}$ is used by industry to reduce emissions, as even the advanced combustion chambers in industrial applications do not achieve complete combustion. Automobiles also use catalytic converters even though combustion efficiency in cars has been improved for generations. While a catalyst is not intended to reduce $PM_{2.5}$ effectively, filtration and electrostatic precipitation may have possible household applications for biomass stoves. Both require electricity but the technologies are well described, fairly simple, not expensive, and efficient. Certainly, where applicable, they add to the approaches intended to mitigate the negative effects of incomplete combustion. ARC has been experimenting with filtration and electrostatic precipitation since 2017.

Catalytic Devices

Catalysts are designed to help burn gases and pollutants by lowering the temperature at which they combust. The most common is a catalytic converter, commonly used in both gas and diesel vehicles, in factories, and also in some wood burning stoves. A catalytic converter is made by adding platinum, palladium, and/or rhodium to the surface of a filter made from ceramic or metal.

Catalytic converters are put into the hot exhaust gas path inside the stove where temperatures are above 426ºC. The hot exhaust gas needs to touch the surface of the catalyst. The speed of the exhaust gas through the catalytic converter and amount of surface area are important. The slower the gas moves through it, the more time is available to burn gases and pollutants. The larger the surface area, the more space exists to burn up emissions. So, a catalytic converter works best when it is hot enough, has a large surface area, and the exhaust gas speed is low.

The catalytic converter works well with gases (30-95% reduction of CO and 30-60% reduction in Organic Gaseous Carbon) but not as well with particulate matter in smoke (30-40% reduction of $PM_{2.5}$) (Hukkanen et al., 2012). It can burn larger smoke particles faster than smaller ones. By lowering the quantity of gases, a catalytic converter helps to stop the particles from growing larger in the exhaust stream.

Some conditions can reduce the efficiency of a catalytic converter. For example, exhaust gases and pollutants which cannot burn (like dirt and water) can stick to the surface. Similar to dirt on tape, the deposits stop the catalytic converter from working well. The major impact when installing a catalytic converter is that it causes a significant pressure drop that will slow the draft generated by the fire. With less draft, a fire will burn more slowly. The designer of a stove with a catalytic converter must keep this in mind.

Recommendations:

- Put the catalytic converter close to the fire so it can get hot enough.
- Do not allow the flame to touch it.
- Clean the catalytic converter when needed.
- The pressure drop caused by the friction in the catalytic converter results in a decrease of draft velocity that must be accounted for in the stove design.

Fibrous Filters

Filters are used for many applications that include industrial flue gas filtration, dust management, automotive air filtration, and residential air filters in heating and cooling systems. Filters are used in urban homes in places like Beijing and New Delhi where the unsafe $PM_{2.5}$ in indoor air is drawn through a filter and removed. A HEPA filter can easily be attached to a box fan of an equal size.

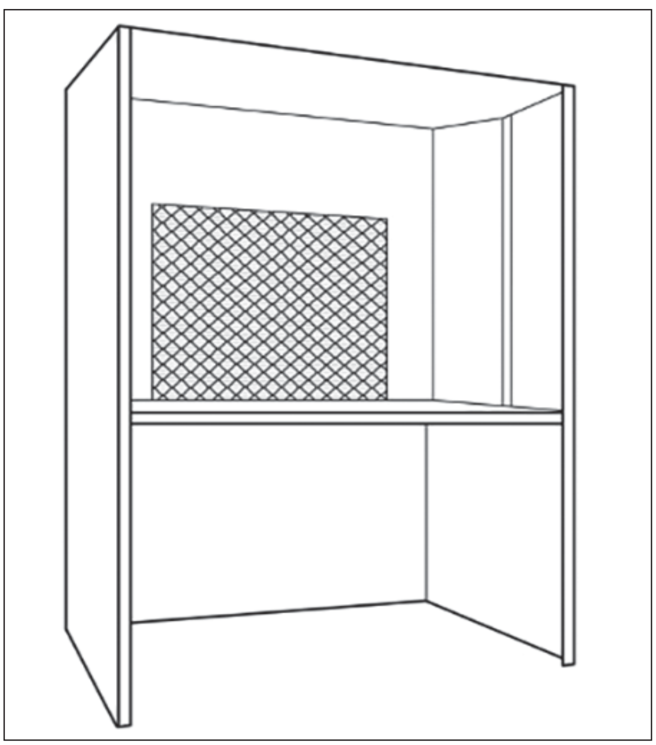
In industrial settings, fibrous filters are implemented as “bag-houses” which report efficiencies of up to 99.9% (Fritsky et al., 2001). These large bags are designed to be operated cyclically and are periodically cleaned. The bag-houses typically collect particles ranging in size from sub-micron to several hundred microns in diameter. Most ducted residential systems feature one-time use filters aimed to improve indoor air quality by removing particles with efficiencies of at least 90%. Fibrous filters are typically constructed out of ceramic, metallic, plastic, or organic fibers depending upon the desired durability, temperature resistance, and removal efficiency at a given particle size.

Recommendations:

- Consider the sizing, durability and wash-ability of the filter.
- The pressure drop exerted on a natural draft stove by a fibrous filter may inhibit primary combustion dynamics enough to discourage implementation. Perhaps the use of a filter in a forced draft exhaust hood is more practical?

A Simple Filtering Solution

In 2017, an enclosure was built in the Aprovecho lab in which a box fan pulled the air and $PM_{2.5}$ through a household furnace filter before it exited into the LEMS emissions hood. The $PM_{2.5}$ (mg/min) was monitored with gravimetric measurement during the high and low power phases of the Water Boiling Test 4.2.3. A stick fed forced draft Rocket stove was used for all tests. The average of seven emissions tests of $PM_{2.5}$ with no filtration was 7.5mg/min. The average of seven tests after the gases and smoke passed through the $12 filter (3M 2200) was 1.5mg/min (Still et al., 2018).



Cooking enclosure in which a $16 box fan pulls smoke through a $12 HEPA furnace filter.

The 100% replacement of traditional biomass stoves by cleaner burning models rarely occurs. Cooking with LPG has been accompanied by a continued use of the open fire resulting in only a 45% reduction in $PM_{2.5}$ in kitchens in Guatemala (Masera et al., 2015; Ruiz-Mercado et al., 2011). A recent study in India found that 40% of families continued to use the traditional stove alongside the improved stove. When an improved stove was used exclusively the measured levels of $PM_{2.5}$ were reduced from the baseline measurement of 139 µg/m^3 to 51 µg/m^3. However, when the traditional and improved stoves were both being used the average level of $PM_{2.5}$ rose to 92 µg/m^3 (Aung et al., 2016).

Smoke hoods have been installed in Nepal that can accommodate different stoves while diverting smoke up a chimney (Bates, 2005). Perhaps a forced draft smoke hood that captured $PM_{2.5}$ could be used to decrease both indoor and outdoor pollution? Perhaps various stoves would be used under the forced draft hood?

Electrostatic Precipitators

Electrostatic precipitation (ESP) is widely used in industry to trap emissions of PM from a variety of sources with efficiencies of up to 95% - 99% (Hartmann et al., 2011). Smoke passes by electrodes (frequently wires or bars) charged with a high negative voltage, causing particulates inside the smoke to become negatively charged as they pass by. A second set of electrodes (frequently plates) carries a similarly high positive voltage. The negatively charged particles are pulled towards the positive electrodes and stick to them. Continuous operation cycles are interrupted by periodic cleaning via rapping, brushing, or shaking of the PM entrapping surfaces. This technology has been downsized in Europe to fit small scale industrial and home heating applications burning solid fuels.

The efficiency and effectiveness of electrostatic precipitation depends primarily upon the strength of the electrical field and the size of the particle. A stronger electric field and larger particle size results in a more rapidly charged particle. When particles are too small and too fast moving the ESP field needs to be lengthened to capture the particles.

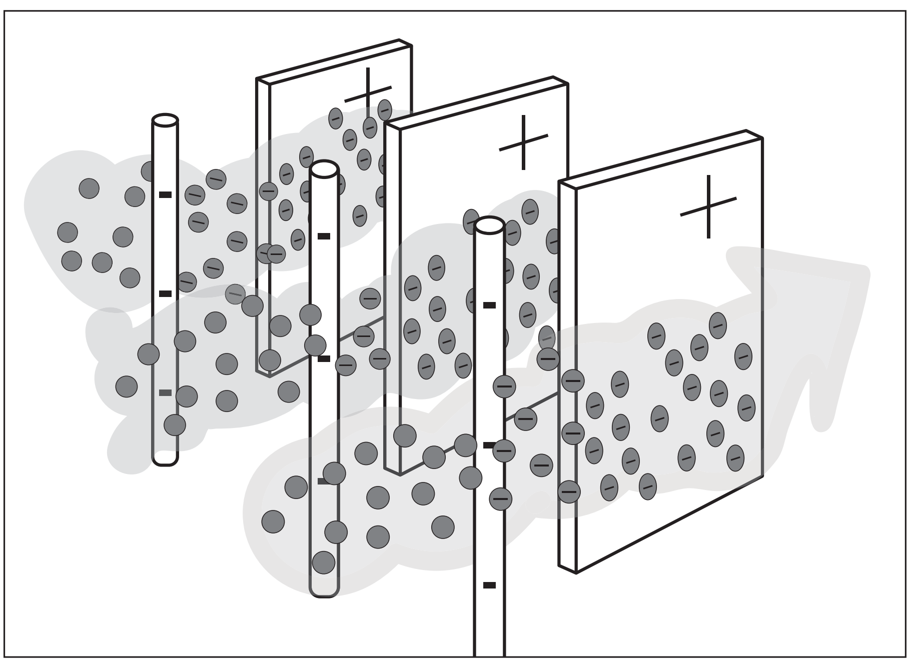
Wood burning European stoves and boilers have been targeted for country-wide reduction of PM emissions. A German study (Hartmann et al., 2011) tested a variety of ESP systems in both lab and field settings for their effectiveness. The application of the ESPs varied greatly from chimney top separators, to flue gas tube integrated models, to boiler attached models.

The Swiss OekoTube has been measured to reduce $PM_{2.5}$ by 80.2% - 97.7% depending on the season (Brunner et al., 2018). Other models of ESPs examined in the study also showed promising levels of precipitation efficiency. ESPs have demonstrable $PM_{2.5}$ removal efficiencies of up to 99% across various combustion applications. Use studies at ARC, focusing on cooking/heating stoves in the lab, found $PM_{2.5}$ reduction rates of between 50-97%. While ESPs do not impose a pressure drop reducing draft they do require a steady and reliable power source for proper operation and must be sized properly and cleaned regularly.

A review of the in home effectiveness of many types of ESPs in Europe found that creosote can interfere with proper function (Obernberger, 2011). The positive and negative plates can be coated and then efficiency is reduced. ARC is experimenting with ground placement of the ESP to increase ease of cleaning. Increasing combustion efficiency reduces the periodic maintenance schedule.

Considerations:

- Successful installation requires sizing of the power supply and electrode.
- It is necessary to limit sneakage and rapping re-entrainment.
- Limiting arcing or other sparking is important.
- ESPs require periodic, and perhaps frequent, cleaning of the entrapment surfaces.
- ARC recommends placement on the ground when possible to facilitate cleaning.
- The ESP is low powered but requires electricity to function.



In an Electrostatic Precipitator, smoke particles become negatively charged and stick to positively charged plates.

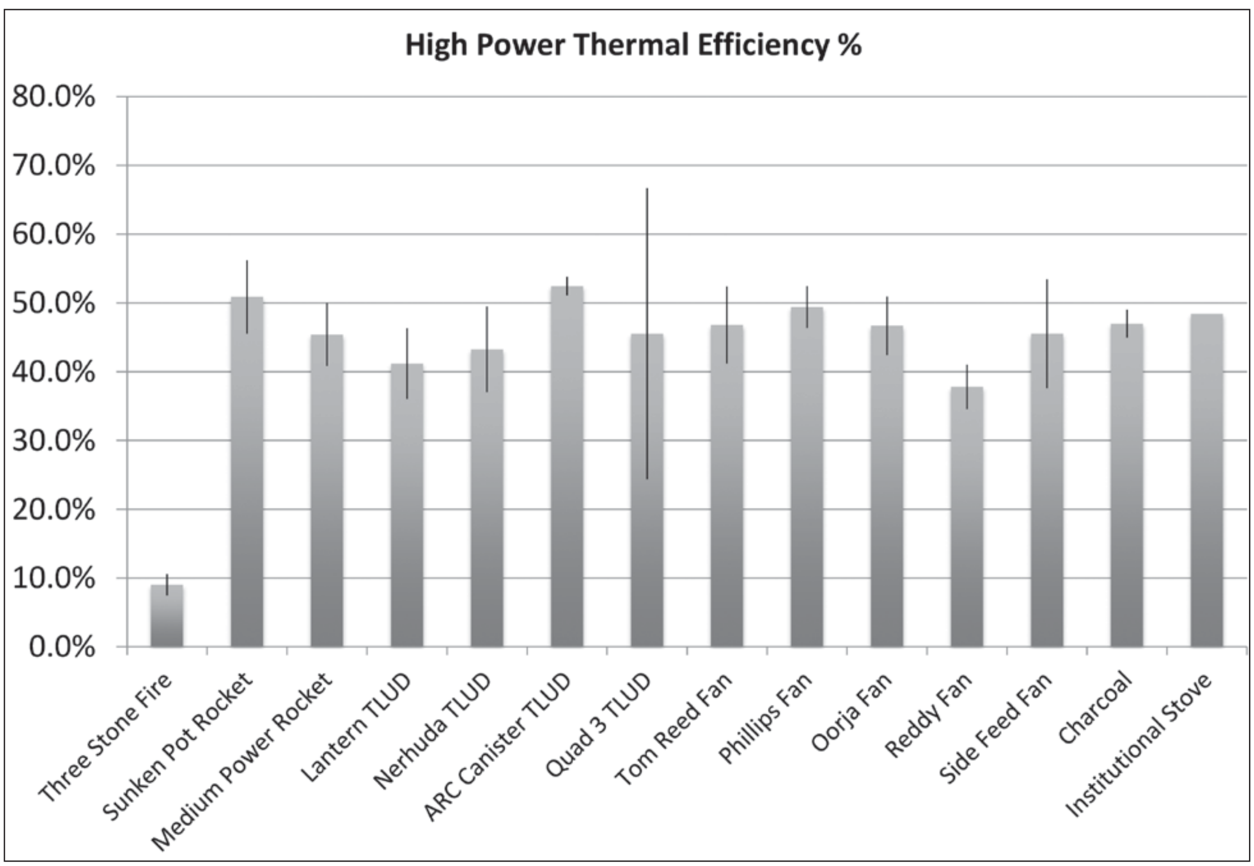
Chapter 9

A Survey of Clean Burning Stoves

Before starting to develop cleaner burning stoves in the DOE project, ARC researchers completed a survey of best performing existing stoves. The hope was that a survey would inform the team about the most successful techniques. The information from the survey was very useful and the stoves described in this book were evolved starting from the highest scoring approaches. The stoves were tested under the LEMS emissions hood with the WBT 4.2.3 and were rated for performance using the 2015 IWA Tier system. The WBT is great for comparing performance. We used the same pot, same amount of water, the same methods of lighting and feeding the fire, and the same wood. The WBT doesn't predict how the stove will perform in use but it's great for learning how to improve heat transfer and combustion efficiency.

High Power Thermal Efficiency

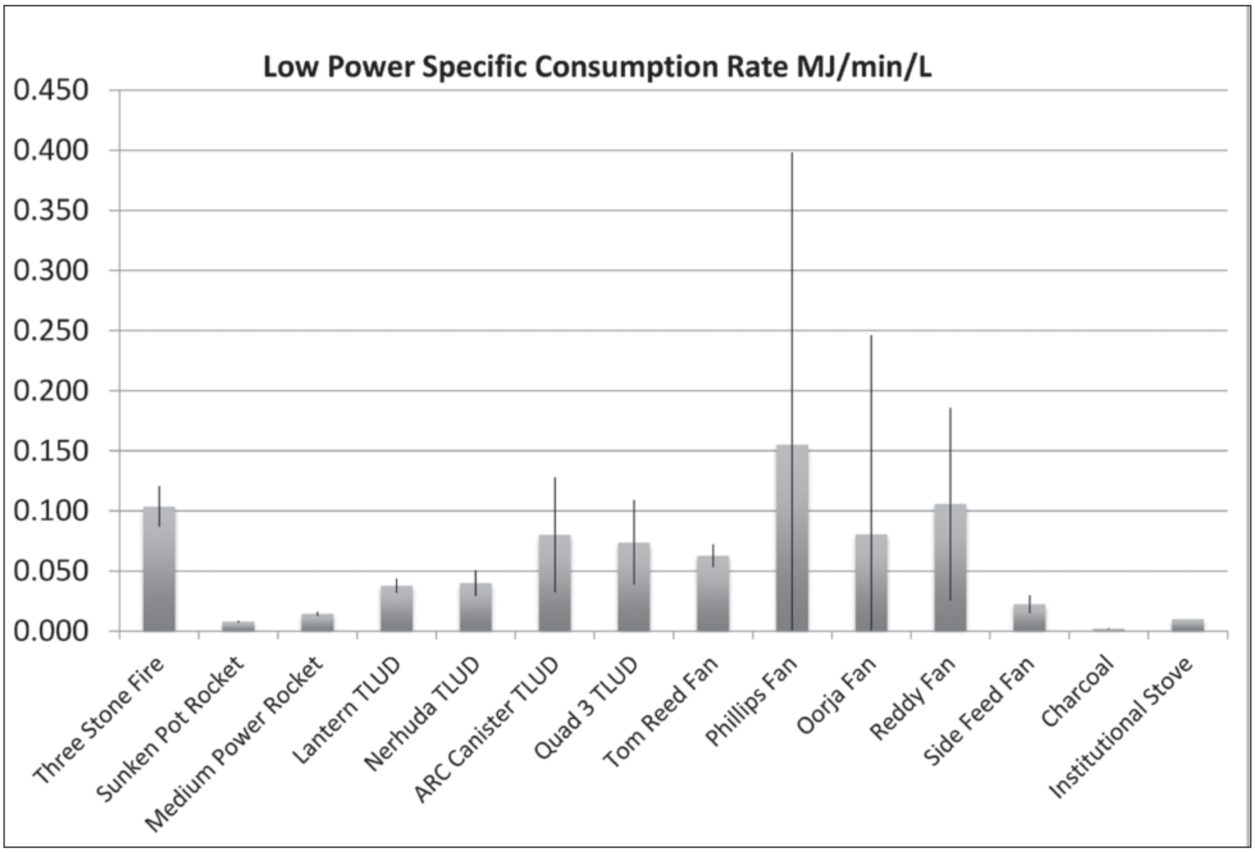
When the following stoves were tested at moderate firepower with a 6mm skirt around the 7 liter pot, a majority of the stoves scored in the Tier 4 category for thermal efficiency. Dr. Samuel Baldwin showed how to achieve higher thermal efficiencies by combining smaller fires with small channel gaps around the pot (Baldwin, 1987). The testing results from the ARC stove survey reinforced the idea that how to improve heat transfer efficiency in cookstoves is relatively well understood and can be achieved by a wide variety of stoves. Using much less fuel compared to the Three Stone Fire was accomplished by all of the stoves.



(≥ 45% for Tier 4) A majority of the stoves scored in the Tier 4 category.

Low Power Specific Consumption

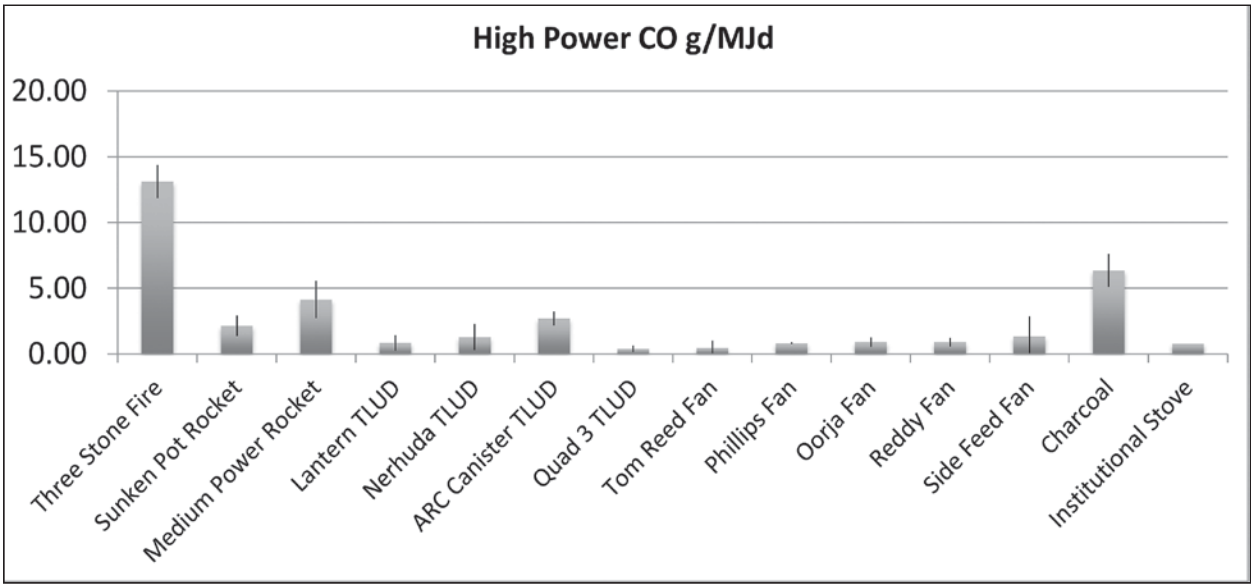
The stoves that metered the biomass fuel (small pieces of wood were added at regular intervals or longer sticks were pushed at a controlled rate into the fire) were able to successfully reduce the firepower to keep the water at the simmering temperature of 97˚C. The TLUDs and fan stoves were clean burning but generally only ran at high power. As a rule of thumb, approximately a three to one turn-down ratio was needed to score well on the Low Power Specific Consumption metrics. The natural draft and forced draft TLUDs did well at high power but again, were not able to reduce power effectively. Closing off the primary air gave the charcoal stove the highest turn-down ratio. Adding an adequate turn-down ability to the TLUDs became a goal of the ARC/DOE investigation.



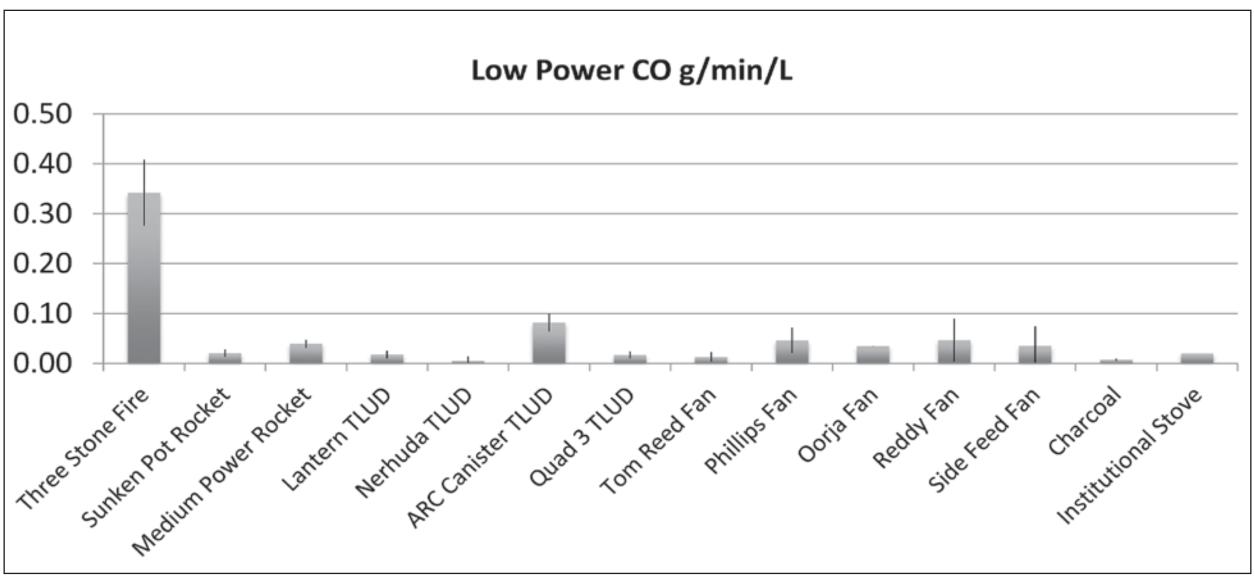
(≤ 0.017 for Tier 4) The stoves that metered the fuel, with an adequate turn-down ratio, scored well on the metric of Low Power Specific Consumption rate.

High and Low Power CO

Since wood burning stoves often do not emit large amounts of CO, the IWA Tier 4 levels, based on protecting health, tended to be fairly easy to achieve. A majority of the cleaner burning cooking stoves were in the Tier 4 category for measures of CO.



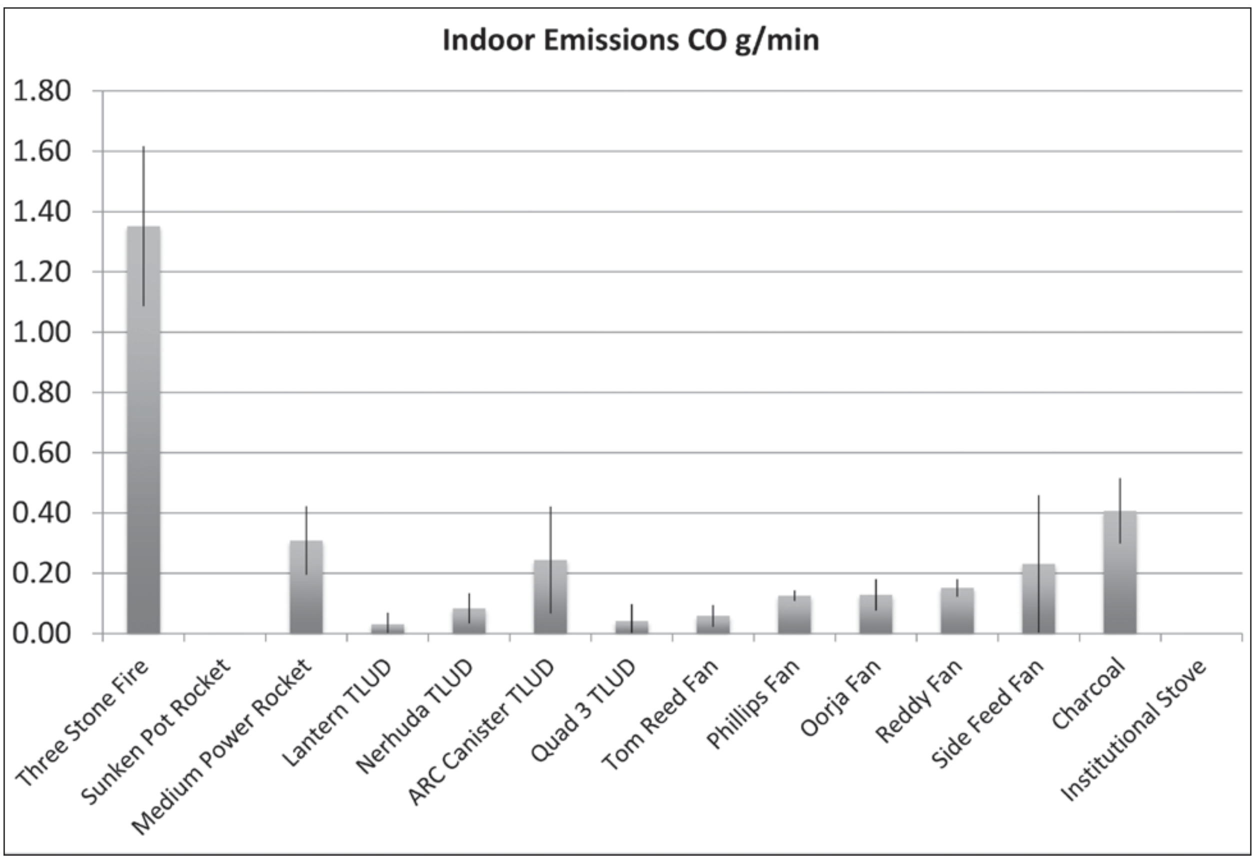
(≤ 8 for Tier 4) The three IWA Tier 4 CO metrics of CO tend to be fairly easy to achieve.



(≤ .09 for Tier 4) Again, the IWA Tier 4 levels for CO are generally achievable. CO is especially low in stoves with an adequate turndown ratio.

Indoor Emissions of CO

Emissions of CO did not appear to be a problem in best practice stoves. Charcoal is known for emitting high concentrations of CO and smaller amounts of $PM_{2.5}$. Combusting the CO in the charcoal stove became a goal of the ARC/DOE project. It was found that in a very well insulated charcoal stove with pre-heated, natural draft, secondary air jets, the CO was combusted more completely (see Chapter 16).

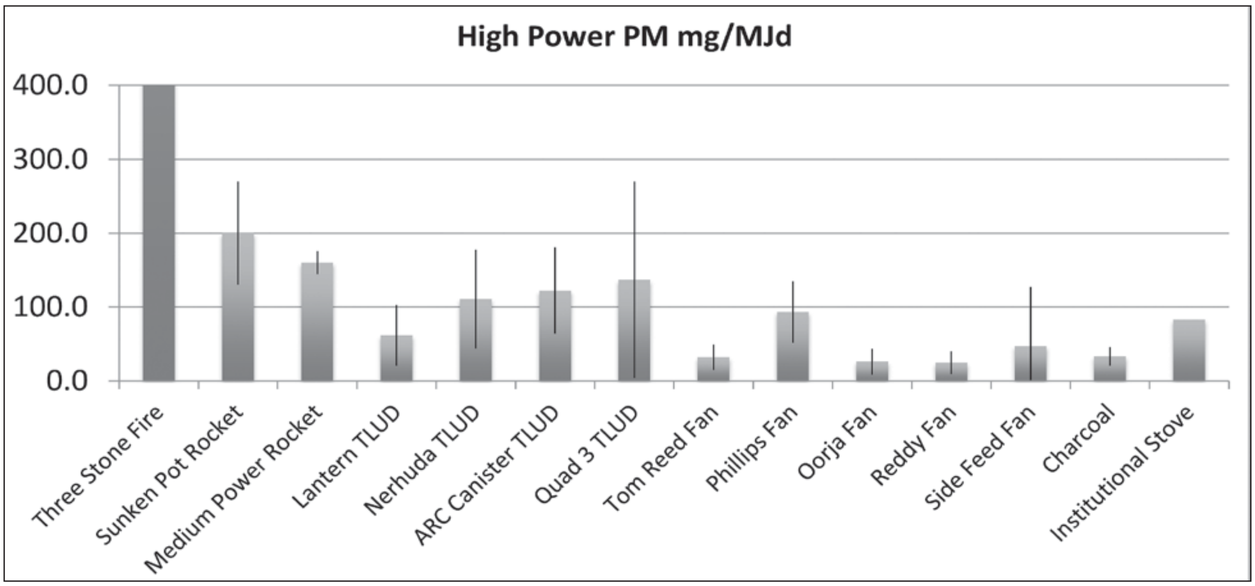


(≤ 0.42 for Tier 4) As in other measures of CO, the improved stoves easily achieved Tier 4 for Indoor Emissions. In a 30 m^3 kitchen with 15 air exchanges per hour these stoves would theoretically not exceed WHO standards protecting health. The chimney stoves (Sunken Pot Rocket and Institutional Stove) were well sealed and essentially all of the emissions exited the room.

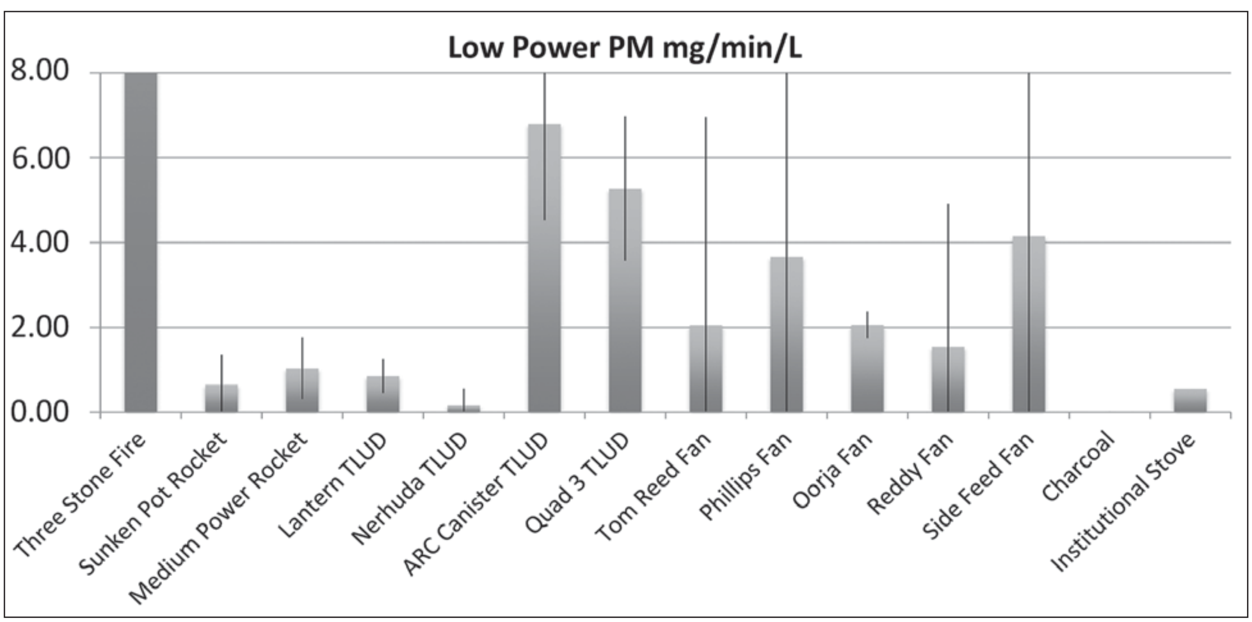
High and Low Power $PM_{2.5}$

While the Tier 4 CO levels are within reach for a variety of stoves, a very small amount of $PM_{2.5}$ is harmful to human health. For this reason, achieving Tier 4 performance on the IWA $PM_{2.5}$ metrics is much more difficult. It turns out that the High Power $PM_{2.5}$ metric (mg/MJd) is easier to meet than the Indoor Emissions metric (mg/min). However, only three forced draft stoves and the charcoal stove scored in the Tier 4 category for High Power $PM_{2.5}$.

Well-made charcoal is known for emitting very small amounts of $PM_{2.5}$. The charcoal stove in these Low Power tests only emitted 0.01mg/min of $PM_{2.5}$. While the fan stoves did well at High Power PM, the forced draft TLUDs could not reduce firepower adequately resulting in less successful Low Power PM scores. On the other hand, the three Rocket stoves (Sunken Pot, Medium Power, and Institutional) with better turndown ratios were in the Tier 4 category, as were some TLUDs.



(≤ 41 for Tier 4) Three forced draft stoves and the charcoal stove scored in the Tier 4 High Power category in this preliminary survey of existing stoves.



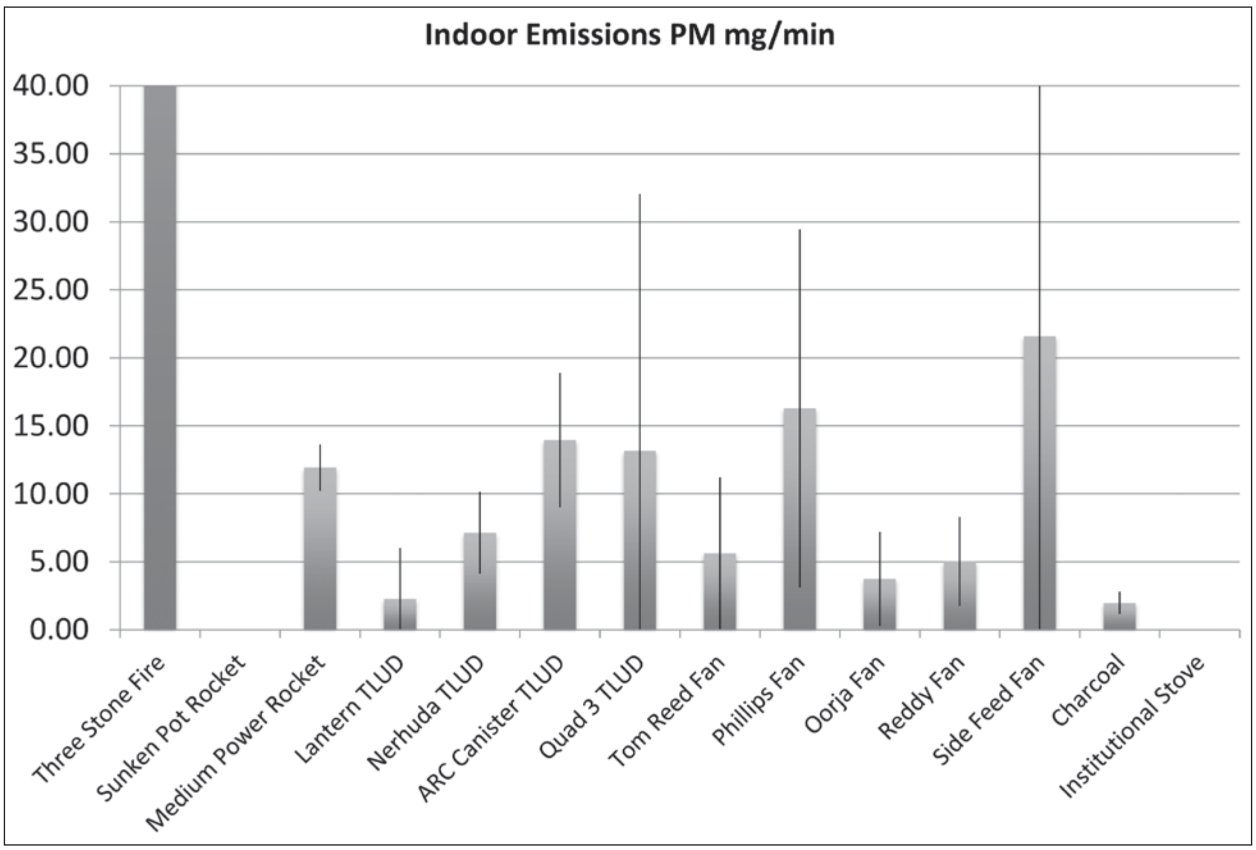
(≤ 1 for Tier 4) In a few stoves the low power performance was better for $PM_{2.5}$. Even the natural draft Rocket stove did relatively well. Rocket stoves do better at low power. Stoves without a sufficient turn-down ratio were not as successful.

Indoor Emissions of $PM_{2.5}$

Stoves with fully functional chimneys, like the Sunken Pot and Institutional Stove, protect inhabitants from $PM_{2.5}$ in places like the United States and Europe. The Sunken Pot and Institutional Stove did not leak and the emissions were removed from the emission hood by the chimney.

In this survey, the charcoal stove and one low power TLUD were the only stoves that achieved Tier 4 on the $PM_{2.5}$ Indoor Emissions metric. Even the best unvented fan stoves did not come close to reducing emissions to safe levels. Reducing the Indoor Emissions of $PM_{2.5}$ was identified as another goal for the ARC/DOE work.

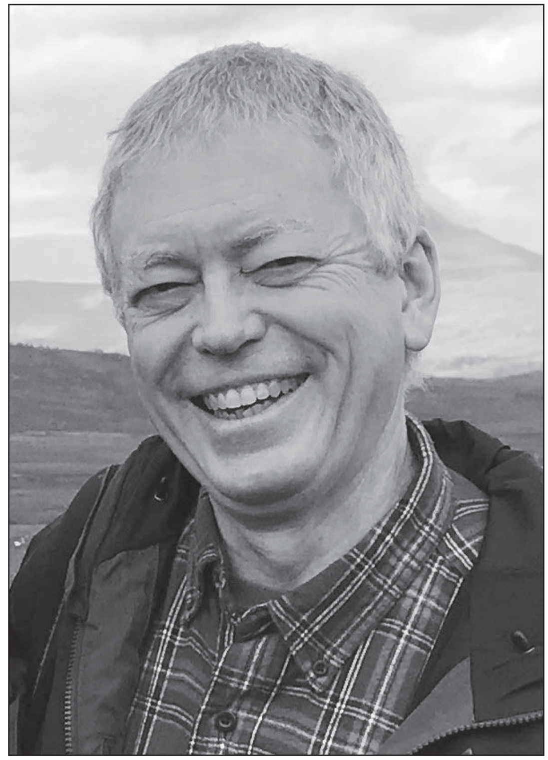
The WHO intermediate indoor guidelines estimate that health is protected when up to 7.1 mg/min of $PM_{2.5}$ escapes unburnt in stoves with chimneys. These in-use chimneys are estimated to remove 75% of the pollution from the kitchen. Adding a chimney to a stove used indoors is mandated by law in the USA and Europe for good reasons. Eventually, we added chimneys that removed essentially all emissions from the room to all of the DOE stoves.



(≤ 2 for Tier 4) Even when carefully tended and using low firepower and 6mm channel gaps around the pot, most of the wood burning stoves did not come close to achieving the Tier 4 standard for Indoor Emissions.

Clean Stove Survey Results

- The Three Stone Fire was dramatically outperformed on all measures by the cleaner burning stoves.
- A large range of stoves achieved over 40% thermal efficiency when tested at medium power with a 6mm pot skirt.
- Stoves with a large turn-down ratio scored in the Tier 4 low power categories. While TLUDs could be clean burning at high power if they were unable to adequately reduce power, they did not do well on the fuel use and emissions metrics based on Specific Consumption.
- Cleaner burning wood stoves easily achieve Tier 4 on measures of CO.
- Unfortunately, even the best wood burning stoves emitted more $PM_{2.5}$ than required by the new WHO intermediate unvented indoor air standards and the similar IWA Indoor Emissions Tier 4 metric.
- A charcoal burning stove did well and scored in the Tier 4 range on all metrics. When the wood is completely burnt out of it, the charcoal did not make appreciable amounts of smoke.
- Improving the turn-down ratio and the combustion efficiency in a range of stoves became goals for the DOE project.



Dr. Sam Baldwin, Chief Science Officer at the Department of Energy's Office of Energy Efficiency and Renewable Energy, started and has continued to support the science based research and development of cookstoves.

The EPA launched the Partnership for Clean Indoor Air in 2002. Jacob Moss, Brenda Doroski, Jim Jetter and John Mitchell (l to r) jump started the new world of stoves.

(Left to right) Claudia Africano, Doña Justa Nuñez, and Sebastian Africano with the Doña Justa stove in Honduras (Trees, Water, and People).

Chapter 10

Proyecto Mirador: The Business of Stoves

by Richard Lawrence and Esther Adams

Though all stove projects will face different challenges, it is fair to say that many common ones exist. And of course, without a good stove, you have nothing. But, aside from all the technical considerations, it is an unavoidable fact that operating a stove project is just plain tough. Since establishing Proyecto Mirador in 2004, we have certainly seen our share of challenges. Working in Honduras, where crime is extremely high and governmental control minimal, Mirador has had to stay nimble and flexible in order to adapt its strategies to the adverse conditions we encounter in the field. Our operations have evolved from a staff of three to more than 165 employees, both direct and indirect, making us one of the largest employers in Western Honduras aside from the government itself. We've grown from a small, charity-funded operation that built 125 stoves in 2004, to a carbon-financed operation that has built roughly 200,000 stoves as of 2019. Along the way we've had to grow, adjust, and improve according to changing conditions, and at no point have we looked up and said, "This is getting easier." But we have learned a lot of valuable lessons, and it is my hope that this chapter will offer a general road map for stove projects to reach viability and, ultimately, sustainability.

Components of a successful stove project

A good stove

The first requirement for a project's success is an efficient, durable, usable stove. While performance metrics are central, they are not the only consideration. The key is to find affordable and culturally appropriate technology that will present a minimum of challenges in terms of adoption. A well-engineered stove may look great in the lab, but falter in the field due to cultural considerations. For this reason, the importance of field testing, using protocols like the Kitchen Performance Test (KPT), cannot be underestimated.

In Mirador's case, we have chosen to replace the traditional Honduran fogon, a plancha based chimney cookstove, with a functionally similar but more efficient cousin, the *Dos por Tres*, which is adapted from another plancha stove called *La Justa*. While we could have chosen a more efficient stove overall (one that uses LPG, for example), the cost of fuel limits use and gas stoves do not meet the full range of Honduran cooking needs. Our beneficiaries' diets rely on staples like corn, beans and rice; and they must have a stove with enough surface area to cook tortillas while accommodating several pots at a time. Many *Dos por Tres* users supplement their cooking with gas or electricity, but they use their auxiliary stoves for quick tasks such as boiling water for coffee. And, in the poorest homes, wood is the only viable option.

A professional organization

Assuming a culturally appropriate, efficient stove has been chosen and field testing completed, the next thing to consider is how to create an organizational structure that can effectively support dissemination. In doing so, establishing solid, ethical local leadership is paramount. An effective organization must have a foundation that can support execution and growth while accounting for cultural contingencies, navigating governmental and regulatory requirements, and providing responsive feedback to its international counterparts wherever applicable. Establishing local management in turn creates local jobs, thus further benefiting the communities the project serves. Local talent can be used for material provisions, construction and implementation, administration and management, as well as the implementation of technology.

At the same time, a sustainable model can be greatly enhanced if the project's leadership includes international business acumen and a thorough understanding of finance. In many cases this will entail a division of leadership between the center of operations and an international branch, which in Mirador's case is based in the U.S. One could not function without the other. While we could not execute the project without Honduran leadership, it would not be financed without its U.S. support structure.

Strategic partnerships

A measure of third-party involvement is required in order to support research and development, implement technology, and perform monitoring and data analysis. Industry alliances can be helpful in establishing a network of support and access to funding, while local partners can provide help with operational support, warehousing, and the like. It is also important to stay mindful of political factors and maintain healthy relationships with local politicians and any government agencies that might factor into the process. And, of course, it is critical to establish long-term financial partners that are invested in the project's success.

Access to capital

The demand for stoves continues to increase globally, largely as a result of the efforts of industry organizations like the Clean Cooking Alliance (formerly the Global Alliance for Clean Cookstoves) as well as the health research community. Despite the growing demand for improved cookstoves, project developers often underestimate the amount of capital that is required to get a stove project off the ground.

The ideal type of startup capital for project developers comes from "long term donated equity," whereby the funder provides capital without the need for reimbursement and financial return is calculated in terms of the measurable benefits that the project offers. This type of capital should be sought in earnest and, once established, leveraged through whatever mechanisms are possible in order to accomplish a high Return on Investment (ROI).

Carbon finance is another important option for leveraging capital and providing a viable instrument of value transfer to the investor. In a carbon project, every improved cookstove installed generates carbon reductions, which are in turn quantified and sold on the open market. In this way, carbon finance enables periodic injections of capital through carbon sales and the original equity investment is multiplied. Carbon savings can only be realized after stoves are verified and credits are issued and sold, all of which can add up to a significant delay. For that reason, substantial capital is required to sustain project operations in the interim.

Another means to leverage capital is to quantify and monetize the project's "co-benefits"—its health, economic, and environmental benefits—and incorporate them to determine an identifiable ROI. By quantifying these cash and non-cash benefits through the calculation of the stove's Net Present Value (NPV), stove projects are better positioned to attract funding. (I will elaborate further on both carbon finance and the quantification of benefits later in this chapter.)

A market-based supply chain

Not surprisingly, the attributes that contribute to a project's stability also serve to enhance brand value and attract investment. For example, it is beneficial to use locally sourced materials when possible. This not only serves to create local jobs, thus raising the project's profile and garnering respect, but also streamlines operational finances and helps to simplify logistics. Locally manufactured products also eliminate the outflow of foreign currency reserves from developing countries. By mobilizing local capital, the project gains credibility while supporting the local economy. It is also critical to ensure there is sufficiently high demand from the beneficiaries; this requires not only a reputable product but also an affordable one. Mirador operates on a no-cash model whereby beneficiaries are responsible for donating time and cheap, locally available materials to the stove construction, while (thanks to carbon finance) Mirador supplies the precision parts for the firebox, plancha and chimney at no cost to the consumer. The result is a large backlog of requests for stove construction, without having to direct resources toward marketing the product.

Training of beneficiaries

Many stove projects follow a distribution model that ends when the stove is sold or delivered. In many cases consumers are left to integrate a new stove, or even a new cooking practice, with little or no support from the provider. This often results in "stove stacking," whereby the consumer still uses her traditional stove in parallel to the improved cookstove, or it can lead to the abandonment of the new technology and a return to traditional practice. The "build it and leave it" business model is inadequate to address the complexities that underlie successful stove adoption. Ideally, each sale or installation should be supplemented by direct, face-to-face training to ensure consumers understand proper use and maintenance of the stove. Over the years Mirador's training program has evolved to the point where each beneficiary has at least 3 points of contact with our staff, in the form of community meetings and private visits during which she receives repeated training and has the opportunity to ask questions and voice concerns. Some families, particularly those who have had trouble maintaining the stove, will receive one to two additional visits from Mirador to ensure adoption is successful. Follow-up visits also provide a means to assess stove performance, fix any construction errors, and replace parts.

In the end, this system creates a financial advantage from Mirador's standpoint: because we cannot collect carbon credits on stoves that are abandoned, higher adoption rates mean more carbon is generated and hence sold to support the project. In the absence of carbon finance, high adoption rates still help establish credibility and thus enable access to other forms of capital. For projects that sell stoves directly to the beneficiaries, brand value is enhanced and thus demand increases.

Effective monitoring

Just as it is important to follow up with beneficiaries to ensure their experience is a success, it is equally important to document these interactions and organize the data. Mirador has chosen to monitor its stove installations and user interactions using a comprehensive workflow built on the Salesforce.com platform, although there are countless other possibilities available in various price ranges depending on the level of complexity and customization. The crucial point is to understand the importance of data management and embrace technology as integral to the operational workflow.

In Mirador's case the investment in building a customized system was a costly but rewarding necessity. We would not have evolved to our current capacity and level of sophistication without it. Our project is subject to verification by the Gold Standard, our chosen carbon credit certification standard, and the monitoring requirements are many, varied and stringent. But even without such strict reporting requirements, any project will limit itself from advancing past a certain point without a technologically strong monitoring system in place. We are living in an age where the quantification of benefits is paramount to a project's credibility, and competition for investment is fierce. Making a sizeable investment in technology can add enormous value if the deal is properly executed. However, it is important to balance the level of investment against financial realities. System design and implementation are only the beginning of the road, and the higher the level of customization, the more ongoing support the system will require.

Minimally, a sound organization should be able to document and monitor the location of the stoves it disseminates, collect basic household data, and track stove use and abandonment. Ideally there should be serial numbers and GPS marks so that stoves can be accurately identified and mapped. A computerized system for collecting survey data can become a useful tool for market development, reporting and, wherever certification is at issue, compliance. If designed properly, a simple data management system can be used to document and fix issues as they arise, provide a mechanism to avoid repeating mistakes, and ultimately streamline workflow and continuously improve operations.

A scalable model

As demand increases, a healthy project should be positioned to expand responsively. Any business must plan for expansion in advance and stay well ahead of the rolling train. A model we've found to be effective is what we call the Programa de Ejecutores. Under this system, Mirador assigns responsibility for stove construction to microenterprises headed by Ejecutores (implementers), who in turn hire technicians to execute stove construction. The Ejecutores and their employees are trained under Mirador's regimes, and each is subject to incentive-based compensation.

Some have hired midlevel management to expand their own operations, while others manage their technicians directly. Mirador gives the Ejecutores the tools and training they need to create a successful business, while our direct team of Supervisors conducts tight monitoring to ensure the Ejecutores' work is up to appropriate quality standards.

In order to expand, Mirador hires more Ejecutores to build stoves, more Supervisors to conduct monitoring, and more suppliers to provide stove parts. Since building and materials are outsourced, a small, core management team is all that is required to keep operations running smoothly. This structure not only simplifies management requirements, but also enables checks and balances that incentivize the Ejecutores to build quality stoves. This results in continuous improvement as the project grows, rather than a degradation of quality as scale increases.

Of course, this is not the only effective model to address scale, but it is one that can be replicated or adapted for many different project types. The important thing is to carefully consider a project's goals, constraints, and parameters; plan a system for growth; and execute it diligently. Throughout the process, technology must be harnessed and integrated intelligently to maximize success.

Building Brand Value

Earlier we mentioned the importance of quantifying co-benefits in order to attract capital. This section will discuss the matter in a bit more detail, keeping in mind that different projects will vary in terms of their approach to monetization.

When approached thoughtfully, it is not difficult to formulate an argument that backing stoves is a good idea. Stoves address 11 of the UN's 16 Sustainable Development Goals (SDGs): (1) No Poverty; (2) Zero Hunger; (3) Good Health and Well Being; (4) Quality Education; (5) Gender Equality; (7) Affordable and Clean Energy; (8) Decent Work and Economic Growth; (11) Sustainable Cities and Communities; (13) Climate Action; (15) Life on Land; (16) Peace, Justice and Strong Institutions.

Due to the breadth of co-benefits offered by cookstove projects, the "stove story" resonates with a huge cross-section of demographic groups; and co-benefits create natural relationships with consumer companies. When effectively presented, all these attributes can be quantified and, in turn, monetized. To that end, in 2017 and 2018, the Gold Standard Foundation transitioned to a new certification structure, called Gold Standard for the Global Goals ("GS4GG"), that focuses on the SDGs as the primary basis for quantifying co-benefits. Projects can choose either to attach "SDG Contributions" to their carbon credits or to certify "SDG Impacts" that are verified under separate methodologies and packaged separately from the carbon reductions. SDG Impacts can include, for example, health benefits expressed as Averted Disease Adjusted Life Years (ADALYs), as well as gender, water, and fair-trade certification.

In order to present a convincing case to investors, it is useful to undergo a credible, third-party valuation of the project's co-benefits. In Mirador's case, the value of the benefits was calculated at 10x the cost of the stove. Once the project's benefits have been quantified and documented, the task is to cultivate financial partners who understand the value of co-benefits (and, where applicable, carbon credits) to brand enhancement, and partners who comprehend the project's ability to leverage its benefits in strictly commercial terms. The product is not simply a stove; it is also a diverse array of intangible assets that can be marketed creatively.

More on Carbon

There is no doubt that carbon financing can fundamentally transform the economics of a stove project. Ideally, carbon finance can provide a self-perpetuating stream of income that grows to sustain the project's expansion. For every stove that is installed, the corresponding reduction in carbon generates more income for the project. Carbon incentivizes a project to build high quality stoves. A more efficient stove will generate greater carbon savings and, consequently, higher income.

While projects that rely on sales for their primary source of income must establish a clientele that can afford to buy the stove, carbon incentivizes a project to help the poorest consumers. Put simply, a carbon project enters the room and looks for the poorest of the poor, while a sales project has to look for buyers who can afford the stove. People with lower incomes tend to be more dependent on wood; even if they should have a gas or electric stove, which in some cases are donated by the government or an NGO, they will use it sparingly if they cannot afford to sustain the cost of fuel or electricity. People with the financial means to purchase stoves are also more likely to have the wherewithal to purchase gas or electricity and because of convenience, may use wood less often. Thus, in higher-income households, replacing an inefficient stove with improved technology will have less impact and generate a lower amount of carbon savings overall.

Likewise, wherever efficient means are unavailable or too expensive to operate—and thus inefficient stoves are used extensively—each replacement stove generates higher carbon savings and thus, more income to the project. For this and many other reasons, it is important to know your target market. Research, persistence, and a great deal of trial and error are involved in determining which consumers will be most beneficial to the health and longevity of the project and which consumers might present problems that threaten its integrity.

There are many avenues available to stove projects for carbon certification ranging from the Clean Development Mechanism (compliance market) to Verra (formerly the Voluntary Carbon Standard, or VCS) and the Gold Standard (voluntary market). Mirador has chosen Gold Standard certification over other alternatives because of its rigorous certification of sustainable benefits in addition to carbon savings. Gold Standard stove credits are considered "charismatic" and therefore trade at a relatively high premium. However, whether or not sustainability is addressed as part of carbon certification, quantifying the project's co-benefits will still create brand value, maximize pricing, and open up other creative possibilities for income generation. In fact, the value of a stove project's co-benefits, if correctly documented, will typically outweigh the value of the carbon.

Still, while carbon finance presents a very attractive alternative in theory, there are several things to consider before launching on the complex task of certification. First, carbon certification requires a huge amount of capital and human resources. It is vital to have an adequate commitment of long-term equity capital to fund the initial cash outflow and sustain project operations during the process of certification. Even after a project is listed, validated, and finally registered, the first verification and subsequent issuance must be secured before carbon credits can actually be sold. In Mirador's case there was about a 3-year lag from the time we first started documentation for validation, to the time we had issued credits to sell.

Depending on the build rates already in place at the time of certification, most projects cannot expect the first issuance, or even the second, to provide enough income to sustain the project. In the long term, growth rates and carbon prices will determine whether or not carbon is sufficient or whether further capital is required to expand. In any case, it will take a while for a carbon project to mature to a point of sustainability. In order to maximize cash flow and minimize the drain on start-up capital, it is important to sell credits immediately upon issuance (to the extent possible), and to sell forward credits whenever possible.

Developers routinely underestimate the expense and time needed to secure certification, as well as the ongoing commitment to the studies, tests, surveys and documentation that are required to maintain compliance. For larger projects, a UN Designated Operational Entity (DOE) is usually required to perform onsite audits and generate reports for validation and verification; and, in most cases, a capable third party must be hired to perform ongoing research and development, data analysis, and technological support. A laboratory such as Aprovecho Research Center can be a key ally in this regard. These alliances are critical to meeting the demands of carbon finance and they lend credibility to the claims a project sets forth in its documentation.

In the end, proper attention to such details will always make a project better. Carbon raises the bar by providing a framework through which the project must continue to improve, and deficiencies must be addressed as they arise. Despite the hardships involved, the net result is positive. Carbon is transformative not only to a project's economics, but to its quality as well.

Demand for Carbon

Certification and compliance are half the story; the task of selling carbon presents yet another host of challenges. There are a number of ways projects can sell carbon: direct to buyer; through a broker; or through a cookstove consortium such as Nexus. Mirador operates in the voluntary market, which means that purchasers are not under regulatory obligation to reduce their emissions with the purchase of offsets.

It is tough to set up a long-term relationship for carbon offtake, especially at times when the market for carbon is low. Carbon trade prices have fluctuated over time and individual price points vary widely, even among projects that are similar in nature. While brokers can assist with sales, the cost to the project for their services is dear and the result is often unpredictable. Large buyers often work directly with carbon brokers who, in some cases, may manage projects of their own and give preference to their own projects over others. When a buyer places a tender, the tender often includes constraints that limit the number of providers that can present projects. Moreover, the purchase of carbon offsets is not transparent: buyers often do not permit sellers to use their names or disclose pricing. Whenever possible, despite the difficulties involved, it is beneficial to establish long-term strategic partnerships and take responsibility for selling carbon in-house.

There is much work ahead to increase market demand for carbon and create a viable future for carbon finance. Just as governments must be engaged in order to affect regulations that enhance demand in the compliance market, engaging corporations at the highest levels will be paramount to the continued success of the voluntary market. As companies move from the initial stage of carbon reductions, in which savings are affordable and easy to implement (CFL bulbs, efficient heat, etc.) to a stage where much larger and more complicated investments are required to make further incremental savings, high quality carbon offsets can be a valuable alternative. It is important for carbon projects, and the industry as a whole, to make a case that offsets are an economical way for corporate buyers to raise their profile, and to put pressure on governments to require that corporations offset their carbon emissions.

While there is much to be accomplished, we must not give up on carbon when the market gets tough. Carbon finance is fundamentally transformative to the projects that choose to harness it. The bottom line is that carbon certification is worth the energy when properly managed. And carbon finance is worth the advocacy that is required to establish a global framework for long-term viability.

Improving a Stove Project

We've already touched on several components that are needed to establish a successful stove project. I will now give a few examples that illustrate how an organization might integrate its resources to approach the challenges that come up in project management.

Obviously, it is of primary importance to establish a strong organization, create a sound business plan, and follow it diligently. That said, the business plan must be structured such that the organization is at once nimble, flexible, and scalable. Mirador is a non-profit organization that is run with for-profit business discipline, and we have found that to be a good model for stove projects. Paying strict attention to business execution enables us to maximize productivity and maintain quality, while a non-profit structure presents an unassailable case to financial supporters.

Through data driven studies, a successful project needs to continuously search for weak points and attack them one by one with real commitment, energy and resources. Some solutions are simple and cheap, while others are hard and expensive. As Carl Sandburg once said, "Life is like an onion: You peel it off one layer at a time, and sometimes you weep." And running a successful stove project means attending diligently to each layer as it is exposed. Here I will give a few examples to illustrate the types of problems that can come up and what can be done to address them.

For the first several years Mirador's installations strictly followed plans for the original La Justa stove.

It successfully eliminated the smoke from the kitchen and reduced fuelwood consumption, and the beneficiaries loved it. Since our goal was to improve the health of stove users who had been breathing toxic smoke all their lives, the Justa fit the bill. But when it came time to consider carbon certification in earnest, we began to ask whether the efficiency of the Justa could be improved in order to maximize carbon savings. After careful testing, Aprovecho Research Center recommended structural changes that indeed accomplished our goal. First, as the plancha was square, the sides were not warming up as much as the center, where the heat of the fire circulated front to back underneath. Figuring this represented a loss of energy, Aprovecho recommended that we modify the shape of the plancha to a rectangle. In doing so, we essentially trimmed off the sides where the heat was not getting efficiently distributed. This simple modification alone served to increased fuelwood savings by several percentage points; and in turn, carbon savings increased.

Another problem arose when the earlier stoves began to age: despite the existence of a thin patch positioned on the underside of the plancha directly above the hottest part of the fire, planchas will still wearing out after 2-3 years when the patch burned through. So we added a second patch on the opposite end of the cooktop, such that the entire plancha could be rotated 180° to extend the life of the stove doubly. We also encountered a durability issue whereby the corners of the plancha would sometimes buckle, resulting in a cooktop that was no longer perfectly flat and allowed some heat and smoke to seep through the corners. Our response was to add a “tube” of steel outlining the perimeter of the plancha from underneath, which resolved the issue.

Lastly, in order to improve airflow we added a small grate, positioned in the front of the stove mouth, to raise the wood up slightly off the floor. The grate is made of reclaimed rebar and adds about $2 to the cost of the stove, a worthwhile investment given the increase in efficiency. And perhaps the best invention we’ve come up with is the “Cinco,” a simple tool that performs all five of the maintenance steps necessary to keep the Dos por Tres in good working order. The Cinco is simply a long, flat piece of metal with a 90° bend at one end, and the value it has added can hardly be measured. All of these developments and modifications relied on having flexible production facilities and skilled technical resources, both internal and external, to identify the source of the problem and define the process for remediation.

Some problems are simple and cheap, like those described above; others are complex and costly. Here is an example that illustrates how elusive a problem can be. Over the years, through careful monitoring and documentation, we observed that there are certain houses in which perfect stoves simply do not work perfectly. We defined these cases as duendes, or “gremlins,” and set about a “Ghostbuster” campaign to eradicate them. With the help of stove engineer Dr. Dale Andreatta, and our internal supervisory and technical staff, we were eventually able to identify that the positioning of the stove (and thus, the chimney) in the home made a big difference with draft in certain cases.

If the roof was slanted a certain way relative to the prevailing wind, or the height of the chimney was not just right relative to the slope of the roof, draft was compromised and stove performance destroyed. No one told us that the location of the stove in the home would make a difference, and it took years for us to figure that out. In response, we have since implemented a system whereby an inspector, who is well-versed in these contingencies, visits each home and determines the optimal build site of each stove before construction can begin. This has improved our abandonment rates, not only by determining correct placement to optimize stove function, but by weeding out any households in advance that are inappropriate to receive a Dos por Tres—i.e., households that have already modified their practice to use electric or gas extensively and do not really need to have another woodstove. This in turn improves leakage figures and boosts carbon savings.

Perhaps the most costly—but indisputably the most transformative—solution we’ve implemented is our comprehensive cloud-based monitoring and workflow system, built and customized by Mogli (formerly Tact Global) on the Salesforce.com platform. The development of the system required a tremendous investment of time and resources, both internal and external. Up-front development costs were extensive, and implementation was also costly and presented many unforeseen challenges. Most of our direct and indirect employees did not have prior experience with computers and, in some cases, they had never even touched a computer before at all. We put smartphones in the hands of Supervisors who were familiar with cell phones but had never seen a touchscreen, let alone used handheld technology to conduct their work. It became clear that we would need a technology expert on staff in Honduras for training and troubleshooting, so we hired an IT specialist who has more than exceeded our expectations in his ability to develop and maximize the capabilities of the system. And the rest of our staff has acquired valuable skills that may never have been available to them otherwise.

Today Mirador's operations are fully computer-based. Every bit of information we've gathered from the beneficiaries or observed about the stoves is available, real-time, for analysis and reporting. The reporting capabilities of our system have streamlined our annual carbon verification nearly to the point of routine, and we've amassed qualitative data through over 300,000 surveys of beneficiaries that makes us nimble and responsive in our ability to report to our funders and partners. After several years the ongoing costs associated with our technology program are now relatively stable, but not insubstantial. Although we could have chosen a more frugal approach, we would never have reached our current level of sophistication as a project, nor would we have been able to attain such a high level of confidence in the data we report. The industry has so far not presented a viable, open-sourced system on its own (although a few attempts are in the works), so the value added is tremendous.

Moving Forward

Since we started in 2004, there have been huge developments in the industry. ISO standards are now in progress to codify performance and sustainability metrics; stove testing centers have sprung up all around the world and testing equipment keeps improving. As a next step, the industry must collectively document and quantify the co-benefits of stoves to reduce the burden of proof and minimize cost to individual projects. Over time these contributions, in combination, will serve to streamline the process of project implementation and improve the odds of success.

The obstacles that come up are many, and they will differ from project to project according to cultural, geographical and economic constraints. But with commitment, perseverance, and a carefully executed business plan, it is possible to grow a stove organization that is viable in the long term. Executed properly, stove projects are a win/win for all concerned. Just a word of caution: don't be idealistic. Be honest with yourself; this is hard work. The "soft skills" that surround the "hard stove" are just as important as the stove itself, and the business of running a stove project must be approached seriously and with sincere determination.

Projecto Mirador head staff, L to R: Elder Mendoza Mejia, Director of Operations; Emilia Mendoza, Director (Honduras); Richard Lawrence, Executive Director (USA). Photo credit: Charlotte Boulton Photography.

Chapter 11

ARC/ASAT and Stove Dissemination

Dr. Larry Winiarski, the Technical Director at ARC, invented the Rocket stove design principles in 1982 and immediately started teaching projects how to make Rocket stoves. The concept went "viral" and the Rocket stove can now be found worldwide. It's probable that millions of Rocket stoves are made yearly by many types of organizations.

Since 1976, Aprovecho has investigated how stoves can use less wood and make fewer emissions. ARC specializes in involving cooks and as many shareholders as possible in the stove design and implementation process. Early books and publications emphasized the importance of the user and their culture (Aprovecho Institute, 1984a, 1984b).

Documenting the progress has resulted in books, presentations, and journal articles many of which are available at www.aprovecho.org. For about a decade, ARC staff taught two to three stove seminars per year in a total of fifteen countries for the Partnership for Clean Indoor Air sponsored by the US EPA. ARC helped the five stove projects supported by the Shell Foundation with technical assistance (2003-2007). More recently, ARC has been assisting about 20 stove projects a year, making videos, publishing an informational e-newsletter, and has written the book you are reading. We publish a lot of open source information. There are CAD drawings of the stoves included in this publication. Our goal is to provide information in a usable form to the multiple stakeholders in the stove space. The SSM Jet-Flame is an open source invention.

ARC consultants work with for-profit companies to assist their stove improvements and we develop new products with them. Our consultants work in the lab in Oregon and go to factories in other countries, as well. ARC invented the LEMS/ PEMS emission hoods in order to improve stoves and has sold over sixty of them with software and accessories to testing centers, universities, and factories. Aprovecho usually helps set up the equipment and train the staff. As mentioned, Sam Bentson invented a gravimetric measurement system for $PM_{2.5}$ and a black carbon addition to the LEMS. Sam just completed making the 2020 LEMS compliant with ISO 19867.

Sometimes Aprovecho becomes involved with projects and establishes long term relationships. ARC has helped to design stoves with BURN, Trees, Water and People, HELPS International, NorthWest Medical Teams, Proyecto Mirador, Proleña, Shell Foundation, Mercy Corps, and other groups.

In 2008, ARC created ASAT, a for profit organization that sells stoves. ARC does research and development and ASAT brings the inventions to market. A lot of this work has been done together with our partner, Shengzhou Stove Manufacturer (SSM).

Shengzhou Stove Manufacturer sells about four million coal burning cookstoves and combustion chambers per year in four nearby Chinese provinces. ARC has been working with SSM since

Huiyang Shen and Meirong Mo at Shengzhou Stove Manufacturer in China.

2007 and SSM now exports about one million, high quality Rocket stoves to countries around the world yearly. The new SSM Jet-Flame can be used in Rocket stoves and open fires to create improved heat transfer and combustion efficiency. Mr. Shen, the owner and stove engineer at SSM, improves the stoves he sells on a regular basis using their in-house LEMS emissions lab.

This book is dedicated to Huiyang Shen and Meirong Mo who make highest quality stoves available to international markets. SSM is an amazing partner. Mr. Shen improves the efficiency of manufacturing and reduces the cost of the stove with new materials. Ms. Mo is responsible for plant management and finance. Mr. Shen and his staff are familiar with the new technologies and how to manufacture modern stoves at affordable prices. The export production capacity of the factory is approximately two million stoves per year. SSM manufactures Rocket stoves, the Jet-Flame, forced draft pellet stoves, institutional stoves, and many other accessories. See www.ssmstoves.com.

Wenxiao Shen (Manager Assistant) and Chenkai Wang (Division Busiiness Manager) prepare to test the Jet-Flame in the SSM lab.

The SSM brand is preferred by customers in part because of the year-by-year refinement of the product. The factory has an ISO compliant LEMS with trained staff to do iterative development, testing, and input improvements in products as suggested by customer responses. Students and researchers from the nearby Zhejiang University use the equipment as a part of their studies.

The ARC designed cookstoves are frequently brought to market by SSM, a self-financed manufacturer. Unlike other large scale manufacturers/distributors, SSM has not received grants or outside financial support and is a stand alone, profitable enterprise. ASAT provides technical assistance, contacts, and refers potential buyers to the manufacturer. The assistance can include engineering, capacity building of many kinds, and introducing SSM to the international community involved with stoves such as the Clean Cooking Alliance. SSM and ARC won the Ashden Award in 2009.

Finding the Existing Solution

In many countries there are manufacturers and supply chains selling cookstoves. ASAT has limited funds and time to get improved stoves into use. Helping established businesses and finding existing stove opportunities is the approach that has worked to move improved stoves into higher levels of mass distribution. Our motto is “Don’t invent, locate!”

This approach has at least two important advantages. The market for the stove exists, and the consumer is buying the product. The market price has been established. Assistance from foreign organizations can improve facets of the operation to make the local business a greater success. Time is not wasted trying to sell unwanted stoves that are too expensive. Because ASAT is a small company, trying to create demand for a product does not work as well as locating where interest exists.

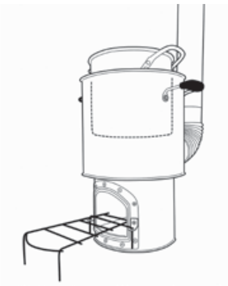
There are many organizations looking to loan capital to competent businesses that can move existing stove projects to scale. ASAT has helped entrepreneurs to locate opportunities that require added competencies to thrive and grow. There are many countries where stove manufacturers, distributors, and retailers have proven sales. Assistance with technical advice, additional capital, and business acumen can help move the project to achieve mass distribution. A realistic business plan can attract interest from banks and other lending institutions. Improving the existing stove is often a path to greater success, as well.

The most successful route to mass distribution may be when a great idea, like Dr. Winiarski's Rocket stove, takes off by itself and goes viral. Throwing multiple products into existing markets and watching for interest is a great way to gauge marketability. It's also inspiring and reassuring to think about the hundreds of brave people around the globe trying to help humanity with better stoves. The Rocket stove has been successful in large part because the stove community has more than its share of idealistic and driven entrepreneurs. Ideas that go viral have exponential influence and take on a life of their own but it's the enthusiastic individuals that often create change. Individuals can make huge differences, constellating action, and helping to ease the burdens around them. This is an optimistic endeavor because people, from so many walks of life, are empowered to affect change.

Dr. Larry Winiarski checks out locally manufactured stoves in Central America.

Peter Scott, CEO and Founder of BURN Maufacturing, Nairobi, Kenya.

Six Clean-Burning Cookstoves



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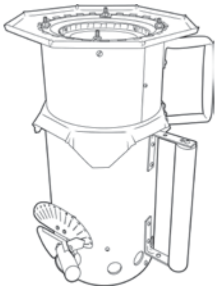

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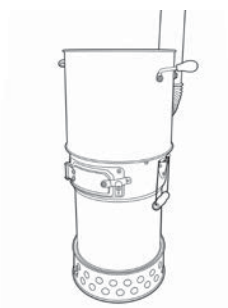

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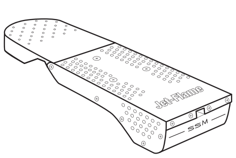

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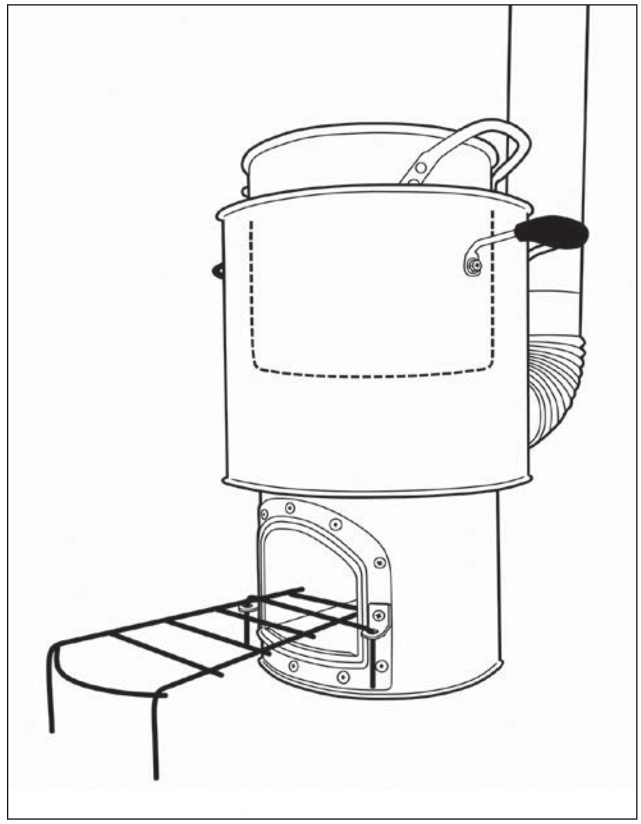
Chapter 12

Natural Draft Sunken Pot Rocket Stove

High Power $PM_{2.5}$**: 11.7mg/min @ 2.7kW** **Low Power** $PM_{2.5}$**: 7.7mg/min @ 1.5kW**

In this Rocket stove, the pot is sunk below the top of the stove body in a fitted hole. The hot gases are forced to flow very closely next to the bottom and sides of the pot increasing heat transfer efficiency. The hot gases then flow down to the chimney which is placed below the bottom of the pot.



CAD drawings are found in Appendix A.

Test Results

Stove type/model		Sunken Pot Rocket		Average Tier
Location		Average	COV	
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	49.7%	4%	4
Low Power Specific Consumption	MJ/min/L	0.020	19%	3
High Power CO	g/MJ_d	2.22	38%	4
Low Power CO	g/min/L	0.05	42%	4
High Power PM	mg/MJ_d	152.2	53%	3
Low Power PM	mg/min/L	1.73	58%	3
Indoor Emissions CO	g/min	0.25	41%	4
Indoor Emissions PM	mg/min	11.8	46%	2

Dr. Larry Winiarski and the Rocket Stove

Dr. Larry Winiarski invented the Rocket stove and has helped hundreds of stove projects worldwide. Since 1982, Larry has taught the staff at ARC how to make improved stoves.

Moving the pot closer to a dirty fire can reduce the fuel used to cook but can also result in poorer combustion efficiency and more pollution made per meal cooked. The cold pot "quenches" the fire. The new generation of improved stoves need to be both clean burning and fuel efficient. And, at the same time, the good stove has to please the cook!

The Rocket stove was invented by Dr. Larry Winiarski in 1982 at Aprovecho Research Center. His intention was to clean up the combustion first and then force the cleaner gases closer to the pot thereby achieving both improved combustion and increased heat transfer efficiency. The approach, outlined in his design principles, includes the well-known Rocket combustion chamber, but the various heat transfer techniques are as important in creating an improved stove.

Field tests have shown that a low mass Rocket stove, with pot skirt, reduced fuel use by about 40%. $PM_{2.5}$ was also reduced by about the same amount (Pilishvili et al., 2016; USAID, 2007; USAID, 2010; USAID, 2011; Yip et al., 2018). A review of Rocket stove intervention impacts in the WHO "Indoor Air Quality Guidelines: Household Fuel Combustion" booklet found that $PM_{2.5}$ was reduced by an average of 260 µg/m^3 and CO by 3.41 ppm (3.9 µg/m3), with percentage reductions of 48% (PM) and 39% (CO) (WHO, 2015). The results of the WHO review seem to be in general agreement with the other reports.

Low cost techniques that improve heat transfer efficiency have succeeded in field tests and saving fuel can often be achieved at little added expense. Saving fuel naturally reduces the smoke made during a cooking task. Low mass, insulated Rocket stoves with pot skirts are successful in saving fuel–the sunken pot Rocket stove in this book achieved close to 50% thermal efficiency. However, numerous field studies have shown that high mass Rocket stoves without pot skirts do not necessarily save fuel compared to the open fire and traditional stoves. Both Dr. Baldwin and Dr. Winiarski point out that insulation and the channel gap under and around the pot are important techniques for saving fuel. The heavy mud and clay stove body absorbs and diverts heat that could have gone into cooking the food in the pot. Generally, a high mass Rocket combustion chamber by itself should not be expected to use less fuel compared to a three stone fire (USAID, 2011).

The Rocket stove is dependent on metering the fuel for cleaner combustion. When too much of the stick is pushed into the combustion chamber too much woodgas is made, the fuel/air ratio is too rich, and more of the un-combusted gas and smoke escape. The Rocket stove burns more cleanly at a moderate or low firepower when a greater percentage of the woodgas flows into flame (Udesen, 2019). Tighter channel gaps matched with lower firepower also force a greater percentage of the heat into the pot(s).

An EPA survey of stove performance concluded that well-insulated Rocket stoves were significantly cleaner burning at medium power (Jetter et al., 2012). In Joshua Agenbroad's thesis "A Simplified Model for Understanding Natural Convection Driven Biomass Cookstoves," low powered operation of the Rocket stove (1.5kW to 2.7kW) was associated with improved combustion characteristics (lower emissions rates of CO and $PM_{2.5}$) (Agenbroad, 2010). For these reasons, ARC reduced the amount of the burning stick in the Sunken Pot Rocket Stove. A fence in the back of the combustion chamber allowed only 8cm of the tips of the sticks to combust. Experiments determined that even 9cm of the stick burning resulted in higher emissions. Of course, firepower is reduced, as well.

The Natural Draft Sunken Pot Rocket Stove with Chimney closely follows the Winiarski design principles. When close to optimal thermal efficiency (49%) is combined with a well-insulated low mass combustion chamber in which only 8cm of the tip of the sticks are allowed to burn, the Rocket stove can score moderately well on the IWA metrics. The new stove is in the Tier 3-4 range on most of the metrics but emitted 11.8mg/min of $PM_{2.5}$ (Tier 2 for Indoor Emissions), which significantly exceeds the 2015 WHO Indoor Air Intermediate Guideline of 7.15mg/min for a vented stove in real use. Emissions of CO are typically low in improved cookstoves and the WHO guidelines for CO are easily met in laboratory tests. Adding an SSM Jet-Flame to this stove dramatically reduced emissions (see Chapter 17).

Dr. Winiarski's Design Principles

Over the years, Dr. Winiarski's ten design principles have been shown to effectively improve all types of stoves. They are easy to teach and are useful when design committees are evolving a prototype. While engineers and researchers may understand how to achieve better heat transfer and combustion efficiency it is the regional user who understands how a stove must function to cook food successfully. The local retailer and distributor know what will sell. Both Dr. Winiarski and Dr. Baldwin recommend the use of Design Committees to engage all stakeholders in the stove design process (Baldwin, 1987). The Winiarski design principles have been used for decades to teach cooks, manufacturers, retailers, funders, and engineers how to create improved stoves together as a team.

Principle One

Surround the fire using lightweight heat resistant materials. The combustion chamber should be insulated.

Insulation is light and full of small pockets of air. Fire resistant examples of insulation used in cookstoves include ceramic fiber, rock wool, pumice rock, wood ash, rice hull ash, vermiculite, perlite, and fire brick that is less than 0.7g/cc. For best performance the insulation, like dry wood ash or rockwool, should have an R-value of around 3.0 per inch of thickness.

Although difficult, abrasion resistant, insulative fire brick can be made from fired sawdust and clay. The sawdust burns out and leaves pockets of air. Anthill clay is especially good for making firebrick. Locally made ceramic tile (baldosa in Spanish) can be used to make a long lasting and replaceable combustion chamber that is surrounded by any of the loose types of insulation. Well-made baldosa combustion chambers are lasting 7 years in Proyecto Mirador griddle stoves in Central America. Expensive refractory metals, such as FeCrAl or FeCrSi, are available that can be used as the walls of a combustion chamber and surrounded by loose fill insulation. However, most stainless steels have a limited lifespan in this application (Brady et al., 2017).

Important: In stoves that are not in constant use, avoid using heavy materials like brick, sand, clay, or cement around the fire. When starting the cold stove the heavy materials warm up slowly, cooling the fire and robbing heat from the pot. It does not make sense to heat up 50 kilos of stove every morning when the cook wants to cook 4 kilos of breakfast.

Principle Two

As well as insulating around the fire, insulate the path between the fire and the pot(s), griddle, or surface to be heated.

It is best if every space within the stove is insulated with lightweight materials, except where the hot gases are flowing closely next to the surface to be heated, such as the pot(s) or griddle. Insulation reduces the amount of heat that passes into the stove body. In an insulated stove more heat is available for cooking. Insulation keeps the gases as hot as possible which increases heat transfer and combustion efficiency and helps to reduce the fuel needed for cooking. ARC recommends maintaining a temperature as close as possible to 900°C in the combustion chamber to burn up $PM_{2.5}$.

Important: Remember that insulation is very lightweight and full of tiny, isolated holes of air.

Principle Three

Include an insulated enclosed space (like a short internal chimney) above the fire in the combustion chamber.

When flames are made under a short insulated chimney, usually about 30cm in length, the flames, air, gases, and smoke will be forced to mix to a greater degree than in an open fire. The partial mixing can burn some of the harmful emissions. The short chimney above the fire also increases the speed of the air drawn into the fire, which helps the fire to burn hotter and assists beneficial mixing. The pot should be placed above the short chimney so hot gases contact its bottom and sides. Forcing the hot gases to scrape past the pot at high speed helps to heat the pot of food more quickly while using less fuel. Do not let the pot or other impediment slow the velocity of the gases. Maintain constant cross sectional area throughout the stove. Adding forced draft mixing in which jets of air enter the fire from below or from the sides can dramatically reduce emissions.

Principle Four

Heat and burn the tips of the sticks pushing only enough wood into the fire to make flame, not smoke.

Hot biomass makes woodgas that is burned up if the right amount of well-mixed smoke, gas, and air join with the hot flame for a long enough period of time. Escaping emissions consist of the woodgases that have not been burnt in the flame. Try to burn only the tips of the wooden sticks. Keep the unburnt portion of the wood sticks cold enough so they don't smolder and make unwanted woodgas. The goal is to heat the tip of the stick to make only the needed amount of gaseous fuel.

Principle Five

High and low heat can be controlled by how many sticks are pushed into the fire.

When wood gets hot enough, it makes gases that can catch on fire. If two or three tips of wooden sticks are pushed into the fire, there is a small fire. When more sticks get hot and release more gas then the fire gets bigger. In a Rocket stove the amount of heat is controlled by the amount of wood pushed into the fire, not by reducing the air entering the fire. Reducing the air needed for burning can result in less complete combustion and greater amounts of smoke and gas. On the other hand, reducing the colder excess air entering the fire can be beneficial by increasing combustion temperatures. Do not reduce the amount of air entering the fire past the point where the fire becomes less clean burning.

Principle Six

The air entering the fire should pass under the sticks as well as over the sticks.

The air drawn into the fire and charcoal under the sticks (primary air) helps to keep the fire burning. Pulling air under the fire into the charcoal made from the burning wood makes the fire hotter. The stove should create a continual flow of air into the fire. This will help keep the wood burning and maintain sufficient flame above the sticks. The air passing through the coals helps to raise the temperature of the fire so that more of the gases become flame and the rate of made charcoal is constant. One goal in a Rocket stove is to keep from making more and more charcoal. The incoming air passing over the sticks (secondary air) helps to mix and combust the air, flame, gases, and smoke.

Principle Seven

If a lot of charcoal is being made by the fire then there is too little primary air entering the combustion chamber.

It is beneficial for a fire to make some charcoal as the wood is burnt. However, if the charcoal starts to pile up under the fire, there may be too little primary air entering the combustion chamber. The combustion zone may also be too cold. Making too much charcoal is an indication of probable incomplete combustion.

A hotter, cleaner burning fire will not make much charcoal as it is being used. Make sure that enough primary air is freely flowing under the fire into the coals. A grate under the charcoal helps to burn the charcoal more quickly compared to having charcoal sit on the floor of the combustion chamber.

Principle Eight

Do not restrict the volume of gases moving through the stove. All of the spaces in a stove should have about the same cross sectional area so that the flow of hot gases through the stove is slowed down as little as possible.

The door through which wood is pushed into the fire, the spaces in the stove in which the hot gases flow, and the chimney should all have about the same cross sectional area so that the gas velocity is unimpeded. Design all the spaces in the stove so that the same amount of gases can freely flow through the stove and up the chimney. Gases are very light and do not transport much heat so a lot of hot gas needs to flow next to the pot(s) or griddle to effectively cook food. Slowing down the gases reduces the amount of heat that enters the pot or griddle. If less heat enters the surface to be heated then more wood is used for cooking. Increase heat transfer efficiency and add more pot or griddle surface area to absorb a greater percentage of the heat and cool exit temperatures.

Principle Nine

Use a grate under the sticks and fire.

If possible, do not place the sticks of wood on the floor of the combustion chamber. Primary air needs to pass under the sticks through the charcoal and into the fire. A stick support in the fuel entrance lifts the sticks up so the air can pass underneath them. When burning sticks of wood it is best to have them side by side with a space between each stick. In this way, each stick helps keep the other stick burning. This kind of fire makes flame above the burning wood that can more effectively burn the made woodgas.

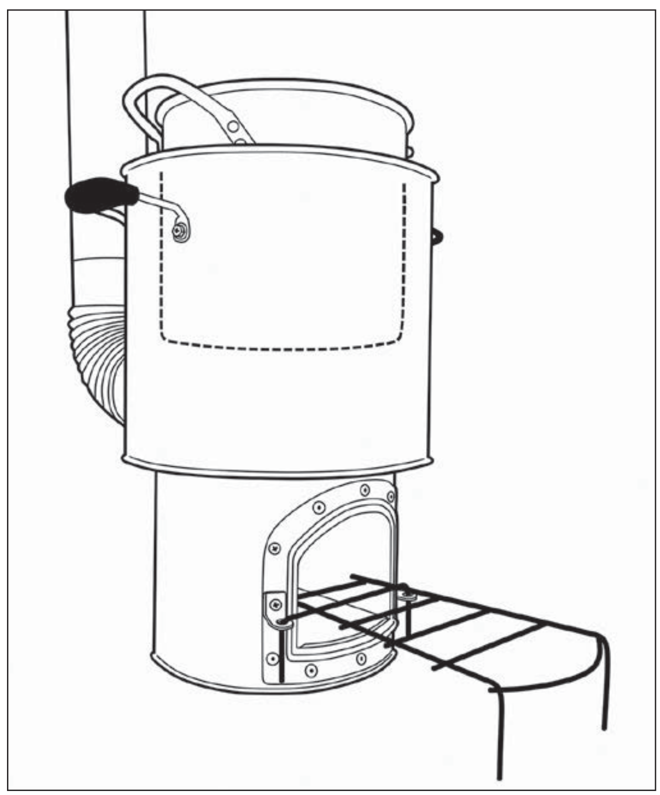
Principle Ten

Force as much heat as possible into the pot(s) or griddle by using properly sized channel gaps.

It is necessary to force the hot gases to flow close to the pot or griddle by making narrow channels next to the surface to be heated. However, if the spaces are too small then the velocity of the gases is reduced and there can even be a back draft. It is necessary to use the right sized spaces around the pot(s) or griddle. If the hot gases flow through big spaces next to the pot(s) or griddle, the gases go up the middle of the space avoiding the surface to be heated and more wood is used when cooking. As a rule of thumb, maintain equal cross sectional area in all the spaces in the stove so that the same amount of gases can flow unimpeded through the stove and up the chimney. Then do a final adjustment of the channel gap under the emissions hood.

The two most important techniques for cooking with less fuel are:

- Keep the gases that touch the pot(s) or griddle as hot as possible.
- Force the hot gases to flow as closely and as quickly as possible against these surfaces without reducing the temperature or velocity. Gas does not hold much heat per volume. Faster hot gases will transfer more heat than slower moving hot gases.



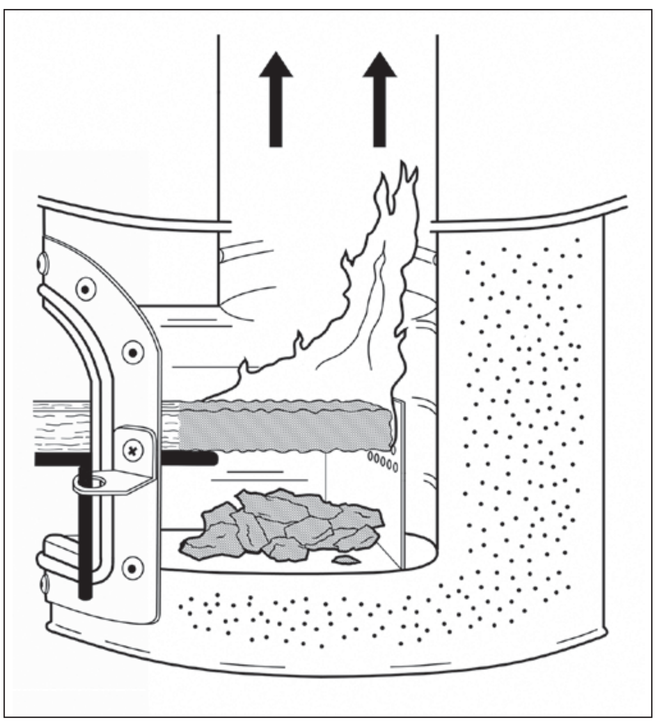
Sunken pot and stick support in the Rocket Stove.

Natural Draft Sunken Pot Rocket Stove Design Features

The Natural Draft Sunken Pot Rocket Stove has a thin walled refractory metal combustion chamber. Rock wool insulation and parallel sheets of stainless steel surround the combustion chamber. The 7 liter pot is submerged into the stove body and the pot fits tightly so the smoke is forced to flow into the chimney.

A fence located at the back of the combustion chamber allows only 8cm of the stick to burn. The hot gases scrape past the sides of the pot in a 6mm channel gap and then flow down a larger space to exit out of the chimney which is located below the bottom of the pot. Allowing only 8cm of four 1cm x 2cm sticks of wood to burn creates a firepower of about 2.7kW. This amount of flue gas can flow unimpeded through the 6mm channel gap close to the submerged pot.

When a low mass, well-insulated Rocket combustion chamber is combined with an effective heat transfer mechanism the emissions made per liter of food cooked can be substantially reduced. At close to 50% thermal efficiency, less wood is burned to boil and simmer water. As Dr. Winiarski points out in his design principles, wood can burn relatively cleanly when only the tips of the sticks are on fire. The rest of the stick is outside of the combustion chamber and remains too cold to make woodgas.



The fence in the back of the combustion chamber allows 8cm of the sticks to burn. The metered amount of made wood gas enters the flame and is more thoroughly combusted. The charcoal under the sticks helps to maintain combustion, but the air flowing through the charcoal is sufficient to combust the charcoal at close to the rate of creation.

The stick support is not solid, to reduce the heating of the wood sticks outside of the combustion chamber by conduction. The high R-value insulation can be made from ceramic fiber, rock wool or separated sheets of aluminum and stainless steel foil. The air spaces between the sheets and the shiny surfaces are also very effective in reducing heat loss. The shiny side of the foil is facing away from the fire to reduce losses from radiation. Shiny surfaces have low emissivity. The combustion chamber is 10cm in diameter and the depth of the fuel magazine is shortened to 11cm.

Decreasing the mass surrounding the fire and increasing the effectiveness of the insulation raises the temperature of the fire resulting in a higher velocity draft and more flame above the sticks. The higher velocity incoming air also burns the char-

The lower door in this Shengzhou Stove Manufacturer Rocket stove controls the amount of primary air entering the fire from below. Too much primary air increases the rate at which wood gas is produced and results in a smoky fire.

coal at a faster rate and the greater amount of flame can capture and combust more of the gaseous fuel. In a Rocket combustion chamber the incoming air pushes the flame against the back wall and any gaseous fuel that does not enter the flame will escape into the room air. For this reason, the mixing above the fire is only partially effective in a natural draft Rocket stove.

It is a useful construct for ARC designers to think of the air entering the Rocket stove under the sticks as primary, and that secondary air flows over the sticks. The role of primary air is the same as in a Top Lit Up Draft Stove (TLUD), to control the rate at which woodgas is made. The velocity and volume of primary air also controls how fast the made charcoal is consumed. Some charcoal under the burning sticks is beneficial when it helps to keep the wood burning. But when too much made charcoal builds up it can block the entry of primary air under the sticks and reduce the production of needed flame.

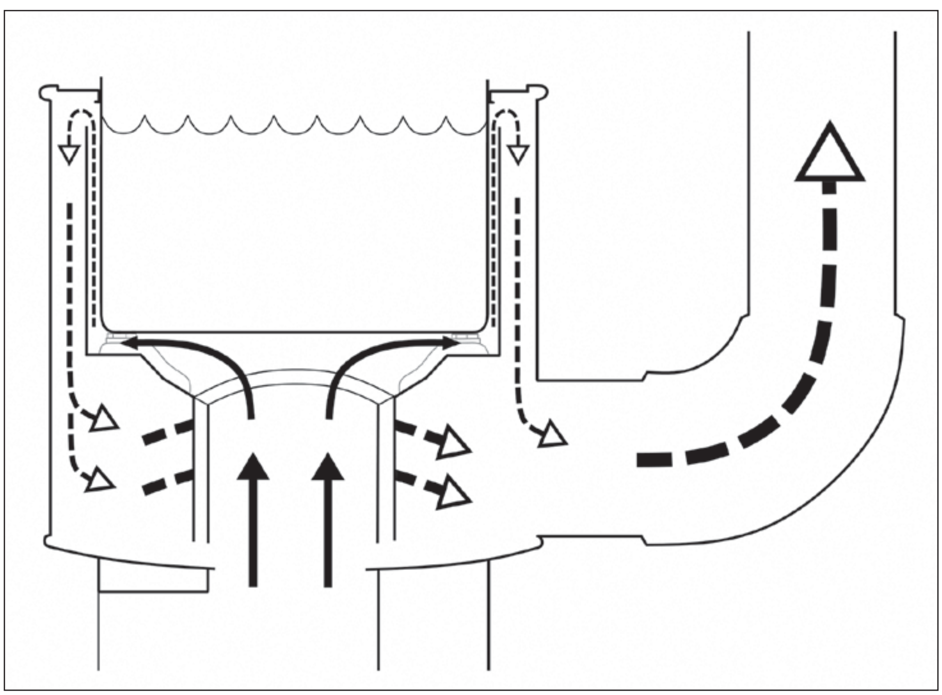
When the insulated short chimney in the Rocket combustion chamber is filled with flame, as in a TLUD, the woodgas has the greatest chance of being more completely consumed. Creating as much flame as possible with the least amount of woodgas is more likely to result in cleaner combustion.

Only the tips of the wood are burned and the amount of primary air is maintained to moderate the rate of reactions. Pushing a couple of centimeters of a wood stick into flame is unlikely to produce smoke. On the other hand, pushing a long length of a stick into a fire will almost certainly make smoke. In a two door Rocket stove, the lower door (primary air) needs to be almost completely closed to slow down the production of woodgas and to create a cleaner burning flame.

The secondary air flowing over the sticks of fuel supplies necessary oxygen to the fire and helps to facilitate mixing. By pushing the flame against the back wall, the secondary air helps to concentrate the flow of woodgas, flame, and air. In a Rocket stove, more complete mixing (with jets of forced air) can be used to create cleaner combustion. Natural draft does not create enough pressure or penetration to create jets of air that accomplish molecular mixing.

It can easily be imagined that cooks may not like lower firepower and a sunken pot. Burning four 1cm x 2cm sticks only produces 2.7kW of firepower, and cooks may want to boil the water faster. The cleaner burning Rocket stove is somewhat like a car that has a brick under the accelerator pedal. The car can only be driven at medium speed. Taking out the fence at the back of the combustion chamber allows for faster cooking but the added wood then makes extra gases and smoke that escape the fire as potentially harmful emissions.

Only one fitted pot seals into the hole on top of the stove. Cooks often want to use more than one pot! On the other hand, a sunken pot stove with close to 50% thermal efficiency boils 5 liters of water in about 15 minutes and can be attractive to cooks.



The hot gases flow next to the pot in a 6mm channel gap.

Testing this kind of stove in the project area is absolutely necessary. The Sunken Pot stove is like a Ferrari and cooks may need a pickup truck.

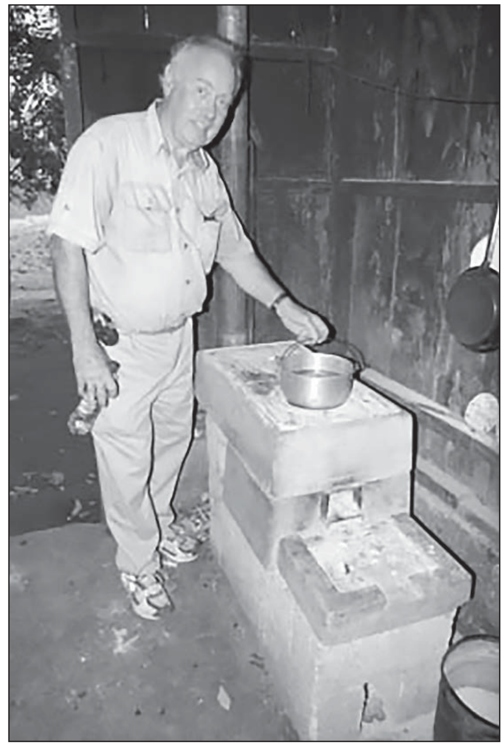
Stoves with Chimneys

Many long time colleagues like Don O'Neal (HELPS International) have suggested that ARC should only design stoves with chimneys that remove smoke from the room and are more likely to protect health. Adding a chimney to the Natural Draft Sunken Pot Rocket Stove does increase the complexity and the cost of the stove. However, an unvented stove can be expected to only partially lower emissions in a room, even when it is carefully operated.

The thermal efficiency in a sunken pot stove is close to optimal and the tight fitting pot and chimney reduce fugitive emissions into the room when the pot is in place. The auto-damper (Chapter 19) can be used to divert smoke and gases up the chimney when the pot is removed. A flat top version of the stove allows the use of many sized pots (pg. 100), but dramatically lowers heat transfer efficiency to around 25%.

Selling an unvented biomass stove in the USA for in-house use is illegal. Adding chimneys to ARC stoves makes a lot of sense and is necessary to protect health. Even with a chimney, the successful health intervention has to include scheduled maintenance to make sure that the chimney continues to be fully functional. ARC has been assisting stove projects since 1976. One certain observation is that maintenance is necessary for stove success. Stoves are not a "build and leave" product—we did that in our early years and came back to find that the stoves were no longer working. Providing continual training and maintenance is required to maintain the intended function and to ensure the efficacy of the intervention.

CAD drawings of the Natural Draft Sunken Pot Rocket Stove are found in Appendix A.



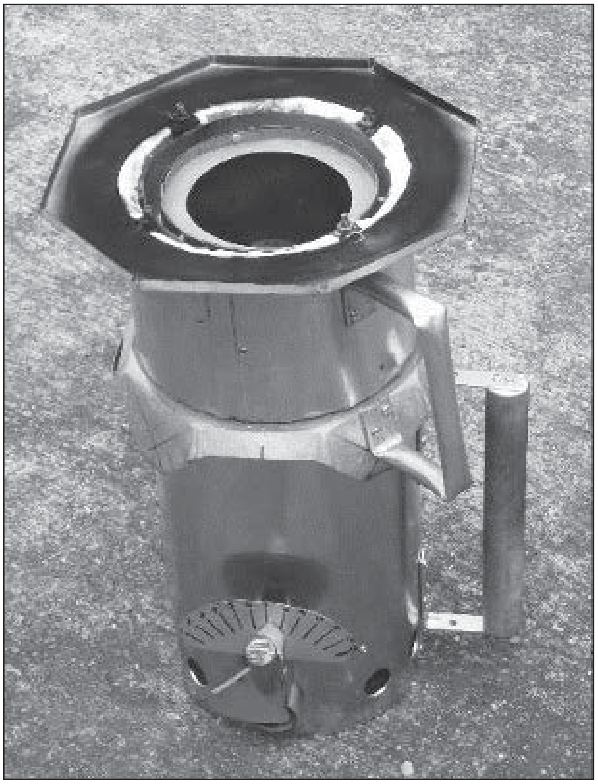
Don O'Neal, HELPS International, with the plancha stove that he designed.

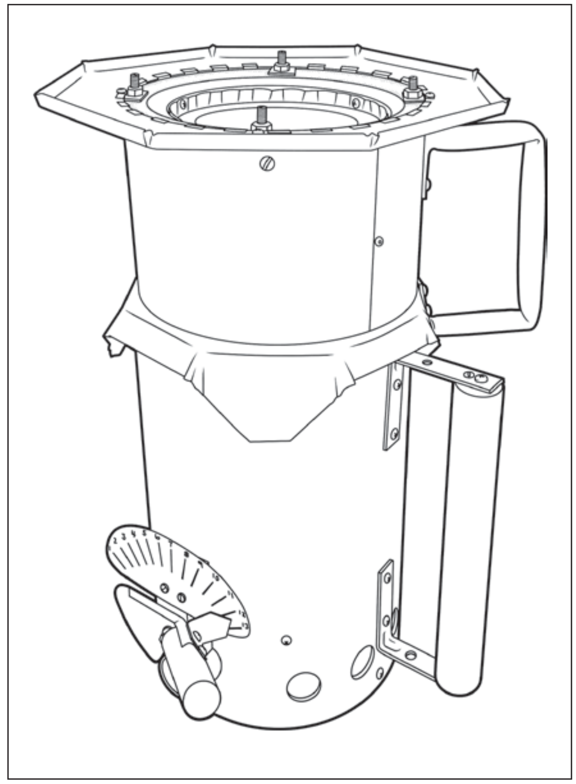
The flat top Rocket stove with chimney allows for the use of different sized pots.

Chapter 13

Kirk Harris Natural Draft Top Lit Up Draft (TLUD) Stove

High Power $PM_{2.5}$: 0.7mg/min @ 5.1kW   Low Power $PM_{2.5}$: 1.7 mg/min @ 1.8kW





In this TLUD, the primary combustion chamber is filled below the level of the secondary air holes with closely packed biomass pellets. An external lever controls the amount of primary air entering the combustion chamber through a valve. The secondary air is pre-heated, and increasing mixing is accomplished with static mixers.

CAD drawings are found in Appendix B.

Test Results

Stove type/model		Natural Draft TLUD		Average
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	45.2%	4%	4
Low Power Specific Consumption	MJ/min/L	0.023	10%	3
High Power CO	g/MJd	0.01	1004%	4
Low Power CO	g/min/L	0.01	33%	4
High Power PM	mg/MJd	8.0	16%	4
Low Power PM	mg/min/L	0.10	52%	4
Indoor Emissions CO	g/min	0.001	1041%	4
Indoor Emissions PM	mg/min	0.73	17%	4

Top Lit Up Draft Stoves

Dr. Tom Reed, Dr. Alexis Belonio, and Dr. Paul Anderson (left to right) have developed many of the Top Lit Up Draft stove designs.

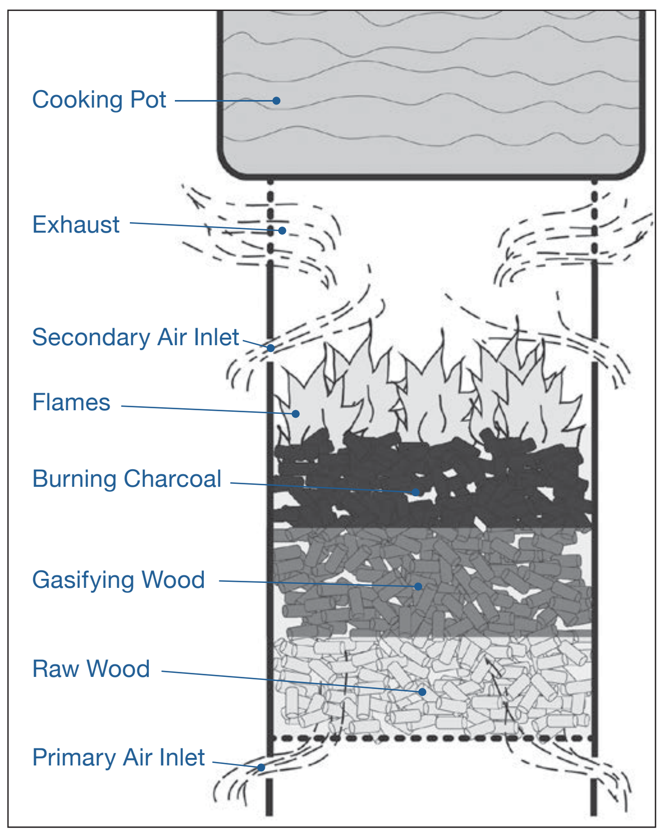
Gasifier stoves– where gas from solid fuels is made, transported, and then burned– have a long history including the early 1800's system that sent coal gas to the street lights in London. In 1985, Dr. Thomas Reed invented a natural draft variation intended for cooking food. In 1998, Dr. Reed began work on a smaller, forced draft model and marketed the successful WoodGas camp stoves. In 2015, the WoodGas stove was chosen as the "clean burning stove" in the Global Alliance for Clean Cookstoves round robin testing project.

Independently in the 1990's, Norwegian Paal Wendelbo developed the "Peko Pe," a natural draft TLUD cookstove in Uganda. Since 2001, Dr. Paul Anderson has been working with many experimenters in the United States and around the world as TLUDs have become more successful and popular. Dr. Ron Larson assisted Dr. Reed for decades and promotes the bio-char produced by the TLUD as a possible method to address climate change. Dr. Alexis Belonio has developed clean burning natural draft and forced draft top loaded stoves and is an expert in the combustion of rice hulls. Mr. Kirk Harris has recently created very clean burning, natural draft TLUDs with high and low power settings.

Dr. Reed's forced draft design has inspired similar stoves such as the Mimi Moto, British Petroleum Oorja, the Philips stove and others. The ARC Top Lit Forced Draft Stove in this book is based on his innovations (see Chapter 15). Like Dr. Larry Winiarski, Dr. Tom Reed has had a tremendous influence on stove work worldwide. Great ideas can take on a life of their own and talented and altruistic people like Dr. Reed and Dr. Winiarski have given these gifts to the world.

In a TLUD stove, a batch of biomass fuel is top lit so that the complete top of the fuel is on fire. The gases and smoke pass up through burning charcoal into the flame and combust. The woodgas enters into the zone of combustion supplied with secondary air and the flame is sustained. In a Rocket stove the woodgas only rises into flame. Passing first through a layer of burning charcoal helps to clean up combustion.

The amount of gaseous fuel, the shape of the flame, and the residence time in the flame can be adjusted by changes in the geometry of the TLUD. A mod-



In a TLUD, the woodgas passes through burning charcoal. Flame is sustained by secondary air entering into the fire.

ern TLUD usually consists of two parts: the fuel reactor that holds the fuel/initial combustion zone and the combustor unit in which more complete, secondary combustion occurs.

Located near the bottom of the fuel reactor, limited primary air controls the rate of combustion, determining the amount of made gas and the subsequent firepower. Over the top of the burning fuel bed, larger jets of secondary air or static mixers can force the well-mixed gaseous fuel and air into the flame for a long enough period of time for almost complete combustion to occur.

After the biomass (dry pellets of Douglas fir were used in the ARC experiments) has been burned, a bottom layer of charcoal is often left in the fuel reactor chamber. Charcoal (bio-char) can be created and then saved when the amount of primary air is insufficient to maintain combustion. Or if sufficient primary air enters the fuel reactor, the charcoal remains lit after the wood is consumed and can be used for cooking. A TLUD or Rocket stove can utilize the wood flame to boil (high power) and the made charcoal for simmering (low power) as a method for achieving efficient fuel use and adequate turn-down, especially when a lid covers the pot.

ARC Natural Draft Top Lit Up Draft Stove Design Observations

The ARC staff have been testing and developing TLUD stoves for many years. Dr. Tom Reed, Paal Wendelbo, Dr. Paul Anderson, Dr. Tom Larson, Art Donnelly, Kirk Harris, and others have spent time at the ARC lab working with the emission hoods to improve their TLUDs. Data from the survey of stoves that preceded the DOE stove iterative development project revealed that while TLUDs could be clean burning at high power (up to about 5Kw) the ability to lower firepower for efficient simmering was generally missing.

Kirk Harris worked on increasing the turn-down ratio in a clean burning TLUD for about two years. He brought the prototype stoves to the ARC lab and fine-tuned his approach. His Tier 4 TLUD is a combination of many factors. The firepower is controlled with limited primary air. The static devices in the combustor achieve very clean burning with thorough mixing. Kirk also added swirl that increased dwell time in the flames. Balancing the inputs to achieve clean combustion and lowered fuel use was a time consuming but obviously rewarding process.

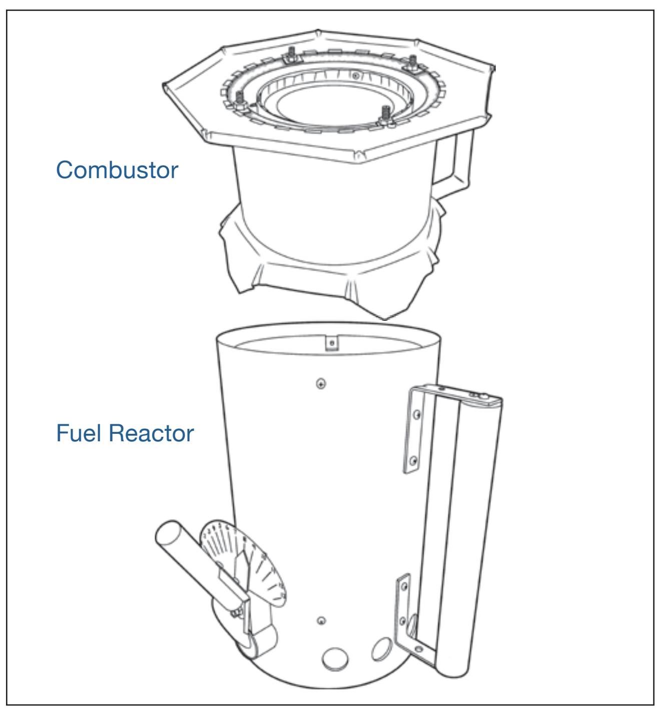
The following observations emerged from hundreds of tests of TLUD stoves under the LEMS emissions hood. They are impressions that are believed to be descriptive. At the same time, the investigation of TLUD technology continues at a rapid pace and the following observations are expected to evolve as experience accumulates.

- Lighting the entire upper layer of fuel at the same time is important and starts the clean burning process. The secondary air holes located above the fuel bed provide needed air to combust the gases and smoke. With enough force, the symmetrical jets of secondary air can create a “roof” of flame covering the fuel that controls the air/fuel ratio in the combustion chamber.
- The flame above the fuel bed can be directed to fill a constricted space so the gases and smoke are more likely to completely flow into the flame. A hole in a horizontal flat plate of metal above the secondary air holes seems to work well. Static mixers can serve the same purpose.
- The secondary air holes need to provide oxygen for combustion while imparting sufficient velocity to the air jets to cover the top of the fuel bed and mix the gaseous fuel, air, and flame. Increasing the amount of air and velocity of the jets of secondary air generally decreases emissions. This is an important technique used by ARC researchers when attempting to improve a TLUD. However, too much secondary air can decrease combustion and thermal efficiency by cooling the gases.
- Controlling the primary air with a damper that can close tightly against the bottom of the reactor chamber can effectively raise

and lower firepower. Decreasing primary air lowers the firepower and can reduce the emissions of smoke. Reducing the primary air and thereby slowing the reactions (rate of production of woodgas) is a successful method when tuning a TLUD.

- The width of the combustion chamber influences the firepower of the stove. As the diameter increases so does the potential firepower. Cylindrical fuel chambers 10cm to 12cm in diameter can create moderate power. Smaller diameter fuel chambers seem to be less likely to produce an excess of gaseous fuel which is then not completely combusted in the flame. The depth of the combustion chamber influences the length of burn.
- Pre-heating the secondary air helps to increase both combustion and heat transfer efficiency. However, experiments at ARC have shown that TLUDs without pre-heated secondary air can be clean burning.
- When insufficient primary air enters the fuel bed the flame can expire before all of the wood has been changed into charcoal, resulting in smoke. The clean transition from wood to charcoal burning requires sufficient primary air so that all the wood is burned out of the made charcoal. The maintained flame above the fuel has to be stable enough to switch from burning the gases made by the wood to the gases (mostly CO) made from the charcoal.
- When the fuel used in a TLUD is small, compact, and uniform, as with heating stove pellets, the bottom of the fuel magazine can be woven wire. The pellets are closely packed together preventing excess primary air from overly increasing the rate of reactions in the fuel bed. When the fuel load burns and decreases in height the increased amount of primary air can ensure that all of the wood is changed into charcoal before the transition from woodgas to charcoal gas occurs. Of course, the flame must be sustained through the transition.
- When the fuel size is larger and there are air holes between the pieces of fuel, limiting the primary air with a lever, as in the Harris stove, is necessary to control the rate of reactions. When too much gaseous fuel is created the measured emissions usually increase. Very little primary air seems to be required to maintain clean combustion.
- An effective enclosure around the combustion chamber may be needed to keep the wind from disturbing the flame. In areas with wind, the windscreen must be very protective. A little gust of wind can cause the TLUD to make smoke.
- When tuning a TLUD under the emissions hood, ARC designers generally reduce the primary air and increase the secondary air to determine if clean burning can be achieved. It seems to be easier to make low power TLUDs clean burning. Since even natural draft TLUDs can be very clean burning, ARC designers only trust gravimetric (pump and filter) measurements of $PM_{2.5}$. We only use gravimetric measurements for clean burning stoves.

The Kirk Harris Natural Draft TLUD Stove



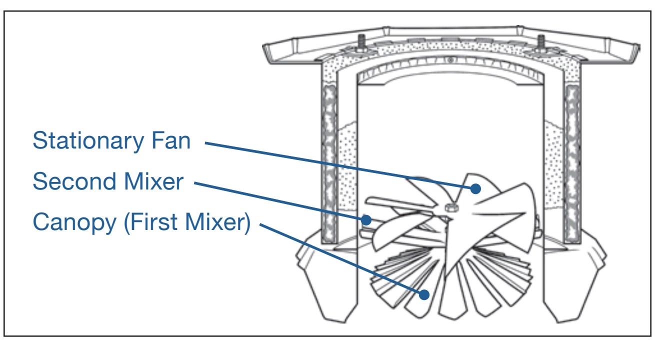
The Harris TLUD has two separate sections for ease of use.

Kirk Harris attended the Aprovecho Winter Open House in January of 2014. He brought a natural draft TLUD stove that had a limited turn-down ratio. When he returned to the 2014 Summer Stove Camp his new TLUD was improved in several ways. The stove was very clean burning and had impressive high power (5kW) and low power (1.7kW). His next iteration was developed at the Aprovecho lab and was tested at the Lawrence Berkley National Burn Lab.

The Layout of the Stove

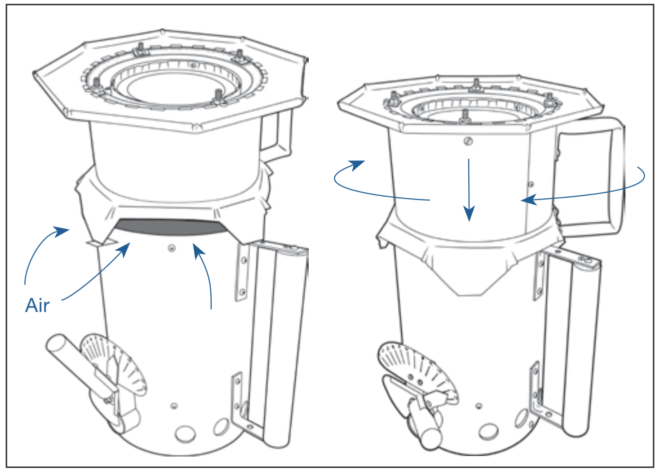
The stove has two separate sections, the fuel reactor which is the bottom section that holds the fuel and primary air control, and the combustor, the top section that enhances mixing the gases and increases combustion time. Removing the combustor section allows access to clean and fill the fuel reactor chamber.

Several devices that enhance combustion are attached to the bottom of the combustor and held above the fuel reactor chamber. These include the Canopy (first mixer), that mixes the woodgas with the secondary air, a Second Mixer which adds more secondary air after the flame has burned for a time, and a Stationary Fan that spins the gases. The Canopy also assists the stove's turn-down capability by blocking secondary air from falling into the fuel reactor chamber.



Start Up

The fuel reactor chamber is loaded with fuel and the fire is lit at the top. Once the fire is started, the Combustor is placed on short legs above the base. The openings between the legs allows air to feed the new flame from above, keeping it burning. After one to two minutes, the fuel begins gasifying and the flame moves up to the secondary burner. The Combustor is then rotated to align the legs with openings in the base, and lowered to its operating position. If the Combustor is put into the operating position immediately, the Canopy will block the air from reaching the new flame and it will be starved of air and extinguished. The raised position also makes use of the new flame to preheat the Combustor.

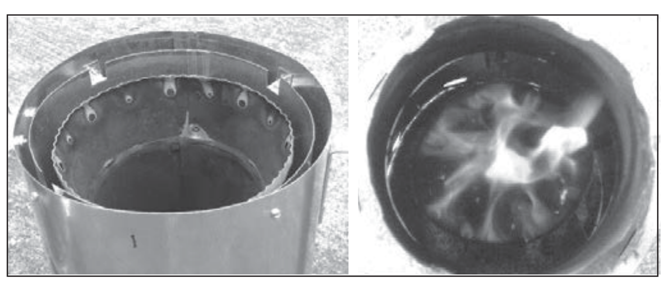


At start up, the Combustor is raised to allow air in (L), then rotated and lowered for operation (R).

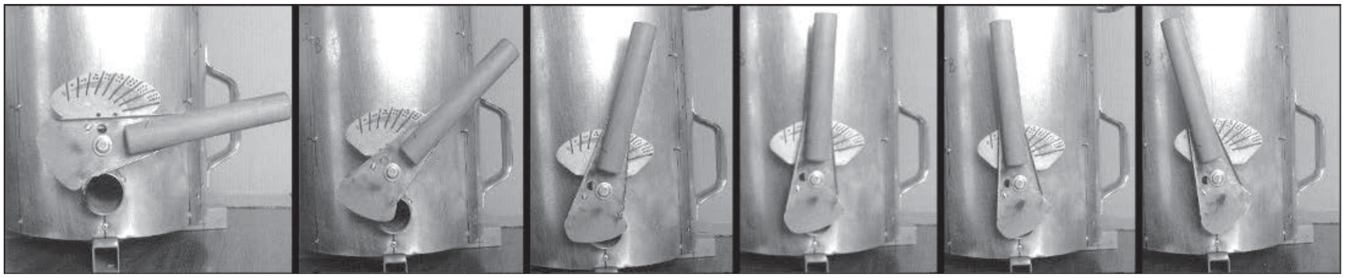
Power Level Adjustment

The stove has a turn-down ratio of about 3 to 1. The power level is controlled by the primary air valve that is adjusted by a hand lever. The valve is designed to adjust the primary air quickly as the lever is moved at high power and more slowly with an equal lever movement at low power. This function is designed to give the cook enhanced control at all power levels (see photos, next page).

Turn-down is enabled by a line of pilot flame holes located just below the secondary burn area. At low power levels the pilot flames maintain flame presence and heat by mixing a small amount of air into the woodgas. Without the pilot flames the sec-



Pilot flame holes help sustain flame during turn-down.



The hand lever adjusts primary air flow.

ondary flame would be diluted, cooled, and extinguished by excessive secondary air.

Adjusting the secondary air has no effect on the performance of the stove. For this reason, the stove has no secondary air control.

Mixing and Burning

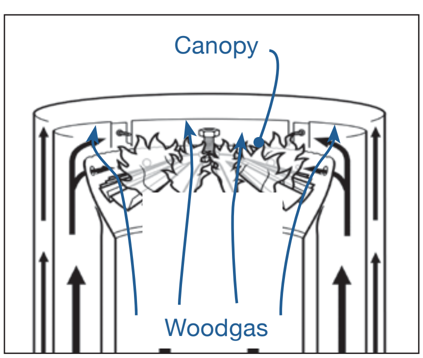
Pre-heated secondary air meets the woodgas at the top edge of the fuel reactor chamber. The widened chamber top with fluted edge is intended to give the gas and air more surface contact for rapid mixing. The Canopy, which covers the center of the fuel reactor chamber, forces the rising column of woodgas outward to meet the air. The Canopy has radial slits, and as woodgas comes up through the slits it is formed into sheets which push into the air and flame above. This forms ridges of flame as the air surrounds the gas sheets from both sides. The combination of a widened fluted chamber edge and the Canopy with its slits provides considerable surface contact between the woodgas and air.

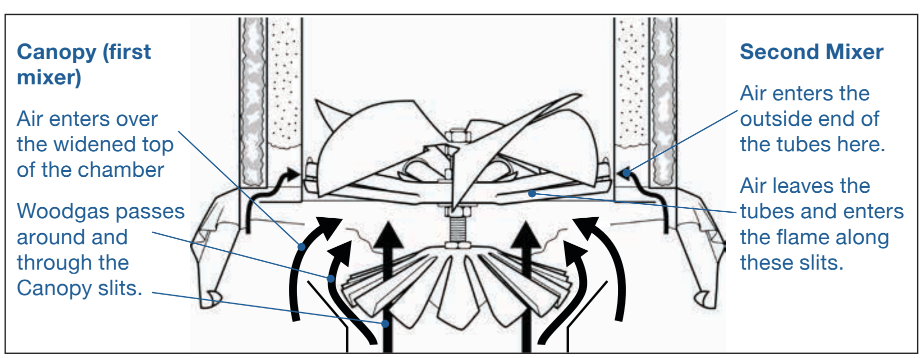
The secondary mixing technique makes use of the pressure difference between the air and woodgas created by the buoyant force of the lighter woodgas and enhanced by the Venturi effect. The woodgas passes around the Canopy (First Mixer) and through its slits. The total open space around and through the Canopy adds up to half the area of the fuel chamber. Because this is a constriction, the woodgas must accelerate as it passes, creating a drop of pressure. The resulting difference in pressure helps push the woodgas and air together. The enhanced pressure difference combined with the large surface contact mixes the woodgas and air.

Another static mixer (Second Mixer) also forces air into the flame. It consists of six tubes positioned radially in the flame path. The outside ends of these tubes are outside of the combustion chamber. Air enters through the open outer ends, travels into the combustion chamber through the tubes, and is injected into the flame through slits along the sides of the tubes. It also uses pressure differences enhanced by the Venturi effect, which is created as the flame gases accelerate around the tubes.

Combustion Time

Woodgas is very dirty because in addition to the easily burned gases it contains hard-to-burn carbon particles and long chain hydrocarbons. For clean burning, the stove relies on combusting the easily burned gases first (carbon monoxide, hydrogen, methane). This flame is given some time to burn, heating and cracking the long chain hydrocarbons and carbon particles. After this initial burn time, more air is added at the second mixer to combust the more easily burned gases and particulates. After



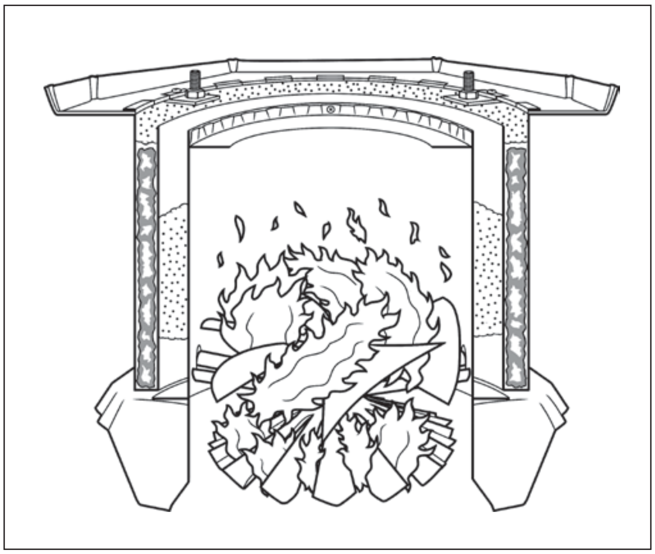


the mixers, the flame enters a stationary fan blade that spins it. This forces the flame up the Combustor chamber into a spiral path that is longer than a direct path, giving it more residence time to burn.

Keeping the Flame Hot

The walls of the stove are insulated to keep them hot and to radiate heat back into the flame. Openings or materials that conduct heat out the side of the stove have been minimized to bring the maximum amount of heat to the cooking vessel.

Spinning the flame at the stationary fan compresses the flame and concentrates its heat, assisting more complete combustion. If unburned gases touch the cooking vessel and cool to below the required combustion temperature, soot and smoke can form creating emissions and wasting fuel. The stove design is intended to keep the flame hot and to fully burn the gases before they reach the cooking vessel.



The Stationary Fan spins the flame to add residence time.

Flow Resistance

A low-power flame seems to be more sensitive to flow resistance than a high-power flame, so the flow resistance through the stove cannot be more than the low-power flame can overcome. This is very important for this stove which places several elements in the flame path: the Canopy, the radial mixing tubes, the stationary fan, and the cooking vessel. Each of these elements is designed to minimize its contribution to flow resistance.

Design Summary

- A primary air control provides the cook with control of the power level.
- Pilot flames and the Canopy support a low-power flame, enabling effective turn-down.
- A widened and fluted top edge on the fuel reactor chamber increases surface contact between the air and woodgas for rapid mixing and burning.
- A canopy device also forces the woodgas outward to meet the air and forms it into sheets for more effective mixing. The Canopy also helps with turn-down.
- A second mixer is designed to burn the hydrocarbons and carbon particulates cracked by the heat of the initial flame.
- Insulation helps to keep heat from leaking out of the sides of the stove, keep the flame hot, maintain a clean burn, and deliver as much of the heat as possible to the cooking vessel.
- A stationary fan blade spins the flame into a spiral path for longer dwell time and to contain the heat of the flame for cleaner burning.
- The static mixers were designed to minimize flow resistance.

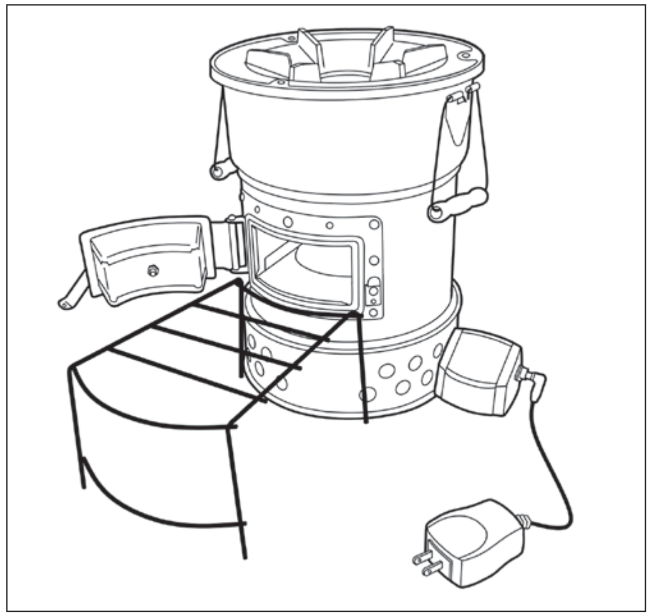
CAD drawings of the Harris Natural Draft TLUD are found in Appendix B.

Kirk Harris with two TLUD stoves.

Chapter 14

Side Feed Bottom Air Forced Draft Rocket Stove

High Power $PM_{2.5}$: 4.5mg/min @ 3.3kW Low Power $PM_{2.5}$: 3.8 mg/min @ 1.4kW



In this Forced Draft Rocket stove, the sticks are pushed horizontally into the fire as they are consumed. Adding forced draft to the Rocket stove accomplishes better mixing of gases, flame, smoke, and air. A chimney was added to comply with new WHO standards. This stove was the inspiration for the SSM Jet-Flame that functions in the same ways (see Chapter 17).

CAD drawings are found in Appendix C.

Test Results

Stove type/model Location		Side Feed Forced Draft		Average Tier
		Average	COV	
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.1%	4%	4
Low Power Specific Consumption	MJ/min/L	0.010	8%	4
High Power CO	g/MJ_d	1.76	30%	4
Low Power CO	g/min/L	0.01	24%	4
High Power PM	mg/MJ_d	47.2	53%	3
Low Power PM	mg/min/L	0.47	48%	4
Indoor Emissions CO	g/min	0.16	22%	4
Indoor Emissions PM	mg/min	4.5	57%	3

Andy McClean Worked With Mr. Shen to Develop The Stove

Andy McClean developed the Side Feed Forced Draft Rocket Stove at ARC with Dean Still and worked with Mr. Shen at Shengzhou Stove Manufacturer to build the various prototypes.

The Side Feed Bottom Air Forced Draft Rocket Stove follows the same feed pattern used in a Three Stone Fire and in most traditional stoves. The sticks are pushed horizontally into the fire. The made charcoal falls beneath the sticks and helps to keep the sticks lit by radiation. Adding forced draft to the Rocket stove accomplishes better mixing of gases, flame, smoke, and air. A fan pushes forceful jets of primary air into the burning fuel from underneath the floor of the combustion chamber. Temperatures in the combustion chamber rise dramatically. The natural draft of the fire and the upwards motion of the jets of air direct the fire up the Rocket's short insulated chimney that leads to the pot.

Experiments with Secondary Air

ARC researchers first tried to add jets of secondary air into the side of the flame in the vertical section of the Rocket combustion chamber. Generally, the approach to side feed forced draft stoves has followed this secondary air technique invented by Dr. Tom Reed for his WoodGas stove, a forced draft TLUD with air jets above the fuel bed but blowing into the flame (see pg. 87). ARC researcher Mark Witt started working on a side feed fan stove with added jets of forced draft into the side of the flame in 2005. In 2009, ARC Lab Manager Nordica MacCarty worked on a single jet approach that swirled the air above the burning sticks of wood. Several side feed fan stove prototypes with jets of secondary air were shown at the annual ETHOS (Engineers in Technical and Humanitarian Opportunities of Service) conference over the years.

However, when these prototype stoves were tested under the LEMS emissions hood the results were generally disappointing. Researchers at UC Berkeley experimented with air jets aimed above the fuel (Caubel et al., 2018). A University of Washington team found that it was most successful to have the jets meet in the middle of the flame using the minimal volume and velocity of air (Udesen, 2019). When the jets of air are too strong back drafting out of the open fuel door in a Rocket stove occurs. Too much air also cools the fire reducing, combustion and heat transfer efficiency.

There are industrial burners that position jets of primary air underneath the fuel bed to clean up combustion. Both Underfeed Stokers and Fluidized Bed Boilers use primary air that enters the fuel bed from underneath the fire. Underfeed Stokers push the fuel (and forceful jets of air) into the bottom of the fuel bed where heat creates burnable gases and combusts them. The fuel is located over a grate where it is exposed to air and radiant heat from the made charcoal. Underfeed Stokers supply both fuel and primary combustion air from beneath the grate assuring that the top of the fuel pile is not cooled by secondary air.

Fluidized Bed Boilers are a recent type of combustion chamber developed for the clean burning of biomass. The flow of air and fuel to the fuel bed is controlled so that the temperature stays constant. Excess air is needed to achieve close to complete combustion even though the above-stoichiometric levels of air decrease the heat transfer efficiency.

Jets of secondary air can also be used above the fuel bed in Underfeed Stokers and Fluidized Bed Boilers to further improve combustion efficiency.

The technique of using jets of bottom-air-only has been used in cookstoves. In 2007, ARC tested the bottom-air-only Wood Flame stove made in Canada. In the Wood Flame stove high velocity jets of primary air shoot up into the burning wood. The stove was very clean burning and its performance was comparable to Dr. Reed's WoodGas TLUD stove (Still et al., 2014). The test results are included in "Test Results of Cook Stove Performance" that includes detailed comparisons of performance and emissions in eighteen cookstoves. (Available at www.aprovecho.org.)

In 2013, with DOE funding, ARC built the bottom-air-only stove and has been experimenting with improving the technique, resulting recently in the SSM Jet-Flame accessory manufactured by SSM in China (Chapter 17). There are several advantages in a bottom-air-only approach. The jets of air are directed into the fuel bed from holes in the floor of the combustion chamber. Since the pre-heated air flows vertically, back-drafting out of the fuel door is not difficult to overcome. The increased velocity of the higher temperature flue gases also improves heat transfer efficiency.

Adjusting Firepower

The Side Feed Bottom Air Forced Draft Stove can reduce firepower to simmer food just like a natural draft Rocket stove by pushing fewer sticks into the combustion chamber. The side feed stove can simmer water at 97°C using two 1cm x 2cm sticks. In a forced draft Rocket stove, the velocity of the jets of air should be decreased when the fire is smaller. The Jet-Flame reduces the volume and velocity of air for low power operation. Injecting too much air cools the combustion chamber and eliminates the made charcoal needed for hotter and more complete combustion of the sticks of wood.

The fan speed has an effect on firepower, but it is not as determinant as the number of sticks or the length of the burning portion of the sticks. Feeding four 1cm x 2cm sticks at about 2.5cm per minute into the stove creates approximately 3kW of firepower. Only the tips of the wood, about 8cm long, are allowed to combust.

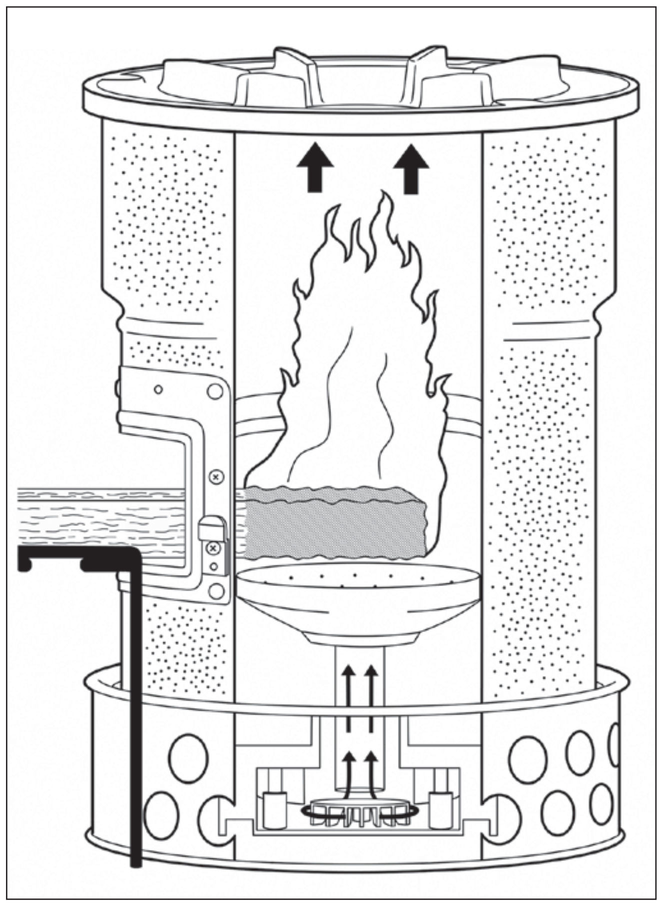
Fuel Chamber Considerations

For cleanest burning, the sticks need to be close to or touch the made charcoal where the air is injected. Locating the sticks very close to the made charcoal also makes it easier to sustain the fire. The small jets of air disperse quickly and the mixing effect is diminished about 12cm above the burning sticks.

A large fuel-feeding door causes excessive heat loss to the environment through radiative heat transfer, so a smaller 5cm high door was chosen for this reason. Unfortunately, a decreased door height makes it more difficult to see the fire and to know when to add more sticks of fuel.

Side Feed Under Air Design Details

Forced air jets blow up into the charcoal and wood fire through small holes located in the floor of



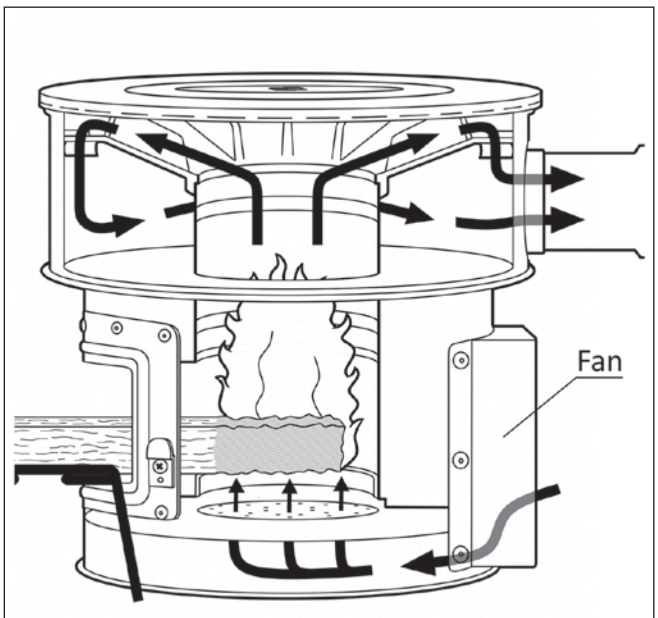
A fan blows forceful jets of air up into the combustion chamber. Only the tips of the wood are burning. The powerful jets of air create a zone of mixing above the floor of the combustion chamber.

the combustion chamber. The 30 air holes in the Jet-Flame have a diameter of 2mm and create 50 standard liters of air per minute at a pressure of 0.75 inches of water column. At lower power 20-30 standard liters of air per minute are a good match for cleaning up the smaller fire.

The fuel door in the Side Feed Bottom Air Forced Draft Stove is 5cm high and 10cm wide. The base plate with the air holes is made of a high quality refractory metal such as FeCrAl or FeCrSi. The combustion chamber is insulated with 0.7grams per cubic centimeter refractory ceramic.

The Rocket insulated short chimney above the fire helps to pull the fire upwards and is needed to keep the high velocity gases from back drafting out of the open fuel door. A chimney was added to the stove to help protect health and to comply with guidance from the WHO. A flat top with chimney approach and a sunken pot with chimney design were developed for this stove.

Secondary air directed into the fire could be added in the vertical portion of the Rocket combustion chamber. The extra mixing might support cleaner combustion, if it did not reduce temperatures below our estimation of 900°C. A narrowing cone shaped combustion chamber with secondary air jets at various points along the side was tested. Several prototypes were constructed. However, the additional jets lowered heat transfer efficiency and in these tests did not improve the emissions of $PM_{2.5}$ or CO. Further testing is needed.



A flat top version allows the use of a chimney but reduces thermal efficiency.

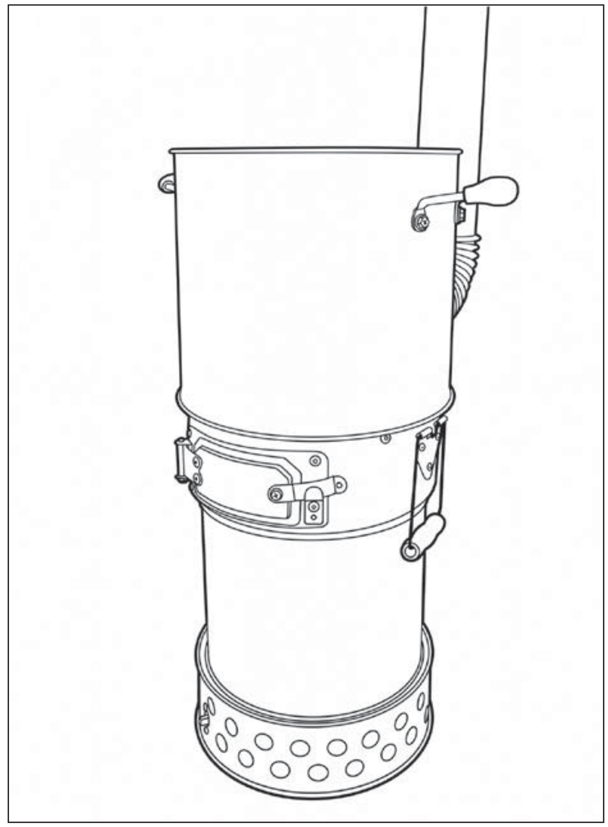
CAD drawings of the Side Feed Forced Draft Rocket Stove are found in Appendix C.

Chapter 15

Top Lit Forced Draft Stove

High Power $PM_{2.5}$: 3.9mg/min @ 4.1kW Low Power $PM_{2.5}$: 0.3mg/min @ .93kW

The fan blows jets of primary air into the bottom of the batch loaded fuel and secondary air jets into the flame in the combustion chamber. A door located below the pot support facilitates the metering of fuel.



CAD drawings are found in Appendix D.

Test Results

Stove type/model Location		Top Loaded Forced Draft		Average Tier
IWA Performance Metrics	**units**	Average	COV	
High Power Thermal Efficiency	%	42.7%	9%	3
Low Power Specific Consumption	MJ/min/L	0.010	25%	4
High Power CO	g/MJ_d	0.35	34%	4
Low Power CO	g/min/L	0.04	4%	4
High Power PM	mg/MJ_d	37.4	26%	4
Low Power PM	mg/min/L	0.06	104%	4
Indoor Emissions CO	g/min	0.22	5%	4
Indoor Emissions PM	mg/min	3.9	25%	3

Dr. Tom Reed's WoodGas stove is adapted by ARC

Dr. Tom Reed, going strong at 89, enlightens the ARC 2015 Winter Open House.

Dr. Tom Reed and Dr. Ronal Larson in "*A Wood-Gas Stove for Developing Countries*" (Reed and Larson, 1996) point out that cooking with natural gas is often preferred by cooks but they remind the reader that gas can also be made from wood and burned in the same manner as other gases. In the paper they describe a natural draft "inverted downdraft gasifier" cookstove that makes and burns woodgas. Dr. Reed added a fan to that stove, which further decreased emissions. High velocity jets of secondary air positioned above the fuel bed shoot into the flame increasing the mixing of gases, smoke, air, and flame, resulting in close to complete combustion. The amount of primary and secondary air are controlled by a two speed fan.

Learning From The WoodGas Stove

ARC copied many of these TLUD inventions in the Top Lit Forced Draft Stove. The batch of fuel is lit on top and forms a layer of charcoal under the flame. Wood gas is created in and under the hot charcoal layer. When the top of the fuel bed is covered with flame all of the made woodgas rises through the charcoal into the flame. As the fuel bed is consumed and lowered, the flame, which is sustained by the jets of secondary air, is further from the fuel bed. This amount of separation does not occur in a Rocket stove. In a Rocket stove the flame is right above the burning sticks of wood.

The WoodGas forced draft stove could be purchased in various sizes. The largest version was intended for family sized cooking. The cook places the needed amount of fuel to complete the cooking task in the combustion chamber. In a TLUD the remaining made charcoal (bio-char) can be extinguished for later use, or by letting more primary air enter the bottom of the combustion chamber, the charcoal can be used for continued cooking. Bio-char is a garden supplement and can be a source of stored carbon. Using the made charcoal for the simmering portion of the cooking task reduces the fuel used to cook food and can provide the turn-down ability needed for fuel efficient simmering.

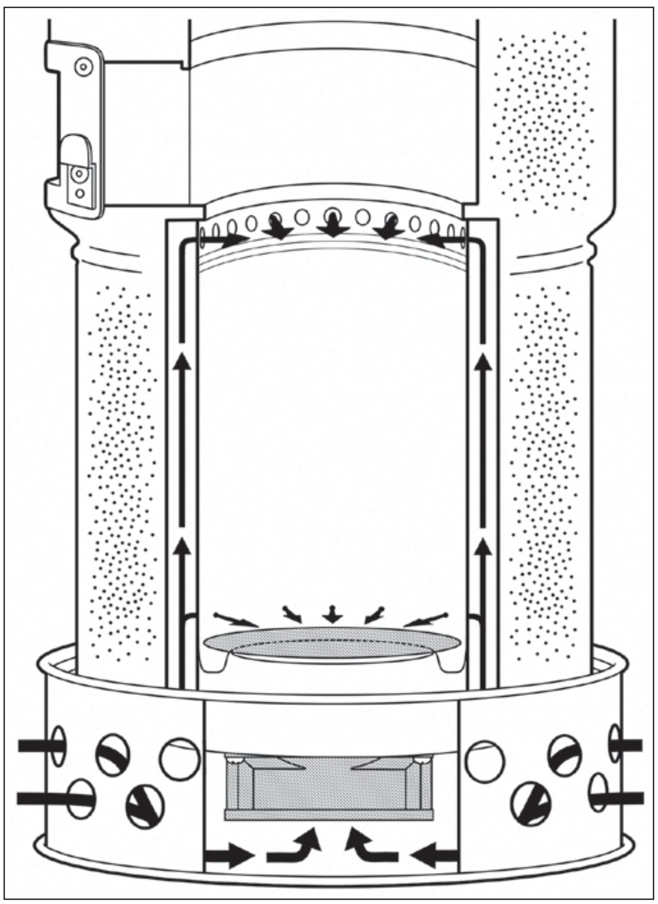
In the ARC stove survey, the Reed WoodGas stove was tested and it was impressively clean burning at high power, but it could not simmer water at 97°C unless small bits of wood were slid under the pot

The WoodGas forced draft stove was fuel efficient and clean burning at high power in tests under the emissions hood.

into the combustion chamber. The stove was further developed by ARC researchers using the iterative design process. A more stable base, a fuel door, handles, and a Winiarski constant cross sectional stove top were added to Dr. Reed's stove concept. The fuel door allows for small chunks of wood to be added more easily during the simmering phase.

The Reed WoodGas stove was tested (only at high power) in the Global Alliance 2015 Round Robin testing. When tested at ARC the score of 2.03mg/min for $PM_{2.5}$ was impressively low. Perhaps when wood pellets are used in real world cooking the results might be similar to lab data? The same fuel is top lit and the variables involved in feeding fuel are diminished. ARC will investigate if the use of pellets results in more predictable in-field emissions.

The ARC version of the Reed stove is 29cm high with an external diameter of 15cm. The combustion chamber is 13.5cm high with an inner diameter of 13cm. The cast iron stove top is 26cm in diameter. A 10cm x 10cm computer fan is powered by grid generated electrical power. The fan blows air up a narrow channel, then through ten 2mm holes around the perimeter near the bottom of the combustion chamber and through thirty 4mm holes near the top of the combustion chamber.



Dr. Reed's invention has inspired stove designers around the world. ARC added a fuel door and adjusted the velocity and volume of primary and secondary air to clean up the combustion of added fuel at low power.

Improving Fuel Efficiency During Turndown

As in other TLUD batch fed stoves, adding too much fuel during the simmering phase resulted in smoke. Just turning down the fan speed does not decrease the primary air enough to sufficiently lower firepower. The excess steam production in the cooking pot when operated at high power coupled with the higher fuel use lowered the IWA low power scores. The low power IWA emission metrics are based on the amount of CO and $PM_{2.5}$ made per minute per liter of water, so losing water by making excess steam also lowered the emissions scores.

ARC developed two ways to improve fuel use when simmering with batch fed TLUD stoves. The initial batch of fuel can be measured to just bring the water to boil. Then chunks of wood can be slowly metered into the made charcoal in the bottom of the combustion chamber. The second method is to use more fuel to start with and then burn the made-charcoal during the simmering phase.

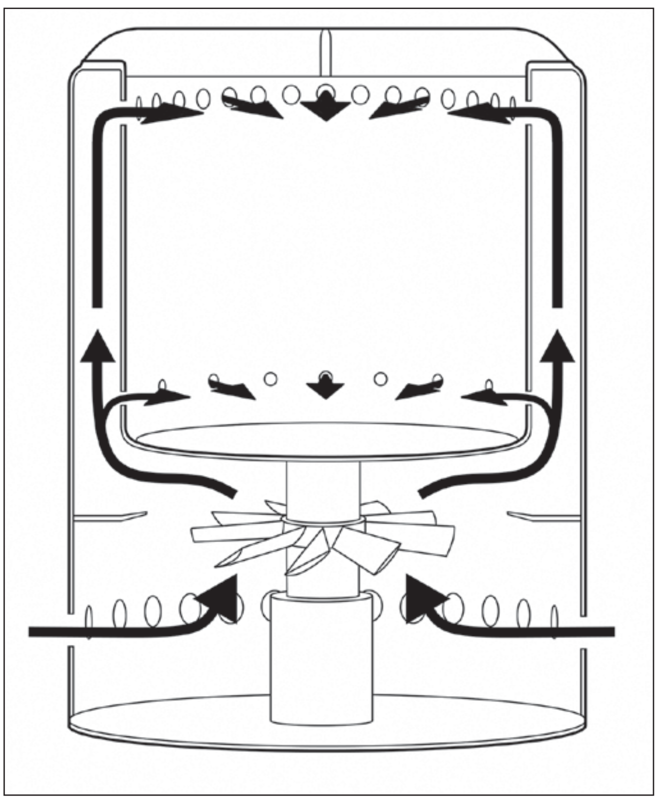
Learning From TLUD Stoves

Several of the TLUD stoves in the DOE survey scored well on the IWA metrics for high power operation. Most of the high power scores in the initial stove survey (Chapter 9) were in the Tier 3 to 4 range. The Philips forced draft stove and the British Petroleum forced draft Oorja scores are similar to the Reed stove.

The Philips stove was developed by Dr. Paul van der Sluis for the Philips Company at their research lab in Eindhoven, The Netherlands. The fan, attached to the bottom of the stove, forces preheated air through nine 2cm diameter holes at the bottom of the 11cm diameter by 14.5cm deep combustion chamber and through twenty-seven 2cm holes near the top. Ceramic plates protect the steel inside the combustion chamber from the damaging heat and flame. The stove is plugged into the wall and a small battery is charged.

The Oorja fan stove was created by Dr. H. S. Mukunda for the British Petroleum Company and features a high mass cast refractory cement combustion chamber. The cast combustion chamber seems to be long lasting and inexpensive. British Petroleum manufactured many of these stoves which were sold in India.

The Reddy Enterprises stove, also made in India, is an example of an easy to construct type of forced draft stove. A computer fan (8cm x 8cm) blows room air into the large plenum created between a sheet metal combustion chamber and the inside of the sealed stove body. The plenum pressurizes the air, which then enters the combustion chamber at a high velocity through smaller holes close to the bottom (primary air) and larger holes around the perimeter near the top (secondary air) of the combustion chamber.



A small amount of primary air enters the combustion chamber of the WoodGas stove to control the rate of production of wood gas. Forceful jets of pre-heated secondary air create a zone of mixing above the fuel bed.

Placing the fan directly on the side of the Reddy stove exposes it to the heat from the combustion chamber. ARC researchers inserted insulation (aluminum foil and ceramic fiber) between the fan and combustion chamber. The best levels of emissions performance were achieved with the fan at high power. When operated as a batch stove the Reddy, like other TLUD stoves, was unable to turn down the firepower resulting in higher than necessary fuel use at low power.

The simplicity of the Reddy stove is interesting. The large plenum does not seem to negatively influence the effectiveness of the forced draft. ARC researchers were pleasantly surprised that large plenums could be used in fan stoves. Manufacturing a low cost Reddy type stove with a refractory cement combustion chamber seems to be an interesting possibility.

ARC's TLUD Iterations

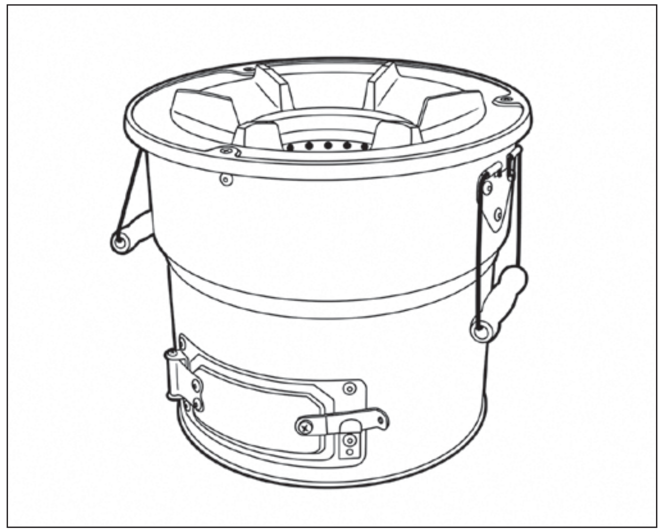
The added fuel door in the ARC stove makes metering added fuel easier for cooks. In the Philips, WoodGas, Reddy, and Oorja stoves, the pieces of metered fuel are fed in the small space under the pot which seems a bit awkward. Having to feed the fuel under the pot also encourages taller pot supports which decrease heat transfer efficiency. A chimney was eventually added to the Top Lit Forced Draft Stove to comply with the WHO indoor air guidelines.

CAD drawings of the Top Lit Forced Draft Stove are found in Appendix D.

Chapter 16

Charcoal Stove

High Power $PM_{2.5}$: 1.8mg/min @ 2.3kW Low Power $PM_{2.5}$: 0.1mg/min @ .28kW



The ARC charcoal stove has an air tight door to control primary air. Very little air is required for simmering. The combustion chamber is made from a cylinder of refractory metal. Secondary air rises in an annulus and jets of pre-heated air create a zone of mixing above the fuel bed. The stove is very well insulated which raises temperatures quickly above the auto-ignition temperature of CO in the combustion chamber.

CAD drawings are found in Appendix E.

Test Results

Stove type/model		Charcoal		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.0%	4%	4
Low Power Specific Consumption	MJ/min/L	0.002	10%	4
High Power CO	g/MJ_d	6.35	19%	4
Low Power CO	g/min/L	0.01	11%	4
High Power PM	mg/MJ_d	28.2	54%	4
Low Power PM	mg/min/L	0.01	6%	4
Indoor Emissions CO	g/min	0.41	25%	4
Indoor Emissions PM	mg/min	1.8	58%	4

The ARC team develops an efficient charcoal stove

Ryan Thompson and Sam Bentson improved the emissions equipment and many types of stoves, including the Charcoal Stove.

Approximately 7,000 years ago, charcoal fires, which can produce higher temperatures than wood, were used to smelt copper. Burning charcoal also made the production of iron and glass possible. Copper can be melted at around 800˚C but to create bronze requires temperatures close to 1100˚C. Fanning charcoal, adding manually forced air to increase the rate of burn, made the Bronze Age possible. Blowing jets of air into the made charcoal under burning wood also enables the SSM Jet-Flame (Chapter 17) to elevate temperatures above 900°C, which is needed to effectively combust particulate matter with limited residence time.

Charcoal Pros and Cons

When wood is combusted in a pit in the ground with loose earth piled on top of it, most of the oxygen is kept out of the combustion process and charcoal is produced. The volatile compounds in the wood such as water, methane, hydrogen, and tar escape as smoke and gas. Making smoke free charcoal, in which all the volatile gases and bits of wood have been removed, is temperature dependent. Wood turns into brown and soft charcoal at lower temperatures (around 300˚C) but when it is made at higher temperatures charcoal is cleaner burning, black, and hard.

Brown charcoal is easy to light but black charcoal requires more fanning and larger amounts of starter. Black, smoke free charcoal is mostly pure carbon. In well-made charcoal only approximately 25% by weight of the original biomass remains. Burning off the volatile compounds consumes and wastes between 50% and 80% of the energy in the wood. Making charcoal is a very energy inefficient process (Aprovecho Institute, 1984a).

When charcoal is lit, the carbon combines with oxygen and forms CO_2, CO, water, and other gases. Although most of the energy is lost when making charcoal, the end product is higher in energy by weight. Charcoal contains about 32 MJ/kg while wood has around 20 MJ/kg. Pure carbon charcoal burns steadily without much tending, and can produce almost no smoke but charcoal emits a lot more potentially harmful CO compared to wood.

Charcoal is generally an urban fuel produced by rural workers. Although it has been referred to as "an energy source for the poor" (Wood and Baldwin, 1985) current use by higher income urban populations seems to place charcoal above wood on an energy ladder. Wood is generally preferred by rural populations.

Charcoal is a complicated fuel. It emits a lot of CO but, if it is well made, almost no smoke. When rural workers cut down trees and transform them into charcoal in a pit, the smoke pollutes the rural environment. The charcoal has had most of the smoke removed in the countryside, making a higher quality, low $PM_{2.5}$ fuel for urban cooks. Rural entrepreneurs can make money producing the cleaner burning fuel, transporting it to town and selling it. It can be imagined that, while indoor air in urban cities stays cleaner, the outside air in forests gets smokier. Health may be protected in the one environment while it is damaged in the other. How the charcoal is started in large part determines how much smoke is emitted from a charcoal stove. If wood is burnt on top of charcoal to start it, the result is very smoky.

Starting a coal burning stove can have the same problem. In China, coal is made into round honeycomb briquettes with vertical holes that are lined up as multiple pucks of fuel are used for cooking. Electric starting devices that light the briquettes with little production of smoke are now commonly used. Honeycomb briquettes made from charcoal have also been manufactured in South Africa.

Dr. Rob Bailis pointed out in his doctoral dissertation “Fuel from the Savannah: the Social and Environmental Implications of the Charcoal Trade in sub-Saharan Africa” that charcoal burns with low emissions of particulate matter (Bailis, 2005). Different charcoal stoves operated by amateur cooks at an ARC Summer Stove Camp in 2010 frequently scored in the Tier 4 ranges for $PM_{2.5}$ at high and low power.

After testing many charcoal stoves, the ARC staff can appreciate the affection that cooks have for charcoal. The cook can leave the pot and attend to other work. Such multi-tasking is not possible when using a wood burning stove as it requires almost constant attention. Batch loaded stoves such as charcoal, coal, and TLUD stoves assist the cook with relatively constant heat and a greater degree of freedom.

Improving the Charcoal Stove

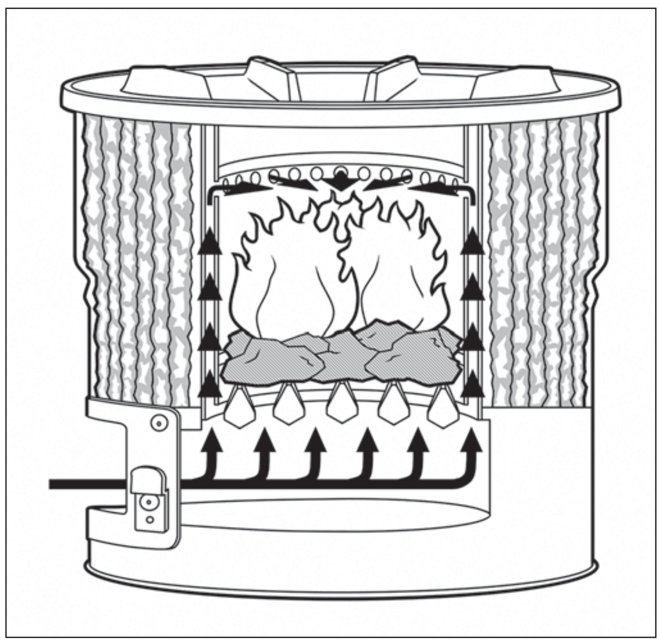
In *“Improving the Charcoal Stove for Haiti,”* Christa Roth and Christoph Messinger point out requirements for an improved charcoal stove (Roth and Messinger, 2010):

- The need for a high turn-down ratio.
- Reduce heat losses through the bottom and the sides of the stove.
- Maximize heat transfer to the pot.
- Reduce emissions of CO.
- Use as little fuel as possible for cooking.

ARC researchers spent four years (2011-2014) experimenting with charcoal stoves and tested many of them under the emissions hood. It became evident that if the CO could be reduced and the thermal efficiency increased, an all Tier 4 charcoal stove was a possibility. Many months of iterative changes and testing in the DOE project resulted in a stove that did achieve Tier 4 on all of the eight IWA measures. ARC General Manager Samuel Bentson and ARC researcher Ryan Thompson led the development effort.

The charcoal stove in this book is 26cm high with a diameter of 27cm. 3cm of insulation made from parallel sheets of stainless and aluminum foil isolate the stove body from the combustion chamber that has a diameter of 12cm and is 13.5cm deep. A refractory sheet metal cylinder creates a plenum that allows pre-heated secondary air jets to enter the combustion chamber just above the burning batch of fuel. Thirty 0.5cm holes evenly spaced near the top of the combustion chamber direct jets of pre-heated air into the flame above the charcoal creating a zone of mixing. A cast iron grate is located in the bottom of the combustion chamber. The amount of primary air is controlled by an airtight door that directs the primary air to enter the charcoal from underneath.

A Winiarski cast iron stove top that maintains constant cross sectional area increases heat transfer efficiency to the pot. A skirt around the pot creates a 6mm channel gap. The channel gap of 6mm was matched to the firepower of the stove. The secondary jets of air assist the batch-loaded charcoal to burn hotter, increase mixing of the CO and flame, and the flames and radiation very close to the bottom of the pot increase, heat transfer.



Primary air enters the fuel bed from below. The large door is completely open for high power operation. Jets of secondary air create a zone of mixing above the fuel. The door can be almost completely closed to create a large degree of turn-down for simmering.

Improvements, Not Innovations

It is interesting that incremental improvements to each part of the prototype charcoal stove, not new innovations, increased performance. The improvements in the Charcoal Stove are:

- A larger diameter door increases the amount of incoming primary air which results in the higher firepower required for quick boiling and frying, and more flame above the charcoal pile. The amplified flame helps to burn up the CO. The increased firepower boils 5L of water in less than 30 minutes. The door is almost completely shut to efficiently simmer water. Charcoal requires very small amounts of primary air to simmer a pot of water covered by a lid.
- The amount of charcoal placed into the combustion chamber has a dominant influence on the amount of fuel used to cook. For greatest efficiency it is important to use the minimum amount of charcoal needed for the cooking task. When more than the minimum amount is lit, the fuel used for cooking increases. 350g of charcoal is the maximum amount that can be loaded into the stove to achieve a Tier 4 rating for thermal efficiency.
- The R-value of the insulation needs to rapidly create the hotter temperatures (620°C) required to burn up the CO. Multiple sheets of stainless and aluminum foil, trapping layers of air, are used as insulation in the ARC stove.
- The secondary air needs to be rapidly preheated to keep the temperatures high enough in the combustion chamber. The penetration of the secondary air jets should cross the top of the burning pile of charcoal to meet in the middle.
- A skirt gap of 6mm assists high power Tier 4 thermal efficiency. Almost completely shutting the air-tight primary air door for simmering creates a large turn-down ratio.

The insulation in the ARC/DOE charcoal stove was made from sheets of stainless and aluminum foil.

Charcoal Stove Design Principles

Ryan Thompson wrote the following charcoal stove design principles in 2012:

Principle One

Size the combustion chamber for the required task.

Whatever fuel is loaded into the stove will be burned at a rate proportional to the amount of air made available to it. In most cases, more fuel means higher firepower because there is always excess air. For small amounts of food/water, where not much power is required, either load a small amount of fuel into the stove, or use a stove with a small combustion chamber. For cooking lots of food at once, use a stove with a big combustion chamber.

Principle Two

Charcoal stoves can have a high turn-down ratio.

If the air supply to a charcoal fire is reduced close to zero, the fuel will still keep burning. Once the air supply is increased, the firepower will also increase. Normally there is a spike in CO when the air supply is increased sharply, but it tends to stabilize once the firepower comes back up.

Principle Three

Use secondary air jets to burn up the CO.

Most charcoal stove designs have air coming in from the bottom and sides of the fuel bowl. The air must pass through the burning charcoal before it gets to the top where the CO is. If hot air is added above the charcoal, it is available to combust the CO. Try to keep the bottom of the batch of charcoal as cold as possible.

Principle Four

Put the pot close to the charcoal.

This maximizes heat transfer from radiation.

Principle Five

Insulate the stove body.

Insulate the stove body until a temperature of 620˚C or higher is achieved above the burning fuel five minutes or less after lighting. Insulation needs to be lightweight and trap still air. Examples of very good insulation are: ceramic fiber, rock wool, wood ash, sheets of foil, etc.

Principle Six

Use small channel gaps between the pot and stove.

The pot can be located very close to the top of the burning charcoal. A skirt around the pot helps increase the heat transfer efficiency from convection. Both convective and radiative heat transfer are important in a charcoal stove.

Principle Seven

Maintain a constant cross sectional area.

Keep a constant cross sectional area throughout the stove to start the design process and reduce as directed by experimentation under the emissions hood. This will help to keep the velocity of the draft as high as possible.

Principle Eight

Supply a large amount of primary air to assure sufficient firepower.

Make the primary air door large enough to boil the water quickly. It can be partially closed to reduce power when desired. The door has to be almost airtight to reduce firepower sufficiently when simmering in a pot with a lid.

Charcoal Stove Details

A stainless steel and aluminum foil insulation was developed for use in the charcoal stove. The insulation is based on either creating a “bubble wrap,” trapping air between the layers of foil, or wrapping multiple layers of ceramic fiber or rock wool with aluminum or stainless steel foil. Two layers of stainless steel foil closest to the combustion chamber reduce temperatures further away from the fire, allowing lower cost aluminum foil to be used nearer the outside of the stove. Seven to ten layers of foil with the least amount of touching result in a very light weight insulation that is more effective than ceramic fiber in quickly raising temperatures in the combustion chamber.

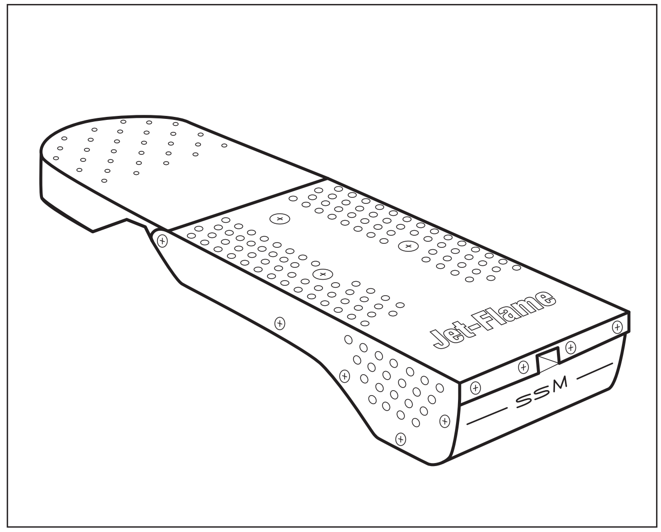
CAD drawings of the Charcoal Stove are found in Appendix E.

Chapter 17

The SSM Jet-Flame

High Power PM2.5: 1.8 mg/min @3.98kW Low Power PM2.5: 5.3mg/min @ 2.3kW

The Jet-Flame directs thirty jets of preheated primary air up into the burning charcoal and wood elevating, temperatures and creating mixing.



A drawing is found in Appendix F.

Test Results

Stove type/model		Jet-Flame		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	40.6%	2%	3
Low Power Specific Consumption	MJ/min/L	0.032	4%	2
High Power CO	g/MJ_d	2.82	9%	4
Low Power CO	g/min/L	0.09	12%	4
High Power PM	mg/MJ_d	26.6	24%	4
Low Power PM	mg/min/L	1.13	22%	3
Indoor Emissions CO	g/min	0.39	11%	4
Indoor Emissions PM	mg/min	5.0	20%	3

The SSM Jet-Flame

The Jet-Flame slides into the combustion chamber.

There are industrial burners with jets of primary air underneath the fuel bed that clean up combustion. Both Underfeed Stokers and Fluidized Bed Boilers use primary air that enters the fuel bed from underneath the fire. Underfeed Stokers push the fuel (and forceful jets of air) into the bottom of the fuel bed. Fluidized Bed Boilers are a recent type of combustion chamber developed for the clean burning of biomass. Added secondary air jets directed into the side of the flame (with pre-heating in some cases) can also be used to increase combustion efficiency. The flow of air and fuel to the fuel bed is controlled so the temperature stays constant. Some excess air is needed to achieve close to complete combustion even though the above-stoichiometric ratios are cooling to some degree. The Jet-Flame operates in somewhat the same manner.

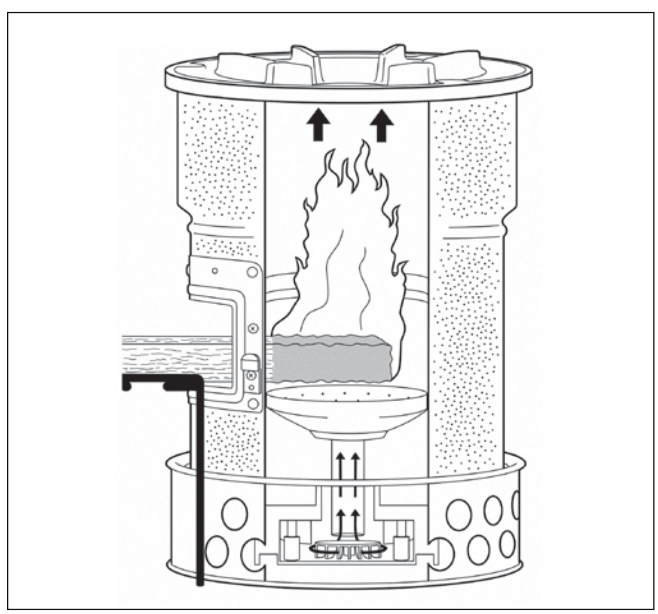
With DOE funding in 2015, ARC built a bottom-air-only prototype stove and has been experimenting with improving the technique, resulting in the Jet-Flame accessory manufactured by SSM. There are several advantages in a bottom-air-only approach. The jets of air flow into the fuel bed from holes in the floor of the combustion chamber. Since the pre-heated jets are vertical, back-drafting out of the fuel door in a Rocket type stove is easier to overcome. The jets of air super-heat the charcoal layer underneath the sticks of wood and increase mixing. The increased velocity of the higher temperature gases also improves heat transfer efficiency.

Control of firepower in the Jet-Flame/Rocket stove is still achieved, in large part, by adjusting the number of sticks present in the combustion chamber and by controlling the rate at which they are fed into the fire. At the same time, high velocity jets of air raise the firepower by increasing the charcoal temperature and maintaining low emissions with a higher fuel feedrate. Control of firepower by adjusting primary air is a feature in modern TLUD stoves.

The Jet-Flame is the floor of the combustion chamber. A two watt fan, invented for this purpose, blows 30 jets of air into the bottom of the fire through 2mm holes. The Jet-Flame with Power Control has a switch that allows the fan to deliver more or less air to the fire. As mentioned, while the firepower is moderated by the feed rate, changing the amount of air supplied to the fire also influences firepower and emissions. As the firepower is reduced, the amount of air needed for the combustion of CO and $PM_{2.5}$ is also decreased. Too much air lowers the temperature in the combustion zone below the desired 900°C.

History

Starting in 2004, Aprovecho Research Center was hired by the Shell Foundation to bring Rocket type



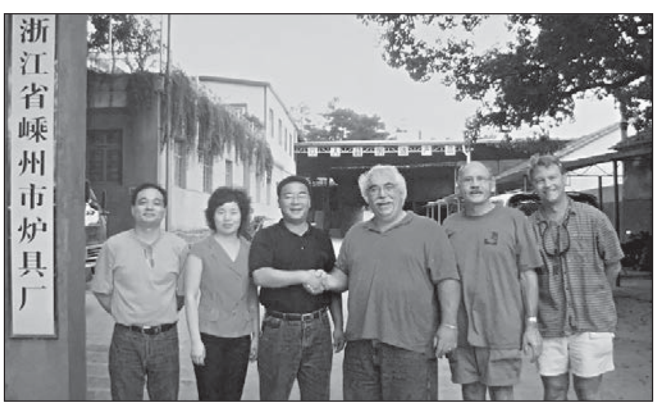
The 2015 bottom-air-only forced draft stove.

stoves to India. Protecting health was a major component of the project. Unfortunately, even the low mass, natural draft Rocket stove did not burn cleanly enough to accomplish that goal. Higher temperatures and a lot more mixing were needed. Making affordable Rocket stoves cleaner burning became an important goal for Aprovecho.

The Rocket stoves that we helped to build at that time were field tested in Africa and found to reduce the fuel used to cook and subsequent emissions by about 40% (USAID, 2007; USAID, 2010; USAID, 2011). A reduction of at least 90% was estimated to protect health (US Department of Energy, 2011). The WHO later quantified the allowable $PM_{2.5}$ emissions to be 1.75 mg/min for unvented stoves and 7.15 mg/min for vented stoves (WHO, 2015).

Aprovecho discovered that manufacturing a low mass, improved Rocket stove in India was difficult because cookstoves were generally not factory produced. At the same time, thousands of factories in China were mass producing low cost stoves. We located Shengzhou Stove Manufacturer (SSM), a cookstove company near Hangzhou, China, and signed a partnership agreement in 2007. The company had a long tradition of manufacturing affordable, insulative, abrasion-resistant refractory ceramic combustion chambers that became a key component in Rocket stoves.

Approximately one hundred thousand SSM stoves were exported and sold in India in the following years and Aprovecho has worked closely with SSM ever since. Currently, the factory has yearly sales of about one million Rocket type stoves outside of China and annual multi-million coal burning cookstove sales in China. Since 2019, SSM has invested four million dollars in a new state of the art stove manufacturing system.



In 2007, ARC and SSM became partners.

ARC was hired in 2018 by the Gates funded Global Health Laboratories (GHL) that develops technologies to improve the lives of people in low and middle income countries. We were tasked to co-innovate a solution to integrate fan-driven jets of air into a Rocket stove to reduce emissions. ARC built on previous work to develop a stove accessory and the Jet-Flame was the result. We brought the idea to SSM, and the company's founder Mr. Shen, division business manager Chenkai Wang, and the engineering team worked tirelessly to turn the prototype into a product for mass manufacturing. See: www.jet-flame.com

The Jet-Flame prototypes were also tested in Kenya so that cooks could help to design the final product. We learned more about how forced draft works in the lab, but the cooks taught us how the stove needs to cook food. We also learned that a lowest possible retail price is important for commercial success. Luckily, cast iron production is inexpensive in China. Field testing revealed that the Jet-Flame can complement a range of cookstoves including modern Rockets, open fires, sand/clay stoves, and earthen Rockets.

The Jet-Flame is powered by 2 watts of electricity from a five-volt USB connector. It can be used with a cellphone charger, power bank, solar panel, or solar home system. The Jet-Flame was initially designed for grid-connected consumers in Kenya who use biomass and for owners of a solar home system. A photovoltaic system from SSM is available to provide home energy for off-grid areas including lighting, cell phone charging, and cleaner cooking. There is a potential for carbon credits from biomass fuel savings to support a photovoltaic home "energy makeover" for off-grid families.

Research and Development

Three forced draft techniques that had been tested in the DOE project were further investigated: (1) blowing the jets up into the flame from the bottom, (2) aiming the jets into the middle of the flame and

(3) directing the jets just above the flame. These experiments confirmed the previous conclusions showing that fan-driven jets of air, introduced underneath the fire, seemed to be most effective in making Rocket stoves significantly cleaner burning and more fuel efficient. Further experimentation is needed to determine if a combination of primary and secondary air jets is superior. Hundreds of tests of iterations led ARC researchers to hypothesize that bottom air works by super-heating the charcoal bed (over 1100°C), helping the sticks to burn hotter, and by creating turbulence in and above the fire that mixes the flammable gases with air for more complete combustion.

The development effort with GHL, led by Dr. Dan Lieberman, tuned and optimized the size and location of the jets of air. We ended up delivering the jets of air using thirty 2mm in diameter holes in a plenum with a static pressure of 0.75 inches of water column. This compromise was effective at high and medium firepower, but field testing revealed that too much air entered the combustion zone at low power. This cools the fire, making the small fire harder to maintain, and creates higher emissions of CO and $PM_{2.5}$. The Jet-Flame with Power Control was created with a switch that allows the fan to deliver more or less air to the fire. Experiments revealed that 50 standard liters of air per minute (SLM) works well at high power, 30SLM at medium power, and 20SLM at low power. We think that for a given Jet-Flame airflow rate, there is an ideal stick feeding rate (firepower) that leads to cleanest combustion.

At high Jet-Flame airflow (around 4kW to 6kW firepower) there is a lot of mixing, so even when the sticks are fed more rapidly into the combustion chamber and the excess air is reduced to around 40%, the combustion efficiency stays close to optimal. Reducing the excess air down to 20% may be possible due to the very high heat and mixing created by the forceful jets of air. Too low excess air (less than 20% above stoichiometric) results in smoke because there is too much woodgas and not enough air in the combustion zone.

On the other hand, too much excess air (above approximately 100%) also results in smoky conditions because, we imagine, that too much air is cooling the fire. Too much excess air also burns away the charcoal and only the sticks are burning. Maintaining sufficient charcoal is important with forced draft bottom air because the air jets blowing up into the charcoal create the high temperatures that are needed for close to complete combustion.

At low firepower (3kW) too much air is worse, it burns up the charcoal and can blow out the fire. Also, the reduced velocity and volume of air doesn't seem to result in as thorough mixing. ARC hypothesizes that because the mixing is less at low power/ low air flow, not as much woodgas can be burned cleanly. On the plus side, because the jets of air aren't as vigorous at low flow they don't burn the charcoal as fast. The sticks of wood do not need to be fed as quickly into the fire to keep them burning and making charcoal. With higher temperatures and more mixing, the Jet-Flame is cleaner at high power.

Learning from the C-Quest Capital/Jet-Flame Stove

Starting in 2019, C-Quest Capital began Jet-Flame Rocket stove projects in Malawi, Zimbabwe, Zambia, Kenya, Rwanda, Laos and India. We were surprised that at hot start the high mass CQC

The CQC sand/clay brick Rocket stove with SSM Jet-Flame in Malawi (2020).

Rocket stove was very clean burning. An included 10cm high pot skirt with 6mm channel gap helps to generate higher thermal efficiencies. An ISO 19867 test in the ARC lab at 3.98kW with 50 standard liters per minute air flow resulted in 1.8mg/min for $PM_{2.5}$. With reduced temperatures and mixing at 3.4kW (30 standard liters per minute) the $PM_{2.5}$ emissions were 2.8mg/min. As temperatures and mixing were further reduced at 2.3kW (20 standard liters per minute) $PM_{2.5}$ emissions rose to 5mg/min. Unlike natural draft Rocket stoves, the bottom air, forced draft version is cleaner burning at higher firepowers (see below).

Stove type/model		CQC HotA 4.28.20	CQC HotB 4.28.20	CQC HotA 4.29.20	CQC HotB 4.29.20	CQC HotA 5.4.20	CQC HotB 5.4.20	CQC HotC 5.4.20	Average	n = Upper CI Bound	7 Conservative CI Bound	
Location		Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho				
Fuel species		DF	DF	DF	DF	DF	DF	DF	DF	1 - P =	0.1	
Date		4.28.20	4.28.20	4.29.20	4.29.20	5.4.20	5.4.20	5.4.20	4.28.20			
ISO Performance Metrics	**units**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**				**CI < 1/3 of Tier**
Thermal Efficiency With Char	%	42.8%	45.5%	41.7%	44.1%	42.6%	45.0%	45.6%	43.9%	45.0%	42.8%	P > 90%
Thermal Efficiency Without Char	%	42.8%	45.5%	41.7%	44.1%	42.6%	45.0%	45.6%	43.9%	45.0%	42.8%	P > 90%
CO per Energy Delivered to Cooking Pot	g/MJd	1.10	0.79	1.89	1.40	0.89	1.15	0.53	1.11	0.78	1.43	P > 90%
PM per Energy Delivered to Cooking Pot	mg/MJd	17.7	13.1	27.2	22.4	16.9	15.2	6.5	17.0	12.1	21.9	P > 90%
		Tier	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Average**	**High Tier Estimate**	**Low Tier Estimate**	**Tier CI Range**
Thermal Efficiency With Char		4.2	4.5	4.1	4.4	4.2	4.4	4.5	4.3	4.50	4.27	0.23
Thermal Efficiency Without Char		4.2	4.5	4.1	4.4	4.2	4.4	4.5	4.3	4.50	4.27	0.23
CO per Energy Delivered to Cooking Pot		5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.00	5.00	0.00
PM per Energy Delivered to Cooking Pot		4.7	4.8	4.6	4.6	4.7	4.8	4.9	4.7	4.87	4.70	0.17

Stove type/model		CQC HotA 4.28.20	CQC HotB 4.28.20	CQC HotA 4.29.20	CQC HotB 4.29.20	CQC HotA 5.4.20	CQC HotB 5.4.20	CQC HotC 5.4.20	Average	Upper CI Bound	Conservative CI Bound
Basic Operation	units										
HOT START- HIGH POWER											
Time to boil Pot #1	min	16	13	19	16	16	15	14	16	17	14
Temp-Corrected Time to Boil	min	15.5	12.5	17.6	15.4	15.1	13.6	13.4	14.7	16.0	13.5
Test duration	min	35	35	35	35	35	36	35	35	35	35
Firepower	watts	4,154	4,486	3,353	3,622	4,025	4,194	4,042	3,982	4,260	3,704
Average Cooking Power	kW	1,844	2,111	1,470	1,701	1,815	1,988	1,949	1,840	1,994	1,686
Char mass productivity	%	-3%	-3%	-4%	-4%	-4%	-4%	-4%	-3.7%	-3%	-4%
Measured Emissions Rate											
HOT START- HIGH POWER		(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)			
CO	gr/min	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CO2	gr/min	26	29	21	25	26	27	26	26	27	24
PM2.5	mg/min	2.0	1.7	2.4	2.3	1.8	1.8	0.8	1.8	2.2	1.4

Hot start, high power test results of the SSM Jet-Flame in the CQC stove.

Stove type/model		CQC Hot.A 5.26.20	CQC Hot.B 5.26.20	CQC Hot.C 5.26.20	CQC Hot.A 5.27.20	CQC Hot.B 5.27.20	CQC Hot.C 5.27.20	Average	n = Upper CI Bound	6 Conservative CI Bound	
Location		Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho				
Fuel species		DF	DF	DF	DF	DF	DF		1 - P =	0.1	
Date		5.26.20	5.26.20	5.26.20	5.27.20	5.27.20	5.27.20	5.26.20			
ISO Performance Metrics	**units**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**				**CI < 1/3 of Tier**
Thermal Efficiency With Char	%	35.9%	36.8%	37.9%	38.0%	37.5%	39.0%	37.5%	38.4%	36.6%	P > 90%
Thermal Efficiency Without Char	%	35.6%	36.4%	37.4%	37.6%	37.2%	38.5%	37.1%	38.0%	36.3%	P > 90%
CO per Energy Delivered to Cooking Pot	g/MJd	4.79	4.55	4.11	4.80	4.63	3.75	4.44	4.09	4.78	P > 90%
PM per Energy Delivered to Cooking Pot	mg/MJd	44.3	37.4	33.5	38.7	39.1	13.7	34.4	25.6	43.3	P > 90%
		Tier	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Average**	**High Tier Estimate**	**Low Tier Estimate**	**Tier CI Range**
Thermal Efficiency With Char		3.5	3.6	3.7	3.8	3.7	3.8	3.7	3.84	3.66	0.18
Thermal Efficiency Without Char		3.5	3.6	3.7	3.7	3.7	3.8	3.7	3.79	3.62	0.17
CO per Energy Delivered to Cooking Pot		3.8	3.9	4.2	3.8	3.9	4.4	3.9	4.22	3.86	0.25
PM per Energy Delivered to Cooking Pot		4.3	4.4	4.5	4.4	4.4	4.8	4.4	4.63	4.32	0.31

Stove type/model		CQC Hot.A 5.26.20	CQC Hot.B 5.26.20	CQC Hot.C 5.26.20	CQC Hot.A 5.27.20	CQC Hot.B 5.27.20	CQC Hot.C 5.27.20	Average	Upper CI Bound	Conservative CI Bound
Basic Operation	units									
HOT START- MED POWER										
Time to boil Pot #1	min	24	24	22	23	22	21	23	24	22
Temp-Corrected Time to Boil	min	22.8	22.4	21.2	22.1	21.4	19.9	21.6	22.5	20.7
Test duration	min	35	35	35	35	35	35	35	35	35
Firepower	watts	3,321	3,292	3,378	3,215	3,296	3,545	3,341	3,434	3,249
Average Cooking Power	kW	1,294	1,313	1,382	1,328	1,346	1,487	1,358	1,416	1,301
Char mass productivity	%	-6%	-5%	-5%	-6%	-6%	-5%	-5%	-5%	-6%
Measured Emissions Rate										
HOT START- MEDIUM POWER										
CO	gr/min	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.3
CO2	gr/min	23	23	23	23	23	24	23	24	23
PM2.5	mg/min	3.4	2.9	2.8	3.1	3.2	1.2	2.8	3.4	2.1

Hot start, medium power test results of the SSM Jet-Flame in the CQC stove.

Stove type/model		CQC HOT.A 6.29.20	CQC HOT.B 6.29.20	CQC HOT.C 6.29.20	CQC HOT.A 6.30.20	CQC HOT.B 6.30.20	CQC HOT.C 6.30.20	CQC HOT.D 6.30.20	CQC HOT.E 6.30.20	CQC HOT.F 6.30.20	Average	n =	9	
												Upper CI	Conservative	
Location		Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho	Aprovecho		Bound	CI Bound	
Fuel species		DF	DF	DF	DF	DF	DF	DF	DF	DF		1 - P =	0.1	
Date		6.29.20	6.29.20	6.29.20	6.30.20	6.30.20	6.30.20	6.30.20	6.30.20	6.30.20				
ISO Performance Metrics	**units**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**				**CI < 1/3 of Tier**
Thermal Efficiency With Char	%	34.1%	36.7%	35.6%	37.3%	36.0%	37.6%	40.4%	39.8%	39.3%	37.4%	38.7%	36.1%	P >90%
Thermal Efficiency Without Char	%	33.7%	36.5%	35.4%	36.7%	35.2%	37.1%	39.4%	39.1%	38.8%	36.9%	38.1%	35.7%	P >90%
CO per Energy Delivered to Cooking Pot	g/MJ_d	7.26	8.32	7.06	7.88	6.30	6.42	6.25	6.67	5.35	6.83	6.27	7.40	P >90%
PM per Energy Delivered to Cooking Pot	mg/MJ_d	124.7	92.7	94.0	108.8	89.9	71.3	72.5	78.3	56.4	87.6	74.7	100.5	P >90%
		Tier	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Average**	**High Tier Estimate**	**Low Tier Estimate**	**Tier CI Range**
Thermal Efficiency With Char		3.4	3.6	3.5	3.7	3.5	3.7	4.0	3.9	3.9	3.7	3.87	3.61	0.26
Thermal Efficiency Without Char		3.3	3.6	3.5	3.6	3.5	3.7	3.9	3.9	3.8	3.6	3.81	3.57	0.24
CO per Energy Delivered to Cooking Pot		2.9	2.7	3.0	2.8	3.3	3.2	3.3	3.1	3.6	3.1	3.33	2.95	0.26
PM per Energy Delivered to Cooking Pot		3.5	3.8	3.7	3.7	3.8	3.9	3.9	3.8	4.0	3.8	3.91	3.75	0.16

Stove type/model		CQC HOT.A 6.29.20	CQC HOT.B 6.29.20	CQC HOT.C 6.29.20	CQC HOT.A 6.30.20	CQC HOT.B 6.30.20	CQC HOT.C 6.30.20	CQC HOT.D 6.30.20	CQC HOT.E 6.30.20	CQC HOT.F 6.30.20	Average	Upper CI Bound	Conservative CI Bound
Basic Operation	units												
HOT START- LOW POWER													
Time to boil Pot #1	min	No Boil	No Boil	No Boil	No Boil	No Boil	No Boil	No Boil	No Boil	No Boil			
Temp-Corrected Time to Boil	min												
Test duration	min	35	35	35	35	35	35	35	35	35	35	35	35
Firepower	watts	2,373	2,198	2,352	2,145	2,267	2,222	2,084	2,312	2,348	2,256	2,318	2,193
Average Cooking Power	kW	913	924	952	912	917	950	955	1,035	1,040	955	986	925
Char mass productivity	%	-8%	-9%	-8%	-9%	-8%	-8%	-8%	-8%	-8%	-8%	-8%	-9%
Measured Emissions Rate													
HOT START- LOW POWER													
CO	gr/min	0.4	0.5	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.4
CO2	gr/min	17	16	16	17	15	15	14	15	15	16	16	15
PM2.5	mg/min	6.8	5.1	5.4	6.0	4.9	4.1	4.2	4.9	3.5	5.0	5.6	4.4

Hot start, low power test results of the SSM Jet-Flame in the CQC stove.

Jet-Flame Combustion

David Evitt, Chief Operating Officer of ASAT, has been experimenting with the Jet-Flame since 2018 and will continue as he works with Dr. Nordica MacCarty at Oregon State University. The effect of bottom air jets is not the same as jets of air that penetrate into the side of a flame. In the first place, the air is directed into a layer of charcoal and then into flame, which is, in some ways, similar to the TLUD stove.

A normal Rocket stove or open fire has natural draft buoyant flow diffusion flames. The heat from the fire causes the air/flames/woodgas near the fire to expand and become less dense than the surrounding atmosphere. The low density air/flames/woodgas are pushed up by the dense, colder surrounding air. That colder air flows into the bottom of the fire filling the void left by the low-density rising hot air. The incoming fresh air brings in the oxygen to keep the fire burning. The velocities involved in buoyant flow are relatively low creating laminar flames.

In a diffusion flame, the unburned fuel vapors are concentrated inside the flame, and the oxygen is outside the flame in the atmosphere. The flame is only burning on the surface at the fuel/oxygen interface where the molecular mixing (diffusion) brings the air/fuel mixture to within the flammability limits of the fuel. Laminar buoyant flow diffusion flames burn the fuel slowly. It takes time for the fuel and air to mix and often the flame cools off below the point of sustaining combustion before all the fuel burns creating smoke. A cold pot above the fire makes this worse.

The insulated riser section of a Rocket stove attempts to give the laminar flames enough time at a high enough temperatures to burn more completely before they significantly cool off when contacting the pot. In most natural draft configurations the primary air is drawn across the top of the charcoal bed. Without sufficient primary air the charcoal accumulates during the burn. The new charcoal covers the previously made charcoal and smothers it. This process limits the heat output from the charcoal and the energy left in the smothered charcoal is less available for cooking. The charcoal can build up so much during cooking that it fills the space under the wood and reduces the airflow. With little air under the burning sticks, the flame is diminished. The excess charcoal is often emptied from the stove as cooking continues.

Fire is built directly on the top surface of the Jet-Flame, which is pierced with 2mm holes. The air holes direct high velocity jets of pre-heated air into the charcoal bed from below. This heats the charcoal slowing its accumulation. An equilibrium is reached where the charcoal bed burns and heats the wood creating new charcoal, maintaining about the same level. A natural draft Rocket stove with sufficient draft can also achieve this desired state of equilibrium.

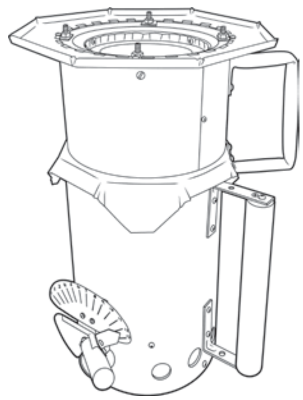
The hot jets of air emerge from the charcoal and pierce the laminar flames emitted by the wood creating turbulent eddies that "stir up" the flames creating bulk mixing of the fuel and air to enhance the speed of mixing and combustion. The zone of heat and mixing made by the jets of air creates short, intense flames that burn the fuel more completely before they cool off too much to sustain combustion.

The jets of air from the Jet-Flame boost the temperature in the combustion chamber by burning the charcoal and creating turbulence to mix the fuel and air so it can burn more completely in the short time available as the flow travels from the fire to the pot. The heat from the fanned charcoal and rapidly mixing fuel increase the temperature of the flames as they contact the pot. The residence time in the CQC Rocket stove, from the fire to the pot, varied from 0.09 seconds at high flow/high power to 0.15 seconds at low flow/low power. The temperature just above the fuel bed ranged from 907°C to 1,002°C. Temperatures of 730°C to 826°C were measured below the pot. Higher temperatures allow shorter residence times that can still complete combustion of the fuel.

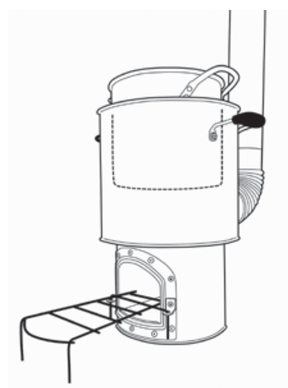
The high temperatures also increase the buoyant flow velocities which are enhanced by the momentum imparted by the jets of air. The jets of air in the Jet-Flame contributed from 20% to 34% to the total flow through the stove. This relatively fast flow (1.8m/s at high power) thins the boundary layer of still air on the bottom of the pot improving the convective heat transfer coefficient. The hotter charcoal bed also increases radiative heat transfer to the bottom of the pot. Burning the charcoal and preventing its accumulation allows more of the energy from the fuel to be utilized during cooking. Thermal efficiencies of 54% for high-power hot-start tests were measured at ARC using a Jet-Flame with a sunken pot SSM Rocket stove and a pot skirt with a 6mm channel gap (see chart, next page).

Favorite Stoves

With the CQC/Jet-Flame stove, two more high performance stoves have emerged as favorites at Aprovecho.



The Harris Natural Draft TLUD is a remarkable stove that is a pleasure to use. Mr. Harris worked for years to invent a TLUD with a three to one turn down ratio and very low emissions. His stove is truly improved and commendable. (We would add a chimney to make the stove perfect.) The staff very often choose this pellet stove to cook lunch. We agree with Dr. Tom Reed that carbon neutral woodgas is the "natural" gas (see Chapter 14).



Dr. Larry Winiarski invented the sunken pot Rocket stove with chimney in 1982 for the Red Cross. Many larger versions of this stove have been manufactured including the Colgan's In-Stove and the BURN Institutional Stove. Adding the Jet-Flame to the Rocket combustion chamber results in a stove that has improved thermal efficiency combined with very low emissions of CO and $PM_{2.5}$. We wish that, when asked for a health protecting stove in 2004, we had been this far along. Since the stove and chimney did not leak in lab tests, the stove did not emit measurable amounts of fugitive emissions into the hood. With a Jet-Flame, the sunken pot chimney stove achieved all ISO 19867 Tier 5 ratings for both thermal efficiency and emissions of CO and $PM_{2.5}$ (see Chapter 12).

Sam Bentson, ARC Lab Manager, and David Evitt, ASAT COO, with the Winiarski designed sunken pot Rocket stove with Jet-Flame and chimney.

Stove type/model		Isosunken3	Isosunken5	Isosunken6	Isosunken7	Isosunken8	Isosunken3	N =	5
Location		apro	apro	apro	apro	apro	Average	Low Tier Estimate	Stdev
Fuel species		df sticks	df sticks	df sticks	df sticks	df sticks	df sticks	α =	0.10
Date		1.18.19	1.19.19	1.20.19	1.20.19	1.21.19	1.18.19		
ISO Performance Metrics	**units**	**Value**	**Value**	**Value**	**Value**	**Value**			
Thermal Efficiency With Char	%	54.8%	54.0%	52.7%	53.4%	55.6%	54.1%	53.0%	1.2%
Thermal Efficiency Without Char	%	53.4%	52.6%	51.3%	52.0%	53.0%	52.5%	51.7%	0.8%
CO per Energy Delivered to Cooking Pot	g/MJ_d	Chimney takes all smoke out of the room							
PM per Energy Delivered to Cooking Pot	mg/MJ_d								
CO Emissions Rate, Normalized	g/min								
PM Emissions Rate, Normalized	mg/min								
		Tier	**Tier**	**Tier**	**Tier**	**Tier**			
Thermal Efficiency With Char		5.0	5.0	5.0	5.0	5.0	5.0	5.0	
Thermal Efficiency Without Char		5.0	5.0	5.0	5.0	5.0	5.0	5.0	
CO per Energy Delivered to Cooking Pot		5.0	5.0	5.0	5.0	5.0	5.0	5.0	
PM per Energy Delivered to Cooking Pot		5.0	5.0	5.0	5.0	5.0	5.0	5.0	
Basic Operation	units								
COLD START- HIGH POWER									
Temp-Corrected Time to Boil	min	13.5	10.1	13.6	13.8	10.0	12.2	10.3	1.9
Average Cooking Power	kW	2,135	2,214	2,033	1,897	2,537	2,163	1,934	240
Energy Delivered to the Cooking Pot	kJ	3,842	3,985	3,660	3,414	4,567	3,894	3,481	433
HOT START - MEDIUM POWER									
Temp-Corrected Time to Boil	min	20.2	15.8	16.3	17.7	12.6	16.5	13.9	2.8
Average Cooking Power	kW	1,544	1,679	1,629	1,642	2,265	1,752	1,474	291
Energy Delivered to the Cooking Pot	kJ	2,779	3,023	2,933	3,152	4,077	3,193	2,704	512
HOT START - LOW POWER									
Temp-Corrected Time to Boil	min	No Boil	No Boil	No Boil	No Boil	No Boil			
Average Cooking Power	kW	891	946	1,028	1,015	1,193	1,015	906	114
Energy Delivered to the Cooking Pot	kJ	1,604	1,702	1,851	1,827	2,147	1,826	1,631	205

ISO 19867 test results of the sunken pot Rocket/Jet Flame with chimney.

A drawing of the SSM Jet-Flame is found in Appendix F.

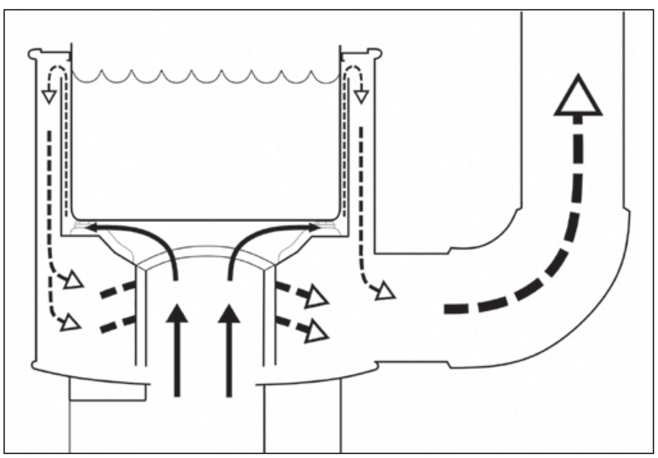
Chapter 18

Two Ways To Add A Chimney To A Cookstove

Sunken Pot Chimney

Dr. Winiarski invented the sunken pot approach to adding a chimney to a cookstove in 1981. The pot is sealed down into the stove body forcing the hot gases to flow in an appropriately sized channel gap next to the pot resulting in increased heat transfer efficiency (see below). The gases then flow down the outside wall of the skirt decreasing the temperature difference between the inside and outside gases. In this way, heat transfer loss is further reduced.

The chimney is placed below the bottom of the pot so optimal heat transfer can be accomplished. This technique, using a tight skirt with a narrow channel gap, can also be used to regulate the primary air entering the combustion chamber thereby reducing excess air, elevating temperatures, and increasing heat transfer efficiency. The tightness of the skirt can be adjusted under the emissions hood to control the air/fuel ratio which assists combustion efficiency.

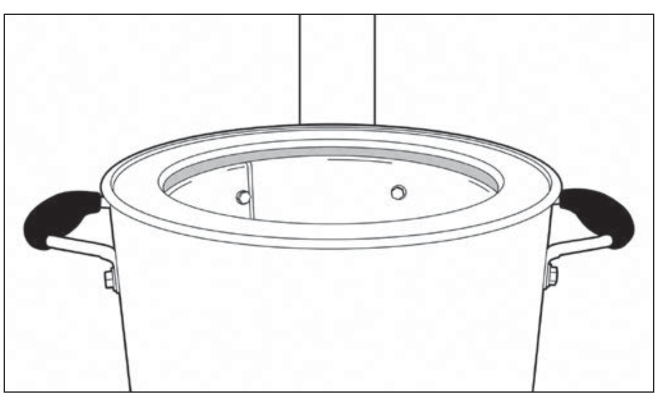


The disadvantage of the sunken pot technique is that a dedicated pot is required. Only one perfectly sized pot fits into the hole. ARC has introduced the sunken pot in many countries and users frequently object to it. Cooks often use different sized pots and don't like being limited to one pot that fits down into the stove body. On the other hand, there are a proportion of cooks who are attracted by the above 45% thermal efficiency, as fuel usage and most importantly time to boil is dramatically reduced. The sunken pot technique creates a Rocket stove that can amaze users because water boils so quickly, but they may not be able to live with using the one pot.

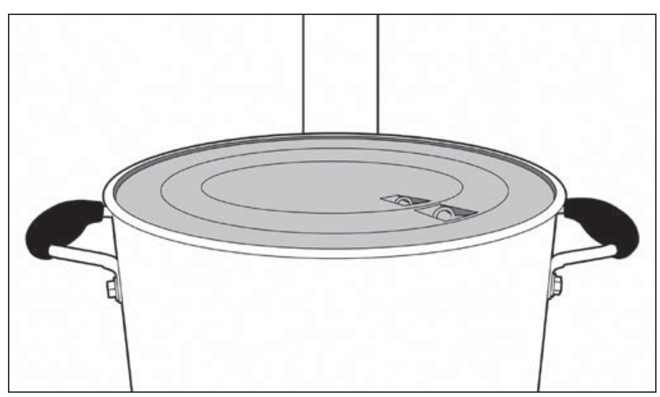
Flat Top Chimney

ARC developed an alternate flat top stove in an attempt to satisfy users who use multiple pots. Pots of many sizes block the circular openings on top of the stove and the pollution is sent up the chimney. The inserts can be removed exposing as much of the bottom of the pot as possible to the hot gases (see below and next page).

The hot gases contact the bottom of the pot and then pass between the pot support and the flat top



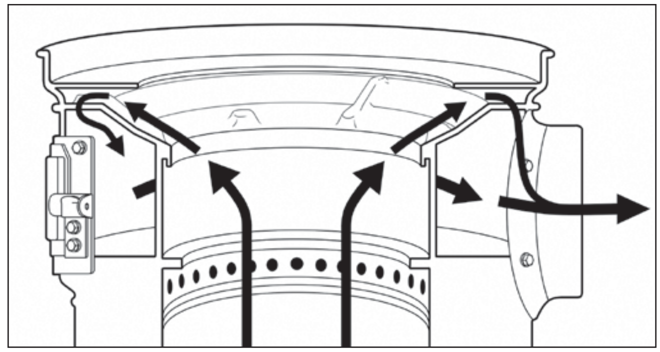
The sunken pot method requires one cooking pot sized to fit into the opening.



In the Flat Top chimney design the hot gases flow under the removable plates (or under the pot that sits on the stove top).

next to the inner wall of the stove body. The gases flow down and enter the chimney.

Unfortunately, the flat top approach is dramatically less fuel efficient compared to the sunken pot stoves. The high temperature and fast velocity gases in the forced draft stoves now only contact a portion of the bottom of the pot. With careful tending the flat top can achieve up to 30% thermal efficiency but 25% is more likely. It's hard for a stove designer used to over 45% thermal efficiency to be contented with a flat top stove although hopefully the design will encounter an appropriate circumstance.



In the flat top design, the gases flow under the top and out through the chimney.

Adding a Chimney to a Pot Skirt

A third way to attach a chimney to a stove is to simply add a chimney to the pot skirt. Because the hot gases flow more directly into the chimney the thermal efficiency is diminished compared to the double walled technique favored by Dr. Winiarski. However, the heat transfer efficiency is still quite good. It is important to remember that constant cross sectional area must be maintained between the exterior of the pot and the exit hole of the chimney. A bulge in the outside of the skirt where the chimney is connected assures that the flue gases maintain beneficial velocity.

A pot skirt with attached chimney.

Chapter 19

The Auto-Damper

Simply adding a chimney to a cooking stove may not decrease exposure to $PM_{2.5}$ enough to protect health. When the pot is removed from the stove top the cook can be exposed to the escaping emissions as smoke pours into the kitchen instead of going up the chimney. ARC designers wondered if an automatic device that immediately diverts the smoke up the chimney when the pot is removed might help to reduce exposure. Andy McClean developed the working models used in the DOE project.

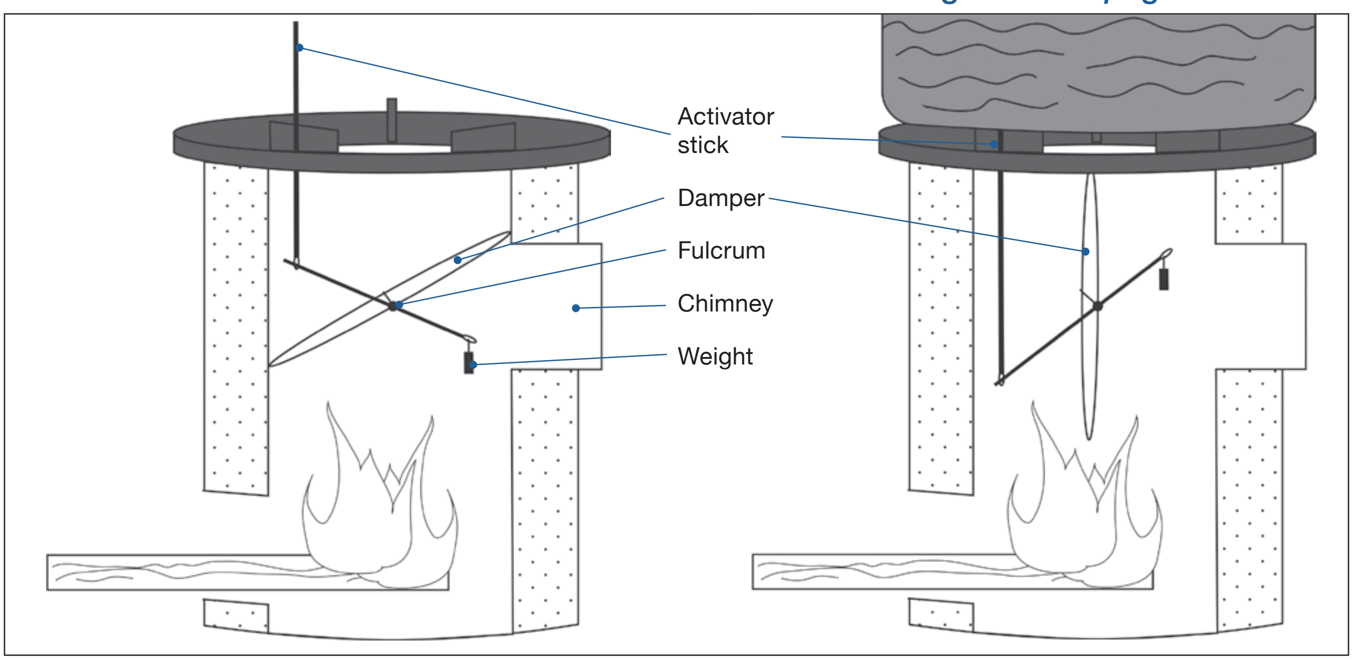
All stoves require maintenance to be a part of an effective intervention. The walls of the combustion chamber will eventually need to be replaced. Chimneys have to be cleaned on a regular basis and an inexpensive metal stove pipe can corrode fairly quickly although better quality chimneys last a long time in the US. Hopefully, an auto-damper might add one more layer of protection to the system?

The damper quickly blocks the combustion chamber and keeps smoke going up the chimney when the pot is removed. It is also possible for the cook to place a cover over the hole but a lot of smoke can reach the cook and family in a short time.

The auto-damper is opened when a vertical stick above the surface of the cook top is pushed down by the bottom of the pot. The weight that holds the damper closed above the combustion chamber is pushed down, the damper moves, and the hot flue gases go up to the bottom of the pot. When the pot is removed, the stick is no longer held down. A weight on the outside of the auto-damper or a spring moves the damper, balanced on a fulcrum, back to the original closed position.

The auto-damper was patented by ARC. A new invention is patented for a variety of reasons, including being sure that useful technologies stay available for general use. ARC intends inventions like the auto-damper to be free of charge to organizations helping humanity. Although describing inventions publicly provides some protection, new laws in the United States reinforce the multiple reasons to more fully protect intellectual property intended for free access. The newer SSM Jet-Flame, that was developed in partnership with the Gates funded Global Health Labs, is not patented but was described in multiple publications to try to assure free and unrestricted use of the invention.

See CAD drawings on next page.



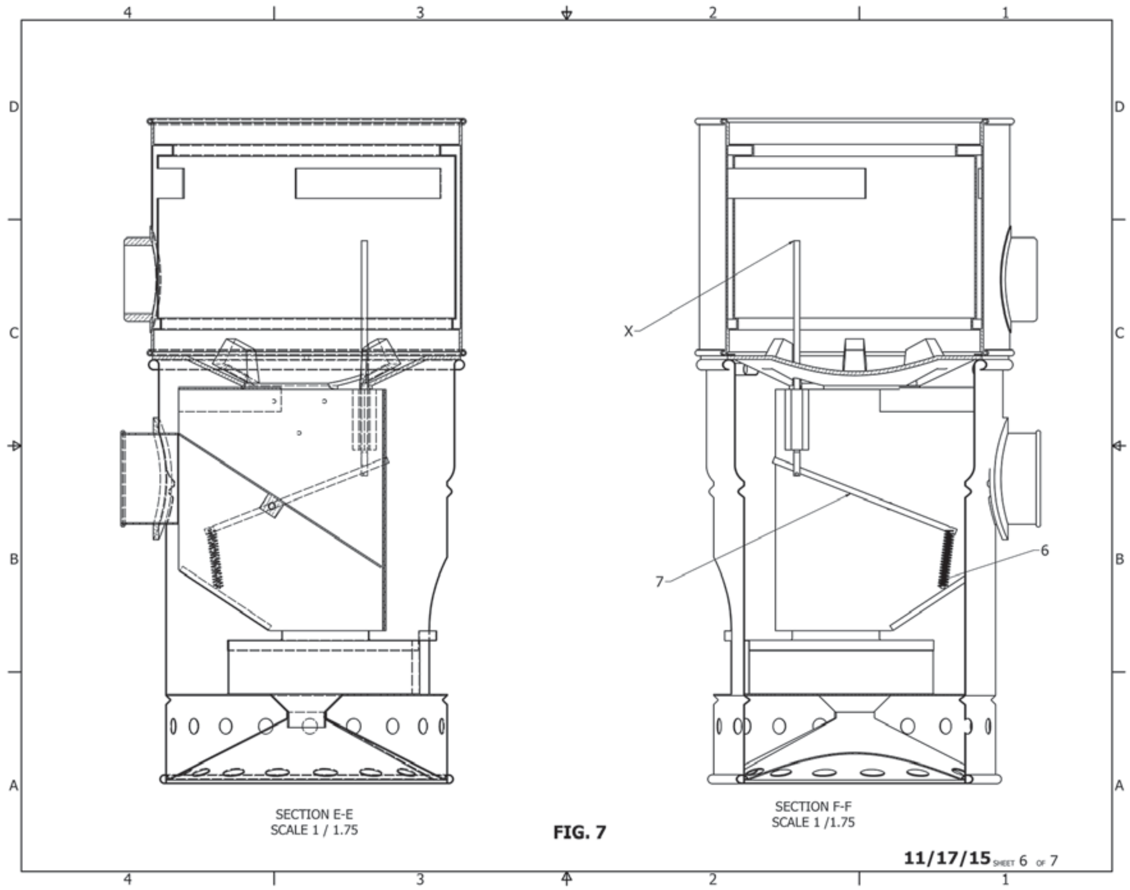

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FIG. 7

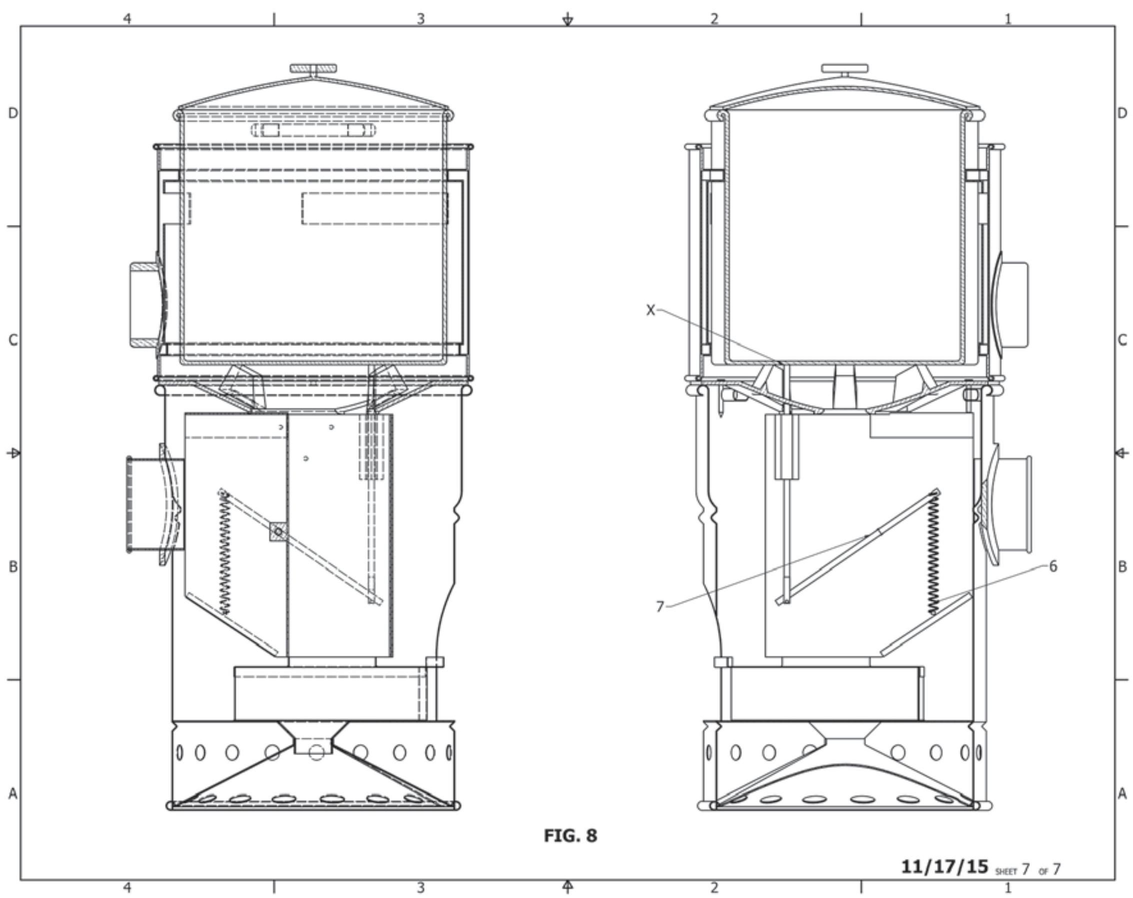
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FIG. 8

Chapter 20

Summary

Taking someone sailing before reading the instruction book works better. If their interest is sparked, there is a reason to become involved. Reading a book and thinking about it doesn't necessarily make you an important, empowered human being. You are one in a thousand who has done the same thing. But completing an experiment makes you unique. Suddenly, you know something that others do not know. At Aprovecho, learning is invention.

Trying to design, manufacture, and sell an affordable wood burning stove that pleases the cook, uses the least wood, doesn't make smoke, and protects health has greatly enriched the life of the mind here at ARC. The researchers change one thing at a time in a prototype, test the stove, and keep on going as we learn how fire works. Day after day, the stove evolves closer towards perfection. Effort equals success. And every day, when we look at the test results, is a bit like Christmas. Ideally, testing happens simultaneously in the lab and in the homes of the cooks.

It's a stimulating pursuit with holistic pleasures (including eating).

Climate change is challenging daily life, and wondering what comes next can be unsettling. However, one of the benefits of climate change may be that it gives passengers on planet Earth something real to face, together, as a team.

Have you been looking for purpose in life? Why not pick a problem and solve it? Anyone can be proactive and be a big help to neighbors.

There are hundreds of Appropriate Technology technologies that have not been scientifically improved. The scientists at ARC are trying to make wood burning clean enough to be carbon neutral. Improving other technologies is equally or more important. How people in Low and Middle Income countries can best grow food, live comfortably, make water safe to drink, dry crops, and live elegantly in a warmer Earth are technological problems that need solutions. Since the solutions must be affordable, experiments are also not expensive. Developing design principles for solar distillation, for example, and then creating practical devices has the potential to help millions of people. If we start now, the solutions will be available sooner.

Any serious person is invited to visit our campus to experience how problems can be solved by ordinary people. We organize monthly half day seminars that explain how to start and maintain a privately funded research center like ARC. We discuss experimental iterative development, statistical confidence, Appropriate Technology, getting famous, and becoming an important human being by solving problems.

For more information see: www.aprovecho.org and schedule a visit!

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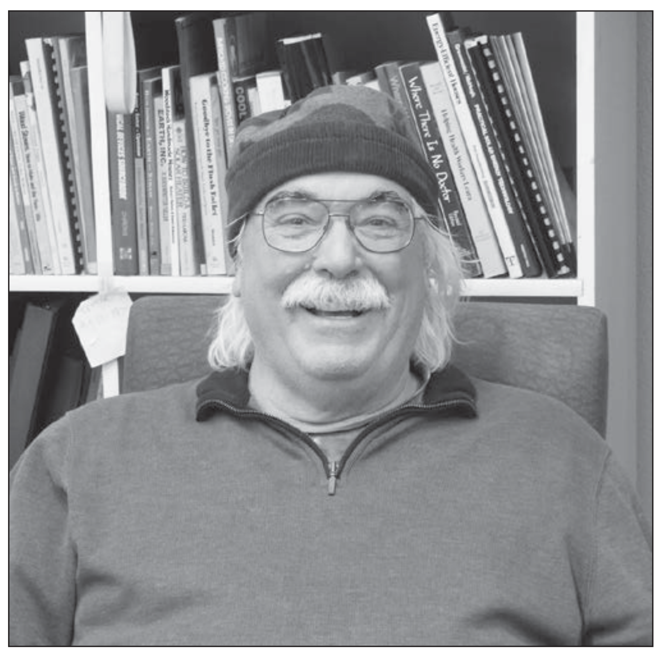

Dean Still is the Executive Director of Aprovecho Research Center and principle author of this book.

References

Agenbroad, J. (2010). *A Simplified Model for Understanding Natural Convection Driven Biomass Cooking Stoves.* Colorado State University.

Aprovecho Institute. (1984a). *Charcoal: Small Scale Production and Use.* GATE/GTZ.

Aprovecho Institute. (1984b). *Fuel-Saving Cookstoves*. GATE/GTZ.

Aung, T. W., Jain, G., Sethuraman, K., Baumgartner, J., Reynolds, C., Grieshop, A. P., Marshall, J. D., & Brauer, M. (2016). Health and Climate-Relevant Pollutant Concentrations from a Carbon-Finance Approved Cookstove Intervention in Rural India. *Environmental Science & Technology, 50*(13), 7228–7238. https://doi.org/10.1021/acs.est.5b06208

Bailis, R. (2005). *"Fuel from the Savannah: the Social and Environmental Implications of the Charcoal Trade in sub-Saharan Africa."* University of California, Berkeley.

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., Still, D., & Smith, K. R. (2007). Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project. *Energy for Sustainable Development, 11*(2), 57–70. https://doi.org/10.1016/s0973-0826(08)60400-7

Baldwin, S. F. (1987). *Biomass Stoves: Engineering Design, Development, and Dissemination.* Volunteers in Technical Assistance.

Bates, L. (2005). *Smoke, Health and Household Energy, Vol. 1.* Practical Action. https://assets.publishing.service.gov.uk/media/57a08c5d40f0b652dd0012a6/R8021b.pdf

Berrueta, V. M., Edwards, R. D., & Masera, O. R. (2008). Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy, 33*(5), 859–870. https://doi.org/10.1016/j.renene.2007.04.016

Boman, C., Petterson, E., Lindmark, F., Öhman, M., Nordin, A., & Westerholm, R. (2005). *Effects of Temperature and Residence Time on Emission Characteristics during Fixed Bed Combustion of Conifer Stem-wood Pellets.* Umeå University.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., … Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres, 118*(11), 5380–5552. https://doi.org/10.1002/jgrd.50171

Brady, M. P., Banta, K., Mizia, J., Lorenz, N., Leonard, D. N., Yamamoto, Y., DeFoort, M., & Keiser, J. R. (2017). Alloy Corrosion Considerations in Low-Cost, Clean Biomass Cookstoves for the Developing World. *Energy for Sustainable Development, 37*, 20–32. https://doi.org/10.1016/j.esd.2016.12.002

Brunner, T., Wuercher, G., & Obernberger, I. (2018). 2-Year field operation monitoring of electrostatic precipitators for residential wood heating systems. *Biomass and Bioenergy, 111*, 278–287. https://doi.org/10.1016/j.biombioe.2017.01.025

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R., et al. (2006). *Design Principles For Wood Burning Cook Stoves*. EPA, United States Environmental Protection Agency. http://aprovecho.org/publications-3/

Burnett, R. T., Pope, C. A., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., Shin, H. H., Singh, G., Hubbell, B., Brauer, M., Anderson, H. R., Smith, K. R., Balmes, J. R., Bruce, N. G., Kan, H., Laden, F., Prüss-Ustün, A., Turner, M. C., Gapstur, S. M., … Cohen, A. (2014). An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environmental Health Perspectives, 122*(4), 397–403. https://doi.org/10.1289/ehp.1307049

Caubel, J. J., Rapp, V. H., Chen, S. S., & Gadgil, A. J. (2018). Optimization of Secondary Air Injection in a Wood-Burning Cookstove: An Experimental Study. *Environmental Science & Technology, 52*(7), 4449–4456. https://doi.org/10.1021/acs.est.7b05277

Champion, W. M., & Grieshop, A. P. (2019). Pellet-Fed Gasifier Stoves Approach Gas-Stove Like Performance during in-Home Use in Rwanda. *Environmental Science & Technology, 53*(11), 6570–6579. https://doi.org/10.1021/acs.est.9b00009

European Commission. (2010). *Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling.* https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52010DC0011&from=EN

Fritsky, K. J., Kumm, J. H., & Wilken, M. (2001). Combined PCDD/F Destruction and Particulate Control in a Baghouse: Experience with a Catalytic Filter System at a Medical Waste Incineration Plant. *Journal of the Air & Waste Management Association, 51*(12), 1642–1649. https://doi.org/10.1080/10473289.2001.10464391

Grieco, E., & Baldi, G. (2011). Analysis and modelling of wood pyrolysis. *Chemical Engineering Science, 66*(4), 650–660. https://doi.org/10.1016/j.ces.2010.11.018

Hartmann, H., Turowski, P., & Kiener, S. (2011). *"Electrostatic precipitators for small-scale wood combustion systems – Results from lab and field tests."* http://task32.ieabioenergy.com/wp-content/uploads/2017/03/06_Hartmann.pdf

Hroncová, E., Ladomersky, J., Valíček, J., & Dzurenda, L. (2016). Combustion of Biomass Fuel and Residues: Emissions Production Perspective. *Developments in Combustion Technology, Chapter 1.* https://doi.org/10.5772/63793

Hukkanen, A., Kaivosoja, T., Sippula, O., Nuutinen, K., Jokiniemi, J., & Tissari, J. (2012). Reduction of gaseous and particulate emissions from small-scale wood combustion with a catalytic combustor. *Atmospheric Environment, 50*, 16–23. https://doi.org/10.1016/j.atmosenv.2012.01.016

International Energy Agency, & Priddle, R. (2010). *World Energy Outlook 2010.* http://www.worldenergyoutlook.org/media/weo2010.pdf

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC.

ISO. (2012). *"Guidelines for evaluating cookstove performance."* International Organization for Standardization. https://www.iso.org/standard/61975.html

ISO, International Organization for Standardization. (2018). *"ISO 19867-1:2018 Clean cookstoves and clean cooking solutions — Harmonized laboratory test protocols."* International Organization for Standardization. https://www.iso.org/standard/66519.html

Jetter, J., Zhao, Y., Smith, K. R., Khan, B., Yelverton, T., DeCarlo, P., & Hays, M. D. (2012). Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards. *Environmental Science & Technology,* 46(19), 10827–10834.

https://doi.org/10.1021/es301693f

Jetter, J., & Kariher, P. (2009). Solid-fuel household cook stoves: Characterization of performance and emissions. *Biomass and Bioenergy,* 33(2), 294–305. https://doi.org/10.1016/j.biombioe.2008.05.014

Johnson, M., Edwards, R., Alatorre Frenk, C., & Masera, O. (2008). In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmospheric Environment, 42*(6), 1206–1222. https://doi.org/10.1016/j.atmosenv.2007.10.034

Johnson, M., Lam, N., Brant, S., Gray, C., & Pennise, D. (2011). Modeling indoor air pollution from cookstove emissions in developing countries using a Monte Carlo single-box model. *Atmospheric Environment*, *45*(19), 3237–3243. https://doi.org/10.1016/j.atmosenv.2011.03.044

Johnson, N. G. (2005). *Risk analysis and safety evaluation of household stoves in developing nations.* Iowa State University. https://doi.org/10.31274/rtd-20200616-14

Keeling, R. F., Piper, S. C., Bollenbacher, A. F., & Walker, S. J. (2008). Atmospheric CO2 Records from Sites in the SIO Air Sampling Network. *Carbon Dioxide Information Analysis Center (CDIAC).* https://doi.org/10.3334/cdiac/atg.012

Lefebvre, A. H., & Ballal, D. R. (2010). "Chapter 4: Aerodynamics" in *Gas Turbine Combustion: Alternative Fuels and Emissions, Third Edition (3rd ed.)*. CRC Press.

Li, J., Paul, M. C., Younger, P. L., Watson, I., Hossain, M., & Welch, S. (2016). Prediction of high-temperature rapid combustion behaviour of woody biomass particles. *Fuel, 165*, 205–214. https://doi.org/10.1016/j.fuel.2015.10.061

Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., AlMazroa, M. A., Amann, M., Anderson, H. R., Andrews, K. G., Aryee, M., Atkinson, C., Bacchus, L. J., Bahalim, A. N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M. L., … Ezzati, M. (2012). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet,* 380(9859), 2224–2260. https://doi.org/10.1016/s0140-6736(12)61766-8

Loo, S., Koppejan, J., & Van Loo, S. (2012). *The Handbook of Biomass Combustion and Co-firing.* Taylor & Francis.

Lu, H., Robert, W., Peirce, G., Ripa, B., & Baxter, L. L. (2008). Comprehensive Study of Biomass Particle Combustion. *Energy & Fuels, 22*(4), 2826–2839. https://doi.org/10.1021/ef800006z

MacCarty, N. A., & Bryden, K. M. (2015). A unified set of experimental data for cylindrical, natural draft, shielded, single pot, wood-fired cookstoves. *Energy for Sustainable Development, 26*, 62–71. https://doi.org/10.1016/j.esd.2015.03.004

MacCarty, N., Bentson, S., Cushman, K., Au, J., Li, C., Murugan, G., & Still, D. (2020). Stratification of particulate matter in a kitchen: A comparison of empirical to predicted concentrations and implications for cookstove emissions targets. *Energy for Sustainable Development, 54,* 14–24. https://doi.org/10.1016/j.esd.2019.09.006

MacCarty, N., Still, D., & Ogle, D. (2010). Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy for Sustainable Development*, *14*(3), 161–171. https://doi.org/10.1016/j.esd.2010.06.002

Masera, O. R., Bailis, R., Drigo, R., Ghilardi, A., & Ruiz-Mercado, I. (2015). Environmental Burden of Traditional Bioenergy Use. *Annual Review of Environment and Resources, 40*(1), 121–150. https://doi.org/10.1146/annurev-environ-102014-021318

Merrill, R., Missar, C., Gage, T., Bukey, J. (1974) *Energy Primer*. Merrill R, Missar C, Gage T, Bukey J, editors. Portola Institute.

Noonan, C. W., Ward, T. J., & Semmens, E. O. (2015). Estimating the Number of Vulnerable People in the United States Exposed to Residential Wood Smoke. *Environmental Health Perspectives, 123*(2). https://doi.org/10.1289/ehp.1409136

Obernberger, I. (2011). *Survey on the present state of particle precipitation devices for residential biomass combustion with a nominal capacity up to 50 kW in IEA Bioenergy Task 32 member countries.* IEA Bioenergy. https://www.bios-bioenergy.at/uploads/media/Filter-study-IEA-Dez-2011.pdf

Pilishvili, T., Loo, J. D., Schrag, S., Stanistreet, D., Christensen, B., Yip, F., Nyagol, R., Quick, R., Sage, M., & Bruce, N. (2016). Effectiveness of Six Improved Cookstoves in Reducing Household Air Pollution and Their Acceptability in Rural Western Kenya. *PLOS ONE, 11*(11), e0165529. https://doi.org/10.1371/journal.pone.0165529

Prasad, K. K., & Sangen, E. (1983). *Technical aspects of woodburning cookstoves, a report from the Woodburning Stove Group.* Eindhoven University of Technology.

Reed, T. B., & Larson, R. (1996). A wood-gas stove for developing countries. *Energy for Sustainable Development*, 3(2), 34–37. https://doi.org/10.1016/s0973-0826(08)60589-x

Roden, C. A., Bond, T. C., Conway, S., Osorto Pinel, A. B., MacCarty, N., & Still, D. (2009). Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. *Atmospheric Environment*, 43(6), 1170–1181. https://doi.org/10.1016/j.atmosenv.2008.05.041

Roden, C. A., Bond, T. C., Conway, S., & Pinel, A. B. O. (2006). Emission Factors and Real-Time Optical Properties of Particles Emitted from Traditional Wood Burning Cookstoves. *Environmental Science & Technology, 40*(21), 6750–6757. https://doi.org/10.1021/es052080i

Roth, C. & Messinger, C. (2010). "*Improving the Charcoal Stove for Haiti, Stove Camp 2010.*" http://www.stoves.bioenergylists.org/taxonomy/term/314?page=1

Ruiz-Mercado, I., Masera, O., Zamora, H., & Smith, K. R. (2011). Adoption and sustained use of improved cookstoves. *Energy Policy, 39*(12), 7557–7566. https://doi.org/10.1016/j.enpol.2011.03.028

Smith, K. R. (1987). *Biofuels, Air Pollution, and Health: A Global Review (Modern Perspectives in Energy).* Springer.

Still, D. & Kness, J. (no date), *Capturing Heat.* Aprovecho Research Center.

Still, D., Bentson, S., & Li, H. (2014). Results of Laboratory Testing of 15 Cookstove Designs in Accordance with the ISO/IWA Tiers of Performance. *EcoHealth, 12*(1), 12–24. https://doi.org/10.1007/s10393-014-0955-6

Still, D. K., Bentson, S., Murray, N., Andres, J., Yue, Z., & MacCarty, N. A. (2018). Laboratory experiments regarding the use of filtration and retained heat to reduce particulate matter emissions from biomass cooking. *Energy for Sustainable Development, 42*, 129–135. https://doi.org/10.1016/j.esd.2017.09.011

Tangang Yuntenwi, E. A. (2008). *Improved Biomass Cookstoves: A Strategy Towards Mitigating Indoor Air Pollution and Deforestation; a Case Study of the North West Province of Cameroon.* Germany: (n.p.).

Udesen, D. J. (2019). *The optimization, evaluation, and design of a side-feed wood-burning cookstove with fan-driven secondary air injection.* University of Washington.

USAID. (2007) *Summary Evaluation Report of Fuel-Efficient Stoves in IDP Camps–Summary*

Evaluation Report, Uganda. USAID, https://pdf.usaid.gov/pdf_docs/Pdacm098.pdf

USAID. (2010). *Evaluation Of Manufactured Wood-Burning Stoves In Dadaab Refugee Camps, Kenya*. USAID. http://www.ehproject.org/PDF/ehkm/usaid-kenya_stoves2010.pdf

USAID. (2011). *In Home Emissions Of Greenhouse Pollutants From Rocket And Traditional Biomass Cooking Stoves In Uganda*. USAID. https://berkeleyair.com/wp-content/publications/Johnson_et_al-2011-In-home_emissions_of_greenhouse_gas_pollutants_fro.pdf

US Department of Energy. (2011) "*Biomass Cookstoves Technical Meeting Summary Report.*" US DOE Office of Energy Efficiency and Renewable Energy. https://www1.eere.energy.gov/bioenergy/pdfs/cookstove_meeting_summary.pdf

Vanormelingen, J., & Van den Bulck, E. (1999). Optimization of Overfire Air Systems of Cylindrical Combustion Chambers. *Environmental Engineering Science, 16*(5), 353–373. https://doi.org/10.1089/ees.1999.16.353

VITA. (1985). *Testing the Efficiency of Wood-Burning Cookstoves: International Standards.* Volunteers in Technical Assistance.

WHO Regional Office for Europe. (2006). *Air Quality Guidelines Global Update 2005: Particulate Matter, ozone, nitrogen dioxide and sulfur dioxide* (A EURO Publication). World Health Organization.

WHO. (2015). *WHO Indoor Air Quality Guidelines: Household Fuel Combustion*. World Health Organization.

WHO. (2018a). Air Pollution and Child Health: prescribing clean air. World Health Organization. https://www.who.int/ceh/publications/air-pollution-child-health/en/

WHO. (2018b). *Ambient (outdoor) air pollution.* World Health Organization. https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Wood, T. S., & Baldwin, S. (1985). Fuelwood and Charcoal Use in Developing Countries. *Annual Review of Energy, 10*(1), 407–429. https://doi.org/10.1146/annurev.eg.10.110185.002203

Yang, Y. B., Sharifi, V. N., Swithenbank, J., Ma, L., Darvell, L. I., Jones, J. M., Pourkashanian, M., & Williams, A. (2008). Combustion of a Single Particle of Biomass. *Energy & Fuels, 22*(1), 306–316. https://doi.org/10.1021/ef700305r

Yip, F., Christensen, B., Sircar, K., Naeher, L., Bruce, N., Pennise, D., Lozier, M., Pilishvili, T., Loo Farrar, J., Stanistreet, D., Nyagol, R., Muoki, J., de Beer, L., Sage, M., & Kapil, V. (2017). Assessment of traditional and improved stove use on household air pollution and personal exposures in rural western Kenya. *Environment International, 99,* 185–191. https://doi.org/10.1016/j.envint.2016.11.015

Zhang, J., Smith, K. R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M. A. K., Rasmussen, R. A., & Thorneloe, S. A. (2000). Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. *Atmospheric Environment, 34*(26), 4537–4549. https://doi.org/10.1016/s1352-2310(99)00450-1

Zhi, G., Chen, Y., Feng, Y., Xiong, S., Li, J., Zhang, G., Sheng, G., & Fu, J. (2008). Emission Characteristics of Carbonaceous Particles from Various Residential Coal-Stoves in China. *Environmental Science & Technology, 42*(9), 3310–3315. https://doi.org/10.1021/es702247q