2009

The uses of laboratory testing of biomass cookstoves and the shortcomings of the dominant U.S. protocol

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by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Kenneth Mark Bryden, Major Professor
Ron Nelson
Brian Steward

Iowa State University

Ames, Iowa

2009

DEDICATION

I would like to dedicate this thesis to the people of Nuevo San Jose, Guatemala; Santa Anita La Union, Guatemala; and Nana Kenieba, Mali.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

An estimated three billion people worldwide, most of them in developing countries, rely on the burning of biomass in order to cook their food. Biomass combustion is associated with a number of negative health and environmental effects, and much effort has been put into designing cookstoves that use less fuel and have fewer toxic emissions in order to reduce the severity of these effects. Laboratory tests are often used in the design process to determine whether a given alteration has improved the design, as a tool to compare different stoves' suitability to a chosen application, and as a means of certifying whether a stove meets a certain benchmark or regulation. In this thesis, I show that a limited set of variables that affects the field performance of a stove and its eventual acceptance by potential users can be tested in the laboratory, and only a subset of these variables is captured by the dominant laboratory protocol used by organizations in the United States. A number of questionable assumptions underlying this protocol are examined, and it is shown that there exists the potential for serious error in its reported values under certain conditions. The key assumptions examined are that the stove being tested in a continuous-feed stove, the fuel supply is homogenous, all water in the test vaporizes at the local boiling point, the ash content of the fuel is so small as to be unimportant, the procedure of sorting char from unburned fuel is unbiased, and the calorific value of char is one and one-half times that of raw fuel. In the case of a high ash content fuel, such as dung or agricultural residues, the failure to properly account for ash may lead to a relative error in reported values of emissions, fuel consumption, and energy efficiency of greater than ten percent. The assumption of all water vaporizing at the local boiling point, although physically incorrect, is shown to lead to relative errors in test results on the order of one percent, and is thus judged to be an acceptable assumption under ordinary circumstances. Test modifications are shown that effectively address ash content and broaden the test's applicability to batch-feed stoves. The sort-and-mass procedure used for energy accounting in the test is shown to

consistently bias results in the direction of overestimating efficiencies and underestimating fuel use.

CHAPTER 1. OVERVIEW OF STOVES

1.1 Introduction

With a global human population exceeding six billion people, a lot of food is being cooked using a lot of *somethings*. In the industrialized world, that *something* usually takes the form of a stove that is heated by electricity or by burning a gaseous fuel such as natural gas or liquefied petroleum gas. Outside of the industrialized world, the cooking device is rarely powered by electricity, and is far more likely to be powered by burning either liquefied petroleum gas or some sort of solid fuel, usually some sort of biomass such as wood, dung, or charcoal. Estimates put the total number of people throughout the world who rely on solid biomass fuels at three billion, or roughly one-half of the world's human population (Desai et al., 2004). The problems that surround burning biomass for cooking purposes affect a very large number of people, and this number is not likely to be reduced significantly in the near future (World Resources Institute, 2005). Even in areas where governments are actively attempting to displace the use of biomass fuels by subsidizing the cost of electricity, people continue to use biomass for cooking because it tends to be less expensive, and electricity is valued for its ability to power television sets and other devices that cannot be powered with wood (Madubansi and Shackleton, 2007).

1.2 Cooking technologies in use in the developing world

By far the most common type of stove in use in the developing world is the traditional stove commonly referred to as the three stone fire, and depicted in Figure 1.1. It is a simple but surprisingly effective device consisting of three stones placed on the ground so that they support a pot, pan, griddle, or grill. A fire is built between the stones, providing heat to the pot, pan, etc., as well as heat and light to the surrounding area. A well-built three stone fire can have a thermal efficiency approaching 20% (Bussmann, 1988), a low emissions profile, and moderately low fuel use. A poorly built three stone fire, on the other hand, can have an abysmal thermal efficiency, high emissions with lots of smoke and irritating particles, and very high fuel use.

In an attempt to address some of the issues of the three-stone fire, governments, humanitarian organizations, and corporations have introduced a great variety of stove designs to many areas of the developing world. These designs may be classified according to a number of criteria, the first being according to fuel: wood, charcoal, dung, agricultural residues, kerosene (called paraffin outside of the U.S.), liquefied petroleum gas (LPG), and sunlight. Although kerosene and LPG have a number of advantages over the other combustible fuels in terms of cleanliness, efficiency, and often emissions, they are still out of reach for a majority of people in the developing world due to cost and availability. Solar cookers and solar ovens, which simply use radiant solar heat for cooking have limited application in many areas due to weather patterns, day length, and local food preferences. This leaves the aforementioned three billion people relying on solid biomass fuels, because there is effectively no alternative.

A second classification of stoves is based on the fuel feeding procedure: continuous-feed, batch-feed, or mixed-feed. Continuous-feed stoves allow fuel to be added at any time, much like an open fire. They usually have direct open access to the combustion chamber through a fueling port that remains open. Batch-feed stoves are fueled once at the beginning of a burn cycle with a charge of fuel. No additional fuel is added during the burn cycle. Mixed-feed stoves accommodate batch-feeding, but also allow fuel to be added in discrete quantities during the burn cycle. Many gasifier type stoves (discussed later) are mixed-feed stoves because they require a deep fuelbed to begin operation, but thereafter fuel can be added in small, discrete quantities. Although the fueling procedure is generally used as the criteria for this classification, it is also useful to think of this classification in terms of extinction procedure: continuous-feed stoves can be extinguished by cutting off the fuel supply, but the fuel supply for a batch-feed stove cannot be cut off because all of the fuel available for that burn cycle is already in the combustion chamber. Extinction in a batch-feed device relies on either fuel burnout or strict oxygen control. Mixed-feed stoves are somewhere in between because although the fuel supply can be cut off, there may be a noticeable lag before extinction is complete since there is some amount

Figure 1.1 The three-stone fire.

of unburned fuel that cannot be readily removed from the combustion chamber.

The combustion regime is the basis of a third classification, and indicates the degree of coupling between ’primary combustion’–the pyrolysis and solid-char reactions that occur in the fuelbed– and ’secondary combustion’–the gas-phase reactions that occur in the presence of oxygen away from the fuelbed. The terminology used for this classification is inconsistent, with vaguely-defined terms such as ’non-gasifier’, ’semi-gasifier’, ’gasifier’, and being popular at the moment. Better defined terms are ’closely-coupled’, ’loosely-coupled’, and ’decoupled’. Closely-coupled combustion is the familiar combustion of an open fire in which pyrolyzed volatiles are oxidized directly above the fuelbed (sometimes

in the fuelbed if the packing is sufficiently loose), and the radiant heat generated by combustion of the volatiles is a major source of the energy required for further pyrolysis. Loosely-coupled combustion occurs when there is a clear spatial separation between the fuelbed and the zone of volatiles combustion. There will generally be a separate oxygen supply to the zone of volatiles combustion, but usually no means of stabilizing a flame here, with flames occasionally ’licking up’ from the fuelbed. Pyrolysis in the fuelbed still relies partly on radiative energy from the combustion of volatiles, but also relies heavily on the exothermic conversion of solid char to carbon monoxide. Decoupled combustion occurs when the pyrolysis and char reactions are entirely separated, both energetically as well as spatially, from the subsequent oxidation of gaseous volatiles. Such a separation requires separate oxygen sources for the fuelbed reactions and the volatiles reactions. Pyrolysis in the fuelbed is entirely dependent on either the conversion of char to CO or on an external heat source. Very few cooking stoves in the developing world use decoupled combustion, although notable exceptions, such as stoves connected to village-scale gasification plants in China, do exist. Many of the concepts discussed in this paper can not be readily applied to such stoves due to the wide range of processing or storage systems that may exist between the production of volatiles and their subsequent combustion.

The fourth major classification deals with how the direction of travel of the ignition front in the fuelbed compares with the direction of airflow through the bed. The options are ’concurrent-flow’, ’counterflow’, and ’cross-flow’. Concurrent-flow refers to air and the ignition front traveling in the same direction through the fuelbed. Open fires are usually concurrent-flow. Counter-flow refers to air and the ignition front traveling in opposite directions, and is typical of the so-called 'Top-lit updraft' devices in which fuel in a packed bed is ignited on the top of the bed, but the airflow begins at the bottom of the bed and proceeds to the top. Cross-flow refers to airflow that is perpendicular to the direction of the ignition front. There are very few examples of this type of flow in use in a developing country cookstove, and it is included here only for completeness.

A fifth classification of stoves has to do with whether convection, conduction, or radiation is the major heat transfer mechanism between the stove and the cookpot. The convection-dominated stoves place some part of the cookpot directly in the path of the combustion products, whereas the conduction-dominated stoves first heat a large griddle (often called a *plancha*, due to its popularity in Latin American countries), which then heats the cookpot or food via conduction. Most charcoal fueled stoves rely on radiation as the major heat transfer mechanism, and work by suspending the cookpot just above a bed of hot coals. Convection- and radiation-dominated stoves generally exhaust the products of combustion directly into the room, whereas conduction-dominated stoves usually exhaust these gases outside of the room, but there are enough exceptions to this rule to necessitate another classification criterion.

Whether a stove exhausts the products of combustion into the room containing the stove or outside the room is the sixth classification criterion. While one often sees the terms 'chimneyed stove' and 'non-chimneyed stove' used to indicate the exhaust procedure of the stove, these terms are somewhat confusing given the implication that a 'chimneyed stove' will rely on the temperature differential of the chimney for draft. A better classification terminology is 'room-exhausted' and 'outside-exhausted'.

As alluded to in the previous paragraph, it is also necessary to designate whether a stove relies on natural draft or forced draft to effect airflow through the device. Importantly, not all natural draft stoves rely on chimneys that exhaust products to the outside. In fact, there is a large class of stoves referred to as 'rocket stoves' that rely on natural draft but are room-exhausted stoves. All forced-draft cookstoves known to the author that are currently being produced or sold in the developing world are room-exhausted. The usual reasons for eschewing natural draft in favor of forced draft are to have finer control over burn rate and to allow the use of internal passages that create a higher pressure drop (usually for heat transfer reasons).

Table 1.1 illustrates the use of these classifications to describe a number of stoves found in the developing world.

Each of the criteria for classification has an impact on the user experience of the stove, the potential health impacts of cooking with the stove, and the problems encountered with attempting to quantify the performance of the stove. Some of these variables are crucial in determining whether a given performance test can be meaningfully used to compare two dissimilar stoves, and also have an impact on the amount of error likely to be encountered when testing a stove. In this regard, this thesis will generally focus on issues in one of the main laboratory protocols in use today that cause problems when attempting to test batch-feed stoves.

1.3 Health impacts of stoves

Upon looking at who, specifically, is affected by the problems of burning biomass for cooking, a few important trends become clear. First, since women are responsible for cooking throughout most of the world, they are more heavily impacted by the problems of cooking than are men. Second, small children traditionally stay at home with their mothers during the day in most areas where biomass is used for cooking food, so they, too, tend to be heavily affected by the by burning of biomass fuels. Lastly, the poor are more likely to use biomass fuels than are their wealthier neighbors. The end result is that the world's poor are disproportionately affected by the problems surrounding the acquisition and burning of biomass fuels (Barnes et al., 1994; Eckholm et al., 1984).

The major health and safety issues associated with cookstoves and process of gathering fuel for these stoves are burns, acute respiratory infections, chronic obstructive pulmonary disease, cancer, low birth weight, cataracts, blindness, hernia, back pain, hypertension, and physical or sexual assault (Desai et al., 2004; Naeher et al., 2007; Martin, 2007; Diaz et al., 2007; McCracken et al., 2007). The respiratory and circulatory ailments in particular are associated with specific gaseous compounds such as carbon monoxide, but also with a large class of compounds generally emitted as particulate matter. Recent evidence points to particles with an aerodynamic diameter under 2.5 um, usually denoted by $PM_{2.5}$, as the most likely culprits (World Health Organization, 2003). A number of carcinogenic compounds such as benzo[a]pyrene and other polycyclic aromatic hydrocarbons are emitted in sufficient quanitites from the burning of biomass in existing stoves to warrant attention from health organizations

Stove Name	Fuel	Fuel Feeding	Coupling	Airflow	Heat Transfer	Exhaust	Draft	Region of Use
Three-stone fire	W, C, D, A	C	C	Co	V	R	N	All
Lorena	W	C	C	Counter	V	O	N	Latin America, Africa
Plancha Lorena	W	C	C	Counter	D	O	N	Latin America
Vesto	W, C, D, A	M	L	Co or Counter	V	R	N	Africa
Philips	W, C, A	M	L	Co	V	R	F	India
Ecofogon	W	C	C	Counter	D	O	N	Brazil, Nicaragua
StoveTec Greenfire	W	C	C	Counter	V	R	N or F	India
Jiko	C	M	C	Co	R	R	N	Africa
VITA	W, D, A	C	C	Counter	V	R	N	Africa
HELPS	W	C	C	Counter	D	O	N	Latin America
Basic Rocket	W, A	C	C	Counter	V	R	N	All
Oorja	A	B	L	Counter	V	R	F	India, SE Asia
KEY	W = wood, C = char, D = dung, A = Ash	C = continuous, M = mixed, B = batch	C = closely, L = loosely	Co = concurrent, Counter = counter	V = convection, D = conduction	O = outside, R = room	F = forced, N = natural	

Table 1.1 A selection of stoves found throughout the developing world.

(Ministry for the Environment, 2003).

1.4 Environmental Impacts of Stoves

1.4.1 Global Climate Change

A reason for designing better cookstoves that has been gaining importance since the 1990s has to do with the effects of combustion emissions on global climate change. Although there is some debate about the degree to which the warming of the global climate is caused by human activities, there is a large amount of evidence indicating that carbon dioxide (CO_2) plays a major role in the warming. Combustion of hydrocarbon fuels, which includes nearly every burnable fuel currently in use throughout the world, directly results in the emission of CO_2 along with a number of other chemicals. Perfect combustion of any pure hydrocarbon fuel results in the release of CO_2 and water. In practical situations, a number of other chemicals are also released, and it is these other chemicals that are largely responsible for the health impacts of combustion. CO_2 is not known to directly cause adverse health effects in the levels that it is released by most combustion processes, but its effect on global climate change appears to be problematic.

The burning of biomass fuels creates CO_2, but the CO_2 released by their combustion is often considered to be "carbon neutral" since the carbon released during their combustion was pulled out of the atmosphere within the lifetime of the plant. The situation with coal, gasoline, and other fossil fuels is different because the carbon contained in those fuels was pulled from the atmosphere millions of year ago. According to the Intergovernmental Panel on Climate Change, annual CO_2 emissions in 2004 were roughly twice their value in 1970, largely due to the increase in fossil fuel use during that period (IPCC, 2007).

Although the majority of attention surrounding global climate change is focused on the role of carbon dioxide, there are a number of other gases and emissions from combustion processes that potentially affect the global climate. Nitrous oxide (N_2O) is released in combustion processes and has a global warming potential[1] (GWP) of 298 (MacCarty et al., 2008). Much smaller amounts of this gas

[1] Global warming potential as used here is the total radiative forcing over a 100 year period that is caused by one mole of a gas or aerosol relative to the radiative forcing of one mole of CO_2 over the same period.

than CO_2 are released during most combustion processes, but due to its significantly higher GWP, even small amounts affect global climate. The level of nitrous oxide emission from a particular combustion process is affected by the nitrogen content of the fuel, magnitude and location of temperature gradients in the flame, average flame temperature, and presence or absence of catalyzing agents in the fuel or combustion environment (Tsuji, 2003; Law, 2006).

Methane (CH_4) is created during the de-volatilization stage of biomass combustion and has a GWP of 25 (MacCarty et al., 2008). It is generally considered to be a product of incomplete combustion, since given adequate oxygen and sufficient temperature, methane is easily burned off. Methane is typically produced in noticeable quantities only in the early stages of combustion in most well-designed stoves. Stoves capable of properly mixing air into the combustion process usually have very low levels of methane emission. Important exceptions are de-coupled combustion (gasifying) stoves and charcoal stoves, both of which have been found to produce relatively large amounts of methane. In the case of de-coupled combustion stoves, this is likely due to poorly staged combustion, or to excess gas production during certain phases of the burn. For charcoal stoves, excess methane production is often the result of low-quality charcoal that still contains a significant fraction of volatiles which are not fully burned due to the localized nature of the char surface reactions.

The combustion of biomass also produces emissions of particulate matter, small particles of a large variety of solids and liquids usually containing unburned carbon. Black soot is a commonly-known type of particulate emission from many combustion processes. Despite the large variety of compounds forming these particulates, most of them fall into one of two broad classes. The first class is that of particles that behave as elemental carbon. These compounds are strong absorbers of electromagnetic radiation and result in a direct warming of the atmosphere, with a GWP of 680 (MacCarty et al., 2008). The second class of particles behaves as organic carbon and tends to scatter electromagnetic radiation rather than absorbing it, resulting in an approximate GWP of -50 (MacCarty et al., 2008). The negative sign indicates that particulates in the class of organic carbon have a net cooling effect on the atmosphere. The amount of each type of particulate emitted is dependent on the temperature and nature of the combustion process. Smoldering fires, for example, tend to emit more organic carbon that do flaming fires, and vice versa.

1.4.2 Deforestation

In the 1970s and 1980s, widespread deforestation was one of the main driving forces behind improved cookstove programs throughout the world. As environmental policy and awareness have shifted, much less attention is now placed directly on deforestation and in developed countries one more often hears deforestation mentioned in conjunction with its role in global climate change. While the loss of carbon sinks in the form of forests may have an important effect on long-term global climate change, it is clear that deforestation has immediate and potentially long-term effects on local and regional micro- and macro-climates due to desertification and soil erosion. Deforestation also contributes to species extinction through the destruction of natural habitat, which is the primary cause of species extinction throughout the world (Pimm and Raven, 2000). Nearly half of all plant species and one third of all land-dwelling animal species are found in twenty-five "biodiversity hotspots" (Myers et al., 2000). Most of these hotspots are in tropical forests, and all of the hotspots are in areas being threatened by deforestation or other forms of habitat destruction. These hotspots formerly covered a total of 11.8% of terrestrial land area, but today cover a meager 1.4%. Nearly all of these critical areas are found in the developing world, in areas in which poverty is high, access to electricity is low, and biomass fuels are the predominant energy source for cooking and heating. Globally, the cutting of wood for fuel is not thought to be a key factor in deforestation – that dubious distinction goes to other pressures such as expansion of cropland and grazing land – but in some areas, particularly in the areas surrounding large cities in the developing world, it is clearly a major factor and its impact on the scale of deforestation may be reduced through the introduction of stoves with superior fuel economy (Madubansi and Shackleton, 2007; Eckholm et al., 1984).

CHAPTER 2. USES OF TESTING

2.1 Introduction

Given the array of potential health and environmental impacts of using biomass fuels for cooking, it is understandable that such a large variety of stove designs have been developed. But which designs effectively address these problems? Do some designs perform worse than the traditional three-stone fire? What can be changed in underperforming designs to make them perform better? All of these questions point to the need for some sort of performance testing. The form that testing should take is another issue in its own right, but it is clear that some sort of qualitative or quantitative performance data is needed. Before looking at a few specific roles that stove testing currently fills, it will be useful to examine two instances that illustrate the dangers of inadequate testing.

2.2 Failures related to poor testing

2.2.1 The Lorena Stove

In the late 1970s and early 1980s, the oil energy crisis helped bring about new awareness among governments and humanitarian and development non-governmental organizations (NGOs) of the trend toward deforestation and fuelwood shortage throughout the developing world. The problem was particularly acute in Central America, and being relatively close to the United States, this region received a lot of attention from American organizations. Armed with data from the World Bank and the UN Food and Agriculture Organization, many groups began to attempt to address the problem through tree planting programs and other attempts at reforestation. In many cases, the same organizations also sponsored programs to alleviate what was seen as both a major pressure on the forests as well as a looming humanitarian crisis: the use of wood for cooking[1].

The response to the issue of fuelwood use was rather straightforward: introduce something that uses less wood than a three-stone fire. Obvious choices to people in the industrialized world, such as kerosene and LPG, were simply not options on the table in Central America – the price was too high and there was no existing sales, maintenance, and transport infrastructure to support those fuels. So a better wood fire was the logical direction. Given that the three-stone fire had been around for many thousands of years, and that the industrialized countries had surpassed this technology hundreds of years ago, it seemed as though it should be easy to build a stove that used less fuel than a three-stone fire. This attitude permeated the improved stove programs. The result was a very heavy mud-and-sand (*lodo* (mud) + *arena* (sand) = *lorena*) stove that actually used more fuel than the three-stone fire. The problem was that no one at the time knew the stoves used more fuel, because they were not properly tested.

The designers had made an obvious mistake in conflating heat capacity and thermal resistance, but the real practical failure was not a misunderstanding of heat transfer; it was a lack of appropriate testing. Had the fuel use of this stove been tested against that of the three-stone fire under controlled conditions, it would have been clear that something was amiss. But controlled testing did not occur, and the implementing organizations instead reached for a much less precise instrument: the user survey. After building a new stove for a family, an aid worker would return after some weeks and simply ask vague, and quite possibly leading, questions about the stove. Everyone reported that the stove was wonderful and used far less fuel than the open fire. A fuel savings of fifty percent was reported over and over (Eckholm et al., 1984; Smaller, 1981).

A few years after the Lorena design was created, it was tested against a three-stone fire. Field tests were devised to closely monitor the wood consumption habits of a household. The results were not encouraging: the thermal efficiency of the Lorena stove was demonstrably lower than the three-stone fire, and families using it actually used more fuel than those who used only the three-stone fire.

[1]As noted in Chapter 1, this view has undergone some revision since the early 1980s and it is now thought that, in most circumstances, the primary pressures of deforestation are expansion of cropland and grazing land. There are still a few places surrounding urban areas, e.g. the area around Bamako, Mali, in which fuelwood pressures are considered to be the major driver of deforestation and desertification. The status of fuelwood shortages as a looming humanitarian crisis remains largely unchanged from thirty years ago.

The stove had in fact aggravated the problem it was intended to alleviate. All was not lost, however, because the Lorena had two notable advantages over a three-stone fire. First, it vented smoke directly to the outside, thereby reducing the exposure of cooks to respiratory and ocular irritants. Second, the stove was judged to provide a more comfortable work height than the tree-stone fire (Smaller, 1981). Even so, testing at the very beginning may have identified the fuel issue, or at least have changed the expectations of the implementers.

2.2.2 Indian stove program

In 1983, the Indian Department of Non-conventional Energy Sources began a pilot project to develop an improved stove for use in rural Indian areas in order to address the fuelwood crisis in those areas. In 1985, the program moved out of the pilot phase to become the National Programme on Improved Chulhas (NPIC). Between 1983 and 1998, the program disseminated just under thirty million improved stoves. The Ministry of Non-conventional Energy Sources has reported national savings of some 120 million metric tons of fuelwood due to the use of these stoves during the period 1983-1998, with the yearly savings equalling 9% of the annual fuelwood demand. Kishore and Ramana (Kishore and Ramana, 2002) have shown this figure to be based on a number a poor assumptions, and estimate that the actual savings are between one twenty-fifth and one tenth of the reported savings.

The two major points of departure between the government estimates and those of Kishore and Ramana are the expected lifespan of a stove and the fuel savings per stove. First, the government estimates assume an indefinite lifespan for a stove, so that a stove installed in 1983 is assumed to still be functioning with the same performance in 1998. Based on field data, Kishore and Ramana estimate that the useful lifespan of the stoves installed by the program is less than three years, and thus rather than there being 30 million improved stoves in use by 1998, there were more likely between 4 and 6 million improved stoves in use. The second point of departure is that of the fuelwood savings per stove. In light of the testing information presented in a report to the United Nations (FAO, 1993) and the Ministry's internal annual report (Ministry of Non-Conventional Energy Sources, 2002), the NPIC estimates appear to have been based on a comparison of the thermal efficiency of the improved stoves in relation to the thermal efficiency of the traditional stoves determined through a laboratory water boiling type test. In fact, a laboratory-determined thermal efficiency above 20% appears to have been the main requirement for a stove to be included in the program (World Bank, 2002). Kishore and Ramana base their estimates on a number of field trials which compared the actual fuel use of the improved stoves to the traditional models, and thus use a figure of estimated fuel savings that is roughly half of the NPIC figure.

While the NPIC has not been a complete failure in terms of saving fuelwood, neither has it been a great success. In addition to the actual fuel savings per stove being much lower than originally anticipated, it turns out that a significant number of people simply refuse to use the improved stoves. Both failures have been attributed to the program's over-reliance on laboratory performance tests and an under-reliance on field performance tests and user-needs and -preference studies (World Bank, 2002). In terms of laboratory tests specifically, the failures of the NPIC illustrate the danger of relying on a single performance metric – in this case thermal efficiency based on a single cookpot – rather than a group of performance metrics that might give more information about the overall performance of the stove.

2.3 Types of testing

As the examples of the Lorena stove and the Indian NPIC show, there are two types of testing that are important when designing a stove and attempting to build a user base: laboratory testing and field testing. Although the majority of this report will be concerned specifically with laboratory testing, it is important to understand the major differences between the two types of testing and the useful contexts of each because *both* are required to produce a successful design.

2.3.1 Laboratory testing

Laboratory testing is a tightly controlled process that is intended to provide repeatable, reproducible results. The main characteristics that are tested in the laboratory are safety, durability, and physical performance characteristics such as combustion quality, emissions, heat transfer, power range, and thermal efficiency (Woodburning Stove Group, 2000). The majority of laboratory testing of stoves for developing countries is focused on the physical performance characteristics because these have historically been considered to be more important than safety and durability to the agencies devising and carrying out tests. Nearly all physical performance tests involve heating water as this process can often be used to simulate an actual cooking task and also provides a convenient means to measure the "useful output" of the stove.

Because laboratory testing is intended to be a repeatable procedure, it is useful and suitable as an aid to the design process in the capacity of identifying areas of poor performance and determining the effect of a design alteration on the performance. Because laboratory testing is intended to be reproducible, it is potentially suitable for comparing the performance of different stoves, although it must be recognized that the accuracy and utility of this sort of comparison is dependent on the similarity between the test procedure and the situation to which one would like to apply the comparison. In a similar vein, laboratory testing is potentially useful for predicting the field performance of a stove, but this relies heavily on either simulating actual field use or conducting the test in such a way that the results can be corrected to account for differing conditions in the field. The three major performance tests in use at this time (India, China, UCBWBT) measure performance in a strictly-defined way, but do so in a way that is applicable to a very narrow range of use cases, and so have limited application in predicting actual field performance. The Woodburning Stove Group at Eindhoven has made a compelling case for the use of tests that provide performance data over a wide range of use scenarios, the equivalent of providing performance curves for pumps rather than the minimum and maximum performance points. Although the Woodburning Stove Group originally stated the case for such a test nearly two decades ago, their argument has been largely ignored by the majority of people involved in stove design and testing.

By itself, laboratory testing is unsuitable for verifying real-world performance outcomes. Real users do not use stoves in a tightly-controlled, repeatable, reproducible way, and this influence cannot be ignored when attempting to verify whether a certain stove design has reduced actual fuel use or has led to lower emissions in the home. Lab testing is also unable to give all of the information needed when designing a stove, in partcular because it cannot give information on potential user acceptability or help in identifying critical user constraints, such as typical cooking scenarios or user preferences. These applications – outcome verification, identification of user constraints, and measure of potential user acceptability – must rely on field tests.

2.3.2 Field Testing

Field testing, loosely, is testing that takes place with actual users, in their environment. Studies of actual fuel use, studies of emissions concentrations in users' homes, studies of user attitudes toward a stove, and studies of users' needs and preferences are all types of field tests. While the last two types of studies might be labeled by others as market tests, they should properly be considered as field tests, because the information they provide gives clues as to how a user might use a stove. The other types of field tests are used to gather data on a stove in actual use situations, and by their nature, cannot be as tightly controlled as lab testing because they rely on monitoring actual use rather than the idealized use required by a strict laboratory procedure. Field testing, rather than lab testing, is the proper way to verify a performance outcome such as reduced fuel use or emissions, since there is no guarantee that any laboratory test will simulate the full – or even typical – range of use scenarios for a stove. Field testing is designed to do just this. Field testing is a necessary complement to laboratory testing, because unlike laboratory testing, field testing can be used to identify the key user contraints that affect stove use and acceptance. Field testing can also provide a basis for connecting laboratory test results to predictive models of field performance.

2.4 Testing as an aid to the design process

Chronologically, the first use of testing for any stove should be during the design process, with the goal of determining whether the stove is functioning as intended. Once a design element has been altered, testing should be used to determine what impact the alteration had on performance. If a particular design is altered in order to address a safety concern, does the change negatively affect some other aspect of performance? This sort of design iteration testing is highly recommended by a number of publications on stove design and testing (Bussmann, 1988; Baldwin, 1987; De Lepeleire et al., 1981; Todd, 2001). Baldwin in particular suggests using this type of testing to optimize certain features of a design, such as the shape of the combustion chamber and the gap between the stovetop and pot (for convection-dominated stoves).

From a test design standpoint, this kind of test is relatively easy to devise, because as long as the same procedure is followed each time, the data from one design iteration of the stove can be directly compared to the data from a different iteration. One need not be concerned whether the test is applicable to a wide variety of stove types and operating conditions. The main difficulty is choosing performance metrics that are meaningful and that do not cause a designer to focus on the wrong aspects of performance. This is a trickier issue than it may appear at first glance, as the history of the Indian National Programme on Improved Chulhas discussed in the previous section illustrates. It is clear that some form of market study must be used first to understand the needs and desires of the potential user base in order to determine the weight that should be given any single performance metric. For example, if market studies indicate that a certain user base is more concerned about improved respiratory health than decreases in fuel use, then the test used (or at least its interpretation) should place more weight on emissions characteristics than on fuel-related metrics such as thermal efficiency or specific fuel consumption. To ensure that the test results are meaningful, the test must be based on one or more key use scenarios that is typical of the cooking culture in the potential user base. If, for example, the cooking culture is based on long, low-power use scenarios, a test based exclusively on short, high power operation will not provide meaningful information.

2.5 Testing as a means of comparison

A second use of testing is to compare different stoves when trying to choose between models. NGOs, companies, and consumers all have some variation of this need. NGOs usually have limited funds to apply to a stove program, and want to be able to look at the range of stoves available and choose a model that will effectively address the political, environmental, or health issue (or combination thereof) which they deem important. This need is heightened by the large variety of stoves designs that exist in some form throughout the developing world. NGOs are often interested in finding a stove that is appealing to the end-user but at the same time has certain performance characteristics, some of which may not be important to the end user. One of the lessons of the Lorena stove was that those NGOs succeeded in designing a stove desirable to at least some subset of the intended users, but that was not capable of delivering on the intended mission of the NGO. Finally, consumers who purchase their stoves would like a way of distinguishing the benefits of one stove over another at the time of purchase.

All of these comparison desires point to the need for a test that is robust and capable of meaningfully allowing such comparison. The task is considerably more difficult than that of testing the effect of a design change on a single stove, because any test that will allow meaningful comparison must take into account the quirks and details that come along with each of the classification criteria mentioned in Chapter 1. As an example, consider attempting to compare the fuel use of a continuous-feed stove with that of a batch-feed stove. What task should be performed to make the comparison? Batch-feed stoves have a finite running length due to the way fuel is added. If the test lasts for too long, the batch-feed stove may not even be able to complete the test. What fuel should be used to compare the two stoves? Batch-feed cookstoves often use fuel that is processed into pellets or other small pieces, whereas most continuous-feed stoves are designed with long sticks of wood as the intended fuel. A test that will allow a meaningful comparison between stoves must either specify a fueling and operating regime that works for a large variety of stoves, or must include some way of accounting for differing operating and fueling regimes.

2.6 Testing for certification

The third major purpose of testing is in order to document that a stove meets an internal, regional, national, or international benchmark or regulation. There exists a patchwork of regulations that stoves must satisfy in the industrialized world, and the situation is only slightly less complex in the developing world. The World Health Organization has set targets for indoor air quality, and many governments have instituted regulations intended to persuade stove manufacturers to meet the WHO targets. In China, for instance, there are strict limits on the minimum acceptable combustion efficiency of a stove (as determined by the CO/CO_2 ratio), as well as limits on emissions such as carbon monoxide and particulate matter. There is currently an effort underway by a few large stove manufacturers and NGOs to put into place strict international regulations on stoves and (apparently) prevent the sale or dissemination of stoves that do not meet those regulations. While the details of this effort are somewhat unclear at the moment, it is clear that some sort of international regulation will likely be implemented in the next few years, if for no other reason than the money potentially available through carbon credits has sparked the interest of financiers, and the carbon-trading market requires proof of emission performance. The handful of large NGOs that fund a significant portion of stoves work throughout the world are also logically concerned that the projects they fund are effective, and so have internal benchmarks that must be met by any stove project in order to ensure continued funding. The most common performance metrics currently being used in this capacity are combustion efficiency, thermal efficiency, task-specific fuel consumption, safety, and CO and particulate matter emissions.

CHAPTER 3. TESTING METRICS

3.1 Introduction

Once one is convinced of the utility of testing, it becomes necessary to decide which characteristics should be tested and what the appropriate metrics are to meaningfully describe performance. This chapter examines a number of characteristics that have been shown to have an influence on a stove's effectiveness in the field, then discusses which characteristics can be suitably tested in a laboratory setting and which characteristics are the most important to focus on.

3.2 Characteristics influencing stove effectiveness

The concept of "stove effectiveness" is somewhat less simple than it may seem at first blush. A rather naïve measure of effectiveness would be the amount of fuel a stove uses, and, in fact, this idea dominated thought about stoves in the late 1970s and early 1980s. But the actual measure of a stove's effectiveness is rather more subtle and properly includes outcomes that users deem important as well as outcomes that designers and implementers deem important. In the end, a stove's effectiveness is measured by its total impact on both the human and non-human worlds, and this is clearly affected many factors besides fuel use. In fact, the single most important factor is not fuel use, emissions, or safety: it is whether people are willing to use the stove, because even the most fuel-economical stove in the world will have no positive impact if people refuse to use it. The question of stove effectiveness can be usefully re-posed as "What characteristics affect whether a potential user will accept or reject a stove?" Characteristics that address this question are marked under the heading "User Need" in Table 3.1.

User acceptance, although crucial to the effectiveness of a stove, is not the only important aspect.

Consider the converse of a very fuel-economical stove that no one will use: a fuel-wasting stove with horrible emissions that is extremely popular. The stove meets whatever criteria the users look for in accepting a stove, but it fails miserably at obvious aspects of having a positive impact on health and environment. Certainly any NGO, government, or business that is concerned about health effects and fuel demand will not want to be involved with this stove, and from their viewpoint, this stove is not effective. The stove characteristics that are likely to be of concern to an NGO, government, or business are marked under the heading "External Need" in Table 3.1.

A quick glance at Table 3.1 will show that the list of characteristics that may influence a user's decision to accept or reject a stove is larger and farther-ranging than the list of characteristics that are generally important to external agencies such as NGOs, governments, and businesses. The implication is that there are more potential pitfalls associated with the user side of the equation, and a design that succeeds in meeting all of the criteria important to an external agency may still fail to attract end users and have a meaningful impact. In order to increase the chances of success, external agencies must take into account a broader range of characteristics than those that directly interest them.

3.3 What can be tested in the lab?

Some of the characteristics in Table 3.1, such as the conferral of status, the appearance, and the dimensions of the stove are influenced greatly by the culture of the intended market and are characteristics that should be *field* tested, but cannot be easily tested in a laboratory. Other characteristics, such as presence or absence of a griddle, portability, and cost represent constraints on a successful design, but also do not require laboratory tests. A quick scan of Table 3.1 will show that the following characteristics are appropriate to being tested in a laboratory setting:

- Fuel economy
- Emissions
- Safety
- Durability

	User Need	External Need
General Characteristics		
Fuel Economy	x	x
Emissions	x	x
Safety	x	x
Durability	x	x
Cost	x	x
Conferred Status	x	
Appearance	x	
Familiarity	x	
Usability Factors		
How much training?	x	x
Ease of lighting	x	x
Ease of control	x	x
Ruggedness	x	x
Can woman use it alone?	x	x
Does it have griddle?	x	
Where can you put pots?	x	
Convenience Factors		
High Power	x	
Low Power	x	
Cleanliness	x	
Portability	x	
Noise	x	
Smell	x	
Attention to fuel while running	x	
Must fuel be processed?	x	x
Dimensions, especially height	x	
Number of pots at once	x	
How hot to use / physical discomfort	x	
Maintenance regimen	x	x
Will it accommodate range of pots?	x	
Will it accommodate a range of fuels?	x	

Table 3.1 Major characteristics influencing the effectiveness of a stove design. User needs are those that affect whether a potential end-user will accept or reject a stove. External needs are those that tend to be important to NGOs, governments, businesses, and other stove funding or distributing agencies.

- Ease of lighting
- Ease of control
- High power
- Low power
- Noise
- Attention to fuel while running
- Must fuel be processed?
- How hot to use
- Will it accommodate range of pots?
- Will it accommodate a range of fuels?

The other characteristics are either simple design constraints (portability, does it have a griddle?) or cannot be sufficiently tested in a laboratory (familiarity, smell, how much training?). A few characteristics deserve special mention. Durability usually refers to how long a stove would last under typical operating conditions, and can be tested in the laboratory by cycling the stove many times and looking for cracking, burnout of fans or controls, and loss of seal on doors or dampers. Ruggedness is somewhat different, since it refers to the stove's ability to survive atypical operating conditions or use scenarios such as being dropped. If the environment that a stove is likely to end up in is well known, then meaningful ruggedness tests can be devised, but in the general sense ruggedness is more appropriately tested through in-field pilot programs and so is left out of the list of laboratory tests given here.

The last two items in the list, accommodation of a range of pots and accommodation of a range of fuels, appear to be simple design constraints. However, since the combustion efficiency and thermal efficiency (and by extension emissions and fuel use) vary based on fuel and the coupling between the stove and pot, any broadly applicable stove test must attempt to run the stove with a range of fuels and range of pot shapes and sizes. It also happens that these two characteristics are often critical to the acceptance of a stove and so should at least be verified before sending a stove into the field. One of the test protocols in wide use today, the University of California Berkeley Water Boiling Test (Bailis et al., 2007), requires using a single standardized fuel and a single standardized test pot. These features of the protocol were intended to make tests of different stoves directly comparable, but have led to accusations that the test is designed around a specific stove, and to the much more serious problem that the protocol encourages designs optimized for a single fuel and pot that may be entirely atypical of the intended use of the stove. In this respect, the test results from this protocol may be deceptive or meaningless, depending on one's interpretation.

3.4 Which metrics are most important?

A single test will be unable to capture information on all of the characteristics mentioned in the list in Section 3.3, so at the very least multiple tests will be required to capture this information. What one would really like is to be able to say that some pieces are less important and can be safely ignored. But it is difficult to say which characteristics should always be measured and which can be passed over, because, as mentioned before, each market has its own priorities and a characteristic that is unimportant in one may be critical in another. Even so, it is clear from experience that few organizations will be willing to undertake long and expensive testing (unless it is legally mandated), so some way is needed of reducing the characteristics to be measured to a set that contains only those characteristics that are usually the most important. Table 3.1 hints at one strategy: test all characteristics that are important to both users and external agencies. The downside of this approach is that it is too restrictive and has the effect of implying that the views of external agencies are more important than the views of users.

The major existing test protocols deal with this issue by testing the characteristics important to external agencies and adding in a few characteristics that the agencies have identified as commonly being important to users. The characteristics captured by the three major cookstove test protocols are thermal efficiency, fuel economy, emissions, high power, and low power. These three protocols also capture an explicit "time to boil" metric, which in our lists would be a component of the high power and low power metrics. It should be noted that the factors captured by the protocols do not include safety, fuel processing requirements, attentiveness to fueling, ease of control, ability to use a range of fuels or pots, exposure of user to waste heat, and stove durability. This work will not address these missing issues, but any developments of future tests should carefully consider these issues and how to deal with them adequately.

CHAPTER 4. ISSUES WITH THE BERKELEY TEST PROTOCOL

4.1 Introduction

There are three major laboratory protocols being used to test stoves in 2008: the UC Berkeley Water Boiling Test, a water boiling test promulgated by the government of India, and a water boiling test promulgated by the government of China. All three of these tests inherit their ideas and techniques from the VITA water boiling test that was developed in the early 1980s. There are minor differences between how these three tests are carried out, which equipment is specified, and so forth, but the underlying concepts are the same and they share many of the same problems. This chapter examines the UC Berkeley protocol and explore some of its problems. The UC Berkeley protocol was chosen for this examination because its lineage to the VITA test is clear, it has undergone a number of revisions since the 1980s, the Chinese test is largely based on it, it is the most common laboratory test used by European and American NGOs, and, most importantly, it is the framework which is being suggested as a possible international standard at the World Health Organization. If this test has problems, they should be identified and corrected because this test may well replace other tests.

4.2 Overview of Berkeley WBT protocol

The Berkeley Water Boiling Test (UCBWBT) protocol (Bailis et al., 2007), in its third revision as of 2007, is a water boiling type laboratory test that is intended to measure the thermal efficiency of a pot-stove system, specific fuel consumption (defined below), time-to-boil, and fuel burn rate. These metrics are measured in three use cases: a high power case in which the stove is cold at the start, a high power case in which the stove is hot at the start, and a low power case that requires maintenance of a sub-boiling simmer temperature. An emissions component has been added to this test by researchers at

Colorado State University, University of Illinois Urbana-Champaign, and a committee of the NGO Engineers in Technical and Humanitarian Opportunities of Service (ETHOS). The emissions component specifies protocols to measure carbon monoxide, carbon dioxide, and particulate matter emitted during the test. Although the emissions test is not yet officially part of the UCBWBT, the other performance metrics gathered during the UCBWBT heavily influence the interpretation of the emissions data.

Like all water boiling tests, the UCBWBT relies on temperature change and mass loss of water in a pot on the stove as an indication of heat transferred into the pot. The basic concept is straightforward: a known amount of fuel is burned in the stove, and the change in enthalpy of water in cookpot can be measured. If this is done over a specified time period, thermal efficiency, fuel consumption, etc. can be calculated. It will be useful to define each of the metrics reported by the UCBWBT before discussing potential issues with their capture or calculation. In all cases, the protocol specifies a particular type of cookpot to be used and requires that no lid be used on the pot.

4.2.1 Time to boil

The amount of time required to bring a pot with 5 kg of cool water to the local boiling point is measured during both of the high power tests. The reported metric has units of minutes and is calculated such that the temperature rise of the water is normalized to 75° C. The idea behind this metric is that users are frequently concerned about the length of time that a cooking operation will take, and having a standardized “time to boil” allows stoves to be compared in this regard.

4.2.2 Burning rate

The time-averaged rate of fuel mass loss is reported for all three sections of the test. This is reported as grams of dry fuel per minute. The procedure involves measuring the total mass of fuel burned in the stove, converting this to an energy basis, subtracting the amount of energy required to remove moisture from the fuel, then converting this energy back to a theoretical “dry fuel” basis. The reported figure does not include the calorific value of the fuel used, making the utility of this metric somewhat questionable in its current form. The intent is to provide a means of calculating the likely fuel mass requirement for a given task.

4.2.3 Thermal efficiency

The time-averaged thermal efficiency of the pot-stove combination is reported as a percentage. The test calculates this as the ratio of enthalpy change of the water in the cookpot to the maximum theoretically available energy from combustion assuming no condensation of moisture in the product gases. The protocol itself inexactly describes this quantity as the “ratio of the work done by heating and evaporating water to the energy consumed by burning wood,” but the calculated value is actually in line with the stated definition. The intent and usefulness of this metric has been the subject of much debate, dating back to the early 1980s when VITA suggested that the thermal efficiency had been previously given too much weight in the design process. The Woodburning Stove Group at Eindhoven subsequently released a number of papers in the late 1980s and early 1990s that attempted to refute this claim and restore thermal efficiency as a valuable metric. The current trend is to again de-emphasize the value of this metric. The 2007 revision of the UCBWBT warns the reader that

> A direct calculation of thermal efficiency derived from the Water Boiling Test is not a good indicator of the stove’s performance because it rewards the excess production of steam.

and

> As we state elsewhere, we wish to de-emphasize the role that thermal efficiency plays in discussions of stove performance and stress other, more informative indicators such as the burning rate and specific consumption at high and low power, and the turn-down ratio, which indicates the degree to which power output from the stove can be controlled by the user.

A major reason for the continuing disagreement about this metric is that different groups are using the test for slightly different purposes. In some cases the thermal efficiency is a useful metric, and in others it is not, which raises the question of whether a well-defined intent of the whole test has been properly established.

4.2.4 Specific fuel consumption

Specific fuel consumption is reported as grams of fuel per liter. Its definition is somewhat akin to fuel economy. From the UCBWBT:

> Specific consumption can be defined for any number of cooking tasks and should be considered "the fuelwood required to produce a unit output" whether the output is boiled water, cooked beans, or loaves of bread. In the case of the cold-start high-power WBT, it is a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with [a] cold stove.

Like the time to boil, this metric is normalized to a 75° C temperature rise, and like the burning rate, it is reported in terms of equivalent dry fuel. This specific fuel consumption is intended to be used as the main performance metric for determining whether a stove's fuel economy has been helped or hurt by a design change, and for comparing the fuel economy of two stoves.

4.2.5 Firepower

The time-averaged firepower is reported in watts. Interestingly, the firepower that is reported is not the useful power to the cookpot, but is instead simply the burn rate multiplied by the lower heating value of the fuel.

4.2.6 Turn-down ratio

The turn-down ratio is reported as a positive real number that is equal to the firepower of the stove at high power divided by the firepower of the stove at low power. Note that due to the definition of firepower used in this test, the turn-down ratio represents turn-down of the fueling rate and does not immediately yield useful information about the amount of turn-down of heat to the pot. Additionally, since the low power firepower is determined from a narrowly defined simmer process which may involve running the stove above its true minimum power, the stated turn-down ratio is actually the ratio between maximum available firepower and simmering firepower, and does not represent the full magnitude of turn-down for fueling rate. The intent of this metric is to report the amount of control the user has over available heats, but in its current form, this metric fails to provide this information.

4.3 Unknown correlation to field results

Since at least the VITA protocol of 1983, observers have noted the lack of an obvious correlation between results of laboratory water boiling tests and fuel consumption of a stove in the field. Bailis presented a talk on this subject at the 2007 ETHOS conference, and more recently Bailis et al. (2007) note in their updates to the UCBWBT that

> While lab-based tests allow stove developers to differentiate between well-designed and poorly-designed stoves, they give little indication of how the stoves are actually used by the people who are targeted by stove projects. In order to know if stove projects are having the desired impact (whether it is fuel conservation, smoke reduction, or both), the stoves must be measured under real conditions of use.

Curiously, the same authors also claim that

> Lab-based tests are also more appropriate when comparing stoves that are used in different regions of the world. There is a great amount of variation in cooking practices, fuels, and household environments throughout the world's developing regions that makes direct comparisons of actual stoves in people's kitchen very difficult.

It is unclear what the utility is of comparing two stoves that are used in different regions of the world if the test underlying the comparison gives as little information about real-world performance as the first quotation seems to indicate. Despite the unknown correlation between performance on the UCBWBT and performance in the field, the outputs of this test are being used to compare stoves for suitability in specific field applications, and there are anecdotal reports of program funding decisions being made based on performance on the test. In 2007 Aprovecho published a book titled *Comparing Cookstoves* that relies exclusively on the UCBWBT to rate stove performance. Although there is little indication at this point about how the information in this book is actually being used by agencies conducting cookstove projects, the title certainly implies its intended use.

4.4 Implicit assumptions in test procedure and reporting

Despite the protocol's authors' warnings about the utility of the UCBWBT, it is being used to compare stoves and to predict field performance, and is being suggested by some groups as the basis for international benchmark standards. A detailed review of the current test is in order, beginning by examining a few assumptions implicit in the test which either restrict its usefulness in meeting parts of its intended purpose, or which potentially lead to significant errors in the accuracy of reported metrics. The key assumptions that may cause problems are that the stove being tested in a continuous-feed stove, the fuel supply is homogenous, all water in the test vaporizes at the local boiling point, the ash content of the fuel is so small as to be unimportant, the procedure of sorting char from unburned fuel is unbiased, and the calorific value of char is 1.5 times that of raw fuel.

4.4.1 Continuous-feed

The UCBWBT implicitly assumes a continuous-feed stove. This is problematic because some of the key energy accounting operations specified in the test, notably removing, sorting, and massing hot fuel, can be unsafe or even impossible with a batch-feed stove. The test assumes that extinction can be effected through removal of the fuel supply, but as noted in Chapter 1, this is contrary to the batch-feed design. For many batch-feed stoves, this type of extinction involves tipping the stove to dump out a large mass of hot fuel. Since batch-feed devices usually rely on radiative heat transfer within the fuelbed to drive pyrolysis, a significant fraction of the total fuel mass is above the minimum temperature needed for pyrolysis and copious amounts of smoke are emitted during this procedure. Depending on the amount of time it takes to extinguish the flames on this pile and fuel and cool it down below the minimum pyrolysis temperature, significant errors in the amount of fuel actually used during the operating portion of the test may be created.

A second issue with the assumption of a continuous-feed stove has to do with the length of time required by certain parts of the test. A continuous-feed stove can be run indefinitely, because its burn-cycle time is not limited by an initial mass of fuel. If the stove must be run for 1.5 hours, this is no problem as long as the operator has the required quantity of fuel on hand. One simply feeds in more fuel to extend the test. Batch-feed stoves, by their nature, have a concrete time limit on the length of the burn cycle because they are limited by the mass of fuel that can be packed into the device before ignition. If the stove was designed to be able to run for 1 hour on a batch of fuel and the test calls for 1.5 hours, the stove will be unable to complete the test.

4.4.2 Homogenous fuel supply

The protocol assumes that fuel density, ash content, and moisture content are consistent throughout the fuel supply. While a requirement to have a homogenous fuel supply would be reasonable, it must not go unstated. The protocol's assumption of fuel homogeneity extends to partially burned wood. The method the protocol uses to determine the amount of energy used during the test involves extinguishing the fire and then removing any unburned fuel and char from the stove. This mass is then sorted into groups labeled unburned fuel and char. The unburned fuel is massed and subtracted from the mass of the initial pile of reserve fuel (which initially included fuel that would be used throughout the test). The difference is the amount of raw fuel that was consumed, and this is ascribed a total energy based on the fuel's lower heating value. The char is massed and is ascribed an energy based on 1.5 times the fuel's lower heating value. The energy of the char is then subtracted from the total energy to arrive at the net energy "consumed" during the test. This procedure fails to account for potential moisture differences between truly unburned fuel and fuel has not been visibly charred but has lost most of its moisture. The degree of error introduced depends on the initial moisture content of the fuel, the size and shape of the fuel, and the exposure of the fuel to radiation from combustion. In batch-feed and mixed-feed stoves this can be a severe problem because large masses of moisture may have been lost from apparently unburned fuel during the test, and the protocol will as a result underestimate the amount of available energy left in the unburned fuel, and thus overestimate the apparent fuel use.

Equally troubling is the common use of tables of biomass calorific values (these are actually built in to a calculation spreadsheet that is distributed with the UCBWBT protocol) to guess at the calorific value of the fuel a given test operator is using. Such pre-determined calorific values are useful when dealing with a very large sample of a given biomass species, but cannot be trusted when dealing with relatively small sub-samples of biomass on the scale of 1-2 kg because there is a high likelihood that such a sub-sample will not exhibit the average properties of the much larger sample. For example, the presence of bark in a test sample can increase the total ash content significantly and will affect the calorific value. Two obvious ways to address this issue readily present themselves: either require that a few samples of raw fuel from every test be subjected to bomb calorimetry, or run enough test trials to ensure that a stove has been run, on average, with the "average fuel." The protocol currently allows the reporting of results after three trial runs. It is exceedingly unlikely that such a few number of runs are statistically meaningful (for this issue in particular and for experimental noise issues in general).

4.4.3 Energy accounting

In addition to energy accounting errors resulting from uncertainty in the calorific value of the raw fuel, there are a few other energy accounting errors in the protocol. One error results from the assumption that the latent heat of vaporization of water is always 2260 J/g. Oddly, the protocol specifies a procedure to determine the local boiling point but does not then adjust the calculations involving vaporization of water to use the corresponding latent heat of vaporization. This is probably a simple oversight, but it may be a holdover from the historical debate about whether this test should be a tightly-controlled laboratory test or a looser, less accurate field test. In a loose, inaccurate field test, this sort of error would be completely swamped by other errors and it would not be worth the trouble to adjust the value of the latent heat of vaporization in the calculations. In a more tightly controlled laboratory test, there is simply no reason *not* to fix this conceptual error.

Two separate energy accounting errors, which will be discussed in more detail in Chapter 6, involve the assumption that everything that is labeled as char during the sort-and-mass procedure is indeed char. Depending on the burn length and fuel chemistry, there can be a significant amount of ash that is erroneously counted as char. Even with ash taken properly into account, the sorting procedure is consistently biased in the direction of overestimating the amount of energy contained in the remaining char.

A third energy error that also involves char is the test's assumption that char has a calorific value that is 1.5 times that of unburned fuel. In reality, the situation is not so simple and char's calorific value is influenced by the fuel chemistry and the time-temperature history of the char. Chars that have been exposed to higher temperatures have a higher calorific value than those that have been exposed to lower temperatures because the fuel becomes increasingly de-oxygenated with exposure to heat. This issue can become important in batch-feed stoves or other stoves that tend to produce a deep bed of char during the test.

CHAPTER 5. TEST MODIFICATIONS TO ACCOMMODATE BATCH-FEED STOVES

5.1 Introduction

Modern, high-volume manufacturers of stoves intended to burn wood, agricultural residues, and dung have tended to gravitate toward four basic designs: a continuous-feed, closely-coupled, counterflow, convection-dominated, room-exhaust, natural draft “rocket” stove; a continuous-feed, closely-coupled, counterflow, conduction-dominated, outside-exhaust, natural draft “plancha” stove; a mixed-feed, loosely-coupled, concurrent-flow, convection-dominated, room-exhaust, forced draft stove; and a batch-feed, loosely-coupled, counterflow, convection-dominated, room-exhaust, forced draft stove. The first three designs together are being commercially produced in quantities of perhaps 500,000 per year, but a single large manufacturer is now producing a stove of the last design in quantities of roughly 100,000 per year. With a market in which a significant fraction of batch-feed stoves are being produced on a large scale, it is clearly problematic that the laboratory test being pushed as suitable for regulatory purposes does not accomodate batch-feed stoves very well, as indicated by the number of issues raised in Chapter 4 that especially affect batch-feed stoves. Luckily, the situation is not intractable, and a few changes to the protocol can help put batch-feed stoves on a more equal footing with continuous-feed stoves.

In developing the following modifications of the existing protocol, several criteria were kept in mind:

1. Fueling: Fuel should not be added to a batch-fed stove while it is in operation, since doing so would violate the idea of batch feeding.

2. Operation: No portion of the test should require operating the stove outside of its design param-

eters.

3. Safety: Test modifications should not negatively impact the safety of the test operator.

4. Intent: Modifications to the test should not violate the spirit and intent of the original test.

5. Broad Applicability: Where possible, modifications should also be applicable to continuous-feed or mixed-feed stoves; that is, ideally the modifications should not "break" the test for these other stoves.

5.2 Operating cycle

The amount of fuel required to complete the combined hot-start and simmer sections of the test may be more than the stove is designed to hold. In its current form, the WBT indicates that the fuel left at the end of the hot-start section be put back into the stove and re-lit, and further assumes that fuel can be added to the stove as necessary. Since batch-fed devices are not designed so that fuel can be added during operation and few are designed to allow hot-starting, the simmer section of the existing WBT is difficult at best to apply to batch-feed stoves. The suggested modification for this situation addresses both this problem as well as the general problem of unsafe hot-starts at the beginning of the simmer section of the test.

Suggested modification: Rather than placing hot fuel back into the stove at the beginning of the simmer section of the WBT, the tester should allow the stove to cool down until it is safe to refuel, and then refuel it with a new charge of unburned fuel. This is in contrast to the current procedure, which calls for replacing a hot mix of unburned and partially-burned fuel into the stove and re-lighting it. A pot of water should be brought to boiling using another stove or other heating device. The stove should then be lit, and the pot of boiling water removed from the other heating device, quickly massed, and then placed on the stove being tested. The pot should be left on the stove as long as the stove is capable of maintaining a simmering temperature. Once lit, fuel should not be added to the stove. The amount of actual simmer time should then be recorded as the time this stove is capable of maintaining "simmering" as defined by the WBT. This simmering time should be reported as a figure or merit alongside other figures such as thermal efficiency, specific consumption, etc. The remaining fuel in the stove should be removed, sorted, and massed as in the unmodified test, but these figures should only be used in the calculation of firepower and thermal efficiency. The specific fuel consumption calculation should assume that there was no fuel remaining in the device, because in this case the leftover fuel represents energy that could not be used to complete the task.

Rationale: This modification to the test clearly satisfies the fueling, operation, and safety criteria mentioned earlier. It also satisfies the broad applicability criterion because simmer performance of continuous-feed and mixed-feed stoves could also be tested in this manner, although there is no reason to extend the simmer time of such stoves beyond 45 minutes – if they are capable of simmering at all, they are capable of simmering indefinitely. Safety is greatly enhanced for stoves or fuels that require an accelerant to light because the accelerant can now be added to cold, raw fuel rather than hot, partially burned fuel. Once again, satisfaction of the intent criterion requires the most explanation.

The simmering section of the WBT is intended to measure a stove's performance and ability to maintain a relatively low and consistent power level similar to that used in some cultures to cook rice or beans. It is important to realize that the existing test does not measure the performance of the stove in a way that integrates the initial high power boiling process with the low power simmering process – instead, there is an explicit separation between the two power regimes. This modification to the test preserves a similar separation between the two power regimes, but allows a meaningful judgment of how the low-power regime is used in batch-fed devices without causing unnecessary safety risks. The presentation of simmering time that the fuel-stove combination is capable of is a useful figure of merit in determining whether a particular fuel-stove combination may work for a given cooking culture.

The reason for using the remaining fuel to calculate only firepower and thermal efficiency but not specific fuel consumption is that the firepower and thermal efficiency only make sense if the energy in the remaining fuel (most likely all char at this point) is properly accounted for. The specific consumption, on the other hand, should properly be defined by the total amount of fuel used to complete the task. In a batch-feed stove, the total amount of fuel used to complete the task is whatever was initially put into it. The specific fuel consumption of batch devices used for simmering will likely appear to be higher than that of many continuous-feed stoves, and it may be tempting to assume that this difference in how specific fuel consumption is calculated makes the consumption of batch-feed devices appear artificially high. The reverse is actually true: the existing protocol for dealing with continuous-feed stoves makes their specific fuel consumption on the simmer test appear artificially low. Most real-world cooks do not snuff the fire and remove the fuel from the stove once the cooking is complete; instead, they simply let the remaining fuel burn out. There are exceptions, such as refugee camps, in which cooks may actually remove the fuel from the stove, snuff it, and save it for later, but this does not appear to include the majority of users. If the WBT is being used to compare two stoves strictly on the basis of specific fuel consumption as a predictor of field performance, the procedure for continuous-feed stoves should be altered to reflect this fact.

5.3 Safety

Hot-starting, the practice of building a new fire in a stove that is still hot from the previous fire, is difficult and unsafe in some batch-feed stoves because fuel cannot be easily loaded while the stove is hot. In other stoves, the lighting procedure may require the use of accelerants (such as kerosene or alcohol) that are unsafe to use near hot surfaces. Two sections of the WBT require hot-starting the stove: the "hot-start" section and the "simmer" section. The type of start required in the simmer section is potentially more unsafe than the one required at the beginning of the hot-start section because in addition to the walls of the stove being hot, the fuel is hot. For fuel-stove combinations that require an accelerant to start, hot fuel can lead to very fast vaporization and flaring of the accelerant, creating an unnecessary risk for the test operator.

Suggested Modification (hot-start section): The hot-start portion of the test should be performed only if the stove is designed so that it is safe to do so. If the design of the stove is such that a hot-start is unsafe, impractical, or would simply never be done during normal use, then the hot-start portion of the test should not be performed. Results for this section of the test should be presented as "not applicable" along with a short explanation of why a hot-start should not be performed on the stove. Suggested standard explanations are "Unsafe to load while hot", "Unsafe to light while hot", and "Not designed for cooking tasks that require hot-start". It should be noted that certain types of batch-feed stoves are safe to hot-start, and will be used this way in practice; for these stoves, the hot-start section of the WBT should still be performed.

Rationale: The logic of omitting a test procedure in cases in which it is unsafe or meaningless in terms of real-world use should stand on its own without further explanation. The question then becomes whether this modification is in line with the five modification criteria stated earlier. The fueling criterion is clearly satisfied. The operation criterion is satisfied since this modification allows the tester to omit the section that requires the stove to be operated outside of its design parameters. The safety criterion is satisfied since the modification allows the test section to be omitted if it is deemed unsafe. The modification satisfies broad applicability because this modification will work fine with continuous-feed stoves, some of which may be unsafe to light hot, and the modification does not break the test for other stoves. The intent criterion is somewhat trickier and requires more explanation.

The hot-start section of the WBT was originally developed based on field experience with stoves that have high heat capacities. Examples of such stoves are the Lorena stove, Prolena's Ecofogon, and most user-built clay stoves. The high heat capacity of these stoves results in much of the heat that is generated early on from a cold start being absorbed by the body of the stove, significantly lowering the heat available to the pot or food being cooked. Stoves like this often exhibit a large increase in apparent heat transfer efficiency to the pot once the bulk of the stove has warmed up. Since these high heat capacity stoves are frequently used to cook large meals that require many hours of cooking, the user is likely to experience this change in heat transfer efficiency during normal operation. In order to capture the performance of these stoves in such a usage pattern, the hot-start section of the WBT was added in order to simulate the effect of running the stove for an extended period of time.

Batch-feed stoves used for cooking applications will also experience a change in heat transfer efficiency once they heat up, but the practical effect is often different from the case of a continuous-feed stove. Many batch-feed cookstoves have relatively small fuel chambers, capable of holding only enough fuel for a 30-45 minute burn. The difference in heat transfer efficiency that occurs after the stove heats up is thus hidden from the user in a practical sense, because in many cases, only a single high-power cooking task can be performed during the burn time of the stove. For small batch-feed stoves that cannot be refuelled while hot (due to safety or impracticality), the end result is that all real-world fires are cold-start fires. Thus, omitting the hot-start section of the WBT when testing such stoves actually preserves the intent of the test better than ignoring the reality of the stove's design parameters and performing the hot-start section anyway. Other batch-feed stoves are designed with long burn times in mind, and this presents a very different use case. For such a stove, the batch-cycle performance is probably much more important than the cold start or hot start portion alone. Most such batch-feed stoves will be on the scale of institutional stoves, and should likely be tested differently from smaller home-use stoves anyway.

5.4 Energy accounting

5.4.1 Reducing sort-and-mass error while increasing safety

Separation of char from unburned fuel can be a time-intensive and error-prone process in batch-feed devices, particularly those which use pellet fuels. The way that energy accounting is performed in the WBT involves quenching the fire and separating unburned fuel from char after completing a given task such as bringing a pot of water to a boil. The unburned and char fractions are then massed, and the remaining energy content is estimated. In the case of batch-feed stoves, the process of sorting unburned fuel from char is difficult and time-intensive because hot, burning char is mixed in with unburned fuel. The pieces of fuel are usually small, since many batch-feed devices rely on pellets or small briquettes, and tongs must be used to sort the fuel fractions. That the existing WBT requires this process to be carried out very quickly between the hot-start and simmer portions of the test only amplifies the problem and leads to excess error in the data.

Suggested Modification: The previous two suggested modifications go a long way to addressing this problem because they remove much of the time pressure in weighing the fuel by requiring that a new charge of fuel be used in the stove at the beginning of both the hot-start and simmer sections. In addition to those modifications, it is suggested that pellet fuels be emptied directly into a metal pot with a tight fitting lid, both of known mass. The pot should not be significantly larger than the anticipated volume of fuel that it must contain (3x to 5x is a reasonable ratio). The lid need not be entirely air-tight, but should seal well on the rim of the pot in order to drastically lower the amount of oxygen available to the fuel inside. The lid should be placed on the pot after the fuel has been put in. The pot with fuel and lid should be massed and then set aside for about ten minutes to allow the fuel to cool down. The fuel should then be sorted and massed. The following calculation procedure should be followed to determine the final masses of unburned fuel and char. Let $m_{snuff\,pot,empty}$ be the mass of the empty pot with lid. Let $m_{snuff\,pot,full}$ be the mass of the pot with lid and containing all fuel removed from the stove at the end of the test. Then:

$$m_{fuel\,in\,pot} = m_{snuff\,pot\,full} - m_{snuff\,pot\,empty}$$

If m_{char} is the mass of char measured after the fuel has cooled and has been sorted, $m_{unburned\,fuel}$ is the mass of unburned fuel measured after the fuel has been sorted, then

$$m_{fuel\,solids} = m_{char} + m_{unburned\,fuel}$$

and finally

$$m_{unburned\,fuel,corrected} = m_{unburned\,fuel} + m_{fuel\,in\,pot} - m_{fuel\,solids}$$

The final masses of char and unburned fuel that should be used for estimating the remaining energy content of the fuel are given by m_{char} and $m_{unburned\,fuel\,corrected}$, respectively. The char mass given here, m_{char}, should be treated as an uncorrected char mass as per Section 6.3.3.

Rationale: In this case, the fueling, operation, safety, and intent criteria are all implicitly satisfied. The modification can also be applied to continuous-feed stoves without much trouble, and so satisfies the broad applicability criterion. The most attractive feature of dealing with fuel in this manner is that the test operator can avoid having to expose herself to the risks associated with breaking apart and sorting very hot fuel. The extra time and improved safety provided by this modification allow the tester to examine the fuel more critically, and more accurately break char off of the unburned fuel. The purpose of the calculation procedure given above is to account for the gases that continue to be driven off of the fuel as long as there is unburned fuel that is hotter than 250° C. In the oxygen-starved environment inside the closed pot, the conversion of fixed carbon (char) to gases ceases very quickly, but the pyrolysis of unburned fuel will continue until the fuel is sufficiently cool. When the pot is opened after ten minutes to begin sorting and weighing the fuel fractions, thick smoke will billow out of the pot for a few seconds. The lid will also be covered by droplets of condensed gases. Given that the char reaction halts much more quickly than the pyrolysis reaction, most of this smoke and condensed liquid is due to pyrolysis of the unburned fuel, so the mass that is lost to this smoke and liquid should properly be ascribed to the unburned fuel fraction.

5.4.2 Dealing with stoves from which fuel cannot be removed

Some batch-feed devices are designed such that it is impractical or extremely unsafe for hot fuel to be removed from them during operation. In some cases, fuel can be relatively safely removed from small batch-feed devices by turning them on their side and raking the fuel out with long tongs or some similar implement. In other cases this may be impossible because the stove is permanently affixed to the floor and cannot be tipped, or there may be a safety mechanism that closes off the fuel chamber when the stove is tipped. There may be other reasons that the fire cannot be quenched and the fuel removed during operation. Since the fuel cannot be removed at the completion of a task and massed, one must use a different method to estimate the energy remaining in the fuel.

Suggested modification: This modification involves two sections: a calibration section that must be performed for each stove model, and a test section. The method involves selecting a power at which the stove can be consistently run, and using a calibrated pot to determine the amount of energy left in the fuel after the test portion. This modification does not replace basic tests such as the cold, hot, or simmer tests, but instead provides a way to estimate the amount of energy remaining in the fuel at the end of such tests for stoves for which the quench-sort-and-mass procedure is not possible. The use of this modification also allows the determination of hot-start performance for large batch devices that have a high heat capacity, if that is deemed necessary.

Calibration section: The purpose of the calibration portion of this modification is to determine the stove-pot coupled efficiency for a specific pot being heated at a reproducible firepower. This pot and firepower can then be used at the end of tests run at other firepowers or with other pots in order to determine the amount of energy remaining in the fuel at the end of the test. This calibrated pot will be referred to as the burnout pot, and the chosen firepower as the burnout firepower.

The burnout pot should be filled with 5 kg water and the mass and temperature recorded. Measure out a “normal” batch of fuel as usual, light, and place pot on the stove. The stove should be run at the burnout firepower, which must be reproducible and as constant as possible. A lid or floating insulation should be used with the pot in order to suppress convection currents over the water’s surface that would cause vaporization. Allow the water to come to a boil and then begin to closely monitor the pot. When the firepower of the stove drops low enough that it can no longer maintain a boil, pull the pot off the stove and mass it to determine the moisture lost to evaporation. Calculate the enthalpy change of water in the pot as

$$\Delta h_{water} = m_{water,initial} \cdot c_{p,water} \cdot \Delta T_{water} + m_{water,vaporized} \cdot h_{fg,boiling}$$

where $h_{fg,boiling}$ is the heat of vaporization at the local boiling point. One may safely assume that the bulk of vaporized water will be vaporized very close to the boiling point due to the presence of the lid or insulation, making it acceptable here to ignore the actual temperature dependence of h_{fg}. Calculate the fuel energy used as

$$E_{fuel,used} = m_{fuel,batch} \cdot LHV_{fuel}$$

where LHV_{fuel} is the lower heating value of the fuel on an as-received basis. Note that this assumes the entire fuel mass was used, even though there is likely a small amount of fuel remaining in the stove. The burnout efficiency is then taken as the long-range average efficiency for the entire process; that is,

$$\eta_{burnout} = \frac{\Delta h_{water}}{E_{fuel,used}}$$

This process should be repeated at least five times to get a meaningful average for the burnout pot efficiency. Once the calibration portion has been completed for a given stove design, it need never be performed again for that stove design unless the tester decides to use a different burnout pot or burnout firepower, or, obviously, if the stove design is changed in a way that would affect heat transfer efficiency.

Test section: The purpose of the test section is to test the stove for performance at any desired firepower or operating condition. The basic process is to run whichever test (cold start, hot start, simmer) is needed, then replace the test pot with the burnout pot and adjust the stove to burn at the pre-determined burnout firepower. This procedure will allow the tester to estimate the energy that was left in the fuel remaining at the end of the test period, and so calculate efficiencies, emission factors, etc.

The test could be a cold start, hot start, simmer test, or any other test that is needed. Once the required physical event or time period has passed, the test pot should be removed from the stove and replaced with the burnout pot containing 5 kg of cool water of known temperature (with lid or insulation, however it was originally calibrated). The burnout pot should be left on the stove and the temperature of the water monitored until one of the following occurs:

1. If the burnout pot came to a boil, remove the burnout pot when boiling ceases.

2. If the burnout pot does not get hot enough to boil, then remove the burnout pot once the temperature of the water has reached its peak and begins to drop.

The idea is to remove the burnout pot before it begins to recapture a significant amount of heat from the body of the stove. The following calculation can then be used to estimate the energy that remained in the fuel at the end of the test period:

$$E_{fuel,remaining} = \frac{\Delta h_{water}}{\eta_{burnout}}$$

The energy used during the test period is then

$$E_{used,test\ period} = m_{fuel,initial} \cdot LHV_{fuel} - E_{fuel,remaining}$$

Rationale: The modification presented here preserves the fundamental intent of the test in that it allows the capture of performance metrics at high and low power, and allows the amount of fuel used to be related to the same tasks as the unmodified WBT. This modification could also be used with continuous-feed or semi-continuous-feed stoves by using the burnout pot while burning the fuel remaining at the end of a test section, rather than quenching the fire, sorting char from unburned fuel, and massing. For stoves that use long sticks, this modification may not offer an improvement in accuracy, but it is likely to offer an accuracy improvement for stoves that use pellets or other small, discrete chunks of solid fuel. For such discrete fuels, the process of sorting char from unburned fuel is error-prone, and this burnout process may be more accurate. [1]

[1] This modification was originally suggested by Crispin Pemberton-Pigott as an alternative to using the Indian method of continually putting on new pots of cool water. It remains to be seen whether this method is more or less accurate than the Indian method, but it certainly requires less work to perform repeated tests once a stove-pot combination has been calibrated.

CHAPTER 6. FURTHER EXPLORATION OF ENERGY ACCOUNTING ERRORS

6.1 Introduction

Chapter 4 briefly mentioned a few errors in the energy accounting procedure of the UCBWBT. If the UCBWBT is to be used as the basis for emissions testing, it is important to better understand these energy accounting errors so that they can be corrected and improve the accuracy of the test, and that is the focus of this chapter. Where there is sufficient existing data, the likely magnitude of these errors is indicated. This is necessary in part because the dose-response curves for some emissions species are nonlinear, and a small difference in emission/megajoule could lead to a noticeable difference in health effects.

6.2 Effective calorific value of fuel

The effective or net calorific value of the test fuel, defined as the dry-basis lower heating value (LHV) minus the energy required to evaporate moisture in the fuel, is used throughout the UCBWBT to estimate the available energy in the fuel. In specifying the calculation method to determine the effective calorific value, the test's authors have implicitly assumed that all tests will be conducted at a pressure of 1 atm and make no note that the calcluations must be altered to reflect the actual conditions at the test location. In Section 4.4.3, it was mentioned that the test consistently assumes that water evaporates at 100° C; this is one specific area in which that assumption may cause problems. When adjusting the fuel's energy content for moisture, the current protocol specifies that the mass of water be multiplied by 2260 kJ/kg. There are two problems with this method: the first is that this calculation is only meaningful if the original LHV was specified with a reference state at 100° C. It is somewhat unusual for LHV to be specified with a reference state at 100° C; much more common for solid fuels is a reference state at 25° C. The second problem with this calculation is that it assumes the fuel moisture will be vaporized at 100° C, irrespective of the local boiling point.

Combining these two issues, it is easy to examine the extreme case in which a reference state of 25° C is used for LHV and moisture is assumed to evaporate at 25° C versus the other extreme case in which a reference state at 100° C is used for both enthalpies. The LHV can be calculated from knowledge of higher heating value on a dry basis, HHV, along with percent hydrogen content on a dry mass basis, h, percent moisture content on a wet mass basis, MC, and the heat of vaporization, h_{fg}, at the chosen reference state via

$$LHV = (1 - MC/100) \cdot HHV - \left(\frac{MC}{100} + \frac{h \cdot (1 - MC/100)}{100} \cdot 9 \right) \cdot h_{fg}$$

For a reference state of 25° C, h_{fg} equals 2442 kJ/kg, and 2256 kJ/kg for a reference state of 100° C. Using a hydrogen content of 6 percent and an HHV of 20,000 kJ/kg, both of which are typical values for biomass fuels, the percent difference between the two values of LHV, calculated as $percent\ difference = \frac{LHV_{2256} - LHV_{2442}}{LHV_{2442}}$, is shown in Figure 6.1 over a range of moisture contents. The figure indicates that even at a very high moisture content of thirty percent (wet-basis), the relative difference between the calculated LHVs is only slightly more than one percent. Considering that this is well within the uncertainty of the HHV of most fuels, one may conculde that it is safe to ignore this particular issue.

6.3 Char energy content

Most of the energy accounting issues with the UCBWBT involve estimating the amount of energy contained in the fuel remaining at the end of the test. Unsurprisingly, this means that wood that has been converted to char is the most frequent culprit. There are two main ways in which the energy content of the char may be estimated erroneously: by using an incorrect calorific value for the char, and by incorrectly labeling char as unburned fuel (or *vice versa*).

6.3.1 Incorrect calorific value

The UCBWBT calls for treating all char as though it has one and one half times the calorific value of the unburned fuel from which it was produced. This assumption can be seen to be questionable

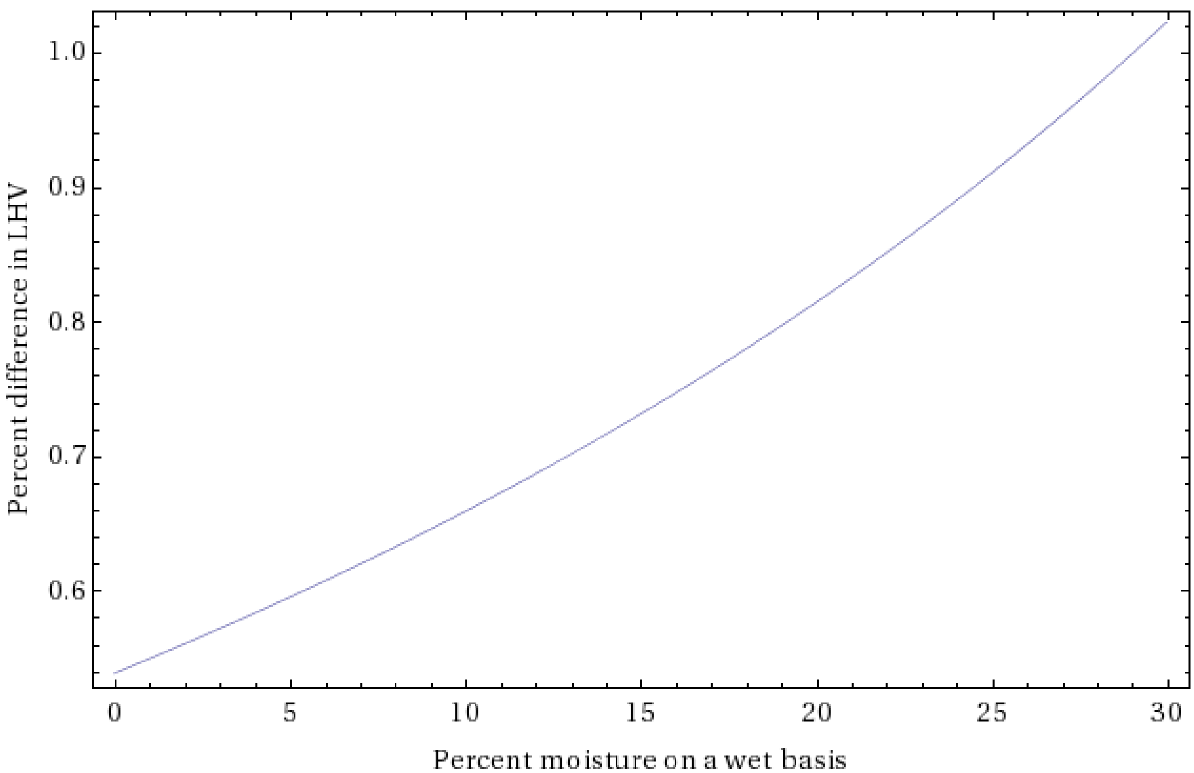

Figure 6.1 Percent difference between lower heating values with reference states at 25° C and 100° C

simply by examining a table, such as Table 6.1, which shows the calorific values of a few common biomass fuels and their chars.

In addition the effect of raw fuel chemistry on the calorific value of the char, the time-temperature history of the char also has an effect on its calorific value. The conversion of raw fuel to char is not a single, fixed-temperature process, but a temperature-dependent process that first involves the evaporation of moisture from the fuel. Once the moisture is gone from a layer of fuel, that layer is able to heat up to a temperature above the boiling point of water and begins to undergo the chemical decomposition called pyrolysis or carbonization. During this stage, the lighter volatile compounds of the fuel are driven out at lower temperatures, while those compounds that are bound to the fuel with higher-energy bonds require higher temperatures before being driven off. Once all of the volatile chemicals have been driven away, only char (pure carbon) and ash remain in the fuel. This state of pure carbon is truly attained only at very high temperatures in a reducing environment. In a practical stove, the “char” that is removed at the end of a test will be chemically, and therefore calorifically, somewhere between raw fuel and pure carbon. In order to understand the effect this may have on estimates of the energy remaining in the fuel at the end of a test, it will first be instructive to examine Table 6.2, which shows the variation of the LHV of chars formed at different temperatures for six biomass fuels. The literature from which these values were pulled (references shown in the table) gives data as HHV, but this is not directly useful for our purposes here because a rise in HHV could theoretically be offset by a rise in mass percent of hydrogen (if, for example, oxygen was selectively blown off during carbonization). It is easy to show that hydrogen drops as a percentage of total mass with rising carbonization temperature, but it is still better to convert HHV to LHV. In order to be able to convert HHV to LHV, only data for which the associated chemical compositions and moisture as a percentage of mass were given is used, allowing the conversion of HHV to LHV via

$$\begin{aligned} LHV &= \left(1-\frac{MC}{100}\right)HHV - \Big(\frac{MC}{100}\frac{kg\,H_2O}{kg\,fuel} + \frac{h\cdot(1-MC/100)}{100}\frac{kg\,H_2}{kg\,fuel} \\ &\quad \cdot\frac{1}{2}\frac{kmol\,H_2O}{kg\,H_2}\cdot 18\frac{kg\,H_2O}{kmol\,H_2O}\Big)\cdot 2442\frac{kJ}{kg\,H_2O} \end{aligned}$$

where LHV and HHV both have units of $\frac{kJ}{kg\,fuel}$, MC represents moisture content (on a wet mass basis) as a direct percentage; ie, 6%=6, and h is the hydrogen content on a percent dry mass basis.

Fuel	LHV (kJ/kg)	Char LHV (kJ/kg)	LHV / Char LHV	Reference
White Oak	18,237	22,588 (@565 C)	1.24	Gaur and Reed (1998)
Redwood	19,733	28,114 (@550 C)	1.42	Gaur and Reed (1998)
Quercus rotundifolia	18,384	32,193 (@ 550 C)	1.75	Cordero et al. (2001)
Pinus halepensis	18,896	30,976 (@550 C)	1.64	Cordero et al. (2001)
Casuarina	18,158	26,916 (@ 950 C)	1.48	Gaur and Reed (1998)
Eucalyptus	18,130	27,308 (@ 950 C)	1.51	Gaur and Reed (1998)

Table 6.1 Dry-basis lower heating value of some common biomass fuels and their chars

	Carbonization Temperature (° C)												
		230	250	270	290	300	350	400	450	500	550	600	
Fuel	Raw LHV (kJ/kg)	Char LHV/Raw LHV											Reference
Reed Canary Grass	17,045	-	1.07	1.13	1.18	-	-	-	-	-	-	-	Bridgeman et al. (2008)
Wheat Straw	16,591	1.07	1.10	1.17	1.28	-	-	-	-	-	-	-	Bridgeman et al. (2008)
Willow	17,983	1.04	1.07	1.11	1.14	-	-	-	-	-	-	-	Bridgeman et al. (2008)
Quercus rotundifolia	18,384	-	-	-	-	1.20	1.45	1.53	1.63	1.61	1.75	1.75	Cordero et al. (2001)
Pinus halepensis	18,896	-	-	-	-	1.15	1.36	1.45	1.53	1.59	1.64	1.66	Cordero et al. (2001)

Table 6.2 Carbonization temperature dependence of char calorific value

Table 6.2 very clearly shows that the matter removed at the end of a test which visually appears to be charred fuel may have a fairly large range of calorific value depending on its temperature exposure history inside the stove. Looking at the extreme cases, assuming $LHV_{char}/LHV_{raw\,fuel}$ to be equal to 1.5 when it is actually equal to 1.75 will result in an estimate of remaining energy that is actually 14% too low, and assuming $LHV_{char}/LHV_{raw\,fuel}$ to be equal to 1.5 when it is actually equal to 1.04 will result in an estimate of remaining energy that is 44% too high. Since running a stove at different firepowers or with slightly different fuels will result in different time-temperature histories for the fuel, it is difficult to say when this issue may be problematic, or even how to identify it without running other tests. Calorimetry of the leftover fuel from many trials using different fuels, stoves, and burn rates could be used to better understand how different conditions in the stove affect the average calorific value of the remaining chars. This issue also points toward the advantages of methods, such as the one described in Section 5.4.2, which do not require knowledge of the calorific value of the char but instead require only that the calorific value of the as-received fuel be known.

6.3.2 Incorrect sorting of char from unburned fuel

The process of sorting char from unburned fuel at the end of the UCBWBT's test sections represents a potential source of analytical bias. As mentioned previously, char and unburned fuel are sorted and then massed separately, with different calorific values assigned to each in an attempt to estimate the amount of energy remaining in the fuel, and thus the amount of energy used during the test. The energy remaining in uburned fuel and char at the end of a test section may be calculated as

$$E_{remaining} = m_{unburned\,fuel} \cdot LHV_{fuel} + m_{char} \cdot LHV_{char}$$

Considering the ratio of calorific value of char to calorific value of unburned fuel, it can be shown that errors in the sorting procedure can lead to significant errors in the energy estimates. Although one might hope that such errors would balance themselves out over the course of a number of trials, this is unlikely because a balancing out of this effect would require alternately overestimating and underestimating the *mass* of char. But sorting takes place visually and it is much more likely that if there is any balancing out of error, it will be based on volume. Char has a density that is roughly half that of raw fuel (for wood, at least), and since the sorting process is done on a visual basis, it is much more likely that in terms of mass, raw fuel will be counted as char rather than *vice versa*. To do otherwise would require that a much larger volume of char be labeled as raw fuel.

To illustrate this, assume that in the course of testing a stove, one has produced a certain volume of char and is left with a certain volume of apparently unburned fuel (which had made it as far as being put into the stove). The expression for energy remaining may be put on a volumetric basis as

$$E_{remaining} = \rho_{fuel} \cdot v_{unburned\,fuel} \cdot LHV_{fuel} + \rho_{char} \cdot v_{char} \cdot LHV_{char}$$

By introducing a mislabeled volume of fuel, Δv, it can be seen that char mislabeled as unburned fuel will result in

$$E_{rem,caf} = \left(\rho_{fuel} \cdot v_{unburned\,fuel} + \rho_{char} \cdot \Delta v\right) LHV_{fuel} + \left(\rho_{char} \cdot v_{char} - \rho_{char} \cdot \Delta v\right) LHV_{char}$$

and unburned fuel mislabeled as char will result in

$$E_{rem,fac} = \left(\rho_{fuel} \cdot v_{unburned\,fuel} - \rho_{fuel} \cdot \Delta v\right) LHV_{fuel} + \left(\rho_{char} \cdot v_{char} + \rho_{fuel} \cdot \Delta v\right) LHV_{char}$$

Making the substitutions $\rho_r = \frac{\rho_{char}}{\rho_{fuel}}$, $\xi = \frac{LHV_{char}}{LHV_{fuel}}$, $t = \frac{\Delta v}{v_{unburned\,fuel} + v_{char}}$, and $R = \frac{v_{unburned\,fuel}}{v_{unburned\,fuel} + v_{char}}$, noting that $\frac{v_{unburned\,fuel}}{v_{unburned\,fuel} + v_{char}} = 1 - R$, and dividing by $E_{remaining}$, it can be shown that

$$\frac{E_{rem,caf}}{E_{remaining}} = \frac{(R + \rho_r \cdot t) + (\rho_r (1 - R) - \rho_r \cdot t)\,\xi}{R + \rho_r \cdot \xi\,(1 - R)}$$

and

$$\frac{E_{rem,fac}}{E_{remaining}} = \frac{(R - t) + (\rho_r (1 - R) + t)\,\xi}{R + \rho_r \cdot \xi\,(1 - R)}$$

By assigning a ratio of densities, ρ_r, and ratio of calorific value, ξ, to the unburned fuel and char, it is possible to plot of the ratio of estimated energy to actual energy if one perturbs about the "true" value volumetrically. Figure 6.2 shows via the topmost (solid) line the effect of progressively mislabeling a certain volumetric fraction of raw fuel as char. The bottomost (dashed) line shows the effect of mislabeling char as raw fuel. The middle (dotted) line allows one to easily judge the relative deviations of the other two from the case of no mislabeling. Since the area between the topmost line and the middle line is greater than the area between the bottomost line and the middle line, the figure shows that if a consistent volume of fuel is alternately mislabeled into one category or the other, the net effect will be to overstate the amount of energy in the remaining fuel. In this way, random errors

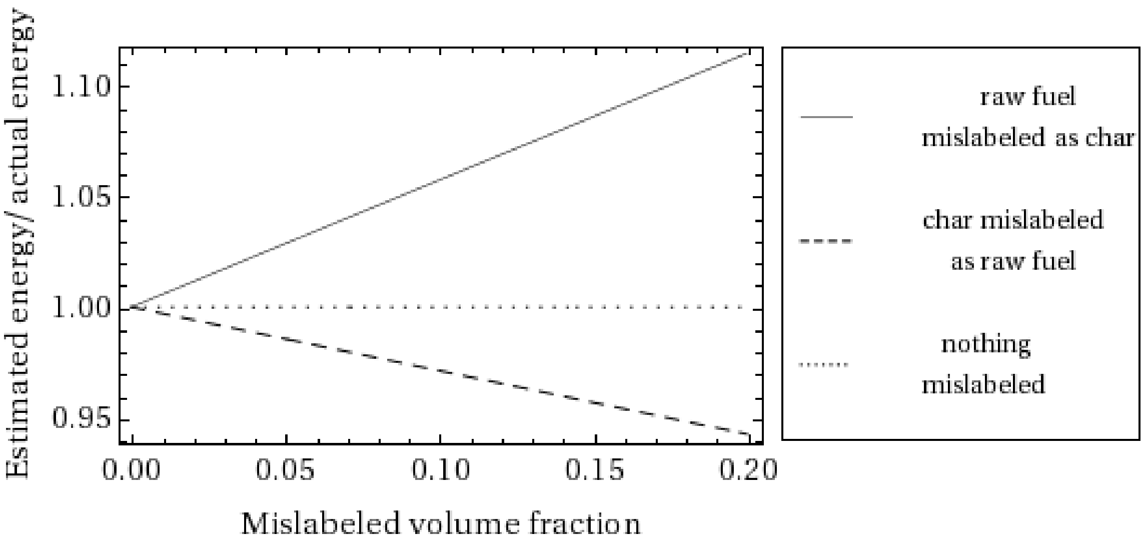

Figure 6.2 Effect of sorting errors on estimate of energy remaining in the fuel, using density ratio $\rho_r = 0.5$ and energy ratio $\xi = 1.5$.

do not cancel out but lead to a definite bias. Figure 6.3 shows the relative bias in energy values that would occur over a range of mislabeled volume fractions, density ratios, and energy ratios using a fixed volume fraction of unburned fuel, $R = 0.5$. The relative bias here is defined as $Relative\,bias = \left(\frac{E_{rem,fac}}{E_{remaining}} - 1\right) - \left(1 - \frac{E_{rem,caf}}{E_{remaining}}\right)$. Figure 6.4 shows the relative bias in the same way, but with energy ratio fixed at 1.7 and the volume fraction of unburned fuel, R, left to vary. As should be expected, the influence of energy ratio is greater than that of volume fraction of unburned fuel. Taken together, both figures indicate that there is always a bias toward overestimating the amount of energy remaining in the fuel at the end of a test.

6.3.3 Failure to address ash content

When sorting and massing the unburned fuel and char fractions remaining at the end of a test section, the current UCBWBT protocol does not properly account for ash content, but instead counts ash mass as char mass. For relatively short tests with most woods, this will not be a large source of error, but with dung or agricultural residue, or with long tests in stoves that are very effective at burning up their char, the counting of ash as char could introduce a serious error. The current protocol specifies placing all fuel sorted as "char" into a metal container and then massing this container. One

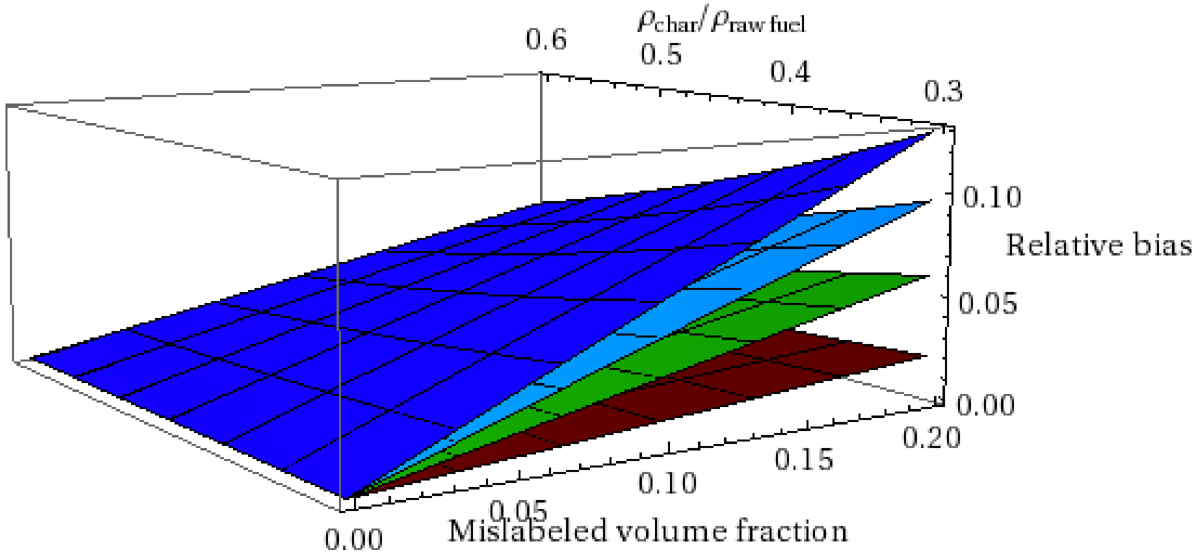

Figure 6.3 Relative bias in energy calculation during sort-and-mass procedure as a function of mislabeled volume fraction, density ratio, and energy ratio (ξ). The latter is represented here by the distinct surfaces with red surface representing $\xi = 1.1$, the green surface $\xi = 1.3$, the cyan surface $\xi = 1.5$, and the blue surface $\xi = 1.7$. In all cases, the volume fraction of unburned fuel is set to $R = 0.5$.

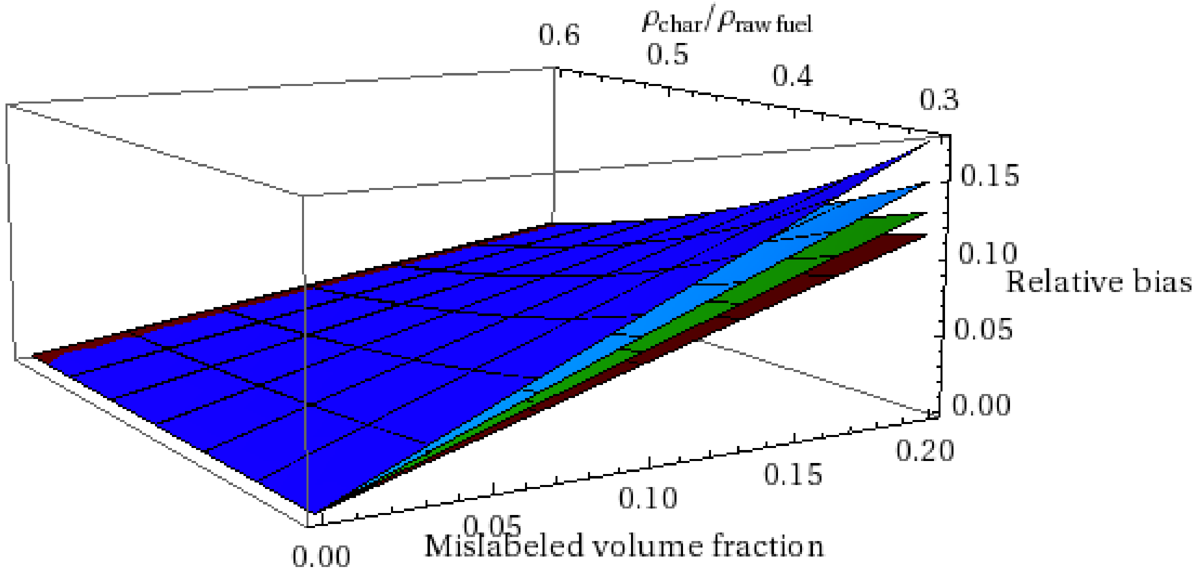

Figure 6.4 Relative bias in energy calculation during sort-and-mass procedure as a function of mislabeled volume fraction, density ratio, and total volume fraction of unburned fuel (R). The latter is represented by the distinct surface with the red surface representing $R = 0.9$, the green surface $R = 0.5$, the cyan surface $R = 0.3$, and the blue surface $R = 0.1$. In all cases, the energy ratio is set to $\xi = 1.7$.

then calculates the net change in char during a test section as

$$m_{char} = m_{full\,char\,container} - m_{empty\,char\,container}$$

There is no deduction for the mass of free ash that should be present in addition to the char. This ash may be accounted for by calculating the change in char mass as

$$m_{corrected\,char} = m_{char} - \left(m_{raw\,fuel\,burned} - m_{char}\right) AC_{fuel}$$

where AC_{fuel} is, of course, the ash content of the fuel on a mass (wet) basis. With some agricultural residues, AC_{fuel} can approach 20%, so it is clearly a potential problem if ash is counted as char.

From the mass of char and mass of raw fuel used, the energy used during a given section of the UCBWBT is calculated as

$$E = m_{raw\,fuel\,burned} \cdot LHV_{fuel} - m_{char} \cdot LHV_{char}$$

A standard error propagation treatment indicates that the absolute value of the absolute error in the energy is

$$\Delta E = \left| \frac{\partial E}{\partial m_{raw\,fuel\,burned}} \right| \cdot \Delta m_{raw\,fuel\,burned} + \left| \frac{\partial E}{\partial m_{char}} \right| \cdot \Delta m_{char}$$

Setting $\Delta m_{raw\,fuel\,burned}$ equal to zero so as to examine only the effect of Δm_{char} onΔE, and defining $\xi = \frac{LHV_{char}}{LHV_{fuel}}$, the expression for absolute error in energy becomes

$$\Delta E = \xi \cdot LHV_{fuel} \cdot \Delta m_{char}$$

Ordinarily one would examine the relative error in energy, $\frac{\Delta E}{E}$, but in this case it is more meaningful to examine the relative deviation from the corrected energy, E_c, given by $\frac{\Delta E}{E_c}$. The corrected energy is similar to the previous expression for energy but with the incorrect char mass, m_{char}, being replaced by the correct char mass, $m_{corrected\,char}$. But $\Delta m_{char} = m_{char} - m_{corrected\,char}$, yielding

$$E_c = m_{raw\,fuel\,burned} \cdot LHV_{fuel} - (m_{char} - \Delta m_{char}) \cdot \xi \cdot LHV_{fuel}$$

Making the substitutions $R = \frac{m_{char}}{m_{raw\,fuel\,burned}}$ and $\Delta m_{char} = (m_{raw\,fuel\,burned} - m_{char}) \cdot AC$, it can be shown that

$$\frac{\Delta E}{E_c} = \frac{\xi \cdot (1-R) \cdot AC}{1 - \xi \cdot R + \xi \cdot (1-R) \cdot AC}$$

Figures 6.5 through 6.8 show the effect of ash content on the relative error in estimated char content and consequent error in the calculation of total energy consumed during the test for four separate tests using two different fuels, under the assumption that $\xi = \frac{LHV_{char}}{LHV_{fuel}} = 1.5$. The amount of fuel burned, uncorrected char mass, and ash content of the fuel is shown at the top each figure. The actual error that is caused by negelcting the ash in these tests is marked on each figure by a point on the curves of error in char mass and error in total energy. For example, Figure 6.5 represents a test run using oak wood with an ash content of 1.5% as the fuel. In this case, the failure to account for ash in the supposed char fraction results in an overestimation of the actual amount of char by 20.3%. A calculation of the total fuel energy used in the test shows that this error in char causes an underestimation of the amount of energy used by 2.3%. Figure 6.7 shows a similar situation using an agricultural residue pellet as the fuel, but in this case the error in the energy calculation is much larger at 15.7%. Such an error in the calculation of energy used in the test will cause fuel consumption to be understated by the same 15.7%, and will cause the thermal efficiency to be overstated by 15.7%. Firepower will be underestimated, and there will be serious errors in any emissions metrics that are stated on an energy basis or on an "equivalent dry fuel" basis. e

In examining Figures 6.5 through 6.8, it is apparent that a similar error in the estimate of char mass does not always cause a similar error in the total energy used estimate. This can be understood by considering the calculation of the relative error in the energy estimate and the relative error in the char mass estimate. An expression for $\frac{\Delta E}{E_c}$ was developed above, and by a similar process it can be shown that

$$\frac{\Delta m_{char}}{m_{corrected\,char}} = \frac{(1-R)\cdot AC}{R-(1-R)\cdot AC}$$

In this way, both relative error in energy and relative error in char mass can be seen as a function of ash content and R, the mass ratio of char to unburned fuel. Figure 6.9 depicts a three-dimensional plot of percent error in energy in terms of ash content and R, again with $\xi = 1.5$. The slight curvature of this surface can be detected by the deviation of the color bands from the meshlines (bands of color represent similar values of percent error). The apparent exclusion of part of the parameter space is due to the fact that R must be greater than or equal to AC, since it should not be possible to have an amount of "char" remaining that is less than the total amount of ash contained in the initial fuel. The

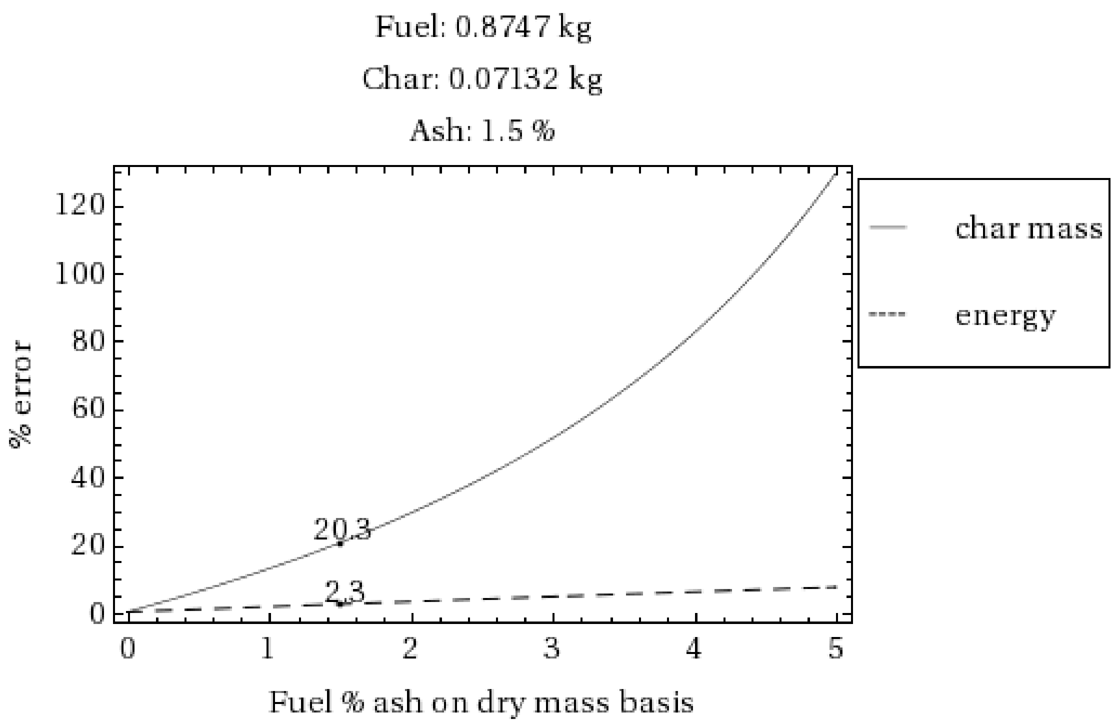

Figure 6.5 Relative error in char mass and subsequent calculation of total energy used as a function of ash percentage. Oak wood used as fuel. Char LHV is assumed to be 1.5 times raw fuel LHV.

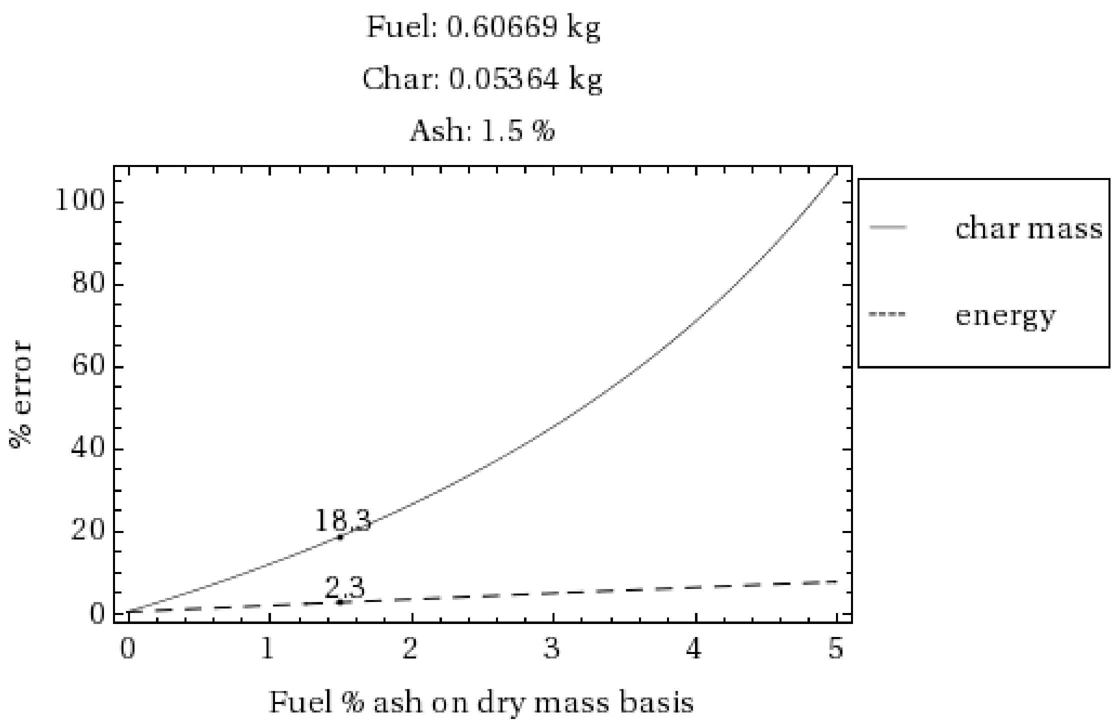

Figure 6.6 Relative error in char mass and subsequent calculation of total energy used as a function of ash percentage. Oak wood used as fuel. Char LHV is assumed to be 1.5 times raw fuel LHV.

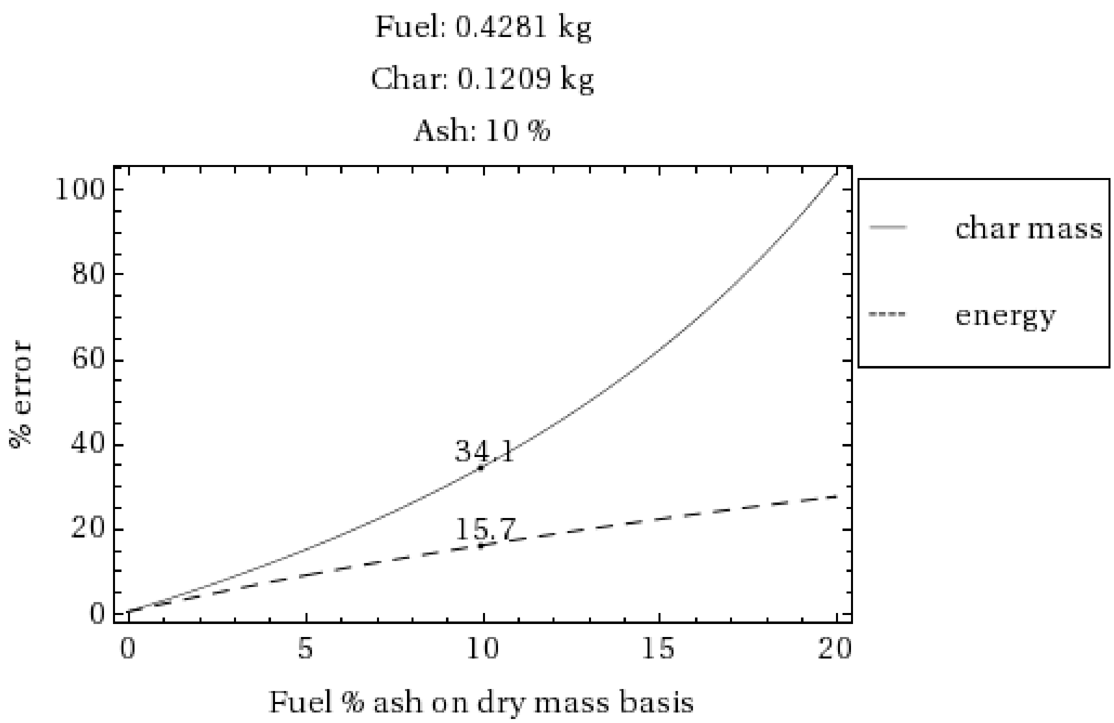

Figure 6.7 Relative error in char mass and subsequent calculation of total energy used as a function of ash percentage. Agricultural residue pellets used as fuel. Char LHV is assumed to be 1.5 times raw fuel LHV.

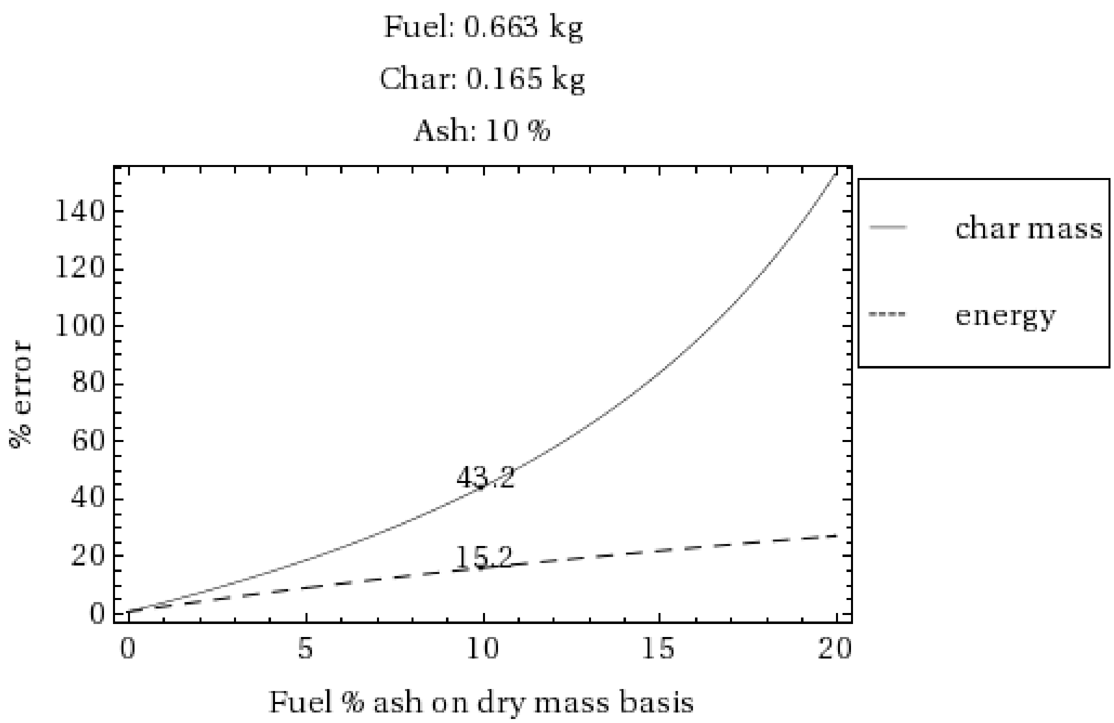

Figure 6.8 Relative error in char mass and subsequent calculation of total energy used as a function of ash percentage. Agricultural residue pellets used as fuel. Char LHV is assumed to be 1.5 times raw fuel LHV.

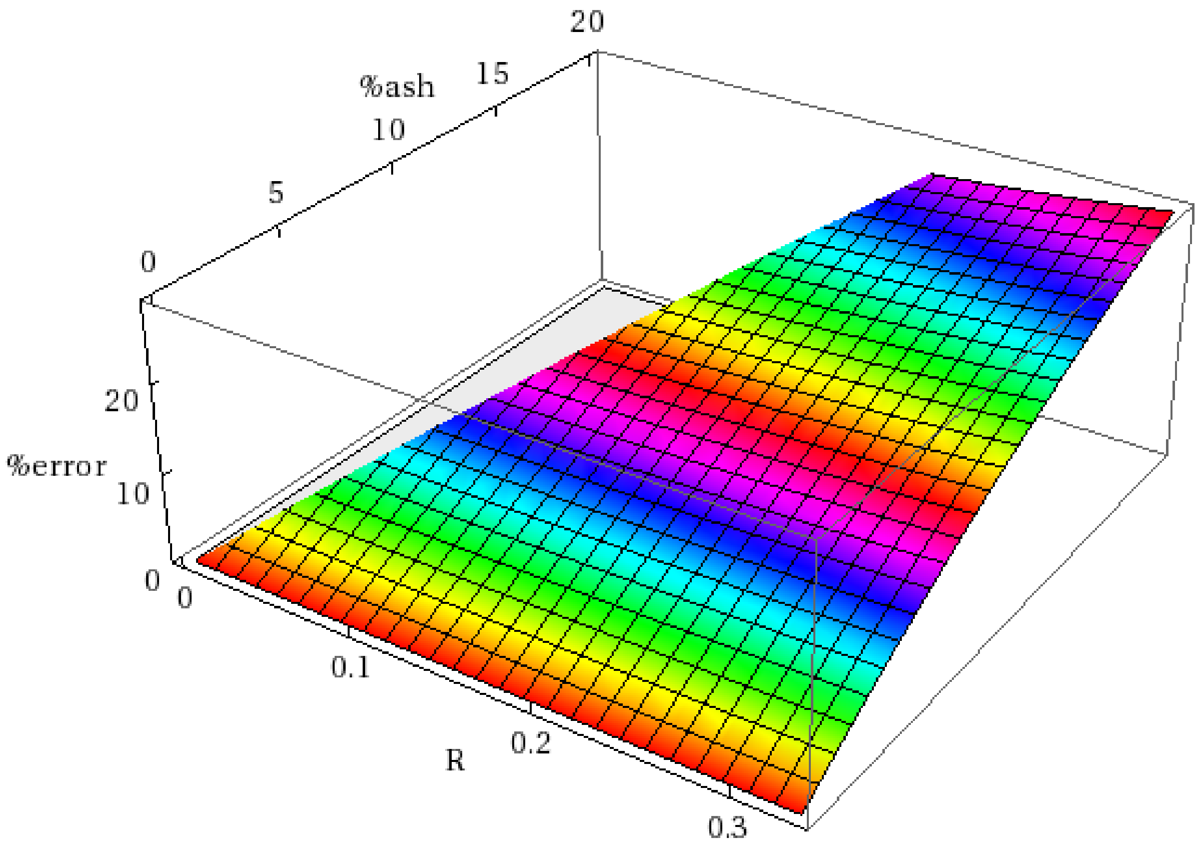

Figure 6.9 Relative error in total energy used as a function of ash content and the ratio, R, of uncorrected char mass to burned fuel mass.

relative error in energy is clearly a strong function of ash content and at best a weak function of R. This may be contrasted with Figure 6.10, which depicts the relative error in char mass in a similar manner. Unlike the relative error in energy, the relative error in char mass is a strong function of R and behaves asymptotically near the region in which $R = AC$. The more important result in terms of test metrics is the error in energy, since this error will greatly affect most other outputs of the UCBWBT.

6.4 Conclusions

This chapter has examined four issues with the energy accounting procedures in the UCBWBT that may lead to inaccuracies in the reported metrics. One of these issues, that of the use of an incorrect heat of vaporization when calculating the effective calorific value of the fuel, has been shown to be

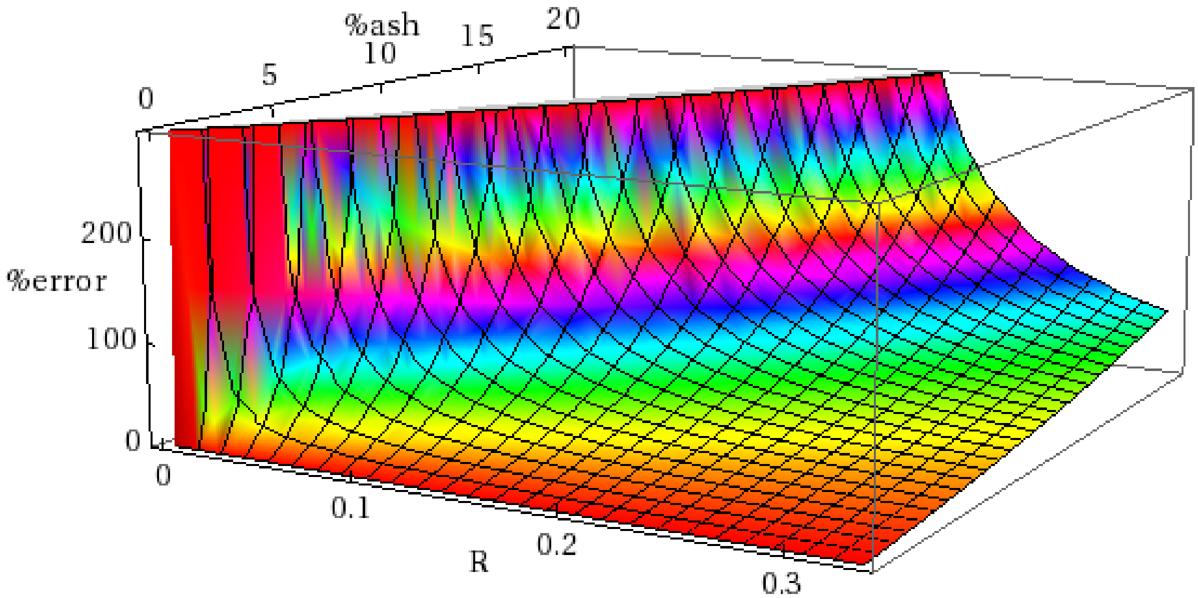

Figure 6.10 Relative error in char mass as a function of ash content and the ratio, R, of uncorrected char mass to burned fuel mass.

at its very worst only a minor source of error. Another issue, that of ignoring the temperature and species dependence of the calorific value of char, has been shown to be potentially problematic, but a meaningful estimate of the typical magnitde of this error will require further testing. A third issue, that of incorrectly sorting the char from the unburned fuel left at the end of a test section, has been shown to be potentially troublesome and consistently biased, although the likely magnitude of relative error involved is under five percent. One clearly significant issue, that of failing to address ash content in the material removed from a stove at the end of a test, has been raised. Only in the cases of this issue and that of the much less significant use of an incorrect heat of vaporization have alternative calculation methods been proposed that can effectively reduce or eliminate the error.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER INVESTIGATION

7.1 Summary of conclusions

Chapter 4 introduced several assumptions implicit in the UCBWBT which either restrict its usefulness in meeting parts of its intended purpose, or which potentially lead to significant errors in the accuracy of reported metrics. The key assumptions that may cause problems are that the stove being tested in a continuous-feed stove, the fuel supply is homogenous, all water in the test vaporizes at the local boiling point, the ash content of the fuel is so small as to be unimportant, the procedure of sorting char from unburned fuel is unbiased, and the calorific value of char is 1.5 times that of raw fuel.

Chapter 5 introduced modifications to the UCBWBT to address the assumption that the stove being tested is continuous-feed and allow for the testing of batch-feed stoves in a safer, more accurate fashion. These modifications include an altered operating cycle, a safety modification dealing with re-starting a stove containing hot fuel, the use of a snuffing pot to contain hot fuel and allow for more time between test sections, and a modification that eliminates the need to remove hot fuel from a stove altogether.

Chapter 6 further explored the potential errors in energy accounting caused by the remaining assumptions. The use of a technically incorrect heat of vaporization when calculating the net calorific value of the fuel was shown to cause a relative error on the order of one percent in all test results involving the energy demand or fuel use of the stove. The assumption of negligible ash content was shown to have the potential of causing much larger errors, greater than ten percent, in the same reported values. The absolute value of the relative error in total energy used due to failure to account for ash may be calculated as

$$\left|\frac{\Delta E}{E_c}\right| = \frac{\xi \cdot (1-R) \cdot AC}{1 - \xi \cdot R + \xi \cdot (1-R) \cdot AC}$$

where $\xi = \frac{LHV_{char}}{LHV_{fuel}}$, $R = \frac{m_{char}}{m_{raw\,fuel\,burned}}$, and AC is the ash content of the fuel on a wet mass basis. This error may be avoided by altering the calculation of char mass remaining to account for ash content. The relevant formula is

$$m_{corrected\,char} = m_{char} - \left(m_{raw\,fuel\,burned} - m_{char}\right) AC_{fuel}$$

Additionally, the procedure of sorting char from unburned fuel at the end of a test section was shown to have an unavoidable bias of overestimating the total amount of energy remaining in the fuel, resulting in consistent overestimates of the efficiency of the stove and underestimates of its true fuel use. The size of the error in test results introduced by this bias will vary based on the type of fuel, the care taken by the test operator, and the ratio of char to total fuel consumed, but may in general be considered to be on the order of a few percent. The assumption that $LHV_{char} = 1.5 \cdot LHV_{fuel}$ was shown to have the potential to cause errors of up to ten percent in the estimate of energy used in the test, but at present the likely magnitude of such errors cannot be determined because there is insufficient data on the overall composition of fuel left over from operating stoves under various conditions.

Taking these errors together, the existing UCBWBT should be considered to have a minimum method error of between five and ten percent. Depending on the fuel used, the method error may be as high as twenty percent, as in the case of a fuel with a high ash content. If the test is altered to properly account for ash, the minimum method error drops to about five percent. The UCBWBT currently reports the uncertainty of fuel use and other results as the intra-test variation between three trials. It is not uncommon to see uncertainties of one percent or less reported for factors such as fuel use and energy efficiency. The sources of error identified in this thesis indicate that even if the repeatability of the test can be brought to such a fine level, the actual deviation of the test results from true values is much more likely to be on the order of ten percent. If results of the current UCBWBT are being used to compare two stove designs, the relative error in thermal efficiency, specific fuel use, firepower, turn-down ratio, and any emissions factors expressed on a per-energy or per-mass-of-fuel-consumed basis should be assumed to be ten percent, regardless of that cited as the intra-test error.

7.2 Recommendations for further investigation

7.2.1 Develop procedures to capture a greater number of stove characteristics

The stove characteristics captured by the UCBWBT, and other protocols derived from the VITA procedure, do not include safety, fuel processing requirements, attentiveness to fueling, ease of control, ability to use a range of fuels or pots, exposure of user to waste heat, and stove durability. Johnson (2005) developed a safety testing procedure that is capable of addressing the major relevant physical safety issues. This safety test procedure is slowly being adopted by many groups as the basis for safety comparisons. As yet there is no standard way to test any of the other factors mentioned, and work should be done to develop meaningful protocols.

7.2.2 Extend tests to evaluate performance over a wide range of use scenarios

As mentioned in Chapter 3, the Woodburning Stove Group at Eindhoven University of Technology made a compelling case in the 1980s for the use of tests that provide performance data over a wide range of use scenarios, the equivalent of providing performance curves for pumps rather than the minimum and maximum performance points. Their argument has been largely ignored by the majority of people involved in stove design and testing, and this should be remedied. The starting place is to understand, at least in general terms, why the Woodburning Stove Group's suggestion has so far failed to gain traction. Was the suggested method deemed too difficult, expensive, or lengthy? Was there some objection to it on conceptual grounds that has not been addressed? Is inertia to blame, with people not wanting to radically change the testing and reporting method? Or has the suggestion gone unheeded so long simply because it wasn't publicized well enough? Whatever the case, the performance test of the future must capture a variety of use scenarios, and do so in a way that allows meaningful comparison of the stoves.

7.2.3 Explore composition of partially-burned beds of fuel

The issue raised in Section 6.3.1 dealing with a lack of information about the actual energetic composition of fuel left over at the end of a test bears further study in order to put bounds on the error likely to be encountered in any procedure that assumes a single calorific value for “unburned fuel” and a different, single calorific value for “char.” Two paths present themselves as being useful: the first would be to perform calorimetry on the entire mass of fuel remaining after a trial, with many trials taking place that represent a variety of use scenarios. Most solid fuel calorimetry is currently performed using a bomb calorimeter, which is typically limited to 10-15g of fuel per test. Given this, it would be necessary to either grind all the fuel so that it could be thoroughly mixed to provide a small sample whose total energy represents the proper average of the entire fuel mass, or to build a calorimeter that operates on a principle similar to a constant-pressure flow-through calorimeter. The second path that appears worthy of investigation is to study the time-temperature history of fuel in small combustion devices with the purpose of being able to develop and verify better computational models of changes in the available fuel energy under different circumstances.

APPENDIX
RELEVANT SECTIONS OF THE UCBWBT

Because direct reference to parts of the UCBWBT will be necessary to make the best use of this thesis, the most important pieces relevant to the discussion have been included in this appendix as a convenience to the reader. Please note that the page numbers at the top of each page continue the pagination of this thesis, while everything within the solid-line frame is a direct image of pages from the UCBWBT.

The Water Boiling Test (WBT)

Prepared by Rob Bailis, Damon Ogle, Nordica MacCarty, and Dean Still with input from Kirk R. Smith and Rufus Edwards – for the Household Energy and Health Programme, Shell Foundation

Introduction

This modified version of the well-known Water Boiling Test (WBT) is a rough simulation of the cooking process that is intended to help stove designers understand how well energy is transferred from the fuel to the cooking pot. It can be performed on most stoves throughout the world. The test is not intended to replace other forms of stove assessment; however, it is designed as a simple method with which stoves made in different places and for different cooking applications can be compared through a standardized and replicable test.

It is important to understand both the strengths and weaknesses of the WBT. Strengths include the WBT's simplicity and replicability. In addition, it provides a preliminary understanding of stove performance, which is very helpful during the design process. Data obtained from a just few days of testing will help in the development of better stoves, which can then to be tested by cooks in their intended environment. Visser (2003) has shown that by determining thermal efficiency at high and low power, as is done in this version of the WBT, fuel use can be roughly predicted for various cooking tasks.

However, the WBT also has weaknesses. In order to be applicable to many different types of stoves, the WBT is only a rough approximation of actual cooking. It is done in controlled conditions by trained technicians. Therefore, it can't provide much information about how the stove performs when cooking real foods. To get an understanding of how the stove performs cooking foods cooked by local people, stove testers should use the Controlled Cooking Test (CCT) that has been developed in parallel with this test. Similarly, the WBT can't be used to accurately predict actual changes in fuel consumption among families who adopt an improved stove. A Kitchen Performance Test (KPT), which compares fuel consumption in households using the improved to households using a traditional stove, should be conducted before drawing any conclusions about changes in fuel consumption among real stove-users. The KPT has also been developed to be used together with the CCT and WBT. Further discussion of the WBT and variations used in China and India is found in Appendix 1.

The WBT developed for the Shell HEH program consists of three phases that immediately follow each other.

1) In the first phase, the cold-start high-power test, the tester begins with the stove at room temperature and uses a pre-weighed bundle of wood or other fuel[1] to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test.

2) The second phase, the hot-start high-power test, follows immediately after the first test while stove is still hot. Again, the tester uses a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot.

3) The third phase follows immediately from the second. Here, the tester determines the amount of fuel required to simmer a measured amount of water at just below boiling for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

This combination of tests measures some aspects of the stove's performance at both high and low power outputs, which are associated with the stove's ability to conserve fuel. However, rather than report a single number indicating the thermal efficiency of the stove, which is not necessarily a good predictor of stove performance,[2] this test is designed to yield several quantitative outputs. Different stove designers may find different outputs more or less useful depending on the context of their stove program. The outputs are:

- time to boil (adjusted for starting temperature);
- burning rate (adjusted for starting temperature);
- specific fuel consumption (adjusted for starting temperature);
- firepower
- turn-down ratio (ratio of the stove's high power output to its low power output); and
- thermal efficiency

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[1] This test was originally designed for woodstoves, but has been adapted to accommodate other types of stoves and fuels. See Appendix 3 for a discussion of the use of non-woody fuels.

[2] A direct calculation of thermal efficiency derived from the Water Boiling Test is not a good indicator of the stove's performance because it rewards the excess production of steam. Under normal cooking conditions, excess steam production wastes energy because it represents energy that is not transferred to the food. Temperatures within the cooking pot do not rise above the boiling point of water regardless of how much steam is produced. Thus, unless steam is required for the cooking process – for example in the steaming of vegetables [1], excess steam production should not be used to increase indicators of stove performance.

For more information on each indicator, see Appendix 2, which defines each measure and explains how it is calculated.

Before starting the tests…

The following five steps should be completed before beginning the actual tests.

1) Be sure that there is sufficient water and fuel. If possible, try to obtain all of the wood from the same source. It should be well-dried and uniform in size. If kindling is to be used to start the fire, it should also be prepared ahead of time and included in the pre-weighed bundles of fuel.
2) Perform at least one practice test on each type of stove in order to become familiar with the testing procedure and with the characteristics of the stove. This will also provide an indication of how much fuel is required to boil the required amount of water. **As a rough guide, procure at least 15 kg of air-dried fuel for each stove in order to ensure that there is enough fuel to test each stove three times. Large multi-pot stoves may require even more than 15 kg.**
3) The practice tests should also be used to determine the **local boiling point of water**. The local boiling point of water is the point at which the temperature no longer rises, no matter how much heat is applied. This should be determined by the following procedure:
   - ⇒ Choose whether you will use the large or small standard pot. Measure 5 liters of water for the large standard pot (or 2.5 liters for the small standard pot). Bring it to a rolling boil. Make sure that the stove's power output is high, and the water is fully boiling!
   - ⇒ Using the same thermometer that will be used for testing, measure the boiling temperature when the thermometer is positioned in the center, 5 cm above the pot bottom. You may find that even at full boil, when the temperature no longer increases, it will still oscillate several tenths of a degree above and below the actual boiling point.
   - ⇒ The tester should record the temperature over a five minute period at full boil and note the maximum and minimum temperatures observed during this period. The maximum and minimum temperatures should then be averaged and this result recorded as the "local boiling temperature" on the data and calculation form. (this need only be done once for your test location - see note 2).
4) One full WBT requires at least 10 liters of cool water for each pot being used. If water is scarce in your area, water used one day may be cooled and reused in the next day's testing. But, do not start any tests with water that is significantly above room temperature.

5) Make sure that there is adequate space and sufficient time to conduct the test without being disturbed. Testing should be done indoors in a room that is protected from wind, but with sufficient ventilation to vent harmful stove emissions. It will take 1½ - 2 hours to do the high and low power test for each stove. You will save time if you prepare enough bundles of fuel to conduct several tests before starting the first test.

Beginning of Testing Procedure

Equipment used for the Water Boiling Test:

- Scale with a capacity of at least 6 kg an accuracy of ±1 gram
- Digital Thermometer, accurate to 1/10 of a degree, with thermocouple probe suitable for immersion in liquids
- Wood moisture meter (optional)
- Timer
- Standard pot(s) (see note 1)
- Wood fixture for holding thermocouple probe in water (see diagram in Appendix 4)
- At least 10 liters of clean water for each WBT (in locations where water is scarce, this may be cooled and reused for later tests)
- Heat resistant pad to protect scale
- Small shovel/spatula to remove charcoal from stove
- Tongs for handling charcoal
- Dust pan for transferring charcoal
- Metal tray to hold charcoal for weighing
- Heat resistant gloves
- 2 bundles of air-dried fuelwood each weighing between 1 and 2 kg for each test (each stove is tested three times). More fuel may be needed for high-mass stoves.

Initial steps: to be done once for each tests

1. Fill out the first page of the Data and Calculations form. This includes information about the stove, fuel and test conditions. Number each series of tests for future reference.
2. Measure each of the following parameters. These should be recorded once for each series of tests. Record the measurements on page 1 of the Data and Calculation form.
   a) Air temperature.
   b) Average dimensions of wood (length x width x height). This is to give a rough idea of the size of fuel used for the test. You should use similarly sized wood

for every test to reduce variation in test conditions. If the stove design requires a specific size of fuel then you should use the optimal size for the stove. Otherwise, use sticks 2-5 cm in diameter (see Note 3 for a discussion of the effects of fuel wood variation on stove performance).

c) Wood moisture content (% - wet basis): to be determined 1) By weighing a sample of fuel, drying the sample completely in a controlled manner, and weighing it again or 2) By using the wood moisture meter included in the testing kit. (See Note 4 and the section on variables and calculations below for full details of defining and measuring moisture content). The Data and Calculation form contains a special worksheet to record and process your measurements. See the form for a more detailed explanation.

d) Dry weight of standard supplied pot without lid. If more than one pot is used, record the dry weight of each pot. If the weights differ, be sure not to confuse the pots as the test proceeds. **Do not use pot lids for this, or any other phase of the WBT (see Note 5)**. The standard pot (supplied with the test equipment) should be used wherever possible (see notes). If it is not compatible with the stove, use a pot that is typically used and note its dimensions in the "comments" section of the Data and Calculations worksheet.

e) Weight of container to be used for charcoal.

f) Local boiling point of water determined by using the same digital thermometer and sensor that will be used in the testing (see Note 2).

g) If you have access to a camera (not included in standard kit), photograph the stove. If you don't have access to a camera, use a tape measure to record the dimensions of the stove and describe it in the space provided.

3. Prepare 2 bundles of fuel wood. These should be pre-weighed: one for each of the two measurement phases of the test. The fuel should be relatively uniform in size and shape: split big pieces of wood and avoid using very small pieces (except for kindling, which should also be prepared in advance if necessary) (see Note 3).

4. Once these parameters have been measured and recorded and the fuel is prepared, proceed with the test.

Phase 1: High Power

Data recorded in the remaining phases of the test should be recorded on page two of the Data and Calculation form.

1. Prepare the timer, but do not start it until fire has started.

2. Fill each pot with 5 kg (5 liters) of clean room temperature water (if using the smaller standard pot, fill the pot with 2.5 kg or 2.5 liters of water). The amount of water should be determined by placing the pot on the scale and adding water until

the total weight of pot and water together is 5 kg (or 2.5 kg) more than the weight of the pot alone. Record the weight of pot and water in the Data and Calculations Sheet.

(If the stove can not accommodate the standard pot and the pot that is used can not accommodate 5 (or 2.5) kg of water, OR if a multi-pot stove is used with non-standard pots that can not accommodate 5 (or 2.5) kg of water, fill each pot ~2/3 full and record the change in procedure in the comment space. Record the weight of the pot(s) with the water on the Data and Calculation Form. Use the same amount of water for each test iteration.)

3. Using the wooden fixtures, place a thermometer in each pot so that water temperature may be measured in the center, 5 cm from the bottom. If there are additional pots, use the additional thermometers if possible. Record the initial water temperature in each pot and confirm that it does not vary substantially from the ambient temperature.

4. The stove should be at room temperature. Start the fire in a reproducible manner according to local practices. Record any starting materials that are used other than the wood from the first bundle of pre-measured wood (e.g. paper or kerosene).

5. Once the fire has caught, record the starting time. Throughout the following "high power" phase of the test, control the fire with the means commonly used locally to bring the first pot rapidly to a boil without being excessively wasteful of fuel.

6. When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do the following:

   a. **Record** the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.

   b. Remove all wood from the stove and extinguish the flames (flames can be extinguished by blowing on the ends of the sticks or placing them in a bucket of ash or sand; do not use water – it will affect the weight of the wood). Knock all loose charcoal from the ends of the wood into the container for weighing charcoal.

   c. Weigh the unburned wood removed from the stove together with the remaining wood from the pre-weighed bundle. **Record** result on the Data and Calculation form.

   d. For multi-pot stoves, measure the water temperature from each pot (the primary pot should be at the boiling point). **Record** the temperatures on the Data and Calculation Form.

   e. Weigh each pot, with its water. **Record** these weights on the Data and Calculation form

f. Extract all remaining charcoal from the stove, place it with the charcoal that was knocked off the sticks and weigh it all. **Record** the weight of the charcoal + container on the Data and Calculation Form.

Summary

⇒ Make sure that you have recorded time and temperature of the boiling water in the first pot, the amount of wood remaining, the weight of Pot # 1 with the remaining water, and amount of charcoal remaining on the Data and Calculation Form. For multi-pot stoves, be sure that you have recorded the temperature that each additional pot reached **when Pot # 1 first came to its full boiling temperature**.

⇒ This completes the high power phase. Now, begin the high power-hot start test, immediately while the stove is still hot. ***Be careful not to burn yourself!***

Phase 2: High Power (Hot Start)

1. Reset the timer, but do not start it until fire has started.
2. Refill the pot with 5 (or 2.5) kg of fresh cold water. Weigh the pot (with water) and measure the initial water temperature; **record** both measurements on the Data and Calculations sheet. For multi-pot stoves, fill the additional pots, weigh them and record their weights.
3. Light the fire using kindling and wood from the second pre-weighed bundle designated for this phase of the test.
4. Record the starting time, and bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the second pre-weighed bundle.
5. Record the time at which the first pot reaches the local boiling point as indicated on the Data and Calculation form. Record this temperature for the first pot.
6. After reaching the boiling temperature, quickly do the following (speed is important at this stage because we want to keep the water temperature as close as possible to boiling in order to allow us to proceed directly to the simmer test):
    a. Remove the unburned wood from the stove. Knock off any loose charcoal, but try to keep it in the combustion area (you will not weigh the charcoal at this stage). Weigh the wood removed from the stove, together with the unused wood from the previously weighed supply. **Record** result on Data and Calculation form.
    b. **Record** the water temperature from other pots if more than one pot is used.

c. Weigh each pot, with it's water and **record** the weights. After weighing, immediately replace each pot on the stove (**remember, we want to keep the water temperature as close as possible to boiling in order to proceed directly to the simmer test!**).

7. Replace and relight the wood removed from the fire ***proceed immediately*** with the low power test.

Phase 3: Low Power (Simmering)

This portion of the test is designed to test the ability of the stove to shift into a low power phase following a high-power phase in order to simmer water for 45 minutes using a minimal amount of fuel. For multi-pot stoves, **only the primary pot will be assessed for simmering performance** (see the discussion of multi-pot stove-testing in Appendix 5).

Start of Low Power test

1. Reset the timer.
2. Replace the thermometer in the pot. Adjust the fire to keep the water as close to 3 degrees below the established boiling point as possible.

It is acceptable if temperatures vary up and down, but;

⇒ **The tester must vigilantly try to keep the simmering water as close as possible to 3 degrees C below the local boiling point (see notes 6 and 7).**

⇒ **The test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.**

3. For 45 minutes maintain the fire at a level that keeps the water temperature as close as possible to 3 degrees below the boiling point.
4. After 45 minutes rapidly do the following:

   a. Record the finish time of the test (this should be 45 minutes). Record this and all remaining measurements on the Data and Calculation Form under the heading "Finish: 45 minutes after Pot # 1 boils".

   b. Remove all wood from the stove and knock any loose charcoal into the charcoal container. Weigh the remaining wood, including the unused wood from the pre-weighed bundle.

   c. Record the final water temperature on Data and Calculation Form – it should still be roughly 3 °C below the established boiling point.

d. Weigh the pot with the remaining water. Record the weight on the Data and Calculation Form.

e. Extract all remaining charcoal from the stove and weigh it (including charcoal which was knocked off the sticks). Record the weight of pan plus charcoal.

This completes the WBT. The test should be conducted a total of three times for each stove.

Analysis

Input the results of this WBT into the Data and Calculation software. Output will be viewable in the "Results" worksheet.

While a full discussion of statistical theory is beyond the scope of this stove-testing manual, we will rely on some basic ideas of statistical theory to decide whether or not the results of these tests can be used to make claims about the performance of different stove models. For more discussion, see Appendix 6.

Notes on the WBT

1. **Pots:** The capacity, dimensions and material of the pot have a significant influence on stove performance. In order to maximize the comparability of the WBT across different types of stove ***we recommend that testers use one of two standard pots*** depending on the design and power output of the stove being tested. The recommended pots are 1) a large pot (with a 7 liter capacity) and 2) a small pot (with a 3.4 liter capacity)[INCLUDE A PHOTO OR SCHEMATIC OF THE POTS?]. Depending on the power output of the stove and cooking practices in the area where the stove is used, testers should use either the large or small standard pot unless the stove requires a specific pot in order to function properly. If testers use a non-standard pot, they should record the capacity, dimensions, weight, and material. Use of a non-standard pot may bias the results and make them difficult to compare to other WBTs.

2. **Boiling point:** The local boiling point of water is the point at which the temperature no longer rises, no matter how much heat is applied. This should be determined empirically by the following procedure: Put 5 liters of water in the standard pot and bring it to a boil. Using the same thermometer that will be used for testing, measure the boiling temperature when the thermocouple is positioned in the center, roughly 5 cm above the pot bottom. The tester will find that even at full boil (when new higher temperatures are no longer observed), the temperature will oscillate several tenths of a degree above and below the actual boiling point. The tester should record the temperature over a five-minute period at full boil and note the maximum and minimum temperatures observed during this period. The maximum and minimum temperatures should then be averaged

and this result recorded as the "local boiling temperature" on the data and calculation form. (This need only be done once for your test location).

The local boiling temperature is influenced by several factors including altitude, minor inaccuracies in the thermometer, and weather conditions. For these reasons, the local boiling temperature cannot be assumed to be 100° C. For a given altitude h (in meters), the boiling point of water may be estimated by the following formula:

$$T_b = \left(100 - \frac{h}{300}\right)^{\circ}C$$

3. **Fuels:** The type and size of fuel can affect the outcome of the stove performance tests. In order to minimize the variation that is potentially introduced by variations in fuel characteristics VITA (1985) recommends taking the following precautions:

    - Try to use only wood (or other fuel) that has been thoroughly air-dried. Wooden stocks 3-4 cm in diameter may take from 3-8 months to dry fully. Dung or crop residues take somewhat less time in dry conditions. For woodfuel, drying can be accelerated by ensuring that the wood is stored in a way that allows air to circulate through it.

    - Different sizes of solid fuels fuel have different burning characteristics. While stove users may not have the ability to optimize fuel size, testers should try to use only similar sizes of wood to minimize this source of variation.

4. **Moisture content of wood:** well-dried fuel contains 10-20% water while fresh cut wood may contain more than 50% water by mass (wet basis). Ideally, fuel used for both testing stoves and for cooking by project beneficiaries should be dried as much as local environmental conditions allow. However, dried fuel is not always available and both stove testers and household cooks must use what they can get. In order to control for variations in fuel moisture content, stove testers should measure it and account for it in their stove performance calculations. Thus, there is a space for moisture content to be input in the Data and Calculation form and software.

    There are two ways of defining fuel moisture content: on a **wet basis** and on a **dry basis**. In the former, the mass of water in the fuel is reported as a percentage of the mass of wet fuel and in the latter case, it is reported as a percentage of the mass of the dry fuel. The calculations for each are shown below followed by a plot showing how both wood moisture on a wet basis and wood mass vary with wood moisture defined on a dry basis for one kg of oven-dry wood. **Unless otherwise specified, we will report wood moisture on a wet basis**. The testers should always take care to specify which basis they are using.

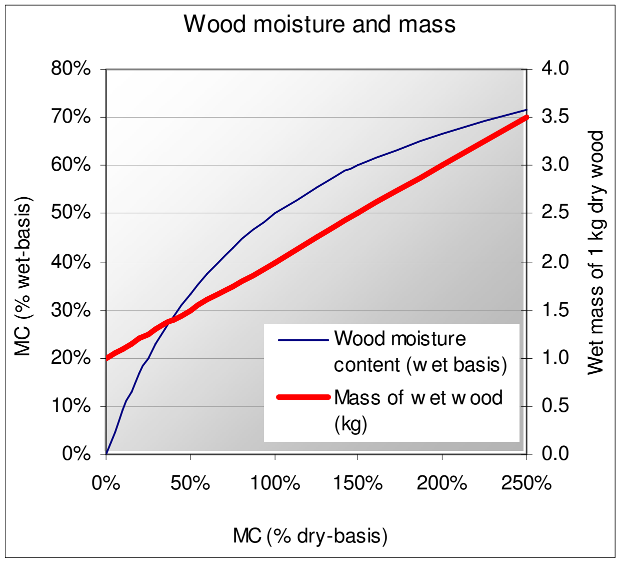
$$MC_{wet}(\%) = \frac{(\text{Mass of fuel})_{wet} - (\text{Mass of fuel})_{dry}}{(\text{Mass of fuel})_{wet}} * 100 \quad \text{and}$$

$$MC_{dry}(\%) = \frac{(\text{Mass of fuel})_{wet} - (\text{Mass of fuel})_{dry}}{(\text{Mass of fuel})_{dry}} * 100$$

The two moisture contents are related in this way: $MC_{wet} = \frac{MC_{dry}}{MC_{dry} + 1}$.

Measuring moisture content can be done in two ways. The most precise way is to use the equations listed above by weighing a sample of the air-dry fuel (Mass of fuel)$_{wet}$ and weighing it again after it has been completely dried (Mass of fuel)$_{dry}$. Take a small sample (200-300 g) of the fuel randomly from the stock of fuel to be used for the tests. Weigh the sample and record the mass. Dry the sample an oven at a few degrees over 100 °C and weigh it again. This may be done at the testing site if an oven is available, or the wet sample may be weighed on-site and then stored carefully and dried later, when an oven is available.

To dry the sample, put it in an oven and then remove it and weigh the sample every two hours on a sensitive scale (±1 g accuracy) until the mass no longer decreases. The oven temperature should be carefully controlled so that it doesn't exceed 110°C (230°F). If the wood is exposed to temperatures near 200°C (390°F), it will thermally break down and lose matter that is not water, causing an inaccurate measurement of moisture content.



A second way to measure wood moisture is with a wood moisture meter. This device measures fuel moisture on a **dry basis** by measuring the conductivity between two sharp probes that are inserted in the wood. This is more convenient than oven-drying because the measurement can be rapidly done on site as the fuel is being prepared. The probes should be inserted parallel with the grain of the wood. The device may be adjusted for different species and calibrated for different ambient temperatures. The meter reads up between 6% and 40% moisture (dry basis). If the sample of wood is wetter than 40%, the meter will yield an error.[3] Wood moisture can vary in a given piece of wood as well as among different pieces from a given bundle. When the meter is used, take three pieces of wood randomly from the bundle and measure each piece in three places. This yields nine measurements overall. The moisture of the bundle should be reported as the average of these nine measurements. Convert this average to a **wet basis** using the formula (this is done automatically in the computer spreadsheet) $MC_{wet} = \frac{MC_{dry}}{MC_{dry} + 1}$. Record this average in the Data and Calculation sheet.

Note - the moisture meter is not designed to measure non-woody fuels and should not be used on dung or crop residues. If dung or crop residues are used,

[3] 40% moisture on a dry basis is equivalent to roughly 29% moisture on a wet basis.

then the oven-drying method is recommended. See Appendix 3 for further discussion.

5. **Lids:** The WBT should be conducted without lids. This may seem counterintuitive, because lids generally improve the performance of the stove. However, the main purpose of the WBT is to quantify the way that heat is transferred from the stove to the cooking pot. While a lid helps to *retain heat* in the pot, and should therefore be used for any actual cooking task, it does not effect the *transfer of heat* from the stove to the pot. Hence, a lid is not needed for the WBT even if lids are commonly used among communities for which the improved stove is intended.

   In fact, lids can complicate the WBT by increasing the variability of the outcome and making it harder to compare results from different tests. As Baldwin writes, "If a lid is used then the amount of water evaporated and escaping is somewhat dependent on the tightness of the lid's fit to the pot, and very dependent on the firepower. If the firepower is so low that that the temperature is maintained a few degrees below boiling, effectively no water vapor will escape. If the firepower is high enough so that the water boils, the escaping steam will push the lid open and escape," (from Chapter 5, note 2, p. 263).

   The water lost has different effects on each indicator of stove performance. However, since it is difficult to standardize the lid's "tightness of fit", even for a standardized pot, we recommend testers not use the lid for the WBT. This should have little impact on the high power testing phase – indicators like specific consumption and thermal efficiency are both relatively insensitive to evaporated water.

   However, the indicators derived from the low power test are more sensitive to the amount of water evaporated. Again, from Baldwin, "By not using a lid, evaporation rates are higher and the stove must be run at a somewhat higher power to maintain the temperature than is the case with a lid" (p. 263).

6. **Power control:** Many stoves lack adequate turndown ability. The tester may find that it is impossible to maintain the desired temperature without the fire going out (especially after the initial load of charcoal in the stove has been consumed). If this is the case, the tester should use the minimum amount of wood necessary to keep the fire from dying completely. Water temperatures in this case will be higher than 3° below boiling, but the test is still valid. The tester should not attempt to reduce power by further splitting the wood into smaller diameter pieces.

7. **Procedural changes:** Measurements of stove performance at both high and low power output can give an indication of how a stove will behave in actual cooking conditions. As far back as 1985, a number of stove experts started to question the wisdom of relying solely on thermal efficiency calculations, and recommended that they be replaced by another standard:

…some of the procedures described here differed significantly from what has been recommended in the past. The main difference is in the concept of efficiency used. These standards are based on a broader description and justification of efficiency than Percent Heat Utilized (PHU). They interpret evaporation as a measure of energy wasted, not energy used [2, page ix].

The revised test presented here is based on the procedures proposed by VITA (1985) and Baldwin (1987), but has incorporated minor changes described below:

- Specific Consumption is defined as the ratio of the total amount of wood used to the amount of water "cooked" [3], but was modified for multi-pot stoves to reward heat transferred to secondary cooking pots (see Appendix 5).
- It can be difficult to make a smooth transition from high-power to low power tests. Methods used in past testing procedures have suggested extinguishing and weighing wood and charcoal as well as weighing boiling hot water, and rearranging the fire and cooking pot in rapid succession, which is both risky and stressful. This revised version of the WBT follows the suggestions described in VITA Procedural Notes 3 [2], which allows for a more relaxed testing procedure with minimal loss in accuracy.
- During the low power simmer test, the tester is instructed to try to keep the water temperature as close to 3°C below the predetermined boiling point as possible. Different amounts of steam are produced at each degree point below boiling. For this reason, it is necessary to minimize the variation in temperature to ensure that tests are comparable.
- A hot-start test is incorporated in the high power phase in order to account for the different performance of stoves that are kept hot throughout the day. This is important for massive stoves, whose performance may vary significantly between cold and hot starting conditions.
- Simmering occurs for 45 minutes rather than 30, (as suggested in VITA, 1985) because the large amount of charcoal some stoves create during the high power phase can skew the results if the simmering test is too short. The presence of charcoal helps to keep small amounts of wood burning. A 45-minute simmering period is long enough for the stove at low power to establish a burning equilibrium, as excess charcoal made at high power is normally consumed within 30 minutes.

Appendix 2

An explanation of the calculations used in the WBT

The WBT consists of three phases: a high-power phase with a cold start, a high power phase with a hot start, and a low power (simmer) phase. Each phase involves a series of measurements and calculations. The calculations for the one-pot test are described below. For stoves that accommodate more than one pot, the calculations will be adjusted to account for each pot. These adjustments are explained below.

Variables that are constant throughout each phase of the test

HHV	Gross calorific value (dry wood) (MJ/kg)
LHV	Net calorific value (dry wood) (MJ/kg)
m	Wood moisture content (% - wet basis)
c_{eff}	Effective calorific value (accounting for moisture content of wood)
P	Dry weight of empty Pot (grams)
k	Weight of empty container for char (grams)
T_b	Local boiling point of water (deg C)

Explanations of Variables

HHV – Higher heating value (also called gross calorific value). This is the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel *if* it is completely combusted *and* the combustion products are cooled to room temperature such that the water produced by the reaction of the fuel-bound hydrogen is condensed to the liquid phase.

LHV – Lower heating value (also called net heating value). This is the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel *if* it is completely combusted *and* the combustion products are cooled to room temperature but the water produced by the reaction of the fuel-bound hydrogen remains in the gas phase. For woodfuels, LHV typically differs from HHV by 1.32 MJ/kg.[5]

[5] Dry wood typically consists of 6% hydrogen by mass. Thus, one kg of dry wood contains 60 g of hydrogen, which reacts to form 540 g of H_2O. The difference in enthalpy between the liquid and gaseous phases of 540 g of water at room temperature is roughly 1.32 MJ, thus, for a typical sample of moisture-free wood, HHV and LHV differ by 1.32 MJ. In Baldwin (1986), the difference between HHV and LHV is given as 1.39 MJ/kg, but this applies to water vapor at 100 ºC, which is not typically how LHV is defined [3, p. 55].

m – This is the % wood moisture content on a wet basis, defined by the following formula:

$$m = \frac{(\text{mass of wet fuel}) - (\text{mass of dry fuel})}{\text{mass of wet fuel}} * 100$$

This can be determined gravimetrically (by weighing a sample of wet fuel, drying the sample, and weighing it again) or through the use of a wood moisture meter (see description of test procedure).

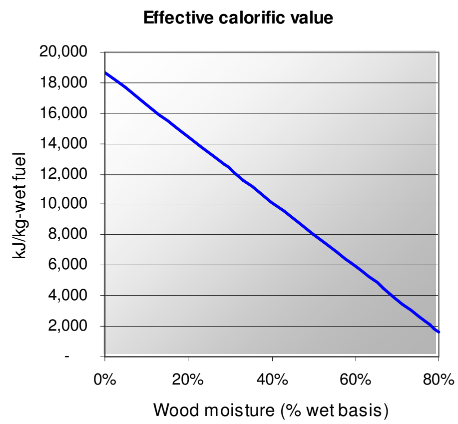
If the Delmhorst J-2000 moisture meter is used in this test to measure wood moisture content, be aware that it provides moisture content on a *dry basis*. In order to use 'm' in the following analysis, the output of the instrument must be converted to moisture content on a *wet basis*. *Dry basis* must be converted to *wet basis* using the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1 + MC_{dry}}$$

c_{eff} – This is the effective calorific value of the fuel, with takes account of the energy required to heat and evaporate the moisture present. This is calculated in the following way:

$$c_{eff} = \frac{LHV * (\text{mass of dry fuel}) - (\text{mass of water in fuel}) * (80 * 4.186 + 2260)}{\text{mass of wet fuel}}$$

where 80°C represents the typical change from ambient temperatures to the boiling point of water, 4.186 kJ/(kg•°C) is the specific heat capacity of water, and 2260 kJ/kg is the energy required to evaporate one kilogram of water. The graph below shows c_{eff} as a function of wood moisture content (wet basis) assuming an HHV of 20,000 kJ/kg (LHV of 18,680 kJ/kg), which is a typical value for hardwoods. Note that at 50% moisture, which is not uncommon for freshly cut (green) wood in moist climates, the effective energy content of the fuel is reduced by more than half.



P – This is the weight of the empty pot. For multi-pot stoves, this is followed by an index number 1 – 4.

K – This is the weight of the charcoal container that will be used to hold the char when it is removed from the stove and weighed.

T_b – This is the local boiling point of water, which should be determined empirically in order to account for variations as a result of altitude.

1. **High power test (cold start)**

Variables that are directly measured		**Variables that are calculated**	
f_{ci}	Weight of fuel before test (grams)	f_{cm}	Wood consumed, moist (grams)
P_{ci}	Weight of Pot with water before test (grams)	Δc_c	Change in char during test phase (grams)
T_{ci}	Water temperature before test (ºC)	f_{cd}	Equivalent dry wood consumed (grams)
t_{ci}	Time at start of test (min)	w_{cv}	Water vaporized (grams)
f_{cf}	Weight of wood after test (grams)	w_{cr}	Water remaining at end of test (grams)
c_c	Weight of charcoal and container after test (grams)	Δt_c	Duration of phase (min)
P_{cf}	Weight of Pot with water after test (grams)	h_c	Thermal efficiency
T_{cf}	Water temperature after test (ºC)	r_{cb}	Burning rate (grams/min)
t_{cf}	Time at end of test (min)	SC_c	Specific fuel consumption (grams wood/grams water)
		SC^T_h	Temp-corrected specific consumption (grams wood/grams water)
		FP_c	Firepower (W)

Explanations of Calculations

f_{cm} – Wood consumed (moist): This is the mass of wood that was used to bring the water to a boil found by taking the difference of the pre-weighed bundle of wood and the wood remaining at the end of the test phase:

$$f_{cm} = f_{cf} - f_{ci}$$

Δc_c – Net change in char during test phase: This is the mass of char created during the test found by removing the char from the stove at the end of the test phase. Because it is very hot, the char will be placed in an empty pre-weighed container of mass k (to be supplied by testers) and weighing the char with the container, then subtracting the two masses.

$$\Delta c_c = c_c - k$$

f_{cd} – Equivalent dry wood consumed: This is a calculation that adjusts the amount of wood that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the wood and (2) the amount of char remaining unburned. The calculation is done in the following way:

$$f_{cd} = f_{cm} * (1 - (1.12 * m)) - 1.5 * \Delta c_c$$

The factor of $1-(1.12*m)$ adjusts the mass of wood burned by the amount of wood required to heat and evaporate $m*f_{cm}$ grams of water. It takes roughly 2260 kJ to evaporate a kilogram of water, which is roughly 12% of the calorific value of dry wood. Thus if wood consists of m% moisture, the mass of wood that can effectively heat the pot of water is reduced by roughly $1-(1.12*m)$ because the water must be boiled away (see [3] for further discussion).

The factor of $1.5*\Delta c_c$ accounts for the wood converted into unburned char. Char has roughly 150% the calorific content of wood, thus the amount of wood heating the pot of water should be adjusted by $1.5*\Delta c_c$ to account for the remaining char. Note, in the simmer phase it is possible that there will be a net loss in the amount of char before and after the test, in which case Δc is negative and the equivalent dry wood increases rather than decreases.

W_{cv} – Water vaporized: This is a measure of the amount of water lost through evaporation during the test. It is calculated by simple subtraction of initial weight of pot and water minus final weight of pot and water.

$$w_{cv} = P_{ci} - P_{cf}$$

w_{cr} – Water remaining at end of test: This is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot.

$$w_{cr} = P_{cf} - P$$

Δt_c – Time to boil pot #1: This is simply the time taken to perform the test. It is a simple clock difference:

$$\Delta t_c = t_{cf} - t_{ci}$$

Δt^T_c – Temperature-corrected time to boil pot #1: this is the same as above, but adjusts the result to a standard 75 °C temperature change (from 25 °C to 100 °C). This adjustment standardizes the results and facilitates a comparison between tests that may have used water with higher or lower initial temperatures.

$$\Delta t^T_c = (t_{cf} - t_{ci}) \times 75/(T_{cf} - T_{ci})$$

h_c – Thermal efficiency: This is a ratio of the work done by heating and evaporating water to the energy consumed by burning wood. It is calculated in the following way.

$$h_c = \frac{4.186*(P_{ci}-P)*(T_{cf}-T_{ci})+2260*(w_{cv})}{f_{cd}*LHV}$$

In this calculation, the work done by heating water is determined by adding two quantities: (1) the product of the mass of water in the pot, $(P_{ci} - P)$, the specific heat of water (4.186 J/g°C), and the change in water temperature $(T_{cf} - T_{ci})$ and (2) the product of the amount of water evaporated from the pot and the latent heat of evaporation of water (2260 J/g). The denominator (bottom of the ratio) is determined by taking the product of the dry-wood equivalent consumed during this phase of the test and the LHV.

R_{cb} – Burning rate: This is a measure of the rate of wood consumption while bringing water to a boil. It is calculated by dividing the equivalent dry wood consumed by the time of the test.

$$r_{cb} = \frac{f_{cd}}{t_{ci} - t_{cf}}$$

SC_c - Specific fuel consumption: Specific consumption can be defined for any number of cooking tasks and should be considered "the fuelwood required to produce a unit output" whether the output is boiled water, cooked beans, or loaves of bread. In the case of the cold-start high-power WBT, it is a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with cold stove. It is calculated in this way:

$$SC_c = \frac{f_{cd}}{P_{cf} - P}$$

SC^T_c – Temperature corrected specific fuel consumption: This corrects specific consumption to account for differences in initial water temperatures. This facilitates comparison of stoves tested on different days or in different environmental conditions. The correction is a simple factor that "normalizes" the temperature change observed in test conditions to a "standard" temperature change of 75 ºC (from 25 to 100). It is calculated in the following way.

$$SC^T{}_c = \frac{f_{cd}}{P_{cf} - P} * \frac{75}{T_{cf} - T_{ci}}$$

FP_c – Firepower: This is a ratio of the wood energy consumed by the stove per unit time. It tells the average power output of the stove (in Watts) during the high-power test.

$$FP_c = \frac{f_{cd} * LHV}{60 * (t_{ci} - t_{cf})}$$

Note, by using f_{cd} in this calculation, we have accounted for both the remaining char and the wood moisture content.

High power test (hot start)

In this test, measurements and calculations are identical to the cold start test except that the char remaining is not extracted and weighed. Simply substitute the subscript 'h' for the subscript 'c' in each variable as in the table below. Char remaining is assumed to be the same as the char remaining from the "cold start" phase.

Variables that are directly measured

f_{hi}	Weight of fuel before test (grams)
P_{hi}	Weight of Pot with water before test (grams)
T_{hi}	Water temperature before test (ºC)
t_{hi}	Time at start of test (min)
f_{hf}	Weight of wood after test (grams)
c_h	Weight of charcoal and container after test (grams)
P_{hf}	Weight of Pot with water after test (grams)
T_{hf}	Water temperature after test (ºC)
t_{hf}	Time at end of test (min)

Variables that are calculated

f_{hm}	Wood consumed, moist (grams)	$f_{hm} = f_{hf} - f_{hi}$
Δc_h	Net change in char during test phase (grams)	$\Delta c_h = c_c - k$ (assumed to be equal to cold start)
f_{hd}	Equivalent dry wood consumed (grams)	$f_{hd} = f_{hm} * (1-(1.12 * m)) - 1.5 * \Delta c_h$
w_{hv}	Water vaporized (grams)	$w_{hv} = P_{hi} - P_{hf}$
w_{hr}	Water remaining at end of test (grams)	$w_{hr} = P_{hf} - P$
Δt_h	Time to boil pot #1	$\Delta t_h = t_{hf} - t_{hi}$
$\Delta t^T{}_h$	Temp -adjusted time to boil pot #1	$\Delta t^T{}_h = (t_{hf} - t_{hi}) \times 75/(T_{hf} - T_{hi})$
h_h	Thermal efficiency	$h_h = \frac{4.186 * (P_{hi} - P) * (T_{hf} - T_{hi}) + 2260 * (w_{hv})}{f_{hd} * LHV}$
r_{hb}	Burning rate (grams/min)	$r_{hb} = \frac{f_{hd}}{t_{hi} - t_{hf}}$
SC_h	Specific fuel consumption (grams wood/grams water)	$SC_h = \frac{f_{hd}}{P_{hf} - P}$
$SC^T{}_h$	Temp-corrected specific consumption (grams wood/grams water)	$SC^T{}_h = \frac{f_{hd}}{P_{hf} - P} * \frac{75}{T_{hf} - T_{hi}}$

FP_h	Firepower (W)	$FP_h = \frac{f_{hd} * LHV}{60 * (t_{hi} - t_{hf})}$

Low power (simmering) test

In this test, the initial measurements are the same as in the high power tests, however the goal of this test is to maintain water at a high temperature with minimal power output from the stove. Since the goal differs, the interpretations of the calculations also differ from those of the high power phases. In addition, one important assumption is made using data from the hot start high power test and one additional calculation is performed that does not appear in the high power tests. These are both explained below.

The assumption made in this test is based on the amount of char present when the water first boils. The low power phase starts by repeating the high power hot start test, however when the water comes to a boil, it is quickly weighed without disturbing the char and then the fire is tended to maintain the water within a few degrees of boiling for 45 minutes There will be char remaining in the stove from the wood that was used to bring the water to a boil. Removing that char from the stove, weighing it and relighting it disturbs the fire and may result in the water temperature dropping too far below boiling. Thus, the recommended procedure is to assume that the char present at the start of the simmer phase is the same as the char that was measured after the high power cold start test (Δc_c). While this is not entirely accurate, the error introduced by this assumption should be minimal – especially if the tester(s) followed an identical procedure in bringing the water to a boil.

Variables that are directly measured

f_{si}	Weight of unused fuel when the water first boils (grams)
P_{si}	Weight of Pot with water when the water first boils (grams)
T_{si}	Water temperature at boiling ($T_{si} = T_b$) (ºC)
t_{si}	Time at start of simmer phase test (min)
f_{sf}	Weight of unburned wood remaining after test (grams)
c_s	Weight of charcoal and container after test (grams)
P_{sf}	Weight of Pot with water after test (grams)
T_{sf}	Water temperature at end of test (ºC)
t_{sf}	Time at end of test (min)

Variables that are calculated

f_{sm}	Wood consumed, moist (grams)	$f_{sm} = f_{sf} - f_{si}$
Δc_s	Net change in char during test phase (grams)	$\Delta c_s = c_s - k - \Delta c_c$
f_{sd}	Equivalent dry wood consumed (grams)	$f_{sd} = f_{sm} * (1-(1.12*m)) - 1.5*\Delta c_s$
w_{sv}	Water vaporized (grams)	$w_{sv} = P_{si} - P_{sf}$
w_{sr}	Water remaining at end of test (grams)	$w_{sr} = P_{sf} - P$
Δt_s	Duration of phase (min)	$\Delta t_s = t_{sf} - t_{si}$
h_s	Thermal efficiency	$h_s = \frac{4.186*(P_{si}-P)*(T_{sf}-T_{si})+2260*(w_{sv})}{f_{sd}*LHV}$
r_{sb}	Burning rate (grams/min)	$r_{sb} = \frac{f_{sd}}{t_{si}-t_{sf}}$
SC_s	Specific fuel consumption (grams wood/grams water)	$SC_s = \frac{f_{sd}}{P_{sf}-P}$
FP_s	Firepower (W)	$FP_s = \frac{f_{sd}*LHV}{60*(t_{si}-t_{sf})}$
TDR	Turn-down ratio	$TDR = \frac{FP_h}{FP_s}$

There is no temp-corrected specific consumption in the simmer phase because the test starts at T_b and the change in temperature should be limited to a few degrees.

It is important to remember that the goal of this part of the test is to maintain the water at a temperature just under boiling, and one should interpret the results accordingly. Whereas the specific consumption in the high power tests (SC_c and SC_h) indicated the mass of fuel required to produce one liter (or kilogram) of boiling water, the specific consumption in the simmer phase (SC_s) indicates the mass of wood required to *maintain* each liter (or kilo) of water three degrees below boiling temperature. These are not directly comparable, but rather tell two different measures of stove performance. The same is true for other indicators, like burning rate and firepower.

It is also important to acknowledge that over-reliance on thermal efficiency can lead to misleading results, particularly in the simmer phase. Because thermal efficiency accounts for sensible heat as well as evaporative losses, it rewards for the generation of steam. In most cooking conditions, excess steam production does not decrease cooking time, as the temperature in the pot is fixed at the boiling point. Thus, producing excess steam, while it does reflect wood energy transferred to the cooking pot, is not necessarily a good indicator of stove performance. As we state elsewhere, we wish to de-emphasize the role that thermal efficiency plays in discussions of stove performance and stress other, more informative indicators such as the burning rate and specific consumption at high and low power, and the turn-down ratio, which indicates the degree to which power output from the stove can be controlled by the user.

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