PERFORMANCE CHARACTERIZATION OF BIOMASS-FUELED CAMP STOVES

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By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC: Analog to Digital Converter

ADC: Amplification for High-Resolution

CCT: Controlled Cooking Test

CJC: Cold Junction Compensation

CS: Ceramic Stove

HHV: Higher Heating Value

KPT: Kitchen Performance Test

LHV: Lower Heating Value

NTC: Negative Temperature Coefficient

PS: Patsari Stove

RS: Rocket Stove

RV: Recreational Vehicle

SACNAS: Society for the Advancement of Chicanos and Native Americans in STEM

TS: Traditional Stove

TSF: Three Stone Fire

UTS: U-Type Stove

WBT: Water Boil Test

WCED: World Commission on Environment and Development

ABSTRACT

PERFORMANCE CHARACTERIZATION OF BIOMASS-FUELED CAMP STOVES

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Western Carolina University (December 2019)

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Camping is one of the United States' preferred outdoor activities, attracting 40.5 million participants in 2016. Biomass is any plant or animal material used for energy production. Campers prefer fossil-fueled stoves over biomass-fueled stoves because they emit less smoke and perform well at high-altitudes. Emission of smoke and formation of creosote are disadvantages of wood-fueled stoves which are linked to thermal efficiency. Biomass-fueled stoves allow campers to harness sustainable fuel, such as branches or leaves, to use when cooking. Biomass is readily available in the wilderness, so the user does not have to carry conventional fuels. In this research, eight commercially available wood-fueled camp stoves are tested using the water boil test. Their performance is compared with each other and with a prototype stove. The water boil test is used to answer five research questions in this study: What is the boil time? What is the thermal efficiency? What is the firepower? What is the specific fuel consumption? And what is the burning rate? Tests are performed in an open environment to simulate campsite aerodynamic conditions. Sticks of white pinewood were kiln-dried down to a moisture content of 6% and used as fuel. Results determine thermal efficiencies range from 4 to 22%; boil times range from 8 to 65 minutes; firepower values range from 2.3 to 6.5 kW; specific fuel consumption values range from 0.1 to 0.5 grams; burning rate values range from 7 to 20 grams. Biomass energy accounts for roughly 9% of the primary energy consumption in the

World. Over half of the consumption is connected to cooking and heating, often using inefficient fires that impact user health. Woody biomass has a net energy gain ratio greater than 1, which means that the energy input is less than the energy produced from the fuel. The cost of producing energy from woody biomass feedstocks, compared to fossil fuel feedstocks remains a major barrier. Technological developments can improve the methods used to grow and harvest biomass. The increased use of efficient biomass-fueled stoves can reduce health impacts on users, fossil fuel dependency, and deforestation due to lessened fuel consumption.

CHAPTER ONE: INTRODUCTION

This chapter provides an overview of this research along with contextual information about camping in the United States. This chapter also provides the motivation behind this research and its potential importance to the effort of providing improved cookstoves for the outdoor industry as well as the developing world.

1.1 Motivation

1.1.1 Sustainability

The motivation for this research was sustainability and renewable resources. The Brundtland Report, also called Our Common Future, is a publication that was released in 1987 by the World Commission on Environment and Development (WCED). It defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development has three sectors, economic, environmental and social; sustainability promotes the advancement of the economic and social sectors using methods that avoid degradation, over-exploitation or pollution of the environmental sector. Health impacts caused by smoke emitted from household stoves led to research, development and implementation of improved stoves in developing countries. Research of fossil fueled stoves has been conducted but no research has been conducted on biomass-fueled camping stoves, which was another motivating factor for this study.

The World's energy is obtained from coal, oil, natural gas and biomass. In 2017, biomass energy accounted for roughly 9% of the primary energy consumption in the World [1]; an estimated 2.5 billion people used biomass to cook their meals that year [2]. In 2018, renewable energy accounted for 11% of US primary energy consumption; within the renewable resource category, biomass accounted for 45% of the energy consumption; other sources of renewable energy include: geothermal, hydroelectric, solar, and wind energy [3]. The shift to renewable energy economy must include strategies for the stabilization and increased production of sustainable wood, to satisfy the growing demand, both in the traditional and modern sectors [4]. In developed countries like the United States, the usage of wood as cooking fuel is significantly less than other countries. Wood stoves are not preferred because the create creosote and smoke; the amount of smoke emitted depends on the efficiency of the stove. The use of efficient wood-fueled stoves could decrease the amount of emissions and creosote formed, which would therefore decrease the health impacts on users. With less smoke emitted, efficient stoves will be more attractive to campers as a product to purchase; the smoke will not be bothering the person while they are trying to cook. Lessened fuel consumption is obtained by using efficient stoves and it could lead to reduced deforestation rates. Using forest residue as biomass fuel could reduce the amount of fuel available for wildfires. Most fires are caused because people do not know how to properly extinguish a fire after they are finished with it; fire bans and regulations are created to stop those individuals from destroying natural resources. Fire restrictions imposed by the U.S. Forest service apply to public lands and have three stages based on a risk/benefit assessment. Stage I fire restrictions allow wood stove usage. Stage II prohibits all open fires or campfires in both campgrounds and private residences. Stage III is implemented when stages I and II are no longer effective in preventing human-caused wildfires [5]. Training campers about fire safety could reduce the number of wildfires because their education will make them more conscious about their actions.

1.2 Camping in the United States

Camping is one of the United States' preferred outdoor activities, attracting 40.5 million participants in 2016 [6]. Fig. (1) shows a pie chart representing the type of shelter that campers used in 2016. During that year, people aged 18 and older enjoyed the outdoors and slept in: tents, bivouac shelters, recreational vehicles and cabins. Table I was obtained from the American Camper Report and it shows the participation rate by shelter type in 2016. There were 10.1 million people who went backpacking that year; 14.7 million people went camping in an RV, and 27.7 million people went camping in their car. Table II was also obtained from the American Camper Report and it shows the camping participation by age in 2016. During that year, 21 percent of campers were aged 6-12; 18% were aged 13-17; 14% were aged 18-24; 16% were aged 25-44 and 8% were 45 or older.

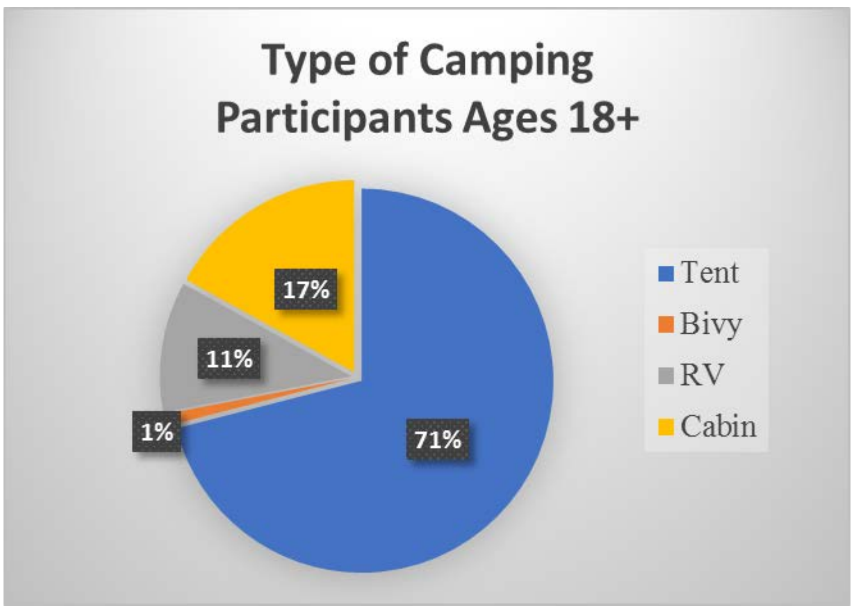

Fig. (1): Type of Camping by Sleeping Structure [6]

Table I: Camper Participation by Shelter [6]

Type of Participant	Number of Participants	Participation Rate	Days per Participant
Car Camping	27.7 million	9%	9.6
RV Camping	14.7 million	5%	12.3
Backpacking	10.1 million	3%	13.9
All	40.5 million	14%	14.5

Note: some people participated in several types of camping

Table II: Camper Participation by Age [6]

Participant Age	Participation Rate in 2016
6-12	21%
13-17	18%
18-24	14%
25-44	16%
45+	8%

1.2.1 Backpacking. Backpacking is an adventure that blends hiking with backcountry camping. It lets the user broaden their horizons beyond the car campground to enjoy a richer, more immersive outdoor experience. A key distinction from day hiking is the size of the person's pack, which must carry all of life’s essentials [7]. When people go camping in a car or RV, they have the ability of bringing large, relatively heavier gear with them; they stay within a close distance of the vehicle during the entire trip, so they don’t burn energy carrying the gear on them. Backpackers venture deep into the public forests to get away from the city bustle for a few days. There are backpackers that are considered ultra-light backpackers, which means they rely less on gear and more in their own judgement on how to stay safe, healthy and comfortable on the trail [8]. Since backpackers are very mindful about the weight they carry in their pack, they will want to have a very light-weight stove.

1.3 Camping Stove Data

The American Camper Report conducted a survey on first-time camping participants aged 18 years and older. The participants were asked to name items that they would pack in preparation for their first camping trip. The results show that 33% of respondents chose a camping stove as an item they would pack. When asked how often they replaced their camp stove, the response was every 2.5 years [6]. Table III contains the other 9 items that respondents said they would pack for their first camping trip.

Table III: Top Ten Items Purchased for the First Trip [6]

Top Ten Items Purchased for the First Trip	% of Respondents
Flashlight	55%
Cooler	53%
Tent	48%
Sleeping Bag	46%
Cooking Utensils	38%
Portable grill	37%
Backpack	35%
Airbed	34%
Propane or Liquid Fuel	34%
Camp Stove	33%

A flashlight was the most popular item chosen by respondents. Cooler was the second most popular choice among respondents, followed by a tent, sleeping bag, cooking utensils, portable grill, backpack, airbed, propane or liquid fuel and camp stove. The report did not specify what fuel the portable grill and camp stove would use. The responses include ‘propane or liquid fuel’ which shows that 34% of the survey respondents would likely use a fossil fueled stove when camping for the first time. If the user is camping in an area that does not have a fire ban, they should use a biomass-fueled stove. The readily available and sustainable fuel will reduce the camper’s dependence on fossil fuels.

The following section reviews the literature that was used as a reference for this study. This study uses the water boil test (WBT) to answer five research questions, which are: What is the boil time? What is the thermal efficiency? What is the firepower? What is the specific fuel consumption? And what is the burn rate? After the methodology chapter, the results are presented, and conclusions are discussed.

CHAPTER TWO: LITERATURE REVIEW

This chapter contains the history of portable stoves, types of camping stoves and types of fuels used in them. Wood as a fuel and its advantages is also discussed in this chapter. Two examples of research in which the WBT has been used to determine the performance of a cookstove design are introduced. The methods of heat transfer that occur during the WBT are explained.

2.1 History

This section introduces the history of the portable cooking stove and two of the early designs created by stove pioneers who manufactured cooking gear for the outdoors. Although these stoves were not very light weight or collapsible, they were the first designs that were efficient and portable.

2.1.1 Soyer Portable Stove. Alexis Soyer was a French inventor who committed himself to feeding the poor and needy in London. After the Revolution of 1830 he went to London and worked as chef of the Reform Club. In 1847, he was commissioned by the government to open kitchens in Dublin for the benefit of Irish sufferers from famine. From 1855 until 1857, he was in the Crimea serving as a cooking adviser to the British army, which was suffering from poor diet. Soyer invented relishes and sauces, innumerable kitchen utensils, and several types of stoves [9]. A Soyer stove consisted of a drum with an enclosed furnace. One stove was capable of cooking for fifty men and the cooking process required less than 10% of the wood required by open fires. It could use fuels such as coal, wood, peat and even animal dung [10]. Although 2 could be carried by a donkey, these stoves were not exactly collapsible; but its design is one of the first to be engineered for movability; Fig. (2) depicts a drawing of a Soyer Stove.

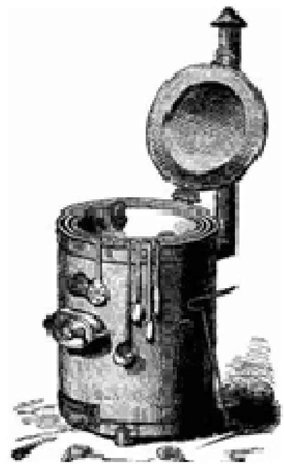

Fig. (2): Soyer Stove [10]

2.1.2 Hibachi Portable Stove. The hibachi portable stove design was imported from Japan, Hawaii, and Taiwan. A hibachi is a small charcoal-fueled stove used for preparing skewered meats and vegetables. Because of its size, the hibachi was much favored by apartment dwellers that didn't have big outdoor spaces for the larger grills. It was made of metal with wooden handles and it measured: 15.24 cm x 44.45 cm x 28.575 cm (6 in x 17 1/2 in x 11 1/4 in) [11]. Fig (3) depicts a hibachi stove.

Fig. (3): Hibachi Stove [11]

2.2 Stove Research

Improved stove designs have been developed with the assistance of scientific testing and research. Two projects which use the WBT are introduced in this section. These projects were conducted in developing countries where people still use wood as a cooking fuel. Demand for wood-based energy is even higher in developing countries where bioenergy is often the only readily available, accessible source of heat and fuels [12]. Ceramic stoves are used by families in the communities studied. The stoves are used inside the home, where the smoke can get trapped. The health implications caused by smoke inhalation have motivated researchers to seek for a more efficient stove.

2.2.1 Performance Evaluation of Wood-Burning Cookstoves in Rural Areas near Pucallpa, Peru.

A performance study was conducted on a group of three wood-burning stoves used at homes in the country of Peru. Both stoves were made of ceramic; one of them was named ceramic stove (CS), pictured in Fig. (4); the other was named rocket stove (RS), pictured in Fig. (5). The designs were compared to the traditional stove (TS), pictured in Fig. (6). Water boil tests (WBT) and controlled cooking tests (CCT) were used to determine the stoves' performance. Three common wood species from the area were used as fuel; they were: guava, citrus and mango. The results showed that the CS and RS were more efficient than the TS during the WBT; the results also proved that both the CS and RS used less energy than the TS during the CCT [13].

Fig. (4): Ceramic Stove [13]

Fig. (5): Rocket Stove [13]

Fig. (6): Traditional Stove [13]

2.2.2 Energy Performance of Wood-Burning Cook Stoves in Michoacán, Mexico.

A performance study was conducted where three stove types used in households were compared: U-type stove (UTS) pictured in Fig. (7); three stone fires (TSF) pictured in Fig. (8), and the Patsari stove (PS) pictured in Fig. (9). Fig. (10) shows a diagram of the cross-section of the PS. The study used three methods of evaluation, WBT, CCT and a kitchen performance test (KPT). Three variations of the WBT where used: a test at high-power cold start, high-power warm start, and a low-power test to simulate slow cooking tasks. The results showed that the UTS and TSF had thermal efficiencies ranging from 13 to 19% for the three test variations. In the low-power phase, the specific fuel consumption was much greater for the UTS and TSF than it was during the high-power phases. The PS showed an efficiency of 7% for the high-power cold start test; 17% for the high-power warm start test, and 30% for the low-power test. The PS showed a much lower specific fuel consumption in the low-power test, relative to the high-power cold start test. For the cold start tests, the firepower of the UTS was 6.4 kW; the firepower of the both the TSF and the PS was 9 kW. During the CCT, the PS showed a considerably lower fuel consumption compared to the TSF and the UTS. In this study, the CCT consisted of cooking tortillas; the TS used the least fuel to cook the tortillas, followed by the TSF and the UTS. In this study, the KPT was used to evaluate fuel-wood consumption of households in communities under real usage conditions. Daily fuel use and cooking tasks were monitored over a period of one year. Families were instructed to only use a certain stove and different households were given different stoves. The results after one year showed that the families which had been using the PS saved 67% in fuel consumption, compared to the families that used the UTS and TSF. The researchers emphasized that the further implementation of the improved cookstove could significantly improve the quality of life of rural people with potential benefits to surrounding environment [14].

Fig. (7): U-type stove (UTS)

Fig. (8): Three Stone Fire (TSF)

Fig. (9): Patsari Stove (PS) [14]

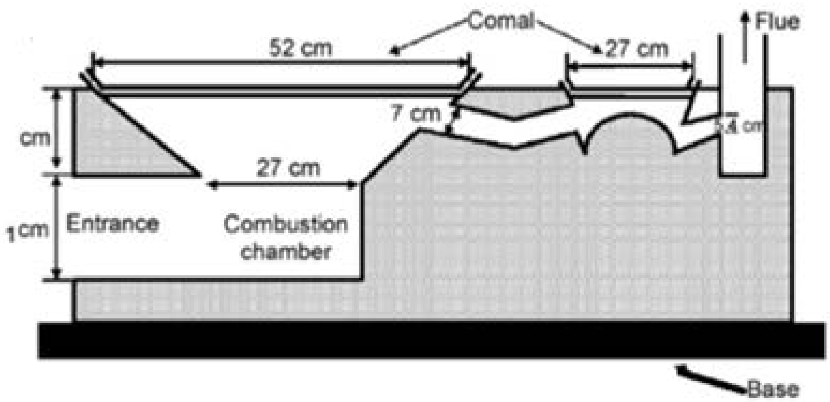

Fig. (10): Patsari Stove cross-section [14]

The stoves in the studies mentioned are made of ceramic; the stoves in this study are made of metal. Regardless, they provide a basis of information about the water boil test and the methods used to test cook stoves.

2.3 Stove Fuel

This section provides an overview of the types of renewable and non-renewable fuels available for camping stoves. Biomass, wood and ethanol are covered in the renewable fuels section. Liquid fuels, canister fuel and chemical fuel are covered in the non-renewable fuels section.

2.3.1 Fuel Heating Value

There are two types of heating values: higher heating value (HHV) and lower heating value (LHV). This research uses the HHV of wood to calculate performance outputs. HHV is the amount of energy released when one kg of dry wood is burned, and all water released in burning process is condensed. LHV is the amount of energy released when one kg of dry wood is burned, and water released is evaporated [15]. The HHV of the wood was obtained through calorimetry testing, discussed in the methods section. The LHV of the wood-char is also required to calculate thermal efficiency and it was obtained from a literature source [16].

2.3.1.1 Moisture Content. Wood is often mistaken to be a solid, compact material; because of their cellular structure, they are quite porous. Moisture content refers to the weight of moisture contained in a piece of wood, expressed as a percentage of its oven dry weight. There are two classifications of water content in wood, one is called free water and the other is imbibed water. Free water is contained in the cell cavities, whereas imbibed water is contained in cell wall voids. The moisture content has a direct effect of the physical and mechanical properties of wood [17].

Moisture content influences the net calorific heating value significantly. Vaporizing one kilogram of water requires around 2.6 MJ (0.7 kWh); thus, if wood has a high moisture content, the net heating value of the fuel is reduced. Table IV shows the heating values of wood fuels with different moisture contents. Fig. (11) is a graph of the moisture content vs the calorific value of wood. This research uses white pinewood with a moisture content of 6%. The wood was obtained as planks of fresh-cut pine trees donated by Sunrise Sawmill in Asheville, North Carolina. The planks were cut into sticks using a table saw and a miter saw. To lower the moisture content in the sticks, they were kiln dried for 24 hours at 105°C (221°F). The final moisture content of the wood was measured at 6%.

Table IV: Heating Values of Wood with Moisture [12]

Fuel Type	Moisture Content (%)	Heating Value (MJ/kg)
Green Wood	50	9.5
Seasoned Wood	20	15.5
Dry Sawdust	13	16.2
Wood Pellets	10	16.8
Dry Wood (non-resinous)	0	19
Dry Wood (resinous)	0	22.5
Dry Stemwood	0	19.1
Dry Bark	0	19.6
Dry Branches	0	20.1
Dry Needles	0	20.4

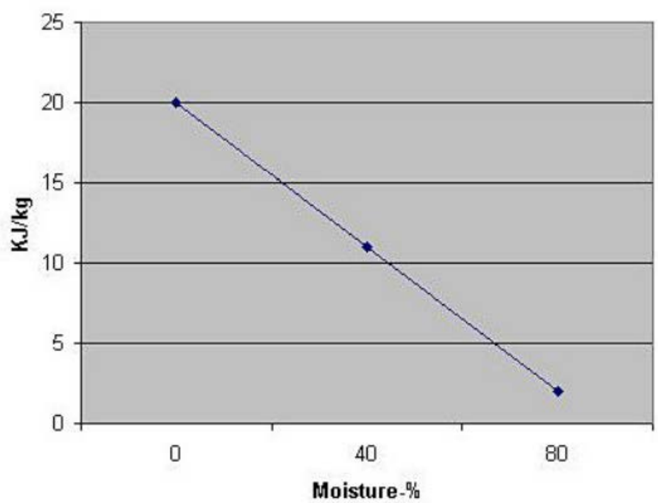

Fig. (11): The Effect of Moisture Content on the Heating Value of Wood [15]

The potential energy value of a fuel is determined by its chemical and physical properties. When burned completely, half the mass of the wood is converted to carbon dioxide and the other half is converted to water. This process liberates about 19 MJ/kg of heat energy for hardwoods and 22 MJ/kg of energy for softwoods. In general, softwoods have higher heating values than hardwoods, and branches have a higher heating value than stem wood. Moisture content also affects the potential heating value; the drier the fuel, the higher the heating value [12].

Fossil fuels are more energy dense and have higher heating values than woody biomass alternatives. From an economic perspective, whether the United States chooses to embrace an alternative energy future will depend upon political and social choices. At this time, costs of producing energy from woody biomass feedstocks, compared to fossil fuel feedstocks remain a major barrier to market development. Table V shows the heating values of fossil fuels compared to wood.

Table V: Heating Values of Fossil Fuels and Wood [12]

Fuel Type	Heating Value (MJ/kg)
Propane	50.0
Kerosene	46.5
Diesel Oil	45.6
Fuel Oil	43.0
Natural Gas	37.3
Coal	29.2
Wood Pellets	19.8

To be a viable alternative, biomass should provide a net energy gain or produce more energy than the amount it takes to grow and process the fuel. This net energy gain is measured by energy ratios; ratios below 1 indicate that the energy input is higher than the energy output. research shows that woody biomass utilization results in energy ratios above 1; energy input is less than energy produced. current technologies used to produce electricity from wood give ratios between 6 and 7, surpassing other competitors. Increasing these ratios to 10 or 15 is even possible with technological improvements [12].

2.3.2 Renewable Fuel

Renewable fuels can be processed or unprocessed. Stoves that use unprocessed renewable fuels are biomass stoves. Stoves that use processed renewable fuel are denatured alcohol stoves, also called ethanol stoves. Ethanol is processed and sold from stores, so the availability of it is limited to the amount that a camper brings with them. Wood and ethanol come from trees and crops respectively, both of which can be planted and grown again. Biomass is any organic matter that can be used as an energy source. Biomass stoves can burn twigs, pine straw, pinecones, wood, forest residue, animal feces, garbage and agriculture byproducts.

2.3.2.1 Wood Fuel. Wood implies anything from twigs, branches, pine straw or forest residue. The three main sources of forest residue are slash, thinning remains, and un-merchantable wood. Slash is logging debris left in the forest after a harvest [18]. Thinning is probably the most important operation carried out in forests managed for timber production. By removing the smaller, weaker and poorer quality trees, growth is concentrated on the better trees remaining. This results in a greater volume of good quality and larger diameter timber being harvested from a crop, which commands a higher price from the sawmills [19]. Un-merchantable wood is material that is unsuitable for conversion to industrial wood products due to size, form, or quality. Un-merchantable wood includes rough, rotten, and dead trees; the tops, limbs, and cull sections from harvested trees; or small and non-commercial trees [20]. The main sources of clean energy in the US today are wood and processed biofuels. Until the mid-1800s, wood gave Americans 90 percent of the energy they used. Today, biomass provides four percent of the energy used; it has been replaced by coal, natural gas, and petroleum [21] [22]. Regardless, wood is still the main source of energy for over two billion people. Wood also provides more than fourteen percent of the World's total energy today [12]. When camping with a wood-fueled stove, the user does not need to carry fuel with them because they can often gather biomass, such as twigs and leaves and forest residue, from around the campsite. If it is raining, it is better to pick the fuel before it gets wet. If it is already wet, it can be broken into small pieces and it will burn better. Some camping areas have burn bans so users must beware of the laws of the area they are camping in. Wood fuel has several environmental advantages over fossil fuels. The main advantage is that wood is a renewable resource, offering a sustainable, dependable supply. Other advantages include the fact that the amount of carbon dioxide (CO2) emitted during the burning process is typically 90% less than when burning fossil fuel. Wood fuel contains minimal amounts of sulfur and heavy metals. It is not a threat to acid rain pollution, and particulate emissions are controllable [23].

The chemical components in wood are cellulose, hemicellulose, lignin, organic extractives and inorganic minerals (ash). Cellulose and hemicellulose are formed by long chains of carbohydrates, whereas lignin is a complicated component of polymeric phenolics. Lignin content ranges from 18 to 35%, and carbohydrate content ranges from 65 to 75%. Organic extractives and ash content ranges from 4 to 10%. Wood and bark also contain extractives, such as terpenes, fats and phenols. Overall, wood has an elemental composition of about 50% carbon, 6% hydrogen, 44% oxygen and trace amounts of several metal ions [24]. Softwoods tend to have higher Carbon content than hardwoods. Softwoods also tend to have a lower Oxygen content than hardwoods.

The total amount of energy released when a fuel is consumed is known as the heating value and is measured in joules per gram, or mega-joules per kilogram (MJ/kg). Compared to many other fuels, wood has a relatively low carbon content (some 50 % of dry weight) which leads to relatively low heating value per dry weight [15].

2.3.2.2. Ethanol Fuel. Ethanol and methanol are processed biomass fuels [21]; ethanol is also known as denatured alcohol. Alcohol stoves appeal to ultralight backpackers because they weigh only an ounce or two [25]. Ethanol is the same as denatured alcohol and it is made domestically, most commonly from corn. It is also made from cellulosic feedstocks, such as crop residues and wood, though this is not as common. Most ethanol in the United States is produced from starch-based crops by two processes called dry-milling and wet-milling. The dry-milling process grinds corn into flour and ferments it into ethanol. The wet-mill process produces corn sweeteners, along with ethanol, corn oil and starch. Wet mills separate the starch, protein, and fiber in corn prior to processing these components into products [26].

2.3.3 Non-renewable Fuels

Non- renewable fuels are mainly derived from petroleum; there are liquid fuels, canister fuels and chemical fuels.

2.3.3.1 Liquid Fuel. Liquid-fuel can be white gas (naphtha) which is a colorless, volatile petroleum distillate, usually an intermediate product between gasoline and benzene, used as a solvent or fuel [27]. Naphtha burns cleaner than most others because it evaporates (vaporizes) at a lower temperature [28] The clean burning property is the reason why naphtha is the most used fuel. Liquid-fuel can also be kerosene, but users do not like to use it because it has a strong odor and if it is not refined well, it can clog up a stove. Fuels in some parts of the world are dirtier and less refined than elsewhere [28]. Lastly, liquid-fuel can be automotive gasoline, but it is used as a last resort because of its downsides. Gasoline contains additives designed to make car engines run smoother, but these additives can harm the seals in a stove's pump and fuel line, making them harder and more prone to leaking. Gasoline will also produce more smoke and fumes than white gas [28].

Liquid-fueled stoves perform well in high elevations and cold weather. One of its disadvantages is that it requires priming, which involves igniting a few drops of fuel in a cup below the burner, creating a small flame that pre-heats the fuel line. This enables the stove to convert liquid fuel into a vapor. They also require periodic maintenance such as cleaning the fuel line or replacing O-rings. The fuel bottle also requires pumping during the cooking process to maintain pressure at the burner. Although liquid-fueled stoves perform better at high-altitudes, they are loud, have limited fuel, require priming and cleaning; therefore, they are only necessary when the user is on a high-altitude expedition.

2.3.3.2 Canister Fuel. Canister stoves weigh a few ounces, fold up and require low maintenance. The burner screws onto the top of pressurized fuel canisters that contain two gases, isobutane and propane. No priming is required to light the canister stove and most models let the user adjust the flame for simmering. Canister fuel also has disadvantages like, small arms that cannot hold a big pot. It is difficult to know how much fuel is left so campers often pack more than they need. Compared to liquid fuel, the cost of canister fuel is greater. And finally, they create waste in the form of empty containers that must be disposed of properly due to the left-over fuel inside [25]. Canister stoves have problems lighting at high altitudes and have limited fuel, so they are not often used at high altitude. Another disadvantage of a canister stove is waste generation in the form of empty canisters, which are dangerous to recycle because of leftover fuel.

2.3.3.3 Chemical Fuel. These stoves can fold up and they use a fuel that is shaped as a tablet. The tablet is made of hexamine, also known as Hexamethylenetetramine, it is an odorless, white crystalline powder or colorless lustrous crystal. The compound is considered toxic and may be harmful by inhalation, ingestion or skin absorption. It is an irritant of the skin, eyes, mucous membranes and upper respiratory tract [29].

2.4 Heat Transfer Process

Heat transfer is the physical act of thermal energy being exchanged between two systems by dissipating heat. In this study, thermal energy is exchanged between the wood and the water via combustion, with losses to the ambient. Energy is exchanged by three types of heat and mass transfer discussed in this section. The amount of thermal energy available between two systems is determined by the temperature; the heat flow represents the movement of thermal energy [30].

2.4.1 Water Boil Test

The water boil test (WBT) yields many indicators of stove performance such as boil time, thermal efficiency, firepower, specific fuel consumption and burning rate. This study uses a 1-liter water boil test; this study also uses a stainless-steel pot and lid; the pot measures 114 mm (4.5 in) in diameter by 127 mm (5in) in height. Since a backpacker typically cooks for themselves or another person, they do not need to boil a large volume of water; therefore, a liter was chosen as the amount of water to be boiled.

2.4.1.1 Altitude. When boiling water at altitude, more time is needed because of the decreased air pressure [31]. Above 2,500 feet, the atmosphere becomes much drier. The air has less oxygen and atmospheric pressure, so cooking takes longer. At altitudes above 3,000 feet, preparation of food may require changes in time, temperature or recipe. The reason is the lower atmospheric pressure due to a thinner blanket of air above. At sea level, the air presses on a square inch of surface with 14.7 pounds pressure which decreases about 1/2 pound per 1,000 feet. As atmospheric pressure decreases, water boils at lower temperatures. At sea level, water boils at 212 °F (100°C). With each 500-feet increase in elevation, the boiling point of water is lowered by just under 1 °F. Because water boils at a lower temperature at higher elevations, foods that are prepared by boiling or simmering will cook at a lower temperature, and it will take longer to cook [32]. Fig. (12) is a graph that shows how the boiling point of water decreases with increased altitude.

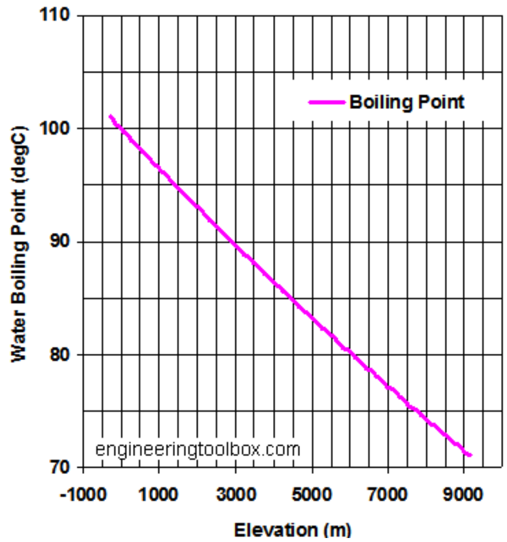

Fig. (12): Boiling Point by Elevation [33]

2.4.2 Wood Combustion

The three elements of fire are heat fuel and oxygen. A heat source is responsible for the initial ignition of fire; it is also needed to maintain the fire and enable it to spread. Heat allows fire to spread by drying out and preheating nearby fuel and warming surrounding air. Fuel is any kind of combustible material. It's characterized by its moisture content, size, shape, quantity and the arrangement in which it is spread over the landscape. The moisture content determines how easily it will burn. Oxygen supports the chemical processes that occur during fire. Air contains about 21 percent oxygen, and most fires require at least 16 percent oxygen content to burn. When fuel burns, it reacts with oxygen from the surrounding air, releasing heat and generating combustion products (gases, smoke, embers, etc.). This process is known as oxidation [34].

Wood is complex fuel that undergoes dramatic changes as it burns. As the previous sections explain, cellulose and hemi-cellulose and lignin and inorganic ash are the chemical components of wood. Lignin is rich in carbon and hydrogen, which are the main heat producing elements; thus, its calorific value is higher than that of cellulose and hemicellulose (carbohydrates). Most types of wood will start combusting at about 300°C [35]. The gases burn and increase the temperature of the wood to about 600°C (1,112°F). When the wood has released all its gases, it leaves charcoal and ashes. Charcoal burns at temperatures exceeding 1,100 degrees Celsius (2,012°F) [36]. Pyrolysis is an exothermic reaction that tends to be self-sustaining once started. When wood combusts, the electrons in the carbon atoms excite and move around. When they de-excite, they release energy in the form of visible light. Atomic energy release is the reason why the flames of a fire are yellow.

Up to 85% of the mass and 60% of the heating value from wood is contained in gases produced by pyrolysis. Smoke and creosote represent unburned fuel; creosote is the condensed portion of smoke. Over 100 chemical compounds including CO, CH_4 and many hydrocarbons are in smoke, all of which can be burned. Smoke and creosote are formed because the conditions of the fire were not appropriate to allow the gases to burn.

Primary combustion is the burning of solid material directly. In wood combustion, this is the burning of the charcoal, also known as hot coals or embers. Secondary combustion is the burning of the gases produced from pyrolysis. Complete combustion produces only Carbon Dioxide $(\mathrm{CO_2})$ and water ($\mathrm{H_2O}$); no smoke or creosote are formed. Incomplete combustion produces significant levels of Carbon Monoxide (CO) and many hydrocarbons. These unburned components represent lost heating value, pollutant emissions and potential creosote formation [37].

2.4.2.1 Oxidation. Oxidation-reduction reactions are also known as redox reactions. They are chemical processes in which electrons are transferred from one atom, ion, or molecule to another. Explosions, fires, batteries, and even our own bodies are powered by oxidation-reduction reactions. Redox reactions are a combination of two processes: oxidation, in which electrons are lost, and reduction, in which electrons are gained; the two processes cannot occur independently of each other. Combustion reactions are redox reactions that occur when oxygen oxidizes another material. Redox reactions can occur relatively slowly, as in the formation of rust, or much more rapidly, as in the case of burning fuel. There are simple redox processes, such as the oxidation of carbon to yield carbon dioxide; the reduction of carbon by hydrogen to yield methane, and more complex processes such as the oxidation of glucose in the human body [38]. During the combustion of wood, electrons are transferred from carbon atoms in the wood to oxygen atoms in the air. The oxygen atoms undergo reduction, gaining electrons, while the carbon atoms undergo oxidation, losing electrons. Thus, oxygen is the oxidizing agent and carbon is the reducing agent in this reaction.

2.4.2.2 Pyrolysis. Pyrolysis is the heating of an organic material, such as biomass, in the absence of oxygen. Because no oxygen is present, the material does not combust, instead, the chemical compounds (i.e. cellulose, hemicellulose and lignin) that make up that material, thermally decompose into combustible gases and charcoal. Most of these combustible gases can be condensed into a combustible liquid, called bio-oil, though there are some permanent gases (CO_2, CO, H_2, and light hydrocarbons). The pyrolysis of biomass produces three products: liquid bio-oil, solid biochar and gaseous syngas. The pyrolysis process can be self-sustained, as combustion of the syngas and a portion of bio-oil or biochar can provide all the necessary energy to drive the reaction [39].

2.4.3 Types of Heat and Mass Transfer

This section discusses the pool boiling configuration, the boil curve and the stages within it. Heat flux and critical heat flux are discussed. The similarities between boiling point and saturation temperature are covered. Three types of heat and mass transfer methods that occur during a WBT are explained.

2.4.3.1 Pool Boiling. The most common boiling configuration is known as pool boiling. It occurs when a pool of liquid is heated from below through a horizontal surface. In pool boiling, the liquid is not moving in the beginning; motion of the fluid is due to natural convection currents and the motion of the bubbles under the influence of buoyancy. There are four stages in boiling; they are known as natural convection boiling, nucleate boiling, transition boiling and film boiling [40] [41]. Fig. (13) illustrates the four boiling stages on the water boiling curve. In the graph, the x-axis represents the excess temperature, which is the temperature difference between the heat source and the saturation temperature of the fluid. The y-axis represents heat flux, which is the rate of energy transfer per unit area. The dashed blue line shows the section of the boil curve that this study uses to compare the performance of camping stoves.

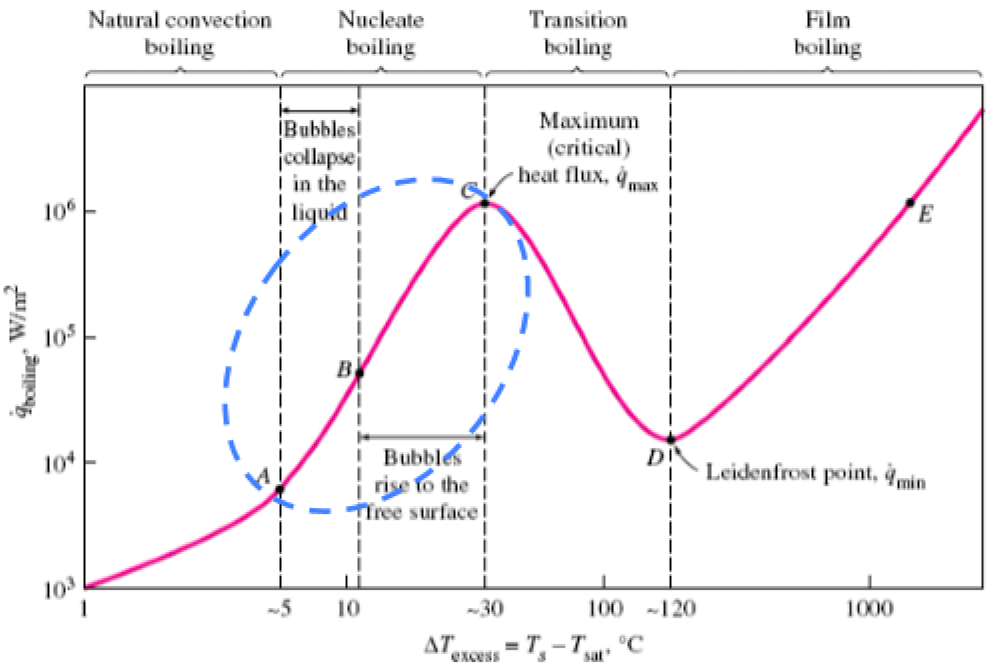

Fig. (13): Boiling Stages [41]

The temperature at which water is evaporated at a given pressure is called saturation temperature or boiling point. The term saturation defines a condition in which the mixture of vapor and liquid can exist together at a given temperature and pressure [42].

Subcooled boiling occurs when the temperature of the main body of the liquid is below the saturation temperature. Saturated boiling occurs when the temperature of the main body of the liquid is equal to the saturation temperature. Fig. (14) shows the difference between subcooled and saturated boiling.

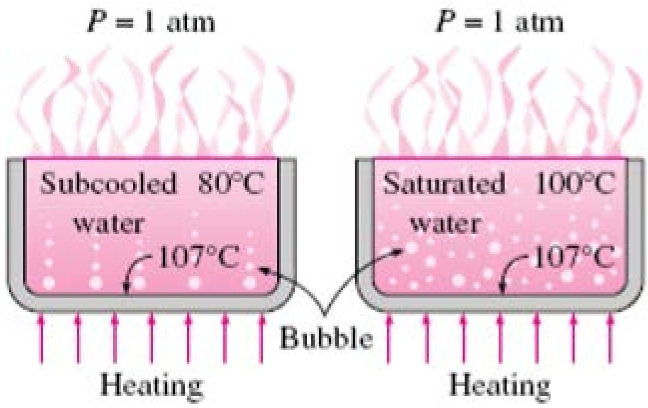

Fig. (14): Subcooled and Saturated Boiling

Evaporation occurs at a temperature during the liquid-vapor interface; when the vapor pressure is less than the saturation pressure of the liquid. Boiling occurs at the solid-liquid interface; when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid.

2.4.3.2 Heat Flux. Heat flux is the rate of heat energy transfer through a given surface. Heat flux density is the heat rate per unit area. The SI basic SI unit of energy is the Joule; one Joule per second ($\frac{J}{s}$) is equivalent to a Watt (W). In the SI system, heat flux density is measured in ($\frac{W}{m^2}$); in the US customary system, heat flux is measured in ($\frac{Btu}{ft^2}$). Heat rate is a scalar quantity, while heat flux is a vector quantity [43]. Vector quantities refer to the physical quantities characterized by the presence of both magnitude as well as direction; for example: displacement, force, torque, momentum, acceleration and velocity [44].

2.4.3.3 Natural Convection. Convection is heat transfer by the movement of liquids or gasses [45]. Natural convection, also known as free convection, is a type of mass and heat transport, in which the fluid motion is generated only by density differences in the fluid occurring due to temperature gradients, not by any external source like a pump, fan, or suction device. In natural convection, fluid surrounding a heat source receives heat and via thermal expansion becomes less dense and rises; heavier (denser) water molecules fall, while lighter (less dense) molecules rise, leading to fluid motion. Thermal expansion is the increase, or decrease, of the size, length, area, or volume of a body, due to a change in temperature. Thermal expansion is large for gases, and relatively small, but not negligible, for liquids and solids [46]. Natural convection can only occur in a gravitational field or in the presence of another proper acceleration, such as: acceleration, centrifugal force or Coriolis force [47]. Creation of convective currents is based on three factors: the presence of a heat source, the presence of proper acceleration and the geometry of the hot surface. Heat source is required, because convection currents are generated by density differences in the fluid occurring due to temperature gradients. Proper acceleration, such as a gravitational field, is required because it allows natural convection to occur. The geometry and orientation of the hot surface is important because the ratio of air available for combustion is dependent on the design of the burner [48]. Natural convection also depends on the variation of temperature on the surface and the thermophysical properties of the fluid involved [49].

During a WBT the heat from the wood is transferred to the water through natural convection. The heat of the fire also heats up the air surrounding the stove, creating natural convection of air. The heat in the water is lost to the ambient through the natural convection of the air surrounding the pot. In the boil curve, natural convection occurs up to point A, between an excess temperature of 1 to 5°C; it is followed by nucleate boiling.

2.4.3.4 Nucleate Boiling. When water is boiled, the fluid near the bottom surface of the pot heats up first. As the water gets hot, it becomes less dense and rises; then it is replaced by the cooler, more dense water molecules near the top of the pot. Because of gravity, the water molecules continually exchange in this way [50]. As the bottom surface temperature is raised slightly above the saturation temperature, bubbles form near the hot surface [51]; this bubble formation is called nucleate boiling. The bubbles rise, due to buoyancy and then collapse, as they reach the denser, relatively cooler water near the top of the pot. This motion not only helps to move the water around more quickly, but the bubbles themselves transfer heat energy as well. Nucleate boiling occurs during an excess temperature of 5-30°C. In Fig. (15), nucleate boiling occurs from point A to point C of the curve. From point A to point B, the bubbles formed are isolated and they collapse as they rise; from point B to point C, the bubbles form continuous jets and columns (plumes) that rise to the top surface of the liquid. In hydrodynamics, a plume is a column of one fluid moving through another. Several effects control the motion of the fluid, including momentum (inertia), diffusion and buoyancy (density differences). Pure jets and pure plumes define flows that are driven entirely by momentum and buoyancy effects, respectively. Flows between these two limits are usually described as forced plumes or buoyant jets [52]. Entrainment is defined as the transport of fluid across an interface between two bodies of fluid by a shear induced turbulent flux [53]. In region A–B the stirring and agitation of the liquid is caused by the entrainment of the liquid to the heater surface; this increases the heat transfer coefficient. Large heat fluxes obtainable in region A-B, are caused by the combined effect of liquid entrainment and evaporation. The heat flux increases at a lower rate after point B; it reaches a maximum at point C. The bubbles form at an increasing rate during nucleate boiling; the number of nucleation sites also increases as the curve approaches point C [41]. In the boil curve, point C is known as the critical heat flux.

2.4.3.5 Critical Heat Flux. The nucleate boiling heat flux cannot be increased indefinitely; along the boil curve, the critical heat flux is reached at point C. Critical heat flux is the point at which the energy transferred to the liquid begins creating localized vapor blankets near the hot surface [54].

2.4.3.6 Transition Boiling. Between an excess temperature of 30 to 120°C, transition boiling occurs. When the excess temperature is increased past point C along the boil curve, the heat flux decreases; this is because a large portion of the hot surface is covered by a vapor film, which acts as insulation [55]. In the boil curve, transition boiling occurs from point C to point D. The highly turbulent bubble flow created by transition boiling indicates the water has reached boiling point. During the transition boiling stage, film boiling also occurs.

2.4.3.7 Film Boiling. In the boil curve, film boiling occurs from point D to point E. The film acts as thermal insulation due to the low thermal conductivity of the vapor, relative to that of the liquid; this significantly reduces the convection coefficient. As a result, the excess temperature increases and the boil curve reaches point D, also called the Leidenfrost point [56]. The Leidenfrost effect is a physical phenomenon in which a liquid in contact with a mass significantly hotter than the liquid's boiling point, produces an insulating vapor layer, keeping that liquid from boiling rapidly [57]. Beyond the Leidenfrost point, a continuous vapor film blankets the surface and there is no contact between the liquid phase and the surface; beyond point D along the boil curve, the hot surface is completely covered by a continuous stable, vapor film. At that point, heat transfer rate increases with increasing excess temperature, due to radiation and conduction to the liquid [56].

A typical boiling process does not follow the boiling curve beyond point C. Fig. (15) shows the curve behavior during a typical boiling process. When the power applied to the heated surface exceeds the value at point C, even slightly, the surface temperature increases suddenly to point E. When the power is reduced gradually, starting from point E, the cooling curve has a sudden drop in excess temperature and point D is reached [37].

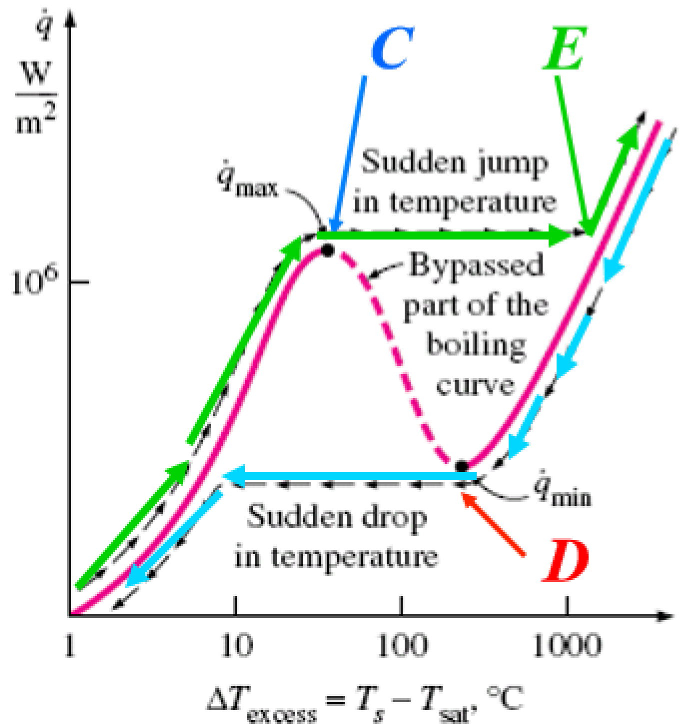

Fig. (15): Typical Boiling Process [37]

2.4.3.8 Conduction. When burning a fire in the stove, conduction occurs on the places that the stove supports are touching the pot. Conduction occurs through physical contact and transfers heat via direct molecular collision. An area of greater kinetic energy will transfer thermal energy to an area with lower kinetic energy [30]. The stoves are made of metal, which possesses thermal conductivity properties. Thermal conductivity is a material property that describes ability to conduct heat. Thermal conductivity is defined as “the quantity of heat transmitted through a unit thickness of a material, in a direction normal to a surface of unit area, due to a unit temperature gradient, under steady state conditions". Thermal conductivity units are ($\frac{W}{cm\cdot°C}$) in the SI system and ($\frac{Btu}{hr\cdot ft\cdot°F}$) in the US customary system. [58]. Table VI shows a list of heat conducting metals, lowest to highest average thermal conductivity, in ($\frac{Btu}{hr\cdot ft\cdot°F}$) at room temperature. Table VII shows the same data but in ($\frac{W}{cm\cdot°C}$) at room temperature. From the eight stoves tested in this research, seven were made of stainless steel and one was made of titanium; the prototype 1 stove was manufactured from aluminum. Stainless steel has the lowest thermal conductivity of 5.8 ($\frac{Btu}{hr\cdot ft\cdot°F}$) or 0.1 ($\frac{W}{cm\cdot°C}$). Titanium is second with a thermal conductivity of 11.6 ($\frac{Btu}{hr\cdot ft\cdot°F}$) or 0.2 ($\frac{W}{cm\cdot°C}$). Aluminum has the highest thermal conductivity of 138.8 ($\frac{Btu}{hr\cdot ft\cdot°F}$) or 2.4 ($\frac{W}{cm\cdot°C}$) [58].

Table VI: Thermal Conductivity of Metals ($\frac{Btu}{hr\cdot ft\cdot°F}$) [59]

Stainless Steel: (5.8)
Titanium: (11.6)
Lead (23.1)
Carbon Steel (28.9)
Wrought Iron (34.7)
Iron (40.5)
Aluminum Bronze (46.3)
Copper brass (63.6)
Aluminum (138.8)
Copper (231.3)
Silver (248.6)

Table VII: Thermal Conductivity of Metals ($\frac{W}{cm \cdot °C}$) [59]

Stainless Steel: (0.1)
Titanium: (0.2)
Lead (0.4)
Carbon Steel (0.5)
Wrought Iron (0.6)
Iron (0.7)
Aluminum Bronze (0.8)
Copper brass (1.1)
Aluminum (2.4)
Copper (4.0)
Silver (4.3)

2.4.3.9 Radiation. Heat transfer through radiation takes place in form of electromagnetic waves mainly in the infrared region. Radiation emitted by a body is a consequence of thermal agitation of its composing molecules [60]. Thermal radiation ranges in wavelength from the longest infrared rays through the visible-light spectrum to the shortest ultraviolet rays [61]. The intensity and distribution of radiant energy within this range is governed by the temperature of the emitting surface. The heating of the Earth by the sun is an example of transfer of energy by radiation [62]. When boiling water with a wood-fueled stove, the pot is heated by thermal radiation emitted from the fire. During a WBT, heat from the pot is also lost due to radiation to the surrounding environment.

CHAPTER 3: METHODS

This chapter describes the methods and setup that this study uses to conduct water boil tests; the instruments and equipment used to gather data during testing; the methods used to test samples in a bomb calorimeter are explained in this chapter; and the equations used to calculate performance outputs.

3.1 Test Instrumentation

3.1.1 Thermocouples

In this study, the pot was covered with a lid. Five holes were drilled through the lid to allow the attachment of a structure made of bamboo skewers. The skewers were fixed in place using a two-part epoxy. There was a hole in the middle of the lid which measured 4mm (0.16 in) in diameter. The pot lid was instrumented with 4 K-type thermocouple probes placed at 0.75in, 1.50in., 2.50in., and 3.50in. from the bottom of the pot. Fig. (16) depicts the thermocouple type used in this research. Fig. (17) depicts an illustration of the instrumented pot lid. Thermocouples work based on a principle that in 1821, Thomas Johann Seebeck discovered that when two strips of different electrically conducting materials were separated along their length but joined together by two “legs” at their ends, a magnetic field developed around the legs, provided that a temperature difference existed between the two junctions [63]. The joined end is also called the measurement “hot” junction. The other end, where the wires are not joined, is connected to the signal conditioning circuitry traces, made of copper. This junction is called the reference “cold” junction [64].

Fig. (16): K-Type Thermocouple [65]

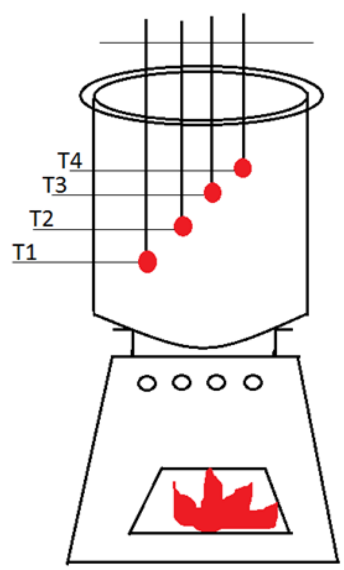

Fig. (17): Pot Lid Instrumentation

3.1.1.1 Thermocouple Types. Thermocouples are available in different combinations of metals (calibrations). The most common are thermocouples known as Types J, K, T, E and N. There are also high temperature calibrations which are types R, S, C and GB [66]. Fig. (18) lists the four different types of thermocouples and the temperature range in which they are designed to work.

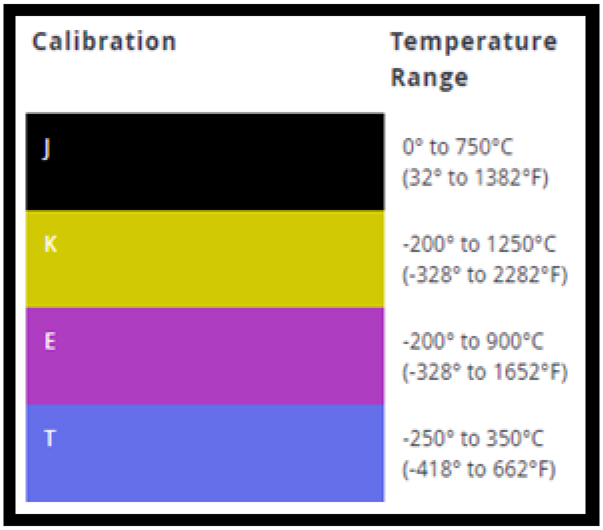

Fig. (18): Thermocouple Types and Working Temperatures [66]

Thermocouples are manufactured in a variety of styles, such as thermocouple probes, thermocouple probes with connectors, transition joint thermocouple probes, infrared thermocouples, bare wire thermocouple or just thermocouple wire [67]. Thermocouples can be insulated with materials like Teflon, fiberglass, Kapton and stainless steel [68]. The thermocouples used in this research were wire thermocouples insulated with Teflon.

3.1.1.2 Thermocouple Signal Conditioning. Four types of signal conditioning are required when using thermocouples. The four types are amplification for high-resolution (ADC), cold junction compensation (CJC), filtering and linearization. The datalogger that this study uses applies the four types of conditioning to the thermocouple signal.

3.1.1.3 Amplification for High-Resolution. Thermocouples generate very low-voltage signals, usually measured in microvolts. To acquire these signals with a measurement device, the signal must be amplified until it can be accurately measured with a standard 12-bit measurement device. Alternatively, a measurement device with a high-resolution ADC can be used [69].

3.1.1.4 Cold Junction Compensation. Thermocouples require some form of temperature reference to compensate for unwanted parasitic thermocouples. A parasitic thermocouple is created when a thermocouple is connected to an instrument. Because the terminals on the instrument are made of a different material than the thermocouple wire, voltage is created at the junctions, called cold junctions, which changes the voltage output by the actual thermocouple. Traditionally, the temperature reference was 0 °C. The National Institute of Standards and Technology (NIST) thermocouple reference tables are created using this setup. Although an ice bath reference is quite accurate, it is not always practical. A more practical approach is to measure the temperature of the reference junction with a direct-reading temperature sensor, such as a thermistor or an IC sensor, and then subtract the parasitic thermocouple thermoelectric contributions [69]. Thermistors use metal oxides beads that are encapsulated in either epoxy or glass. Typically, a thermistor will show large NTC (negative temperature coefficient). Thermistors are highly sensitive and can be made small (to the size of a pin) for sensing in small spaces [70].Fig. (19) depicts a diagram of a thermocouple with its hot and cold junctions. Cold junction compensation compensates for the missing thermoelectric voltage since the thermocouple cold end at the instrument is not at (0°C /32°F) [71].

3.1.1.5 Filtering. A thermocouple can act much like an antenna, making it very susceptible to noise from nearby 50/60 Hz power sources. Therefore, application of a 2 or 4 Hz lowpass filter is required to remove power line noise from the signal [69].

3.1.1.6 Linearization. The output voltage of a thermocouple is not linear with temperature; therefore, the system must perform linearization either through hardware or software [69]. Linearization is a mathematical process

of finding the linear approximation of inputs and corresponding outputs [72]. Appendix A shows a K-Type thermocouple reference table.

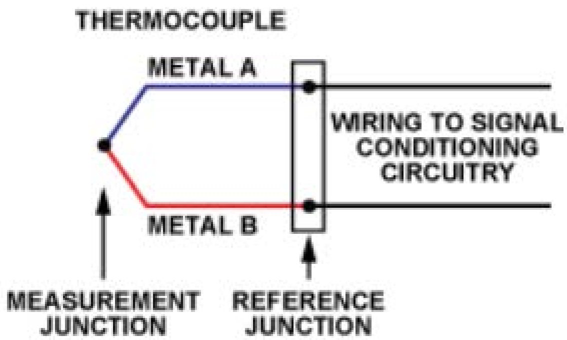

Fig. (19): Thermocouple Diagram [64]

3.1.2 Data Logger

An Omega 4-Channel Datalogger Thermometer was used to record the temperature every two seconds during every test. The temperature was recorded in degrees Celsius. The instrument has a memory card where the data is stored; using Microsoft Excel, time and temperature logs can be plotted in a graph. The model number of the datalogger is: RDXL4SD. The instrument reads the signal from the thermocouple and uses four types of signal conditioning to determine the temperature value being measured. Fig. (20) depicts the datalogger instrument. The specifications for the data logger are shown in Appendix B.

Fig. (20): Omega RDXL4SD Datalogger [73]

3.1.3 Wood-Fuel

The wood-fuel used in this research was white pine obtained from Sunrise Sawmill, which is in Asheville, NC. The wood was picked from a pile of recently cut logs; several planks were gathered and taken to the Western Carolina Construction Management shop in order to cut them down into small sticks measuring 9.5 cm (3.75 in) long, with a cross-section of 1 cm x 1 cm (0.4 in x 0.4 in). Fig. (21) shows the mill from where the wood was obtained. Fig. (22) shows a picture of the wood after it had been cut into sticks. Fig. (23) shows the cross-section of the wood sticks. Using a table saw and a miter saw, 40 pounds of sticks were cut from the planks of wood. This research used wood that was cut with tools that would not be available to a camper in the wilderness. This was done to keep the fuel consistent during testing and to ensure that the methods were consistent in every test. During an actual camping trip, a user finds twigs, branches, pine straw, pinecones and forest residue to burn in their stove.

Fig. (21): Sunrise Sawmill [74]

Fig. (22): Wood Fuel Cut into Sticks

Fig. (23): Wood Fuel Stick Cross-Section

3.1.4 Moisture Meter

A General Tools digital moisture meter was used to determine the moisture content in the wood before and after kiln drying. The model of the moisture meter is MMD4E and it is pictured in Fig. (24). The instrument works by measuring the resistance between test pins inserted into a piece of wood; the reading is used as a proxy for the object's absolute moisture level [75]. The wetter the wood is, the lower the resistance that the current will have traveling from one pin the other. Low resistance would translate to high moisture content and vice versa. The specifications for the moisture meter are shown in Appendix C.

Fig. (24): Moisture Meter [75]

3.1.5 Scale

A My Weigh scale was used to measure the mass of the fuel and water before and after the test. The mass of the empty pot, empty fuel container and wood charcoal were also recorded during every test. The model of the scale is 7001DX and it is pictured in Fig. (25). The specifications for the scale are shown in Appendix D.

Fig. (25): 7001DX Scale [76]

3.2 Stoves Tested

The eight commercially available stoves tested in this study are pictured in Fig. (26). The stoves were purchased from online vendors, who shipped them to the Western Carolina University Campus. The stove prices range from 14 to 100 US dollars; stove weights range from 213 to 1411 grams. Table VIII contains information about the stoves, such as: weight, dimensions, build material and price.

Solo [77]

Ouspots [78]

Emberlit [79]

Lixada [80]

Zhongmei [81]

12-Survivors [82]

Yoler [83]

Hot Ash [84]

Fig. (26): Stoves Tested

Table VIII: Stove Information

#	Name	Weight (g.)	Disassembled Dimensions (in.)	Assembled Dimensions (in.)	Price	Material
1	Emberlit Stove	213	(L=5.0) (W=5.0) (H=0.3)	(L=5.5) (W=5.5) (H=6.0)	$85	Titanium
2	Lixada	225	(Dia.=4.5) (H=4.0)	(Dia.=4.5) (H=8.3)	$14	Stainless Steel
3	Solo	235	(Dia.=4.2) (H=3.8)	(Dia.=4.2) (H=5.7)	$70	Stainless Steel
4	Zhongmei	349	(Dia.=5.5) (H=3)	(Dia.= 5.5) (H=6.5)	$20	Stainless Steel
5	12-Survivors	350	(L=5.75) (W=6.0) (H=0.45)	(L=5.75) (W=5.75) (H=6.0)	$28	Stainless Steel
6	Ouspots	437	(Dia.= 5.3) (H=2.8)	(Dia.=5.3) (H=7.5)	$20	Stainless Steel
7	Yoler	715	(L=7.9) (W=6.1) (H=1.0)	(L=7.9) (W=6.1) (H=7.1)	$30	Stainless Steel
8	Hot Ash	1411	(L=8.9) (W=3) (H=3.2)	(L=8.9) (W=6) (H=7.2)	$100	Stainless Steel

3.3 Calculations

This section describes the equations used, their constants and their variables. The calculations used to determine moisture content and heating value are explained in this section. The equations used to calculate boil time, thermal efficiency, firepower, specific fuel consumption and burning rate are also introduced in this section.

3.3.1 Wood Moisture Content

The moisture content in the white pinewood was determined after drying it for 24 hours at 105°C (221°F), at the Green Energy Park in Dillsboro, NC. The weight of moisture contained in a piece of wood expressed as a percentage of its oven dry weight is referred to as moisture content. Equation (1) calculates moisture content (mc); where W_g is the green weight of the wood, and W_0 is the oven dry weight of the wood.

$$mc = \left(\frac{W_g - W_0}{W_0}\right) * 100\% \qquad (1)$$

3.3.2 Wood Calorimetry

To calculate the thermal efficiency of stoves, the energy in contained in the fuel must be known. A bomb calorimeter is an instrument used to determine the amount of energy that is contained in a sample. A Parr brand, 1241 Adiabatic Oxygen Bomb Calorimeter and 1108 oxygen combustion vessel (OCV), were used to determine the amount of energy in the samples of white pinewood. A Mettler Toledo brand, model MS204S, analytical balance was used to measure the mass of the fuel samples during calorimetry testing. The methods by [85] were used to operate the bomb calorimeter; methods from [86] were used to operate the OCV. The bomb calorimeter is pictured in Fig. (27) and the OCB is pictured in Fig. (28). The MS204S analytical balance is pictured in Fig. (30). Specifications of the 1241 bomb calorimeter are shown in Appendix E. Specifications of the 1108 oxygen bomb are in Appendix F.

A stainless-steel thermistor, made by Vernier, was used to measure the temperature of the water in the bomb calorimeter. The thermistor is pictured in Fig. (29). Specifications for the thermistor are in Appendix G. The Vernier brand, data-collecting software “Logger Lite”, was used to log the temperature every half second for the duration of every test.

The calorific value obtained in a bomb calorimeter test represents the gross heat of combustion for the sample or the HHV; this is the energy by the combustion of the fuel plus the energy that was used to evaporate the moisture in the sample. The lower heating value (LHV) subtracts the energy used to evaporate the moisture in the sample. When water converts from a liquid to a gas, a quantity of heat energy known as the latent heat of vaporization is required to break the hydrogen bonds. At 100 °C, 540 calories per gram of water are needed to convert one gram of liquid water to one gram of water vapor, under normal pressure [87]. During calorimetry testing, mass of the moisture in the sample was measured in grams, by wiping the inside of the bomb after burning a sample. That value was multiplied by 540, to obtain the value of energy that was used to evaporate the moisture. The result was subtracted from the HHV to obtain the LHV of the wood. A scale was used to weigh the samples ss

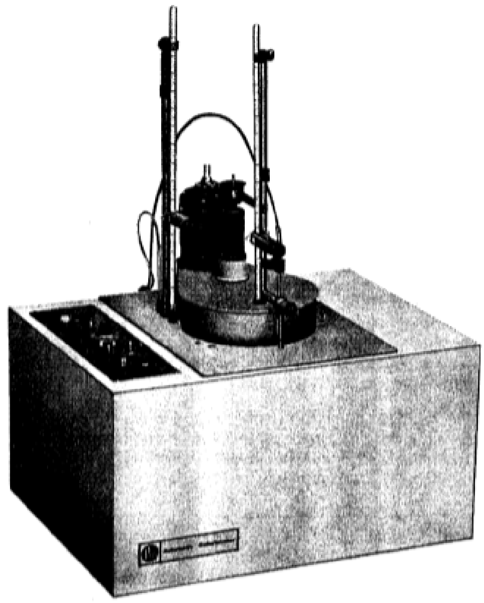

Fig. (27): Parr 1241 Bomb Calorimeter [88]

Fig. (28): 1108 Oxygen Combustion Vessel [86]

Fig. (29): Vernier Thermistor [89]

Fig. (30): MS204S Analytical Balance [90]

3.3.2.1 Pellet Press. When testing for calorific value in an oxygen bomb, there is a small cup that is used to hold the sample. The wood in the research was cut into chips and then put into the sample cup; there was a problem with chips because they would get blown out of the sample cup when they bomb was being purged. To fix this issue, a pellet press was modeled and fabricated; the press and other parts were machined on a lathe at the Western Carolina University machine shop, located in Belk building. The press was modeled using computer aided design (CAD) software called Creo Parametric 3.0; Fig. (31) shows the CAD model of the press. Fig. (32) shows the fabricated press and plunger; Fig. (33) shows the pellets of wood next to a U.S quarter for size comparison. Although the press worked for making wood pellets, there was an issue when pressing wood-char. Since the powder was very fine, it accumulated between the press and plunger, locking them together. This was the reason why the calorimetric value of the char was obtained from literature.

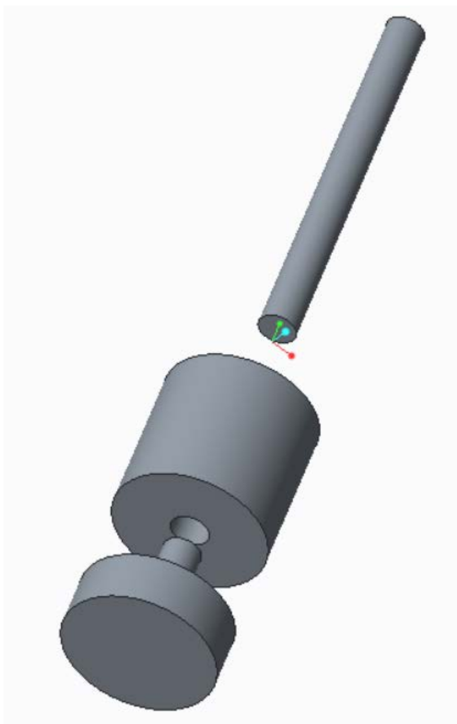

Fig. (31): Pellet Press Creo Model

Fig. (32): Pellet Press and Parts

Fig. (33): Wood Pellets

3.3.2.2 Calorimeter Standardization. The bomb calorimeter is standardized by burning a sample of a standard material with a known heat of combustion under controlled and reproducible operating conditions. Benzoic acid is used as a reference material for fuel calorimetry because it burns completely in oxygen; it does not absorb moisture from the air, and it is readily available in very pure form. The procedure for the standardization test is the same as the one for testing a sample. Equation (2) calculates the energy equivalent of benzoic acid.

$$W = \frac{Hm + e_1 + e_3}{t} \qquad (2)$$

Where H is the heat of combustion of benzoic acid; m is the mass of the acid sample; t is the temperature rise; e_1 is the correction for heat of formation of nitric acid; and e_3 is the correction for heat of combustion of the firing wire. To determine the amount of energy released by the fuse, it must be measured before and after testing. The remaining fuse length is subtracted from the initial, and that value is multiplied by the heat of combustion of the wire, which was 2.7 calories per centimeter for No. 34 B & S gage iron wire. The energy from the fuse and from the formation of nitric acid are added to the heat of the sample in (2) but subtracted in (3).

3.3.2.3 Gross Heat of Combustion. Equation (3) calculates the gross heat of combustion (HHV). Where t is the temperature rise of the water in °C; W is the energy equivalent of the calorimeter in calories per degree Celsius; M is the mass of the sample in grams; e_1 is the correction for heat of formation of nitric acid, in calories; e_2 is the correction for the heat of formation of sulfuric acid, in calories; e_3 is the correction for heat of formation of fuse wire, in calories. In this research, e_2 and e_3 were calculated; e_1 was neglected.

$$H_g = \frac{tW - e_1 - e_2 - e_3}{m} \qquad (3)$$

Calorimetry is the science of measuring quantities of heat. A Gram-Calorie is a unit of energy equal to the amount of heat required, at a pressure of one standard atmosphere, to raise the temperature of 1 kilogram of water by 1°C [91]. A Kilo-Calorie is a unit of energy equal to the amount of heat required, at a pressure of one standard atmosphere, to raise the temperature of 1 gram of water by 1°C the A British thermal unit (Btu) is another unit of hear equal to the amount of energy required, at a pressure of one standard atmosphere, to raise the temperature of one pound of liquid water by 1 °F [92]. The calorific value (also named heat of combustion or heating value) of a sample is defined as the number of heat units liberated by a unit mass of a sample when burned with oxygen in an enclosure of constant volume. Calorific value, as measured in a bomb calorimeter denotes the heat liberated by the combustion of all carbon and hydrogen with oxygen to form carbon dioxide and water, including the heat liberated by the oxidation of other elements, such as sulfur, which may be present in the sample. When calculating the heat of combustion, a table of conversions is essential. Table IX shows energy unit conversions between the US and SI measuring systems.

Table IX: Energy Conversions

1 Joule = 0.0009 Btu
1 Gram-Calorie = 4.2 Joules
1 Kilo-Calorie= 4184.0 Joules
1 Gram Calorie = 0.003 Btu
1 BTU = 1055.1 Joules
1 BTU = 252.2 Gram-Calories
1 BTU = 0.252 Kilo-Calories
1 Kilo-Calorie = 3.9 Btu

3.3.3 Water Boil Test Outputs

The water boil test gathers data that is used to determine the performance of a stove. The outputs of the WBT are boil time, thermal efficiency, firepower, specific fuel consumption, and burning rate.

3.3.3.1 Boil Time. Altitude affects boil time (t); increased altitude means decreased air pressure, and therefore, longer boil time. This research conducted WBT experiments at an altitude of 2150ft, which made the water boil at 97.9 °C (208.2 °F) [93]. Another factor that affects the cook-time or boil-time is how well the fire is tended by the user. If a fire is well-fed, it emits heat continuously to the pot; if a fire is under-fed, it starts to die out and time is lost getting it burning again. If a fire is over-fed, there is not enough oxygen present to combust all the fuel, so a lot of smoke is emitted. It is essential to learn how to feed the stove being used so it can perform optimally. Equation (4) calculates the boil time; where t_f is the final time and t_i is the initial time.

$$t = t_f - t_i \qquad (4)$$

3.3.3.2 Thermal Efficiency. Thermal efficiency (η), is the amount of heat that is transferred to the water in a pot on the cook stove compared to the amount of heat available from combustion. Equation (5) is used to calculate thermal efficiency. Where E_{Pot} heat transferred to the water in the pot and E_{Fuel} is energy released by the fuel. The parameters in are collected before and after the test, leading to an average thermal efficiency for the entire test. cp_w is the heat capacity of water at 100°C. $m_{water,i}$ is the initial mass of the water. ΔT is the change in temperature over the course of the test. $h_{H2O,fg}$ is the heat of vaporization at the ambient pressure (assumed to be one atmosphere). Δm_{water} is the mass of the water that was evaporated during the test. f_{cd} is the mass of the fuel consumed during the test. MC is the percent moisture of the wood. LHV_{wood} is the lower heating value of wood.

$$\eta = \frac{E_{Pot}}{E_{Fuel}} = \frac{cp_w * m_{water,i} * \Delta T + h_{H2O,fg} * \Delta m_{water}}{f_{cd} * (1 - MC) * LHV_{wood} - f_{cd} * MC * y * LHV_{wood} - LHV_C * m_c} \quad (5)$$

Y is a factor to account for the energy lost to evaporation of the moisture in the wood. Equation (6) is used to calculate Y; where $T_{boil}$is the boiling temperature at one atmosphere of pressure and T_{amb} is the ambient temperature [94].

$$y = \frac{\left| cp_w * (T_{boil} - T_{amb}) + h_{H2O,fg} \right|}{LHV_{wood}} \quad (6)$$

3.3.3.3 Firepower. Firepower FP_c is a ratio of the wood energy consumed by the stove per unit of time during the test. Equation (7) is used to calculate firepower, where: $t_{ci} - t_{cf}$ is the duration of the specific test phase (in min) [95].

$$FP_c = \frac{f_{cd} * LHV_{wood}}{60 * (t_{ci} - t_{cf})} \quad (7)$$

3.3.3.4 Specific Fuel Consumption. Specific fuel consumption SC_c is the fuelwood required to produce a unit output. In the case of the cold-start high-power WBT, it is a measure of the amount of wood required to produce one liter of boiling water starting with cold stove. Equation (8) is used to calculate specific fuel consumption; where f_{cd} is the equivalent dry wood consumed. P_{cf} is the weight of pot with water after test. P is the weight of the empty pot [95].

$$SC_c = \frac{f_{cd}}{P_{cf} - P} \qquad (8)$$

3.3.3.5 Burning Rate. Burning rate r_{cb} is a measure of the rate of wood consumption while bringing water to a boil. Equation (9) is used to calculate burning rate; where f_{cd} is the amount of wood used during the test; t_{ci} is the time at the start of the test, in minutes. t_{cf} is the time at the end of the test, in minutes [95].

$$r_{cb} = \frac{f_{cd}}{t_{ci} - t_{cf}} \qquad (9)$$

CHAPTER FOUR: RESULTS

This chapter presents the results of the wood moisture content calculations, as well as the results of calorimetry testing. This chapter also presents the five stove testing outputs, which include: boil time, thermal efficiency, firepower, specific fuel consumption and burning rate.

4.1 Wood Fuel Moisture Results

A 1 kg sample of wood pieces was weighed before and after kiln drying at 105°C (221°F) for 24 hours. Table X contains the weights measured. The moisture meter was used to measure the moisture content of each piece in the 1 kg sample. The Table XI contains the values measured from the pieces before drying. Table XII contains the values measured from the pieces after drying. The average moisture content of the sample was 29.8 % before drying and 5.8%, after drying. The oven dry-weight was subtracted from the green-weight, and the result was divided by the dry-weight. That value was multiplied by 100 to obtain a moisture content percentage [17]. The moisture content of the 1 kg sample was calculated to be 5.6 %, a value which is in the same region as the average value measured with the moisture meter.

Table X: Wood Moisture Content by Weight

Green Weight Sample (g)	**Dry Weight Sample (g)**	**Moisture Content (%)**
1000	947	5.596621

Table XI: Wood Moisture Before Drying

29.6	28.4	30.2	28.1	33.1	30.5	27.7	32.5	32.5	30.5	27.1	27.1	29.6	30.7
32.1	28.6	29.1	33.9	29.8	29.5	29.3	31.1	31.6	29.6	28.6	29.6	28.1	32.6
30.5	31.5	28.6	29.6	28.1	32.6	28.7	30.8	30.5	28.9	31.6	31.8	28.4	27.9
31.6	31.7	28.4	36.1	29.6	27.1	27.2	31.3	30.5	31.2	29.5	29.8	28.6	27.1
29.6	29.6	33.4	31.5	28.4	28.6	27.7	30.6	29.6	30.8	32.6	31.5	28.9	31.1
31.5	28.1	29.1	28.1	29.8	31.9	29.1	29.8	28.7	29.6	30.2	30.5	31.2	31.7
29.3	29.7	30.1	29.1	28.4	27.8	28.8	30.6	30.2	32.6	27.2	31.3	30.5	30.6
27.8	29.3	29.3	36.5	28.2	29.8	29.6	29.9	32.6	29.4	27.7	30.6	29.6	29.8
30.9	27.9	29.3	31.8	28.4	27.9	27.3	30.1	31.5	31.6	29.1	29.8	28.7	29.1
31.9	29.5	31.8	29.8	28.6	27.1	27.1	29.6	30.7	28.1	28.8	30.6	30.2	27.7
30.5	27.7	32.5	32.5	30.5	29.6	33.4	31.5	28.4	28.6	29.6	29.9	32.6	27.9
29.5	29.3	31.1	31.6	29.6	28.1	29.1	28.1	29.8	31.9	29.4	28.4	29.6	29.5
32.6	28.7	30.8	30.5	28.9	29.7	30.1	29.1	28.4	27.8	30.2	31.9	28.3	29.6
27.1	27.2	31.3	30.5	31.2	29.3	29.3	36.5	28.2	29.8	32.4	31.9	28.4	29.1
28.6	27.7	30.6	29.6	30.8	27.9	29.3	31.8	28.4	27.9	30.5	31.5	28.6	29.6
Average:							29.9						

Table XII: Wood Fuel Moisture After Drying

5.6	5.6	4.8	6.1	5.4	6.5	5.8	6.4	6.1	6.9	6.1	5.9	5.5	6.4
6.1	6.2	6.1	5.8	5.4	5.9	6.4	5.3	5.9	5.3	5.5	5.3	5.3	5.3
6.3	5.7	6.4	6.7	4.9	6.5	6.9	5.7	5.5	5.7	4.8	5.4	5.7	5.7
5.8	5.4	5.9	5.4	5.8	6.4	5.3	5.9	6.1	5.1	6.1	6.1	5.9	5.9
6.7	4.9	6.5	4.9	6.4	6.5	5.7	6.5	5.8	5.4	6.4	6.6	6.5	6.5
5.4	5.8	6.4	6.1	6.9	6.4	5.1	6.4	5.3	6.1	5.9	5.9	6.1	6.4
4.9	6.4	5.3	5.9	5.3	6.8	6.1	6.8	5.7	5.3	5.4	6.7	5.9	6.8
6.1	6.9	5.7	5.5	5.7	6.1	5.6	5.1	5.1	5.1	5.1	5.8	5.5	6.1
5.9	5.3	5.9	5.6	5.1	6.6	6.9	5.7	5.6	5.9	5.3	5.5	5.3	5.2
5.5	5.7	6.5	6.1	5.5	5.8	5.3	5.9	5.9	5.5	5.7	6.5	5.7	6.1
5.1	5.1	6.4	6.6	5.8	6.1	5.7	6.5	6.1	5.1	5.1	6.4	5.9	6.1
6.1	6.1	6.8	6.8	6.1	5.2	5.1	6.4	6.2	6.1	6.1	6.8	6.5	5.1
5.4	6.6	6.1	6.4	6.3	5.8	6.3	5.1	5.1	5.4	6.6	6.1	6.4	5.3
5.2	5.4	6.6	6.8	5.1	6.7	5.3	5.2	6.3	5.2	5.4	6.6	6.8	5.5
6.3	6.1	6.5	6.3	6.3	6.4	5.9	6.5	4.9	6.4	6.2	6.5	6.1	5.1
Average:							5.9						

4.2 Calorimetry Results

This section presents the benzoic acid calibration results, as well as the wood calorimetry results.

4.2.1 Benzoic Acid Calibration.

The heating value calculated for 0.9902 grams of acid was 2451.8 Cal/g·°C (10,265.2 J/g ·°C) after fuse correction. The sample made the water temperature rise 2.56 °C and the test burned 9.7 cm of fuse. Fig. (34) shows a temperature vs. time graph obtained for the acid test. Table XIII shows the data that was gathered during the test as well as the calorimetric value calculated.

Table XIII: Acid Calibration Test 1

Fuse Burned (cm)	Cup (g)	Sample & Cup (g)	Sample (g)	Heat of Combustion of Acid (cal/g)	Heat of Combustion of Fuse (cal/cm)	Temperature Rise °(C)	Calorimetric Value with fuse Correction (cal/g)
9.7	14.0771	15.067	0.9902	6318	2.7	2.562252868	2451.855427

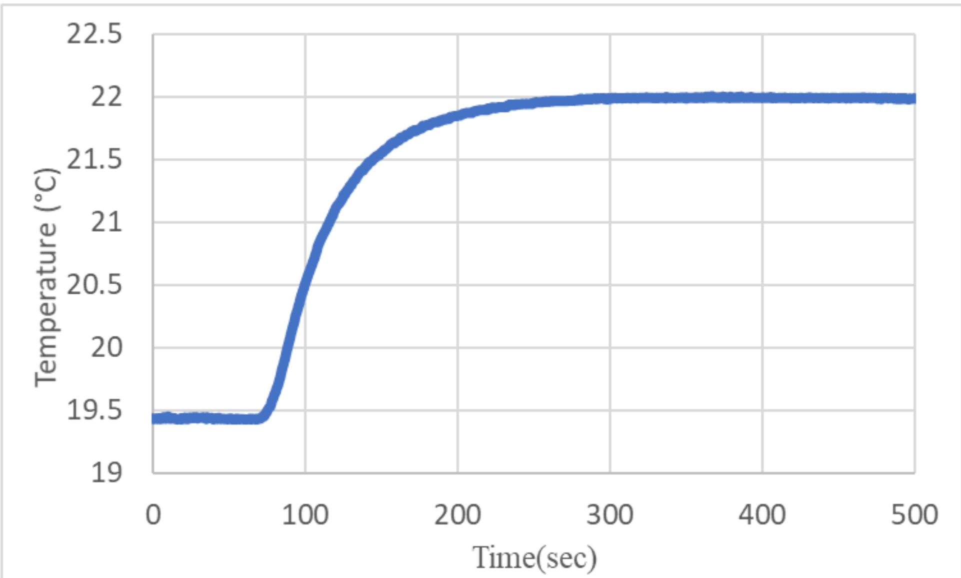

Fig. (34): Benzoic Acid Calibration

4.2.2 White Pine Calorimetry

There were three tests of white pine pellet samples conducted. The fist test burned a sample that weighed 1.0848 grams and it had a heating value of 4652.7$\frac{gram-calories}{gram}$ (8369.3 $\frac{Btu}{lb}$) after corrections. The sample made the water temperature rise 2.08 °C and the test burned 9.6 cm of fuse. The second test burned a sample that weighed 0.9765 grams and it had a heating value of 4628.6 $\frac{gram-calories}{gram}$ (8325.9 $\frac{Btu}{lb}$) after corrections. The sample made the water temperature rise 1.86 °C and the test burned 9.5 cm of fuse. The third test burned a sample that weighed 0.9225 grams and it had a heating value of 4507.1 $\frac{gram-calories}{gram}$ (8107.4 $\frac{Btu}{lb}$) after corrections. The sample made the water temperature rise 1.71 °C and the test burned 9.7 cm of fuse. Figs. (35-37) show temperature vs. time graphs obtained from the logging software Logger Lite for wood tests 1-3. Table XIV shows the data that was gathered during the three wood tests, as well as the calorimetric values calculated. Finally, the three heating values were averaged for white pine with a result of 4596.1 $\frac{gram-calories}{gram}$ (8267.5 $\frac{Btu}{lb}$) (19230.1 $\frac{Joules}{g}$); The value converted to $\frac{Joules}{gram}$ units was used in the calculations of efficiency, firepower, specific fuel consumption, and burning rate.

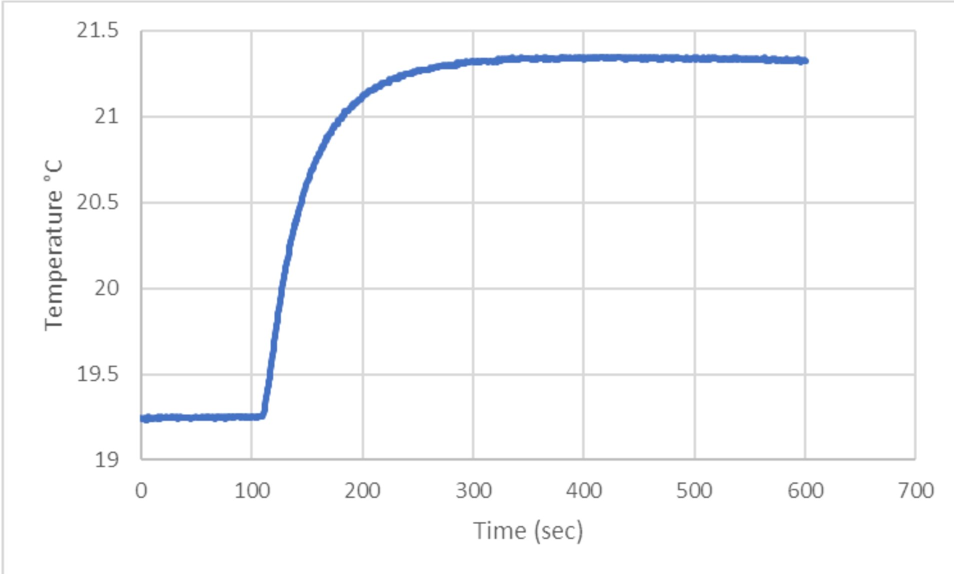

Fig. (35): White Pine Calorimetry Test 1

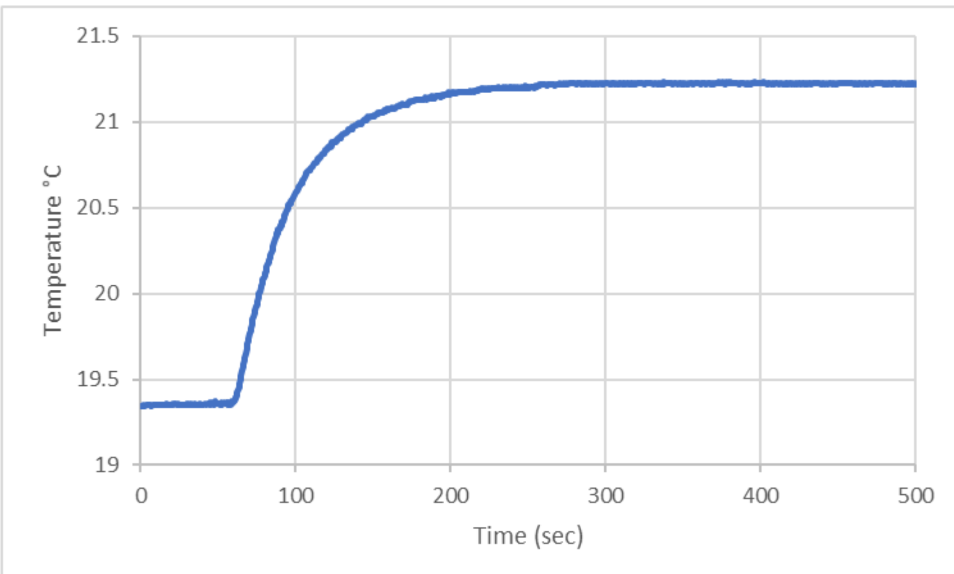

Fig. (36): White Pine Calorimetry Test 2

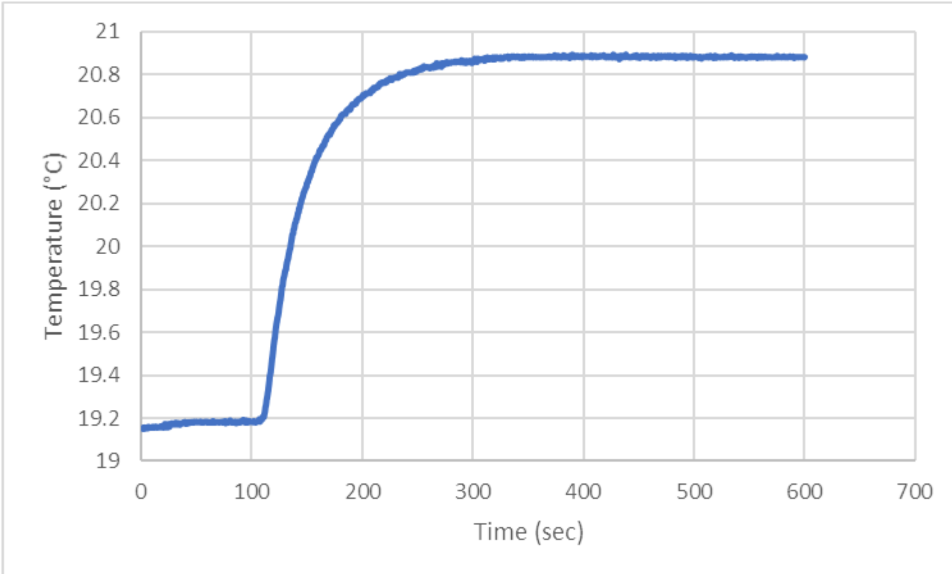

Fig. (37): White Pine Calorimetry Test 3

Table XIV: White Pine Calorimetry Tests

Test (#)	Fuse Burned (cm)	Cup (g)	Sample & Cup (g)	Sample (g)	Energy Equivalent of Calorimeter (cal/g)	Heat of Combustion of Fuse (cal/cm)	Temperature Rise °(C)	Moisture (g)	Calorimetric Value with Corrections (cal/g)
1	9.6	13.976	15.0607	1.0848	2451.8	2.7	2.083477	0.06	4652.656
2	9.5	14.078	15.0541	0.9765	2451.8	2.7	1.866842	0.06	4628.607
3	9.7	13.983	14.9051	0.9225	2451.8	2.7	1.716655	0.05	4507.097

4.3 Performance Outputs

4.3.1 Efficiency Results

Table XV shows the data gathered during round one of stove testing, using the water boil test of 1 liter of water. Table XVI shows the data gathered during round one of stove testing, using the water boil test of 1 liter of water. During the first round of testing, the stove with the highest efficiency was the Solo stove, with an efficiency of 16.9%; the stove with the lowest efficiency was the Hot Ash stove, with an efficiency of 4.3%. For the second round of testing, the Hot Ash stove was removed from the group because it was an outlier in performance. During the second round of testing, the stove with the highest efficiency was the prototype 1 stove, with an efficiency of 22.1 %; the stove with the lowest efficiency was the 12-Survivors, with an efficiency of 9.7%.

Table XV: Stove Test Results Round 1

	Weight (g)	Efficiency (%)	Wood Used (g)	Boil Time (min)	Firepower (W)	Specific Fuel Consumption (g wood/ g boiled water)	Burning Rate (g wood/ min)	Char (g)	Evaporated Water (g)
Solo	235	16.9	129	11.0	3748	0.1	11.7	8	13
Zhongmei	349	16.8	146	9.3	5042	0.1	15.7	15	19
Yoler	715	15.7	160	11.5	4459	0.2	13.9	17	23
Ouspots	437	14.8	169	11.4	4747	0.2	14.8	22	16
Lixada	225	13.0	171	11.2	4947	0.2	15.3	15	10
Emberlit	213	12.5	183	13.6	4319	0.2	13.5	19	10
12 Survivors	350	9.9	257	13.3	6193	0.3	19.3	29	22
Hot Ash	1411	4.3	475	65.2	2335	0.5	7.3	18	9

Table XVI: Stove Test Results Round 2

	Weight (g)	Efficiency (%)	Wood Used (g)	Boil Time (min)	Firepower (W)	Specific Fuel Consumption (g wood/ g boiled water)	Burning Rate (g wood/ min)	Char (g)	Evaporated Water (g)
Prototype 1	221	22.1	115	8.3	4430	0.1	13.8	13	18
Solo	235	16.2	134	11.5	3744	0.1	11.7	14	8
Zhongmei	349	13.6	156	10.2	4926	0.2	15.4	12	8
Ouspots	437	13.5	186	11.7	5104	0.2	15.9	27	15
Yoler	715	13.1	189	10.2	5968	0.2	18.6	23	20
Emberlit	213	10.8	190	12.4	4927	0.2	15.4	13	6
Lixada	225	10.6	227	11.5	6348	0.2	19.8	35	17
12 Survivors	350	9.7	245	12.1	6500	0.2	20.3	25	19

4.3.2 Boil Time Results

During round one of stove testing, the stove that had the highest firepower was the Zhongmei stove, with a time of 9.3 minutes. The stove that took the most time to boil one liter of water was the Hot Ash stove, with a time of 65.2 minutes. During round two of stove testing, the stove that boiled the water in the least time was the prototype 1 stove, with a time of 8.3 minutes. The stove that took the most time to boil one liter of water was the 12-Survivors stove, with a time of 12.1 minutes.

4.3.3 Firepower Results

During round one of stove testing, the 12-Survivors stove had the highest firepower, at 6500 W. The stove that had the least firepower was the Hot Ash stove. During round two of stove testing, the stove that had the most firepower was the 12-Survivors stove, at 6500 W. The stove that had the least firepower was the Hot Ash stove, at 2335 W.

4.3.4 Specific Fuel Consumption Results

In the first round of stove testing, the stove that had the highest specific fuel consumption was the Hot Ash stove, at 0.5 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$. The stove that had the lowest specific fuel consumption was the Solo stove, at 0.1 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$. In the second round of stove testing, the stove that had the highest specific fuel consumption was the 12-Survivors stove, at 0.2 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$. The stove that had the lowest specific fuel consumption was the Prototype 1 stove, at 0.1 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$.

4.3.5 Burning Rate Results

In the first round of stove testing, the stove that had the highest burning rate was the 12-Survivors stove, at 19.3 $\frac{grams\ of\ wood}{minute}$. The stove that had the lowest burning rate was the Hot Ash stove, at 7.3 $\frac{grams\ of\ wood}{minute}$. In the second round of stove testing, the stove that had the highest burning rate was the 12-Survivors stove, at 20.3 $\frac{grams\ of\ wood}{minute}$. The stove that had the lowest burning rate was the Solo stove, at 11.7 $\frac{grams\ of\ wood}{minute}$.

4.3.6 Char Remaining After Testing

In the first round of stove testing, the stove that produced the most char was the 12-Survivors stove, at 29 grams. The stove that produced the least char was the Solo stove, at 8 grams. In the second round of stove testing, the stove that produced the most char was the Lixada stove, at 35 grams. The stove that produced the least char was the Zhongmei stove, at 12 grams.

4.3.7 Water Evaporated During Testing

In this study, the pot was covered with a lid. There was a hole in the middle of the lid which measured 4mm (0.16 in) in diameter. Water evaporated through the hole during the test. During round one of testing, the stove which had the most water evaporation was the Yoler stove, at 23 grams. The stove which had the least water evaporation was the Hot Ash stove, at 9 grams. During round two of testing, the stove which had the most water evaporation was the Yoler stove, at 20 grams. The stoves which had the least water evaporation was the Emberlit stove, at 6 grams.

4.4 Time vs Temperature Graphs

The time vs temperature graph of round one testing is shown is Fig. (38). The time vs temperature graph of round two testing is shown is Fig. (39).

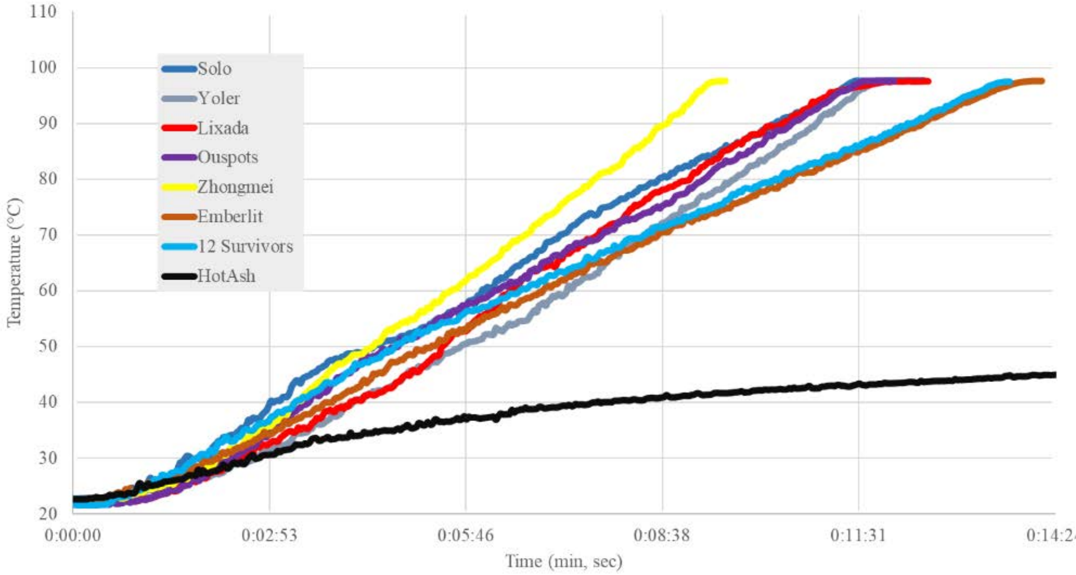

Fig. (38): Temp vs Time Graph of First Round of Testing

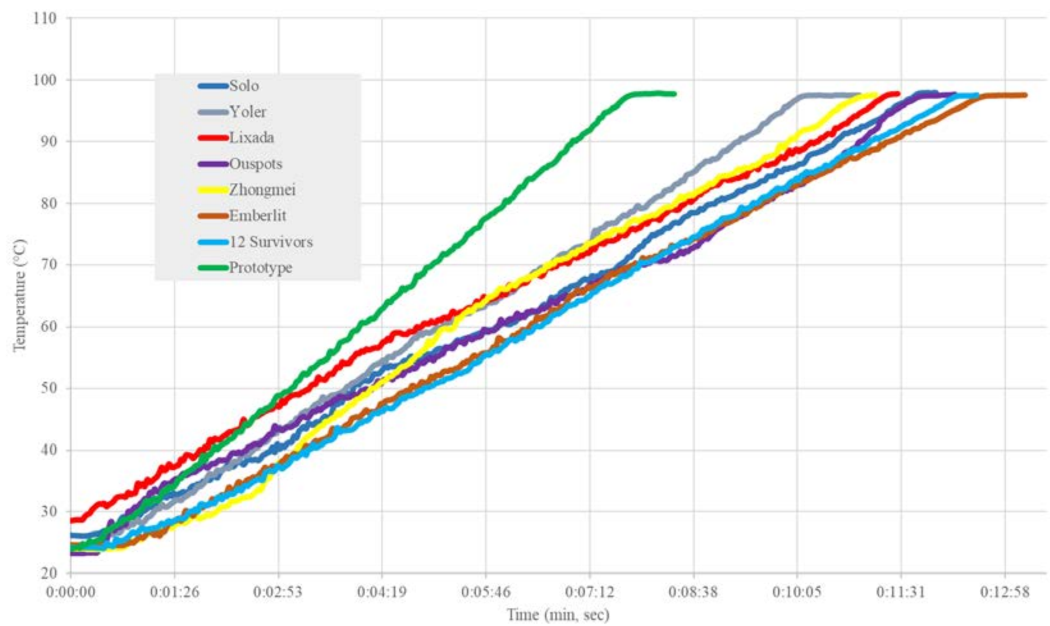

Fig. (39): Temp vs Time Graph of Second Round of Testing

CHAPTER FIVE: DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH

5.1 Discussion

Eight commercially available biomass-fueled camp stoves were tested for their cooking performance, using a water boil test of 1 liter of water, performed in outdoor environmental conditions to simulate the aerodynamic conditions of a camp site. The weight of the portable stoves is important because the user carries it with them while they hike in the wilderness; increased stove weight means increased energy used to transport it. From the eight stoves purchased and the prototype designed, the stove that weighs the least is the Emberlit, at 213 grams. The stove that weighs the most is the Hot Ash at 1411 grams; after the Hot-Ash stove, the next heaviest stove is the Yoler, at 715 grams. The efficiency of a stove is important because it determines how well the fuel is burned; the efficiency of a stove is also based on the geometry of the stove and its airflow characteristics. The stove with the overall highest efficiency was the prototype 1, with a value of 22.1%. The stove with the overall lowest efficiency was the Hot Ash, at 4.3%. The Hot Ash stove was removed from the group because it was an outlier. The stove that placed second in overall lowest efficiency was the 12-Survivors stove, at 9.7%. The firepower, specific fuel consumption and burning rate are three values that help determine the performance of a stove for a specific task. The performance values of each stove are discussed in the subsections below.

5.1.1 Solo Stove

The Solo stove is manufactured out of stainless steel and it sells for $69.99 online. It features a cylindrical, double-wall design to let the fire breathe through all the holes located on the top and bottom of the inner and outer walls. The fuel is added through the gap between the pot and the stove. To pack the stove, the user removes the top piece, flips it upside down and inserts it in the body. When packed, the stove is still cylindrical but shorter in height. The collapsed stove can be put into a case for transport or storage. The best test of the Solo stove had a boil time of 11 minutes; an efficiency of 16.9%; a firepower of 3748 W; a specific fuel consumption of 0.1 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 11.7 $\frac{grams\ of\ wood}{minute}$. During the test, 13 grams of water were evaporated; 8 grams of char were produced. An advantage of this stove is the double wall design which makes it efficient. A disadvantage of this stove is that the opening used to insert wood allows the flames to come out and waste energy to the ambient; the fire also reaches the handle, making it very hot to the touch. A disadvantage of this stove is that the feeding opening is positioned close to the top of the stove; this makes the feeding task more difficult because of the angle at which the fuel must be inserted. The fuel also must also be very small to fit through the opening and into the burn chamber. Another disadvantage of this stove is that it occupies more space than the cubical design stoves, when disassembled. Fig. (40) shows the Solo stove. Fig. (41) and Fig. (42) show the temperature vs time graphs of round one and two for the Solo stove.

Fig. (40): Solo Stove [77]

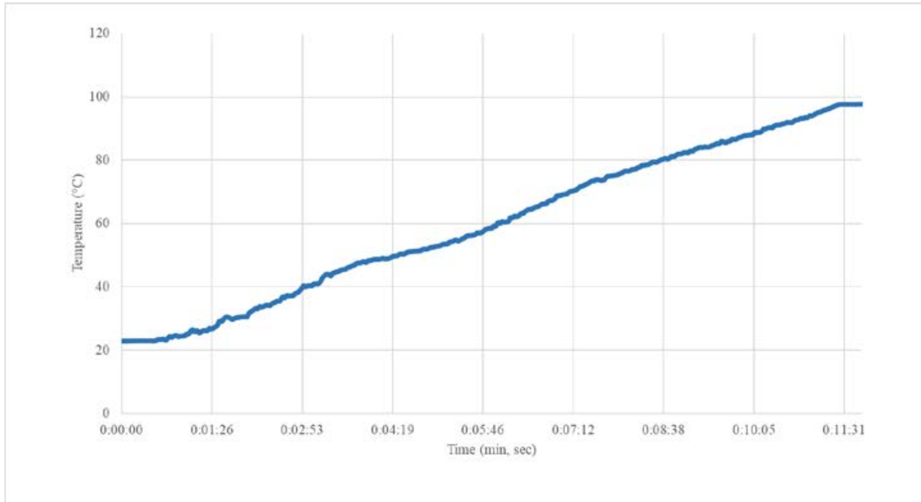

Fig. (41): Solo Stove Test Round 1

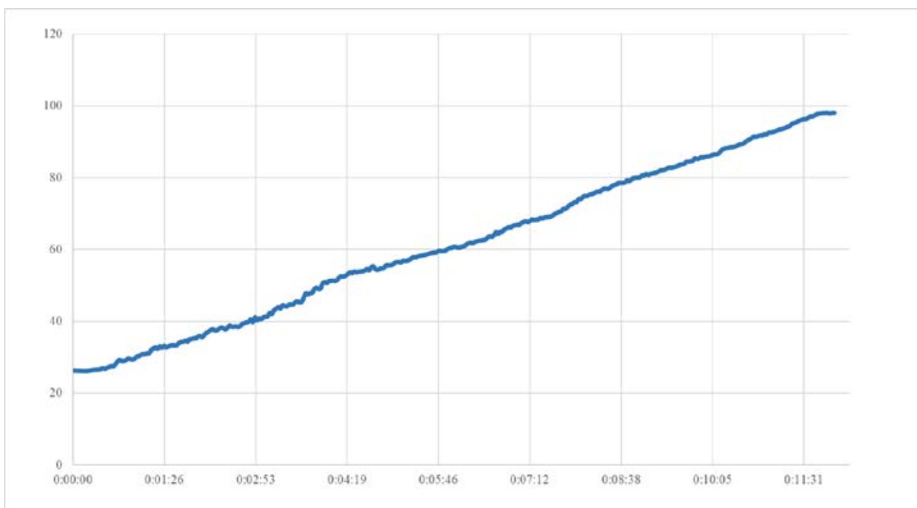

Fig. (42): Solo Stove Test Round 2

5.1.2 Ouspots Stove

The Ouspots stove is manufactured out of stainless steel and its sells for $20.00 online; it features a cylindrical design. An advantage of this stove is that it comes with a dish adapter, to burn ethanol fuel. When fueled by wood, the stove is fed through the gap between the pot and the body. To pack the stove, the user removes the two cylindrical sections, flips them upside down and inserts them inside of each other. The packed stove is still a cylinder but shorter in height. The collapsed stove can be placed into a case for transport or storage. The best test of the Ouspots stove had a boil time of 11.4 minutes; an efficiency of 14.8%; a firepower of 4747W; a specific fuel consumption of 0.2 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 14.8 $\frac{grams\ of\ wood}{minute}$. During the test, 16 grams of water were evaporated; 22 grams of char were produced. A disadvantage of this stove is that the opening used to insert wood causes the flames to come out and waste energy to the ambient; the fire also reaches the handle, making it very hot to the touch. Another disadvantage of this stove is that its cylindrical design occupies more space than the cubical design stoves, when disassembled. Fig. (43) shows the Ouspots stove. Fig. (44) and Fig. (45) show the temperature vs time graphs of round one and two for the Ouspots stove.

Fig. (43): Ouspots Stove [78]

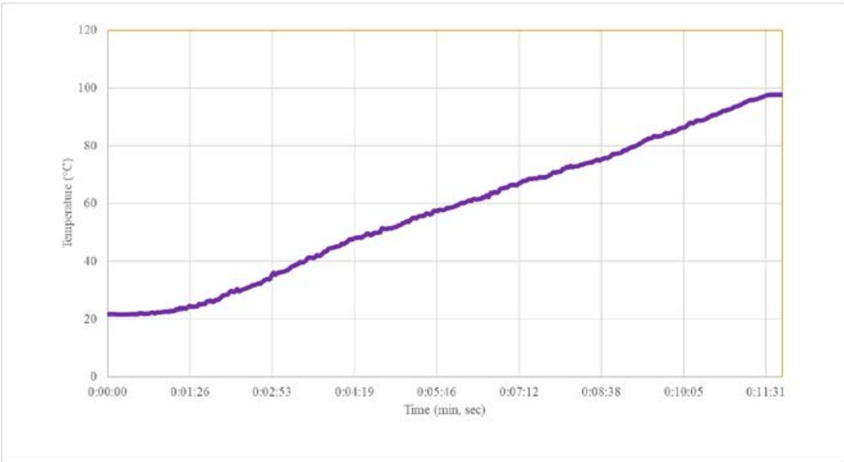

Fig. (44): Ouspots Stove Test Round 1

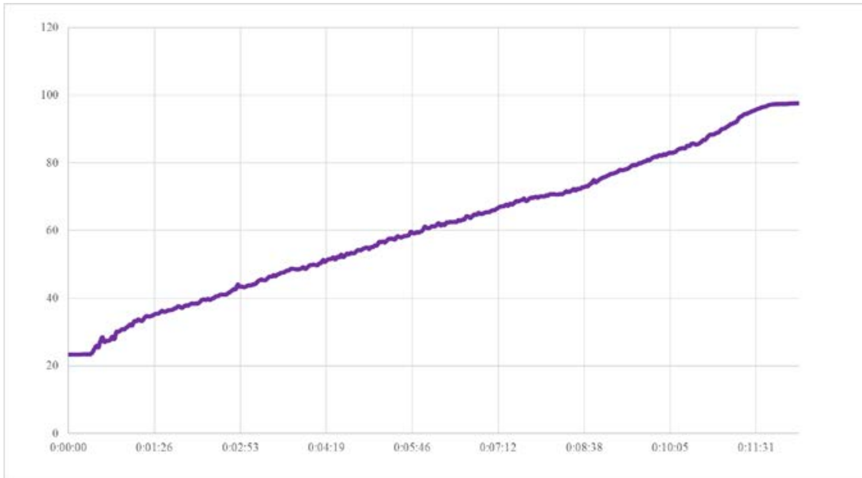

Fig. (45): Ouspots Stove Test Round 2

5.1.3 Emberlit Stove

The Emberlit stove is manufactured out of stainless steel and titanium. The titanium version sells for $85.00 online and it was tested in this study. It is a cubical type of stove with a bottom piece, where the fire sits. 4 panels are assembled by sliding a pair of slots into the next panel's pair of slots. At the top, there are two small pieces that act as reinforcement and as a pot rest. The fuel is added through the opening in the front panel and the holes placed along the bottom let the fire breathe. The titanium version of the Emberlit stove was used for this research. The best test of the Emberlit stove had a boil time of 13.6 minutes; an efficiency of 12.5%; a firepower of 4319W; a specific fuel consumption of 0.2 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 13.5 $\frac{grams\ of\ wood}{minute}$. During the test, 10 grams of water were evaporated; 19 grams of char were produced. An advantage of this stove is the panel design, which allows it to disassemble flat. A disadvantage of this stove the fire reaches the handle, making it very hot to the touch. Fig. (46) shows the Emberlit stove. Fig. (47) and Fig. (48) show the temperature vs time graphs of round one and two for the Emberlit stove.

Fig. (46): Emberlit Stove [79]

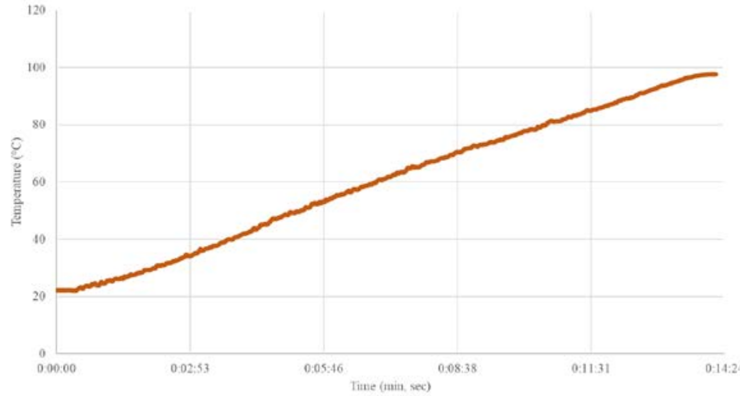

Fig. (47): Emberlit Stove Test Round 1

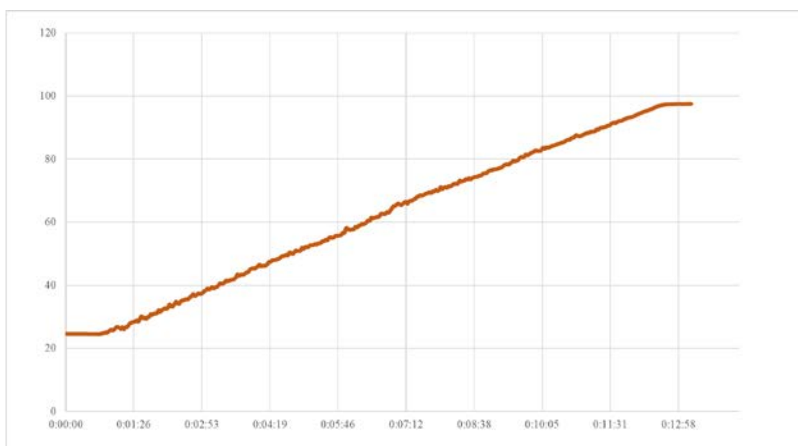

Fig. (48): Emberlit Stove Test Round 2

5.1.4 Lixada Stove

The Lixada stove is manufactured out of stainless steel and it sells for $14.00 online. The stove has a tall cylindrical design with a large opening used to feed insert the fuel. There are large holes at the top and bottom of the stove for airflow. The stove consists of three main pieces that interlock; it also has two small pieces that act as pot supports. To pack the stove, the user slides the pieces into each other; the disassembled stove is a cylinder that is the height of one of the main sections. The stove can be placed in a case for travel or storage. The best test of the Lixada stove had a boil time of 11.2 minutes; an efficiency of 13%; a firepower of 4947W; a specific fuel consumption of 0.2 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 15.3 $\frac{grams\ of\ wood}{minute}$. During the test, 10 grams of water were evaporated; 15 grams of char were produced.

An advantage of this stove is the cylindrical design, which tends to be efficient. Another advantage of this stove is the size of the burn chamber, which allows for a large quantity of fuel to be burned at once. Another disadvantage of this stove is caused by the large air holes, which allow heat to escape and be lost to the ambient. Another disadvantage is the location of the feeding hole, which is positioned close to the top of the stove; this makes the feeding task more difficult because of the angle at which the fuel must be inserted; the fuel also must also be very small to fit through the opening and into the burn chamber. Another disadvantage of this stove is that the fire reaches the handle, making it very hot to the touch. Fig. (49) shows the Lixada stove. Fig. (50) and Fig. (51) show the temperature vs time graphs of round one and two for the Lixada stove.

Fig. (49): Lixada Stove [80]

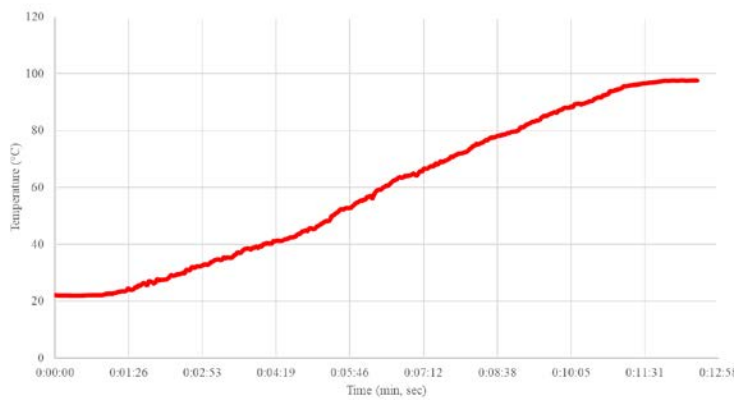

Fig. (50): Lixada Stove Test Round 1

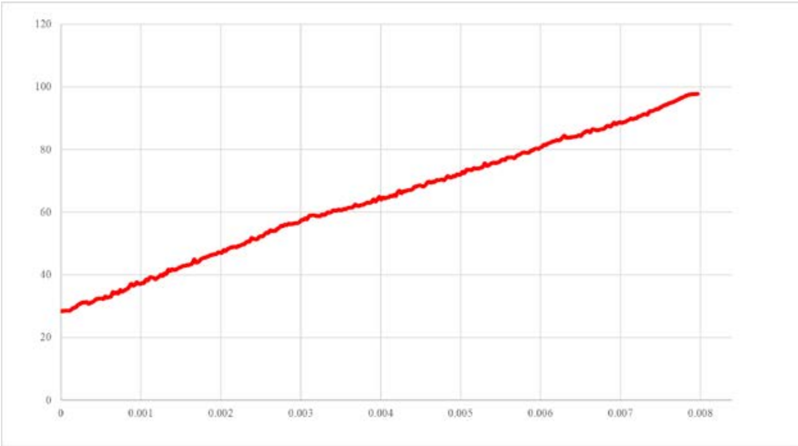

Fig. (51): Lixada Stove Test Round 2

5.1.5 Zhongmei Stove

The Zhongmei stove is manufactured out of stainless steel and it sells for $20.00 online. The stove has a cylindrical design which lets the pot rest on the three triangle-shaped legs that are attached to the top ring with a rivet. The fuel is added through the small gap between the pot and the top ring. The stove has rectangular shaped holes on the bottom and top sections; the middle section has a double wall design. To pack the stove, the user separates the three cylindrical sections and inserts them into each other. The stove can be placed in a case for transport or storage. The best test of the Zhongmei stove had a boil time of 9.3 minutes; an efficiency of 16.8%; a firepower of 5042W; a specific fuel consumption of 0.1 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 15.7 $\frac{grams\ of\ wood}{minute}$. During the test, 19 grams of water were evaporated; 15 grams of char were produced. An advantage of this stove is the cylindrical design, which tends to be efficient. A disadvantage of this stove is that it occupies more space than the cubical design stoves, when disassembled. Another disadvantage of this stove is the feeding hole; fuel must be inserted through the gap between the pot and the stove, which is around 25mm (1 in); this forces the user to put their hand very close to the flames, increasing the risk of a burn. Fig. (52) shows the Zhongmei stove. Fig. (53) and Fig. (54) show the temperature vs time graphs of round one and two for the Lixada stove.

Fig. (52): Zhongmei Stove [80]

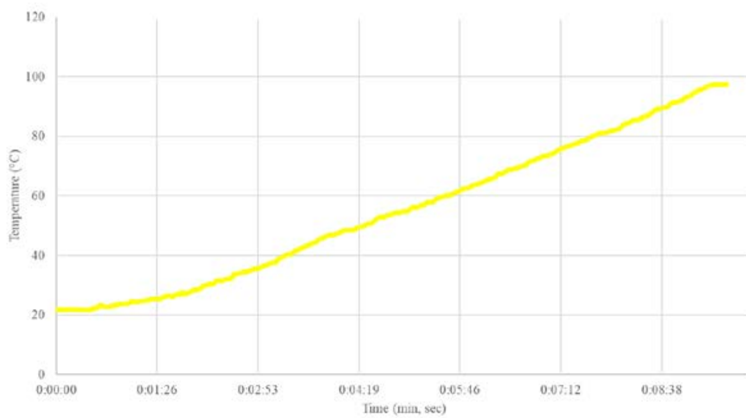

Fig. (53): Zhongmei Stove Test Round 1

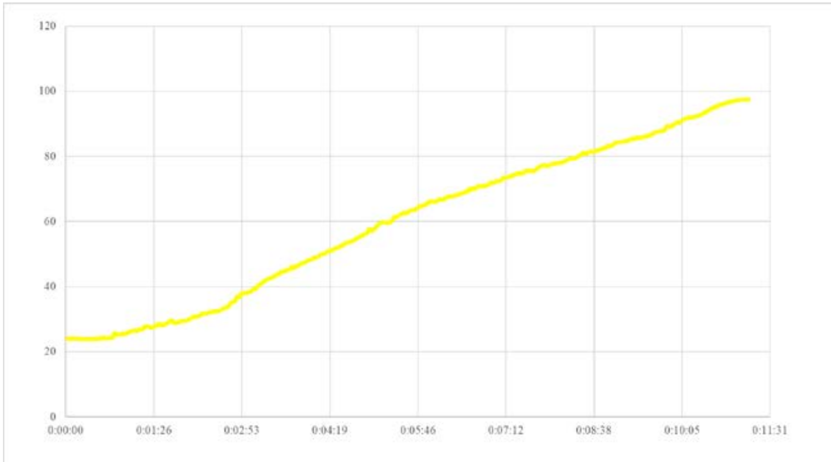

Fig. (54): Zhongmei Stove Test Round 2

5.1.6 12-Survivors Stove

The 12-Survivors stove is manufactured out of stainless steel and it sells online for $28.00. The stove has a cubical design with 4 panels attached by hinges. There is a bottom panel and a top grate with a handle that acts as a pot support or grill. The fuel can be added through the hole on the front panel. To pack the stove, the user removes the grate and bottom panel; the four hinged panels are then unlatched and the stove packs down flat. The stove can be put in a case for transport or storage. The best test of the 12-Survivors stove had a boil time of 13.3 minutes; an efficiency of 9.9%; a firepower of 6193W; a specific fuel consumption of 0.3 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 19.3 $\frac{grams\ of\ wood}{minute}$. During the test, 22 grams of water were evaporated; 29 grams of char were produced. An advantage of this stove is the cubical hinged design, which makes it very simple to setup. A disadvantage is the design, which allows the flames reach the pot handles, making them very hot to the touch. Fig. (55) shows the 12-Survivors stove. Fig. (56) and Fig. (57) show the temperature vs time graphs of round one and two for the 12-Survivors stove.

Fig. (55): 12-Survivors Stove [82]

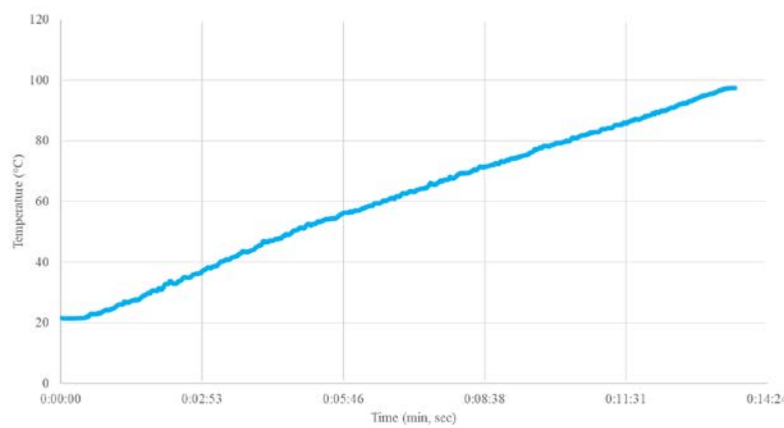

Fig. (56): 12-Survivors Stove Round 1 Test

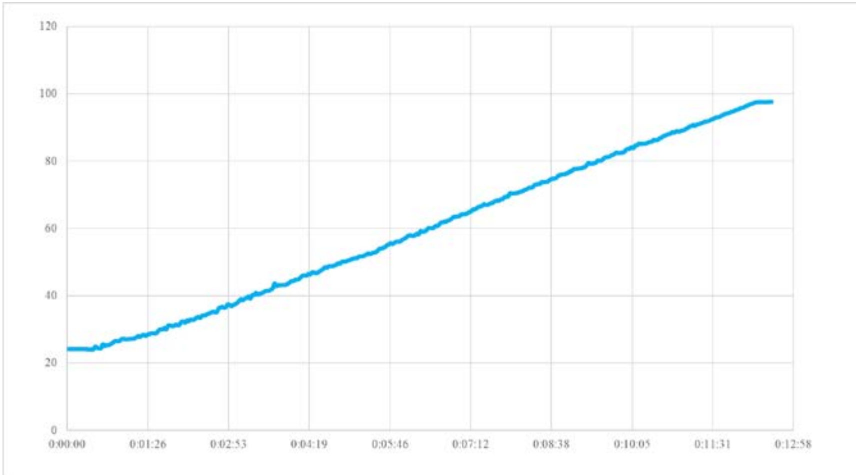

Fig. (57): 12-Survivors Stove Round 2 Test

5.1.7 Yoler Stove

The Yoler stove is manufactured out of stainless steel and sells for $30.00 online. The stove has a cubical design with a wide opening on the front where the fuel is added. The top has a wide grate that is used as a grill or pot support. To pack the stove, the user removes the grate and the panel where the fire sits. The other three panels are hinged together so the stove folds flat and can be put in a bag for storage or travel. The best test of the Yoler stove had a boil time of 11.5 minutes; an efficiency of 15.7 %; a firepower of 4459W; a specific fuel consumption of 0.2 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 13.9 $\frac{grams\ of\ wood}{minute}$. During the test, 23 grams of water were evaporated; 17 grams of char were produced. An advantage of this stove is the hinged panel design, which allows it to disassemble flat; it also allows for quick setup of the stove. A disadvantage of this stove the fire reaches the handle, making it very hot to the touch. The size of the stove acts as an advantage and a disadvantage. The advantage is that something large can be cooked, or a large pan/pot can be used. The disadvantage is that heat lost to the ambient rapidly because of all the openings the stove has; the wind can easily blow the flames away from the pot. Fig. (58) shows the 12-Survivors stove. Fig. (59) and Fig. (60) show the temperature vs time graphs of round one and two for the Yoler stove.

Fig. (58): Yoler Stove [83]

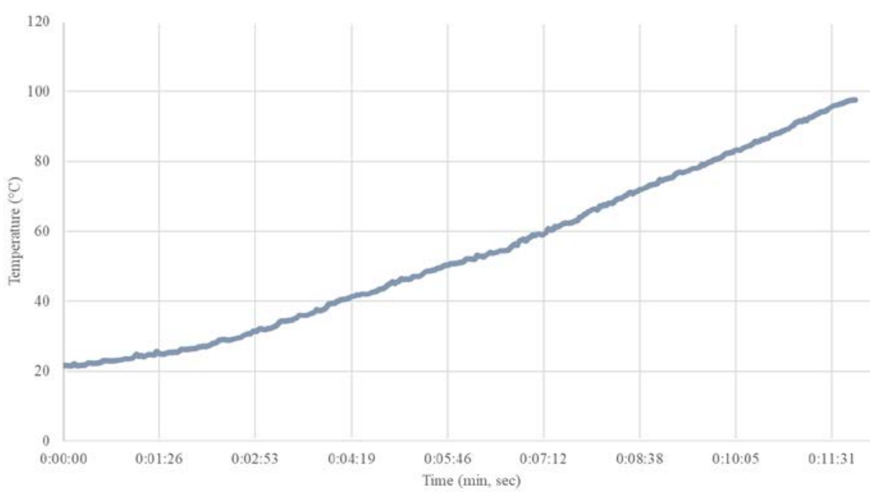

Fig. (59): Yoler Stove Test Round 1

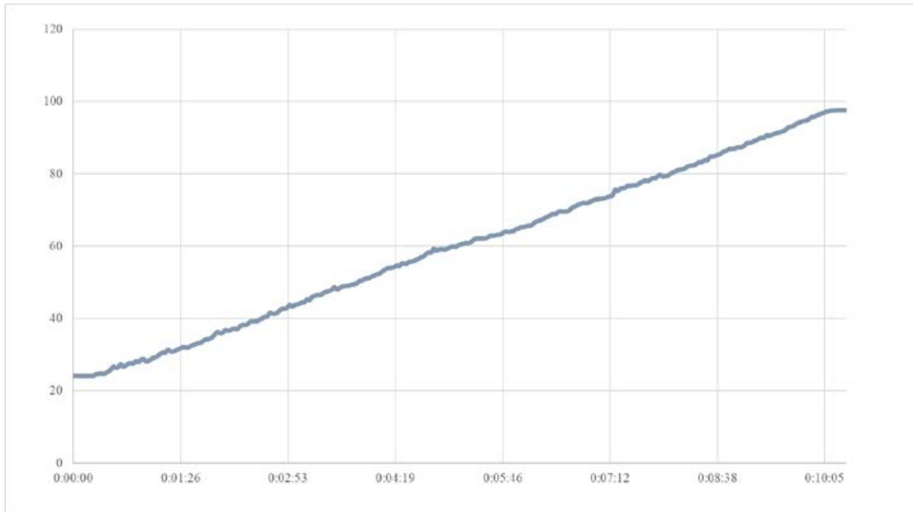

Fig. (60): Yoler Stove Test Round 2

5.1.8 Hot Ash Stove

The Hot Ash stove is manufactured out of stainless steel and it sells online for $100. It has a J-shaped design, different from the rest of the stoves in this research. Fuel is added through the lower opening and the stove is placed on the supports at the top. The stove is rugged and sturdy, but it is also heavy, at 1411g (50oz) To pack the stove, the two butterfly bolts that hold the stove together are removed and it the two pieces disassemble. When the stove is packed, it looks like a metal brick; It can be placed in a bag for storage or travel. The test of the Hot-Ash stove had a boil time of 65.2 minutes; an efficiency of 4.3 %; a firepower of 2335W; a specific fuel consumption of 0.5 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 7.3 $\frac{grams\ of\ wood}{minute}$. During the test, 9 grams of water were evaporated; 18 grams of char were produced. The Hot Ash stove did not have any advantages that could be determined in this study; the stove has many flaws. It is the heaviest stove from the group, it is also the worst performing from the group. The heat seems to get trapped at the 90-degree bend, which makes the metal in that area red hot. The heat is lost to the ambient air through radiation. Fig. (61) shows the Hot Ash stove. Fig. (62) shows the temperature vs time graph obtained from the Hot Ash stove test.

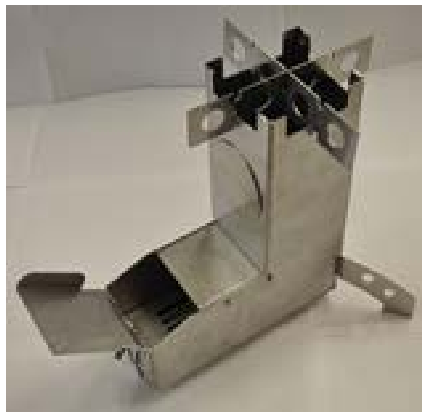

Fig. (61): Hot Ash Stove [84]

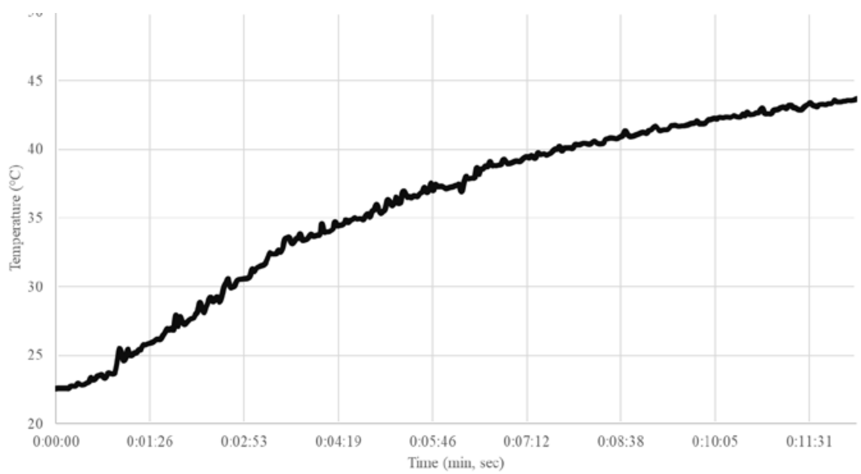

Fig. (62): Hot Ash Stove Test

5.1.9 Prototype Stove

A prototype was designed and modeled in Creo Parametric Student Version. The stove was given the name of "prototype 1". The purpose of making a prototype was to attempt to improve the performance of biomass camping stoves, in the task of boiling a liter of water. The pot that was used in this study was referenced as a surface to design the prototype around. The stainless-steel pot measures 114 mm (4.5 in) in diameter by 127 mm (5in) in height.

The main goal was to keep the heat enclosed near the walls of the pot. Previous testing had shown that any wind would disrupt the flame and waste energy to ambient. Testing also showed that the flames can reach the pot handles, making them very hot to the touch. The high walls of this design keep the wind from blowing the flames away from the pot; they also maintain the flames away from the handle, keeping it cool and making it easier to remove the pot without getting burnt. The fuel can be added through the opening on the front panel, which is located at the lower section of the stove; this simplifies fuel addition. The stove is disassembled by sliding one panel up and the other down, to interlock the slots on the edges. The prototype is made of 26 gage aluminum sheet metal and it is capable of disassembling to a thickness of 3.2 mm (.125 in), it can also be stored in a case for travel or storage. Fig. (63) depicts the 3D model of the prototype. Fig. (64) depicts the prototype stove during testing.

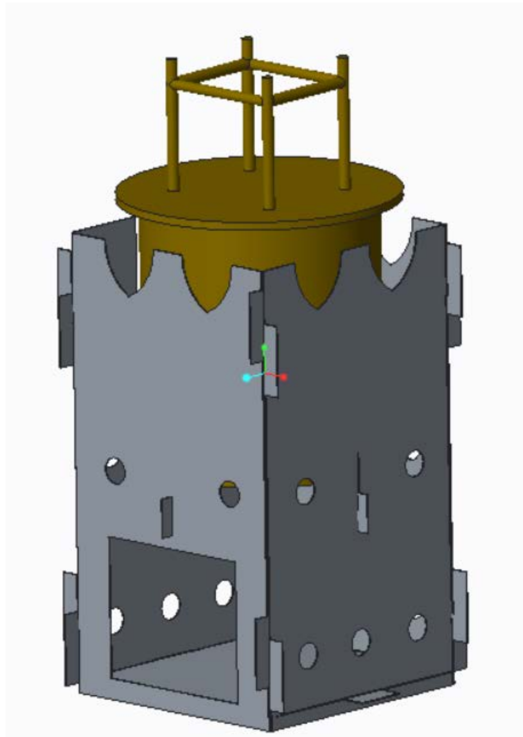

Fig. (63): Prototype Design in Creo Parametric 3.0

Fig. (64): Prototype 1 During Testing

The test of the prototype stove had a boil time of 8.3 minutes; an efficiency of 22.1%; a firepower of 4430W; a specific fuel consumption of 0.1 $\frac{grams\ of\ wood}{grams\ of\ boiled\ water}$; and a burning rate of 13.8 $\frac{grams\ of\ wood}{minute}$. During the test, 18 grams of water were evaporated; 13 grams of char were produced. Fig. (65) shows the temperature vs time graph obtained from the prototype stove test. Multiple tests were conducted for the prototype stove, but one set of data is shown. The tests consumed a consistent amount of fuel; it is believed that this is caused by the high-wall design, which keeps the fire enclosed near the pot, keeping a consistent heat transfer ratio. Prototype 1 testing was also consistent in keeping the pot handles cool to the touch; this reduces the chance of burns.

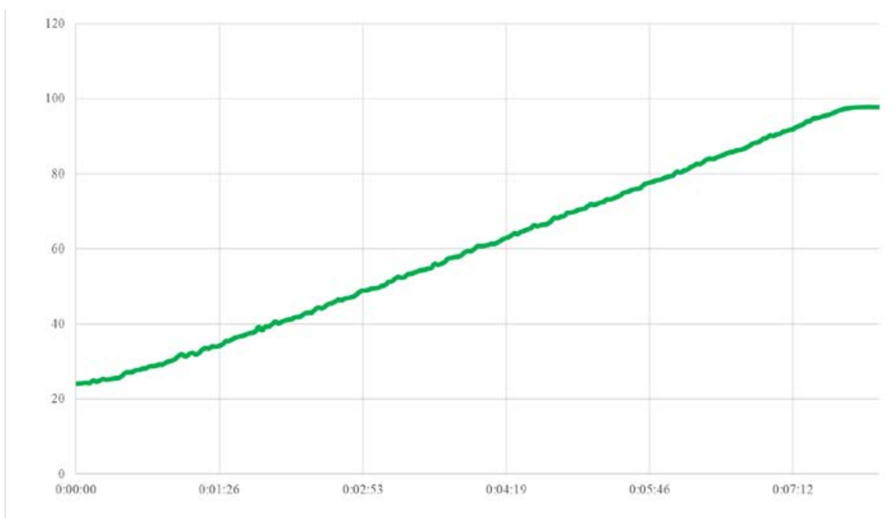

Fig. (65): Prototype 1 Test

5.2 Conclusions & Future Work

This study used the water boiling test of 1 liter of water, to assess a group of commercially available stoves and a prototype stove. There were three main stove designs observed: cubical, cylindrical and J-shaped. The fuel this research used was wood which was cut with tools that would not be available to a camper in the wilderness. This was done to keep the fuel consistent during testing and to ensure that the methods were consistent in every test. During an actual camping trip, a user finds twigs, leaves and forest residue, to burn in their stove. The aerodynamic conditions during testing created a lot of variability for the initial eight commercially available stove. The best two tests achieved by each stove were used in this study. The prototype stove is not affected by wind as much as the other stoves; the high wall design increases the heat transfer ratio. The performance when cooking different meals should be investigated for this group of stoves using a controlled cooking test (CCT). A study of emissions released these biomass-fueled stoves, compared to fossil-fueled stoves, would greatly increase the understanding of these stoves' performance. Testing using a thermal camera could be used to visually prove how the wind affects the heat transfer process when it blows the flames away from the pot. The air flow to the fire burning in the stove is determined by its design; the efficiency of a stove is determined by its airflow characteristics; a further study into the size and location of the air holes in a stove could help determine an optimal design for performance.

Fossil fuels are more energy dense and have higher heating values than woody biomass alternatives. From an economic perspective, whether the United States chooses to embrace an alternative energy future will depend upon political and social choices. At this time, costs of producing energy from woody biomass feedstocks, compared to fossil fuel feedstocks remains a major barrier to market development. To be a viable alternative, biomass should provide a net energy gain or produce more energy than the amount it takes to grow and process the fuel. This net energy gain is measured by energy ratios. Ratios below 1 indicate that the energy input is higher than the energy output. Research shows that woody biomass utilization results in energy ratios above 1; energy input is less than energy produced. Current technologies used to produce electricity from wood give ratios between 6 and 7, surpassing other competitors. Increasing these ratios to 10 or 15 is possible with technological improvements [12].

The total worldwide production of wood in 2000 was about 3.9 billion cubic meters (35 billion cubic feet), of which 2.3 billion cubic meters (81 billion cubic feet) were used for wood-fuels. That means that nearly 60 percent of the world's total wood removals were used for energy purposes. Wood energy provides an alternative to fossil fuels, which could achieve a sustainable future. Wood also provides means to combat global climate change because trees convert carbon dioxide into oxygen, reducing the amount of greenhouse gases in the atmosphere. The shift to renewable energy economy must include strategies for the stabilization and increased production of sustainable wood, to satisfy the growing demand, both in the traditional and modern sectors [4].The utilization of renewable energy should be increased so that future generations are not affected by this generation's decisions and actions.

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APPENDICES

The appendices below list specifications for the instruments used in this study.

Appendix A

K-Type Thermocouple Reference Table [94]

REOTEMP INSTRUMENTS

ITS-90 Table for Type K Thermocouple (Ref Junction 0°C) http://reotemp.com

Thermoelectric Voltage in mV

°C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138

Thermocouple Resolution Range and Accuracy [73]

Sensor Type	Resolution	Range	Accuracy
Type K	0.1°C	-50.1 to -100.0°C	± (0.4 % + 1°C)
		-50.0 to 999.9°C	± (0.4 % + 0.5°C)
	1°C	1000 to 1300°C	± (0.4 % + 1°C)
	0.1°F	-58.1 to -148.0°F	± (0.4 % + 1.8°F)
		-58.0 to 999.9°F	± (0.4 % + 1°F)
	1°F	1000 to 2372°F	± (0.4 % + 2°F)
Type J	0.1°C	-50.1 to -100.0°C	± (0.4 % + 1°C)
		-50.0 to 999.9°C	± (0.4 % + 0.5°C)
	1°C	1000 to 1150°C	± (0.4 % + 1°C)
	0.1°F	-58.1 to -148.0°F	± (0.4 % + 1.8°F)
		-58.0 to 999.9°F	± (0.4 % + 1°F)
	1°F	1000 to 2102°F	± (0.4 % + 2°F)
Type T	0.1°C	-50.1 to -100.0°C	± (0.4 % + 1°C)
		-50.0 to 400.0°C	± (0.4 % + 0.5°C)
	0.1°F	-58.1 to -148.0°F	± (0.4 % + 1.8°F)
		-58.0 to 752.0°F	± (0.4 % + 1°F)
Type E	0.1°C	-50.1 to -100.0°C	± (0.4 % + 1°C)
		-50.0 to 900.0°C	± (0.4 % + 0.5°C)
	0.1°F	-58.1 to -148.0°F	± (0.4 % + 1.8°F)
		-58.0 to 999.9°F	± (0.4 % + 1°F)
	1°F	1000 to 1652°F	± (0.4 % + 2°F)
Type R	1°C	0 to 600°C	± (0.5 % + 1°C)
		601 to 1700°C	± (0.5 % + 1°C)
	1°F	32 to 1112°F	± (0.5 % + 2°F)
		1113 to 3092°F	± (0.5 % + 2°F)
Type S	1°C	0 to 600°C	± (0.5 % + 1°C)
		601 to 1500°C	± (0.5 % + 1°C)
	1°F	32 to 1112°F	± (0.5 % + 2°F)
		1113 to 2732°F	± (0.5 % + 2°F)

Appendix B

RDXL4SD Datalogger Specifications [73]

Circuit	Custom one-chip of microprocessor LSI circuit.
Display	LCD size: 52 mm x 38 mm LCD with green backlight (ON/OFF).
Channels	T1, T2, T3, T4, T1-T2.
Sensor type	Type K thermocouple probe. Type J/T/E/R/S thermocouple probe. PT 100 ohm probe * Cooperate with an 0.00385 alpha coefficient, meet DIN IEC 751.
Resolution Datalogger Sampling Time Setting Range	0.1°C/1°C, 0.1°F/1°F.
Memory Card	SD memory card. 1 GB to 16 GB.
Advanced Setting	Set clock time (Year/Month/Date, Hour/Minute/ Second)
	Decimal point of SD card setting
	Auto power OFF management
	Set beep Sound ON/OFF
	Set temperature unit to °C or °F
	Set sampling time
	SD memory card Format
Temperature Compensation	Automatic temp. compensation for the type K/J/T/E/R/S thermometer
Linear Compensation	Linear Linear Compensation for the full range.
Offset Adjustment	Available for Type K/J/T/E/R/S and Pt 100 ohm.
Probe Input Socket	Type K/J/T/E/R/S 2 pin thermocouple socket.
	Pt 100 ohm : Ear phone socket.
Over Indication	Show " - - - - ".
Data Hold	Freeze the display reading.
Memory Recall	Maximum & Minimum value.
Sampling Time of Display	Approx. 1 second.
Data Output	RS 232/USB PC computer interface.
Power Off	Auto shut off saves battery life or manual off by push button.
Operating Temperature	0 to 50°C.
Operating Humidity	Less than 85% R.H.
Power Supply	A6-AA alkaline batteries
	ADC 9V adapter input. (AC/DC power adapter is optional)
Power Current	Normal operation (w/o SD card save data and LCD Backlight is OFF) : Approx. DC 8.5 mA
	When SD card save the data but and LCD Backlight is OFF) : Approx. DC 30 mA
	* AIf LCD backlight on, the power consumption will increase approx. 14 mA
Weight	489 g/1.08 LB
Dimension	177 x 68 x 45 mm (7.0 x 2.7x 1.9 inch)

Appendix C

MMD4E Pin-Type LCD Moisture Meter Specifications [96]

SPECIFICATIONS

Measurement Range	5 to 50% for wood; 1.5 to 33% for building materials
Measuring Accuracy	±2%
Moisture Range Indications	See tables on page 5
Operating Temperature	32° to 122°F (0° to 50°C) @ <90%RH
Current Consumption	<25mA
Auto Power Off Trigger	3 minutes of inactivity
Backlight Duration	15 seconds
Low Battery Icon Trigger	<7.3V
Dimensions	5.7 x 2.4 x 1.1 in. (145 x 62 x 27mm)
Weight (without battery)	3 oz. (86g)
Power Source	“9V” battery (included)

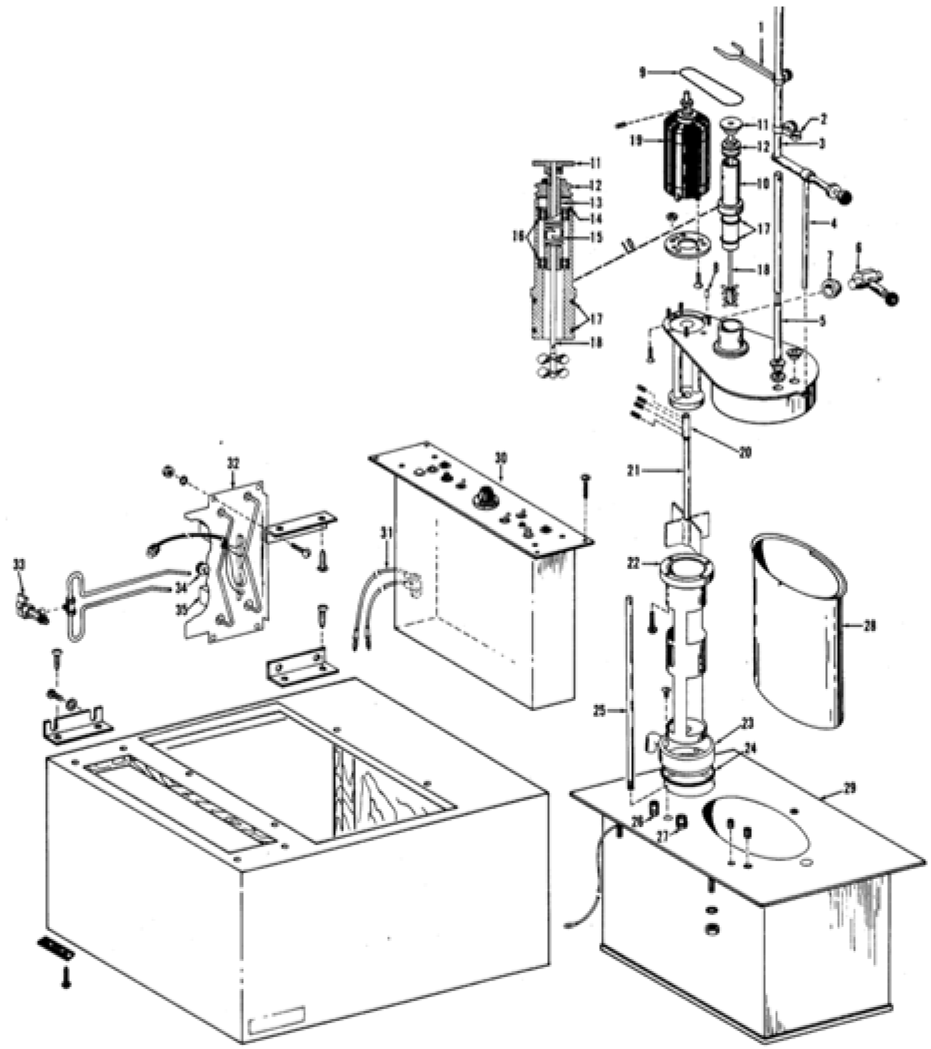
Appendix D

7001-DX Scale Specifications [97]

SPECIFICATIONS			
Capacity	7000g x 1g	**Units**	kg, g, oz, lb:oz, lb
Auto-OFF		2 mins (default time)	
Scale dimension		8.1" x 6.1" x 1.3" (206mm x 155mm x 33mm)	
Tray dimension		5.9" x 5.4" (150mm x 137mm)	
Scale weight		21.6 oz / 612 g	
Operating temperature		Optimum 10-40°C (50-104°f)	
Power Source		3 x AA Batteries / Adapter - DC 5V 300mA	
Tare range		Up to scale's maximum capacity	

Appendix E

Parr 1241 Bomb Calorimeter Parts Diagram [88]



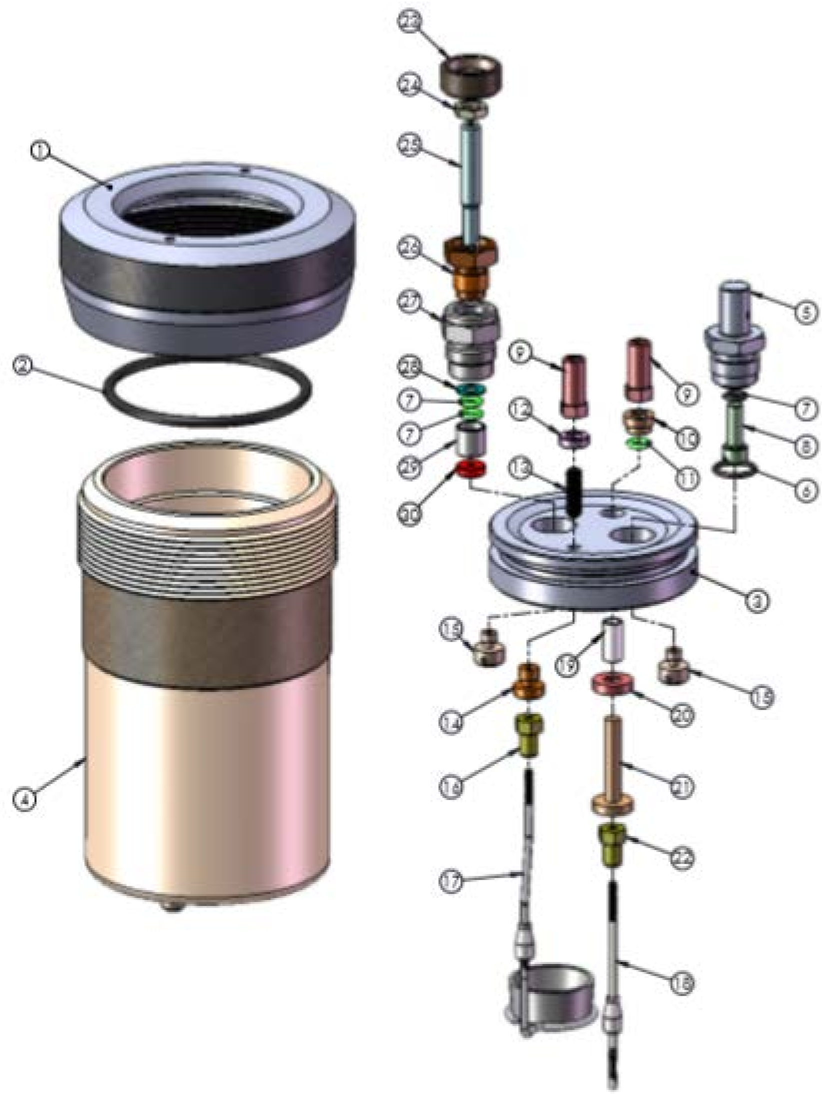
1241 Parr Bomb Calorimeter Parts List [88]

Key No.	Part No.	Description
1	A332DD2	Stirrer lift bracket
2	A270DD3	Thermometer clamp
3	A455DD	Thermometer bracket w/latch
4	A459DD	Safety rod assembly
5	245DD	Thermtr. bracket support rod
6	A323DD	Cover lift assembly
7	243DD2	Cover lift roller
8	SR1214	Roll pin
9	292DD	Drive belt
10	A355DD	Stirrer assembly, complete
11	251DD	Lift disc w/set screw & pin
12	239DD	Stirrer pulley with screw
13	357DD	Bearing hub
14	356HC	Snap ring, large
15	195A	Spring
16	354HC	Ball bearing (2 req'd.)
17	417DD	Sealing ring (2 req'd.)
18	A237DD	Stirrer shaft w/propellers
19	A162E	Motor w/pulley, mtg. plate & cplg.
20	498DD	Coupling with set screws
21	A508DD	Pump impeller assembly
22	A423DD	Pump tube assembly
23	A380DD2	Pump collar assembly
24	483DD	O-ring
25	272DD	Thermometer support rod
26	365DD	Thermistor fitting
27	A364DD	Thermtr. fittg. w/422DD ring
28	A391DD	Calorimeter bucket
29	The following parts are required to replace the calorimeter jacket and/or cover:	
	A376DD2	Jacket assby. w/bucket supports
	A428DD	Cover assembly
	A380DD2	Pump support collar assby.
	A423DD	Pump tube assembly
	A508DD	Pump impeller assembly

Key No.	Part No.	Description
	A323DD	Cover lift assembly
	A243DD2	Cover lift roller
	SR1214	Roll pin
	438DD	O-ring
	A364DD	Thermometer fitting
	365DD	Thermistor fitting
	A162E	Motor w/pulley, mtg. plate & cplg.
30	A300E3	Control panel assembly
31	A297E	Lead wire w/banana plug (2 req'd.)
32	A403DD	Water control panel assby.
33	A135VB	Flow control valve
34	A406DD	Metering valve
35	89HW	Solenoid valve

Appendix F

Parr 1108 Combustion Vessel Parts Diagram [86]



Parr 1108 Combustion Vessel Parts List [86]

Key	Item	Description
1	103A	Screw Cap
	103A6	Screw Cap, Heavy Duty (1108B)
2	230A	O-ring 2-3/8 ID Buna-N
3	394A12	Head, Bare
	394A12CL	Head for Chlorine Service
4	101A 101A4	Vessel Cylinder sold as Part No. AA101A Vessel Cylinder sold as Part No. AA101A4 (1108B)
	101ACL 101A4CL	Vessel Cylinder for Chlorine Service sold as Part No. AA101ACL Vessel Cylinder for Chlorine Service sold as Part No. AA101A4CL (1108B)
5	395A2	Inlet Valve Body
6	415A	O-ring 7/16 ID Buna-N
7	238A	O-ring 3/16 ID Buna-N
8	403A	Check Valve
9	411A	Terminal Nut
10	143AC	Insulator Delrin
11	238A	O-ring 3/16 ID Buna-N
12	388A	Spacer
13	SC1932SC10	Socket Head Set Screw
14	278A3	Adapter Bushing
15	404A2	Deflector Nut
16	406A	Lock Nut
17	5A10	Loop Electrode with Sleeve
18	4A10	Straight Electrode with Sleeve
19	401A	Sleeve Insulator
20	96AC	Electrode Insulator
21	402A	Electrode Core
22	406A	Lock Nut
23	407A	Valve Knob
24	398A	Lock Nut
25	400A	Valve Needle
	A420A	Valve Needle with Knob (Nos. 23, 24, 25)
26	397A	Compression Nut
27	396A	Outlet Valve Body
28	7VBCM	Washer Monel
29	378A	Packing Cup
30	20VB	Valve Seat PCTFE

Appendix G

Mettler Toledo MS204S Analytical Scale Specifications [90]

Capacity (g)	220
Readability (mg)	0.1
Linearity (mg)	0.2
Weighing Units	g, kg, mg, ct, lb, oz, ozt, GN, dwt, mom, msg, tlh, tls, tlt, tola, baht
Calibration Type	Internal
Languages	English, German, French, Spanish, Italian, Polich, Czech, Hugarian
Power (VAC)	120
Description	Newclassic MS Analytical Balance, 220g x 0.1mg