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Performance of corn stoves

David Robert Starks
Iowa State University

Performance of corn stoves

by

David Robert Starks

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Program of Study Committee:
Robert Brown, Major Professor
Gregory Maxwell
Samy Sadaka

Iowa State University

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ABSTRACT

The purpose of this research was to determine the effectiveness of using corn burning heating appliances as an alternative to more traditional natural gas or electric heat. Two models of different sizes and outputs were purchased for the test. The appliances were operated through the winter and into the spring to evaluation their performance.

The equipment was operated following the manufacturer's suggestion. Parameters such as gas composition, ash production and temperature profiles were obtained in order to quantitatively describe the performance of the appliances.

While many natural gas furnaces available to consumers these days reach efficiencies of greater than 95%, solid-fuel appliances remain significantly lower. Observed efficiencies ranged from 10% to 50%, depending on fuel source, method of combustion, and design. Because of the fledgling nature of this industry, performance is not as high as well developed technology, such as gas furnaces, can achieve. However, with enough sustained interest in alternative energy, the application of burning corn for heat shows promise.

1. INTRODUCTION

With the quickly increasing costs of oil and gas, Americans have been searching for new and innovative means of cutting costs where possible. Perhaps this is most evident in the automotive industry, where hybrid vehicle sales have skyrocketed in the last two years. People are anxious for promising new technology, often without regard to whether or not it has been proven to be the most economic choice.

The heating industry has made great strides in increasing the efficiency of heating with natural gas. It is not uncommon to find furnace systems with efficiencies upwards of 95%. Even so, there are alternatives to using conventional utilities. Burning wood for heat has been in existence for as long as fire has existed. But since then, there have been some improvements in the design. Wood pellets made from waste wood are now a common fuel source for people looking for a more natural or green heating fuel; and many products are available that are designed to utilize these pellets. Within the last few years, there has been an increasing interest in using corn.

One of the attractions of using corn is that the processing infrastructure is already in place to make shelled corn readily available. Since the corn does not need to be pelletized, it can be easily fed into an auger system without significant processing. Though, removal of fines is sometimes required, as excess particulate in the corn will cause augers to bind.

An initially apparent problem with using corn is that corn is not the easiest fuel to ignite, and there is not a general consensus among the manufacturers of corn-burning appliances on the best method for combustion. As a result, there are dozens of models on the market, each toting a different feature that sets attempts to be the best at what it does. Some of these innovations work better than others, and currently, it is not always easy to effectively pick and choose what options make for the best design.

In order to make an informed decision, the consumer requires information. However, most information is available only through manufacturers and their dealers. There is no overseeing body that evaluates these appliances to determine their strengths and weaknesses. This is partly because these products are relatively new to the market and not well known to the average consumer. – The mechanization of an appliance specific for burning corn has only been around since the mid 1990's. The other reason is that these products are simply too expensive. Joining the league of owners of corn-burning appliances will easily cost $2,000, making them an intimidating purchase.

With the generous assistance of the Iowa Energy Center, a pilot research program was undertaken at Iowa State University to see if all the buzz about corn heat was all it was worked up to be.

2. BACKGROUND AND LITERATURE REVIEW

2.1. Drive For Alternative Heat

Wood has been burned for centuries for warmth and cooking. Over the years, the formula for using wood for fire hasn't changed much: find an ignition source, keep fuel supplied, and don't smother the fire. Since then, there have been advances in keeping the fire contained as well as adding amenities such as forced air heat exchangers and the like.

However, having chopping wood is a tedious task. The wood must be manually fed into the fire since the diversity in shape and size of wood makes using an automated feed system difficult. After the development of using compressed sawdust or other fine bits of wood to form pellets, an opportunity opened to use a pellet feeding system, such as augers or conveyors. Since the creation of wood pellets, a large number of models of pellet stoves, central heating furnaces and other appliances have emerged since the early 1990's. With the price surge of fossil fuels in the early 2000's, the demand has increased all over Europe and the United States, and a sizable industry is emerging.

2.2. Current Status of Solid Fuel Appliances

As of today, there is a small but increasing market for solid-fuel furnaces. Prior to the hurricane season of 2005, the industry was slowly growing in the U.S., but was viewed by many as a novelty. Many owners of such devices were farmers and others that readily had inventories suitable for burning and were content with a small stove heating a part of the house while saving money by not having to run the gas furnace as often. Some urban areas saw use of this equipment as either a functional décor item, such as a fireplace would fulfill or as an environmental/political statement. In fact, many users boast their freedom from foreign oil. But with high efficiency (greater than 95%) gas furnaces on the market, there was not a large drive to consider alternative sources of heat.

The attitude toward solid-fuel heat changed significantly following the hurricanes of 2005. Following the destruction of many refining operations in the gulf coast, the price of petroleum dramatically increased – most noticeably was gasoline. As the price of natural gas was already making marked increases, there was a large amount of concern that this would significantly raise the cost of heating one's home. Soon, many people were researching alternatives to their older gas furnaces. All options were considered, from electric heat pumps to geothermal machines. Even those without agricultural ties were not long on flooding the solid-fuel appliance manufacturers and distributors with endless queries and purchases. As it would turn out, 2005 was a major sales year for solid-fuel. In fact, many sold out and waiting lists of a year were not uncommon as the cold season emerged.

Unsurprisingly, in the Midwest, the appliances getting a disproportionate amount of attention were the corn stoves and furnaces. Since corn is in a form similar to currently available wood pellets, it was an obvious choice to evolve towards. The main differences from wood are that since corn burns hotter than wood and creates more problems with sustaining combustion, the corn burning appliances had to be built as more aggressive machines. The body and components near the flame had to be built out of thicker, heavier gauge metal. Also, there had to be more creative ways of maintaining airflow and keeping the fire hot because of a new variable with burning corn: clinkers.

Clinkers are a product of a phosphorus-rich fuel. They are formed as the starch burns out of the corn and partially melts, flowing over the burning embers and carrying mineral deposits along. As the starch is burned away and the flame cools, the viscous liquid cools and hardens, forming a structure that looks and feels similar to a coral reef, but consists of phosphates (mostly P_2O_5) and other ash constituents. The size of clinker is dependent on the size of the burn pot and temperature of the fire, but they can range from the size of a few centimeters to as much as 20 cm. Because of their irregular shape, they can be a hindrance to both air flow and fuel flow. Below are some example pictures of clinkers.

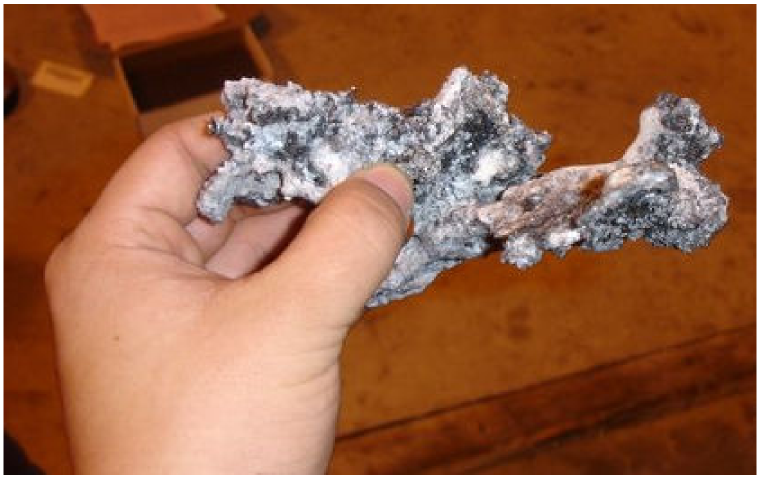

Figure 1: A large clinker formed by burning corn

Figure 2: An abundance of clinker from using a corn furnace

The manufacturers of corn burners have a few options for dealing with clinkers.

- Let them be – One option is to just let them collect. At the end of the day, allow the stove to cool and manually remove the clinker afterwards or before the next burn. If the burn pot is large enough, quite a few days of operation can pass before it is necessary to remove them. If heat is not constantly required, leaving the clinkers sit in a cold stove for a few days can make disposing of them easier. Since the clinker is water soluble, leaving it exposed to room air will soften it up and it will crumble to the touch, which can then be vacuumed out.

- Grind them up – Many stoves utilize this option. Since air is passed up to the fire through a slotted or mesh grate, if the ash and clinker are fine enough, they will pass through these holes into the ash pan. In order to reduce the clinker to manageable size, there is a stirrer rod or grinding axle that will break up the clinker and allow it to pass through to be removed with the rest of the ash.

- Expel them from the burn pot – Currently, only the largest corn furnaces use this option. This method involves using the direction of the fuel flow to cause the clinker and ash to be passed into the ash pan. This can be caused by an upwards flowing fuel stream that spills over the top of the burn pot or by a conveyor system that will dump the waste materials at the end.

Due to the large number of independent manufacturers, there are a large number of options that can be explored as different models are examined. However, it should be mentioned that the scope of this project will only examine representative models

2.3. Current Regulations Regarding Solid-Fuel Appliances

In the United States, there is a large amount of legislation regarding the usage and performance of large scale heat sources such as those present in power plants. However, as the scale decreases, so does the regulatory oversight accompanied with operating a solid-fuel appliance. In general, one would hardly know that these stoves and furnaces would be under any regulation at all. However, due to popularity of wood stoves in rural communities, the EPA drew out codes to regulate the use of small scale stationary appliances. This is covered in Code of Federal Regulations (CFR) Title 40 – Protection of the Environment, Part 60 – Standards of Performance for New Stationary Sources, also referred to as 40CFR60 [18].

In all of 40CFR60, the section of interest in small scale appliances is Subpart AAA (§60.530-§60.539a) – Standards of Performance for New Residential Wood Heaters. The first part of which dictates the jurisdiction of the article based on the size of burn pot, the fuel input rate, the overall weight of the appliance and so on. However, one will note that the key word "wood" is present. This means that if corn, soybeans, grass, or any other such plant matter is burned, 40CFR60 does not apply. In fact, unless a local code governing the generation of excess smoke or noise is violated, there is virtually no regulation of corn-fired stoves or furnaces. However, due to the selling power of having a "certified" appliance, many manufacturers will self-impose the standards laid out in 40CFR60-AAA.

Most people are unaware that the characteristics that 40CFR60-AAA regulates are only with respect to particulate generation [3]. There is a formula that relates the fuel input to particulate output, but because of the differences between corn and wood, this correlation is not applicable. But the other means by which an appliance can be certified is to qualify under an exemption.

Exceptions for 40CFR60 are quite a few, but most will cause the appliance to be governed under another article of the CFR code. The most common exemptions that wood burning stoves utilize are burn rate and air-to-fuel ratio [5]. Small appliances require a fuel feed rate of less than 5 kg/hr. Since wood burns so readily, it is not difficult to design a stove that uses well more than 5 kg/hr, however with corn, this is not often the case because corn has a much higher energy density than wood. The other option a manufacturer would have is to dilute the air flow. Having an air-to-fuel ratio of greater than 35:1 will cause the exhaust to be diluted such that even poorly burning fires will not create a significant smoke signature.

2.4. Stove research in other countries

Some research has been performed on solid-fuel heating in two other regions of the world: Canada [14] and Scandinavia [6], [13]. Canada's Ministry of Agriculture promotes burning shelled corn as alternative to wood. Universities in Scandinavia have done research projects to determine the feasibility of using solar and bio-mass heating to lessen their need for fossil fuels and take on bio-renewable technologies. However, many of these projects were completed on more of a macro-scale than the scope of this project.

2.5. Stove and Furnace Operation

The focus of the project was the appliances themselves. Selecting the models to be tested would have a substantial impact on the outcome of the research. The selection was intended to be done from a consumer standpoint taking into consideration apparent ease-of-use as well as low maintenance requirements. Since there is not a standard means of burning corn, many manufacturers of corn-fired appliances are left to their own ingenuity to develop their stoves.

The notation of "stove" and "furnace" in this industry is semi-ambiguous. Generally, the term "stove" is used for a stand-alone unit. Typically a stove is designed to heat a single room or possibly a whole floor, but is not tied into the residence's central system. Because of their exposed nature, aesthetics are more emphasized. Glass doors to view the flame are common, as well as gold or chrome trim. Heat outputs generally keep below 50,000 BTU/hr. On the other hand, furnaces are physically larger units designed to output significantly more heat. Typical outputs would be 80,000 BTU/hr and up. The blower fans are more powerful as the heated air is normally routed through a building's ductwork. The appearance of furnaces is more comparable to a standard gas-fired furnace. There are typically no glass viewing ports and except for the radiative heat and ash tray, there is not always evidence that there is combustion taking place.

Many smaller units take their design from pellet stoves. Pellet stoves have been around considerably longer and various designs have started to converge. Typically, pellets are fed through an auger into a small burn pot that blows air either over or through the flames. The primary difference between corn and pellet stoves is how strongly each is built. Corn burns at a higher temperature than pellets and therefore corn burning stoves are built with this in mind, utilizing heavier gauge metal sheets and different temperature thresholds. Beyond this, other options are simply amenities. With stoves, trim is often put under consideration since the stove will frequently be the centerpiece of whatever room it is placed. Controls for adjusting airflow and heat output are often standard and are available as dials or as digital panels. Additional equipment for handling clinker is often considered, though the effectiveness or necessity of such amenities is still up for debate. This particular issue will be discussed further on.

In comparison to stoves, there are also units being sold that are designed to heat whole buildings instead of a single room. The larger units are marketed as furnaces, and as such are built in a way that will afford easy transition from gas-fired furnaces. The air circulation is done from the top and exhaust ports are located on the sides to assist in maneuvering chimney pipe around obstacles and out of the building. This is where most of the similarities of corn-burning furnaces end. Unlike stoves, furnace makers do not have a comparable model to work from. The actual burn method varies greatly across different manufacturers. The varieties are too numerous to go into detail, but each method has to deal with four essential duties:

- Adding fuel to the burn pot
- Supplying air to the flame
- Handling clinker
- Power cycling

The first three challenges are all common to stoves, but the last is significantly more important for furnaces than stoves. While having the furnace run at full capacity the entire time is one possible option, it is usually not intended for it to be done that way.

For stoves, thermostats are generally more of an option than a requirement. But most, if not all, furnaces are designed to operate with a thermostat. This means that when the air is colder than the thermostat's set temperature, the furnace should put out significantly more heat than when the air has reached an adequate temperature. Traditionally, home furnaces can compensate for this by keeping a pilot light lit or using an electronic ignition and turning the gas on and off as needed. But as of this publication, only one stove on the market features an auto-ignition capability. This means that the fire must not be allowed to extinguish, but yet not burn at its full potential. Many models use a method that utilizes a “high-fire” (hi-fire) and “low-fire” (lo-fire) system.

Hi-fire is the more familiar mode which uses forced air to fan the flames. Lo-fire is achieved by either reducing the forced air or eliminating it altogether and allowing natural convection to supply the air needed for combustion. This results in less complete combustion of the fuel, thereby creating a dirtier exhaust, but it also reduces heat output. The one means of auto-ignition is available on the Harman PC45 stove. Ignition of the corn is accomplished via a 400 watt heating element embedded in the corn, designed to raise the temperature to over 900 K for ignition. Research and development is still being undertaken in this area and means of providing ignition sources as a common feature will likely be available within the next few years.

The essence of a furnace or other heating appliance is transferring heat from a source into the environment. The means that current technology accomplishes this is through the use of releasing heat energy through combustion and passing this heat on to a heat exchanger for use. Most of the appliances on the market use a form of a cross-flow heat exchanger. Combustion products flow around the exchanger tubes and out through the chimney. The room air is then circulated through these tubes to be warmed and sent out into the room. The effectiveness of this heat exchanger is the arguably the most important operating feature of any heater. As such, it will receive its due attention through the course of this research project.

3. EXPERIMENTAL METHOD

3.1. Experimental Equipment

3.1.1. Introduction

The focus of this research is to characterize the performance of corn stoves through an experimental test program. The following sections detail the equipment used in these experiments.

3.1.2. Country Flame Harvester

The model selected to represent stoves was the Harvester, produced by Country Flame Technologies of Marshfield, Missouri. It was chosen as one of the most likely choices for consumer selection due to its simplicity and low maintenance. Key features of this product are its digital control panel, thermostat compatibility and its clinker stirring feature. The digital control panel relays all pertinent information to the user while also facilitating virtually all functions from a single location on the stove. Having a thermostat capability allows the user to regulate the temperature of the room in a more autonomous fashion as opposed to dialing in different settings on the stove based on how warm the room feels. The clinker agitation system alleviates the user from having to manually remove clinker from the burn pot daily or semi-daily. Instead, the clinker is ground up and allowed to pass into the ash pan along with the rest of the unburned material. Overall, the operation of these stoves is typically not complicated. Figure 3 is a photo of the Country Flame Harvester corn stove followed by a schematic diagram in Figure 4.

Figure 3: Country Flame Harvester stove

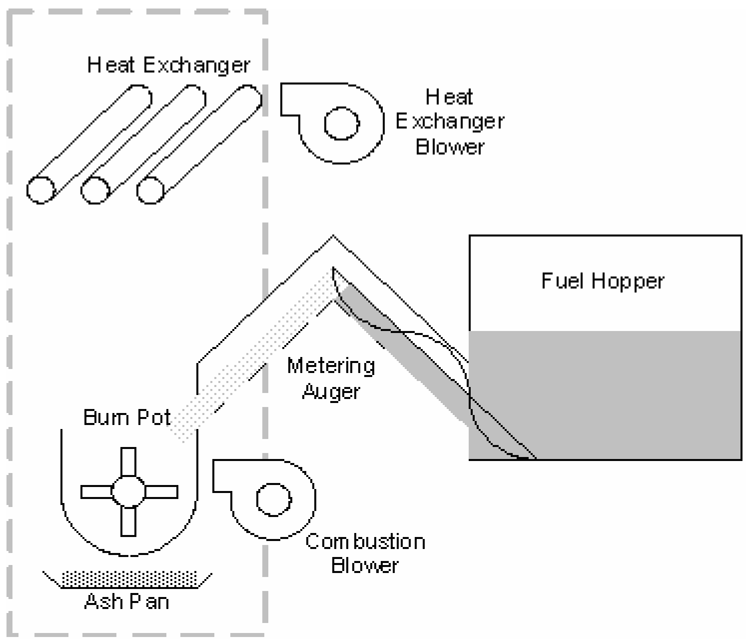

Figure 4: Operational diagram of the Country Flame Harvester stove

Corn is stored is stored in the onboard 75lb (1.3 bu) hopper. At the bottom of the hopper is an auger for metering out the fuel. This auger extends out of the hopper at an upwards angle towards a downward sloping chute. This chute passes through a masonry and steel firewall then empties into the burn put. The burn pot consists of a rectangular, grated steel box with a cylindrical base similar to the illustration in Figure 5. The cylindrical portion has numerous small holes drilled throughout. The holes are small enough that whole kernel corn cannot pass through, but they allow for air to pass up through and for ash and ground clinker to fall into the ash pan. Above, the heat exchanger tubes are heated as the fire and hot air pass by. Room air is then blown through the tubes and out through a vent in the front of the stove.

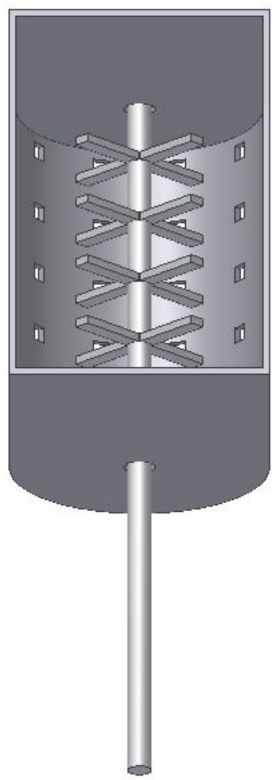

Figure 5: Country Flame Harvester burn pot

The Country Flame model uses 2 rows of small diameter (~0.75") tubes arranged in a stacked 8-7 pattern as shown in Figure 6. The HX tubes are directly exposed to the flame burning below as shown in Figure 7. However, due to the relatively small burn pot, the Country

Flame's heat exchanger has a large variance of temperature across the face of the heat exchanger.

Figure 6: Country Flame Harvester heat exchanger with thermocouples visible

Figure 7: Country Flame Harvester in operation

The burn zone is kept under slight positive pressure from the combustion fan; this forces the exhaust through internal channeling to the back of the stove to be sent out of the building through chimney piping.

3.1.3. LDJ Mfg. model 620-10

The model chosen to represent furnaces is the model 620-10 and is built by LDJ Manufacturing of Pella, Iowa. LDJ is one of the longer established manufacturers of corn-fired furnaces, having been around since 1999. The LDJ model was chosen for a variety of reasons, most notably for the proximity of the manufacturer, ease of use, and appropriateness for residential use. Since furnaces require significantly more work to install than stoves, it may be necessary to consult the manufacturer more frequently. Having a company that was in-state was invaluable during the installation process. In addition, it seemed appropriate to choose a product built in Iowa as a tribute to the Iowa Energy Center's goal of "invest[ing] in initiatives that help Iowa industries and businesses." [1]

LDJ's goal is to "improve the furnace and boiler to the point of being as automatic as other heating products." [11] This is a noteworthy cause, since many larger units are more reminiscent of steam locomotive boilers than of home appliances. Other products seemed less intuitive, and therefore less likely to be chosen by consumers – further excluding them from selection. However, when stripped down to the bare components, most corn-fired furnaces operate very similarly, but since this project focuses on the LDJ model, that is where discussion will focus. Figure 8 is a photo of the LDJ A-Maize-ing Heat 620-10 furnace followed by a schematic diagram in Figure 9.

Figure 8: LDJ 620-10 furnace

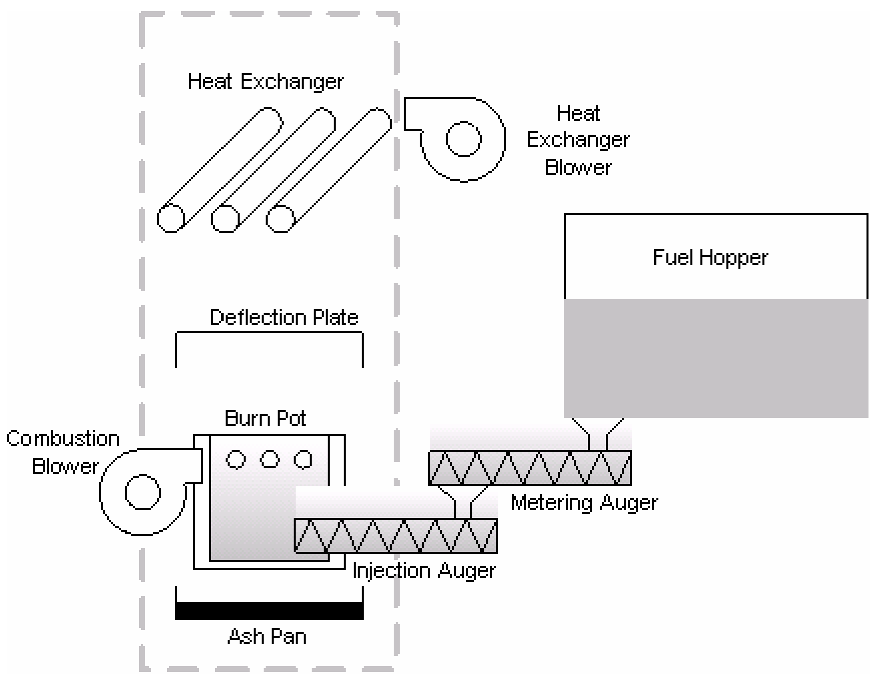

Figure 9: Operational diagram of the LDJ 620-10 furnace

Corn is held in the external fuel hopper. At the bottom of the fuel hopper, there is a slow-speed screw conveyor or auger. The purpose of this auger is to meter or dispense out the fuel at a predetermined rate. The metering auger empties into a second, higher-speed auger, also referred to as an injection auger. If the fuel were to move too slowly into the burn zone, it is possible that combustion would begin outside of the designated area, possibly resulting in undesirable performance, excess smoke, or possible fire damage to the furnace components. The injection auger is designed to quickly move the fuel from a cool, room-temperature state to the burn zone.

In the LDJ furnaces, the fuel is forced into the burn pot from the bottom, creating an upward flowing combusting medium. The flame is sustained on the topmost region of the burn pot. This top flame acts to keep the flame distanced from moving parts to avoid thermal damage. Also, the upwards motion assists in the removal of clinker. As more fuel is added to the bottom of the burn pot, it forces the uppermost contents up and over the edge of the burn pot and into the ash pan. By the time material has reached this point, it is mostly reduced to unusable clinkers.

Figure 10: LDJ 620-10 in operation - notice glowing clinkers surrounded by flames

When it is called for, air is added to combustion through a double-wall system that vents through a set of holes encompassing the top portion of the burn pot. The hot gases then flow upwards into a metal plate the acts to deflect ashes and soot back down towards the flame and ultimately, the ash pan. However, there is space on the sides of the plate to allow the hot gas to pass up and around the heat exchanger tubes.

The LDJ model uses 3 rows of large diameter (~1.5") tubes arranged in a stacked 4-3-4 pattern. The heat exchanger (HX) tubes are not directly exposed to the flames; instead, there is a steel plate that partitions the flame pot from the HX. Hot gases are allowed to pass around the plate and upwards towards the tubes.

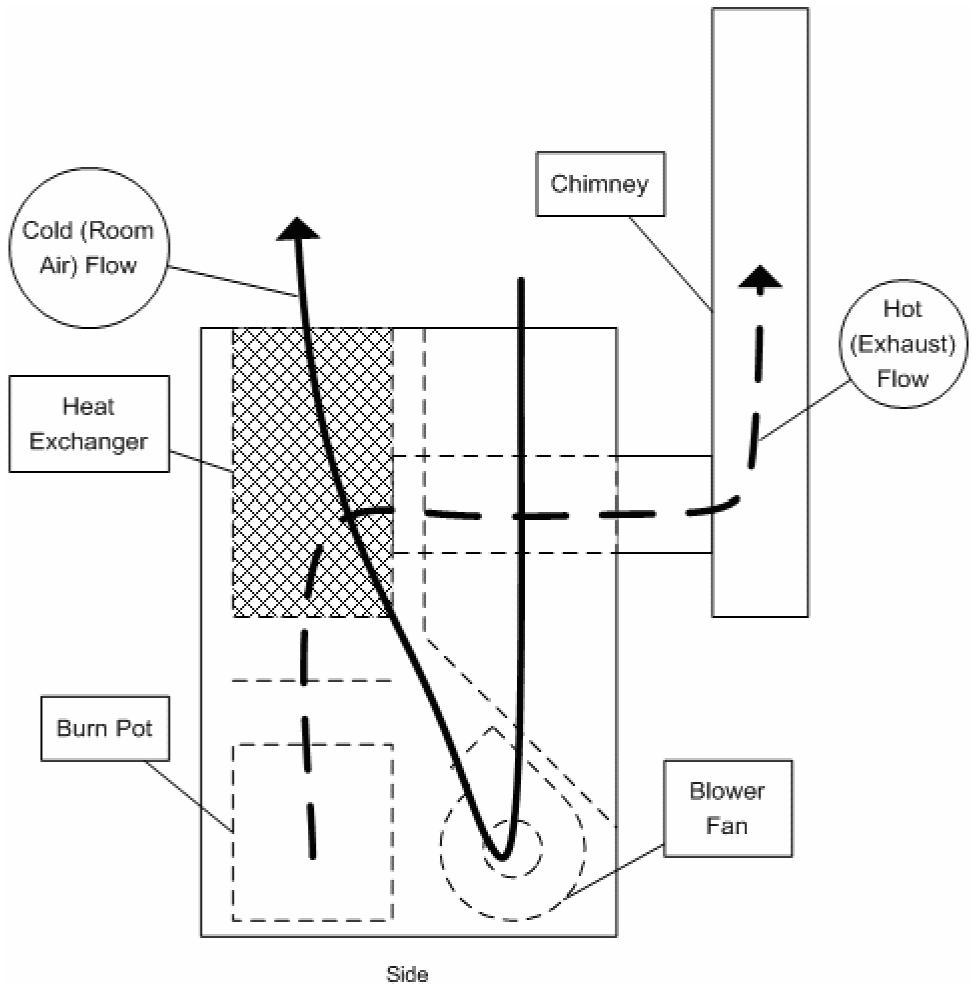

Figure 11: Airflow diagram for the LDJ 620-10 furnace

After the gas leaves the heat exchanger, it is collected into a single pipe that passes through the cold air draw to partially act as a preheater. After this, it is piped out of the back of the stove to be channeled through the chimney ductwork as shown in the following figure.

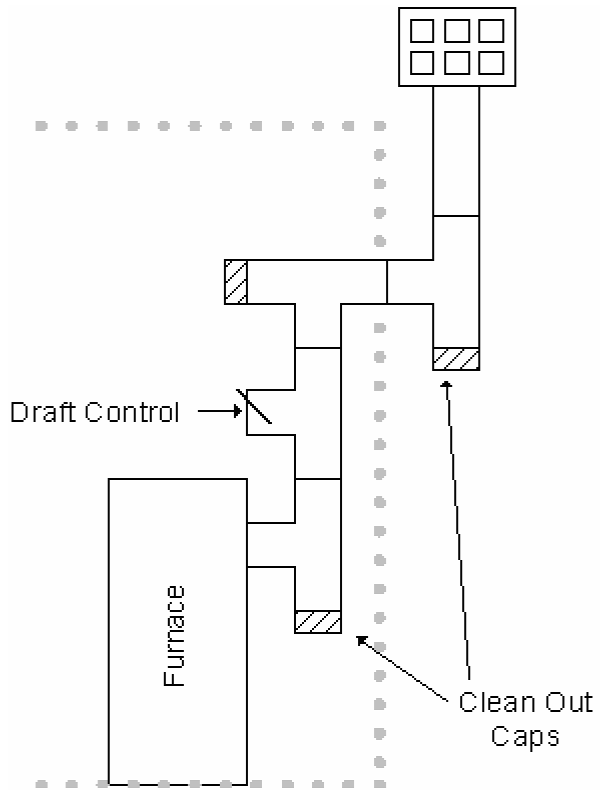

Figure 12: Chimney diagram for the LDJ 620-10 furnace

Something that is important to note about this particular model is the draft control that LDJ institutes. The static pressure of the exhaust port is designed to not exceed 0.04” H_2O vacuum. A high draw will cause too much air to be drawn across the fire and could potentially extinguish the flame. To maintain this pressure in the presence of high cross-winds, there is a damper valve near the exit of the furnace to allow room air to be drawn into the chimney.

3.1.4. Land Instruments LANCOM II Flue Gas Analyzer

In addition to the two test appliances, two other pieces of equipment were employed in this project. To measure gas composition, a LANCOM II Portable Flue Gas analyzer manufactured by Land Instruments was used. The LANCOM II measurement capabilities are summarized in Table 1.

Table 1: LANCOM II gas detection profile

Gas		Name	Resolution		
CO_2	:	Carbon Dioxide	±	0.0001	%
C_xH_x	:	Hydrocarbons	±	0.0100	%
O_2	:	Oxygen	±	0.0100	%
CO	:	Carbon Monoxide	±	1.0	*ppm*
NO_2	:	Nitric Oxide	±	1.0	*ppm*
NO	:	Nitrous Oxide	±	1.0	*ppm*
SO_2	:	Sulfur Dioxide	±	1.0	*ppm*
H_2S	:	Hydrogen Sulfide			*N/A*

A simplified diagram of the LANCOM II is shown below. It consists of a main unit that houses all of the detectors as well as a control and display panel. A sampling wand is then tied to the input port of the LANCOM II. The sampling wand retrieves temperature through an imbedded thermocouple as well as gas samples that it draws through a sintered metal filter. To utilize this analyzer, the sampling wand was inserted deep into the chimney and allowed to draw from the passing flue gas.

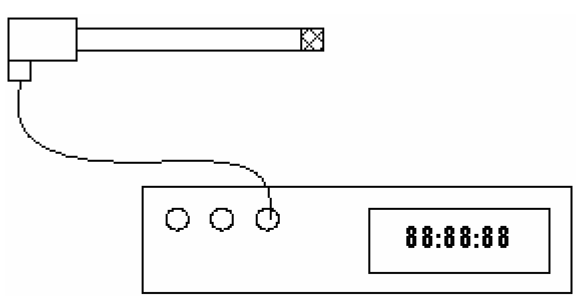

Figure 13: Land Instruments LANCOM II flue gas analyzer

The LANCOM II is equipped with an RS-232 connection and appropriate software for connecting it to a computer running Windows. Using these capabilities, the analyzer permits for data collection at 1 Hz.

3.1.5. Campbell Scientific CR10X Datalogger and Multiplexer

In order to collect temperature information, a board capable of receiving thermocouple inputs is almost a necessity. There was a Campbell Scientific CR10X datalogger on hand which would meet all the requirements. It offered enough differential channels to allow monitoring of multiple thermocouples and various detectors. The CR10X has an onboard non-volatile memory capable of storing 62,000 data points. This allowed for over 20 hours of unmonitored data collection at a sampling frequency of twice per minute. After these points have been filled, it is necessary to download the RAM in order to prevent over-writing of old data.

3.2. Experimental Method

3.2.1. Running the Stove/Furnace

The program involved the operation the appliances according to the manufacturer's instructions. The directions for lighting and operating the appliances were followed from the user's manual. Instrumentation was added in such a fashion that it was believed to not have an impact on the normal operating characteristics.

The Country Flame Harvester has 5 heat settings corresponding to various heat outputs. During thermostat operation, the stove would cycle between setting 1 (lowest) and a user selected level (3 is default.) Without a thermostat, the Harvester will maintain operation at a user defined output level. Operations were to be carried out under all output levels to quantify performance over as broad a range as possible.

The LDJ 620-10 furnace has a variable output setting ranging the feed rates from 80,000 BTU/hr to 165,000 BTU/hr. Operation of this stove was performed at the factory setting of 100,000 BTU/hr, with occasional testing done at upper and lower output ranges.

3.2.2. Temperature Measurements

Owners of these appliances will want to know how well they will heat their home. To be able to address their inquiries, a heat exchanger analysis can be performed. There are four essential temperatures that must be known in order to complete the analysis. However, only three inputs are required for measurement as long as all of the other information about the heat exchanger is known. These three inputs can be any combination of the four essential heat exchanger temperatures:

- Hot in (Exhaust gases leaving the burn pot)
- Hot out (Exhaust gases exiting the heat exchanger)
- Cold in (Room temperature)
- Cold out (Heated room air)

The reason only three of four temperatures must be measured is that the fourth can be solved later by finding the energy transfer of either the cold side or the hot side of the heat exchanger and setting the heat transfer of the opposite side equal. The procedure for performing this calculation is outlined below, with detailed calculations found in Appendix D. The following nomenclature is employed in these calculations:

q : energy transfer
$\dot{m}$: mass flow rate
$\dot{V}$: volumetric flow rate
ρ : density
c_p : specific heat (constant pressure)
C : heat capacity rate
$_h$: hot flow
$_c$: cold flow
$_i$: in flow
$_o$: out flow

Energy transferred is equal to the mass flow rate times the specific heat as well as the change in temperature

$$(1)\ \ q = \dot{m} c_p \Delta T$$

Since mass flow is not known, it can be substituted by the volumetric flow rate times the density

$$(2)\ \ \dot{m} = \dot{V} \rho$$

Thus yielding

$$(3)\ \ q = \dot{V} \rho c_p \Delta T$$

Using this equation, the energy transfer of the cold side can be found

$$(4)\ \ q_c = \dot{V}_c \rho_c c_{p,c} \left(T_{c,i} - T_{c,o} \right)$$

Since an energy balance states that the energy leaving the hot flow must be accounted for by energy entering the cold flow, the same energy transfer equation can be used to find the hot inlet temperature, $T_{h,i}$.

$$(5)\ q_c = q_h = \dot{V}_h \rho_h c_{p,h}\left(T_{h,i} - T_{h,o}\right)$$

After the energy transfers and temperatures are established, efficiency can be calculated by finding the minimum heat capacity rate.

$$(6)\ C = \dot{m} c_p$$

Depending on which value is smaller, C_c or C_h, will produce the maximum theoretical heat transfer.

$$(7)\ q_{\max} = C_{\min}\left(T_{h,i} - T_{c,i}\right)$$

Finally, q can be compared to q_{max} to find the effectiveness of the heat exchanger.

$$(8)\ \varepsilon = \frac{q}{q_{\max}}$$

Solving for the fourth temperature is sometimes necessary if one of the temperatures is highly variable. In this case, due to the nature of a solid-fuel flame, the temperature can easily swing tens of degrees C in a matter of seconds.

Also, knowing exactly where to measure the hot gas can be difficult, given the design of the burn pots. In the larger furnace, there is a deflector plate that the hot gas must flow around, but because of the size of the flame below, the hot gas will frequently alternate which side of the deflector plate it passes. Another challenge is presented in the smaller stove, where the size of the burn pot causes the flame to have at least a 90º viewing window of the heat exchanger. This causes the very outwards zone of the heat exchanger to be noticeably cooler than the central tubes of the exchanger. However, because of the thermal mass of the heat exchanger and the mixing effects of the turbulent fluid, the other three temperatures are significantly more stable, especially over the course of hours. After the appliance has reached stable operation, the first three temperatures can be used to solve for the remaining temperature, $T_{h,i}$

The thermocouples will be placed in key locations corresponding to a well-mixed, representative airflow. Locations for the thermocouples are illustrated in the following Figures 8 and 9. Additional temperatures may be taken as necessary and may include surface and outside temperatures.

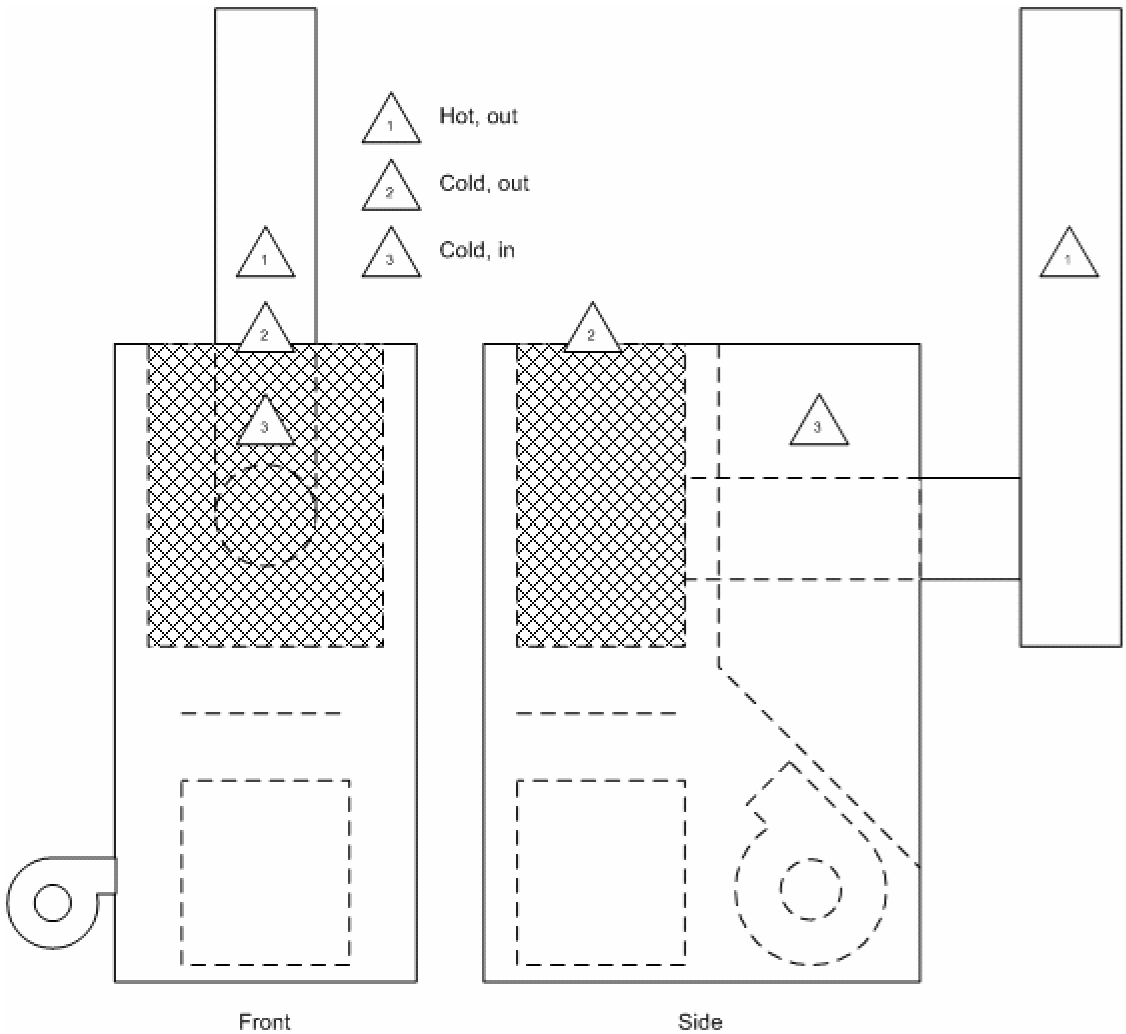

Figure 14: Sensor placement for the LDJ 620-10

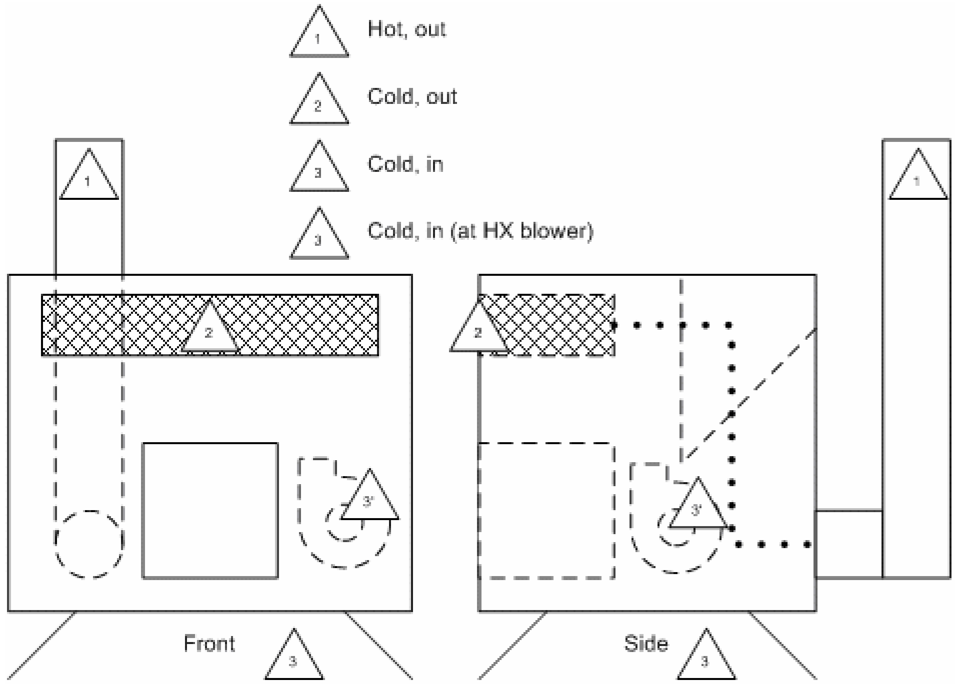

Figure 15: Sensor placement for the Country Flame Harvester

The thermocouples are then connected to the CR10X and sampled at a rate of twice per minute. This allows the CR10X to capture nearly 24 hours worth of data before the memory must be downloaded to avoid memory wrapping (overwriting of old data.)

3.2.3. Sampling Exhaust

When it comes to exhaust, most owners are only concerned with three things. These can be summed up in three general frequently asked questions.

- "Does it create a lot of smoke?"
- "Does it smell bad?"
- "Will I have to worry about carbon monoxide or other dangerous fumes?"

From an emissions standpoint, these can all be addressed by sampling the exhaust gases and doing physical studies using ones own senses.

Empirically, the LANCOM II flue gas analyzer will be used to determine the components of the exhaust stream. This information will be analyzed to determine the combustion efficiency

Due to the non-regulation these stoves and the complications of installing a system to measure particulate from solid-fuel combustion, a quantitative analysis of particulate emissions will not be done.

3.2.4. Measuring Bottom Ash

Apart from supplying the fuel to the furnace or stove, the other regular maintenance task a user must perform is disposing of the leftover soot or "bottom ash." After the conclusion of a test, the remaining ash was collected, weighed, and further oxidized in an ashing oven to determine the amount of carbon that was initially present. In conjunction with the exhaust components, the bottom ash will complete the picture of carbon conversion efficiency.

3.2.5. Determining Volumetric Flow Rates

In order to complete the heat exchanger solution, it is necessary to know the mass flow rate of the fluids passing through the heat exchanger. In order to find the mass flow rate, a combination of volumetric flowrate and equivalent density can be used instead.

The means of obtaining flow rates of a gas in ducting are numerous and can consist of such options as using a hot-wire anemometer or pitot tube readings. The downside for many of these methods is that the gas must be relatively clean to obtain a usable measurement. The hot side of the heat exchanger in these appliances is the product of combustion; this means that it carries soot and tar along the fluid stream. These contaminates make finding an alternate means of determining flow rate necessary. The option that was chosen was to mix additional CO_2 into the gas flows and measure the changes in CO_2 concentrations that accompany the added gas.

The LANCOM II flue gas analyzer was used in determining CO_2 concentrations within gas streams. The time-constant for the CO_2 detector is approximated at 20 seconds. To account for this, the first 60 seconds after changing concentrations was discarded to allow for the concentration levels to stabilize.

In order to complete a data point for volumetric calculation, a low concentration (initial baseline) was sampled, followed by a high concentration, and then concluded the point with an additional concentration (final baseline) to confirm the baseline. As shown below, the difference in CO_2 concentration is directly proportional to the volumetric flowrate.

A volumetric balance on the mixing of a stream of carbon dioxide with the flue gas gives:

$$(9)\quad \dot{V}_0 C_0 + \dot{V}_1 C_1 = \dot{V}_2 C_2$$

where C is the concentration of CO_2, V is the total volumetric flow rate at standard conditions of a gas stream and subscripts 0, 1, and 2 denote baseline flue gas stream, injected CO2 gas stream, and mixed gas stream respectively. Note that:

$$(10)\quad \dot{V}_0 + \dot{V}_1 = \dot{V}_2$$

All quantities are known through measurement except for V_1, which can be solved for.

$$(11)\quad \dot{V}_0 = \frac{C_1 - C_2}{C_2 - C_0}\dot{V}_1$$

On the non-combustion side, the data points were then averaged to determine the cold airflow flow rate. After knowing the two flowrates and three temperatures, the fourth temperature ($T_{h,i}$) can be solved by performing an energy balance.

3.2.6. Measuring Fuel Consumption

It is also of use to know how much fuel is being consumed to produce a given amount of heat. To this effect, a known amount of fuel is used for each test and the time required to expend this fuel is noted at the end of the test.

3.3. Assumptions

In order to effectively manage the calculations required for the quantification of this project, it is necessary to make a certain number of assumptions. These are addressed below.

3.3.1. Average Fuel Homogeneity

While each load of corn may appear to be homogeneous, corn from different locations, even different parts of a field can be significantly different. Because it is not practical to test every piece of fuel is burned, the composition of the corn will be assumed to be consistent with results provided in Appendix A.

3.3.2. Thermodynamic Properties of Air

In order to do certain volumetric flow calculations, it will be necessary to know the density as well as the specific heat of the exhaust gas. This is not a difficult task when it concerns the room air, since there are already property tables for air. But there is not readily available table that describes the mix of gases that comprise the exhaust. Since air is used as the source of oxygen for combustion, the exhaust gas has a similar composition profile, consisting of 80% N_2, 12% O_2, 8% CO_2, and trace amounts of other gases. Taking advantage of the similarities, the data for density or specific heat of air were used when doing calculations requiring the density or specific heat of the exhaust gases. These correlations can be seen in Appendix F.

3.3.3. Turbulent Mixing

In order to assume that the gas composition being sampled is representative of the rest of the flow stream, it is useful to assume that the gases passing by the gas probe are being turbulently mixed so that there is no localized region of high concentrations. The standard method of measuring turbulence for the sake of mixing is the Reynolds number (Re_D).

$$(12)\ \mathrm{Re}_D \equiv \frac{\rho u_m D}{\mu}$$

Where

D : Diameter of the duct
ρ : Density of the fluid
u_m : Mean Velocity of the fluid
μ : Dynamic Viscosity

Indeed, the velocities existing in these systems place the Reynolds number well into the thousands. Also, because of the amount of corners and cross-sectional areas that the gases encounter, it is safe to assume that the gases being sampled are adequately mixed.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Experiment Design

The experiments were performed in a manner that would provide useful data related to consumers and regulatory bodies. These involve the description of the gas composition of the exhaust as well as the effectiveness of the heat exchanger in moving the heat from the fire into the immediate environment.

4.2. Emissions

Since combustion is a chemical reaction that liberates energy, there will be substances left over known as the products of reaction. Some of these are well known like carbon monoxide and carbon dioxide. In order to study the quality of a combustion process, it is useful to know what the components of the exhaust stream are.

As the corn is burned, most of the fuel is converted into gases, hydrocarbons, and various oxides. Since the furnaces use air as its source of oxygen, most of the exhaust gas consists of nitrogen (N_2). The next most abundant are oxygen (O_2) and carbon dioxide (CO_2), with minute amounts of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrocarbons (H_xC_x) and water vapor (H_2O).

4.2.1. Flue Gas Composition

4.2.1.1. LDJ 620-10 Stove

The following table provides a summary of tests conducted on the LDJ 620-10 at the 100,000 BTU/hr setting. Each test was run under the same operational settings, with weather and variances in fuel being the uncontrollable variables. A 95% confidence interval is provided to demonstrate the stability of the system. The N_2 column is a balance value as N_2 was not able to be measured.

Table 2: Summary of Flue Gas Composition for LDJ 620-10 Stove

		CO ppm	SO_2 ppm	NO_2 ppm	NO ppm	C_xH_x %	CO_2 %	O_2 %	N_2 %
Test A	mean	17.4	14.4	9.4	533.4	0.0	9.7	9.2	81.1
	±	0.6	0.3	0.1	2.0	0.0	0.0	0.0	
Test B	mean	729.0	3.7	1.2	156.9	0.0	5.9	15.7	78.4
	±	11.5	0.3	0.1	1.1	0.0	0.2	0.1	
Test C	mean	81.4	31.3	0.0	490.2	0.0	8.0	12.7	79.3
	±	4.7	0.3	0.0	2.1	0.0	0.0	0.0	
Test D	mean	31.8	0.0	15.0	471.8	0.0	8.2	12.4	79.4
	±	22.7	0.2	1.3	76.8	0.0	1.2	1.6	
Test E	mean	311.8	11.0	9.0	329.8	0.0	8.3	12.7	78.9
	±	250.3	12.6	2.9	88.0	0.0	3.2	2.2	
Test F	mean	80.2	4.5	16.4	416.5	0.0	10.9	11.4	77.7
	±	4.6	0.2	0.2	3.7	0.0	0.1	0.1	
Test G	mean	45.0	0.7	13.6	394.9	0.0	8.5	12.1	79.4
	±	2.5	0.1	0.3	2.7	0.0	0.0	0.1	
Test H	mean	167.6	0.1	17.2	312.7	0.0	7.9	12.1	80.0
	±	5.8	0.0	0.2	1.5	0.0	0.0	0.0	
Average		183.0	8.2	10.2	388.3	0.0	8.4	12.3	79.3

These results demonstrate that the LDJ 620-10 is fuel efficient, as reflected by the relatively low CO emissions. On many occasions, it was not uncommon for carbon monoxide to remain in the low double-digit ppm's. Occasionally, due to poor burn conditions such as damp fuel, or poor fuel circulation in the burn put, the CO level will spike. The LANCOM II has a peak

CO detection limit of 2000 ppm, so the amount of skewing is somewhat minimized, but the variability of the flame produced certain spikes that reached the maximum of the analyzer. The 95% confidence interval aids in spotting tests where there was a large amount of variability in the test. It is evident that tests B and E have substantially higher CO emissions than the other tests. It is not precisely known what caused these higher emissions. What is known is that test E was plagued with abnormally high incidents of auger binding, where the corn will cause the metering augers to become stuck, depriving the burn pot of fresh fuel and causing the fuel to be consumed without replacement.. The poorer combustion environment could arise from combustion air not reaching the zone where corn is actually burning, resulting in higher CO emissions. Test B is consistently high and it is supposed that this was due to poor quality fuel due to either much higher starch content or inadequate drying.

Despite the low CO concentrations, it is difficult to ignore the high outputs of NO_x. NO readings exceeded 500ppm, far above federal regulations, discussed below. Because of the higher combustion temperature, the generation of NO is quite prominent. This quality may be flagged if this type of appliance is ever scrutinized by an organization such as the EPA.

4.2.1.2. Country Flame

The following table is similar to the previous table for the LDJ 620-10 and provides a summary of tests conducted on the Country Flame Harvester. Each test result consists of a mean and 95% confidence interval. The tests were conducted on the 4th intensity setting (out of 5), estimated at 30,000 BTU/hr.

Table 3: Summary of Compositions (Country Flame Harvester)

Summary of Compositions (Country Flame Harvester)

		CO	SO_2	NO_2	NO	C_xH_x	CO_2	O_2	N_2
		ppm	ppm	ppm	ppm	%	%	%	%
Test A	mean	638.4	30.9	0.0	148.1	0.0	4.3	16.4	79.3
	±	12.8	0.4	0.0	1.1	0.0	0.0	0.0	
Test B	mean	494.3	0.1	7.0	122.4	0.0	3.8	16.7	79.5
	±	3.6	0.0	0.1	0.6	0.0	0.0	0.0	
Test C	mean	447.3	0.0	10.9	105.2	0.0	3.2	17.5	79.3
	±	5.3	0.0	0.2	1.1	0.0	0.0	0.0	
Test D	mean	454.5	0.0	11.0	110.2	0.0	3.7	16.9	79.4
	±	4.5	0.0	0.1	0.8	0.0	0.0	0.0	
Average		**508.6**	**7.7**	**7.2**	**121.4**	**0.0**	**3.8**	**16.9**	**79.4**

Due to the mixing of the fuel as it burns, the Harvester (CFH) is able to avoid hot and cool spots and burns more uniformly. Unfortunately, despite its more uniform burn, it also produces a slightly more inefficient combustion. The lower concentration of CO_2 and higher CO levels indicates that the Harvester utilizes fuel less efficiently than LDJ 620-10. Carbon monoxide levels are at least twice as high, and it could be argued that they are actually 4 or 5 times as much. On the other hand, carbon dioxide levels are only half as much as seen in the LDJ 620-10. It is unlikely this is caused by less combustion air being available, because the exhaust products in the Harvester have a higher concentration of oxygen (25% more) than the 620-10. The poorer combustion is likely due to the low amount of "thermal mass" available in the burn pot at any given time. The CFH deposits a small amount of corn into the burn pot, estimated at 1 ounce twice per minute. This corn is ignited by corn already burning in the burn pot, however unless operating at or near its maximum output, the CFH does not output enough corn to supply the flame at the rate that the fuel is being consumed. This results in fresh fuel often being barely ignited in time before the current fuel is expended. Because of this process, the carbon monoxide emissions are more than double of the LDJ furnace, even though there as about twice as much excess air being delivered.

Alternately, the CFH operates about half as hot as the LDJ. The lower combustion temperature does not create an environment that produces as much NO_x emissions, making this stove a possibly better environmental choice.

4.2.2. Comparison to Regulated Sources

To demonstrate the effectiveness of these appliances and how far technology could be pushed, it would be useful to compare this technology to something of the same nature. Although they may be larger, coal-fire power plants operate on the same principle as these smaller appliances. However, unlike small solid-fuel burners, the EPA regulates how much pollution power plants can release.

Two closely watched products of combustion are sulfur dioxide (SO_2) and nitrogen oxides (NO_x), both causes of acid rain and other undesirable atmospheric effects. For typical 15% excess air, power plant production of SO_2 is limited to less than 250 ppm and NO_x, less than 100-150 ppm (EPA 40CFR60). This is the generally the same range of excess air that these solid-fuel appliances operate. The results of sampling the test equipment is summarized in the following table

Table 4: Emission Limits

	SO_2	NO_x
Power Plant Limits	<250	<100-150
Country Flame Stove	<30	100-150
LDJ 620-10 Furnace	<30	150-500

As shown, the Country Flame performs within the prescribed limits. However, the LDJ's NO_x production is significantly higher. This is likely caused by a much higher flame temperature (estimated 1000 K hotter) as well as the method LDJ uses to supply air to the flame. The LDJ furnace blows air across the flame as opposed to up through it, such the Country Flame model does.

4.2.3. Combustion Efficiency

As referred to in this text, combustion efficiency is a term that describes the amount of actual energy extracted from combustion relative to maximum amount of energy available from carbon conversion.

Carbon conversion efficiency is a function of consumed carbon relative to total available carbon. Carbon left unburned is still considered a usable fuel source. In order to determine how much carbon there was to begin with and what the mole ratios of the products are, a reaction balance must be done.

$$[\text{Fuel}] + \alpha[\text{Air}] = \beta[\text{Products}] + \gamma[\text{Water}] + \zeta[\text{Unburned Carbon}] \tag{13}$$

For this balance, each of the coefficients, α, β, γ and ζ must be solved to match the moles of carbon, hydrogen, oxygen and nitrogen on each side of the reaction. An account of the elements in each component must be made on each side of the reaction (=) with the corresponding coefficients.

Fuel: carbon, hydrogen, oxygen, and nitrogen

Air: oxygen and nitrogen

Products: carbon, oxygen, and nitrogen

Water: hydrogen and oxygen

Unburned carbon: carbon

The coefficients γ and ζ can be solved by virtue of their accounting for a single unbalanced element: hydrogen and carbon, respectively. Since the air used in combustion and the exhaust gases contain similar constituents (oxygen, carbon, nitrogen), a simultaneous solution must be employed to solve α and β while keeping the other variables balanced. An in-depth discussion of this solution method is demonstrated in Appendix E.

As stated above, most of the products of combustion result in a gaseous mixture that is vented into the atmosphere. However, not all of the fuel that is fed into the burn pot is converted into gases. Some of the fuel remains after the combustion reaction takes place. These remnants are char, soot and ash – known as bottom-ash. After combustion, the remnants were collected from the ash pan and weighed. For every 100 lbs of corn burned, there are 2 pounds of bottom ash remaining. This means that the other 98% of the fuel gets converted into constituents of the exhaust gas.

The bottom ash was the simpler of the two to perform conversion calculations upon. After being collected from individual tests and it was then allowed to oxide in a high temperature oven at 600 C. After oxidization, the crucible contained about half the weight of the original sample, indicating about 50% of the bottom ash is still usable carbon and the remainder (1% of the total fuel input) comprises unusable mineral deposits. Typical constituents of this ash are reported in Appendix A.

After determining the quantity of carbon left in the ash, the carbon conversion efficiency can be calculated. The carbon conversion efficiency for the combustion reaction is found by comparing the mass of the carbon left in the ashes to the total mass contained within the fuel. The presence of unburned carbon in the ash indicates inefficiencies leading to lower carbon conversion.

$$(14)\ \eta_{carbon} = \frac{m_{carbon_{fuel}} - m_{carbon_{ash}}}{m_{carbon_{fuel}}}$$

As shown in Appendix E, the carbon conversion efficiency is very high for these appliances. The amount of carbon left in the form of unburned carbon residue is less than 1% of the amount of carbon originally in the fuel. This yields carbon conversion efficiencies between 98 and 99%. This will be used to describe the combustion (net) efficiency covered in a later section.

4.3. Heat Exchanger

4.3.1. Performance

Both appliances utilize a simple cross-flow heat exchanger system to move the heat from the flame to the room air. This is accomplished by a series of parallel tubes that the cold room air is channeled through while the hot combustion gases pass around the tubes. The effectiveness is determined by amount of energy the heat exchanger can transfer to the cold fluid (room air) relative to the ideal conditions. Typically this is done through a high surface-area device, and true enough, both of the tested stoves have a dozen or more tubes that are used to transfer heat.

However, due to the nature of the fuel, the heat exchanger can not begin to approach ideal. This is due to the particulate and hydrocarbons entrained in the exhaust flow. While there is not a high concentration of hydrocarbons/tars being exhausted, if the gas was to cool too quickly within the heat exchanger, a small amount of tar would accumulate on the tubes, hindering its ability to transfer heat. This, in turn, would cause a buildup of the particulate matter as it stuck to the collected tars. Because of this, the exchangers are purposefully built slightly less efficient to keep the tars in vapor phase until they can be vented outdoors. In addition, many appliances are equipped with a device that effectively scrapes the heat exchanger tubes to keep accumulation to a minimum.

4.3.1.1. LDJ 620-10 Furnace

Because of its larger size and heavier construction, the LDJ 620-10 can produce high burn temperatures. As demonstrated in Appendix F, calculations of the temperature of the gases coming off of the burn pot are estimated to be around 2,000 K at the 100,000 BTU/hr setting and are produced in the range of 25-30 SCFM (found from CO_2 volumetric studies explained previously).

Because of this high temperature, the 620-10 can take advantage of a large temperature differential across the heat exchanger. It is because of the high difference in temperature and large cold airflow (approx 200 SCFM), that the heat transfer from the hot exhaust gases to the room air can be as high as 6 kW, heating the room air by 50 K. The maximum heat transfer obtainable between room temperature and 2000K is just over 5.8 kW. However, keep in mind that this value does not directly correlate to the effectiveness of the heat exchanger. This will be discussed in the section following the overall efficiency. The reason for this organization is that complexity of calculating the heat exchanger effectiveness is beyond the scope of this project. Analyzing radiative view factors, boundary layers, turbulence, and conduction through complex geometries would be another project in and of itself. Instead, since the net efficiency is found as a product of the carbon conversion and heat exchanger efficiency, the performance of the heat exchanger can be back-calculated from the net efficiency.

4.3.1.2. Country Flame Harvester (CFH) Stove

Because of the smaller size of the CFH, a much cooler flame is produced. Hot gas temperatures above 1000K are atypical. Also, the heat exchanger stretches over 16" wide over a small (6") fire pot. Because of this, the outermost portion of the heat exchanger is not exposed to as high a temperatures as the central portion. Temperatures can be as much as 5 degrees (C) cooler towards the outside than the center. As a result, the Country Flame Harvester has an output temperature near 900K with a total heat transfer of 1.2 kW. A derivation of this value can be found in Appendix D.

4.3.2. Combustion deposits

When corn is ashed, a large portion (70%+) remains as K_2O and P_2O_5 (see Appendix A) Because of the high potassium and phosphorus concentrations of the corn, there is sticky soot that is produced as a result of combustion. As mentioned previously, tars and particulate will collect on the HX tubes regardless of how hot the exhaust is. This problem is compounded by the fine, sticky ash that accompanies the exhaust. To counteract this effect, a scraper bar is often found protruding from the side of the heat exchanger. In order to keep the tubes operating near full capacity, the scraper bar must be used about once a day. Less frequently will result in lower output temperature.

4.4. Overall Efficiency

Overall efficiency is also known as net or combustion efficiency. This is an end value describing the amount of usable heat extracted from the fuel when compared to the heat input supplied to the burning device. When considering net efficiency for this scenario, the heat output is only in the form of heated room air. To determine the net efficiency, the change in energy change associated with the change in temperature of the heated room air is divided by the chemical energy of combustion of the fuel.

$$\eta_{net} = \frac{\Delta E_{air}}{Fuel\ Energy} = \frac{\dot{m}_{air} c_{p,air} \Delta T_{cold}}{\dot{m}_{fuel} E_{fuel}} \quad (15)$$

Table 5 depicts the performance of the two tested appliances. The heat output is the calculated values obtained from the previous section. The fuel input column is a function of the caloric value of the fuel multiplied by the feed rate of the stove or furnace. Finally, the net efficiency is the output divided by the input.

Table 5: System Efficiencies

	Fuel Input BTU/hr	Heat Output BTU/hr	Net Efficiency
County Flame	30,000	4,000	13%
LDJ	100,000	20,000	20%

As depicted, the net efficiencies are not very large numbers. The amount of heat that escapes from the system is quite significant and will be explored further in the following section.

4.5. Heat Exchanger Efficiency

Heat exchanger analysis is a complicated component of any research and can be a daunting task in itself. Heat exchangers are subject to conduction, convection and radiation effects; and each of these is a separate, often complicated, calculation in itself. Fortunately, since burning applications are primarily driven by combustion and heat exchanger effects, the effective heat exchanger efficiency can be back-calculated from the previous two efficiencies. In other words, overall or net efficiency is the product of the efficiencies of all of the various components and subsystems of the whole system. In these appliances, the only components of significance are the combustion process and the heat exchanger effectiveness. The product of these two will produce the net efficiency.

$$(16)\ \eta_{net} = \eta_{HX} \times \eta_{combustion}$$

Since net efficiency is a product of the combustion efficiency and the heat exchanger efficiency, the net efficiency can be divided by the combustion efficiency to obtain the heat exchanger efficiency.

In order to find the combustion efficiency, the lost energy from incomplete reactions must be identified. This can be found by looking at the energy released during combustion process, also known as the heat of reaction (H_R), of the carbon-bearing products and comparing it to the chemical energy available within the fuel when fully consumed.

$$(17)\ \eta_{combustion} = \left[H_{R_{fuel}} - \frac{m_{carbon}}{m_{fuel}} H_{R_{carbon}} + \frac{m_{CO}}{m_{fuel}} H_{R_{CO}} \right] \frac{1}{H_{R_{fuel}}}$$

As shown in the conclusion of Appendix E, the combustion efficiency (η_{carbon}) is very high – between 98 and 99%, this means that the heat exchanger efficiency is nearly the same value as the system efficiency – η_{HX} = 20% for the furnace and η_{HX} = 13% for the stove.

	$\eta_{combustion}$		η_{HX}		η_{net}
Country Flame Harvester :	98.6%	x	13.2%	=	13.0%
LDJ 620-10 :	98.7%	x	20.3%	=	20.0%

These numbers are noticeably low for a heat exchanging product. This is due to various factors, most of them related to under-engineering – such as thick-walled heat exchanger pipes and poorly circulated hot-fluid media. With some redesign, these stoves and furnaces have great potential to reach a much higher net efficiency. Any increase in heat exchanger efficiency would be realized quickly since the combustion process produces such high efficiencies.

4.6. Economic Analysis

Ultimately, the bottom line is operating cost. If the new technology is not going to save users any money or make life more convenient, many people will not give it a second thought. To illustrate how the cost corn burning actually falls into the spectrum of heating options, Table 6 has been provided.

Table 6: Fuel Price Table

Fuel Type	BTU value per unit		Units required for MMBTU	Fuel price per unit	Total cost to produce MMBTU	Average Efficiency	Total Cost $/MMBTU
Dry Shelled Corn	8,000	per pound	125.0	$0.027	$3.35	90	$3.72
(as received)	7,500	per pound	133.3	$0.089	$11.90	80	$14.88
Wood Pellets	8,500	per lb	117.6	$0.075	$8.82	80	$11.03
Fuel Oil	139,000	per gal	7.2	$1.400	$10.07	80	$12.59
Natural Gas	1,000	per ft^3	1000.0	$0.013	$12.50	95	$13.16
LP Gas	92,000	per gal	10.9	$1.250	$13.59	90	$15.10
Electricity	3,400	per kWH	294.1	$0.080	$23.53	100	$23.53

This table has been compiled with the most recent data available from the US Dept. of Energy [6] regarding standard utilities and a compilation of other sources to fill in the rest. The first column described the heating fuel and as the table is read to the opposite end, the prices can be compared to establish how much it costs to heat with that particular fuel. Natural gas has been marked since it is the heating fuel most familiar to most people.

The first two rows comprise the effective cost of burning corn for heat. The topmost row is an ideal case. This is the cost most often publicized by dealers to emphasize the cost advantage of using corn. The rated heating value for this supply of corn is 8,000 BTU/lb, which is not unreasonable if dried down to 13-14% moisture. This number is not up for dispute. The number that is most overlooked is the price per unit. Current market price for corn at local Iowa Co-ops is about $1.40 per bushel. However, many Co-ops have stipulations about the minimum amount that must be purchased and what kind of container or vehicle that they can load with their corn. This can present obstacles to who will be able to effectively purchase corn at that price. Also, the cleanliness of the corn can present issues, as most corn burning appliance require that the corn be relatively clean with a low abundance of fines and other particulate.

The other option is to buy corn that has been pre-bagged and can be found in farm-and-fleet type venues. However, this corn can be substantially higher priced. The price paid for the fuel used in this research project was purchased at $4.80/bushel. This price is displayed as the 2nd row of the table, which displays this project's experimental data – "as received." Since bagged corn is almost 3 times more expensive and experimental data places efficiencies about

10% less than advertised values, the effective cost of heating with corn jumped fourfold, placing the cost of heating with corn more than the cost of heating with natural gas.

5. CONCLUSIONS

As a general summary of issues that can be addressed by multiple options, there are a few concerns that appear to be reoccurring.

The smaller stoves suffer from sometimes inadequate amounts of burnable material in their burn pot. This is caused either by a poor feed rate or by an over abundance of clinkers, or sometimes both. Dealing with clinkers is a significantly larger problem for stoves than for furnaces and as of yet, there is no clear winner between grinding them up or allowing them to collect until the stove is cooled off. In one way, this means that the stoves that do have methods for dealing with clinker can be run for longer periods of time than those without. But at the same time, the device that eliminates clinker also eliminates a small amount of corn. When disposing of the ash from the stove, it is not uncommon to see numerous flecks of yellow from kernels that had been ground up. This results in a small, but lower, fuel utilization efficiency. But one large benefit of a stove, is that its placement is much more versatile than a furnace. The environment with a stove is under positive pressure, allowing it to forcefully push exhaust out of a short exhaust pipe. This means that the stove can be vented out of the side of a wall using less than 10' of pipe. Furnaces do not always get this luxury.

Because of their higher fuel consumption, the small scale issues that plague the stoves are not as evident or completely non-existent. One major issue that would make using corn furnaces more convenient is the matter of exhaust. The LDJ 620-10 uses a natural draft to produce the right pressure conditions within the burn zone. But in order to produce this draft, the chimney must clear the roof of the building. This cannot be done through the exhaust piping of a traditional gas furnace, as furnaces need wide exhaust stacks. So a whole new chimney must be installed. This can be both tedious and expensive. A direct vent system would make installing a furnace much more user-friendly.

But more of an issue than the current installation and operating conditions of stoves and furnaces is what lies in their future. There are at least four issues that threaten their advancement and proliferation.

- Cost Effectiveness

As indicated previously, buying a corn burning appliance is not a cheap investment, but the prices are not unbearably different than the cost of a natural gas furnace which range in prices from $3000 to $4000 after installation. What makes corn burning attractive is the fuel cost. From an ideal standpoint, corn is about ¼ the cost of natural gas when used for heating. But in order to keep this cost advantage, there needs to be the means for consumers to effectively obtain and transport corn at a low price. This is typically not an issue for farmers and many others in rural communities, but if corn burning technology is ever to appeal to the urban environment, there will need to be a way to buy inexpensive corn.

- Usability

Not addressed in the actual research project was the subject of the usability of these appliances. Accompanied with installing and turning it on, there is the matter of supplying the stove or furnace with fuel and then disposing of the ash that accumulates as well as the seasonal cleaning. Depending on the model, one could expect to burn through more corn than one would think in order to produce a substantial amount of heat. For example, running at setting 4 (out of 5), the Country Flame Harvester uses approximately 40-50 pounds of corn in 24 hours of operation. This would mean that if used during the 16 waking hours of the day, the expected corn usage could easily be 200 lbs a week. But even this amount can pale in the amount of corn a furnace can use. The LDJ 620-10 has a variable heat output that is initially set at 100,000 BTU/hr. This setting causes the furnace to auger in over 12 lbs per hour in order to satisfy its required heat output. Granted, it is unlikely that the furnace will be running constantly, but during the winter, 60% operation isn't unreasonable. Even this level of operation will consume half a ton of corn per week. Despite its 14 bushel hopper, this means that refills will have to occur more often than once a week. This is a significantly more involved task than turning on the furnace or plugging in an electric heater.

A less involved task is disposing of the ash that remains after combustion. Since roughly 2% of the fuel weight remains after combustion as ash, the ash pans can fill quickly. However, the ash pans are typically sized so that the task of emptying the ash pan can be relegated to once every other day. Even so, it becomes apparent that owning and operating a corn stove is a task that presents formidable chores in and of itself. Perhaps a more innovative way of bringing corn into the house or a better way of disposing the ash would be in order to make the sometimes burdensome task of tending to your furnace a less daunting activity.

- Innovation

As these devices become more popular from oil price hikes or other reasons, designers will find better ways to hook more customers or just to make their products operate better. This will likely cause more people to seriously take a look at these appliances and whether it would be worth while to own a stove either as a compliment to their existing system or as a complete replacement.

- Practicality

This aspect is partially tied to usability. Unless you have a truck at your disposal, transporting the amount of corn needed for an entire winter north of I-80 is quite an effort. Bags provide a more convenient method of purchasing and moving corn, but bagged corn is typically 2-4 times more expensive than bulk corn, but bulk corn is not exactly something that transports well in a minivan. In order to encourage corn heat and at the same time make it a viable prospect, some communities are experimenting with a local service that delivers corn door to door for a reasonable fee. This method could potentially be extended into widespread use, but the logistics of using large amounts of corn is not an issue that can easily be ignored.

It could be argued that these four points are not relevant to a scientific report, but it is difficult to talk about the operating characteristics of these appliances without addressing the reasons people would be interested in using this equipment in the first place. Given that the users are aware of the level of involvement and willing to take a closer look at what makes one stove better than another, then they should continue in seeking out the best option for what they are looking for.

After running tests on these appliances, it is readily evident that they are more efficient than a fireplace to heat a room. For one, they are designed with the notion of delivering forced heat in mind. Fireplaces are primarily designed for display purposes and allow most of their heat to escape through the chimney. Only about 10-15% of the heat from a fireplace is transferred into the room. So now for every dollar that is spent on fuel energy, about 80 cents worth is utilized. There are certain advances that could be made in one model or another, but overall, there is not a firm set of recommendations to make to manufacturers as a whole. As the designers and builders of these appliances get more experience, better designs will ultimately arise.

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APPENDIX A - ULTIMATE ANALYSIS OF IOWA CORN

as provided by:

Hazen Research, Inc.

Golden, CO 80403

Test date: April 25, 2002

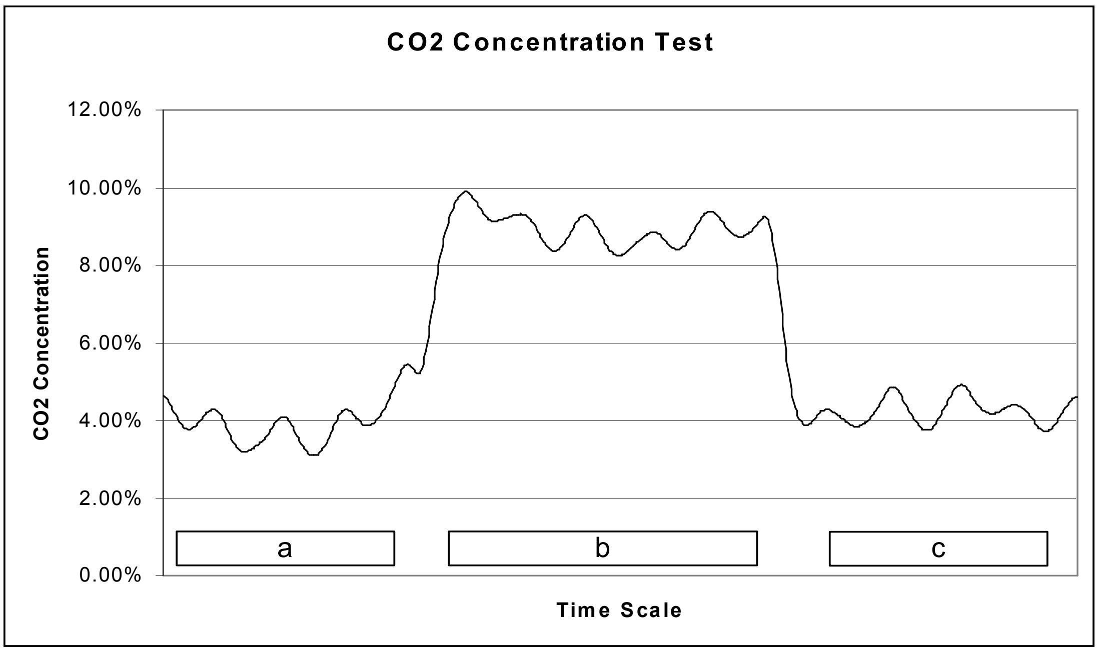
Reporting Basis		As Rec'd	Dry	Air Dry
Proximate (%)				
	Moisture	16.50	0.00	5.22
	Ash	1.01	1.21	1.15
	Volatile	71.55	85.68	81.21
	Fixed C	10.94	13.11	12.42
	Total	100.00	100.00	100.00
Sulfur		0.10	0.12	0.11
Btu/lb (HHV)		6689	8011	7592
MMF Btu/lb		6762	8116	
MAF Btu/lb			8109	
Air Dry Loss (%)		11.90		
Ultimate (%)				
	Moisture	16.50	0.00	5.22
	Carbon	40.70	48.74	46.20
	Hydrogen	5.08	6.08	5.77
	Nitrogen	1.09	1.31	1.24
	Sulfur	0.10	0.12	0.11
	Ash	1.01	1.21	1.15
	Oxygen	35.52	42.54	40.31
	Total	100.00	100.00	100.00
	Chlorine	0.03	0.03	0.03

Elemental Analysis of Ash (calcined at 600C)

SIO2	11.07
AL2O3	2.59
TIO2	0.37
FE2O3	0.97
CAO	1.65
MGO	11.3
NA2O	0.46
K2O	28.6
P2O5	41.39
SO3	0.73
CL	0.01
CO2	0.72
Total	99.86

APPENDIX B - SAMPLE FLOWRATE CALCULATION

To calculate volumetric flowrate, the CO_2 concentration of the gas stream was initially measured to obtain a baseline. After a stable baseline had been established, CO_2 was vented at a known rate into the line upstream of the analyzer. Data was collected during the CO_2 venting as well as after the CO_2 had been turned off in order to reconfirm the baseline.



In the preceding figure, section (a) gives the initial baseline period, section (b) denotes the period of added CO_2, and section (c) is the used to reconfirm the baseline.

When analyzing the data, all of the data points within the allocated time frame are averaged together. For example, the figure indicates the following data:

$$CO_{2,a} \approx 3.8\%$$
$$CO_{2,b} \approx 8.9\%$$
$$CO_{2,c} \approx 4.4\%$$

To obtain the baseline (low), the preceding and following values are averaged. The high (or mixed) value is just the value of the middle (b) data set.

$$\%CO_{2,0} = \frac{\left(CO_{2,a} + CO_{2,b}\right)}{2} = 4.1\%$$
$$\%CO_{2,2} = 8.9\%$$

As discussed in section 3.2.5 – Determining Volumetric Flow Rates, the low and high value equations can be written as relationships between the existing amount of CO_2 and the added value of CO_2.

$$\dot{V}_0 = \frac{C_1 - C_2}{C_2 - C_0}\dot{V}_1$$

where C is the concentration of CO_2, V is the total volumetric flow rate at standard conditions of a gas stream and subscripts 0, 1, and 2 denote baseline flue gas stream, injected CO2 gas stream, and mixed gas stream respectively. Note that:

$$\dot{V}_0 + \dot{V}_1 = \dot{V}_2$$

$$C_1 = 100\%$$

In order to complete this solution, the amount of CO_2 added must be known. The recorded value was observed from a flowmeter calibrated for air. A coefficient must be applied to compensate for differences in density.

$$\Delta\mathrm{CO}_2 = 40\,SCFH_{\mathrm{air}} \times 0.654 \left.\frac{\mathrm{CO}_2}{\mathrm{air}}\right|_{T=250K}$$
$$= 26.2\,SCFH_{\mathrm{CO}_2}$$

Solving the relationship equations, the value for V_0 can be found.

$$V_0 = 500\,SCFH$$
$$= 3.9 \times 10^{-3} \frac{m^3}{s}$$

APPENDIX C - FUEL INPUT CALCULATION

To determine how the manufacturer's claims and the fuel metering correlated, a fuel input calculation could be done. This method calculates the energy density of the corn based on the amount of time a known amount of corn will supply heat, based on the metering speed of the furnace.

Furnace set point: 100,000 BTU

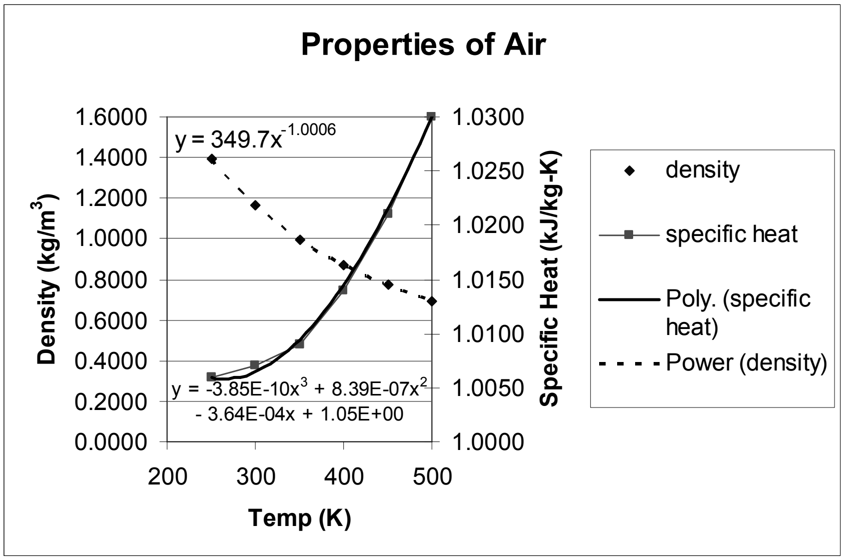
Amount of fuel consumed: 300 lb

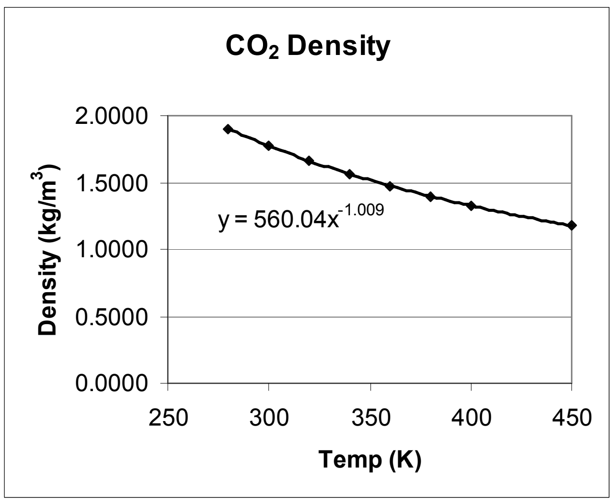
Burn duration: 25 hr

$$\frac{100{,}000\,\frac{BTU}{hr}}{\left(\frac{300\,lb}{24\,hr}\right)} = 8000\,\frac{BTU}{lb}$$

Manufacturer suggested heating value for corn is confirmed at 8000 BTU/hr

APPENDIX D - GAS DATA





APPENDIX E - CARBON CONVERSION EFFICIENCY

Carbon conversion analysis is a combination of the reaction balance of the gaseous materials as well as determining how much remains behind in the ashes and soot.

The more straightforward of the two is the analysis of ashes and soot. This involves the use collection of the remains of a fire and determining the carbon content of this "bottom ash." The bottom ash is collected and then further oxidized in an ashing oven at a temperature around 900K to drive off any remaining carbon.

For the smaller stove, approximately 1.8% of the fuel is left in the ash pan. Of this, about half is usable carbon. The larger furnace has slightly better utilization, leaving 1% of the fuel unused. However, not only was less left behind, what was left has a lower carbon concentration than the stove. In the end, they both have the same Ash/Fuel ratio of 0.8%-0.9%, which is expected since they are using the same corn.

Crucible	Sample	Empty (g)	Filled (g)	Dried (g)	Ashed (g)	Filler (g)	% water	% remaining	Sum (g)	Bucket (g)	Total Collected (g)	Fuel (lb)	Fuel (g)	Total Soot (g)	Total Ash (g)	Soot/ Fuel	Ash/ Fuel
3	CFH 20060210	19.63	20.88	20.85	19.99	1.25	2.8%	29%	601.0	205.4	395.6	50	22680	384.5	112.7	1.7%	0.5%
9	CFH 20060201	20.48	21.93	21.88	21.21	1.45	3.0%	52%	615.6	205.8	409.8	50	22680	397.3	207.9	1.8%	0.9%
2	CFH 20060310	20.01	22.45	22.30	21.32	2.45	6.5%	57%	674.9	205.9	469.1	50	22680	438.8	251.7	1.9%	1.1%
1	CFH 20060203	19.33	22.63	22.59	21.35	3.30	1.2%	62%	586.3	205.7	380.6	50	22680	376.1	232.3	1.7%	1.0%
																1.8%	0.89%
5	LDJ 20060310	17.19	21.33	21.09	19.89	4.14	5.7%	69%	1552.2	205.8	1346.4	300	136078	1269.9	878.1	0.9%	0.6%
7	LDJ 20060201	18.17	23.58	23.37	21.98	5.42	4.0%	73%	1164.1	205.8	958.2	200	90718	920.4	675.2	1.0%	0.7%
6	LDJ 20060222	18.96	25.81	25.57	23.95	6.85	3.6%	76%	1368.0	205.3	1162.7	300	136078	1120.4	846.9	0.8%	0.6%
4	LDJ 20060210	19.55	25.74	25.55	24.61	6.19	3.1%	84%	1684.5	205.7	1478.8	300	136078	1433.4	1208.9	1.1%	0.9%
8	LDJ 20060203	18.64	31.64	31.62	30.79	13.00	0.2%	94%	1477.6	205.8	1271.8	200	90718	1269.4	1188.3	1.4%	1.3%
																1.0%	0.84%

After the analysis on the solids is complete, the data from the emission monitors must be analyzed. Data obtained from the ultimate analysis (see Appendix A) gives the starting point for the reaction equation. The starting reaction coefficients are found using the equation:

$$\left[\text{Coeff}\right] = \frac{\left[\%\,\text{Comp}\right]}{\left[\text{Mol. wt.}\right]}$$

Reactants

	% Composition	Molecular Weight	Coefficient
C	48.74%	12.01	4.06E-02
H_2	6.08%	2.02	3.01E-02
O_2	42.54%	32	1.33E-02
N_2	1.31%	28.02	4.68E-04
Ash	1.33%		
	100.00%		

From the emission monitor, the following composition is known.

Products

	% Composition
CO_2	8.25%
CO	0.01%
NO	0.04%
O2	11.64%
N_2	77.07%
C	3.00%
	100.01%

However, knowing the contents of the products is not enough. To determine the carbon conversion efficiency, the chemical reaction equation must first be known. To determine the stoichiometric equation for a chemical reaction, the reactants and products must be known. In a combustion reaction, fuel and an oxidizer combine to form set of products. In a typical combustion situation, a hydrocarbon fuel combines with air in the environment to product a variety of gaseous products and water.

For the reaction set being investigated in this research project involves the combustion of corn in an atmospheric environment.

$$\text{Reactants} + \text{Air} \Rightarrow \text{Products} + \text{Water}$$

The chemical constituents of corn, as reported by an independent testing facility reports the makeup of corn as follows:

$$\begin{aligned} \text{Carbon } (C) &: 49\% \\ \text{Hydrogen } (H) &: 6.1\% \\ \text{Oxygen } (O) &: 43\% \\ \text{Nitrogen } (N) &: 1.3\% \\ \text{Ash} &: 1.3\% \end{aligned}$$

This is burned in the presence of air, composed primarily of oxygen and nitrogen.

$$\begin{aligned} O_2 &: 21\% \\ N_2 &: 79\% \end{aligned}$$

The exhaust gas created through this reaction was sampled by a gas analyzer and the major components of exhaust consist of the following gases, in order of abundance based on mass percent.

$$\begin{aligned} \text{Nitrogen } (N_2) &: 79\% \\ \text{Oxygen } (O_2) &: 12\text{-}16\% \\ \text{Carbon Dioxide } (CO_2) &: 4\text{-}8\% \\ \text{Carbon Monoxide } (CO) &: <0.05\% \\ \text{Nitrogen Oxides } (NO_x) &: <0.01\% \end{aligned}$$

The remainder of the stoichiometric equation is balanced by the presence of water (H_2O).

To balance the chemical equation, mole percent, not mass percent must be used. Converting mass percent to mole percent only requires knowing the molecular weight of the chemical of interest.

$$\text{mass \%} = \frac{\text{lb}}{\text{lb}_{\text{gas}}}$$

$$\text{molecular weight} = \frac{\text{lb}}{\text{lb-mol}}$$

$$\text{mole \%} = \frac{\text{lb}}{\text{lb}_{\text{gas}}} \times \left(\frac{\text{lb}}{\text{lb-mol}}\right)^{-1} = \frac{\text{lb-mol}}{\text{lb}_{\text{gas}}}$$

After this conversion is done, the formula can now be written, using the initial composition, in the traditional form.

$$\left(40\ \text{C} + 60\ \text{H} + 27\ \text{O} + 1\ \text{N}\right) \times 10^{-3} \frac{\text{lb-mol}}{\text{lb}_{\text{fuel}}} \Rightarrow \text{L}$$

However, after the products are written out, it becomes apparent that the corresponding coefficients are not equal. There maybe 40 carbons on the products side, but only 1 carbon on the reactants side. This is due to a change in mass percent caused by the additional reactants. To account for this fact, various coefficients are added to correlate the amount of products to the amount of reactant.

$$\text{Reactants} + \alpha\left(\text{Air}\right) \Rightarrow \beta\left(\text{Products}\right) + \gamma\left(\text{Water}\right) + \zeta\left(\text{Ash}\right)$$

Where α is in units of moles of air per moles fuel and so on. These factors have to be solved in order to obtain a balance.

Solving stoichiometric coefficients

Using the sample data provided before, the reaction equation can be written as follows:

$$\left[\left(40\ \text{C} + 60\ \text{H} + 27\ \text{O} + 1\ \text{N}\right) \times 10^{-3} \frac{\text{lb-mol}}{\text{lb}_{\text{fuel}}}\right] + \left[\alpha \frac{\text{lb-mol}_{\text{air}}}{\text{lb-mol}_{\text{fuel}}} \left(1\ \text{O}_2 + 3.76\ \text{N}_2\right) \frac{\text{lb-mol}}{\text{lb}_{\text{air}}}\right] \Rightarrow \text{L}$$

$$\left[\beta \frac{\text{lb-mol}_{\text{gas}}}{\text{lb-mol}_{\text{fuel}}} \left(1000\ \text{CO}_2 + 21\ \text{CO} + 5\ \text{NO} + 5000\ \text{O}_2 + 28000\ \text{N}_2\right) \times 10^{-6} \frac{\text{lb-mol}}{\text{lb}_{\text{gas}}}\right] + \left[\gamma \frac{\text{lb-mol}_{\text{H}_2\text{O}}}{\text{lb-mol}_{\text{fuel}}} \left(2\ \text{H} + \text{O}\right)\right] + \left[\zeta \frac{\text{lb-mol}_{\text{C}}}{\text{lb-mol}_{\text{fuel}}} \left(1\ \text{C}\right)\right]$$

The elements on either side of the reaction can now be summed to determine the reaction coefficients.

The first coefficient that can be solved is γ. Since hydrogen only exists in the reactants and in the water component, γ can be fixed. In this instance, $\gamma = 0.03$, creating a total of 0.06 lb-moles of hydrogen per pound of fuel on both side of the equation.

Next, due to the co-dependence upon oxygen and nitrogen, α and β must be solved simultaneously. The constraints on the equation are that total atoms of O and N must be equal on both sides of the reaction. Using a solver algorithm, it can be found that $\alpha = 0.010$ and $\beta = 1.4$, matching oxygen at 47 $\frac{\text{lb-mol}}{\text{lb}_{\text{fuel}}}$ and nitrogen at 77 $\frac{\text{lb-mol}}{\text{lb}_{\text{fuel}}}$. Lastly, the coefficient for unburned carbon, ζ, is balanced to complete the reaction equation – $\zeta = 0.5$.

This gives the final form of the reaction equation as:

$$\left[(40\ \text{C} + 60\ \text{H} + 27\ \text{O} + 1\ \text{N})\times 10^{-3}\frac{\text{lb-mol}}{\text{lb}_{\text{fuel}}}\right] + \left[0.01\frac{\text{lb-mol}_{\text{air}}}{\text{lb-mol}_{\text{fuel}}}(1\ \text{O}_2 + 3.76\ \text{N}_2)\frac{\text{lb-mol}}{\text{lb}_{\text{air}}}\right] \Rightarrow \text{L}$$

$$\left[1.4\frac{\text{lb-mol}_{\text{gas}}}{\text{lb-mol}_{\text{fuel}}}(1000\ \text{CO}_2 + 21\ \text{CO} + 5\ \text{NO} + 5000\ \text{O}_2 + 28000\ \text{N}_2)\times 10^{-6}\frac{\text{lb-mol}}{\text{lb}_{\text{gas}}}\right] + \left[0.03\frac{\text{lb-mol}_{\text{H}_2\text{O}}}{\text{lb-mol}_{\text{fuel}}}(2\ \text{H} + \text{O})\right] + \left[0.5\frac{\text{lb-mol}_{\text{C}}}{\text{lb-mol}_{\text{fuel}}}(1\ \text{C})\right]$$

Giving the final balance on each side as

$$\left.\begin{matrix} 40\ \text{C} \\ 60\ \text{H} \\ 47\ \text{O} \\ 77\ \text{N} \end{matrix}\right) \times 10^{-3}\frac{\text{lb-mol}}{\text{lb}_{\text{fuel}}}$$

After the reaction equation is solved, the combustion energies can be solved. Specifically, calculating how much energy is left unconverted after the combustion process is finished. These calculations will be used to solve for the carbon conversion efficiency.

Products of incomplete combustion, carbon monoxide, hydrogen and unburned carbon, contribute to combustion inefficiencies. To solve combustion efficiency, one must know the amount of chemical energy leaving the system.

$$\eta_{combustion} = \frac{E_{fuel} - E_{incomplete\ products}}{E_{fuel}}$$

For corn, the fuel energy is also known as the caloric value or the heating content. The heating content for corn was obtained from an independent lab. The heating value for dry corn is 8000 Btu/lb. Under optimal conditions, all carbon will convert to carbon dioxide and hydrogen into water. Hydrogen is easily consumed, but carbon has higher activation energies.

In this system, carbon monoxide and unburned carbon contain additional chemical energy that is not liberated for use in the thermal system. Carbon monoxide's lost energy is equivalent to the change in the enthalpy of formation between carbon dioxide and carbon dioxide. The number of moles of carbon in carbon monoxide can be directly correlated to a lost number of moles of carbon dioxide.

In the previous example, the carbon atoms in the gas stream are split at a ratio of 1000:21. This leaves 3e-5 moles of carbon per pound of fuel. The enthalpy of formation for CO is 47,500 Btu/lb-mol. Multiplying together, CO releases 1.4 Btu/lb_{fuel}.

$$2.92\times10^{-5}\,\frac{lb-mol}{lb_{fuel}}\cdot 47540\,\frac{Btu}{lb-mol}\bigg|_{CO}=1.386\,\frac{Btu}{lb_{fuel}}$$

However, CO2 has an enthalpy of formation of 170000 Btu/lb-mol. If the same number of carbon atoms were converted to CO_2 instead, more energy would be released.

$$2.92\times10^{-5}\,\frac{lb-mol}{lb_{fuel}}\cdot 169300\,\frac{Btu}{lb-mol}\bigg|_{CO_2}=4.937\,\frac{Btu}{lb_{fuel}}$$

The difference between the enthalpy of formation for CO and CO_2 is one source of lost chemical energy.

$$(4.937-1.386)\frac{Btu}{lb_{fuel}}=3.551\frac{Btu}{lb_{fuel}}$$

The other evidence of significant reduction in carbon conversion efficiency is leftover carbon in the ashes of the fuel. The average amount of unburned carbon left after combustion was 0.75% by weight. The lost energy due to unburned carbon can be calculated in one of two ways – using the higher heating value (HHV) or calculating the lost enthalpy from not converting carbon to carbon dioxide.

Using the HHV method

$$0.0075\frac{lb_C}{lb_{fuel}}\cdot 14100\frac{Btu}{lb_C}=106\frac{Btu}{lb_{fuel}}$$

Using the enthalpy of reaction method

$$\left[0.0075\frac{lb_C}{lb_{fuel}}\cdot\left(12.01\frac{lb_C}{lb-mol}\right)^{-1}\right]\cdot 169300\frac{Btu}{lb-mol}=106\frac{Btu}{lb_{fuel}}$$

When considered over the given heating value of corn, 8000 Btu/lb, the lost chemical energy is a small contribution. Using the equation stated before for combustion efficiency:

$$\eta = \frac{(8000-106)}{8000}\frac{Btu}{lb_{fuel}} = 98.6\%$$

And since the system efficiency has been shown to be such a low number, the culprit must lie in the heat exchanging system.

Following is a table depicting the results of this solution:

Fuel

		C	H	O	N	Ash
%mass	lb / lb_fuel	48.74%	6.08%	42.54%	1.31%	1.33%
Mol wt.	lb / lb_mol	12.01	1.01	16.00	14.00	
Coeff.	lb_mol / lb_fuel	40.6E-3	60.3E-3	26.6E-3	935.7E-6	

Air

		O2	N2
Coeff.	lb_mol / lb_air	1	3.76

Products

		CO2	CO	NO	O2	N2		C
%mass	lb / lb_gas	4.30%	0.06%	0.01%	16.42%	79.21%		100.00%
Mol wt.	lb / lb_mol	44.01	28.01	30.01	32.00	28.01		12.01
Coeff.	lb_mol / lb_gas	977.1E-6	21.4E-6	4.9E-6	5.1E-3	28.3E-3		83.3E-3
xβ		1.3E-3	29.2E-6	6.7E-6	7.0E-3	38.5E-3	xζ	39.2E-3

Water

	H20
Coeff.	1
xγ	0.03015

	[Fuel]	+ α (mol_air / mol_fuel)	* [Air]	React. TOTALS	= β (mol_gas / mol_fuel)	* [Prod.]	+ γ (mol_H20 / mol_fuel)	* [Water]	+ ζ (mol_C / mol_fuel)	* [U.B.C.]	Prod. TOTALS
		0.010			1.361		0.030		0.471		
C	40.6E-3			**0.0406**		998.5E-6				83.3E-3	**0.0406**
H	60.3E-3			**0.0603**				2.0E+0			**0.0603**
O	26.6E-3		2.0E+0	**0.0468**		12.2E-3		1.0E+0			**0.0468**
N	935.7E-6		7.5E+0	**0.0770**		56.6E-3					**0.0770**

APPENDIX F - ENERGY BALANCE ACROSS HEAT EXCHANGERS

In order to understand the effectiveness of a heat exchanger, it is necessary to know 4 essential temperatures: Hot inlet, cold inlet, hot outlet, cold outlet. Unfortunately, due to the fluctuations within the firepot, it is difficult to take a steady temperature. However, this temperature can be back-calculated from knowing the other 3 temperatures as well as the associated mass flow. The following set of data is from the LDJ 620-10.

$$\dot{V}_{c,0} = 1.06\times10^{-1}\frac{m^3}{s}$$

: Initial Volumetric Cold Flow Rate

$$T_{c,i} = 295K$$

: Temperature of Cold Inlet

$$T_{c,o} = 345K$$

: Temperature of Cold Outlet

$$T_{c,avg} = 320K$$

: Average Temperature of Cold Flow

$$q_c = \left(\dot{V}\rho\right)c_p\Delta T$$

q_c : Energy Transfer of the Cold Flow

$\dot{V}$: Volumetric Flow Rate

ρ : Density of the Fluid

c_p : Specific Heat

ΔT : Temperature Difference

$$= \left(1.06\times10^{-1}\frac{m^3}{s}\times1.089\frac{kg}{m^3}\right)\times1.007\frac{kJ}{kg\cdot K}\times50K$$

$$\approx 5790W$$

$$\dot{V}_{h,0} = 1.27 \times 10^{-2} \frac{m^3}{s}$$

: Initial Volumetric Hot Flow Rate

$$q_h = 5790W$$

: Equal to the Cold Flow Heat Transfer

$$= \left(\dot{V}\rho(T)\right) c_p(T) \Delta T$$

$$= \left(1.27 \times 10^{-2} \frac{m^3}{s} \times \rho\left(T_{h,avg}\right)\right) c_p\left(T_{h,avg}\right)\left(T_{h,i} - 560K\right)$$

$$T_{h,i} = 2040K$$

: Solved Hot Inlet Temperature