

CAMELINA COMPOSITE PELLET FUELS FEASIBILITY FOR  
RESIDENTIAL AND COMMERCIAL APPLICATIONS

by

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of

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## ABSTRACT

The use of wood pellet fuels for heating homes and buildings has been a mainstay in Montana since the first energy crisis of the 1970's. With the increasing demand placed on wood pellet fuels and a steady decrease in supply, alternatives must be explored. Camelina Sativa, an oilseed crop of the mustard family, is rich in oil and pressed for biodiesel. The bi-product, a waste meal, is being tested for many different applications to increase the value of the crop. This research explores the use of camelina meal in multi-fuel pellet mixtures. The meal has a distinct quality of binding to itself with the addition of water. This unique characteristic, along with the high heat output of the meal when burned, led to the advanced research into camelina's possibility of being a major additive in multi-fuel pellet formulations. Camelina was combined with sawdust at 50% by weight and pressed from a KL Series pelletizer. These pellets were tested by the Minnesota Valley Testing Laboratory in Bismarck, North Dakota, against premium wood pellets and the results were analyzed. The camelina fueled pellets offered a higher heat output than premium wood pellets, but also higher percentages of sulfur and ash. To ensure that camelina could be an additive in multi-fuel pellets, testing was done on two different types of pellet stoves with the use of a Bacharach Environmental Combustion Analyzer 450 to obtain emission values. After comparing the results to premium wood pellets, the study was advanced to other waste products in hopes of offering multiple fuels for Montana, all with camelina as the major supplement. To further extend the study, testing of the 50/50 camelina sawdust mixture was performed on a small industrial pellet boiler at the Townsend Elementary School in Townsend, Montana. The results were compared to a testing firm's results (Bison Engineering) on the current fuel used in the boilers for emissions. Results for both applications indicated that the camelina fueled pellet mixtures would be better suited for small industrial applications such as the one the Townsend Elementary School utilizes.

## CHAPTER ONE

## INTRODUCTION AND BACKGROUND

The Wood Pellet

The use of wood chips and wood pellets has become a very common method of heating homes and buildings throughout the United States. As the prices of fossil fuels continue to rise and the demand on wood products escalates, exploring the feasibility and effectiveness of using and burning agricultural materials in biomass boilers and pellet stoves is an expressed need for the State of Montana. Burning wood has been a mainstay supplemental fuel for Montana households, but as businesses and schools build or retrofit facilities, the demand for wood products and/or other biofuel systems has spread very rapidly. While wood chip boilers are readily available, the quality, quantity, and accessibility of wood-burning fuel is limited. This is causing businesses to question the high capital cost of equipment and sustainable accessibility to this fuel.

A timber rich state like Montana (22.5 million-acre forestland base [1]) should not have any problem supplying wood to heat homes, but much of the land is federally owned, making it very hard to access. Pellet processing, however, is not a new development for fuels and agriculture. Pellet-form feed, such as straw, mineral, rabbit, fish and cattle feed, and forage of various sizes have been produced and used in agriculture and fisheries for decades. For heating purposes, wood pellets were first designed in the 1970's in response to an energy shortage in the United States [2]. These wood pellets were generally manufactured from wood waste generated in saw mills and

paper mills. Each year, however, there are fewer and fewer operating mills around Montana. It was discovered that burning wood pellets could become an alternative supply for electricity in the form of wood burning fireplaces or stoves or fossil fuels such as natural gas or propane.

There are many advantages to burning wood pellets over logs. The market is aiming at wood pellet stoves, as there are more than 800,000 of them in practical use throughout homes in the United States [3]. It is estimated in Montana that at least 60% of homes have a wood-burning appliance. Environmentally, emissions from a pellet stove are approximately 1.2 grams per hour, which is substantially lower than the EPA regulations of 7.5 grams per hour [3]. There is little ash left over after burning wood pellets, less than 1%, thus keeping cleanup to a minimum. Wood pellets also produce virtually no creosote, which is a major cause of chimney fires. Since this is a packaged fuel, it is cleaner than conventional wood burning and more convenient to handle than logs. Pellets also generally only require loading once a day, which is significantly less work than adding a log every 30 minutes or so, and they are stored in less space than log or chip fuel [4].

### Camelina Sativa

This study looks directly at the agricultural crop camelina and its potential as a new biofuel, specifically for pellet burning stoves. Camelina (camelina sativa) is a new, rapidly spreading oil-seed crop in the state of Montana. It is a member of the mustard family and a distant relative to canola. The camelina plant is heavily branched, growing

from one to three feet tall, while producing seed pods with many small, oily seeds. This crop is short-seasoned, typically planted in March and harvested in late July, thus reaping the benefits of harvesting before the fickle weather month of August. Harvesting early also allows the ground to absorb later season rainfall so it can enter the next year in good position. Traditionally, camelina has been used to produce an edible vegetable oil and animal feed. The oil of camelina has uncommonly high levels of omega-3 fatty acids, up to 45%, which is uncommon in vegetation. It is also rich in antioxidants and vitamin E. Figure 1 below presents a graphical representation of the different forms of the camelina plant.

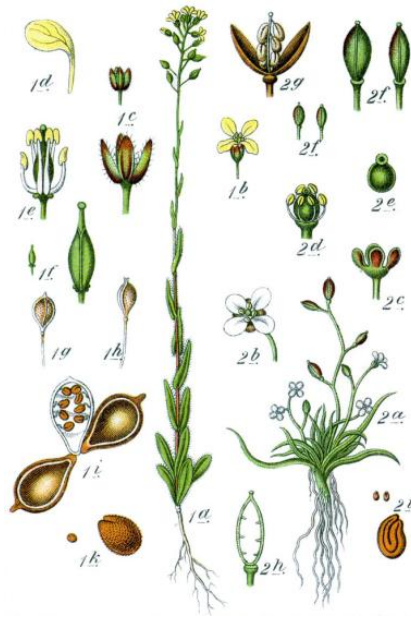


Figure 1: Camelina plant depicted in several forms [5]

With the rising prices of gasoline and the need for alternative fuels, camelina oil is being viewed as a leading source of biodiesel for the future. The seed from camelina

exhibits an oil content between 35% and 38% and has the ability to grow on land that has prior difficulty maintaining crops because it needs very little water, fertilizer, or pesticides [6]. The crop also protects soil from erosion and is promising as a rotational crop. With biodiesel predicted to occupy up to 20% of Montana's fuel consumption, the economical reward of growing camelina becomes apparent.

While the biodiesel made from camelina will surely be profitable, it is the meal leftover from the pressing process that should have an end-use. When camelina seed is cold pressed, only 30% (by weight) oil is obtainable. The resulting meal has an oil content roughly between 10-12% (by weight). This remaining 10-12% oil can be obtained by means of hexane extraction, but this process is very difficult and expensive. There are very few plants capable of hexane extraction and the cost of doing so wouldn't be worth the remaining 10-12% oil. This leaves an extraordinary amount of leftover meal after the cold pressing process. While this meal has been used as a supplement in chicken feed, the Food and Drug Administration (FDA) just recently approved the inclusion of up to 10% in cattle feed [7]. This inclusion has driven the production of camelina and has increased production by up to 200% in 2009. As more camelina is grown and pressed for biodiesel, more niche markets will become available for the leftover meal that isn't being included in feed. A major market for this remaining feed could be heating homes in the form of pellet stoves.

Preliminary studies during the first semester of research in 2007 led to the discovery of the high heat output from camelina meal [8]. Certified burn results from Minnesota Valley Testing Laboratories (MVTL) in Bismarck, North Dakota showed a

heat output of 9994 Btu/lb for camelina meal, compared with a heat output of 8330 Btu/lb for premium wood pellets. This significant difference in heat output encouraged the advanced research of camelina into fuel pellets. While camelina exhibits much higher heat output than wood, it also displays many characteristics frowned upon by the Pellet Fuel Institute (PFI). Namely, a much higher ash and sulfur percentage than wood [3].

### Wood Pellet Production

The production of wood pellets is a tedious, expensive process. There is only one pellet production plant in Montana; Eureka Pellet Mills in Superior, MT. The first step is getting the wood waste into sawdust. A sawmill is the easiest way to accomplish this, and Eureka Pellet Mills has this capability. The next step is to press the sawdust at very high pressures and apply steam. This high pressure steaming process brings out the lignin in the wood, which binds the wood to itself, thus making a pellet. PFI standards on pellets are  $\frac{1}{4}$  inch in diameter and  $\frac{1}{2}$  to  $\frac{3}{4}$  inches in length [3]. The types of wood that are primarily used at Eureka Pellet Mills are Douglas Fir and Lodgepole Pine. To set a baseline of comparison for the study, premium wood pellets were sent to MVTL for a short proximate test. MVTL performs a short proximate test that includes testing for percent ash, percent sulfur, calorific value, and total moisture. Table 1 below gives the results from MVTL and Table 2 lists the standards on all types of pellet fuels as set by PFI [3]. All results from MVTL were based on weight percentage.

Table 1: MVTL results on premium wood pellets from Eureka Pellet Mills

| Pellet       | Calorific Heat Output (Btu/lb) | Moisture (wt. %) | Ash (wt. %) | Sulfur (wt. %) |
|--------------|--------------------------------|------------------|-------------|----------------|
| Premium Wood | 8330                           | 7.05             | 0.54        | 0.01           |

Table 2: PFI fuel standards for all grades of pellets

| Analysis Parameter                  | Super Premium   | Premium         | Standard        | Utility         |
|-------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Bulk Density (lbs/ft <sup>3</sup> ) | 40-46           | 40-46           | 38-46           | 36-46           |
| Diameter (inches)                   | .250 to .285    | .250 to .285    | .250 to .285    | .250 to .285    |
| Pellet Durability Index             | >=97.5          | >=97.5          | >=95            | >=95            |
| Fines (%)                           | <0.5            | <0.5            | <0.5            | <0.5            |
| Inorganic Ash (%)                   | 0-0.5           | 0-1             | 0-2             | 0-6             |
| Length (greater than 1.5 in)        | <1              | <1              | <1              | <1              |
| Moisture (%)                        | <=6             | <=8             | <=8             | <=10            |
| BTU's-Need to specify on bag        | As-Rec. +/- 2SD | As-Rec. +/- 2SD | As-Rec. +/- 2SD | As-Rec. +/- 2SD |

Inspecting Table 2 and comparing the “Premium” column to the results in Table 1 from MVTL it is clear that they match up very well. The last column of Table 2 applies to any pellet made from other materials than wood. Thus, Table 2 gives guidelines for the camelina pellet while Table 1 gives a baseline of results to pursue. PFI also requires that members label their product as to which grade of material is in the bag and that they disclose the type of material as well as all additives being used, and if any of the materials are chemically treated.

### Camelina Characteristics

The camelina pellet process is very different when compared to the wood pellet process. There are many reasons that the processes differ, but mainly due to a lack of

sophisticated equipment. Without professional equipment, a simple yet tedious operation is necessary to replicate the wood pellet results. Without the use of a high pressure steam system, another binder must be used for these pellets. The high heat output of camelina was an initial attraction to the product, but it is the natural binding ability of camelina when wet that makes it a perfect additive for the niche market as described above. When water is added to camelina it becomes very gelatinous, and as it dries it becomes hard like cement. This takes the high pressure steaming process out of the production of camelina pellets, thus reducing equipment and operation costs. After this unique characteristic was identified, the meal was sent off to MVTL to see what other characteristics were exhibited when burned. Table 3 below lists these results.

Table 3: Camelina meal as received by MVTL

| Material      | Calorific Heat Output (Btu/lb) | Moisture (wt. %) | Ash (wt. %) | Sulfur (wt. %) |
|---------------|--------------------------------|------------------|-------------|----------------|
| Camelina Meal | 9259                           | 6.83             | 4.43        | 0.98           |

Two concerns from the results in Table 3 were the high percentages of ash and sulfur in the meal. Although there are no standards listed by PFI for sulfur, burning any fuel with such a high sulfur percentage would surely be a concern for the Environmental Protection Agency's (EPA) emissions regulations [9]. The calorific value, however, surpassed that of premium wood pellets significantly.

The source of sulfur comes from the camelina plant itself. Camelina is a cruciferous crop, and cruciferous crops contain glucosinolates. Glucosinolates contain sulfur. A study was done on camelina to see what glucosinolates are present and results

from a chromatogram gave a total of three; 9-methyl-sulfinyl-nonyl (GSL 1), 10-methyl-sulfinyl-decyl (GSL 2), and 11-methyl-sulfinyl-undecyl (GSL 3). The main glucosinolate present, representing 65% of the total was GSL 2, or glucocamelinin [10]. In Fig. 2 the chemical structure of glucocamelinin is given.

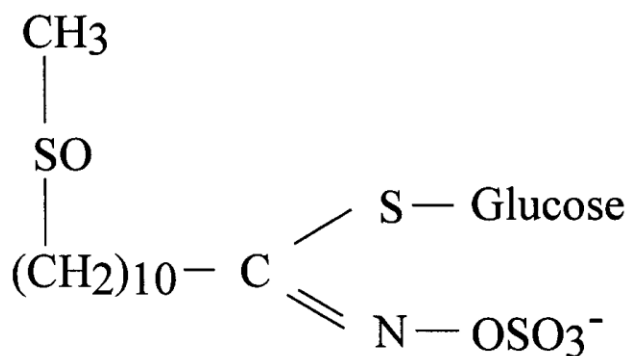


Figure 2: Chemical structure of glucocamelinin

To enhance the positive characteristics of camelina while cutting back on the negatives in creation of a fuel pellet, it was determined that simply using camelina as a supplement in new pellet fuels would be optimal. To verify camelina could be a long-term solution to the dwindling supply of wood products in Montana, many formulations of camelina and sawdust were tested to see what one combination would produce the best pellet in comparison to the premium wood pellet. Combining camelina meal with sawdust is advantageous because the characteristics of each combine to form a desirable pellet. The characteristics of camelina would increase the heat output from the premium wood pellet while the characteristics from the sawdust would help to decrease the percentages of ash and sulfur from the camelina meal.

## CHAPTER TWO

## LITERATURE REVIEW

Crop Selection

When research first began on the project in 2007, direction was provided towards the new oilseed crop, camelina [8]. After considerable research on this crop, it was believed that camelina would increase the heat output of any pellet formulation and exceed the production of wood pellets by over 1000 Btu/lb. As seen in Chapter 1, Table 3, camelina meal does in fact burn about 1600 Btu/lb higher than premium wood pellets. The high heat output along with the natural ability to bind to itself when wet made camelina the focal point for a new pellet formulation in this study. To compete directly with the wood pellet market, however, multiple crops needed to be considered so that regional production could be accomplished. Regional production would give a specific region of Montana its own pellet based on what crop is readily available. It was decided that Montana could be divided into 6 regions. Figure 3 below depicts that initial division, with each colored region representing a different crop. The next task was to find the most prominent crops available in Montana. To start the research, many initial crops were chosen. Possible candidates included wheat straw, sugarbeet pulp, corn, alfalfa, barley, and sunflower hull. Corn was eliminated immediately due to its small availability and its corrosive nature when burned. Wheat straw stood out immediately due to availability [8]. Wheat is Montana's primary crop, and the straw is readily available at a low cost. See Fig. 4 below for Montana's production of wheat. The other crop that stood

out was barley. Barley, like wheat, is very prominent in Montana. Figure 5 depicts the barley production in Montana.

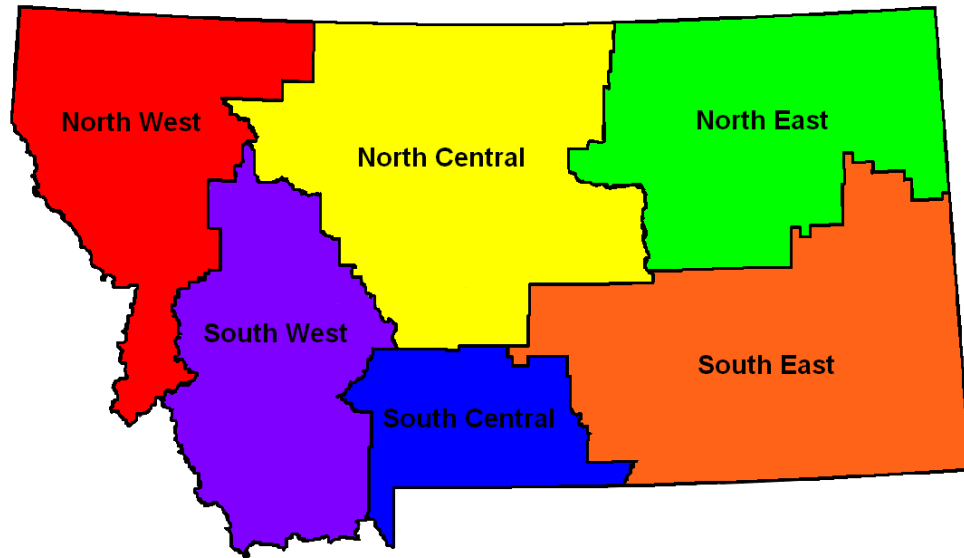


Figure 3: Initial regional breakdown for Montana [8]

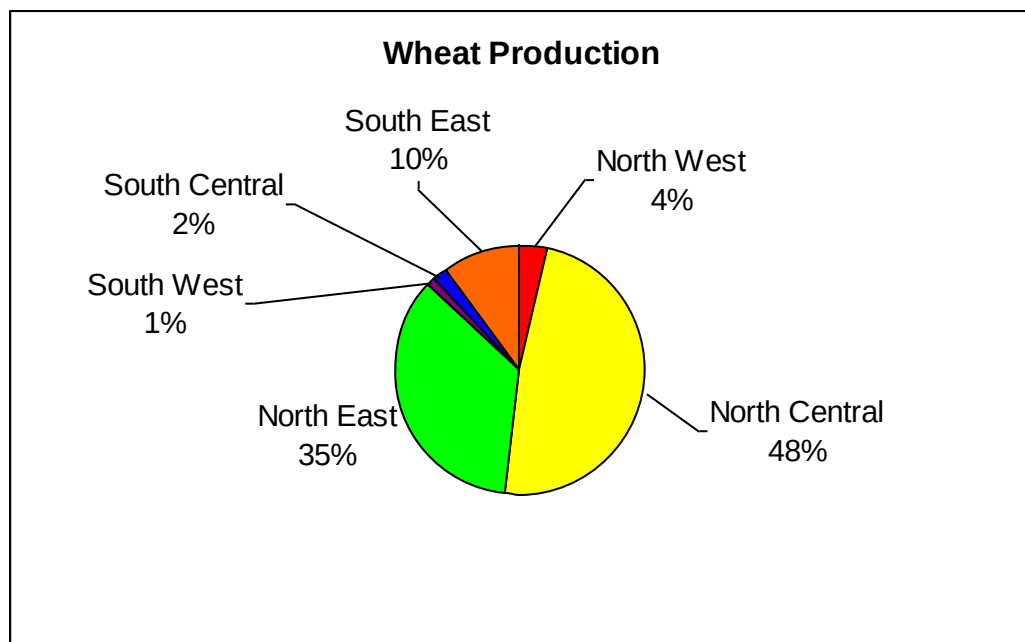


Figure 4: Wheat production in Montana [8]

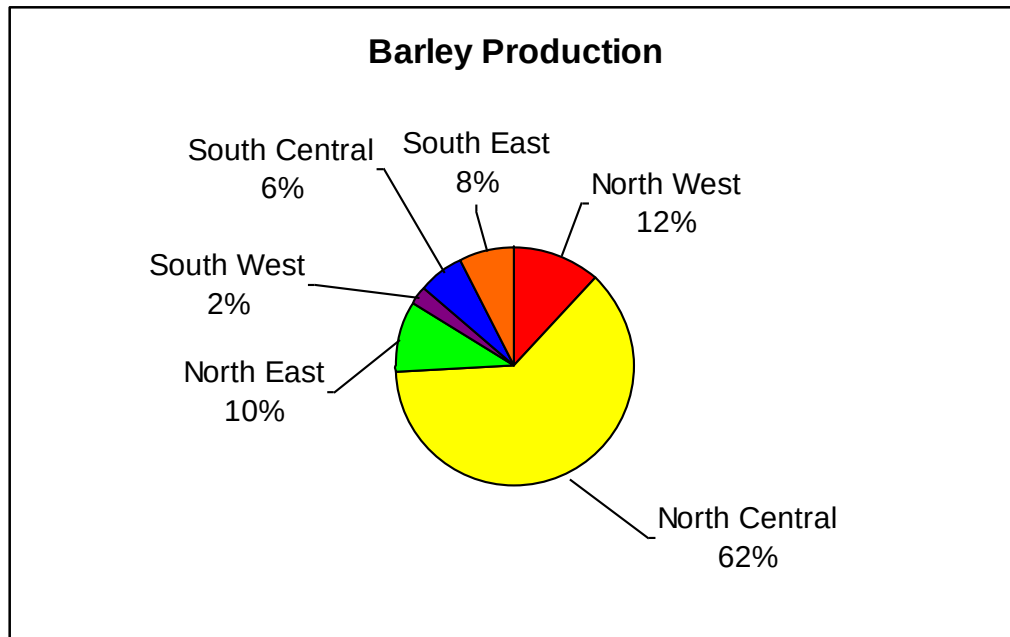


Figure 5: Barley production in Montana [8]

As you can see from Figs. 4 and 5 the majority of wheat and barley is produced in the North Central part of the state. After further research and discussions with plant pathologists at Montana State University [11], it was assumed that burning wheat straw versus barley straw would yield minimal differences in burning characteristics.

Some criteria for choosing proper candidates for new pellets hinged on whether the crop was a waste product or if it had current value in the market. Camelina meal does have end uses but not all of the meal is demanded by other markets, thus allowing another niche market for camelina derived pellet fuels. The same thing can be said for wheat straw. Sunflower hull is a waste product but is very scarce in Montana so it was discarded. Sugarbeet pulp is prominent in southeastern Montana, namely the Billings area. The Western Sugar Cooperative in Billings provides sugar all over the United States. When they produce their sugar, there is a leftover pulp that is a waste product, but

all of their pulp is sold to farmers and fed to livestock, so including it as a possible pellet fuel would require the profits from burning it to outweigh the profits from feeding it.

Once the crops had been narrowed down to those of interest, a matrix was made that would predict the heating output based on specific mixtures in designated regions. Table 4 below lists these results, with each component listed as a weight percentage.

Table 4: Estimated heat outputs for specified formulas in different regions of Montana [8]

|                    | Wheat Straw | Barley Straw | Sugar Beet Pulp | Wood | Camelina | Paper |                  |
|--------------------|-------------|--------------|-----------------|------|----------|-------|------------------|
| Btu Value (Btu/lb) | 6839        | 6500         | 6597            | 8330 | 9994     | 7000  | Estimated Output |
| North West         | 25%         | 20%          | 0%              | 55%  | 0%       | 0%    | 7591.25          |
| North Central #1   | 80%         | 20%          | 0%              | 0%   | 0%       | 0%    | 6771.2           |
| North Central #2   | 50%         | 20%          | 0%              | 0%   | 30%      | 0%    | 7717.7           |
| North East         | 80%         | 0%           | 20%             | 0%   | 0%       | 0%    | 6790.6           |
| South West         | 10%         | 10%          | 0%              | 30%  | 0%       | 50%   | 7332.9           |
| South Central #1   | 30%         | 20%          | 0%              | 10%  | 0%       | 40%   | 6984.7           |
| South Central #2   | 30%         | 0%           | 10%             | 10%  | 50%      | 0%    | 8541.4           |
| South East         | 40%         | 10%          | 30%             | 20%  | 0%       | 0%    | 7030.7           |
| Camelina           | 0%          | 0%           | 0%              | 0%   | 100%     | 0%    | 9994             |
| South Central #3   | 30%         | 0%           | 0%              | 0%   | 70%      | 0%    | 9047.5           |

One material that was added to the matrix was paper. Paper products are waste products in the entire United States, not just Montana. If paper could be incorporated into the pellet formulations it could drastically reduce the amount in landfills.

After analyzing Table 4 it became apparent which waste products would form the most competitive pellet. These were in the South Central Region, and they included the 100% camelina pellet and a 70/30 mixture of camelina and wheat straw. Another formulation from that region included sugarbeet pulp, wood, camelina, and wheat straw. This formulation also offered good initial results but due to the inability to obtain sugarbeet pulp at that point in the research it was no longer considered. When all of the background research was finished there were only three candidates that looked feasible to produce pellet formulations. These included camelina, wheat straw, and barley straw. The next step was to find a way to make pellets and get them tested.

#### Initial Pellet Production

When the project first began in the spring of 2007, the budget was small and equipment was scarce. Finding the right mixtures of camelina, wheat straw, and barley straw was also time consuming. The evolution of making the pellets went through three stages. Originally the use of the Bozeman Fish Technology Center (BFTC) was utilized. They made their own pelletized fish feed and without any equipment for the project, their participation was pivotal. They agreed to help make pellet formulations of wheat, barley, and camelina. Trying to keep consistency between the predicted formulas in Table 4 with only those three materials available, it was determined that a 100% camelina pellet, 80% camelina 20% barley, and 80% wheat straw 20% barley would be sufficient. After collaborating with them, the type of barley they had was merlin barley, and they used 5% vegetable oil in all of their pellets. The camelina was supplied from Dr. Alice Pilgeram

of Montana State University. She obtained the meal from Belgrade and it averaged 11% oil. The wheat straw was provided from the agricultural farm at Montana State University [8].

After all adjustments were made, the final mixtures were as follows: The first formulation was 100% camelina. A 100% camelina pellet would offer a higher heat output than premium wood pellets. The second pellet formula was 80% wheat straw, 15% merlin barley, and 5% vegetable oil. Making this pellet was more tedious because the wheat straw had to be ground up before it could be used in the pellet mixture. Figure 6 gives an idea of what grinding the wheat straw entailed. This grinder was provided by the BFTC and the only way to feed the hopper was by hand. The blades were far enough below the opening to ensure safety.



Figure 6: Grinding up wheat straw at the Bozeman Fish Technology Center [8]

After the wheat straw was ground, which was about half of a bale, it was ready to pelletize. About 25 lbs of meal were obtained from this half bale, and the Bozeman Fish Technology Center was supplied with 100 lbs of camelina. They combined the ground

up wheat straw with merlin barley and vegetable oil, which they provided. This pellet had a problem binding, and there wasn't enough pressure to really pack it together. Strong enough pellets were produced though to get a short proximate test done on them, but for the future production a better binder would be needed for the wheat, which could be substituted with camelina. The last pellet formula was 80% camelina, 15% merlin barley, and 5% vegetable oil.

Since the pellets were made at the Bozeman Fish Technology Center, some properties changed slightly. The pellets were processed with a piston extruder and the final pellet diameter was 5 mm, compared to 6.35 mm for a standard wood pellet. See Fig. 7 below for a picture of the piston extruder. The lengths on these pellets were supposed to be arbitrary based on the cutter, but since they started to curl they became shorter than standard pellets. After the pellets were pressed and cut, they were laid out under an industrial heater overnight to dry out. The following day they were ready to be analyzed.



Figure 7: Piston extruder at the Bozeman Fish Technology Center [8]

Bozeman Fish Technology Center Pellet Results

The results from the Bozeman Fish Technology Center pellets can be seen below in Table 5. The results from Tables 1 and 3 are included in this Table to highlight the comparison between premium wood pellets and camelina meal to that of the BFTC pellets.

Table 5: MVTL results as received from all three pellet formulas derived at BFTC [8]

| Material or Pellet                               | Calorific Heat Output (Btu/lb) | Moisture (wt. %) | Ash (wt. %) | Sulfur (wt. %) |
|--------------------------------------------------|--------------------------------|------------------|-------------|----------------|
| Premium Wood Pellets                             | 8330                           | 7.05             | 0.54        | 0.01           |
| Camelina Meal 12% Oil                            | 9259                           | 6.83             | 4.43        | 0.98           |
| 100% Camelina Pellets                            | 9994                           | 2.61             | 4.4         | 0.83           |
| 80% Camelina, 15% Barley, 5% Veg. Oil Pellets    | 9844                           | 2.23             | 4.14        | 0.71           |
| 80% Wheat Straw, 15% Barley, 5% Veg. Oil Pellets | 7839                           | 5.25             | 8.14        | 0.14           |

Of the three pellet formulas, the 100% camelina pellet demonstrated the highest heat output and was the strongest in compression. The 80% camelina 15% barley pellet also showed very encouraging results. They were only about 100 Btu/lb lower than the 100% camelina pellets and had smaller percentages of ash and sulfur, something that is very desirable when trying to replicate the premium wood pellet. The percent moisture on all of the formulations was below 7%, which was desirable to PFI standards. Besides strength and binding issues with the 80% wheat straw pellet, it was also very high in ash. It was, however, much closer to the premium wood pellet in sulfur percentage. This original study proved that wheat straw would be very viable if a binder such as camelina

was added to it. The results also convey that camelina alone could not replace the wood pellet. Instead, it should be approached as an additive in all future pellet formulations.

### Bottene Commercial Pasta Maker

After the results from the Bozeman Fish Technology Center were analyzed, the project took a new direction. It was realized that these pellets were very different from the premium wood pellet, and components such as vegetable oil were included in the pellet, making it very difficult to form conclusions. Therefore, a Bottene commercial pasta maker donated from Kalispell, pellets were made using only water and a custom built extruding die. Camelina, with its self binding ability when wet, was still the main ingredient in all formulations. Using the pasta maker became difficult due to constraints in pressure.

Without the use of a grinder or drying system, the scope of the project shifted from many pellet formulations to one competitive pellet formulation. If one formulation could be found from the Bottene commercial pasta maker, then expansion of equipment could then include other materials and formulations. To compete directly with the premium wood pellet, the two additives chosen for the pellet formulation were camelina and sawdust. The pasta maker consisted of a horizontal auger that pushed the material through a custom built extruding die with one center punched hole of 1/4<sup>th</sup> inch. However, due to the lack of pressure in the pasta making process, more water had to be added than recommended by PFI standards to extrude the pellets. Naturally, the pasta maker extruded the pellets as long strings, so they had to be hand cut with a knife. Once

cut, they were evenly spaced and placed on a screen that was set on a heater for 12 hours [8].

Since the pellets were so wet, when they dried they had a very low density and had the appearance of long raisins. It was pretty clear that the pasta maker wouldn't be sufficient in making pellets for future production. The three formulations that were produced were 80/20 camelina sawdust, 70/30 camelina sawdust, and 60/40 camelina sawdust by weight [8]. The sawdust used for processing was inconsistent in brand, unlike the Douglas Fir and Lodgepole Pine used in the premium wood pellets out of Eureka. For comparison purposes, 100% camelina pellets were also produced.

#### Bottene Pasta Maker Burn Results

The three formulations described above were burned in an Avalon Newport Avanti PS pellet stove donated from Bare's Stove & Spas in Bozeman, Montana [8]. The stove was a standard wood pellet stove and lacked the capability of integrated fuels, but it was the only stove available at the beginning of the project. All of the fuel formulations in Table 5 were tested for emissions with a Bacharach combustion analyzer [12]. This analyzer tested for carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), oxygen (O<sub>2</sub>), nitrous oxide (NO<sub>x</sub>), nitrogen dioxide (NO<sub>2</sub>), nitrogen oxide (NO), and the temperature of the stack gases.

Due to the lack of integrated fuels capabilities, all three pellet formulations wouldn't ignite alone in the stove. Premium wood pellets had to be used to start the stove and then the pellet mixture of camelina and sawdust had to be added manually [8].

Another problem was achieving maximum burn characteristics. This was impossible to do because the airflow had to be different for each formulation to maintain the burn. The combustion airflow on the stove was designed for wood pellets only, and adjustments are needed to maximize a burn on integrated fuels. All of the adjustments made for each test made it difficult to compare the results on one scale. While some conclusions could be drawn, it was difficult to support the validity of these pellets based on the results obtained. Table 6 below shows the averaged results from the tests run. Tests were also done on premium wood pellets and 100% camelina pellets for comparison.

Table 6: Burn results from stove averaged out over time [8]

| <b>Pellet</b>          | <b>O2 (%)</b> | <b>CO (ppm)</b> | <b>Stack Temp (°F)</b> | <b>NO (ppm)</b> | <b>NO2 (ppm)</b> | <b>NOx (ppm)</b> |
|------------------------|---------------|-----------------|------------------------|-----------------|------------------|------------------|
| 100% Camelina          | 20.34         | 128.8           | 205.6                  | 40.6            | 3.8              | 44.2             |
| Premium Wood           | 18.14         | 456.4           | 255.4                  | 28.4            | 2                | 30.4             |
| 80/20 Camelina/Sawdust | 19.43         | 300.17          | 227.83                 | 95.83           | 6.67             | 102.33           |
| 70/30 Camelina/Sawdust | 18.93         | 262.71          | 235.43                 | 107.71          | 5.86             | 113.57           |
| 60/40 Camelina/Sawdust | 19.72         | 218             | 218.5                  | 73.5            | 4.33             | 77.83            |

The results varied widely when comparing the 100% camelina pellet to the 80/20 camelina sawdust pellet. It also should be noted that the premium wood pellet offered the highest stack temperature of any burn. It also shows significantly lower emissions compared to each camelina mixture. While the lower emissions were expected from the premium wood pellets, the temperature of the stack being higher shouldn't occur. As mentioned above, this occurred because the burns performed on the camelina pellet

mixtures weren't at maximum efficiency. Of all the camelina sawdust mixtures, the closest one to the premium wood pellet was the 100% camelina pellet. The 100% camelina pellet left very large amounts of ash and clinkers due to inefficient combustion [8]. Clinkers are a problem in residential burning, and aren't accepted by industry standards or by consumers. Due to incomplete burning of the pellet fuel, skewed results represented in Table 6 led to a possible false conclusion that the 100% camelina pellet was the best formulation.

The Bacharach analyzer wasn't capable of testing sulfur compounds. Based on the results from MVTL in Table 3, the percentage of sulfur in camelina meal is very high compared to premium wood pellets. Some percentage of wood is needed with camelina to make the ash and sulfur percentages drop. To advance in the project and explore the mixtures and characteristics more closely, sophisticated equipment had to be purchased for pelletizing.

### Advanced Pellet Testing

After one year of research on camelina and its possibility of being an additive in existing wood pellets, it was realized that the equipment that was being used wasn't sufficient enough to get comparable results. The data that was gathered, however, was relevant enough to conclude that advanced investigation must be done on camelina and sawdust mixtures to achieve a pellet that would compare favorably to the premium wood pellet. With more funding, a KL Series Rigid Granular Fodder Machine was purchased from China [13]. This fodder machine was a small scale pelletizer that could produce

pellets of the same quality as the premium wood pellet. The machine consisted of a hopper, roller press, and a template with many ¼ inch holes for extruding. The construction material was a high alloy steel. It was powered by a 2.2 kW, 220 Volt single phase electric motor. This ½ ton press was installed and stored in the Plant Growth Sciences building at Montana State University. See Fig. 8 below for an overview of the pelletizer.

The primary goal of the project was to achieve the best mixture of camelina and sawdust. The focus was to obtain a mixture that would provide the best combustion and physical characteristics as the premium wood pellet. These pellets would only consist of camelina, sawdust, and water. Once appropriate testing was done on this pellet mixture, the project could be expanded to other materials if the results were encouraging on the camelina-sawdust formulation.

#### KL Series Pelletizer Process

The pellet making process was completely different once the KL series pelletizer was purchased. The material was loaded in the hopper on the top of the pelletizer and then forced through the die from a roller press inside the system. The pellets were then cut via a rotating blade. The pellets are then pushed out an opening on the bottom. The machine had a reservoir for lubricating oil for the press. See Fig. 9 for a close up of the pellet cutting wheel and oil reservoir [13]. The friction from the machine helped the pellets bind and pushed them out very warm and moist.

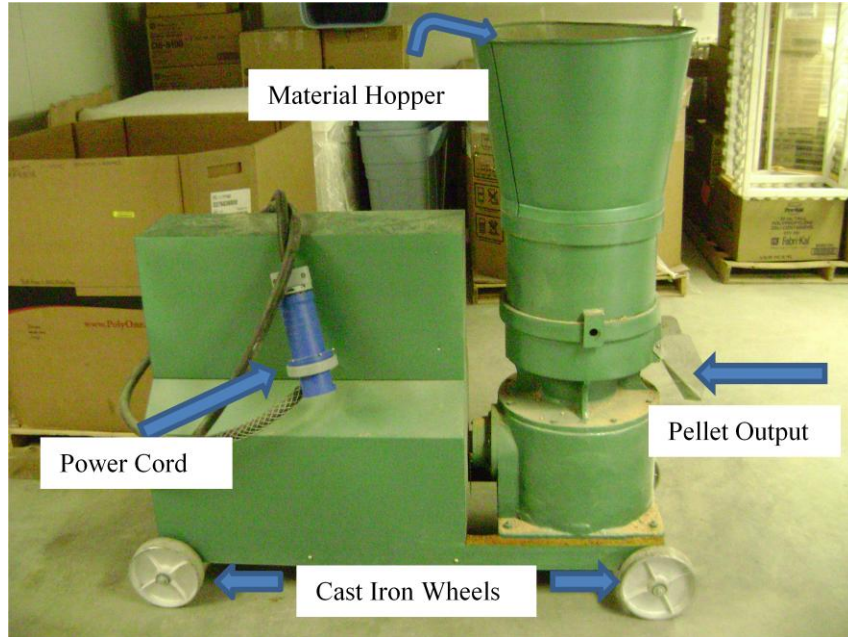


Figure 8: KL Series Pelletizer



Figure 9: Cutting wheel and oil reservoir

Before the mixture was loaded into the hopper, several steps had to be taken to properly prepare it. First, the desired amounts of sawdust and camelina were each

measured in 5 gallon buckets. The total weight of the two materials was 20 lbs. For example, a 50/50 pellet would consist of 10 lbs of each material. Keeping the two materials separate, it was determined that 20% moisture by weight was desirable before entering the pelletizer, so 4 lbs of water were measured and put aside. All three components were taken from the lab to the Plant Growth Sciences Building at Montana State University where the pelletizer was stored. Using a small industrial mixing bin, the three components could be mixed. Since camelina absorbs water immediately, it was determined that mixing the sawdust with the water first was necessary for an even formulation. See Fig. 10 for a picture of the industrial mixing bin. The mixing bin utilized two stationary arms and an electric motor to spin the bin on its axis. This allowed for even mixing of all materials.



Figure 10: Small industrial mixing bin for raw materials

Once the sawdust and water had mixed for about two minutes, the camelina was added and mixed for an additional two minutes. Once the mixture was complete, it was

unloaded back into two 5 gallon buckets, and loaded into the pelletizer. The pelletizer was then activated and set at maximum pressure. The pressure adjustment consisted of two nuts, one stationary and the other tightened or loosened to adjust the pressure of the roller on the extruding die. One disadvantage of this mechanism was that it was impossible to know the exact pressure put into the process. To take any variance out of the process, the pelletizer was always tightened to achieve maximize pressure. See Fig. 11 for a detailed schematic of the roller press system.

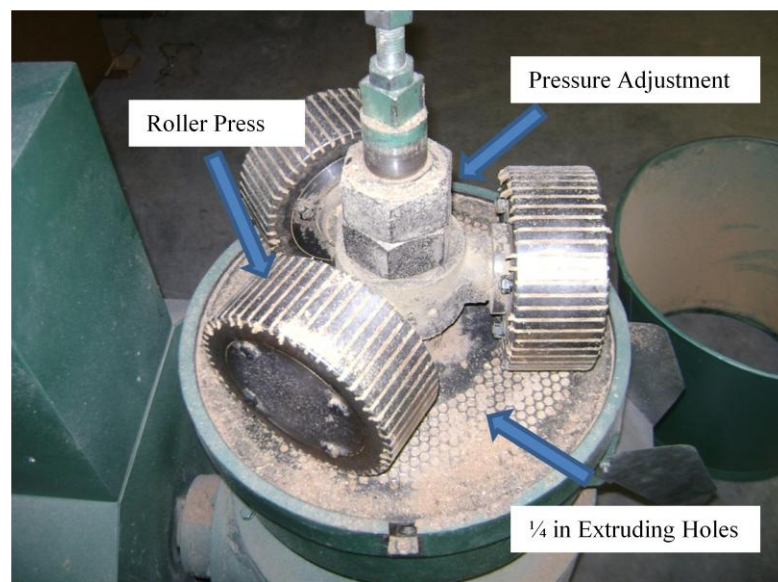


Figure 11: Schematic of the roller press system

After the pelletizer was tightened and activated, it was allowed to warm up for 30 seconds. Then, one 5 gallon bucket of material was slowly dumped into the hopper. At the other end of the system was an empty 5 gallon bucket to catch the extruded pellets. The feed rate of the material was not constant due to hand loading the machine, so trial and error was used to determine the best manual feed rate. After one 5 gallon bucket was

emptied, the other was then loaded into the hopper at the same rate and pushed through the extruding die. All 20 lbs of material just fit into the 5 gallon bucket at the other end of the process, and it was very warm and wet. The 5 gallon bucket was sealed off and any remaining 5 gallon buckets of prepared material were also loaded into the hopper, pressed by the pelletizer, and sealed off. After all materials were pressed, the pelletizer was turned off and left to cool for 5 minutes.

While cooling, the small industrial mixer was cleaned out using a hose with a high pressure nozzle. The camelina becomes very sticky and must be cleaned out immediately or it will dry and become very difficult to remove. The mixer was then stored and the pelletizer was ready to be cleaned. This cleaning consisted of lifting the hopper off the top of the machine, and then lifting the steel casing that encloses the roller press. After both were removed, any excess material was scraped off the surface of the extruding die and the roller press. An air compressor was then used to blow any lodged material off the surface and completely remove all material from the press and die. Then the roller press casing and hopper were re-installed and the pelletizer was stored away. The floor was then cleaned. The sealed pellets were then transported from the Plant Growth Sciences building back to the lab where they would be dried and sealed until tested by MVTL.

### Initial Pellet Formulation Results

A semester of testing different formulations of camelina and sawdust showed that the 50/50 camelina sawdust pellet offered the closest match in all categories regulated by

PFI [13]. This took into account the ease of making the pellets, their durability, and the burn characteristics as tested by MVTL. All of the results can be seen below in Table 7.

Table 7: MVTL results as received on all camelina sawdust formulations [13]

|                  |                   |                |       |      |      |
|------------------|-------------------|----------------|-------|------|------|
| Camelina Content | % of total mass   | 0              | 50    | 75   | 100  |
| Sawdust Content  | % of total mass   | *Premium Wood* | 50    | 25   | 0    |
| Calorific Value  | Btu/lb            | 8330           | 8078  | 8921 | 8990 |
| Ash              | % of initial mass | 0.54           | 2.46  | 3.67 | 4.37 |
| Moisture Content | % of initial mass | 7.05           | 12.93 | 7.22 | 9.3  |
| Sulfur Content   | % of initial mass | 0.01           | 0.51  | 0.81 | 0.96 |

The results in Table 7 show that it is difficult to draw conclusions on what pellet was best because the moisture content wasn't consistent. This was due to the lack of a consistent drying process at the time of the project. The pellets were dried by placing them on a screen and sitting them 6 inches above a heater vent. This resulted in uneven drying and undetermined moisture contents. The other thing MVTL offers is normalized results for moisture content. They do this by calculation based on the short proximate test results. The normalized data can be seen in Table 8.

Table 8: MVTL results normalized on all camelina sawdust formulations [13]

|                  |                   |                |      |      |      |
|------------------|-------------------|----------------|------|------|------|
| Camelina Content | % of total mass   | 0              | 50   | 75   | 100  |
| Sawdust Content  | % of total mass   | *Premium Wood* | 50   | 25   | 0    |
| Calorific Value  | Btu/lb            | 8962           | 9278 | 9615 | 9901 |
| Ash              | % of initial mass | 0.58           | 2.83 | 3.96 | 4.82 |
| Moisture Content | % of initial mass | 0              | 0    | 0    | 0    |
| Sulfur Content   | % of initial mass | 0.01           | 0.59 | 0.81 | 1.06 |

It is clear from the table that as the percentage of camelina is increased above 50%, the amount of ash and sulfur additions are large compared to a minimal heat gain.

Due to these results and the durability and consistency of the 50/50 pellet, it was chosen as the final pellet formulation for comparison to the premium wood pellet [13]. Using Table 8, however, graphs can be built for any combination of camelina and sawdust to see what the correlation is between the percentage of camelina in a mixture to the resulting heat output, ash, and sulfur percentages. The percentages of ash and sulfur relative to camelina content can be seen in Fig. 12 and the heat output versus the camelina content can be seen in Fig. 13.

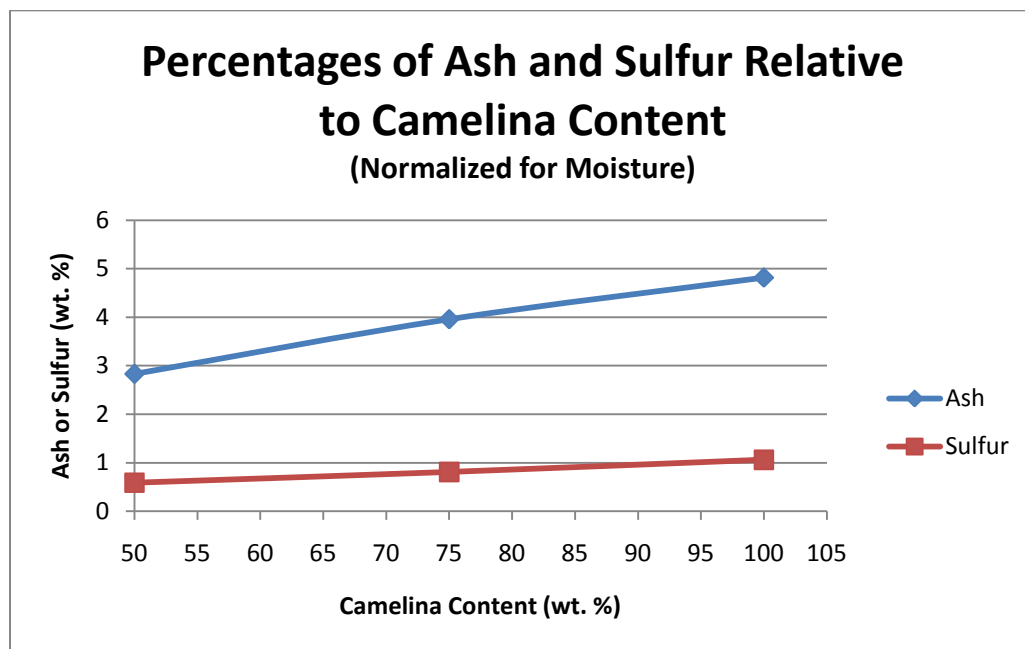


Figure 12: Ash and sulfur percentages based on camelina content [13]

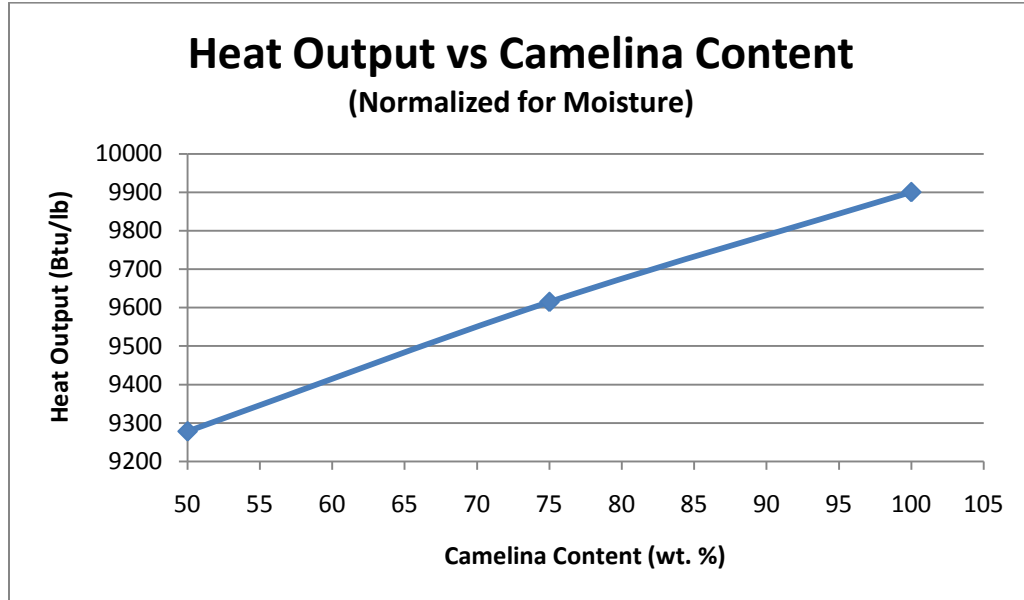


Figure 13: Heat output vs. camelina content for all formulations [13]

General curve fitting methods were applied and linear curve fits proved the best for all three variables. The lowest R squared value was for the ash curve fit, and it was 99.39% accurate. Using the curve fits, predictions can be made for any mixture of camelina and sawdust. Table 9 gives the formulas for all three variables.

Table 9: Predicting formulas for all variables in camelina sawdust mixtures

| Variable    | Formula           | 50/50 Calculated | 50/50 Measured | % error |
|-------------|-------------------|------------------|----------------|---------|
| Heat Output | $y=12.46x+8663.5$ | 9286.5           | 9278           | 0.0916  |
| Ash         | $y=0.0398x+0.885$ | 2.875            | 2.83           | 1.5901  |
| Sulfur      | $y=0.0094x+0.115$ | 0.585            | 0.59           | 0.8475  |

In the formula column, x represents the percentage of camelina in the mixture as a whole number. The table also shows an example calculation for the 50/50 mixture, and the largest percent error was 1.5% for ash. Analyzing the figures, the motivation for adding more camelina would be the additional heat output. Going from 50% to 100%

camelina adds 6000 additional Btu's/lb, while the percentages of ash and sulfur double. All of the facts mentioned above lead to the conclusion that the 50/50 pellet is the best alternative to the premium wood pellet [13].

### Motivation

Two years of research on camelina and its potential as a supplement in future pellet fuels led to two main properties of the camelina meal. The first property was camelina's ability to bind with itself when water is added to it. For a standard pellet process, steam is required for binding. With camelina, only cold water is needed, thus removing the cost of high temperature steam processes and equipment. The second favorable property was camelina's high heat output when burned. This was discovered from taking a sample of the meal and sending it to MVTL for a short proximate test. Two negatives about camelina were the high ash content and the high sulfur content, both of which are much harder to control. After the finding of these characteristics, it became evident that simply formulating camelina by itself as a pellet fuel wouldn't be acceptable by PFI or EPA standards and regulations. After a trial and error of various camelina and sawdust mixtures, the realization that a 50/50 weight mixture would prove most competitive in the existing wood pellet market. This new market would increase the profit for camelina waste. Certified results from MVTL on different mixtures of camelina and sawdust revealed inconsistencies in moisture content, however. These inconsistencies caused varied results on other properties such as heat output, sulfur, and ash. This had to be addressed.

At this point, the goals of this thesis study became the following. Create a drying process that would better control the moisture content of the pellets. Once the pellet was carefully and consistently dried with precision and repeatable accuracy, testing it in different residential stoves was desirable to offer a conclusion on what design of stove would adequately burn the new multi-fuel pellets. The testing would include heat transfer calculations and emission testing on both types of pellets. The final goal of the project is to extend the study to other relative waste products in the hopes of creating multiple pellet fuels for specific regions of Montana. All pellet mixtures would be tested in different stoves for heat output, ash, and emissions. Certified lab results would give a baseline of comparison on all formulations.

## CHAPTER 3

## DRYER FABRICATION AND TESTING

Pellet Drying Process

Due to a lack of a consistent drying process, the moisture content on all pellet formulations varied considerably in previous groups' work [13]. This can be seen by re-visiting Table 7. For this reason and to have a consistent process that would resemble industry practices, a dryer was designed and fabricated with the assistance of student helpers [14]. Moisture was the variable of interest. It must be monitored and controlled. Table 2 shows that PFI requires that utility pellets must have a moisture content less than 10%.

This dryer consisted of a food grade oil drum, a 170 CFM fan, a 600 Watt inline heater, and a humidistat. The 170 CFM fan forced air over the 600 Watt inline heater. The heated air then moved through the pellets. Two construction bricks were placed on their sides at the bottom of the drum and then a piece of expanded metal rested on top of the bricks to allow even flow of air throughout the drum. On the top of the oil drum was a humidistat which had the capability to control the relative moisture in the drum. The air flowed over the pellets and out a vent to the outside of the house [14]. The capacity of this dryer was roughly 150 lbs and drying times were typically between 12 to 16 hours, depending on initial moisture content. Once pellets were extruded from the KL Series pelletizer, they were directly placed in the dryer. Figures 14 through 16 show this dryer in detail.

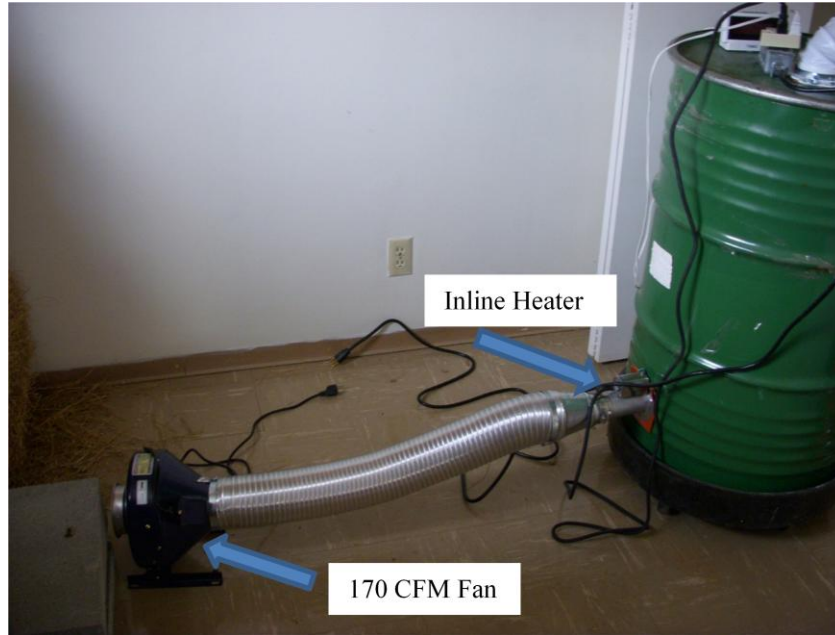


Figure 14: Fan and inline heater setup [14]

As shown in Fig. 14, the fan was connected to the dryer by a section of aluminum vent. The humidistat was connected to a circuit with a fuse that shuts the power off to the inline heater when the humidistat indicates the desired relative humidity in the bin. This prevented over drying in the event that the lab was vacant when the pellets had reached the desired moisture content. It was important, however, to check on the pellets periodically between the 12 and 16 hour mark for completion of the drying. To time the length of drying, a small digital clock was attached to the same circuit as the humidistat and dryer so that the duration of the drying process was known. This clock would also stop when the humidity reached the set value, making it easy to know when the process was complete. Since PFI regulates less than 10% moisture in all utility pellets, the humidistat was set to approximately 8% for all formulations.



Figure 15: Inside of drying bin [14]



Figure 16: Top of dryer and humidistat [14]

Once the pellets finished drying, they were stored in a sealed container to maintain the moisture content achieved in the drying process.

### MVTL Testing

After the dryer was fabricated, 150 lbs of a 50/50 camelina sawdust mixture was extruded to pellets and set to dry to 8% moisture content. After about 12 hours, the pellets were dry and removed from the bin and sealed in a container. A sample was sent to MVTL for analysis. Table 9 gives the results for the dried sample of camelina sawdust pellets as received by MVTL.

Table 10: 50/50 Camelina sawdust pellet results when pressed and dried properly

| Pellet                       | Calorific Heat Output<br>(Btu/lb) | Moisture (wt. %) | Ash (wt. %) | Sulfur (wt. %) |
|------------------------------|-----------------------------------|------------------|-------------|----------------|
| 50/50<br>Camelina<br>Sawdust | 8443                              | 5.79             | 2.63        | 0.45           |

Table 9 shows that the moisture content as received by MVTL was 5.79%. Although the humidistat was set to 8%, it was not a digital control; rather it was an analog knob, so it may have been lower than 8% by the variance on the setting. Also, more drying may occur unless the pellets are sealed with the absence of air. They were sealed, but in a container that had enough air in it to create more drying. This isn't a problem because anything below 10% moisture is acceptable by PFI standards, and in fact allows more heat output.

Once these results were obtained for the final fabricated pellet, they needed to be compared to the results from premium wood pellets and camelina meal itself (as seen in Tables 1 and 3). The comparisons between the three tables lead to some interesting conclusions. The ash on camelina meal alone was 4.43%, and this was roughly cut in half by the addition of 50% sawdust. The sulfur percentage was also cut in half. The heat output of these pellets was higher than premium wood pellets, even though only by a small margin. The tests proved that although the sulfur and ash percentages were still large compared to premium wood pellets, the results from the 50/50 camelina sawdust pellets required more testing before determining the validity of these pellets.

## CHAPTER 4

## ECONOMIC ANALYSIS

Economics plays an essential role in the design process. Rising oil costs have lead Montanans to search for alternative heating sources. This search has led many to the wood pellet, which has been around since the first energy crisis of 1979 [2]. As the demand for wood products has increased, though, the feasibility of an alternative pellet has also become more promising. The primary concern, however, is that the new pellet formulations compare favorably to the premium wood pellets in production and testing. The main properties of the premium wood pellet include: <1% ash content, up to 9200 Btu/lb depending on the brand, and about \$275 per ton (\$0.138 per pound) [3].

The competition for a new integrated fuel pellet in Montana includes existing premium wood pellets made and distributed from Eureka Pellet Mills in Superior, Montana. Their pellets are composed of 100% sawdust from Douglas Fir and/or Lodgepole Pine and have heating values between 8700 and 9200 Btu/lb depending on the moisture content and quality of the specified pellet. If the alternative pellets do not compare to the premium pellets offered by Eureka Pellet Mills, then a lower cost must be realized to help justify the reduction in performance.

Before choosing a specific fuel combination to pelletize, multiple materials needed to be gathered and tested to see if they would offer comparable heating values to premium wood. This information obtained from MVTL Laboratories was reported on an as received basis. Comparing Tables 1 and 3, premium wood pellets and 100% camelina

meal compared favorably. The heat outputs were 9259 Btu/lb compared to 8300 Btu/lb, respectively. The ash content in camelina, however, was considerably higher, 4.4% by weight compared to 0.54%. With a much higher heat output offered by camelina, the higher percentage of ash might be allowable. The primary concern was the considerable increase in sulfur percentages produced by the camelina meal, 0.98% compared to 0.01% for the premium wood pellets. It was assumed that this increase in sulfur would not be acceptable by the EPA when tested for emissions, and would need to be further investigated in future research. Another potential concern was the emission of carbon dioxide into the atmosphere. When emitted from premium wood pellets it is consumed by vegetation, thus adding zero carbon dioxide to the atmosphere. When emitted from other materials, however, it is sequestered carbon dioxide, thus adding to air pollution problems [15].

### The Camelina Pellet Market

There are a few things that are still unknown about camelina, and a major concern is determining the cost of making these pellets. With the removal of the high pressure steam process it is expected that the production price would be significantly less than the wood pellet, but this cannot be assumed until a major economic study is performed on camelina fueled pellets. Another initial concern is if the camelina mixture would be compatible with current stoves. After a few years of testing the mixture, it is clear that it will only burn in the new multi-fuel stoves that are designed to burn a variety of utility pellets. This will drive the cost up for consumers because they would have to buy a new

stove that could handle multi-fuels. For first time purchasers, they would have to weigh the increased cost of the multi-fuel stove to the wood pellet stove with the cost and availability of the fuels offered.

Creosote production is another major concern for the burning of new fuels in multi-pellet stoves. Creosote is a mixture of many chemicals including polycyclic aromatic hydrocarbons, phenol, and cresols created by the high temperature burning of some woods and coal. This mixture of chemicals is very hazardous to the environment. Creosote is a problem with current corn burning stoves, and a stainless steel vent liner is required to prevent premature failure of the ductwork. With the high emission of sulfur and the production of creosote, an increased cost could potentially include a stainless steel liner as well [16].

Another aspect of cost centers on the distribution of pellets around the state. These alternative pellets must be competitive with premium wood pellets at a cost of no more than \$0.10 per pound, so the production and delivery to a potential market must be considered. The premium wood pellet offers very low ash and virtually no sulfur, meaning there must be more incentive for a company like Eureka Pellet Mills to produce these new integrated pellets, for farmers to grow more camelina, and for consumers to purchase the new fuel. Supply and demand and decreased local shipping due to regional production may provide the price reduction incentive needed for consumers while increasing profits for farmers. Table 10 below offers a predicted price of a new 50/50 camelina sawdust pellet fuel and compares that with the price of other common fuels today.

Table 11: Price per million Btu's for common fuels and potential new fuel [3]

| <b>Fuel</b>  | <b>Btu/lb output</b> | <b>Efficiency</b> | <b>Price per ton (\$)</b> | <b>Price Per Million Btu's (\$)</b> |
|--------------|----------------------|-------------------|---------------------------|-------------------------------------|
| Wood         | 8330                 | 80%               | 275                       | 20.96                               |
| 50/50 Pellet | 8449                 | 80%               | 170                       | 12.96                               |
| Electricity  | *N/A                 | 100%              | *N/A                      | 35.17                               |
| Natural Gas  | *N/A                 | 78%               | *N/A                      | 18.51                               |
| Propane      | *N/A                 | 78%               | *N/A                      | 30.74                               |
| Coal         | *N/A                 | 75%               | 250                       | 10.89                               |

\*N/A: Not provided as a measure for this type of fuel

The table shows that the only fuel on the market today that offers a lower cost than the predicted cost of the new pellet fuel is coal. The dirty burn characteristics of coal, however, are frowned upon by the EPA and other clean air organizations. The predicted price of the 50/50 camelina sawdust pellets would make them the most cost efficient heat supply on the market.

The 50/50 camelina sawdust pellet could be pressed and shipped from Eureka Pellet Mills since they have all of the equipment necessary, but due to high costs of transportation, offering regional pellet plants could be advantageous to reduce cost. For example, Montana offers a variety of different crops abundant in different parts of the state. To focus on different crops for specific regions of the state and locally shipping those pellets to local sites could utilize other waste materials and reduce cost.

Due to the high cost of pellet milling equipment, using one or two mobile pellet mills might be a great alternative for Montana. These mobile pellet mills would make several trips per year across the state to produce a predetermined amount of pellets needed for a specified region. On site processing would require power and water, an

industrial size mixer, a large grinder or hammer mill, and drying system for the pellets.

The facility will require ample storage area and a bagging system for the pellets.

Shipping from the facility to the surrounding communities would then commence.

A new bio-based fuel could be economically attractive for the State of Montana for many reasons. First, it would give farmers an incentive to grow more camelina or other crops involved in multi-fuel pellet formulations. The current problem with camelina is that farmers are not profiting enough from it because there is so much waste material that comes from the seed after it is pressed. The majority of the resulting meal goes to waste. If a bio-based fuel is derived from this meal, however, farmers would be able to sell this meal and make an increased profit from the crop yield.

The inclusion of wheat straw and safflower is also economically viable for farmers. Wheat straw is a waste product that is very abundant in Montana. Giving farmers an alternative for the straw would increase the profits from the crop. This also applies to safflower. Safflower is similar to camelina in that it is an oilseed crop with no end-use for the leftover meal. If farmers knew that the waste product from the crops mentioned above had value, they would be more inclined to grow such crops.

The inclusion of forest residue in pellet formulations would be very rewarding for the environment. With logging operations comes forest residue. This is a left over waste with no use. Forest residue offers a higher heat output than premium wood but does have a higher percentage of ash. The inclusion of this waste product would encourage logging companies to clean up the forests while creating a market for another waste product.

Another goal of this project that would stimulate profit involves the production of a bio-based waste-derived pellet fuel. Using cardboard in one of the pellet formulations would increase landfill diversion of cardboard. Although some cardboard is recycled and re-used for shipping processes, a large portion of it ends up in landfills. It would then reduce transportation costs, emissions, and fuel use for land filling materials. The use of cardboard would also help Montana reach its Material Solid Waste (MSW) recycling goal described in the Integrated Solid Waste Management Plan [17]. The inclusion of cardboard may also increase the availability of funds for pellet plants, transportation, and the overall costs of transitioning to agricultural fuels instead of wood burning by the Department of Environmental Quality (DEQ).

#### Other Considerations

Neither the use of pellets as heating fuels nor the use of waste materials in fuel alternatives are new ideas. Both have affected world communities in different ways. The incorporation of different waste materials into pellet fuel technology creates exciting opportunities because of worldwide demand for alternatives to fossil fuel heating. However, alternative fuel sources have both positive and negative characteristics based on production processes, environmental concerns, cost issues, etc. Considerations of agricultural waste-derived pellets are discussed below in a number of contexts.

#### Societal Considerations

The use of Montana agricultural wastes in heating fuels impacts the local community in a number of ways. Harsh Montana winters can cause financial burdens on

many families. The use of crop residues as heating sources is advantageous simply because of the potential low costs inherent in obtaining them. This creates opportunities for producers because of an increased demand for materials that would otherwise have little value. Also, from a production standpoint, supply of these crop residues and waste materials is exceedingly abundant, again lowering cost of producing the pellets. The growth of camelina could have an impact on the agricultural community as well. If the crop growth keeps expanding, it may hinder the production of other crops, which could affect the price of other crops due to supply and demand. Since camelina has the ability to be grown on land that has prior difficulty sustaining crops, it is believed that the crop will be an addition to the annual yield, not a substitution. One other societal consideration would be odors and pollutants emitted from smoke stacks when burned. Camelina has an unpleasant smell and emits more sulfur than premium wood, and if burned on a large scale may become pungent and harmful to the community.

### Global Considerations

Alternative fuel sources are in high demand as oil and other fossil fuel prices increase. Waste-derived pellets may create a low-cost, simply produced fuel source that can be put to use world-wide. Pellet composition can be varied regionally based on available resources; and a simple, uniform production and utilization process can be used in potentially any geographical location. Biodiesel production is the driving force in the growth of camelina, and any additional uses for the meal after it is pressed for the oils would help camelina compete with fossil fuels. Again, large scale pollution would

inherently affect the world, and will be discussed in detail in the environmental considerations.

### Environmental Considerations

Burning fuels inherently creates pollution from an environmental aspect. Emissions standards, ash content, etc. are obvious considerations associated with any type of fuel. Wood pellets generally have very high efficiencies as well as very minimal emissions. Waste-derived pellets should be able to compete closely with wood pellets and therefore need to perform similarly with regard to environmental aspects. Due to the fact that camelina is so high in sulfur content (refer to Table 3), concerns arise with respect to SO<sub>2</sub> emissions, a potentially hazardous gas. SO<sub>2</sub> emissions must therefore be limited or techniques to remove these emissions from the exhaust stream must be developed, primarily at the residential level. Another concern that has been recently observed is the presence of chlorine in camelina. Chlorine is another hazardous gas that is very harmful when inhaled. A sample of 50/50 camelina sawdust pellets were sent to MVTL to get tested for chlorine and the results of that test can be found in Appendix A.

The disposal of waste materials from agricultural operations in an organized fashion reduces the amount of less environment-friendly removal practices such as dumping or free burning. However, the use of these crop residues directly competes with emerging agricultural practices intended to improve soil productivity and limit carbon releases into the atmosphere. Providing demand for crop residues increases the cost of practices like no-till conservation tillage, which helps with soil carbon sequestration and

improves soil productivity. These environmental conflicts show a need for balance between beneficial practices concerning agricultural and fueling practices.

## CHAPTER 5

## REGIONAL DISTRIBUTION

Crop Selection

Experimenting with many different formulations of camelina and sawdust pellets with the KL Series pelletizer led to the conclusion of the 50/50 formula being the most competitive to match the performance of the premium wood pellet. To supplement the study further, regionalizing Montana and targeting crops other than camelina was further explored. First, I obtained statistics on what crops have been produced in the past year for Montana. Using the United States Department of Agriculture (USDA) National Agricultural Statistics Survey for Montana, all crop production in Montana for 2007 and/or 2008 was gathered and analyzed, targeting specific counties [18]. A table of all county information and crop yield is located in Appendix B. From the data gathered, it is clear that wheat straw is very abundant in north central Montana, specifically Pondera, Choteau, Hill and Liberty counties. Other crops that were available and applicable to the project included sugarbeet pulp, safflower, and flaxseed. Sugarbeet pulp is readily available in southeastern Montana, including Bighorn and Yellowstone counties. Safflower is abundant in northeastern Montana, namely Richland and Wibaux counties. Flaxseed is abundant in northern Montana, namely Valley and Sheridan counties. From this information, four crops were chosen for further study. A graphical representation of the state and the regional division is depicted in Fig. 17.



Figure 17: Regional breakdown of Montana

In total, six regions were chosen with specific crops targeted in each region.

Table 12 lists each material and the corresponding color and part of the state. In addition to the four crops chosen (wheat straw, sugarbeet pulp, safflower, and flax straw), two other waste materials, forest residue and corrugated cardboard, were added. A detailed description of each material and the process to obtain each material from the specified region is described in the following sections.

Table 12: Description of materials chosen from Fig. 12

| Material             | Location      | Color       |
|----------------------|---------------|-------------|
| Sugarbeet Pulp       | Southeastern  | Cyan        |
| Safflower            | Northeastern  | Blue        |
| Wheat Straw          | North Central | Green       |
| Flax Straw           | Northern      | Orange      |
| Forest Residue       | Western       | Yellow      |
| Corrugated Cardboard | South Central | Light Green |

### Private Companies Involved

Once all materials for study were identified, establishing contacts that could provide each material was needed. Along with providing materials, finding potential facilities where future pellet production could take place was also investigated. A list of private companies assisting with the goals of this project is below.

- North Dakota Innovations, Tappen, ND—Flax Straw
- Western Sugar, Billings—Sugarbeet Pulp
- Osler Logging, Bozeman—Forest Residue
- Montana Specialty Mills, Great Falls—Safflower and Flax
- Safflower Technologies, Fairview—Safflower
- Montana Container, Bozeman—Corrugated Cardboard
- Montana State University—Camelina Meal

Along with the benefits of utilizing all of the products mentioned above, this project could create jobs in Montana while providing an alternative fuel source to wood. Eventually, as the project progresses, these new multi-fuel pellets also have the potential to provide an excellent export for Montana.

### Obtaining Materials

To obtain the materials needed from Fig. 17, a meeting with each potential client was scheduled. It was important to meet them in person, obtain the materials of interest, and discuss the possibility of future collaboration in their region.

The first product pursued was wheat straw. Although wheat straw can be used as a feed, it is so abundant that another market for it is desirable. With the help of Dr. Mike Vogel and the extension services of Montana State University [19], it was determined that a sustained source of wheat straw could come from Conrad, Montana. Conrad is in Pondera County, and Cheryl Curry of the Pondera Regional Port Authority helped obtain the material and had a few different available facilities for future production of pellets. Working with local farmers, Dan Picard of the extension service office obtained a bale of wheat straw. Possible local facilities were considered and there were multiple matches to the requirements listed in Chapter 4. The wheat straw was obtained and taken back to Bozeman for further analysis and testing.

Flax straw was initially pursued in Valley County, but after talking with a few MSU extension offices in the area it became clear that flax straw was being produced less and less the past few years in Montana. More research pointed to high volumes of flax that are grown in North Dakota. Contact was made with North Dakota Innovations, of Tappen, ND and they said they would provide flax straw for testing [20]. The meal from flax seed is used as a feed, but the straw is difficult to re-till and an annoyance to farmers. Finding an alternative end use for the straw would help increase production in Montana and increase profits for farmers. Unfortunately, North Dakota Innovations never sent the straw and contact was lost, so it was not pursued further. If flax production starts to rise in northern Montana, more research should be done on the flax straw and its possibility as a component in multi-fuel mixtures.

Sugarbeet pulp is very prominent in southeastern Montana, and the pulp is fed to livestock. Although there is already a market for this material, another niche market may increase the supply and demand for this product, resulting in more profits for farmers. Western Sugar in Billings is a major supplier of sugar all over the United States and has large supplies of pulp in the fall. Contact was established with Thomas Lee of Western Sugar [21] and he agreed to supply sugarbeet pulp for testing. Since the pulp was not available until approximately September, 150 lbs of pellet feed was obtained instead. The pellets are produced on site and then sold to farmers as feed. No facilities were investigated for future production. This would be required if sugarbeet pulp becomes relevant in pellet fuels.

Forest Residue is a waste product mainly located in the western part of Montana. Due to the pine beetles killing a good portion of the pine trees in the state, there is a significant demand for logging. After loggers remove trees, there are large amounts of leftover bark, branches, and stumps that can be chipped and used to make pellets. Jeremy Osler, of Osler Logging in Bozeman [22], agreed to provide a sample of wood chips for the study. Forest residue is an important part of the pellet market, and even Eureka mills uses forest residue in lower grade pellets. While forest residue offers more heat energy than sawdust, it is also much dirtier and the fuel has a tendency to produce clinkers when burned. Once again no facility was considered for the production of forest residue. However, if forest residue is proven to be a viable candidate for multi-fuel mixtures, a location around Helena would be ideal.

Safflower, grown mainly in Northeastern Montana, is another oilseed with many uses including vegetable oils, birdseed, and the meal. The oil consists of two types of varieties of the plant. Oleic safflower is very high in monounsaturated fatty acids and Linoleic safflower is high in polyunsaturated fatty acids. The oil market is currently strong for oleic safflower. Oleic oil is a beneficial agent in the prevention of coronary heart disease and is used in cooking, cosmetics, and food coatings and infant food formulations. Recently, the demand on linoleic safflower has reduced mainly to drying agents in paints and varnishes because of its nonyellowing characteristic [23]. The meal has around 24% protein and is high in fiber, so it is used as a protein supplement for livestock and poultry feed. Lastly, safflower is used in birdseed [23].

The climate of North Dakota better suits safflower than Montana, and is grown much more there. However, Safflower Technologies, of Fairview, Montana, does produce safflower and uses it as birdseed [24]. Jerry Bergman of Sydney, Montana obtains meal from them and has recently tested it. Although a visit to Sydney was not taken, Jerry sent 100 lbs of oleic safflower to Bozeman, Montana for testing. Montola Growers Inc. of Culbertson, Montana [25] grows and processes safflower, and could be involved if safflower becomes a viable option for multi-fuel formulations. Montana Specialty Mills is another provider of safflower and is located in Great Falls, Montana [26]. They deal strictly with organic safflower and also limited flax meal. A meeting was arranged with Montana Specialty Mills after which 50 lbs of flax meal was obtained for testing.

The last component of these multi-fuel pellets is corrugated cardboard.

Cardboard is currently being recycled, but eventually still manages to pile up in landfills across the country. There is a large demand for another use for cardboard, and the involvement in multi-fuel pellets is possible. Utilizing up to 10% cardboard in each pellet formula could prove advantageous while decreasing the amount of waste cardboard in landfills today. Montana Container in Bozeman [27] specializes in corrugated cardboard boxes and offered a future supply of cardboard for multi-fuel pellets. If cardboard is proven to be a viable additive in a pellet formulation, a better option for obtaining the material would be to get it from recycling centers or special bins set up for this type of operation.

#### Hammer Mill Grinding

In order to make pellets out of the materials gathered from the specific regions, they needed to be ground to a powder form so that an even mixture of camelina and the material would produce a consistent pellet. In order to accomplish this, a C.S. Bell Model 20 hammer mill with carbon steel contact parts was ordered from a used equipment company in California [28]. The mill has a 5 hp, 220/440 V 3 phase motor with a v-belt drive. The mill was received, but due to possible contamination of soils and the lack of storage space, the location of the mill could not be placed in the Plant Growth Sciences building on campus. Another option was to place it in the laboratory, which offered 240 Volts single phase electric power (the lab used for this project was an old abandoned graduate house). This required a new motor for the mill, and a L1410T

Baldor motor was ordered from Motion Industries in Billings [29]. With the help of Service Electric in Bozeman [30], the starter for the motor was converted to operate on 240 single phase electric power, and the mill was installed where the dryer outlet was in the house.

The next issue involved the screen that filters the ground material. It was fabricated from 12 gauge (.104 inches thick) steel with  $\frac{1}{4}$  inch diameter holes. In order to get the material even more fine, a sheet of stainless steel type 304 was ordered from McMaster Carr [31]. The sheet had a staggered hole pattern and  $\frac{1}{8}$  inch diameter holes with 40% open area. Since 12 gauge was not available for this type of metal, 14 gauge (0.075 inches thick) was used. The different in thickness of the new screens could cause a problem because the screen could be damaged by the material with enough friction. Midwest Welding of Bozeman cut and rolled two screens from the sheet for the mill. Two screens were cut from the sheet so that if one failed there would be a backup.

The process of a hammer mill is quite simple and works on the principle that most materials will crush upon impact using a three step operation. Figure 18 shows a typical hammer mill schematic. First, material is fed through an opening at the top of the mill and gravity carries it to the chamber. Here, the material is struck by rectangular pieces of hardened steel which are attached to a shaft that rotates at high speeds inside the chamber. The repeated impacts of the material with the hardened steel hammers results in finely ground material [32]. Right below the chamber is a perforated metal screen, and as the material gets pulverized, it passes through the screen and is discharged at the bottom of the mill. The size of the holes in the screen determines how finely ground the

finished product will be. Figure 19 is a picture of the mill that was installed in the lab, and that mill matches the description of the mill in Fig. 18 very well.

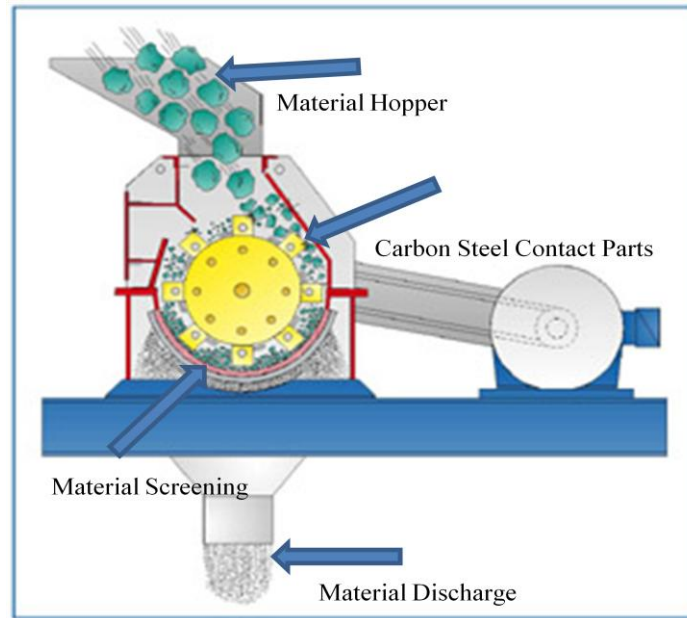


Figure 18: Typical hammer mill process diagram



Figure 19: Hammer mill installed in lab

The mill that was ordered fits the typical schematic almost exactly. The material is fed through the top, and a shield keeps any material from ejecting and causing injury during the hammering process. Using the mill, the forest residue, safflower, corrugated cardboard, and wheat straw were all ground. All of the materials except the safflower were so lightweight that once they passed through the screen they were pushed out the side of the mill by moving air instead of being discharged out the bottom. To accommodate that, a food grade oil drum was used to catch the material using a simple vent to connect the blower output to the tank. After each material was pulverized, it was removed from the tank and stored in a five gallon bucket until it was ready to pelletize.

## CHAPTER 6

## FINAL PELLET FORMULATIONS

MVTL Results

Once all of the materials (forest residue, corrugated cardboard, safflower, wheat straw) were ground up, pellet fabrication and testing could commence. Many different formulations were pelletized and analyzed for density, moisture, strength and durability. The mixture sizes were minimal, usually five pounds total, to minimize waste and time needed to press and dry them. Materials included flax meal, oleic safflower meal, forest residue, wheat straw, corrugated cardboard, and sugarbeet pulp. All formulations were still combined with camelina, and typical variations ranged from 20% to 80% camelina. Some formulas were discarded after being dried because they did not pass the density or durability tests. Once the mixtures were finalized as much as possible, they were sent to MVTL to see if initial results were encouraging enough to pursue the formulation as a possible multi-fuel pellet. Table 13 gives the results from MVTL as received and Table 14 gives the normalized results for moisture content. For comparison, premium wood and the 50/50 camelina sawdust pellets were again included in the table.

The normalized moisture results are very important because they allow for the prediction of heat output, ash, and sulfur percentages for any formulation. However, two data points is insufficient to form relevant visual graphs. Thus, the 50/50 camelina sawdust pellets would again be the basis for comparison since there were multiple tests done with different moisture contents on that pellet formulation.

Table 13: MVTL results as received on all pellet formulations

| Pellet Formulation            | Total Moisture (wt. %) | Ash (wt. %) | Sulfur (wt. %) | Calorific Value (Btu/lb) |
|-------------------------------|------------------------|-------------|----------------|--------------------------|
| Premium Wood                  | 7.05                   | 0.54        | 0.01           | 8330                     |
| 50/50 Camelina Sawdust        | 5.79                   | 2.63        | 0.45           | 8449                     |
| 80/20 Camelina Cardboard      | 11.36                  | 5.29        | 0.66           | 8471                     |
| 50/50 Camelina Forest Residue | 6.57                   | 2.22        | 0.41           | 8647                     |
| 50/50 Camelina Safflower      | 7.58                   | 4.25        | 0.55           | 8914                     |
| 80/20 Camelina Wheat Straw    | 6.61                   | 4.53        | 0.69           | 8739                     |
| 50/50 Camelina Flax Meal      | 9.19                   | 5.43        | 0.57           | 8851                     |
| 70/30 Camelina Sugarbeet      | 12.81                  | 6.69        | 0.49           | 7344                     |
| 50/50 Camelina Sugarbeet      | 10.61                  | 7.62        | 0.42           | 7277                     |

From Table 13, the formulation that appeared closest to the 50/50 camelina sawdust pellet was the 50/50 camelina forest residue pellet. As expected, the ash percentage was about the same and the heat output was higher. The 80/20 camelina cardboard pellet retained too much moisture, even when dried. The results gave around 11% moisture, which is not acceptable by PFI standards. Further drying would have to be done on that formulation before being acceptable by PFI. Both camelina sugarbeet formulations had the same problem, mainly due to the addition of greater than 20% water before pelletizing. More water had to be added in order to get the sugarbeet pellets back into pulp form before combining it with the camelina. The calculated normalized moisture content results offered by MTVL on both sugarbeet mixtures, however, still offered a lower heat output than premium wood pellets. This, along with the existing

market for the pulp, led to the final discarding of any formulations with sugarbeet pulp. The normalized results for the 80/20 camelina cardboard pellets and the 80/20 camelina wheat straw pellets were very positive for heat output, but very negative for sulfur and ash production. The reason for the higher ash percentages are due to the fact that those formulations are both 80% camelina, thus weighing higher the positive effects of heat output for camelina but also the negative effects of ash and sulfur content. Both of the formulations could include a larger percentage of wheat straw and/or cardboard, but the wheat straw was not completely powdered, making it difficult to obtain a high density mixture. The ground cardboard was best compared to pillow stuffing; very lightweight and low in density. Thus, the higher weight percentage of cardboard will lower the density of the pellets significantly.

Table 14: MVTL results normalized for moisture content on all pellet formulations

| Pellet Formulation            | Total Moisture (wt. %) | Ash (wt. %) | Sulfur (wt. %) | Calorific Value (Btu/lb) |
|-------------------------------|------------------------|-------------|----------------|--------------------------|
| Premium Wood                  | 0                      | 0.58        | 0.01           | 8962                     |
| 50/50 Camelina Sawdust        | 0                      | 2.79        | 0.48           | 8968                     |
| 80/20 Camelina Cardboard      | 0                      | 5.97        | 0.74           | 9556                     |
| 50/50 Camelina Forest Residue | 0                      | 2.38        | 0.44           | 9255                     |
| 50/50 Camelina Safflower      | 0                      | 4.6         | 0.6            | 9645                     |
| 80/20 Camelina Wheat Straw    | 0                      | 4.85        | 0.74           | 9358                     |
| 50/50 Camelina Flax Meal      | 0                      | 5.98        | 0.63           | 9746                     |
| 70/30 Camelina Sugarbeet      | 0                      | 7.67        | 0.56           | 8423                     |
| 50/50 Camelina Sugarbeet      | 0                      | 8.52        | 0.47           | 8141                     |

Analyzing both Tables 13 and 14, some important conclusions can be drawn. First, the finalized 50/50 camelina sawdust pellets yield as much heat output as premium wood pellets. Initial predictions were that the high heat output from the camelina meal would dominate, but the results show otherwise. However, with higher densities and more sophisticated equipment, the calorific values in Tables 13 and 14 for all camelina fueled pellet formulations should increase significantly. The 50/50 camelina forest residue pellets compared well to the 50/50 camelina sawdust pellets, and actually performed better in sulfur percentage, heat output, and percentage of ash. Although the ash percentage should be higher, the forest residue obtained was mostly branches, keeping the fuel mixture cleaner than expected.

The results are very encouraging because the data shows that forest residue would be a cheap alternative to sawdust, and it is readily available. The results from the sugarbeet formulations were discouraging, thus confirming the removal of sugarbeet pulp as a possible additive in pellet fuels. The 80/20 camelina cardboard and camelina wheat straw pellets also showed discouraging results. Future addition of cardboard or wheat straw by up to 10% in the 50/50 camelina sawdust or camelina forest residue pellets might offer a superior pellet and help to reduce these two waste products. The 50/50 camelina safflower pellets exhibited double the amount of ash as the sawdust and forest residue pellets, but did offer a much higher heat output. Due to the small supply of safflower in Montana, it may be better suited for its current applications and removed as a candidate for multi-fuel pellets.

## CHAPTER 7

## RESIDENTIAL STOVE SELECTION

To complete the study on all of the integrated formulas produced, burning them in residential pellet stoves was studied. First, two different types of stoves needed to be acquired. The purpose of testing two different types of stoves would be to provide manufacturers and consumers' information on what types of stoves would efficiently burn multi-fuel pellets. After some preliminary research, two stoves from different companies were selected for the study; a Quadra-Fire MT Vernon Advanced Energy pellet stove [33] and a Harman P68 pellet stove [34]. These stoves were chosen before the work on the project commenced [13].

Quadra-Fire MT Vernon Stove

The MT Vernon advanced energy stove, of Hearth & Home Technologies, was made to burn a wide variety of pellet fuels including wood, shelled corn, sunflower seeds, and wheat. The stove offers a digital control where the fuel type is specified and the stove automatically adjusts for a maximum efficiency burn. Some standard features include up to 60,200 Btu/hr input, between 81.4% and 83.6% overall efficiency, a cast iron fluted fire back, an airfoil heat exchanger to maximize heat transfer, and a firepot auto clean system. The maximum Btu/hr input for utility pellets is 54,000, compared to the softwood maximum listed above (60,200 Btu/hr). The heating capacity is between 2400 and 3800 square feet and the stove utilizes a 220 cubic feet per minute convection

air blower [33]. The hopper capacity is 81 lbs. The electrical rating on the stove is 115 VAC, 60 Hz, startup of 5 Amps and a run draw of 1.25 Amps. The stove was tested and certified by OMNI-Testing Laboratory [33]. It has a cast iron shell and a 5 mm ceramic glass front plate. The base cost of the MT Vernon Stove is \$3,899, but purchasing the stove in 2009-2010 qualifies consumers for a U.S. federal tax credit for 30% of the cost of the stove. This credit is part of the American Recovery and Reinvestment Act and would save \$1170 if the very basic MT Vernon was purchased [33].

The MT Vernon stove utilizes a 4-point combustion system for a clean, efficient burn. Figure 20 gives a schematic of the stove and the combustion system.

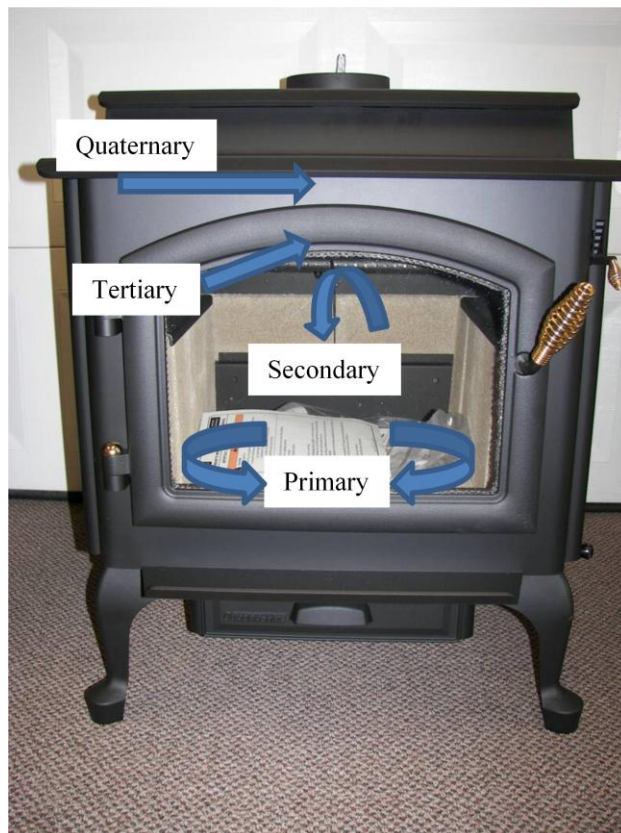


Figure 20: MT Vernon 4-point combustion system

Air flows into the heart of the fire, which is the primary burn zone, and in the secondary zone a shield of air behind the door aids combustion and helps keep the glass clean. The tertiary section is under the baffle and superheated air ignites flammable gases rising from the wood, further cleaning the air being burned. Lastly, the quaternary section burns the remaining impurities above the baffle before they escape to the chimney. Other features of the stove include a top fed auger system that drops pellets from the top of the stove into the burn pot. Also, the burn pot utilizes an auto clean system that automatically opens and drops the ash into an ash drawer. This automatic cleaning system maximizes flame temperature while minimizing the production of clinkers [35].

#### MT Vernon Apparatus and Setup

Before testing the stove, research had to be done on the best way to calculate the heat transfer from the stove. To calculate the heat transfer due to convection air into the room, the mass flow rate of air and the temperature of the air entering and leaving the stove had to be determined. To determine the temperatures at various points on the stove, Type K thermocouple wire was purchased, cut into sections, soldered into thermocouples, and put in an ice bath to reference them to a freezing point temperature. To measure the temperature of the thermocouples automatically, an Agilent data acquisition system was purchased and installed at the laboratory and monitored via computer. Next, the number and placement of thermocouples needed to be determined. For the forced convection air, one thermocouple was placed at the entrance of the airstream, which was extended by use of venting and 4 inch diameter PVC piping. High temperature tape was used to seal the

dryer vent to the 220 CFM convection fan and to the 4 inch PVC piping. The second thermocouple measured the output temperature to the room. It was placed in the center of the output air stream. This would be the hottest point of the output convection air, so the heat output would not be entirely accurate according to the manufacturer's ratings, but only to the comparison between the fuels under study.

To measure the mass flow rate, a more complicated system was required. A series 160 stainless steel Pitot tube (1/8 inch diameter) was purchased from Dwyer [36] and connected to two micro-manometers. The purpose of a pitot tube is to measure the total pressure of an air stream in a duct as the sum of the static pressure and the bursting pressure exerted upon the sidewalls of the duct and the velocity pressure of the moving air. The micro-manometers were required to externally measure the difference between the static pressure and stagnation pressure by viewing changes in heights of water columns. For an accuracy of plus or minus 2%, the duct diameter needed to be 30 times the pitot tube diameter and a smooth straight duct section with a minimum of 8.5 diameters in length upstream and 1.5 diameters downstream from the Pitot positioning was required. The diameter of the PVC duct was 4.25 inches, satisfying the requirement of 3.75 inches, and the length of the duct downstream versus upstream was 19.5 inches and 56.5 inches, respectively. Both lengths satisfied the required lengths downstream and upstream of 5.6 inches and 31.9 inches [36]. The micro-manometers were calibrated and a simple test on an air blower was performed to verify the accuracy of the Pitot tube and manometer setup. Figure 21 gives a picture of the micro-manometers and Pitot tube setup.

Once the mass flow rate from the convection air was ready to be calculated, the radiation from the ceramic glass and steel sides of the stoves needed to be determined (all measured and calculated properties will be discussed in Chapter 8). To measure the radiation, only the temperature of the surfaces needed to be known. Again, Type K thermocouples were mounted at various positions on the stove to aid in the calculation of radiation. Using symmetry as an assumption, only one side of the stove needed to be equipped with thermocouples. When all of the preliminary setup was finalized, a total of 8 Type K thermocouples were attached to the stove. To fix these on the ceramic glass surface, high temperature epoxy was applied. To fix the thermocouples on the steel chamber side, high temperature tape was again used. There were 3 thermocouples installed on the ceramic glass and 3 on the chamber side, with one at the convection air input and one at the output.

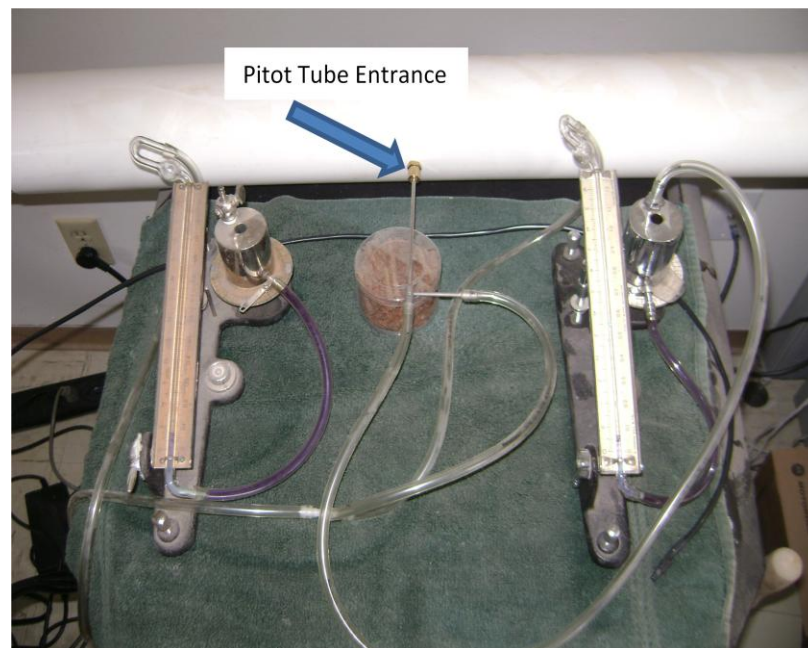


Figure 21: Micro-manometers and Pitot tube setup

### MT Vernon Burn Test Procedure and Settings

When the two stoves were acquired, the MT Vernon stove was tested first. The testing procedure consisted of the following. The first pellet tested on the stove was the premium wood pellet to achieve the base of comparison for the remaining formulas. First, the stove was powered up and given a few minutes to warm up. Then all settings were controlled from the digital system control. Second, the fuel type had to be chosen. To do this, push menu, then highlight “fuel type” using the up/down buttons and press select. Scroll down until you find “softwood pellet” and press select. After that a message prompts the user to make sure the hopper and firebox are clean of any other fuels. Since this was the first test on the stove, it didn’t have any prior fuels. It is now time to load the pellet fuel.

Each test consisted of ten pounds of the given formula, so in this case ten pounds of premium wood pellets were measure and loaded into the hopper and the hopper lid closed. Going to the starting screen on the digital system control, press menu and select “auto/manual/off.” Select manual and press select, then hit done twice to get back to the main screen. With a temperature default of °F, no adjustments are required. The temperature of the room needed to be monitored and controlled, and it was decided that holding the room at 70° F would offer realistic heating conditions. The stove could have been held at maximum performance but this was not the purpose of the study, rather the goal was to understand how other pellet formulas perform with respect to premium wood pellets in residential homes. To set the room temperature at 70° F, press and hold “up” or “down” button from the home screen to change the temperature and then press the “hold

temp” button and press done. The only other setting necessary was the heat output of the stove. Again, to simulate consumer use, the stove was set at medium heat output, which was the default on the stove.

With the ten pounds loaded and all of the settings secure, the stove automatically starts up to the given conditions. For premium wood pellets, this usually took only a few minutes, but for multi-fuel pellets it took longer. When testing other pellet mixtures, all of the settings were the same except the “fuel type.” This was changed from “softwood pellet” to “utility pellet.” The stove usually took between five and ten minutes to ignite the multi-fuel pellets.

All temperature data was gathered via computerized data acquisition. Manual readings had to be taken from the micro-manometers, and the multiple readings were taken at steady state operation to ensure accuracy of the mass flow rate calculations. When a test was finished, all of the remaining pellets were unloaded from the hopper and weighed. This gave the total amount of fuel burned and from there a rate of fuel burned (lbs/hr) could be determined. The ash was also removed from the ash tray and weighed to give a percentage of ash from the fuel.

#### Harman P68 Stove

The Harman P68 pellet stove, also of Hearth & Home Technologies [34], was made to burn any grade of pellet at maximum efficiency. This stove features an Exhaust Sensing Probe (ESP) which controls the exhaust temperature and shuts down the motor automatically if a predetermined high limit temperature is reached. The stove uses a

small temperature sensing probe instead of a thermostat that sends information to a microprocessor on the stove to insure the proper feed of fuel at any time. The stove also allows for a stove temperature mode that allows the stove temperature to be set and controlled, versus the room temperature. The convection air blower provides 135 CFM, and the hopper holds up to 76 lbs of pellets. The stove offers a maximum heat output of 68,000 Btu/hr and the heating capacity is 2,200 square feet and up. The fuse is rated at 6 Amps, and the stove was tested and certified by OMNI-Test Laboratory [34].

The stove utilizes a bottom feed auger, where the pellets are fed in horizontally. The ash is either pushed out or blown out of the burn pot to the ash chamber below. It also offers an accordion style heat exchanger, which increases surface area in small areas to maximize heat transfer efficiency. The P68 Harman stove also qualifies for the tax credit offered by the American Recovery and Reinvestment Act. At a base price of \$3199, the tax credit of 30% would be \$959 in savings.

#### Harman P68 Apparatus and Setup

The same techniques used on the MT Vernon stove were used on the Harman stove. The convection air was measured the same way, with use of the Pitot tube, micro-manometers, and two Type K thermocouples. The radiation, however, required more thermocouples due to more heating surfaces. The stove radiated heat from the glass plate, and the steel top, side, and bottom side. Symmetry was once again assumed for the radiation on the steel plates, so only one side of the stove was mounted with thermocouples. Due to the higher temperatures achieved by the steel sides of the stove,

high temperature epoxy was used for all thermocouple attachment. Three were positioned on the glass plate, three on the main chamber side, one on the bottom chamber side, and two on the top of the chamber. These, along with the two used to measure the convection, resulted in 11 Type K thermocouples compared to 8 for the MT Vernon stove.

#### Harman P68 Burn Test Procedure and Settings

The setup for the Harman stove was quite different than the setup for the MT Vernon stove. Once all testing was completed on the MT Vernon, it was disconnected from the outside venting, and all testing apparatus was removed. Then the P68 stove was inserted into the vent and all thermocouples and ducts mentioned above were attached. The Harman stove did not offer a digital control panel, rather just a board with temperature, blower speed, igniter, and feed adjuster controls. There were no controls for different fuels. To begin testing, the stove was powered up and given a few minutes to warm up. A status light on the board blinks when an error has occurred, and if no error lights are visible, then testing is ready to commence. As with the MT Vernon, 10 pounds of premium wood pellets were loaded into the hopper. The feed adjuster was set at 4 on a scale of 1-6 as recommended by the manual. The temperature dial was set at 70° and the blower was set to medium on room temperature mode. These settings offered the closest comparison to the MT Vernon settings. The stove only took a few minutes to start the premium wood pellets, but it was delayed significantly for the integrated fuels. The data acquisition system was initiated when the test was started and the duration of the test was

again around three hours. The micro-manometers were checked during steady state operation to obtain the mass flow rate of the convection air blower. After the test was done, the amount of fuel burned and percentage of ash were calculated via the same techniques as for the MT Vernon stove.

#### Bacharach Environmental Combustion Analyzer Model 450

The inclusion of emissions testing was very important in the results of the fuels and a Bacharach Environmental Combustion Analyzer (ECA) 450 [12] was lent to the project by Dr. Vic Cundy, a professor of Mechanical Engineering at Montana State University. The analyzer measured and displayed O<sub>2</sub> and CO in the flue gas, primary air temperature, and stack temperature. It then calculated combustion efficiency, and percentages of excess air and CO<sub>2</sub>. It also had the capability to measure NO, NO<sub>2</sub>, and SO<sub>2</sub> but the sensors and control boards for these capabilities were not installed. Since camelina contains high percentages of sulfur and this is a concern of the EPA, the analyzer was sent back to Bacharach and the capability for sulfur compounds was installed on the equipment.

Once the analyzer was returned to the lab, it had to be set up to take measurements in the combustion exhaust. To do this, a hole had to be drilled in the exhaust piping so the probe could be installed. This hole was about a ½ inch in diameter, and the probe could then be installed into the exhaust. To stabilize the probe in the center of the exhaust stream, it was centered in the pipe and secured with a set screw mechanism

on the probe wand. Testing could then be accomplished for heat output and emissions on all pellet formulations and then compared to premium wood.

### Gas Descriptions

Gases measured by the ECA 450 are the following. Oxygen ( $O_2$ ), carbon monoxide (CO), and carbon dioxide ( $CO_2$ ) are all present in the flue gas and measured by the analyzer. These 3 gases determine the combustion efficiency. For hydrocarbon fuels the efficiency will be 100% theoretically if the oxygen is minimized and the carbon dioxide is maximized. In a stoichiometric mixture, all of the fuel and oxygen combine to generate heat, water, carbon dioxide, nitrogen, argon, and a few other components of air. Smoke is the indicator of incomplete combustion and the lower the stack temperature, the higher the combustion efficiency because less heat is lost up the stack. Carbon monoxide is a very toxic gas that results when there is not enough oxygen to allow for complete combustion of the fuel or when there is inadequate mixing of the fuel and air [12].

Other gases measured include Nitric Oxide (NO), Nitrogen Dioxide ( $NO_2$ ), and Sulfur Dioxide ( $SO_2$ ). Nitric Oxide and Nitrogen Dioxide are toxic gases which constitute  $NO_x$  during the combustion processes.  $NO_x$  emissions contribute to the formation of acids in the earth's atmosphere and can react with hydrocarbons and sunlight to produce smog. Typically NO comprises over 95% of the  $NO_x$  found in the stack gases but a significant amount of NO converts to  $NO_2$  in the atmosphere [12]. Sulfur dioxide is emitted due to the glucosinolates in the camelina plant. It is very harmful to the respiratory system and is regulated very closely by the EPA [9]. Chlorine is also a concern, but Bacharach has no capability to measure chlorine emissions.

## CHAPTER 8

## RESIDENTIAL STOVE RESULTS

Equations Used

After gathering all of the data, it was arranged in an excel worksheet. MathCAD was used to obtain the convection and radiation heat transfer values for each mixture. All calculations were for stove operation at steady state. The temperatures for all thermocouples were averaged over the steady state time of operation to obtain one final temperature applied in calculation. The calculations and relevant data are shown in Appendix C.

Pellet Burn Rate and Percentage of Ash

Equations 1 and 2 below show the calculations for percentage of ash and burn rate of the fuel used. This required external measurements after the burn was finished, including the amount of pellets left over in the stove and the amount of ash collected in the ash bin below the burn pot. The units of Eqns. 1 and 2 are lbs and lbs/hr, respectively.

$$\%ash = \left( \frac{\text{TotalAsh}}{\text{Amount Burned}} \right) \cdot 100 \quad (1)$$

$$\text{Burnrate} = \frac{\text{AmountBurned}}{\text{Time}} \quad (2)$$

Where %ash is the total ash (weight) divided by the amount of fuel burned (lbs). The Burnrate is the amount of fuel burned (lbs) divided by the time it took to burn the fuel (hrs).

### Convection Heat Transfer

These equations and constants were acquired from the Incropera heat transfer book [37] except for the Pitot tube calculations, which were provided with the manufacturer's instructions [36]. Average temperatures at steady state were used. From the operating instructions handout from the Pitot tube, Eq. 3 gives the calculated air density in lb/ft<sup>3</sup>.

$$\rho = 1.325 \frac{P_B}{T_{absF}} \quad (3)$$

Where  $P_B$  is the barometric pressure measured from a small barometer or inches of mercury and the reference temperature is measured on the absolute scale. From Eq. 3 the velocity of the air through the pipe can be calculated in Eq. 4 with units of ft/min.

$$v = 1096.2 \sqrt{\frac{P_v}{\rho}} \quad (4)$$

Where  $P_v$  is the velocity pressure in inches of water measured by the two micro-manometers, and  $\rho$  is the density calculated in Eq. 3. Once the velocity is calculated, the mass flow rate and resulting convection heat transfer can be calculated using Eqns. 5 and 6 with units of lbm/s and Btu/hr, respectively.

$$\dot{m} = \rho \cdot A \cdot v \quad (5)$$

$$q = \dot{m} \cdot c_p \cdot |T_{out} - T_{in}| \quad (6)$$

Where  $\rho$  is the density,  $A$  is the area of the pipe ( $\pi/4 \cdot d^2$ ), and  $v$  is the velocity calculated in Eq. 4. In Eq. 6,  $c_p$  is the specific heat of air found in the heat transfer book. This value changed slightly at different output air temperatures by linear interpolation from table values.  $T_{out}$  and  $T_{in}$  are the averaged temperature values used from the data for the convection air input and output.

#### Radiation Heat Transfer

The radiation calculations required multiple calculations using the same equation for different surfaces on the stove. The temperature of the specified surface was the average over the surface of the measured steady state temperatures. The general equation for radiation heat transfer in Btu/hr is below in Eq. 7.

$$q = \varepsilon \cdot A \cdot \sigma \cdot (T_{surface}^4 - T_{surr}^4) \quad (7)$$

Where  $\varepsilon$  is the emissivity of the material,  $\sigma$  is the Stefan-Boltzmann constant,  $A$  is the surface area,  $T_{surface}$  is the temperature of the surface of interest and  $T_{surr}$  is the temperature of the surrounding air. For ceramic glass, the emissivity was 0.95 and for stainless steel it was 0.22 for bare stainless steel (MT Vernon Stove). The Stefan-Boltzmann constant has a value of  $5.67 \cdot 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ . The radiation from the glass plate was added to 2 times the value of the steel surface (due to symmetry) and then

totaled in Btu/hr. The total heat transfer became the addition of the convective heat transfer and the radiation heat transfer. Equation 8 below gives that formula.

$$Q_{\text{total}} = q_{\text{rad}} + q_{\text{conv}} \quad (8)$$

Equation 9 calculates the percentage of heat due to radiation. This subtracted from 100 yields the convective contribution.

$$\% \text{Rad} = \frac{q_{\text{rad}}}{Q_{\text{total}}} \cdot 100 \quad (9)$$

### MT Vernon Stove Results

Calculations were performed on all pellet formulas burned in each stove and then compared. One consideration that had to be addressed was the variance of the outdoor air temperature and the effect on the output of the pellet stove. The convection air moving through the stove was not vented to the outside air as recommended by the manufacturer. Although that method is used to maximize efficiency, using the inside air minimizes the need to correct for variance in outdoor air temperature. To prove this, two different tests were run on the stove with the 50/50 camelina sawdust pellets varying only the outdoor air temperature. The first test was run with an outside temperature of 32° F and the second test was run with an outside temperature of -4° F. The data was then processed and can be seen below in Table 15. The minimal differences in heat transfer from the two different tests allowed for the elimination of outdoor normalization.

Table 15: Burn comparison at different outside temperatures

| Test            | Convection Output Temp | Glass Plate Temp | Stainless Steel Temp | Total Heat Transfer |
|-----------------|------------------------|------------------|----------------------|---------------------|
| Toutside= -4° F | 223.65° F              | 444.84° F        | 163.46° F            | 2580 Btu/hr         |
| Toutside= 32° F | 220.67° F              | 418.05° F        | 173.62° F            | 2492 Btu/hr         |

The results from Table 15 are presented by first graphing the temperature distribution during the burn and then the steady state temperature distribution. Once this data was found, averages of the data were taken to obtain one single temperature for each thermocouple. Figures 23 and 24 show the temperature distribution and the steady state temperature distribution for the 50/50 camelina sawdust pellets in the MT Vernon Stove for test 1 (-4° F) and Figs. 25-26 for test 2 (32° F), respectively. Table 16 gives a representative sample set of steady state data. The averages used in the equations are shown at the bottom of the Table. The rest of the data can be found in Appendix C with the heat transfer calculations following each set of data.

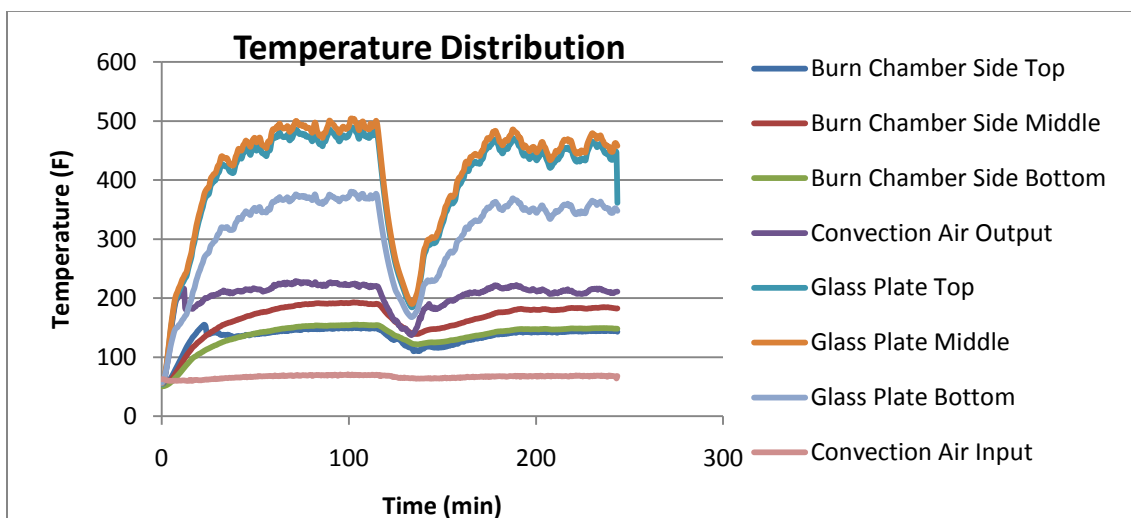


Figure 22: MT. Vernon temperature distribution for Test 1

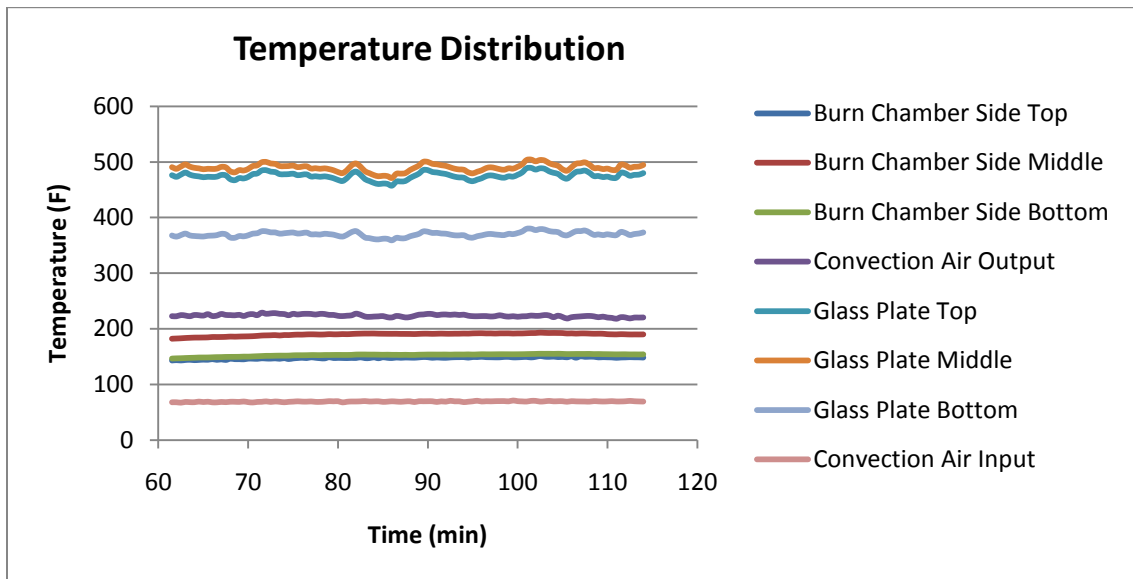


Figure 23: MT. Vernon steady state temperature distribution for Test 1

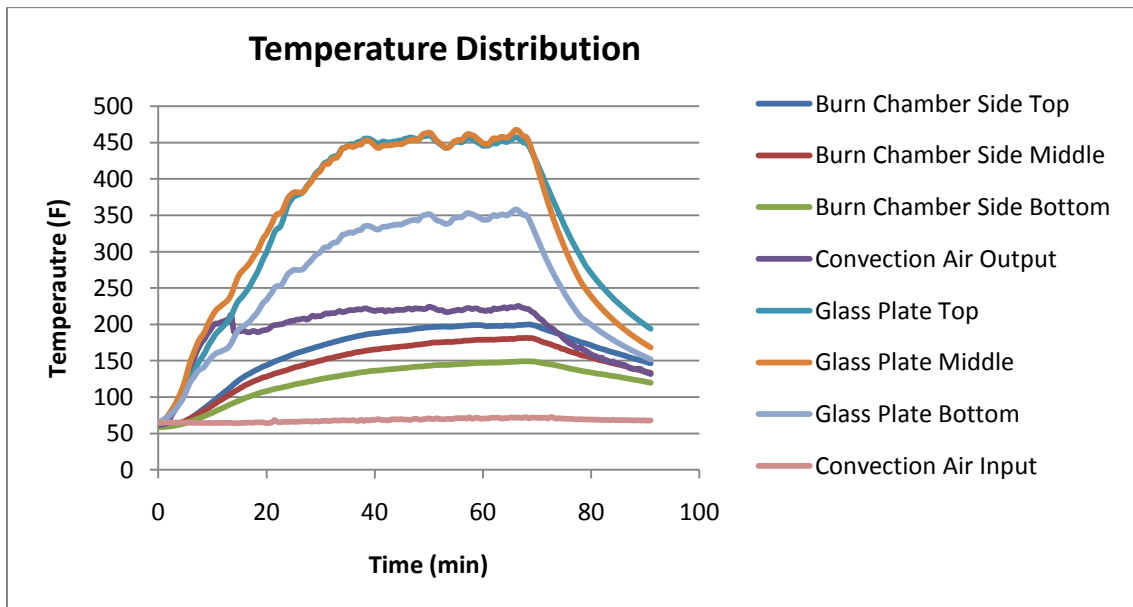


Figure 24: MT. Vernon temperature distribution for Test 2

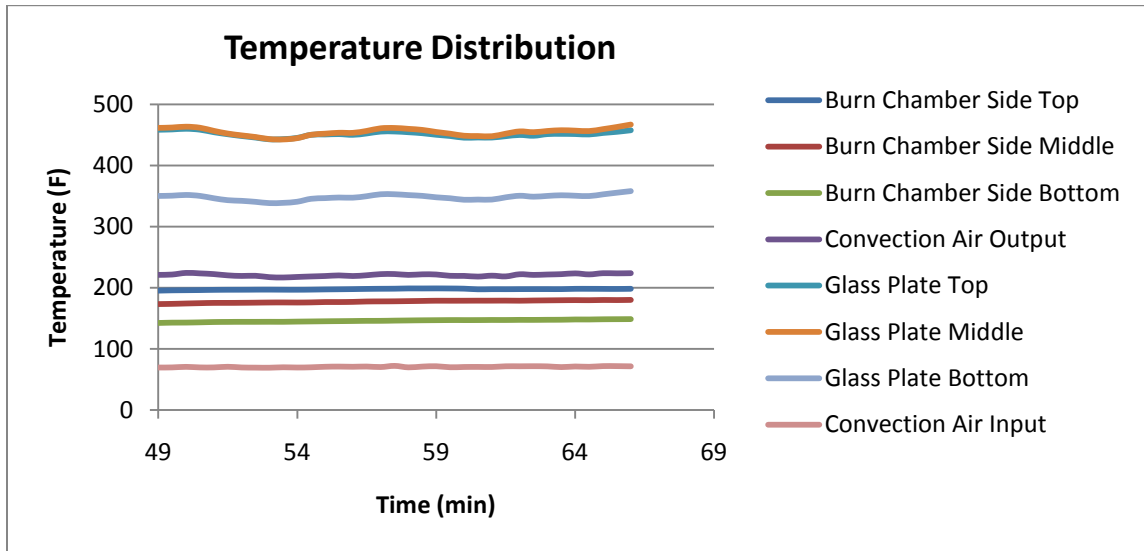


Figure 25: MT. Vernon steady state temperature distribution for Test 2

Table 16: Sample data at steady state conditions

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle (°F) | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|-------------------------|-------------------------|-------------|
| 0.5        | 143.3            | 182.0               | 146.5               | 222.8        | 476.0                | 490.7                   | 367.6                   | 68.1        |
| 1          | 143.9            | 182.4               | 146.9               | 222.6        | 473.1                | 487.8                   | 365.5                   | 68.1        |
| 1.5        | 143.3            | 182.8               | 147.1               | 224.7        | 477.1                | 491.8                   | 368.4                   | 67.4        |
| 2          | 144.2            | 183.3               | 147.4               | 223.8        | 480.8                | 495.6                   | 371.1                   | 68.6        |
| 2.5        | 144.5            | 183.7               | 147.7               | 222.7        | 476.9                | 491.7                   | 367.7                   | 68.2        |
| 3          | 143.9            | 184.1               | 148.0               | 224.8        | 474.8                | 489.5                   | 366.7                   | 68.2        |
| 3.5        | 144.3            | 184.1               | 148.3               | 224.4        | 473.9                | 488.5                   | 366.2                   | 69.2        |
| 4          | 144.8            | 184.3               | 148.4               | 223.8        | 472.4                | 487.0                   | 365.8                   | 68.4        |
| 4.5        | 144.6            | 184.5               | 148.5               | 226.3        | 473.2                | 487.8                   | 367.1                   | 69.0        |
| 5          | 145.7            | 185.2               | 148.7               | 223.0        | 472.9                | 487.5                   | 367.4                   | 68.0        |
| Averages   | 144.2            | 183.6               | 147.8               | 223.9        | 475.1                | 489.8                   | 367.3                   | 68.3        |

Table 16 is a representative set (5 minutes) of data taken from Test 1 at steady state conditions. The averages that are at the bottom of the table would then be used to calculate the convection heat transfer (Air Out and Air In) and the other temperatures would be used to calculate the radiation heat transfer from the burn chamber (BC) and ceramic glass front (all in °F).

Once the stove was run at different outside temperatures and it was proven that this would not significantly affect stove performance, it was time to burn all of the fuels with the ECA 450 to determine the total heat transfer, percentage of ash, burn rate, and emissions. The first test was performed on premium wood pellets. Table 17 below gives all of the results from each fuel except for the emissions, which will be graphically displayed in Figs. 27-31. All tests were performed on manual with medium heat output, holding the room at 70° F with the exception of the 80/20 camelina wheat straw and 50/50 camelina forest residue pellets. The stove had to be run at medium-high output to sustain a longer burn time for these two mixtures. When run on medium output, the stove did not operate at maximum efficiency and in some cases, the burn could not sustain itself and the fire would go out. This small adjustment in stove operation for these two pellet mixtures changes the interpretation of the results slightly.

Table 17: Calculated Results on all formulations

| Fuel                                   | Ash<br>(wt. %) | Burn Rate<br>(lbs/hr) | BC Ave<br>(F) | Air Out<br>Ave (F) | Glass<br>Ave (F) | Total Heat Transfer<br>(Btu/hr) |
|----------------------------------------|----------------|-----------------------|---------------|--------------------|------------------|---------------------------------|
| Premium<br>Wood                        | 0.32           | 3.3                   | 210.56        | 269.71             | 600.7            | 34,570                          |
| 50/50<br>Camelina<br>Sawdust           | 2.31           | 2.2                   | 188.4         | 222.4              | 474.5            | 25,820                          |
| 50/50<br>Camelina<br>Forest<br>Residue | 2.8            | 2.25                  | 161.1         | 203.1              | 411.5            | 22,320                          |
| 80/20<br>Camelina<br>Wheat Straw       | 5.1            | 2.2                   | 146.9         | 205.5              | 408.2            | 23,370                          |
| 50/50<br>Camelina<br>Safflower         | 4.12           | 2.66                  | 167.2         | 232.44             | 494.6            | 27,780                          |

As expected, the percentage of ash was the lowest on the premium wood pellets while the total heat transfer was the highest. The burn rate, however, was also the highest among all formulations. This has to do with the density of premium wood pellets compared to the density of the pellets made in the lab. With a difference of as much as 10 lb/ft<sup>3</sup>, the commercial premium wood pellets burned much faster, thus offering more heat output. Assuming more sophisticated equipment for future production of pellets, the density and heat output would increase on all formulas. It should be noted that the 50/50 camelina safflower pellets offered the highest heat transfer among the integrated formulas, but the ash was about double that of the 50/50 camelina sawdust pellets while providing about 200 Btu's per hour more heat output. Table 18 takes the data from Table 17 and normalizes it for 100,000 Btu's. This allows the other properties of the fuels to be

looked at more closely such as duration of burn, total ash, and total amount of fuel burned.

Table 18: Normalized data to 100,000 Btu's of heat output

| Fuel                          | Duration of Burn (hrs) | Amount Burned (lbs) | Total Ash (lbs) |
|-------------------------------|------------------------|---------------------|-----------------|
| Premium Wood                  | 2.89                   | 9.55                | 0.03            |
| 50/50 Camelina Sawdust        | 3.87                   | 8.52                | 0.20            |
| 50/50 Camelina Forest Residue | 4.48                   | 10.08               | 0.28            |
| 80/20 Camelina Wheat Straw    | 4.28                   | 9.41                | 0.48            |
| 50/50 Camelina Safflower      | 3.60                   | 9.58                | 0.40            |

Table 18 shows information about the different types of fuels. First, the premium wood pellets required shorter burn durations to reach 100,000 Btu outputs than all other mixtures. This is due to the high density of premium wood pellets. The amount burned, 9.55 lbs, was comparable to all formulas except for the 50/50 camelina sawdust and 50/50 camelina forest residue mixtures. The 50/50 camelina sawdust pellets burned a about a pound less, while lasting for an hour longer in the stove. The 50/50 camelina forest residue pellets burned about 0.5 lbs more but lasted roughly 1.5 hours longer than the premium wood pellets. It is important to achieve a maximum heat output with as little fuel as possible. The burning qualities of the camelina derived fuels, however, could be desirable for consumers if they were to save money. The total ash of the premium wood pellets is substantially lower than any of the camelina derived fuels. The 50/50 camelina sawdust pellet offered the closest ash comparison at 0.2 lbs compared to 0.03

lbs for the premium wood pellets. While this would require emptying the ash tray more often, it would not take away from the stoves performance because the MT Vernon stove is made to handle high ash multi-fuel pellet mixtures.

### MT Vernon Stove Emissions Comparison

After compiling all of the information from the ECA 450 into an excel spreadsheet for both start up and steady state conditions, averages were obtained on all measurements for simplicity in calculation. The steady state data is the focus of the study, and is presented in Figs. 27-31 below. Each figure compares the specified value of all fuel mixtures to that of premium wood. The data for each test is located in Appendix C.

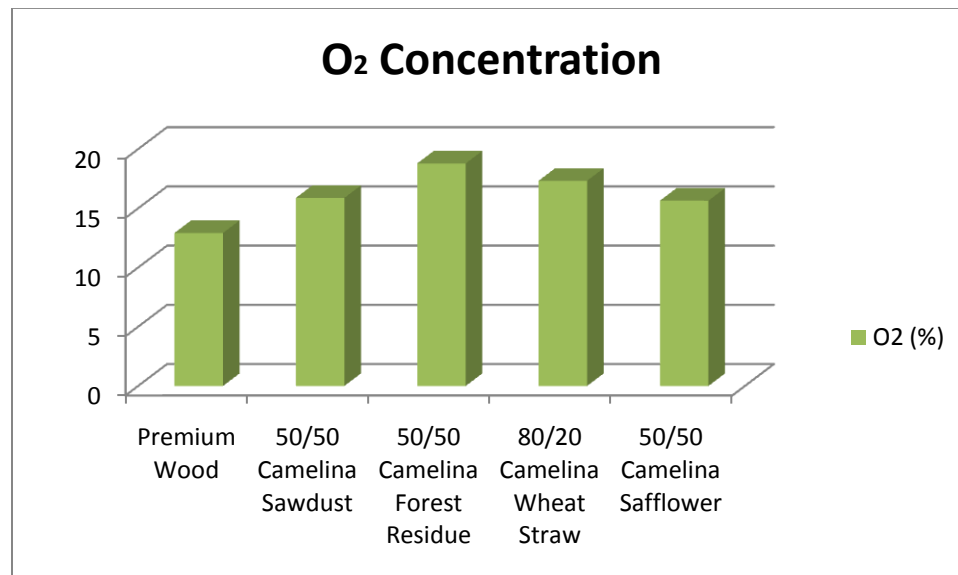


Figure 26: Oxygen concentrations in exhaust gases measured for all fuels

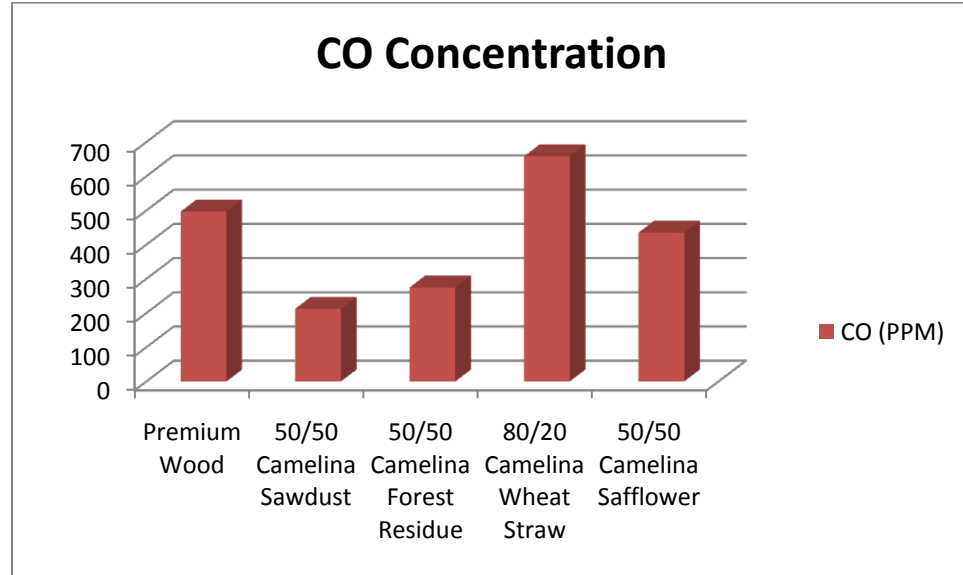


Figure 27: Carbon monoxide concentrations in exhaust gases measured for all fuels

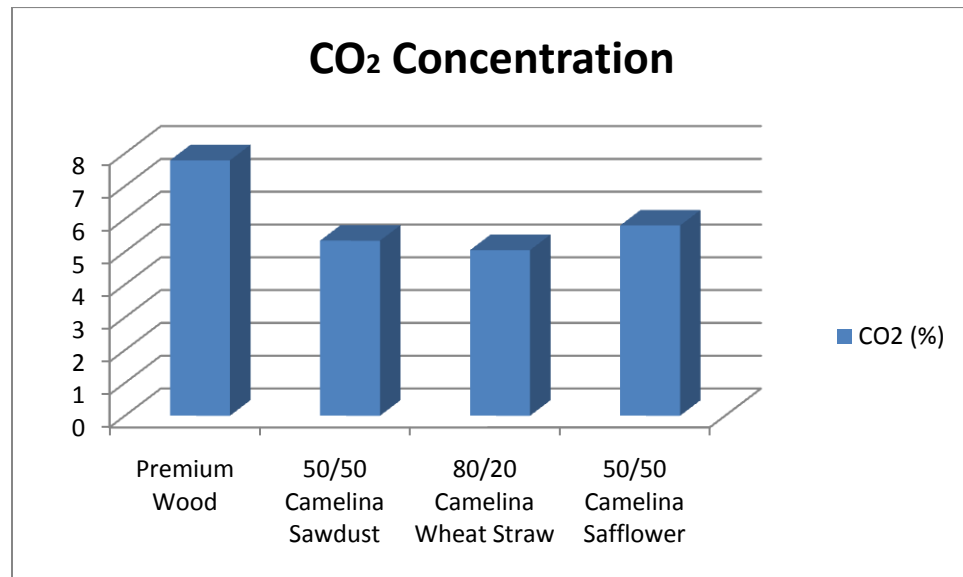


Figure 28: Carbon dioxide concentrations in exhaust gases for all fuels

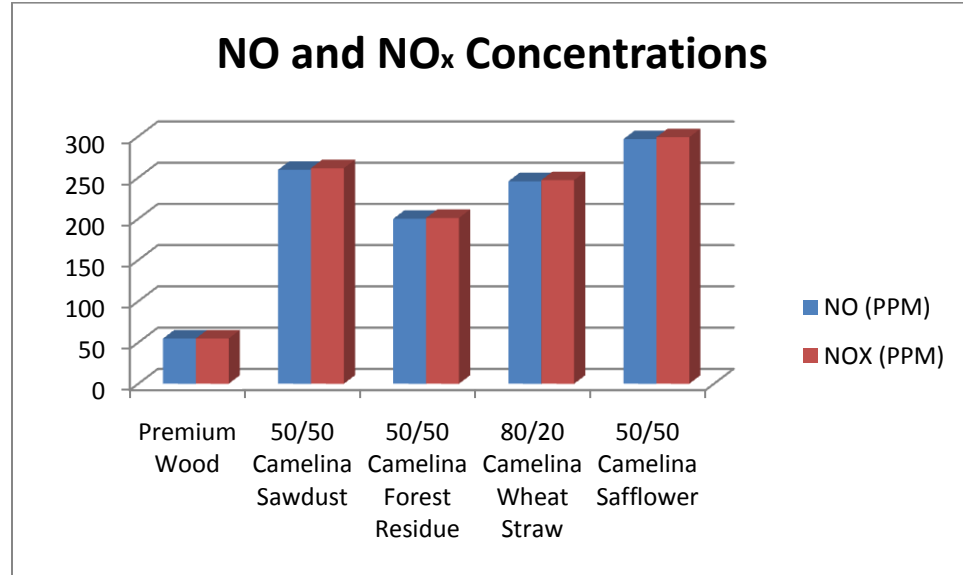


Figure 29: NO and Oxides of Nitrogen concentrations in exhaust gases for all fuels

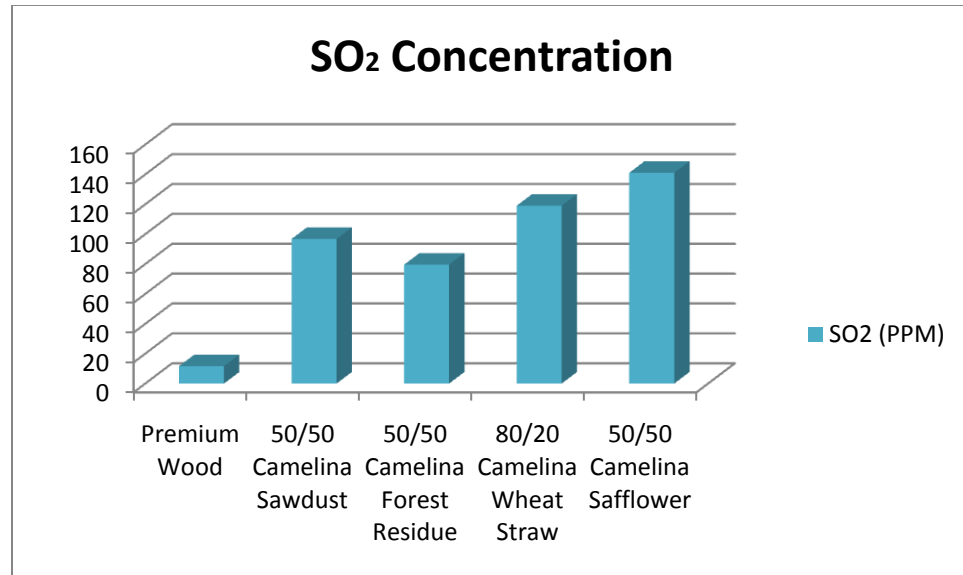


Figure 30: Sulfur Dioxide concentrations in exhaust gases for all fuels

Figs. 27-31 show that, as expected, the emissions from the multi-fuel pellets were higher than those for premium wood pellets except for carbon monoxide and carbon dioxide. Carbon monoxide is a harmful emission, and the 50/50 camelina sawdust pellet offered about 300 parts per million (ppm) less than premium wood pellets. It also produced about 2.5% less carbon dioxide. This is desirable, but the carbon dioxide emitted from premium wood pellets is carbon neutral so there is no net gain of carbon dioxide into the atmosphere. The only formula that had a higher emission of carbon monoxide was the 80/20 camelina wheat straw pellet. The concentrations of oxygen and carbon monoxide relate to the combustion efficiency, and minimizing them both is desirable. Premium wood pellets had at least 3% less oxygen than all other formulas, but the efficiencies of the other mixtures were all above 70%. Premium wood pellets offered combustion efficiencies above 75%. The combination of nitric oxide and nitrogen dioxide produce oxides of nitrogen. Premium wood pellets did not emit any nitrogen dioxide, and the other mixtures were all at 2 ppm or less. The oxides of nitrogen were 5 to 6 times greater for all multi-fuel pellets compared to premium wood pellets, and the sulfur was at least 8 times greater for the multi-fuel pellets. Acceptance of the multi-fuel pellets in the MT Vernon stove will be determined by the limits set by the EPA.

### EPA Regulations

The Clean Air Act requires EPA to set National Ambient Air Quality Standards for 6 common pollutants. These are particle pollution (particulate matter), ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. Particulate matter and

ground-level ozone pollution are the most widespread health threats [9]. Testing of ambient air in a desired town or city and comparing the quality of the air tested to that of the National Ambient Air Quality Standards determines if regulation needs to be applied. Companies or plants that emit large levels of pollution are required by the EPA to have an air permit (greater than 25 tons emitted per year). There are no standards on wood stoves, however, because the stove manufacturers design the stoves to comply with EPA regulations. The air permits apply more to commercial applications, which will be discussed in chapter 9.

#### Harman Stove Results

The procedures and settings on the MT Vernon stove were carried over for the burning of the fuels on the Harman stove as well. Once the stove was powered up, the first burn was premium wood pellets to create baseline data. The results for the premium wood pellets are listed in Table 19 and the corresponding graphs from which the data was acquired are Figs. 27 and 28.

Table 19: Calculated results for premium wood on the Harman stove

| Fuel            | Ash<br>(wt. %) | Burn<br>Rate<br>(lbs/hr) | Stove<br>Side<br>Ave (F) | Stove<br>Top<br>Ave (F) | Bottom<br>Side Ave<br>(F) | Air<br>Out<br>Ave (F) | Glass<br>Ave<br>(F) | Total rate<br>of Heat<br>Transfer<br>(Btu/hr) |
|-----------------|----------------|--------------------------|--------------------------|-------------------------|---------------------------|-----------------------|---------------------|-----------------------------------------------|
| Premium<br>Wood | 0.46           | 4.875                    | 511.6                    | 270.65                  | 265.7                     | 313.4                 | 461.8               | 32,020                                        |

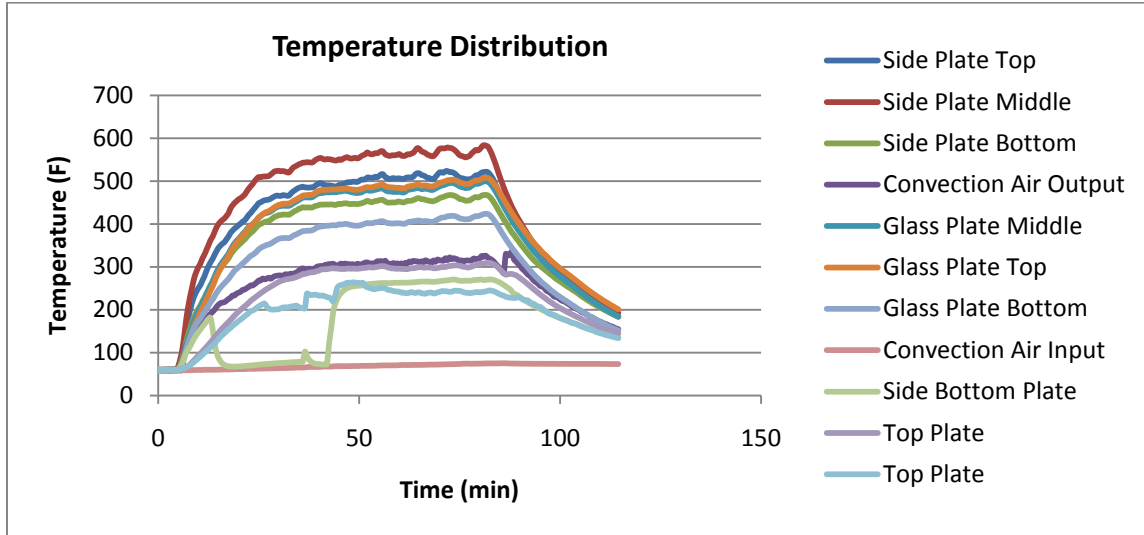


Figure 31: Temperature distribution for premium wood on the Harman stove

The thermocouple on the side bottom plate of the stove had some contact errors that were resolved before the stove reached steady state, as can be seen in Fig. 27. The steady state data that was used for calculations is below in Fig. 28. All of the calculations done on the Harman stove are in Appendix D. Although the total heat transfer was close to that of the MT Vernon stove, it was smaller (31,660 to 34,290 Btu/hr).

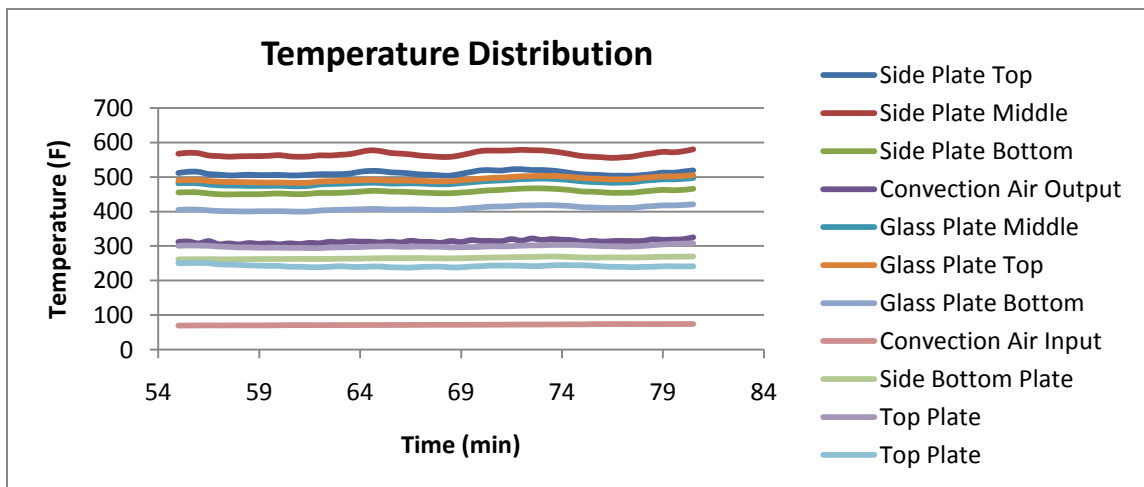


Figure 32: Steady state burn data for premium wood on the Harman stove

### Harman Stove Elimination

After obtaining the results for the premium wood pellets, the 50/50 camelina sawdust pellets were loaded into the hopper and burned using the same settings as the premium wood pellets. The stove could not maintain the burn. The camelina ash was too heavy to be forced out of the burn chamber by the air moving through the chamber. When this occurred, the fire would go out before new pellets could be augered in to push the ash out. The stove was reset and the settings were adjusted to achieve maximum output. The same error situation occurred as the ash put out the fire. After more research was done on the P68 stove with the Harman Stove Company, it was realized that while this stove is made to handle higher ash fuels, it is not made to handle multi-fuel pellet mixtures. The auger design is very efficient for premium wood pellets but the ash is too heavy with multi-fuel pellets and the ash stays in the chamber until the fire burns out. Their website suggests that for multi-fuel pellets one should use the PC45 stove. This stove is made to burn corn, wheat, barley and oats with an exclusive grain burn pot. It comes with two burn pots that are easily interchangeable between corn and other grains [38]. For future studies we recommend the PC45 stove.

## CHAPTER 9

## TOWNSEND INDUSTRIAL BOILER

Boiler Background and Characteristics

This pellet study also involved the potential of using the best multi-fuel pellet in a commercial application. The boilers at Townsend Elementary School were selected [15]. In 2007, with aid from the Montana Fuels for Schools program, the Townsend schools converted both of their boilers from fuel oil and propane to wood pellets. The project was funded from partners including the Fuels for Schools program, the USDA Rural Development, Broadwater Conservation District, Townsend Schools, and The Climate Trust [12]. Changing from fossil fuel burning to pellet burning was projected to save Townsend schools around \$19,000 per year in heating costs while reducing the emission of sequestered CO<sub>2</sub> into the environment. The project has a 30 year life, and total savings are estimated to exceed \$1 million [15].

The price of the system was \$432,000 in design, engineering, and construction costs. The oil burners in the boilers were left in place as fully functional backups for the retrofitted boilers. At first, the fuel the school utilized was comprised of forest residue and sawdust, but over time this changed to whole tree pellets. Whole tree pellets are made of bark, needles, branches, and bolewood, while standard pellets are pressed entirely from bolewood. The system was designed to operate on wood pellets, so this caused clinkers in the combustion chamber. The system had to be shut down several times for repairs and modifications to the ash removal system. After burning through the

first load (30 tons) of these tree pellets, the school switched over to higher grade pellets from Eureka Mills and the system became much more manageable. During the 2008-09 heating season, Townsend burned 296 tons of pellets produced by Eureka Pellet Mills at a total cost of \$38,604 (including transportation). The system also burned about 1,500 gallons of diesel fuel, using it during below zero for 25 heating days. The heating capacity of the boilers is 199 kW (750,000 Btu/hr), and the thermal output is hot water [39].

#### Bison Engineering Emissions Testing

To test the performance of the Townsend boilers, Bison Engineering Inc. in Helena, MT. performed a test on the higher grade fuel pellets that were being burned in the boilers. The upgraded pellets had significantly less ash, 0.53% compared to 4.63% for the old forest residue pellets. This resulted in a much cleaner burn for the boilers, and less maintenance. The test developed by Bison Engineering measured emissions from one of the boilers. Measurements from the stack included oxygen, carbon monoxide, oxides of nitrogen, and particulate matter, and sulfur oxides were calculated. Measurements were obtained on one boiler operating at both high fire and low fire conditions. Table 20 lists the results found in the report prepared by Bison Engineering Inc. [40].

Table 20: Results obtained from Bison Engineering [40]

| Boiler OC | CO (ppm) | NO <sub>x</sub> (ppm) | O <sub>2</sub> (%) |
|-----------|----------|-----------------------|--------------------|
| Low Fire  | 542.8    | 18.6                  | 18                 |
| High Fire | 340      | 30                    | 16.4               |

The lower concentrations of carbon monoxide and oxygen allude to more complete combustion during the boiler's high fire operation. Using the data from Table 20 and performing combustion calculations with correction factors provided by the EPA, the engineers at Bison determined that the boilers were far enough below the requirement of 25 tons emitted per year to continue burning at the rate they were burning [40].

#### 50/50 Camelina Sawdust Burning Procedure

All of the research leading up to the industrial boiler testing showed that the 50/50 camelina sawdust pellet would be the best alternative to premium wood pellets, so it was chosen to be tested in one of the Townsend school boilers. 260 lbs of 50/50 camelina sawdust pellets were loaded and transported to the Townsend school along with the Bacharach ECA 450 to measure the emissions. Upon arrival, one of the two boilers had been shut down and cleaned of all debris. The feed system to the boilers is from a 60 ton silo that utilizes a spring auger with a controlled feed rate to move pellets from the silo to each boiler. Each boiler has its own control panel and can be operated alone or simultaneously with the other boiler. The capacity of the boilers is 199 kW or 750,000 Btu/hr, and the thermal output is hot water. The temperature of the water leaving the boiler should be around 145° F and on very cold days the temperature of the water coming back into the boiler is around 135° F. As the gap between the water temperatures

decreases, the boilers automatically shift into low fire. The water temperature is controlled by the demand for heat in the classrooms and the outside temperature. Figures 34-37 show the characteristics of the Townsend school system.



Figure 33: Spring auger and ash removal systems

Figure 34 shows the system outside, where lightweight ash is transferred from the boiler to the outside and pushed into a sealed oil drum. The heavy ash, including the clinkers, drops out from the stove into a bucket placed on the ground in front of the boilers (See Fig. 35). The large pellet silo, holding 60 tons of pellets at maximum capacity, is not seen in Fig. 34, but is to the left of the spring auger. The spring auger carries pellets from the silo to each boiler and drops pellets in at a specified rate. The pellets are then dropped into the hopper in Fig. 35 and augered from there into the boiler

and burned. Fig. 36 shows the clinker ash removal system and Fig. 37 shows the burn chamber with pellets loaded in.

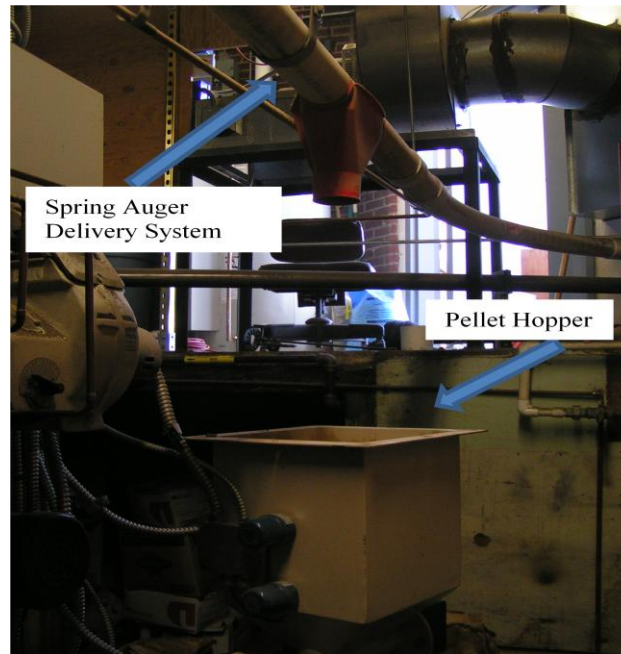


Figure 34: Pellet delivery and hopper system



Figure 35: Ash and clinker removal system



Figure 36: Burn chamber with pellets loaded

#### 50/50 Camelina Sawdust Boiler Results

Holding all control panel settings constant between wood pellets and the 50/50 camelina sawdust pellets, the following things were monitored; Ash, clinker production, emissions, and smell. During the first day of testing, it was too warm outside to run the boiler on high fire, so emissions were gathered on the 50/50 camelina sawdust pellets for the low fire operating condition. The temperature of the stack was a little over 300° F during low fire. The next morning the boiler was restarted and run at high fire for about 5 hours, burning the remaining 150 lbs of 50/50 camelina sawdust pellets. The temperature of the flame was close to 900° F during high fire. All of the results are in Table 21 below. After the 5 hours of high-fire burning, the ash was removed and it was noted that clinkers had formed. Although the clinkers looked very similar to that of the wood pellet clinkers, they were not given enough time to completely form. Typically,

clinkers from the Townsend boiler would build up over a week's time and then be removed from the chamber. Sustained testing would need to be done to determine the extra ash removal and clinker buildup from the 50/50 camelina sawdust pellets compared to the wood pellets currently used. The governing variable on clinker production is the ash fusion temperature at which it starts to bind together.

Table 21: Emissions data from 50/50 camelina sawdust pellets

| Boiler OC | O <sub>2</sub><br>(%) | CO<br>(PPM) | CO <sub>2</sub> (%) | NO (PPM) | NO <sub>2</sub><br>(PPM) | NO <sub>x</sub> (PPM) | SO <sub>2</sub><br>(PPM) |
|-----------|-----------------------|-------------|---------------------|----------|--------------------------|-----------------------|--------------------------|
| Low Fire  | 20.41                 | 192.91      |                     | 51.55    | 0.45                     | 52.09                 | 21.73                    |
| High Fire | 17.45                 | 821.16      | 4.90                | 205.94   | 1.09                     | 207.31                | 66.19                    |

Comparing Tables 20 and 21 shows some interesting results regarding the possibility of using the 50/50 camelina sawdust fuel as a replacement for wood pellets. The combustion efficiency is not as high when using the 50/50 fuel and the carbon monoxide values are higher. However, the sulfur numbers were much lower in both high fire and low fire operation than expected, and this could be due to complete burning of the fuel in a boiler compared to a residential stove. The oxides of nitrogen were also higher than that of wood pellets as expected. A concern noted after the burn test on the Townsend school boiler was the dark color of the burn chamber door after the test was completed. It was significantly darker as opposed to burning wood pellets. The fuel is dirtier by nature, but if the dark color is due to soot buildup, then sustained burning of this fuel would not be acceptable or a safe practice. Further research would have to be done on longer burning cycles of these pellets to determine what that buildup is caused from.

## CHAPTER 10

## CONCLUSIONS AND RECOMMENDATIONS

The results obtained from the residential testing were promising. The MT Vernon stove was able to burn all pellet mixtures, with minor adjustments for the 80/20 camelina wheat straw pellets and the 50/50 camelina forest residue pellets. The 50/50 camelina sawdust pellet performed the best overall compared to the premium wood pellet, producing 2.31% ash compared to 0.32% ash for the premium wood. The ash removal mechanism on the MT Vernon stove allows for removal of this high percentage of ash and, although the 50/50 camelina sawdust pellet produced small clinkers, the automatic ash removal from the chamber solved any issues of the stove stalling. The normalized data presented in Table 18 to 100,000 Btu's was convincing in that the 50/50 camelina sawdust pellet would burn for over an hour longer to emit the total amount of heat while burning about a pound less overall. These results show that burning the new pellet formula would require less loading and the purchasing of fewer bags of pellets, but would require more frequent ash removal. The emissions were slightly skewed for the different pellet mixtures, but overall the primary concerns were apparent. The camelina fueled pellets emitted significantly more sulfur dioxide and oxides of nitrogen, but actually emitted less carbon monoxide. The lower percentages of oxygen during testing of premium wood pellets indicate higher combustion efficiencies than all multi-fuel pellet formulations, and this was the case. Although the carbon monoxide was higher in premium wood pellet burning than in some multi-fuel pellet formulas, this may be due to

incomplete mixing of the air during combustion or other problems inside the combustion chamber. Another emission that needs to be addressed is chlorine. Since camelina has a high chlorine content (see Appendix A), some long term testing would need to be done to see if residential stoves and/or industrial boilers could sustain camelina burning without compromising the stove or boiler and stay under emission limits.

The economics of growing camelina are positive. Farmers are making money from camelina seed due to its applicability in the production of biodiesel, and the leftover feed has been recently approved by the FDA for up to 10% supplement in cattle feed [7]. With another niche market for the remaining feed, farmers would be provided even more incentive to grow camelina. Also, a study in 2006 revealed that the breakeven point for farmers growing camelina was \$1.23, which was lower than the breakeven point of growing spring wheat (\$1.81) at that time [41]. The production costs were between \$45 and \$68/acre.

The results from the Harman P68 stove were not encouraging enough to recommend this stove as an alternative fuels burning stove. After researching the stove more, it was found that the P68 stove is not made to burn integrated fuels [34]. Also, the bottom feed design on the auger system plugged the burn chamber and put out the fire on all formulas that included camelina. Future testing should involve the PC45 Harman stove, which is made to burn corn or wheat by utilizing two different burn pots. This stove could be used in future burning of camelina fueled pellets after sufficient testing confirm its ability to maintain consistent results in the stove.

The results from the Townsend Schools industrial boiler were very encouraging. The pellets burned completely at the same operating conditions that have been used to burn the current wood pellets at the school. Clinkers were formed that were similar to that of the wood pellet clinkers, and the emissions data was low enough when compared to the wood pellets that would not produce more than the 25 ton limit set by the EPA. The ash calculated from the boiler was roughly 3.5%, which is higher than the percentage of ash calculated during the residential burn. This can be attributed to the duration of the test. The ash was not allowed to burn completely, causing a higher weight percentage. Sustained burning of the fuel would drop this ash percentage to around 2.5%. Some further research on the fusion temperature of camelina ash could be done to prove that clinkers would not compromise the life of the boiler.

There were also many issues that arose throughout this project. The first was the un-availability of professional equipment. The equipment used did produce pellets, but at a much lower density than premium wood pellets. With higher pressure equipment, the heat output and combustion efficiency should increase for mixtures made at Montana State University. Another concern was the buildup of soot in the stack or boiler. The emissions data was obtained by a small scale combustion analyzer, and to approve operation of camelina based fuels in an industrial boiler, a certified test by Bison Engineering or another qualified testing firm would have to be done to prove the validity of the measurements mentioned in this report. The residential burning data in the MT Vernon was encouraging enough to recommend this stove as the primary stove to burn camelina fueled pellets. The recommended pellet formula is the 50/50 mixture of

camelina and sawdust. While the MT Vernon stove did a good job of burning this pellet mixture, it will be a long process to get this fuel into consumer households. Existing stoves would need to be retrofitted or a new MT Vernon stove would need to be purchased by consumers. This is something that may never occur, unless the price of current wood pellet fuels increased to a point where alternatives would need to be pursued. Instead, it is recommended that this fuel mixture be pursued as the primary fuel used in large scale operations like the Townsend Schools boilers.

To make sure the fuel is acceptable for long term burning, a certified test would need to be performed by Bison Engineering or another qualified testing firm and then compared to the report already issued for the current wood-based fuel. The stack and burn chamber would also have to be tested after long term continuous operation for soot buildup. The ash removal and clinker production would also have to be tested to see if long term burning would be acceptable. A load of 30 tons of 50/50 camelina sawdust pellets would need to be produced and burned in the Townsend boiler and then conclusions would have to be drawn on its sustainability.

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## APPENDICES

APPENDIX A

CHLORINE CONTENT OF 50/50 CAMELINA SAWDUST PELLETS

Table A.1: Chlorine content of 50/50 camelina sawdust pellets

| 50/50 Camelina Sawdust | Total Moisture (%) | Chlorine ( $\mu\text{g/g}$ ) |
|------------------------|--------------------|------------------------------|
| As Received            | 4.36               | 366                          |
| Dry Basis              | 0                  | 383                          |

APPENDIX B

CROP DATA FOR MONTANA

Table B.1: Crop data by county for Montana

| County   | Crop         | Year | Production (tons) |
|----------|--------------|------|-------------------|
| Chouteau | Camelina     | 2009 | 374.5             |
|          | Wheat        | 2008 | 573,075           |
| Cascade  | Barley       | 2008 | 40,775            |
| Sheridan | Flaxseed     | 2007 | 775               |
|          | Mustard Seed | 2007 | 530.5             |
|          | Safflower    | 2007 | 1,046             |
| Pondera  | Camelina     | 2009 | 684               |
|          | Canola       | 2008 | 3,071.5           |
|          | Barley       | 2008 | 133,800           |
|          | Wheat        | 2008 | 194,525           |
| Teton    | Camelina     | 2008 | 65                |
|          | Hay          | 2008 | 160,900           |
|          | Alfalfa      | 2008 | 120,000           |
|          | Barley       | 2008 | 119,050           |
|          | Wheat        | 2008 | 192,800           |
| Fergus   | Camelina     | 2008 | 88.6              |
|          | Hay          | 2008 | 193,300           |
|          | Alfalfa Hay  | 2008 | 171,000           |
|          | Wheat        | 2008 | 173,050           |
| Gallatin | Camelina     | 2008 | n/a               |
|          | Hay          | 2008 | 159,100           |
|          | Alfalfa Hay  | 2008 | 144,300           |
| Toole    | Canola       | 2008 | 685.5             |
|          | Barley       | 2008 | 56,100            |
|          | Wheat        | 2008 | 160,750           |
| Flathead | Canola       | 2008 | 993               |
| Valley   | Flaxseed     | 2007 | 2,000             |
|          | Mustard Seed | 2007 | 568.5             |
|          | Hay          | 2008 | 134,900           |
|          | Wheat        | 2008 | 176,925           |
|          | Alfalfa Hay  | 2008 | 102,500           |
| Daniels  | Mustard Seed | 2007 | 981               |

Table B.1 (Continued)

| County       | Crop           | Year | Production (tons) |
|--------------|----------------|------|-------------------|
| Richland     | Mustard Seed   | 2007 | 851.5             |
|              | Sugar Beets    | 2007 | 331,500           |
|              | Safflower (#1) | 2007 | 3,665.5           |
|              | Barley         | 2008 | 39,650            |
| Blaine       | Hay            | 2008 | 137,200           |
|              | Alfalfa Hay    | 2008 | 113,500           |
| Beaverhead   | Hay            | 2008 | 192,900           |
| Madison      | Hay            | 2008 | 143,700           |
|              | Alfalfa Hay    | 2008 | 111,000           |
| Powder River | Hay            | 2008 | 132,300           |
|              | Alfalfa Hay    | 2008 | 106,000           |
| Carter       | Hay            | 2008 | 129,700           |
| BigHorn      | Alfalfa Hay    | 2008 | 102,500           |
|              | Sugar Beets    | 2007 | 257,000           |
|              | Camelina       | 2009 | 1402.5            |
| Dawson       | Sugar Beets    | 2007 | 53,500            |
|              | Safflower      | 2007 | 2,009             |
| Carbon       | Sugar Beets    | 2007 | 90,400            |
| Treasure     | Sugar Beets    | 2007 | 92,200            |
| Yellowstone  | Sugar Beets    | 2007 | 170,000           |
|              | Barley         | 2008 | 41,875            |
| Custer       | Sugar Beets    | 2007 | 16,600            |
| Prairie      | Sugar Beets    | 2007 | 42,000            |
| Roosevelt    | Safflower      | 2007 | 98,175            |
| Fallon       | Safflower      | 2007 | 869               |
| Wibaux       | Safflower      | 2007 | 2,071.5           |
| Glacier      | Barley         | 2008 | 130,050           |
| Hill         | Wheat          | 2008 | 408,400           |
| Liberty      | Wheat          | 2008 | 206,875           |

APPENDIX C

MT. VERNON STOVE HEAT TRANSFER CALCULATIONS AND DATA

Nomenclature

The following abbreviations apply to the remaining Tables in Appendix C:

BC Side Top: Burn Chamber Side, Thermocouple location at top of the chamber

BC Side Middle: Burn Chamber Side, Thermocouple location at middle of the chamber

BC Side Bottom: Burn Chamber Side, Thermocouple location at bottom of the chamber

Air Out: Forced Convection Air Output from stove ( $T_{out}$  in MathCAD work)

Glass Plate Top: Thermocouple location at the top of the ceramic glass plate

Glass Plate Middle: Thermocouple location at the middle of the ceramic glass plate

Glass Plate Bottom: Thermocouple location at the bottom of the ceramic glass plate

Air In: Air from the room being pulled into the convection fan ( $T_{in}$  in MathCAD work)

$C_p$ : specific heat

$\rho$ : Density

$v$ : velocity

$d$ : diameter

$\dot{m}$ : mass flow rate

$\epsilon$ : emissivity

$\sigma$ : Stefan-Boltzmann constant

Table C.1: Steady State Data for 50/50 Camelina Sawdust at  $T_{out}=32^{\circ}\text{F}$ 

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle (°F) | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|-------------------------|-------------------------|-------------|
| 0          | 195.1            | 173.1               | 142.3               | 220.9        | 458.4                | 461.6                   | 350.2                   | 69.7        |
| 0.5        | 195.6            | 173.4               | 142.8               | 221.5        | 458.9                | 462.2                   | 350.6                   | 69.8        |
| 1          | 195.9            | 174.1               | 142.9               | 224.1        | 460.0                | 463.6                   | 351.8                   | 70.6        |
| 1.5        | 196.1            | 174.6               | 143.3               | 223.3        | 458.5                | 461.9                   | 350.3                   | 69.8        |
| 2          | 196.5            | 175.1               | 143.8               | 222.1        | 454.4                | 456.8                   | 346.3                   | 69.8        |
| 2.5        | 196.7            | 175.1               | 144.0               | 220.1        | 451.1                | 452.3                   | 343.1                   | 70.8        |
| 3          | 196.7            | 175.3               | 144.1               | 219.1        | 448.2                | 449.3                   | 342.1                   | 69.8        |
| 3.5        | 196.9            | 175.5               | 144.1               | 219.4        | 445.7                | 446.6                   | 340.4                   | 69.5        |
| 4          | 196.9            | 175.8               | 144.2               | 217.2        | 442.9                | 443.2                   | 338.3                   | 69.4        |
| 4.5        | 196.8            | 175.9               | 144.2               | 216.7        | 443.2                | 442.6                   | 338.7                   | 70.0        |
| 5          | 196.7            | 175.8               | 144.5               | 217.5        | 445.2                | 444.7                   | 340.6                   | 69.7        |
| 5.5        | 196.9            | 176.0               | 144.8               | 218.3        | 450.2                | 450.3                   | 345.4                   | 70.0        |
| 6          | 197.3            | 176.6               | 145.0               | 219.0        | 450.7                | 452.1                   | 346.5                   | 70.8        |
| 6.5        | 197.6            | 176.6               | 145.3               | 220.0        | 451.3                | 453.6                   | 347.6                   | 71.0        |
| 7          | 197.9            | 176.9               | 145.5               | 219.0        | 450.2                | 453.4                   | 347.3                   | 70.8        |
| 7.5        | 198.2            | 177.6               | 145.7               | 220.3        | 452.3                | 456.6                   | 349.7                   | 71.1        |
| 8          | 198.5            | 177.7               | 145.8               | 222.1        | 455.4                | 460.9                   | 353.0                   | 70.4        |
| 8.5        | 198.6            | 177.9               | 146.1               | 222.2        | 455.6                | 461.5                   | 353.0                   | 72.0        |
| 9          | 199.1            | 178.2               | 146.4               | 220.9        | 454.4                | 460.1                   | 351.6                   | 69.9        |
| 9.5        | 199.0            | 178.5               | 146.7               | 221.8        | 452.7                | 458.3                   | 350.3                   | 71.1        |
| 10         | 199.1            | 178.9               | 146.8               | 221.5        | 450.2                | 454.9                   | 347.9                   | 71.5        |
| 10.5       | 199.0            | 178.9               | 147.0               | 219.4        | 448.2                | 452.1                   | 346.3                   | 70.0        |
| 11         | 198.6            | 178.9               | 147.0               | 219.2        | 445.6                | 448.7                   | 343.8                   | 70.4        |
| 11.5       | 197.5            | 179.0               | 147.0               | 218.1        | 445.8                | 448.2                   | 344.2                   | 70.6        |
| 12         | 197.7            | 179.0               | 147.2               | 219.6        | 445.8                | 447.9                   | 344.2                   | 70.5        |
| 12.5       | 197.7            | 179.1               | 147.1               | 218.4        | 448.0                | 452.1                   | 347.9                   | 71.5        |
| 13         | 197.8            | 178.9               | 147.3               | 221.9        | 449.9                | 455.8                   | 350.5                   | 71.5        |
| 13.5       | 197.9            | 179.2               | 147.3               | 220.9        | 448.6                | 454.5                   | 348.9                   | 71.6        |
| 14         | 197.9            | 179.5               | 147.5               | 221.5        | 451.3                | 456.5                   | 350.2                   | 71.3        |
| 14.5       | 197.8            | 179.7               | 147.5               | 222.1        | 451.7                | 457.7                   | 351.3                   | 70.3        |
| 15         | 198.4            | 179.9               | 148.0               | 223.3        | 451.4                | 457.1                   | 350.5                   | 71.2        |
| 15.5       | 198.4            | 179.8               | 148.0               | 221.7        | 450.8                | 456.4                   | 350.0                   | 70.7        |
| 16         | 198.3            | 180.1               | 148.3               | 223.6        | 453.2                | 459.5                   | 352.8                   | 71.8        |
| 16.5       | 198.2            | 180.0               | 148.4               | 223.3        | 455.0                | 463.1                   | 355.6                   | 71.7        |
| 17         | 198.4            | 180.3               | 148.6               | 223.6        | 457.5                | 467.1                   | 358.2                   | 71.4        |
| Averages   | 197.6            | 177.4               | 145.8               | 220.7        | 451.2                | 455.0                   | 348.0                   | 70.6        |

### Forced Convection Calculations for 1.5 Hour 50/50 camelina sawdust burn test at 32° F outdoor temp in the MT. Vernon Stove

$$R = F + 459.67$$

$$T_{in} := 70.6254^{\circ}\text{F} \quad T_o := 70.6254$$

$$T_{out} := 220.6755^{\circ}\text{F}$$

$$C_p = .2416 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

#### From Dwyer Series 160 Data Sheet

$$P_B := 24.9 \quad \text{this is the barometric pressure in inches of mercury as measured}$$

$$T_{\text{absF}} := 459.67 + T_o \quad \text{this is absolute temperature of airflow past the pitot static tube}$$

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}}$$

$$\rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .062 \frac{\text{lb}}{\text{ft}^3}$$

#### Calculate Air Velocity

$$P_v := 0.16 \quad \text{This is the velocity (or dynamic) pressure in inches of water, experimentally measured}$$

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.758 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1758 \frac{\text{ft}}{\text{min}}$$

#### Mass Flow Rate

$$d := \frac{4.25}{12} \text{ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ft}^2$$

$$\dot{m} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m} = 0.179 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := m_{\text{dot}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$q_{\text{forced\_conv}} = 2.332 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at max steady state operations

### Radiation Calculations for 50/50 camelina sawdust burn

$$T_{\text{surface}} := \left( \frac{418.0477 + 459.67}{173.6227 + 459.67} \right) \text{R}$$

$$T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{R}$$

$$A_{\text{surface}} := \left[ \frac{20 \cdot 13.5}{8 \cdot \frac{(13.5 + 1.5)}{2}} \right] \text{in}^2$$

$$A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon := \begin{pmatrix} 0.95 \\ 0.22 \end{pmatrix}$$

$$\sigma := .1714 \cdot 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{°R}^4}$$

Stefan-Boltzmann Constant

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ (T_{\text{surface}_0})^4 - (T_{\text{surr}_0})^4 \right]$$

$$q_{\text{radglass}} = 1.571 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ (T_{\text{surface}_1})^4 - (T_{\text{surr}_1})^4 \right]$$

$$q_{\text{radsteel}} = 12.847 \cdot \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + 2q_{\text{radsteel}}$$

$$q_{\text{radtot}} = 1.596 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

### Total Heat Transfer

### Fraction of Radiation:

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 2.492 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}}$$

$$\text{Rad} = 0.064$$

Table C.2: Steady state data for 50/50 camelina sawdust at  $T_{out}=-4^{\circ}\text{F}$ 

| Time (min) | BC Side Top ( $^{\circ}\text{F}$ ) | BC Side Middle ( $^{\circ}\text{F}$ ) | BC Side Bottom ( $^{\circ}\text{F}$ ) | Air Out ( $^{\circ}\text{F}$ ) | Glass Plate Top ( $^{\circ}\text{F}$ ) | Glass Plate Middle | Glass Plate Bottom ( $^{\circ}\text{F}$ ) | Air In ( $^{\circ}\text{F}$ ) |
|------------|------------------------------------|---------------------------------------|---------------------------------------|--------------------------------|----------------------------------------|--------------------|-------------------------------------------|-------------------------------|
| 0          | 143.3                              | 182.0                                 | 146.5                                 | 222.8                          | 476.0                                  | 490.7              | 367.6                                     | 68.1                          |
| 0.5        | 143.9                              | 182.4                                 | 146.9                                 | 222.6                          | 473.1                                  | 487.8              | 365.5                                     | 68.1                          |
| 1          | 143.3                              | 182.8                                 | 147.1                                 | 224.7                          | 477.1                                  | 491.8              | 368.4                                     | 67.4                          |
| 1.5        | 144.2                              | 183.3                                 | 147.4                                 | 223.8                          | 480.8                                  | 495.6              | 371.1                                     | 68.6                          |
| 2          | 144.5                              | 183.7                                 | 147.7                                 | 222.7                          | 476.9                                  | 491.7              | 367.7                                     | 68.2                          |
| 2.5        | 143.9                              | 184.1                                 | 148.0                                 | 224.8                          | 474.8                                  | 489.5              | 366.7                                     | 68.2                          |
| 3          | 144.3                              | 184.1                                 | 148.3                                 | 224.4                          | 473.9                                  | 488.5              | 366.2                                     | 69.2                          |
| 3.5        | 144.8                              | 184.3                                 | 148.4                                 | 223.8                          | 472.4                                  | 487.0              | 365.8                                     | 68.4                          |
| 4          | 144.6                              | 184.5                                 | 148.5                                 | 226.3                          | 473.2                                  | 487.8              | 367.1                                     | 69.0                          |
| 4.5        | 145.7                              | 185.2                                 | 148.7                                 | 223.0                          | 472.9                                  | 487.5              | 367.4                                     | 68.0                          |
| 5          | 144.4                              | 185.1                                 | 149.0                                 | 223.7                          | 473.4                                  | 488.0              | 368.2                                     | 68.0                          |
| 5.5        | 145.3                              | 185.2                                 | 149.1                                 | 226.6                          | 476.5                                  | 491.2              | 370.6                                     | 68.6                          |
| 6          | 144.3                              | 185.4                                 | 149.4                                 | 225.0                          | 475.6                                  | 490.3              | 369.7                                     | 68.3                          |
| 6.5        | 146.4                              | 186.0                                 | 149.5                                 | 224.7                          | 468.8                                  | 483.3              | 364.0                                     | 68.9                          |
| 7          | 145.6                              | 185.8                                 | 149.6                                 | 224.3                          | 467.0                                  | 481.4              | 363.6                                     | 68.9                          |
| 7.5        | 145.6                              | 186.1                                 | 149.6                                 | 225.1                          | 470.8                                  | 485.4              | 366.6                                     | 68.6                          |
| 8          | 145.3                              | 186.3                                 | 150.0                                 | 223.1                          | 470.2                                  | 484.7              | 366.2                                     | 69.3                          |
| 8.5        | 146.6                              | 186.4                                 | 149.9                                 | 225.7                          | 473.0                                  | 487.6              | 368.0                                     | 68.3                          |
| 9          | 146.5                              | 186.7                                 | 150.3                                 | 226.4                          | 477.9                                  | 492.6              | 370.9                                     | 67.7                          |
| 9.5        | 146.3                              | 187.2                                 | 150.7                                 | 224.6                          | 479.2                                  | 494.0              | 371.7                                     | 68.6                          |
| 10         | 147.2                              | 187.9                                 | 151.0                                 | 228.9                          | 484.4                                  | 499.4              | 375.3                                     | 68.8                          |
| 10.5       | 146.8                              | 188.2                                 | 151.3                                 | 226.9                          | 485.0                                  | 500.0              | 375.2                                     | 69.5                          |
| 11         | 146.6                              | 188.4                                 | 151.4                                 | 227.8                          | 482.3                                  | 497.3              | 373.2                                     | 68.6                          |
| 11.5       | 147.1                              | 188.7                                 | 151.6                                 | 228.2                          | 481.6                                  | 496.5              | 373.2                                     | 69.3                          |
| 12         | 146.3                              | 188.0                                 | 151.7                                 | 226.9                          | 477.9                                  | 492.7              | 370.9                                     | 68.8                          |
| 12.5       | 147.4                              | 188.8                                 | 151.7                                 | 226.5                          | 477.7                                  | 492.5              | 371.7                                     | 68.1                          |
| 13         | 145.9                              | 188.7                                 | 151.8                                 | 224.5                          | 477.9                                  | 492.7              | 372.4                                     | 68.8                          |
| 13.5       | 147.0                              | 189.2                                 | 152.2                                 | 226.9                          | 478.7                                  | 493.5              | 373.0                                     | 69.1                          |
| 14         | 147.6                              | 189.6                                 | 152.4                                 | 225.7                          | 476.0                                  | 490.7              | 371.1                                     | 69.6                          |
| 14.5       | 148.1                              | 189.5                                 | 152.4                                 | 226.7                          | 476.9                                  | 491.7              | 371.9                                     | 69.1                          |
| 15         | 147.6                              | 190.0                                 | 152.5                                 | 226.9                          | 477.5                                  | 492.3              | 372.8                                     | 69.1                          |
| 15.5       | 148.9                              | 190.1                                 | 152.7                                 | 226.7                          | 473.6                                  | 488.2              | 369.6                                     | 69.4                          |
| 16         | 148.1                              | 190.0                                 | 152.7                                 | 225.6                          | 474.1                                  | 488.8              | 369.9                                     | 68.7                          |
| 16.5       | 147.3                              | 189.7                                 | 152.6                                 | 226.9                          | 473.1                                  | 487.8              | 369.2                                     | 68.7                          |
| 17         | 147.0                              | 189.9                                 | 152.8                                 | 226.5                          | 473.9                                  | 488.6              | 370.8                                     | 69.1                          |

Table C.2 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 17.5       | 149.1            | 190.4               | 152.8               | 225.0        | 472.6                | 487.2              | 370.0                   | 69.8        |
| 18         | 147.7            | 190.1               | 152.9               | 225.0        | 470.6                | 485.1              | 369.1                   | 69.6        |
| 18.5       | 147.9            | 190.2               | 153.0               | 223.3        | 467.4                | 481.9              | 366.9                   | 69.7        |
| 19         | 147.7            | 190.6               | 152.9               | 222.9        | 465.6                | 480.0              | 365.7                   | 67.9        |
| 19.5       | 147.6            | 190.4               | 152.9               | 223.6        | 470.9                | 485.5              | 369.0                   | 68.9        |
| 20         | 147.9            | 190.8               | 153.1               | 224.2        | 479.0                | 493.9              | 373.7                   | 69.3        |
| 20.5       | 147.7            | 191.2               | 153.6               | 227.2        | 482.5                | 497.4              | 375.5                   | 69.3        |
| 21         | 149.0            | 191.4               | 153.7               | 225.3        | 476.9                | 491.6              | 370.3                   | 69.6        |
| 21.5       | 147.5            | 191.5               | 153.7               | 222.1        | 468.9                | 483.4              | 364.0                   | 70.0        |
| 22         | 147.6            | 191.5               | 153.6               | 221.5        | 465.5                | 479.9              | 362.8                   | 69.3        |
| 22.5       | 148.8            | 191.6               | 153.6               | 222.1        | 462.2                | 476.4              | 361.1                   | 69.5        |
| 23         | 147.3            | 191.3               | 153.4               | 222.4        | 460.2                | 474.4              | 360.6                   | 69.6        |
| 23.5       | 149.0            | 191.2               | 153.3               | 222.9        | 461.0                | 475.3              | 361.8                   | 68.7        |
| 24         | 148.0            | 191.1               | 153.4               | 220.9        | 460.4                | 474.6              | 361.6                   | 69.1        |
| 24.5       | 147.7            | 191.1               | 153.2               | 220.5        | 457.2                | 471.3              | 359.0                   | 69.6        |
| 25         | 148.6            | 191.1               | 153.2               | 223.1        | 464.6                | 478.9              | 363.4                   | 69.2        |
| 25.5       | 148.1            | 190.9               | 153.0               | 222.2        | 464.7                | 479.1              | 362.5                   | 68.9        |
| 26         | 148.6            | 190.9               | 153.2               | 220.5        | 465.6                | 480.0              | 362.8                   | 69.4        |
| 26.5       | 148.4            | 190.8               | 153.0               | 221.2        | 470.8                | 485.4              | 366.1                   | 69.6        |
| 27         | 148.2            | 190.6               | 153.0               | 223.2        | 474.8                | 489.5              | 368.2                   | 68.4        |
| 27.5       | 148.8            | 190.9               | 153.4               | 225.4        | 478.8                | 493.6              | 370.5                   | 69.7        |
| 28         | 149.4            | 191.3               | 153.5               | 225.8        | 485.3                | 500.3              | 375.0                   | 69.7        |
| 28.5       | 149.1            | 191.3               | 153.7               | 226.9        | 485.1                | 500.1              | 374.4                   | 69.8        |
| 29         | 148.1            | 191.0               | 153.7               | 226.5        | 481.8                | 496.7              | 372.2                   | 69.7        |
| 29.5       | 148.7            | 191.2               | 153.6               | 224.7        | 481.0                | 495.8              | 372.4                   | 68.6        |
| 30         | 148.2            | 191.4               | 153.7               | 225.6        | 479.4                | 494.2              | 371.2                   | 69.6        |
| 30.5       | 148.1            | 191.2               | 153.7               | 225.7        | 478.2                | 493.0              | 370.9                   | 69.1        |
| 31         | 148.7            | 191.2               | 153.5               | 225.1        | 475.6                | 490.3              | 369.2                   | 70.4        |
| 31.5       | 149.1            | 191.3               | 153.7               | 225.8        | 473.3                | 487.9              | 367.9                   | 69.5        |
| 32         | 149.2            | 191.3               | 153.7               | 224.8        | 472.0                | 486.6              | 367.8                   | 69.6        |
| 32.5       | 149.3            | 191.6               | 153.7               | 225.4        | 471.5                | 486.1              | 368.1                   | 68.3        |
| 33         | 148.4            | 191.5               | 153.9               | 223.6        | 467.0                | 481.5              | 364.6                   | 69.0        |
| 33.5       | 149.5            | 191.9               | 153.6               | 222.7        | 465.2                | 479.6              | 363.7                   | 69.6        |
| 34         | 149.4            | 192.1               | 153.9               | 222.6        | 468.0                | 482.5              | 366.3                   | 70.5        |

Table C.2 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 34.5       | 149.9            | 192.2               | 154.2               | 222.9        | 470.5                | 485.1              | 367.8                   | 69.3        |
| 35         | 149.2            | 191.8               | 154.1               | 222.9        | 474.4                | 489.0              | 369.7                   | 69.8        |
| 35.5       | 149.1            | 191.8               | 154.0               | 222.2        | 475.7                | 490.4              | 370.4                   | 69.6        |
| 36         | 148.9            | 191.5               | 154.1               | 222.7        | 474.5                | 489.1              | 369.5                   | 69.9        |
| 36.5       | 148.9            | 191.9               | 154.2               | 224.4        | 472.5                | 487.1              | 368.7                   | 69.9        |
| 37         | 149.6            | 191.9               | 154.2               | 222.8        | 471.5                | 486.1              | 368.3                   | 70.0        |
| 37.5       | 149.7            | 191.9               | 154.1               | 221.9        | 474.0                | 488.7              | 370.7                   | 69.5        |
| 38         | 148.8            | 191.6               | 154.1               | 222.7        | 473.4                | 488.1              | 370.1                   | 70.9        |
| 38.5       | 148.9            | 191.8               | 154.2               | 221.7        | 476.7                | 491.5              | 372.0                   | 69.9        |
| 39         | 149.3            | 191.8               | 154.2               | 222.5        | 480.9                | 495.8              | 374.8                   | 69.5        |
| 39.5       | 149.6            | 192.1               | 154.4               | 222.7        | 488.4                | 503.5              | 379.7                   | 69.2        |
| 40         | 148.8            | 192.5               | 154.6               | 223.8        | 489.2                | 504.3              | 379.8                   | 70.3        |
| 40.5       | 149.8            | 192.6               | 154.8               | 223.3        | 486.1                | 501.2              | 377.4                   | 70.3        |
| 41         | 151.2            | 193.2               | 155.0               | 223.5        | 488.4                | 503.5              | 379.1                   | 69.2        |
| 41.5       | 150.1            | 192.9               | 155.0               | 224.7        | 487.5                | 502.6              | 378.4                   | 69.6        |
| 42         | 149.7            | 192.6               | 155.0               | 223.9        | 483.0                | 497.9              | 375.6                   | 70.3        |
| 42.5       | 150.3            | 192.7               | 154.9               | 221.0        | 480.3                | 495.2              | 374.5                   | 69.6        |
| 43         | 149.3            | 192.6               | 155.1               | 223.6        | 478.3                | 493.1              | 373.7                   | 69.8        |
| 43.5       | 149.7            | 192.4               | 154.8               | 221.2        | 472.3                | 486.9              | 369.1                   | 69.8        |
| 44         | 149.0            | 191.7               | 154.5               | 218.6        | 469.8                | 484.3              | 367.9                   | 68.9        |
| 44.5       | 150.7            | 191.9               | 154.6               | 220.9        | 475.7                | 490.4              | 371.5                   | 69.8        |
| 45         | 148.3            | 191.5               | 154.7               | 221.8        | 481.9                | 496.8              | 375.3                   | 69.5        |
| 45.5       | 150.8            | 191.8               | 154.7               | 222.3        | 482.9                | 497.8              | 375.5                   | 69.4        |
| 46         | 149.8            | 191.8               | 154.7               | 223.0        | 484.3                | 499.3              | 376.6                   | 69.3        |
| 46.5       | 150.1            | 191.5               | 154.8               | 223.2        | 480.3                | 495.1              | 373.0                   | 69.1        |
| 47         | 150.0            | 191.2               | 154.5               | 222.4        | 474.4                | 489.1              | 368.8                   | 69.9        |
| 47.5       | 148.8            | 191.3               | 154.5               | 220.9        | 474.6                | 489.3              | 369.6                   | 69.6        |
| 48         | 149.2            | 191.2               | 154.4               | 221.9        | 472.6                | 487.2              | 368.3                   | 69.3        |
| 48.5       | 148.9            | 190.4               | 154.2               | 220.3        | 473.4                | 488.1              | 369.8                   | 69.5        |
| 49         | 148.8            | 190.1               | 154.1               | 219.7        | 471.2                | 485.8              | 368.6                   | 69.9        |
| 49.5       | 148.1            | 190.0               | 154.0               | 218.1        | 471.5                | 486.1              | 368.3                   | 69.4        |
| 50         | 148.6            | 190.4               | 154.0               | 221.0        | 480.4                | 495.3              | 374.1                   | 69.4        |
| 50.5       | 148.8            | 190.2               | 154.1               | 220.5        | 479.2                | 494.0              | 372.1                   | 69.6        |
| 51         | 149.2            | 189.9               | 153.9               | 218.8        | 475.0                | 489.7              | 368.5                   | 70.3        |

Table C.2 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 51.5       | 149.0            | 189.9               | 153.9               | 220.3        | 476.6                | 491.4              | 370.3                   | 69.7        |
| 52         | 148.9            | 189.9               | 153.8               | 220.3        | 477.0                | 491.7              | 371.2                   | 69.4        |
| 52.5       | 148.5            | 190.0               | 154.0               | 220.5        | 479.8                | 494.6              | 373.2                   | 69.2        |
| Averages   | 147.9            | 189.8               | 152.7               | 223.7        | 475.1                | 489.7              | 369.7                   | 69.2        |

### Forced Convection Calculations for 4 hr 50/50 Camelina Sawdust Burn Test at -4° F outside temperature

$$R = F + 459.67$$

$$T_{in} := 69.234^{\circ}\text{F} \quad T_o := 69.234$$

$$T_{out} := 223.65^{\circ}\text{F}$$

$$C_p = .2417 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

### From Dwyer Series 160 Data Sheet

$$P_B := 24.9 \quad \text{this is the barometric pressure in inches of mercury as measured}$$

$$T_{\text{absF}} := 459.67 + T_o \quad \text{this is absolute temperature of airflow past the pitot static tube}$$

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}}$$

$$\rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .062 \frac{\text{lb}}{\text{ft}^3}$$

### Calculate Air Velocity

$$P_v := 0.16 \quad \text{This is the velocity (or dynamic) pressure in inches of water, experimentally measured}$$

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.756 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1756 \frac{\text{ft}}{\text{min}}$$

**Mass Flow Rate**

$$d := \frac{4.25}{12} \text{ ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ ft}^2$$

$$\dot{m}_{\text{dot}} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m}_{\text{dot}} = 0.179 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := \dot{m}_{\text{dot}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$q_{\text{forced\_conv}} = 2.398 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at max steady state operations

**Radiation Calculations for 50/50 camelina sawdust burn test with outside temperature at -4° F**

$$T_{\text{surface}} := \left( \frac{444.85 + 459.67}{163.46 + 459.67} \right) \text{ R} \quad T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{ R}$$

$$A_{\text{surface}} := \left[ \frac{20 \cdot 13.5}{8 \cdot \frac{(13.5 + 1.5)}{2}} \right] \text{ in}^2 \quad A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon_{\text{glass}} := \left( \frac{0.95}{0.22} \right) \quad \sigma := .1714 \cdot 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{R}^4} \quad \text{Stefan-Boltzmann Constant}$$

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ (T_{\text{surface}_0})^4 - (T_{\text{surr}_0})^4 \right] \quad q_{\text{radglass}} = 1.805 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ (T_{\text{surface}_1})^4 - (T_{\text{surr}_1})^4 \right] \quad q_{\text{radsteel}} = 11.393 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + 2q_{\text{radsteel}} \quad q_{\text{radtot}} = 1.828 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

**Total Heat Transfer****Fraction of Radiation:**

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 2.58 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}} \quad \text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.071$$

Table C.3: Steady state data for Premium Wood Pellets

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 0          | 226.9            | 213.0               | 170.3               | 272.8        | 647.4                | 640.8              | 541.7                   | 68.4        |
| 0.5        | 227.1            | 213.6               | 171.1               | 272.8        | 647.5                | 639.7              | 541.7                   | 71.5        |
| 1          | 228.0            | 214.4               | 171.8               | 272.7        | 642.5                | 634.0              | 539.0                   | 71.1        |
| 1.5        | 228.4            | 215.0               | 172.8               | 271.4        | 639.7                | 631.5              | 537.9                   | 69.5        |
| 2          | 229.0            | 215.4               | 172.9               | 271.8        | 636.4                | 628.7              | 537.1                   | 69.6        |
| 2.5        | 229.2            | 216.2               | 173.5               | 271.4        | 632.2                | 624.3              | 534.4                   | 67.5        |
| 3          | 228.9            | 215.8               | 173.6               | 270.7        | 628.9                | 623.3              | 534.0                   | 67.4        |
| 3.5        | 229.2            | 216.4               | 174.0               | 271.1        | 628.7                | 625.2              | 535.5                   | 68.2        |
| 4          | 229.8            | 217.3               | 174.2               | 271.6        | 623.5                | 619.0              | 531.9                   | 68.0        |
| 4.5        | 229.8            | 217.3               | 174.2               | 270.4        | 623.4                | 621.2              | 532.9                   | 70.1        |
| 5          | 230.2            | 217.0               | 174.5               | 270.1        | 626.4                | 624.7              | 535.3                   | 70.7        |
| 5.5        | 230.2            | 217.3               | 174.6               | 268.4        | 626.5                | 624.4              | 535.3                   | 71.1        |
| 6          | 230.5            | 217.8               | 175.0               | 268.8        | 630.0                | 630.9              | 539.2                   | 69.0        |
| 6.5        | 230.8            | 218.8               | 175.2               | 267.7        | 631.0                | 630.5              | 539.1                   | 69.8        |
| 7          | 231.0            | 219.5               | 175.7               | 268.9        | 629.9                | 629.1              | 538.7                   | 71.6        |
| 7.5        | 230.8            | 218.8               | 175.9               | 269.3        | 628.0                | 625.8              | 537.2                   | 69.9        |
| 8          | 231.2            | 219.3               | 176.8               | 267.0        | 625.1                | 621.2              | 534.3                   | 71.0        |
| 8.5        | 231.3            | 219.3               | 176.3               | 268.3        | 626.7                | 623.1              | 535.7                   | 72.2        |
| 9          | 231.8            | 220.2               | 177.2               | 268.0        | 628.7                | 625.4              | 537.2                   | 71.7        |
| 9.5        | 231.8            | 219.8               | 177.5               | 266.9        | 624.6                | 619.7              | 533.9                   | 71.7        |
| 10         | 231.7            | 220.7               | 177.6               | 266.1        | 622.6                | 618.7              | 533.5                   | 70.9        |
| 10.5       | 231.8            | 220.7               | 177.8               | 266.1        | 621.0                | 616.9              | 532.8                   | 71.5        |
| 11         | 231.9            | 220.6               | 178.2               | 265.6        | 615.8                | 609.3              | 527.8                   | 70.0        |
| 11.5       | 231.6            | 220.2               | 178.1               | 265.2        | 613.3                | 608.3              | 526.6                   | 70.7        |
| 12         | 231.3            | 220.2               | 178.3               | 264.5        | 612.3                | 607.9              | 526.6                   | 72.9        |
| 12.5       | 231.1            | 220.1               | 178.3               | 264.2        | 612.5                | 609.2              | 527.8                   | 72.0        |
| 13         | 231.1            | 220.0               | 178.3               | 263.4        | 612.1                | 607.6              | 526.5                   | 72.8        |
| 13.5       | 230.8            | 220.1               | 178.5               | 265.3        | 611.5                | 607.0              | 526.5                   | 72.0        |
| 14         | 230.1            | 219.4               | 178.5               | 263.3        | 614.5                | 611.8              | 528.8                   | 70.8        |
| 14.5       | 230.3            | 219.2               | 178.8               | 265.1        | 621.7                | 620.0              | 533.2                   | 71.6        |
| 15         | 230.6            | 219.8               | 178.7               | 264.0        | 623.0                | 618.3              | 532.5                   | 72.1        |
| 15.5       | 230.6            | 220.0               | 179.0               | 265.0        | 625.5                | 622.9              | 535.2                   | 72.0        |
| 16         | 231.0            | 220.5               | 179.3               | 266.7        | 631.9                | 628.9              | 538.1                   | 72.2        |
| 16.5       | 230.4            | 220.3               | 179.6               | 267.2        | 633.9                | 629.3              | 538.6                   | 72.4        |
| 17         | 231.3            | 220.9               | 179.9               | 268.4        | 640.5                | 637.1              | 542.9                   | 73.1        |

Table C.3 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 17.5       | 231.4            | 221.4               | 180.1               | 270.4        | 645.4                | 638.9              | 544.3                   | 72.0        |
| 18         | 232.0            | 220.9               | 180.5               | 269.5        | 642.5                | 634.3              | 541.8                   | 72.7        |
| 18.5       | 231.3            | 221.5               | 180.3               | 269.8        | 639.5                | 631.6              | 540.3                   | 72.9        |
| 19         | 231.4            | 221.2               | 180.6               | 270.1        | 639.1                | 632.4              | 540.5                   | 73.0        |
| 19.5       | 232.0            | 222.1               | 180.9               | 270.7        | 640.9                | 634.9              | 541.9                   | 72.5        |
| 20         | 232.5            | 221.7               | 180.9               | 271.4        | 643.1                | 638.0              | 544.8                   | 72.7        |
| 20.5       | 232.6            | 221.9               | 181.5               | 270.6        | 640.8                | 635.3              | 544.0                   | 72.5        |
| 21         | 232.6            | 222.7               | 181.7               | 270.5        | 638.3                | 633.2              | 542.8                   | 73.4        |
| 21.5       | 232.7            | 223.0               | 181.8               | 270.9        | 642.1                | 640.0              | 547.1                   | 73.6        |
| 22         | 233.2            | 223.4               | 182.4               | 272.3        | 645.6                | 641.7              | 548.7                   | 72.8        |
| 22.5       | 233.7            | 224.1               | 182.5               | 272.3        | 644.8                | 642.2              | 549.2                   | 73.5        |
| 23         | 234.0            | 224.9               | 183.0               | 272.7        | 644.4                | 640.4              | 549.5                   | 71.9        |
| 23.5       | 234.3            | 224.8               | 183.0               | 272.4        | 640.7                | 637.8              | 548.5                   | 73.3        |
| 24         | 234.8            | 225.7               | 183.3               | 273.6        | 640.6                | 639.2              | 549.1                   | 72.3        |
| 24.5       | 235.1            | 225.8               | 183.5               | 272.4        | 642.2                | 639.9              | 549.7                   | 72.5        |
| 25         | 234.7            | 225.6               | 183.8               | 271.9        | 637.8                | 635.8              | 547.3                   | 71.8        |
| 25.5       | 235.6            | 226.4               | 183.9               | 273.5        | 637.9                | 636.2              | 547.2                   | 72.5        |
| 26         | 235.9            | 226.6               | 184.3               | 273.4        | 640.1                | 637.5              | 547.7                   | 73.6        |
| 26.5       | 235.7            | 227.2               | 184.5               | 272.3        | 641.8                | 640.1              | 549.5                   | 72.5        |
| 27         | 236.2            | 227.1               | 184.5               | 273.9        | 647.1                | 646.5              | 553.9                   | 72.8        |
| 27.5       | 236.4            | 227.8               | 184.9               | 274.9        | 649.0                | 647.5              | 555.7                   | 73.5        |
| 28         | 236.7            | 228.1               | 185.3               | 274.7        | 644.8                | 640.3              | 551.6                   | 72.8        |
| 28.5       | 236.6            | 228.0               | 185.5               | 274.7        | 642.2                | 640.4              | 551.5                   | 72.7        |
| 29         | 237.0            | 228.2               | 185.6               | 274.2        | 641.7                | 639.5              | 551.1                   | 73.2        |
| Averages   | 231.9            | 220.9               | 178.9               | 269.7        | 633.1                | 629.1              | 539.8                   | 71.6        |

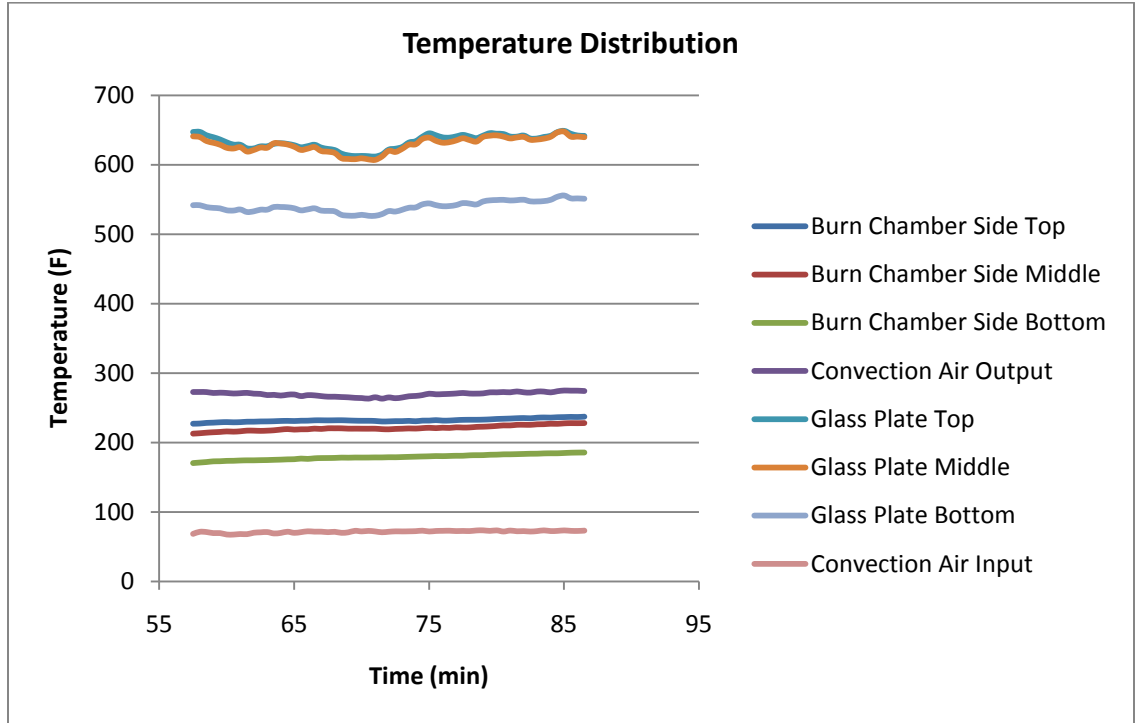


Figure C.1: Steady state temperature distribution for premium wood pellets

Table C.4: ECA 450 data for premium wood pellets at steady state

| Time (min) | O2 (%) | CO (ppm) | EFF (%) | CO2 (%) | NO (ppm) | NO2 (ppm) | NOX (ppm) | SO2 (ppm) |
|------------|--------|----------|---------|---------|----------|-----------|-----------|-----------|
| 1          | 13.9   | 312      | 73.2    | 6.8     | 52       | 0         | 52        | 9         |
| 2          | 13     | 469      | 74.8    | 7.7     | 57       | 0         | 58        | 13        |
| 3          | 13.6   | 155      | 73.9    | 7.1     | 52       | 0         | 52        | 7         |
| 4          | 13.4   | 226      | 74.2    | 7.4     | 52       | 0         | 52        | 5         |
| 5          | 14.3   | 93       | 72.4    | 6.4     | 45       | 0         | 45        | 1         |
| 6          | 12.8   | 131      | 75.2    | 7.9     | 54       | 0         | 54        | 3         |
| 7          | 13.4   | 151      | 74.3    | 7.3     | 54       | 0         | 54        | 1         |
| 8          | 11.7   | 886      | 76.1    | 9       | 60       | 0         | 60        | 20        |
| 9          | 12.1   | 231      | 75.9    | 8.6     | 58       | 0         | 58        | 5         |
| 10         | 12.7   | 752      | 74.9    | 8       | 55       | 0         | 55        | 8         |
| 11         | 11.9   | 1448     | 75.6    | 8.8     | 60       | 0         | 60        | 24        |
| 12         | 13.4   | 217      | 74      | 7.3     | 51       | 0         | 51        | 6         |
| 13         | 13     | 337      | 74.7    | 7.7     | 53       | 0         | 53        | 6         |
| 14         | 13.3   | 814      | 73.8    | 7.4     | 57       | 0         | 57        | 8         |

Table C.4 (Continued)

| Time<br>(min) | O2<br>(%) | CO<br>(ppm) | EFF<br>(%) | CO2<br>(%) | NO<br>(ppm) | NO2<br>(ppm) | NOX<br>(ppm) | SO2<br>(ppm) |
|---------------|-----------|-------------|------------|------------|-------------|--------------|--------------|--------------|
| 15            | 11.3      | 752         | 76.7       | 9.4        | 56          | 0            | 56           | 46           |
| 16            | 12.4      | 503         | 75.5       | 8.3        | 53          | 0            | 54           | 30           |
| 17            | 13.3      | 236         | 74.2       | 7.4        | 53          | 0            | 53           | 6            |
| 18            | 12.2      | 1179        | 75.4       | 8.5        | 62          | 0            | 62           | 20           |
| 19            | 12.8      | 339         | 74.9       | 7.9        | 60          | 0            | 60           | 6            |
| 20            | 12        | 283         | 76         | 8.7        | 58          | 0            | 58           | 8            |
| 21            | 12.2      | 1495        | 75.2       | 8.5        | 62          | 0            | 62           | 24           |
| 22            | 12.6      | 172         | 75.2       | 8.1        | 54          | 0            | 54           | 8            |
| 23            | 15.9      | 249         | 67.2       | 4.9        | 42          | 0            | 42           | 4            |
| Averages      | 12.9      | 496.9       | 74.5       | 7.8        | 54.8        | 0            | 54.9         | 11.7         |

### Forced Convection Calculations for 1.5 hr Premium Wood Test in MT. Vernon Stove

$$R = F + 459.67$$

$$T_{in} := 71.595^{\circ}\text{F} \quad T_o := 71.595^{\circ}\text{F}$$

$$T_{out} := 269.7053^{\circ}\text{F}$$

$$C_p = .2424 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

### From Dwyer Series 160 Data Sheet

$$P_B := 24.9 \quad \text{this is the barometric pressure in inches of mercury as measured}$$

$$T_{\text{absF}} := 459.67 + T_o \quad \text{this is absolute temperature of airflow past the pitot static tube}$$

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}}$$

$$\rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .062 \frac{\text{lb}}{\text{ft}^3}$$

**Calculate Air Velocity**

$$P_v := 0.16$$

This is the velocity (or dynamic) pressure in inches of water, experimentally measured

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.76 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1.76 \times 10^3 \frac{\text{ft}}{\text{min}}$$

**Mass Flow Rate**

$$d := \frac{4.25}{12} \text{ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ft}^2$$

$$\dot{m}_{\text{dot1}} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m}_{\text{dot1}} = 0.179 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := \dot{m}_{\text{dot1}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$q_{\text{forced\_conv}} = 3.092 \times 10^4 \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at steady state operation

**Radiation Calculations**

$$T_{\text{surface}} := \left( \frac{600.6685 + 459.67}{210.5606 + 459.67} \right) \text{R} \quad T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{R}$$

$$A_{\text{surface}} := \left[ 8 \cdot \frac{20 \cdot 13.5}{(13.5 + 1.5)} \right] \text{in}^2 \quad A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon := \begin{pmatrix} 0.95 \\ 0.22 \end{pmatrix}$$

$$\sigma := .1714 \times 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ \text{R}^4} \quad \text{Stefan-Boltzmann Constant}$$

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ \left( T_{\text{surface}_0} \right)^4 - \left( T_{\text{surr}_0} \right)^4 \right] \quad q_{\text{radglass}} = 3.616 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ \left( T_{\text{surface}_1} \right)^4 - \left( T_{\text{surr}_1} \right)^4 \right] \quad q_{\text{radsteel}} = 19.188 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + 2q_{\text{radsteel}} \quad q_{\text{radtot}} = 3.655 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

### Total Heat Transfer

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 3.457 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

### Fraction of Radiation:

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.107$$

Table C.5: Steady state data for 50/50 camelina sawdust pellets

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 0          | 204.1            | 186.2               | 150.1               | 222.9        | 510.9                | 526.7              | 427.0                   | 68.4        |
| 0.5        | 205.1            | 187.5               | 150.8               | 222.9        | 506.8                | 522.4              | 424.0                   | 67.9        |
| 1          | 205.5            | 187.5               | 151.2               | 222.5        | 499.0                | 514.5              | 418.3                   | 68.2        |
| 1.5        | 206.1            | 187.7               | 151.5               | 222.3        | 495.7                | 511.0              | 416.4                   | 68.2        |
| 2          | 206.5            | 188.2               | 152.1               | 222.3        | 495.5                | 510.8              | 416.9                   | 68.4        |
| 2.5        | 206.8            | 188.5               | 152.4               | 222.0        | 493.3                | 508.6              | 415.6                   | 68.6        |
| 3          | 207.0            | 189.0               | 152.9               | 221.6        | 487.1                | 502.2              | 410.8                   | 68.7        |
| 3.5        | 207.1            | 189.2               | 153.0               | 221.0        | 484.7                | 499.7              | 409.6                   | 68.9        |
| 4          | 207.5            | 189.6               | 153.3               | 219.8        | 481.1                | 496.0              | 407.2                   | 68.3        |
| 4.5        | 207.7            | 189.9               | 153.5               | 218.3        | 478.1                | 492.8              | 405.3                   | 68.4        |
| 5          | 207.6            | 189.7               | 153.9               | 218.5        | 478.8                | 493.6              | 406.3                   | 68.7        |
| 5.5        | 207.5            | 189.7               | 154.1               | 217.7        | 477.1                | 491.9              | 405.4                   | 68.4        |
| 6          | 207.4            | 190.3               | 154.2               | 218.2        | 472.2                | 486.8              | 401.6                   | 69.0        |
| 6.5        | 207.7            | 190.0               | 154.4               | 217.2        | 467.1                | 481.6              | 397.6                   | 69.0        |
| 7          | 207.8            | 190.4               | 154.6               | 215.2        | 465.3                | 479.7              | 396.3                   | 69.6        |
| 7.5        | 207.8            | 190.2               | 154.5               | 215.8        | 467.4                | 481.8              | 398.0                   | 69.2        |
| 8          | 207.8            | 190.3               | 154.8               | 216.9        | 474.5                | 489.1              | 403.1                   | 69.4        |
| 8.5        | 208.0            | 190.9               | 154.8               | 216.0        | 481.7                | 496.6              | 407.8                   | 69.1        |
| 9          | 208.4            | 190.9               | 155.2               | 217.6        | 488.8                | 503.9              | 412.9                   | 69.3        |
| 9.5        | 208.5            | 191.2               | 155.5               | 218.3        | 490.5                | 505.6              | 414.5                   | 69.4        |
| 10         | 209.1            | 191.7               | 155.9               | 219.6        | 490.2                | 505.4              | 414.7                   | 70.0        |
| 10.5       | 209.4            | 191.9               | 156.1               | 220.2        | 496.8                | 512.1              | 419.1                   | 69.4        |
| 11         | 209.8            | 192.5               | 156.5               | 221.5        | 500.9                | 516.4              | 422.1                   | 69.7        |
| 11.5       | 210.2            | 193.0               | 156.9               | 221.9        | 503.8                | 519.4              | 424.3                   | 70.4        |
| 12         | 211.4            | 193.9               | 157.4               | 222.5        | 506.8                | 522.5              | 426.6                   | 70.0        |
| 12.5       | 211.8            | 194.3               | 157.7               | 223.3        | 508.3                | 524.0              | 428.1                   | 69.6        |
| 13         | 212.6            | 194.9               | 158.0               | 224.4        | 513.3                | 529.1              | 431.2                   | 69.3        |
| 13.5       | 213.4            | 195.5               | 158.6               | 225.5        | 517.1                | 533.1              | 434.0                   | 69.8        |
| 14         | 213.8            | 195.7               | 158.9               | 226.9        | 515.3                | 531.2              | 433.0                   | 69.6        |
| 14.5       | 214.2            | 196.3               | 159.6               | 225.8        | 510.6                | 526.4              | 429.5                   | 70.1        |
| 15         | 214.3            | 196.7               | 159.6               | 226.3        | 512.9                | 528.8              | 431.4                   | 70.0        |
| 15.5       | 214.8            | 197.4               | 160.1               | 226.0        | 508.1                | 523.8              | 427.9                   | 70.1        |
| 16         | 215.0            | 198.0               | 160.3               | 225.7        | 504.8                | 520.4              | 426.2                   | 70.3        |
| 16.5       | 215.7            | 198.5               | 160.9               | 224.9        | 502.7                | 518.2              | 425.1                   | 69.9        |
| 17         | 215.7            | 198.1               | 160.9               | 224.8        | 502.4                | 517.9              | 425.1                   | 70.4        |

Table C.5 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 17.5       | 216.0            | 198.5               | 161.5               | 224.9        | 505.6                | 521.2              | 427.0                   | 70.3        |
| 18         | 216.7            | 199.2               | 161.9               | 225.7        | 503.4                | 519.0              | 425.5                   | 69.9        |
| 18.5       | 216.8            | 199.4               | 161.8               | 224.8        | 497.4                | 512.7              | 421.1                   | 70.3        |
| 19         | 217.0            | 199.3               | 162.0               | 224.5        | 496.0                | 511.4              | 420.4                   | 70.8        |
| 19.5       | 217.1            | 200.2               | 162.1               | 224.2        | 498.3                | 513.7              | 422.4                   | 70.4        |
| 20         | 217.4            | 200.0               | 162.2               | 223.7        | 494.2                | 509.5              | 419.3                   | 70.3        |
| 20.5       | 217.4            | 199.6               | 162.3               | 223.9        | 494.7                | 510.0              | 420.2                   | 70.3        |
| 21         | 218.1            | 200.9               | 162.7               | 224.6        | 497.9                | 513.3              | 422.8                   | 70.8        |
| 21.5       | 218.3            | 200.7               | 162.7               | 224.7        | 494.3                | 509.6              | 420.2                   | 70.0        |
| 22         | 218.2            | 200.8               | 163.0               | 223.9        | 491.0                | 506.2              | 417.9                   | 70.7        |
| 22.5       | 218.5            | 201.2               | 163.1               | 223.6        | 495.9                | 511.3              | 422.1                   | 70.8        |
| 23         | 216.9            | 201.3               | 163.4               | 224.3        | 493.1                | 508.4              | 420.0                   | 70.4        |
| 23.5       | 216.5            | 201.4               | 163.5               | 222.6        | 490.4                | 505.6              | 418.0                   | 71.0        |
| 24         | 216.1            | 201.5               | 163.7               | 222.8        | 491.2                | 506.4              | 418.8                   | 70.6        |
| 24.5       | 216.1            | 201.3               | 163.7               | 223.4        | 491.6                | 506.9              | 419.6                   | 71.1        |
| 25         | 216.1            | 201.6               | 163.8               | 223.8        | 492.0                | 507.2              | 420.0                   | 70.9        |
| 25.5       | 216.1            | 202.2               | 163.9               | 224.3        | 496.6                | 511.9              | 423.2                   | 71.1        |
| 26         | 216.1            | 202.2               | 164.3               | 225.2        | 500.0                | 515.5              | 425.6                   | 71.1        |
| 26.5       | 215.8            | 202.5               | 164.3               | 225.2        | 504.9                | 520.6              | 429.0                   | 71.1        |
| Averages   | 212.1            | 195.0               | 158.1               | 222.3        | 494.8                | 510.1              | 418.6                   | 69.7        |

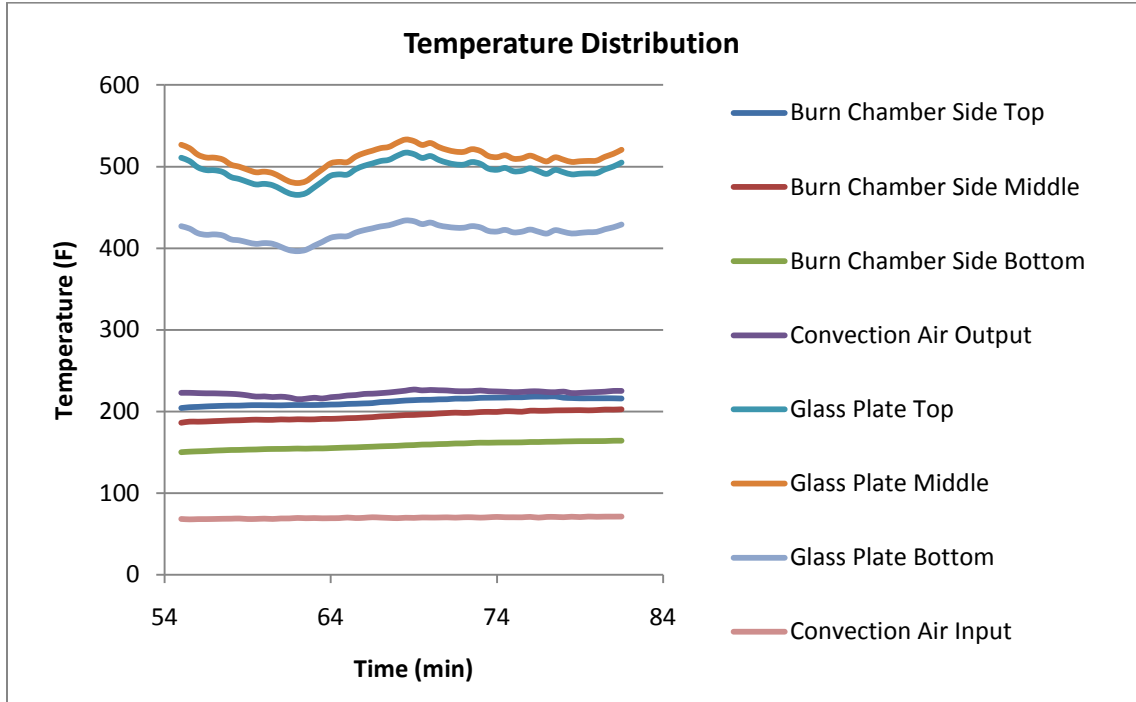


Figure C.2: Steady state temperature distribution for 50/50 camelina sawdust pellets

Table C.6: ECA 450 data for 50/50 camelina sawdust pellets at steady state

| Time (min) | O <sub>2</sub> (%) | CO (ppm) | EFF (%) | CO <sub>2</sub> (%) | NO (ppm) | NO <sub>2</sub> (ppm) | NO <sub>X</sub> (ppm) | SO <sub>2</sub> (ppm) |
|------------|--------------------|----------|---------|---------------------|----------|-----------------------|-----------------------|-----------------------|
| 1          | 15.2               | 166      | 70.6    | 5.5                 | 276      | 2                     | 279                   | 115                   |
| 2          | 17.2               | 431      |         |                     | 218      | 2                     | 220                   | 78                    |
| 3          | 16                 | 183      | 68.5    | 4.8                 | 249      | 2                     | 251                   | 87                    |
| 4          | 17.4               | 165      |         |                     | 227      | 2                     | 228                   | 80                    |
| 5          | 16.9               | 119      |         |                     | 254      | 2                     | 256                   | 73                    |
| 6          | 15.9               | 162      | 69.3    | 4.9                 | 240      | 2                     | 242                   | 82                    |
| 7          | 17.6               | 169      |         |                     | 235      | 2                     | 237                   | 81                    |
| 8          | 16.1               | 182      |         |                     | 277      | 2                     | 279                   | 69                    |
| 9          | 14.9               | 188      | 71.8    | 5.8                 | 271      | 2                     | 273                   | 112                   |
| 10         | 15.3               | 393      | 70.7    | 5.5                 | 257      | 2                     | 259                   | 133                   |
| 11         | 15.8               | 168      | 69      | 5                   | 263      | 2                     | 265                   | 101                   |
| 12         | 15.4               | 207      | 70.4    | 5.4                 | 292      | 2                     | 294                   | 122                   |
| 13         | 15.4               | 205      | 70.2    | 5.4                 | 263      | 2                     | 265                   | 115                   |
| 14         | 14.1               | 400      | 73.1    | 6.6                 | 290      | 2                     | 292                   | 124                   |
| 15         | 16.3               | 191      |         |                     | 253      | 2                     | 255                   | 104                   |

Table C.6 (Continued)

| Time<br>(min) | O2<br>(%) | CO<br>(ppm) | EFF<br>(%) | CO2<br>(%) | NO<br>(ppm) | NO2<br>(ppm) | NOX<br>(ppm) | SO2<br>(ppm) |
|---------------|-----------|-------------|------------|------------|-------------|--------------|--------------|--------------|
| 16            | 15.2      | 353         | 70.9       | 5.6        | 253         | 2            | 255          | 104          |
| 17            | 16        | 272         | 68.5       | 4.8        | 230         | 2            | 231          | 86           |
| 18            | 15.6      | 150         | 69.8       | 5.2        | 266         | 2            | 268          | 93           |
| 19            | 16.8      | 235         |            |            | 232         | 2            | 234          | 99           |
| 20            | 15.2      | 120         | 70.9       | 5.6        | 282         | 2            | 284          | 82           |
| 21            | 15.7      | 190         | 69.4       | 5.1        | 273         | 2            | 275          | 85           |
| 22            | 15        | 272         | 71.6       | 5.7        | 275         | 2            | 277          | 107          |
| 23            | 15.7      | 97          | 69.4       | 5          | 286         | 2            | 288          | 81           |
| 24            | 17.2      | 223         |            |            | 256         | 2            | 258          | 96           |
| 25            | 15.8      | 138         | 69.5       | 5          | 263         | 2            | 265          | 94           |
| 26            | 15.8      | 229         | 69.1       | 5          | 247         | 2            | 248          | 100          |
| 27            | 15.3      | 127         | 70.7       | 5.5        | 279         | 2            | 281          | 111          |
| Averages      | 15.9      | 212.4       | 70.2       | 5.3        | 259.5       | 2.0          | 261.4        | 96.8         |

### Forced Convection Calculations for 1.5 hr 50/50 camelina sawdust burn test in MT. Vernon Stove

$$R = F + 459.67$$

$$T_{in} := 69.73026^{\circ}\text{F} \quad T_o := 69.73026^{\circ}\text{F}$$

$$T_{out} := 222.390611^{\circ}\text{F}$$

$$C_p = .2417 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

### From Dwyer Series 160 Data Sheet

$$P_B := 24.9$$

this is the barometric pressure in inches of mercury as measured

$$T_{\text{absF}} := 459.67 + T_o$$

this is absolute temperature of airflow past the pitot static tube

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}}$$

$$\rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := 0.062 \frac{\text{lb}}{\text{ft}^3}$$

**Calculate Air Velocity**

$P_v := 0.1\text{ft}$  This is the velocity (or dynamic) pressure in inches of water, experimentally measured

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.756 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1.756 \times 10^3 \frac{\text{ft}}{\text{min}}$$

**Mass Flow Rate**

$$d := \frac{4.25}{12} \text{ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ft}^2$$

$$\dot{m}_{\text{dot}} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m}_{\text{dot}} = 0.179 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := \dot{m}_{\text{dot}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$q_{\text{forced\_conv}} = 2.37 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at max steady state operations

**Radiation Calculations**

$$T_{\text{surface}} := \left( \frac{474.499 + 459.67}{188.4143 + 459.67} \right) \text{R} \quad T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{R}$$

$$A_{\text{surface}} := \left[ 8 \cdot \frac{(13.5 + 1.5)}{2} \right] \text{in}^2 \quad A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon_{\text{gl}} := \begin{pmatrix} 0.95 \\ 0.22 \end{pmatrix}$$

$$\sigma := .1714 \times 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{R}^4}$$

Stefan-Boltzmann Constant

$$q_{\text{radglass}} := \varepsilon_o \cdot A_{\text{surface}_o} \cdot \sigma \cdot \left[ (T_{\text{surface}_o})^4 - (T_{\text{surr}_o})^4 \right] \quad q_{\text{radglass}} = 2.085 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ \left( T_{\text{surface}_1} \right)^4 - \left( T_{\text{surr}_1} \right)^4 \right] \quad q_{\text{radsteel}} = 15.376 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + 2q_{\text{radsteel}} \quad q_{\text{radtot}} = 2.116 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

### Total Heat Transfer

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 2.582 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

### Fraction of Radiation:

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.082$$

Table C.7: Steady state data for 50/50 camelina forest residue pellets

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 0          | 175.6            | 166.4               | 136.7               | 208.0        | 437.2                | 453.6              | 369.1                   | 67.2        |
| 0.5        | 176.1            | 167.0               | 137.0               | 208.0        | 439.4                | 455.8              | 370.5                   | 68.8        |
| 1          | 176.5            | 167.6               | 137.2               | 208.4        | 439.4                | 455.7              | 370.5                   | 68.3        |
| 1.5        | 177.0            | 167.7               | 137.4               | 208.7        | 439.7                | 455.5              | 370.8                   | 68.1        |
| 2          | 177.0            | 168.1               | 137.6               | 207.8        | 437.9                | 452.5              | 368.8                   | 68.0        |
| 2.5        | 177.1            | 168.1               | 137.7               | 207.3        | 435.4                | 447.9              | 365.5                   | 69.6        |
| 3          | 177.2            | 168.1               | 137.8               | 206.3        | 433.4                | 445.9              | 364.4                   | 67.3        |
| 3.5        | 177.6            | 168.5               | 138.1               | 205.8        | 433.4                | 445.5              | 364.7                   | 68.6        |
| 4          | 177.6            | 168.5               | 138.2               | 206.3        | 433.2                | 445.1              | 364.9                   | 68.1        |
| 4.5        | 177.6            | 168.3               | 138.4               | 206.3        | 431.7                | 443.5              | 363.7                   | 68.5        |
| 5          | 177.6            | 168.6               | 138.4               | 206.4        | 433.6                | 445.6              | 365.9                   | 69.0        |
| 5.5        | 177.8            | 168.7               | 138.7               | 205.9        | 433.1                | 445.1              | 365.7                   | 68.7        |
| 6          | 177.9            | 169.5               | 138.9               | 207.0        | 435.6                | 447.7              | 368.1                   | 68.1        |
| 6.5        | 178.2            | 169.3               | 139.0               | 206.4        | 433.5                | 445.5              | 366.4                   | 67.9        |
| 7          | 178.2            | 169.6               | 139.1               | 205.7        | 432.7                | 444.7              | 365.4                   | 68.6        |
| 7.5        | 178.4            | 169.3               | 139.3               | 207.3        | 436.3                | 448.4              | 368.1                   | 69.1        |
| 8          | 178.6            | 169.7               | 139.5               | 206.9        | 431.1                | 443.1              | 363.4                   | 68.6        |
| 8.5        | 178.6            | 169.6               | 139.5               | 206.9        | 428.3                | 440.2              | 361.6                   | 69.5        |
| 9          | 178.2            | 169.3               | 139.4               | 205.8        | 423.8                | 435.5              | 358.0                   | 68.3        |
| 9.5        | 178.1            | 169.3               | 139.4               | 205.0        | 421.3                | 433.0              | 356.7                   | 68.4        |
| 10         | 177.9            | 169.1               | 139.4               | 205.9        | 422.9                | 434.7              | 358.6                   | 68.6        |
| 10.5       | 178.0            | 169.3               | 139.5               | 204.9        | 423.3                | 435.1              | 359.3                   | 67.6        |
| 11         | 177.6            | 169.0               | 139.4               | 204.3        | 419.6                | 431.2              | 356.2                   | 69.8        |
| 11.5       | 177.6            | 168.8               | 139.2               | 203.9        | 413.4                | 424.9              | 351.0                   | 68.7        |
| 12         | 177.6            | 168.7               | 139.2               | 202.6        | 412.7                | 424.1              | 350.9                   | 68.4        |
| 12.5       | 177.2            | 168.7               | 139.1               | 202.8        | 417.0                | 428.5              | 354.7                   | 67.7        |
| 13         | 177.3            | 168.7               | 139.2               | 203.8        | 417.7                | 429.3              | 355.5                   | 69.3        |
| 13.5       | 177.2            | 168.4               | 139.2               | 203.4        | 425.7                | 437.5              | 361.2                   | 69.4        |
| 14         | 177.3            | 168.3               | 139.2               | 204.3        | 430.2                | 442.1              | 364.5                   | 69.2        |
| 14.5       | 177.1            | 168.5               | 139.3               | 204.0        | 431.1                | 443.1              | 365.2                   | 68.9        |
| 15         | 177.4            | 168.5               | 139.5               | 204.2        | 430.3                | 442.2              | 364.6                   | 68.9        |
| 15.5       | 177.2            | 168.6               | 139.5               | 203.7        | 426.1                | 437.9              | 361.2                   | 69.2        |
| 16         | 177.3            | 168.4               | 139.4               | 202.9        | 421.3                | 433.0              | 357.7                   | 69.0        |
| 16.5       | 177.0            | 167.9               | 139.3               | 202.1        | 416.2                | 427.7              | 353.3                   | 68.8        |
| 17         | 176.6            | 168.1               | 139.1               | 201.9        | 416.3                | 427.8              | 353.6                   | 70.1        |

Table C.7 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 17.5       | 176.4            | 167.8               | 139.2               | 201.6        | 417.9                | 429.5              | 355.0                   | 68.6        |
| 18         | 176.2            | 167.5               | 139.0               | 201.0        | 416.4                | 428.0              | 353.8                   | 69.1        |
| 18.5       | 176.0            | 167.3               | 138.8               | 200.9        | 421.8                | 433.5              | 357.7                   | 68.7        |
| 19         | 175.9            | 167.3               | 138.9               | 201.9        | 430.7                | 442.6              | 364.1                   | 68.9        |
| 19.5       | 176.3            | 167.6               | 139.1               | 203.0        | 436.3                | 448.4              | 368.1                   | 68.5        |
| 20         | 176.3            | 167.7               | 139.2               | 203.3        | 437.7                | 449.8              | 369.0                   | 69.1        |
| 20.5       | 176.3            | 167.5               | 139.3               | 202.2        | 436.2                | 448.3              | 367.7                   | 68.7        |
| 21         | 176.0            | 167.8               | 139.3               | 202.1        | 437.4                | 449.5              | 369.2                   | 69.1        |
| 21.5       | 176.3            | 167.6               | 139.2               | 202.5        | 432.2                | 444.2              | 364.7                   | 69.4        |
| 22         | 176.2            | 167.5               | 139.3               | 202.6        | 432.5                | 444.5              | 365.3                   | 68.8        |
| 22.5       | 175.8            | 167.5               | 139.2               | 202.1        | 432.8                | 444.8              | 365.9                   | 69.6        |
| 23         | 175.8            | 167.0               | 139.2               | 202.5        | 434.4                | 446.5              | 367.5                   | 68.7        |
| 23.5       | 175.8            | 167.4               | 139.3               | 201.7        | 436.6                | 448.7              | 369.7                   | 68.6        |
| 24         | 176.2            | 167.5               | 139.4               | 201.8        | 431.6                | 443.6              | 365.2                   | 69.6        |
| 24.5       | 175.7            | 167.5               | 139.1               | 201.4        | 432.9                | 444.9              | 366.9                   | 69.3        |
| 25         | 175.7            | 167.5               | 139.3               | 201.9        | 435.1                | 447.2              | 369.2                   | 68.7        |
| 25.5       | 175.5            | 167.6               | 139.4               | 202.1        | 442.3                | 454.5              | 374.8                   | 69.2        |
| 26         | 176.1            | 168.0               | 139.7               | 202.9        | 444.1                | 456.4              | 376.1                   | 69.7        |
| 26.5       | 176.2            | 167.5               | 139.5               | 202.5        | 438.3                | 450.5              | 370.7                   | 68.9        |
| 27         | 175.8            | 167.4               | 139.5               | 202.5        | 439.2                | 451.4              | 371.9                   | 69.5        |
| 27.5       | 176.1            | 168.0               | 139.7               | 202.7        | 438.3                | 450.5              | 371.6                   | 69.3        |
| 28         | 176.0            | 167.8               | 139.6               | 201.6        | 432.2                | 444.2              | 365.7                   | 69.2        |
| 28.5       | 175.8            | 167.4               | 139.5               | 201.4        | 429.1                | 441.0              | 363.9                   | 69.8        |
| 29         | 175.6            | 167.0               | 139.4               | 201.1        | 427.4                | 439.2              | 363.1                   | 69.7        |
| 29.5       | 175.6            | 167.2               | 139.5               | 201.5        | 428.4                | 440.3              | 364.7                   | 69.8        |
| 30         | 175.6            | 167.1               | 139.5               | 200.2        | 425.8                | 437.7              | 362.1                   | 69.7        |
| 30.5       | 175.7            | 167.2               | 139.4               | 200.3        | 426.5                | 438.3              | 362.5                   | 70.5        |
| 31         | 175.7            | 167.1               | 139.5               | 200.8        | 424.5                | 436.2              | 360.4                   | 70.4        |
| 31.5       | 174.9            | 167.0               | 139.3               | 200.4        | 421.2                | 432.9              | 357.1                   | 69.5        |
| 32         | 174.8            | 166.8               | 139.2               | 199.5        | 423.1                | 434.9              | 359.3                   | 70.0        |
| 32.5       | 175.2            | 167.1               | 139.3               | 199.3        | 422.1                | 433.8              | 358.3                   | 70.6        |
| 33         | 174.7            | 166.7               | 139.2               | 198.8        | 422.0                | 433.7              | 358.9                   | 69.8        |
| 33.5       | 174.2            | 166.4               | 138.9               | 198.8        | 421.7                | 433.4              | 358.6                   | 69.5        |
| 34         | 174.4            | 166.4               | 139.0               | 198.7        | 419.2                | 430.8              | 356.5                   | 70.3        |

Table C.7 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 34.5       | 174.1            | 166.0               | 138.9               | 199.3        | 425.4                | 437.2              | 361.3                   | 70.6        |
| 35         | 174.0            | 166.1               | 138.9               | 199.5        | 433.3                | 445.3              | 367.3                   | 71.1        |
| 35.5       | 173.8            | 165.9               | 138.9               | 200.4        | 439.7                | 451.9              | 372.1                   | 69.7        |
| Averages   | 176.5            | 167.9               | 139.0               | 203.3        | 429.4                | 441.6              | 363.5                   | 69.1        |

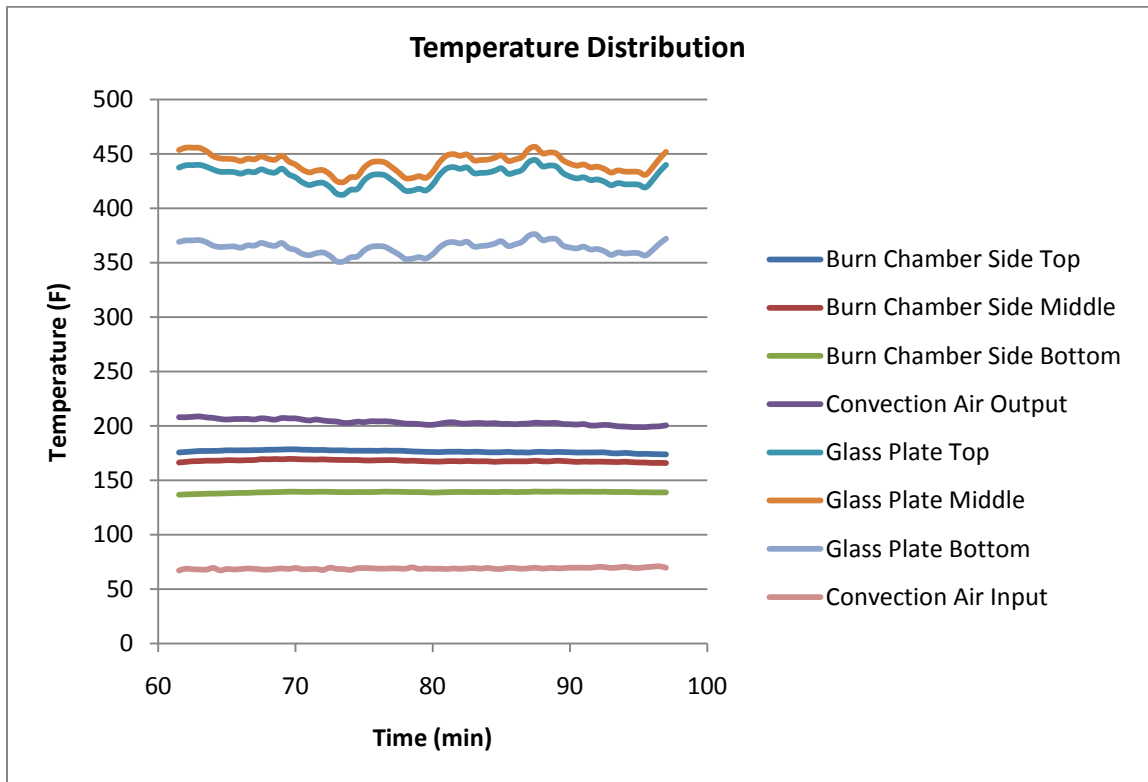


Figure C.3: Steady state temperature distribution for 50/50 camelina forest residue pellets

Table C.8: ECA 450 data for 50/50 camelina forest residue pellets at steady state

| Time (min) | O2 (%) | CO (ppm) | EFF (%) | NO (ppm) | NO2 (ppm) | NOX (ppm) | SO2 (ppm) |
|------------|--------|----------|---------|----------|-----------|-----------|-----------|
| 1          | 17.3   | 321      | 72.3    | 217      | 1         | 219       | 93        |
| 2          | 17.7   | 341      |         | 192      | 1         | 193       | 87        |
| 3          | 17.6   | 396      |         | 185      | 1         | 185       | 74        |
| 4          | 17     | 235      |         | 213      | 1         | 215       | 76        |
| 5          | 16.4   | 240      |         | 225      | 1         | 227       | 80        |
| 6          | 16.5   | 246      |         | 225      | 1         | 226       | 83        |
| 7          | 17.4   | 411      |         | 187      | 1         | 188       | 78        |
| 8          | 18.2   | 513      |         | 157      | 1         | 158       | 84        |
| 9          | 18.1   | 294      |         | 172      | 1         | 173       | 69        |
| 10         | 16.8   | 323      |         | 205      | 1         | 206       | 69        |
| 11         | 18     | 231      |         | 183      | 1         | 184       | 77        |
| 12         | 17.3   | 155      |         | 222      | 1         | 223       | 60        |
| 13         | 17.4   | 228      |         | 207      | 1         | 208       | 80        |
| 14         | 17     | 269      |         | 211      | 1         | 212       | 97        |
| 15         | 71.4   | 285      |         | 196      | 1         | 197       | 83        |
| 16         | 17.8   | 191      |         | 198      | 1         | 199       | 67        |
| 17         | 17.1   | 172      |         | 219      | 1         | 220       | 62        |
| 18         | 17.5   | 248      |         | 190      | 1         | 191       | 73        |
| 19         | 16.1   | 394      |         | 241      | 1         | 242       | 102       |
| 20         | 17.6   | 356      |         | 189      | 1         | 190       | 94        |
| 21         | 17     | 283      |         | 204      | 1         | 205       | 81        |
| 22         | 17     | 190      |         | 209      | 1         | 210       | 69        |
| 23         | 16.7   | 191      |         | 222      | 1         | 224       | 84        |
| 24         | 17.7   | 380      |         | 177      | 1         | 178       | 81        |
| 25         | 16.8   | 289      |         | 206      | 1         | 207       | 85        |
| 26         | 17.4   | 274      |         | 189      | 1         | 190       | 96        |
| 27         | 16.2   | 244      |         | 228      | 1         | 229       | 70        |
| 28         | 18.3   | 235      |         | 181      | 1         | 182       | 76        |
| 29         | 17.5   | 220      |         | 202      | 1         | 203       | 75        |
| 30         | 17.8   | 229      |         | 177      | 1         | 178       | 77        |
| 31         | 18.1   | 174      |         | 192      | 1         | 193       | 76        |
| 32         | 16.7   | 195      |         | 210      | 1         | 211       | 71        |

Table C.8 (Continued)

| Time<br>(min) | O2<br>(%) | CO<br>(ppm) | EFF<br>(%) | NO<br>(ppm) | NO2<br>(ppm) | NOX<br>(ppm) | SO2<br>(ppm) |
|---------------|-----------|-------------|------------|-------------|--------------|--------------|--------------|
| 33            | 17        | 177         |            | 207         | 1            | 208          | 73           |
| 34            | 16.9      | 151         |            | 213         | 1            | 214          | 72           |
| 35            | 16.9      | 412         |            | 211         | 1            | 212          | 101          |
| 36            | 18.4      | 397         |            | 139         | 1            | 140          | 90           |
| Averages      | 18.8      | 274.7       | 72.3       | 200.0       | 1.0          | 201.1        | 79.6         |

### Forced Convection Calculations for 1.5 hr 50/50 camelina forest residue burn test in MT. Vernon Stove

$$R = F + 459.67$$

$$T_{in} := 69.057^{\circ}\text{F} \quad T_o := 69.057^{\circ}\text{F}$$

$$T_{out} := 203.1^{\circ}\text{F}$$

$$C_p = .2414 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

### From Dwyer Series 160 Data Sheet

$$P_B := 24.9 \quad \text{this is the barometric pressure in inches of mercury as measured}$$

$$T_{\text{absF}} := 459.67 + T_o \quad \text{this is absolute temperature of airflow past the pitot static tube}$$

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}} \quad \rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .062 \frac{\text{lb}}{\text{ft}^3}$$

### Calculate Air Velocity

$$P_v := 0.16 \quad \text{This is the velocity (or dynamic) pressure in inches of water, experimentally measured}$$

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.755 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1755 \frac{\text{ft}}{\text{min}}$$

**Mass Flow Rate**

$$d := \frac{4.25}{12} \text{ ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ ft}^2$$

$$\dot{m}_{\text{dot}} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m}_{\text{dot}} = 0.179 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := \dot{m}_{\text{dot}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$q_{\text{forced\_conv}} = 2.078 \times 10^4 \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at max steady state operations

**Radiation Calculations**

$$T_{\text{surface}} := \left( \frac{411.5388 + 459.67}{161.1344 + 459.67} \right) \text{ R} \quad T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{ R}$$

$$A_{\text{surface}} := \left[ \frac{20 \cdot 13.5}{8 \cdot \frac{(13.5 + 1.5)}{2}} \right] \text{ in}^2 \quad A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon := \left( \frac{0.95}{0.22} \right) \quad \sigma := .1714 \cdot 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{R}^4} \quad \text{Stefan-Boltzmann Constant}$$

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ (T_{\text{surface}_0})^4 - (T_{\text{surr}_0})^4 \right] \quad q_{\text{radglass}} = 1.52 \times 10^3 \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ (T_{\text{surface}_1})^4 - (T_{\text{surr}_1})^4 \right] \quad q_{\text{radsteel}} = 11.058 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + 2q_{\text{radsteel}} \quad q_{\text{radtot}} = 1.542 \times 10^3 \frac{\text{Btu}}{\text{hr}}$$

**Total Heat Transfer**

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 2.232 \times 10^4 \frac{\text{Btu}}{\text{hr}}$$

**Percentage of Radiation:**

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.069$$

Table C.9: Steady state data for 80/20 camelina wheat straw pellets

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 0          | 159.6            | 151.1               | 124.5               | 204.4        | 430.0                | 438.0              | 347.7                   | 65.6        |
| 0.5        | 160.1            | 151.2               | 124.9               | 206.0        | 431.7                | 438.9              | 348.5                   | 66.2        |
| 1          | 160.7            | 152.1               | 125.3               | 203.6        | 429.5                | 432.3              | 343.1                   | 65.4        |
| 1.5        | 160.5            | 151.9               | 125.4               | 203.7        | 426.5                | 426.4              | 339.1                   | 65.4        |
| 2          | 160.8            | 151.9               | 125.5               | 202.9        | 422.3                | 418.3              | 333.0                   | 65.7        |
| 2.5        | 160.5            | 151.6               | 125.5               | 202.3        | 418.6                | 413.0              | 330.2                   | 65.2        |
| 3          | 160.6            | 151.9               | 125.6               | 203.3        | 416.7                | 410.5              | 329.1                   | 65.2        |
| 3.5        | 160.6            | 151.6               | 125.7               | 201.7        | 416.9                | 414.2              | 330.9                   | 66.0        |
| 4          | 160.8            | 151.9               | 125.9               | 201.2        | 420.5                | 422.8              | 336.5                   | 66.0        |
| 4.5        | 161.1            | 152.5               | 126.3               | 202.6        | 422.6                | 425.7              | 338.5                   | 65.7        |
| 5          | 161.3            | 152.6               | 126.6               | 202.0        | 425.6                | 430.0              | 341.9                   | 65.9        |
| 5.5        | 161.4            | 152.2               | 126.6               | 201.8        | 423.6                | 424.7              | 337.6                   | 65.8        |
| 6          | 161.1            | 152.5               | 126.6               | 201.6        | 422.4                | 423.7              | 337.0                   | 65.9        |
| 6.5        | 161.4            | 152.1               | 126.9               | 202.0        | 426.7                | 431.6              | 341.3                   | 65.6        |
| 7          | 161.4            | 152.7               | 127.2               | 202.0        | 430.3                | 435.5              | 343.7                   | 66.3        |
| 7.5        | 161.6            | 152.6               | 127.2               | 203.4        | 431.4                | 435.8              | 343.9                   | 66.4        |
| 8          | 161.6            | 152.9               | 127.3               | 203.7        | 433.0                | 437.6              | 344.5                   | 65.9        |
| 8.5        | 161.5            | 152.8               | 127.6               | 203.8        | 440.6                | 448.9              | 350.2                   | 65.9        |
| 9          | 161.7            | 152.8               | 127.7               | 206.0        | 446.0                | 453.1              | 352.7                   | 66.0        |
| 9.5        | 161.8            | 152.8               | 127.7               | 205.0        | 448.6                | 453.5              | 351.8                   | 66.2        |
| 10         | 161.6            | 152.7               | 127.8               | 205.6        | 451.0                | 454.8              | 352.6                   | 66.2        |
| 10.5       | 161.7            | 152.7               | 127.9               | 206.6        | 451.8                | 453.9              | 351.9                   | 66.4        |
| 11         | 161.7            | 152.4               | 127.8               | 207.2        | 453.9                | 458.3              | 354.4                   | 67.4        |
| 11.5       | 161.7            | 152.9               | 128.1               | 208.6        | 458.1                | 462.3              | 357.8                   | 66.5        |
| 12         | 162.1            | 153.1               | 128.3               | 208.7        | 456.4                | 457.3              | 354.0                   | 67.1        |
| 12.5       | 162.1            | 153.0               | 128.3               | 207.7        | 455.8                | 455.2              | 353.3                   | 66.4        |
| 13         | 162.1            | 153.2               | 128.3               | 207.3        | 454.2                | 451.1              | 351.1                   | 67.0        |
| 13.5       | 162.2            | 152.9               | 128.4               | 207.9        | 454.0                | 452.4              | 351.4                   | 66.6        |
| 14         | 162.2            | 152.8               | 128.3               | 207.2        | 453.3                | 450.7              | 351.0                   | 67.4        |
| 14.5       | 161.7            | 152.8               | 128.2               | 207.0        | 449.1                | 443.2              | 346.0                   | 66.4        |
| 15         | 161.5            | 152.0               | 128.0               | 205.8        | 444.7                | 437.0              | 342.3                   | 66.8        |
| 15.5       | 161.2            | 151.9               | 127.9               | 205.5        | 441.8                | 432.4              | 339.2                   | 67.0        |
| 16         | 161.0            | 152.0               | 127.9               | 206.4        | 440.8                | 434.2              | 340.1                   | 67.1        |
| 16.5       | 161.1            | 151.8               | 128.0               | 206.3        | 442.4                | 437.1              | 341.4                   | 66.7        |
| 17         | 161.1            | 152.0               | 128.0               | 207.6        | 445.6                | 442.5              | 344.5                   | 67.3        |

Table C.9 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|--------------------|-------------------------|-------------|
| 17.5       | 161.1            | 152.0               | 128.1               | 207.8        | 448.5                | 447.1              | 347.3                   | 67.4        |
| 18         | 161.2            | 152.1               | 128.1               | 207.6        | 448.9                | 446.0              | 346.5                   | 67.7        |
| 18.5       | 161.0            | 152.0               | 128.0               | 207.4        | 448.8                | 445.7              | 345.8                   | 67.4        |
| 19         | 161.1            | 151.7               | 128.0               | 207.3        | 451.2                | 449.3              | 348.2                   | 68.0        |
| 19.5       | 161.3            | 152.3               | 128.1               | 208.2        | 453.9                | 453.0              | 351.9                   | 67.2        |
| 20         | 161.4            | 152.1               | 128.3               | 208.6        | 455.9                | 456.1              | 355.0                   | 67.3        |
| Averages   | 161.3            | 152.3               | 127.2               | 205.3        | 439.6                | 439.9              | 345.0                   | 66.4        |

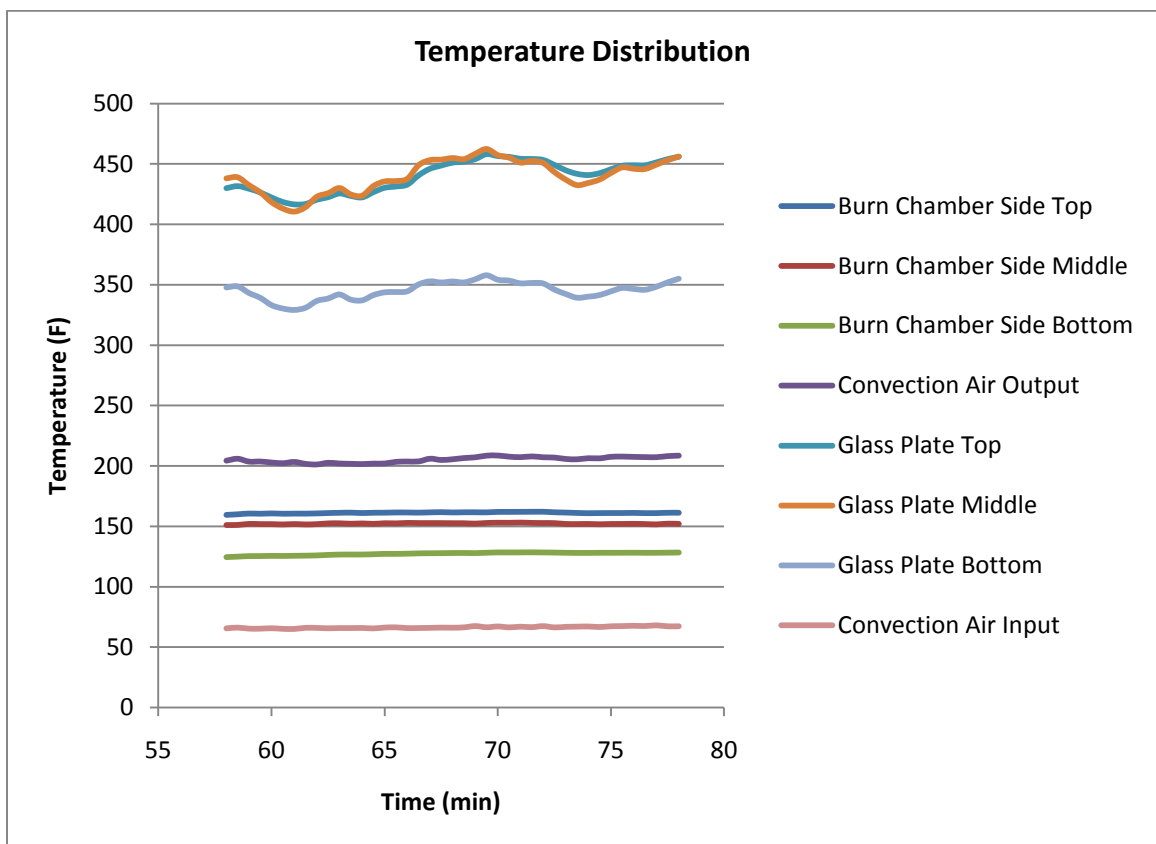


Figure C.4: Steady state temperature distribution for 80/20 camelina wheat straw pellets

Table C.10: ECA 450 data for 80/20 camelina wheat straw pellets at steady state

| Time (min) | O2 (%) | CO (ppm) | EFF (%) | CO2 (%) | NO (ppm) | NO2 (ppm) | NOX (ppm) | SO2 (ppm) |
|------------|--------|----------|---------|---------|----------|-----------|-----------|-----------|
| 1          | 18.1   | 484.0    | -       | -       | 236.0    | 1.0       | 238.0     | 125.0     |
| 2          | 16.4   | 364.0    | -       | -       | 286.0    | 2.0       | 287.0     | 123.0     |
| 3          | 18.2   | 831.0    | -       | -       | 208.0    | 1.0       | 210.0     | 125.0     |
| 4          | 18.6   | 752.0    | -       | -       | 196.0    | 1.0       | 196.0     | 106.0     |
| 5          | 17.6   | 378.0    | -       | -       | 240.0    | 1.0       | 241.0     | 95.0      |
| 6          | 17.5   | 661.0    | -       | -       | 253.0    | 2.0       | 255.0     | 110.0     |
| 7          | 18.4   | 903.0    | -       | -       | 215.0    | 1.0       | 216.0     | 122.0     |
| 8          | 16.6   | 634.0    | -       | -       | 289.0    | 1.0       | 291.0     | 108.0     |
| 9          | 17.4   | 677.0    | -       | -       | 251.0    | 2.0       | 252.0     | 117.0     |
| 10         | 15.6   | 724.0    | 71.0    | 5.2     | 293.0    | 2.0       | 295.0     | 124.0     |
| 11         | 17.5   | 788.0    | -       | -       | 229.0    | 1.0       | 230.0     | 134.0     |
| 12         | 17.7   | 756.0    | -       | -       | 204.0    | 1.0       | 205.0     | 123.0     |
| 13         | 15.8   | 620.0    | 70.2    | 4.9     | 299.0    | 2.0       | 301.0     | 129.0     |
| 14         | 17.2   | 645.0    | -       | -       | 239.0    | 1.0       | 240.0     | 126.0     |
| Averages   | 17.3   | 658.4    | 70.6    | 5.1     | 245.6    | 1.4       | 246.9     | 119.1     |

### Forced Convection Calculations for 1.5 hr 80/20 camelina wheat straw test in MT. Vernon Stove

$$R = F + 459.67$$

$$T_{in} := 66.4286^{\circ}\text{F} \quad T_o := 66.4286^{\circ}\text{F}$$

$$T_{out} := 205.4766^{\circ}\text{F}$$

$$C_p = .2414 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

### From Dwyer Series 160 Data Sheet

$$P_B := 24.9$$

this is the barometric pressure in inches of mercury as measured

$$T_{\text{absF}} := 459.67 + T_o$$

this is absolute temperature of airflow past the pitot static tube

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}}$$

$$\rho = 0.063 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .063 \frac{\text{lb}}{\text{ft}^3}$$

### Calculate Air Velocity

$P_v := 0.16$  This is the velocity (or dynamic) pressure in inches of water, experimentally measured

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.751 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1.751 \cdot 10^3 \frac{\text{ft}}{\text{min}}$$

### Mass Flow Rate

$$d := \frac{4.25}{12} \text{ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ft}^2$$

$$\dot{m}_{\text{dot}} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m}_{\text{dot}} = 0.181 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := \dot{m}_{\text{dot}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$q_{\text{forced\_conv}} = 2.185 \times 10^4 \frac{\text{Btu}}{\text{hr}} \quad \text{This is the heat output to the room due to forced convection at max steady state operations}$$

### Radiation Calculations

$$T_{\text{surface}} := \left( \frac{408.1665 + 459.67}{146.9927 + 459.67} \right) \text{R} \quad T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{R}$$

$$A_{\text{surface}} := \left[ \frac{20 \cdot 13.5}{8 \cdot \frac{(13.5 + 1.5)}{2}} \right] \text{in}^2 \quad A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon := \begin{pmatrix} 0.95 \\ 0.22 \end{pmatrix}$$

$$\sigma := .1714 \times 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{R}^4} \quad \text{Stefan-Boltzmann Constant}$$

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ \left( T_{\text{surface}_0} \right)^4 - \left( T_{\text{surr}_0} \right)^4 \right] \quad q_{\text{radglass}} = 1.498 \times 10^3 \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ \left( T_{\text{surface}_1} \right)^4 - \left( T_{\text{surr}_1} \right)^4 \right] \quad q_{\text{radsteel}} = 9.246 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + q_{\text{radsteel}} \quad q_{\text{radtot}} = 1.516 \times 10^3 \frac{\text{Btu}}{\text{hr}}$$

### Total Heat Transfer

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 2.337 \times 10^4 \frac{\text{Btu}}{\text{hr}}$$

### Fraction of Radiation:

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.065$$

Table C.11: Steady state data for 50/50 camelina safflower pellets

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle (°F) | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|-------------------------|-------------------------|-------------|
| 0          | 165.8            | 155.1               | 126.0               | 228.5        | 503.3                | 509.9                   | 399.1                   | 64.1        |
| 0.5        | 167.1            | 156.6               | 127.1               | 230.0        | 505.3                | 507.9                   | 398.9                   | 63.8        |
| 1          | 168.3            | 157.9               | 128.0               | 230.0        | 504.3                | 503.1                   | 397.4                   | 65.1        |
| 1.5        | 169.5            | 159.0               | 129.0               | 231.2        | 502.0                | 497.4                   | 394.6                   | 64.9        |
| 2          | 170.2            | 159.5               | 129.6               | 230.3        | 498.7                | 491.1                   | 391.4                   | 64.5        |
| 2.5        | 171.3            | 160.5               | 130.4               | 229.9        | 497.2                | 488.6                   | 390.9                   | 64.7        |
| 3          | 172.1            | 161.5               | 131.0               | 229.0        | 496.8                | 488.2                   | 391.6                   | 65.1        |
| 3.5        | 173.1            | 162.4               | 131.8               | 230.6        | 503.2                | 498.1                   | 398.6                   | 64.5        |
| 4          | 174.4            | 162.8               | 132.5               | 231.6        | 509.0                | 504.8                   | 403.7                   | 66.2        |
| 4.5        | 175.4            | 164.4               | 133.1               | 231.0        | 510.0                | 503.5                   | 403.5                   | 64.3        |
| 5          | 176.0            | 164.7               | 133.6               | 230.0        | 505.0                | 494.4                   | 397.3                   | 66.8        |
| 5.5        | 176.7            | 165.3               | 134.0               | 230.3        | 500.1                | 488.7                   | 394.4                   | 65.3        |
| 6          | 176.9            | 165.7               | 134.2               | 228.2        | 497.5                | 486.2                   | 393.7                   | 65.3        |
| 6.5        | 177.0            | 165.9               | 134.3               | 227.5        | 494.2                | 481.8                   | 391.2                   | 66.9        |
| 7          | 177.4            | 165.7               | 134.7               | 227.8        | 493.8                | 482.6                   | 392.3                   | 65.6        |
| 7.5        | 177.8            | 166.5               | 135.0               | 229.3        | 497.6                | 488.9                   | 396.5                   | 66.2        |
| 8          | 178.2            | 167.2               | 135.6               | 230.7        | 499.3                | 490.5                   | 397.9                   | 66.9        |
| 8.5        | 179.0            | 168.2               | 136.2               | 230.2        | 500.0                | 492.8                   | 399.8                   | 66.8        |
| 9          | 179.3            | 168.7               | 136.4               | 228.6        | 501.2                | 494.6                   | 401.4                   | 66.3        |
| 9.5        | 179.8            | 168.6               | 136.7               | 227.2        | 497.0                | 486.5                   | 395.7                   | 66.2        |
| 10         | 180.0            | 168.5               | 137.0               | 228.7        | 498.2                | 489.9                   | 397.4                   | 66.0        |
| 10.5       | 180.3            | 169.2               | 137.3               | 228.8        | 504.3                | 497.3                   | 401.8                   | 66.3        |
| 11         | 180.8            | 169.5               | 137.8               | 229.0        | 507.7                | 503.9                   | 405.3                   | 67.6        |
| 11.5       | 181.3            | 170.1               | 138.3               | 231.7        | 516.0                | 515.8                   | 412.1                   | 66.8        |
| 12         | 181.5            | 170.6               | 138.7               | 231.7        | 520.8                | 521.6                   | 415.4                   | 66.2        |
| 12.5       | 181.9            | 171.2               | 139.1               | 231.9        | 519.8                | 517.0                   | 412.9                   | 67.3        |
| 13         | 182.4            | 171.4               | 139.5               | 232.1        | 523.2                | 523.9                   | 416.0                   | 66.5        |
| 13.5       | 182.6            | 171.8               | 139.9               | 232.4        | 530.2                | 530.2                   | 420.3                   | 66.9        |
| 14         | 183.1            | 172.3               | 140.1               | 232.8        | 527.8                | 523.8                   | 416.1                   | 66.6        |
| 14.5       | 183.3            | 172.3               | 140.3               | 234.4        | 529.4                | 526.9                   | 417.9                   | 68.7        |
| 15         | 183.9            | 173.0               | 140.7               | 235.9        | 532.0                | 529.2                   | 420.1                   | 68.1        |
| 15.5       | 183.7            | 173.1               | 140.8               | 233.4        | 529.0                | 523.8                   | 417.1                   | 67.1        |
| 16         | 184.1            | 173.4               | 141.1               | 233.1        | 526.3                | 519.9                   | 415.0                   | 66.4        |
| 16.5       | 184.2            | 173.3               | 141.1               | 233.5        | 527.4                | 522.5                   | 417.4                   | 67.3        |
| 17         | 184.9            | 173.8               | 141.4               | 231.3        | 522.8                | 513.7                   | 411.5                   | 67.9        |

Table C.11 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle (°F) | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|-------------------------|-------------------------|-------------|
| 17.5       | 184.8            | 173.7               | 141.6               | 231.3        | 520.0                | 514.2                   | 412.4                   | 67.2        |
| 18         | 184.5            | 174.1               | 141.9               | 230.1        | 519.8                | 514.6                   | 413.8                   | 67.4        |
| 18.5       | 184.6            | 173.8               | 142.0               | 228.9        | 517.0                | 512.3                   | 412.3                   | 68.0        |
| 19         | 184.8            | 173.9               | 142.1               | 229.3        | 519.4                | 518.7                   | 416.6                   | 67.7        |
| 19.5       | 184.9            | 174.0               | 142.2               | 229.1        | 519.5                | 518.6                   | 417.0                   | 67.7        |
| 20         | 184.5            | 173.9               | 142.4               | 228.7        | 517.8                | 517.8                   | 417.0                   | 68.1        |
| 20.5       | 184.8            | 174.4               | 142.7               | 230.1        | 522.7                | 529.2                   | 424.7                   | 68.2        |
| 21         | 185.3            | 175.2               | 143.0               | 230.8        | 526.8                | 535.0                   | 429.8                   | 67.3        |
| 21.5       | 185.6            | 175.3               | 143.1               | 230.6        | 524.6                | 530.6                   | 427.7                   | 67.4        |
| 22         | 186.3            | 175.4               | 143.5               | 231.5        | 528.4                | 538.9                   | 433.5                   | 67.0        |
| 22.5       | 186.3            | 176.1               | 143.9               | 231.0        | 529.0                | 537.7                   | 433.6                   | 68.9        |
| 23         | 187.1            | 176.3               | 144.1               | 230.3        | 526.5                | 533.1                   | 430.9                   | 68.2        |
| 23.5       | 186.5            | 176.3               | 144.2               | 230.7        | 523.9                | 529.7                   | 428.5                   | 67.3        |
| 24         | 186.2            | 176.0               | 144.2               | 229.4        | 522.0                | 527.0                   | 426.5                   | 67.5        |
| 24.5       | 186.1            | 176.0               | 144.2               | 228.1        | 516.0                | 515.9                   | 418.4                   | 69.0        |
| 25         | 186.2            | 175.8               | 144.1               | 228.0        | 514.8                | 517.6                   | 418.9                   | 68.7        |
| 25.5       | 186.3            | 176.0               | 144.3               | 228.6        | 518.4                | 522.9                   | 422.4                   | 67.6        |
| 26         | 185.9            | 175.9               | 144.3               | 227.8        | 516.0                | 517.4                   | 418.8                   | 68.3        |
| 26.5       | 186.1            | 175.7               | 144.4               | 227.4        | 511.9                | 512.7                   | 416.3                   | 66.5        |
| 27         | 186.0            | 175.8               | 144.4               | 226.4        | 512.0                | 515.2                   | 419.6                   | 68.8        |
| 27.5       | 186.2            | 176.1               | 144.4               | 227.2        | 509.2                | 511.1                   | 417.4                   | 67.6        |
| 28         | 186.3            | 176.0               | 144.6               | 225.1        | 504.8                | 504.2                   | 413.1                   | 68.1        |
| 28.5       | 185.9            | 175.6               | 144.5               | 225.0        | 503.8                | 505.6                   | 414.0                   | 68.3        |
| 29         | 185.4            | 175.7               | 144.4               | 225.2        | 506.8                | 512.2                   | 418.0                   | 67.3        |
| 29.5       | 185.8            | 176.1               | 144.6               | 227.1        | 514.6                | 526.8                   | 428.2                   | 69.1        |
| 30         | 186.4            | 176.0               | 144.8               | 227.8        | 516.5                | 528.2                   | 429.8                   | 69.6        |
| 30.5       | 186.6            | 176.2               | 145.1               | 227.7        | 517.0                | 530.9                   | 431.2                   | 69.2        |
| 31         | 186.4            | 176.4               | 145.0               | 229.5        | 522.6                | 541.5                   | 437.9                   | 69.9        |
| 31.5       | 186.7            | 176.8               | 145.4               | 229.8        | 523.3                | 540.1                   | 437.5                   | 68.3        |
| 32         | 187.2            | 176.6               | 145.5               | 229.7        | 524.4                | 541.6                   | 439.3                   | 67.4        |
| 32.5       | 187.5            | 176.9               | 145.6               | 230.7        | 531.1                | 555.0                   | 448.3                   | 67.8        |
| 33         | 187.7            | 177.5               | 145.8               | 232.0        | 534.9                | 557.4                   | 451.0                   | 69.1        |
| 33.5       | 188.0            | 178.1               | 146.1               | 232.8        | 538.1                | 560.1                   | 452.6                   | 68.2        |
| 34         | 188.8            | 178.4               | 146.5               | 235.0        | 543.7                | 566.6                   | 456.2                   | 69.6        |

Table C.11 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle (°F) | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|-------------------------|-------------------------|-------------|
| 34.5       | 189.2            | 179.0               | 146.7               | 235.6        | 545.0                | 565.0                   | 457.4                   | 68.7        |
| 35         | 189.0            | 179.1               | 146.8               | 236.9        | 543.3                | 562.1                   | 456.9                   | 69.8        |
| 35.5       | 189.4            | 179.5               | 147.0               | 235.8        | 545.6                | 568.4                   | 460.7                   | 68.8        |
| 36         | 189.6            | 179.9               | 147.5               | 235.9        | 545.7                | 564.6                   | 458.7                   | 69.7        |
| 36.5       | 190.2            | 180.3               | 147.7               | 236.4        | 546.1                | 565.1                   | 458.8                   | 68.3        |
| 37         | 190.5            | 180.5               | 147.8               | 236.7        | 549.3                | 571.2                   | 462.2                   | 69.0        |
| 37.5       | 190.6            | 180.7               | 148.0               | 238.0        | 550.3                | 567.3                   | 460.3                   | 69.0        |
| 38         | 190.7            | 180.7               | 148.0               | 237.6        | 544.9                | 556.6                   | 453.0                   | 69.3        |
| 38.5       | 190.9            | 180.8               | 148.3               | 238.1        | 542.2                | 552.9                   | 450.4                   | 70.4        |
| 39         | 190.6            | 180.6               | 148.2               | 237.4        | 543.2                | 553.8                   | 449.7                   | 68.6        |
| 39.5       | 190.8            | 180.6               | 148.3               | 239.2        | 548.8                | 564.2                   | 453.3                   | 69.8        |
| 40         | 190.7            | 180.7               | 148.3               | 241.1        | 560.0                | 575.1                   | 457.9                   | 69.8        |
| 40.5       | 190.8            | 181.0               | 148.6               | 242.4        | 564.5                | 577.8                   | 458.9                   | 68.8        |
| 41         | 191.2            | 181.1               | 148.8               | 242.3        | 562.7                | 571.2                   | 456.1                   | 69.9        |
| 41.5       | 191.1            | 181.0               | 148.7               | 241.4        | 556.0                | 559.1                   | 448.1                   | 70.2        |
| 42         | 190.8            | 181.1               | 148.7               | 238.5        | 549.3                | 549.1                   | 441.8                   | 70.9        |
| 42.5       | 190.1            | 180.2               | 148.7               | 236.8        | 544.5                | 546.0                   | 438.6                   | 69.7        |
| 43         | 189.9            | 180.0               | 148.4               | 237.0        | 545.3                | 548.6                   | 439.3                   | 68.9        |
| 43.5       | 189.9            | 179.9               | 148.3               | 236.2        | 546.5                | 552.0                   | 440.6                   | 69.9        |
| 44         | 189.3            | 179.4               | 148.3               | 235.5        | 546.1                | 549.8                   | 439.9                   | 69.9        |
| 44.5       | 188.9            | 179.2               | 148.0               | 236.4        | 539.5                | 539.1                   | 432.8                   | 68.4        |
| 45         | 188.5            | 178.8               | 148.0               | 232.6        | 533.6                | 530.1                   | 427.9                   | 70.1        |
| 45.5       | 188.1            | 178.2               | 147.7               | 233.0        | 530.8                | 532.4                   | 429.2                   | 70.3        |
| 46         | 187.9            | 177.9               | 147.4               | 233.2        | 538.8                | 544.2                   | 436.7                   | 69.7        |
| 46.5       | 187.4            | 177.4               | 147.3               | 234.3        | 538.2                | 541.8                   | 434.6                   | 69.4        |
| 47         | 187.0            | 177.1               | 147.2               | 233.5        | 537.4                | 541.9                   | 434.1                   | 70.2        |
| 47.5       | 186.6            | 176.9               | 147.0               | 232.4        | 533.1                | 534.4                   | 430.2                   | 69.6        |
| 48         | 186.2            | 176.5               | 146.6               | 230.8        | 526.1                | 525.2                   | 424.7                   | 70.5        |
| 48.5       | 186.1            | 175.9               | 146.6               | 230.7        | 525.4                | 529.3                   | 426.8                   | 70.6        |
| 49         | 185.9            | 176.3               | 146.5               | 230.1        | 526.5                | 531.7                   | 428.5                   | 69.5        |
| 49.5       | 185.9            | 176.0               | 146.4               | 229.1        | 521.3                | 523.5                   | 423.0                   | 70.5        |
| 50         | 185.4            | 175.7               | 146.2               | 228.8        | 518.1                | 522.0                   | 420.5                   | 69.0        |
| 50.5       | 185.3            | 175.7               | 146.1               | 227.9        | 518.4                | 526.0                   | 422.0                   | 70.5        |
| 51         | 185.1            | 175.2               | 145.8               | 228.0        | 518.4                | 524.9                   | 420.6                   | 71.9        |

Table C.11 (Continued)

| Time (min) | BC Side Top (°F) | BC Side Middle (°F) | BC Side Bottom (°F) | Air Out (°F) | Glass Plate Top (°F) | Glass Plate Middle (°F) | Glass Plate Bottom (°F) | Air In (°F) |
|------------|------------------|---------------------|---------------------|--------------|----------------------|-------------------------|-------------------------|-------------|
| 51.5       | 185.0            | 175.0               | 145.9               | 228.8        | 519.8                | 527.6                   | 420.9                   | 72.4        |
| 52         | 185.1            | 174.9               | 145.7               | 230.8        | 531.6                | 545.0                   | 427.6                   | 69.9        |
| 52.5       | 185.2            | 175.1               | 145.8               | 233.0        | 546.2                | 560.7                   | 436.5                   | 71.2        |
| 53         | 185.5            | 175.7               | 145.9               | 237.2        | 558.6                | 576.1                   | 446.0                   | 71.0        |
| 53.5       | 185.9            | 176.3               | 146.2               | 238.9        | 564.9                | 579.1                   | 449.7                   | 71.2        |
| 54         | 185.9            | 176.2               | 146.2               | 240.1        | 561.6                | 570.1                   | 444.8                   | 70.9        |
| 54.5       | 186.4            | 177.0               | 146.6               | 239.4        | 560.7                | 569.4                   | 445.0                   | 70.8        |
| 55         | 186.7            | 177.0               | 146.7               | 239.3        | 559.9                | 570.6                   | 444.9                   | 71.2        |
| 55.5       | 186.8            | 177.2               | 146.6               | 238.5        | 559.8                | 568.1                   | 443.3                   | 70.7        |
| 56         | 187.2            | 177.3               | 146.8               | 238.4        | 557.5                | 566.5                   | 443.3                   | 70.2        |
| 56.5       | 187.2            | 177.5               | 146.9               | 238.0        | 555.3                | 563.6                   | 443.1                   | 71.4        |
| 57         | 187.3            | 177.5               | 147.1               | 237.5        | 547.9                | 551.4                   | 435.7                   | 72.3        |
| 57.5       | 186.9            | 177.2               | 146.9               | 235.7        | 542.8                | 545.9                   | 432.5                   | 71.1        |
| 58         | 187.1            | 177.2               | 146.8               | 235.4        | 542.5                | 546.3                   | 432.6                   | 72.5        |
| 58.5       | 186.8            | 177.2               | 146.8               | 235.1        | 538.6                | 538.9                   | 427.7                   | 70.3        |
| 59         | 186.7            | 177.1               | 146.7               | 234.7        | 539.1                | 543.7                   | 430.4                   | 72.0        |
| 59.5       | 187.0            | 176.7               | 146.6               | 235.4        | 541.9                | 547.6                   | 432.4                   | 70.8        |
| Averages   | 184.5            | 174.2               | 142.9               | 232.3        | 527.0                | 531.0                   | 425.9                   | 68.4        |

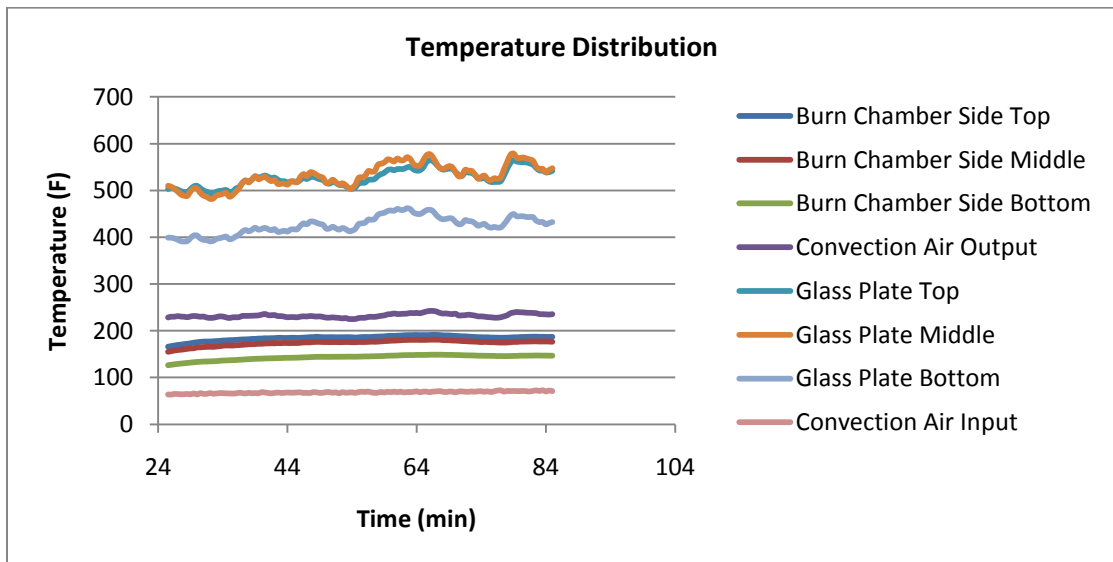


Figure C.5: Steady state temperature distribution for 50/50 camelina safflower pellets

Table C.12: ECA 450 data for 50/50 camelina safflower pellets at steady state

| Time (min) | O2 (%) | CO (ppm) | EFF (%) | CO2 (%) | NO (ppm) | NO2 (ppm) | NOX (ppm) | SO2 (ppm) |
|------------|--------|----------|---------|---------|----------|-----------|-----------|-----------|
| 1          | 15.4   | 213.0    | 69.8    | 5.3     | 308.0    | 2.0       | 310.0     | 115.0     |
| 2          | 15.8   | 236.0    | 68.4    | 5.0     | 279.0    | 2.0       | 282.0     | 128.0     |
| 3          | 17.9   | 347.0    | -       | -       | 242.0    | 2.0       | 244.0     | 110.0     |
| 4          | 15.9   | 679.0    | 67.9    | 4.9     | 312.0    | 2.0       | 314.0     | 129.0     |
| 5          | 15.1   | 1326.0   | 69.7    | 5.7     | 296.0    | 2.0       | 299.0     | 181.0     |
| 6          | 17.0   | 631.0    | -       | -       | 228.0    | 2.0       | 230.0     | 133.0     |
| 7          | 16.2   | 1556.0   | -       | -       | 255.0    | 2.0       | 257.0     | 183.0     |
| 8          | 15.0   | 412.0    | 70.8    | 5.8     | 303.0    | 2.0       | 305.0     | 128.0     |
| 9          | 16.8   | 336.0    | -       | -       | 240.0    | 2.0       | 242.0     | 123.0     |
| 10         | 15.7   | 606.0    | 68.9    | 5.1     | 295.0    | 2.0       | 298.0     | 133.0     |
| 11         | 14.7   | 403.0    | 71.6    | 6.0     | 304.0    | 2.0       | 306.0     | 114.0     |
| 12         | 15.9   | 337.0    | 68.1    | 4.9     | 283.0    | 2.0       | 285.0     | 119.0     |
| 13         | 16.7   | 281.0    | -       | -       | 267.0    | 2.0       | 269.0     | 135.0     |
| 14         | 13.6   | 534.0    | 73.4    | 7.1     | 346.0    | 2.0       | 348.0     | 175.0     |
| 15         | 15.7   | 226.0    | 68.1    | 5.1     | 282.0    | 2.0       | 284.0     | 140.0     |
| 16         | 16.3   | 288.0    | -       | -       | 283.0    | 2.0       | 285.0     | 146.0     |
| 17         | 16.4   | 259.0    | -       | -       | 278.0    | 2.0       | 280.0     | 115.0     |
| 18         | 17.0   | 472.0    | -       | -       | 234.0    | 2.0       | 236.0     | 100.0     |
| 19         | 16.2   | 314.0    | -       | -       | 293.0    | 2.0       | 295.0     | 143.0     |
| 20         | 15.0   | 119.0    | 71.1    | 5.8     | 327.0    | 2.0       | 329.0     | 116.0     |
| 21         | 17.0   | 238.0    | -       | -       | 255.0    | 2.0       | 257.0     | 127.0     |
| 22         | 15.0   | 230.0    | 70.8    | 5.7     | 331.0    | 2.0       | 334.0     | 116.0     |
| 23         | 14.8   | 498.0    | 71.2    | 6.0     | 309.0    | 2.0       | 312.0     | 190.0     |
| 24         | 13.9   | 228.0    | 73.0    | 6.8     | 352.0    | 2.0       | 355.0     | 145.0     |
| 25         | 15.1   | 195.0    | 70.2    | 5.6     | 315.0    | 2.0       | 318.0     | 146.0     |
| 26         | 14.3   | 642.0    | 71.9    | 6.5     | 344.0    | 2.0       | 347.0     | 203.0     |
| 27         | 14.0   | 395.0    | 72.3    | 6.7     | 337.0    | 2.0       | 339.0     | 177.0     |
| 28         | 15.8   | 212.0    | 69.9    | 5.7     | 334.0    | 2.0       | 336.0     | 156.0     |
| 29         | 15.5   | 472.0    | 68.5    | 5.2     | 317.0    | 2.0       | 319.0     | 165.0     |
| 30         | 14.1   | 238.0    | 72.3    | 6.6     | 369.0    | 3.0       | 371.0     | 146.0     |
| 31         | 17.4   | 420.0    | -       | -       | 267.0    | 2.0       | 269.0     | 147.0     |
| 32         | 15.5   | 381.0    | 68.8    | 5.3     | 289.0    | 2.0       | 291.0     | 125.0     |
| 33         | 13.5   | 536.0    | 73.4    | 7.2     | 366.0    | 3.0       | 368.0     | 189.0     |
| 34         | 16.6   | 556.0    | -       | -       | 259.0    | 2.0       | 261.0     | 160.0     |
| 35         | 17.1   | 428.0    | -       | -       | 246.0    | 2.0       | 248.0     | 105.0     |
| 36         | 15.4   | 418.0    | 69.4    | 5.4     | 339.0    | 3.0       | 342.0     | 117.0     |
| Averages   | 15.6   | 435.1    | 70.4    | 5.8     | 296.8    | 2.1       | 299.0     | 141.1     |

### Forced Convection Calculations for 1.5 hr 50/50 camelina safflower burn test on MT. Vernon Stove

$$R = F + 459.67$$

$$T_{in} := 68.4223^{\circ}\text{F} \quad T_o := 68.4223^{\circ}\text{F}$$

$$T_{out} := 232.443^{\circ}\text{F}$$

$$C_p = .242 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = m_{\text{dot}} \cdot c_p \cdot (T_{out} - T_{in})$$

#### From Dwyer Series 160 Data Sheet

$$P_B := 24.5 \quad \text{this is the barometric pressure in inches of mercury as measured}$$

$$T_{\text{absF}} := 459.67 + T_o \quad \text{this is absolute temperature of airflow past the pitot static tube}$$

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}}$$

$$\rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .062 \frac{\text{lb}}{\text{ft}^3}$$

#### Calculate Air Velocity

$$P_v := 0.16 \quad \text{This is the velocity (or dynamic) pressure in inches of water, experimentally measured}$$

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.754 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1754 \frac{\text{ft}}{\text{min}}$$

#### Mass Flow Rate

$$d := \frac{4.25}{12} \text{ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ft}^2$$

$$m_{\text{dot}} := \rho_1 \cdot A_1 \cdot v_1 \quad m_{\text{dot}} = 0.179 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := m_{\text{dot}} \cdot c_p \cdot |T_{\text{out}} - T_{\text{in}}|$$

$$q_{\text{forced\_conv}} = 2.546 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at max steady state operations

## Radiation Calculations

$$T_{\text{surface}} := \left( \frac{494.6321 + 459.67}{167.1943 + 459.67} \right) \text{R}$$

$$T_{\text{surr}} := \left( \frac{T_o + 459.67}{T_o + 459.67} \right) \text{R}$$

$$A_{\text{surface}} := \left[ \frac{20 \cdot 13.5}{8 \cdot \frac{(13.5 + 1.5)}{2}} \right] \text{in}^2$$

$$A_{\text{surface}} = \left( \frac{1.875}{0.417} \right) \cdot \text{ft}^2$$

$$\varepsilon := \begin{pmatrix} 0.95 \\ 0.22 \end{pmatrix}$$

$$\sigma := .1714 \cdot 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{R}^4}$$

Stefan-Boltzmann Constant

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ (T_{\text{surface}_0})^4 - (T_{\text{surr}_0})^4 \right]$$

$$q_{\text{radglass}} = 2.295 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radsteel}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ (T_{\text{surface}_1})^4 - (T_{\text{surr}_1})^4 \right]$$

$$q_{\text{radsteel}} = 12.042 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + 2q_{\text{radsteel}}$$

$$q_{\text{radtot}} = 2.319 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr}}$$

## Total Heat Transfer

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 2.778 \times 10^4 \cdot \frac{\text{Btu}}{\text{hr}}$$

## Fraction of Radiation:

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.084$$

APPENDIX D

HARMAN P68 STOVE HEAT TRANSFER CALCULATIONS AND DATA

Nomenclature

The following abbreviations apply to the remaining Tables in Appendix D:

SP Top: Side Plate Top, Thermocouple location at top of side steel plate

SP Middle: Side Plate Middle, Thermocouple location at middle of side steel plate

SP Bottom: Side Plate Bottom, Thermocouple location at bottom of side steel plate

Air Out: Forced Convection Air Output from stove ( $T_{out}$  in MathCAD work)

Glass Plate Top: Thermocouple location at the top of the ceramic glass plate

Glass Plate Middle: Thermocouple location at the middle of the ceramic glass plate

Glass Plate Bottom: Thermocouple location at the bottom of the ceramic glass plate

Air In: Air from the room being pulled into the convection fan ( $T_{in}$  in MathCAD work)

SB Plate: Side Bottom Plate, Thermocouple location at bottom side plate of stove

TP: Top Plate, Thermocouple location on the top plate of the stove

$C_p$ : specific heat

$\rho$ : Density

$v$ : velocity

$d$ : diameter

$\dot{m}$ : mass flow rate

$\epsilon$ : emissivity

$\sigma$ : Stefan-Boltzmann constant

Table D.1: Steady state data for premium wood pellets

| Time (min) | SP Top (°F) | SP Middle (°F) | SP Bottom (°F) | Air Out (°F) | Glass Plate Middle (°F) | Glass Plate Top (°F) | Glass Plate Bottom (°F) | Air In (°F) | SB Plate (°F) | TP (°F) | TP (°F) |
|------------|-------------|----------------|----------------|--------------|-------------------------|----------------------|-------------------------|-------------|---------------|---------|---------|
| 0.0        | 511.7       | 567.4          | 455.4          | 311.7        | 482.2                   | 490.0                | 405.1                   | 69.2        | 261.5         | 300.9   | 250.2   |
| 0.5        | 515.5       | 570.1          | 456.1          | 313.1        | 482.7                   | 490.9                | 406.1                   | 69.5        | 261.7         | 301.6   | 250.7   |
| 1.0        | 515.2       | 568.8          | 455.7          | 307.4        | 482.0                   | 490.8                | 405.6                   | 69.7        | 261.9         | 301.4   | 250.8   |
| 1.5        | 508.5       | 562.2          | 452.4          | 314.1        | 478.7                   | 488.3                | 403.6                   | 69.8        | 262.0         | 300.8   | 250.3   |
| 2.0        | 507.0       | 560.7          | 450.2          | 305.0        | 476.4                   | 486.4                | 402.0                   | 69.6        | 261.6         | 298.8   | 246.8   |
| 2.5        | 504.5       | 558.8          | 449.7          | 307.4        | 475.6                   | 485.5                | 401.3                   | 69.8        | 261.5         | 297.9   | 246.2   |
| 3.0        | 505.4       | 559.9          | 450.1          | 304.6        | 475.3                   | 485.3                | 400.9                   | 69.8        | 261.9         | 296.3   | 245.2   |
| 3.5        | 506.6       | 560.4          | 450.2          | 308.4        | 474.6                   | 484.7                | 400.6                   | 69.9        | 262.1         | 296.5   | 243.9   |
| 4.0        | 505.6       | 560.6          | 450.2          | 306.2        | 474.7                   | 484.3                | 401.3                   | 69.8        | 262.5         | 295.5   | 243.1   |
| 4.5        | 505.6       | 561.5          | 451.6          | 307.7        | 474.5                   | 484.0                | 401.2                   | 70.0        | 262.3         | 295.5   | 242.4   |
| 5.0        | 506.1       | 563.3          | 452.3          | 304.8        | 475.0                   | 484.1                | 401.4                   | 70.3        | 262.5         | 295.7   | 242.2   |
| 5.5        | 504.7       | 559.8          | 451.1          | 307.7        | 473.8                   | 483.4                | 400.7                   | 70.6        | 262.7         | 295.1   | 239.9   |
| 6.0        | 504.8       | 558.7          | 450.3          | 305.7        | 473.3                   | 483.0                | 400.0                   | 70.7        | 262.8         | 295.2   | 239.9   |
| 6.5        | 506.6       | 559.5          | 451.7          | 308.9        | 474.8                   | 483.8                | 400.6                   | 70.6        | 262.6         | 294.5   | 238.7   |
| 7.0        | 508.2       | 562.8          | 453.8          | 307.9        | 478.7                   | 486.6                | 403.2                   | 70.5        | 262.7         | 294.6   | 238.7   |
| 7.5        | 508.1       | 562.2          | 453.7          | 312.1        | 480.0                   | 487.7                | 404.5                   | 70.8        | 262.9         | 296.0   | 239.8   |
| 8.0        | 508.4       | 564.4          | 454.3          | 310.6        | 480.7                   | 488.5                | 405.3                   | 70.8        | 263.4         | 296.6   | 241.3   |
| 8.5        | 510.1       | 566.3          | 455.9          | 313.7        | 481.7                   | 489.4                | 406.1                   | 70.8        | 263.5         | 296.8   | 239.8   |
| 9.0        | 515.4       | 572.2          | 457.8          | 312.3        | 482.7                   | 490.5                | 406.8                   | 70.8        | 263.8         | 297.5   | 239.3   |
| 9.5        | 518.0       | 577.2          | 460.0          | 312.5        | 483.6                   | 491.3                | 407.7                   | 70.9        | 264.6         | 298.6   | 240.3   |
| 10.0       | 517.3       | 575.1          | 459.8          | 310.1        | 483.1                   | 490.9                | 407.7                   | 70.8        | 264.8         | 299.3   | 240.5   |
| 10.5       | 513.9       | 569.7          | 457.9          | 312.5        | 481.2                   | 489.2                | 406.1                   | 71.1        | 265.3         | 299.4   | 238.4   |
| 11.0       | 512.5       | 567.8          | 457.6          | 310.2        | 481.6                   | 489.4                | 406.1                   | 71.0        | 265.2         | 298.1   | 238.0   |
| 11.5       | 510.3       | 565.4          | 456.3          | 315.1        | 482.1                   | 489.4                | 406.6                   | 71.3        | 265.3         | 298.0   | 237.5   |
| 12.0       | 507.3       | 561.9          | 455.0          | 312.1        | 481.4                   | 488.8                | 406.0                   | 71.3        | 265.5         | 299.1   | 239.2   |
| 12.5       | 506.6       | 560.1          | 454.0          | 311.9        | 480.1                   | 487.8                | 405.1                   | 71.6        | 264.8         | 298.1   | 239.9   |
| 13.0       | 504.3       | 558.2          | 453.1          | 309.0        | 479.1                   | 487.4                | 404.6                   | 71.5        | 264.7         | 298.2   | 240.2   |
| 13.5       | 504.1       | 558.5          | 453.2          | 314.4        | 479.9                   | 487.9                | 404.9                   | 71.6        | 264.6         | 296.6   | 238.1   |
| 14.0       | 509.4       | 563.2          | 455.1          | 311.3        | 482.6                   | 490.3                | 407.5                   | 71.6        | 264.9         | 296.8   | 238.5   |
| 14.5       | 514.7       | 569.5          | 457.1          | 316.8        | 484.9                   | 492.7                | 409.9                   | 71.8        | 265.5         | 297.3   | 240.6   |
| 15.0       | 519.8       | 575.5          | 460.0          | 314.5        | 487.4                   | 495.0                | 412.1                   | 71.7        | 266.1         | 298.2   | 241.6   |
| 15.5       | 520.1       | 576.4          | 461.7          | 314.7        | 489.2                   | 496.9                | 414.3                   | 72.1        | 266.8         | 299.5   | 243.4   |
| 16.0       | 519.1       | 576.3          | 463.1          | 313.8        | 490.4                   | 498.1                | 414.8                   | 72.0        | 267.3         | 299.3   | 243.3   |
| 16.5       | 522.6       | 577.0          | 465.1          | 319.7        | 492.0                   | 499.8                | 415.9                   | 72.3        | 267.8         | 299.8   | 243.2   |

Table D.1 (Continued)

| Time<br>(min) | SP<br>Top<br>(°F) | SP<br>Middle<br>(°F) | SP<br>Bottom<br>(°F) | Air<br>Out<br>(°F) | Glass<br>Plate<br>Middle<br>(°F) | Glass<br>Plate<br>Top<br>(°F) | Glass<br>Plate<br>Bottom<br>(°F) | Air<br>In<br>(°F) | SB<br>Plate<br>(°F) | TP<br>(°F) | TP<br>(°F) |
|---------------|-------------------|----------------------|----------------------|--------------------|----------------------------------|-------------------------------|----------------------------------|-------------------|---------------------|------------|------------|
| 17.0          | 523.0             | 578.6                | 466.7                | 315.2              | 494.1                            | 501.8                         | 417.7                            | 72.4              | 268.3               | 301.2      | 242.7      |
| 17.5          | 520.5             | 577.5                | 467.5                | 321.6              | 494.8                            | 502.3                         | 417.9                            | 72.5              | 268.8               | 301.9      | 241.7      |
| 18.0          | 520.6             | 576.9                | 467.3                | 317.5              | 495.7                            | 503.1                         | 418.5                            | 72.5              | 269.6               | 302.3      | 242.2      |
| 18.5          | 518.8             | 574.2                | 466.4                | 319.8              | 494.8                            | 502.8                         | 418.4                            | 72.7              | 269.9               | 303.1      | 243.9      |
| 19.0          | 515.5             | 570.5                | 464.5                | 318.0              | 493.2                            | 501.5                         | 417.3                            | 72.8              | 269.6               | 303.3      | 244.6      |
| 19.5          | 511.0             | 565.4                | 461.8                | 316.8              | 490.6                            | 499.7                         | 415.7                            | 73.1              | 268.1               | 303.3      | 244.2      |
| 20.0          | 507.7             | 560.6                | 458.4                | 312.0              | 487.5                            | 496.8                         | 412.7                            | 72.9              | 267.3               | 302.4      | 244.1      |
| 20.5          | 506.4             | 558.8                | 457.6                | 314.8              | 485.9                            | 495.3                         | 411.9                            | 73.7              | 266.7               | 301.3      | 242.8      |
| 21.0          | 505.4             | 557.2                | 456.0                | 312.5              | 484.9                            | 494.2                         | 410.9                            | 73.6              | 267.2               | 300.0      | 240.8      |
| 21.5          | 503.7             | 555.4                | 454.1                | 314.2              | 483.4                            | 492.9                         | 410.4                            | 73.8              | 267.2               | 299.6      | 239.6      |
| 22.0          | 504.0             | 557.1                | 454.5                | 314.5              | 484.2                            | 493.3                         | 411.0                            | 73.8              | 267.2               | 298.4      | 239.7      |
| 22.5          | 503.6             | 559.2                | 454.9                | 314.2              | 485.0                            | 493.8                         | 411.1                            | 73.7              | 267.2               | 299.0      | 238.5      |
| 23.0          | 505.6             | 564.9                | 458.0                | 314.5              | 489.1                            | 497.4                         | 414.0                            | 73.6              | 267.7               | 300.5      | 239.7      |
| 23.5          | 508.4             | 568.7                | 460.7                | 319.1              | 491.3                            | 499.3                         | 415.9                            | 73.7              | 268.5               | 302.4      | 239.9      |
| 24.0          | 513.0             | 572.9                | 463.0                | 317.7              | 493.5                            | 501.5                         | 418.0                            | 73.7              | 269.0               | 304.5      | 241.2      |
| 24.5          | 512.4             | 571.5                | 461.9                | 318.5              | 493.4                            | 501.5                         | 417.9                            | 73.9              | 269.3               | 305.9      | 241.0      |
| 25.0          | 516.0             | 574.5                | 463.1                | 319.3              | 494.8                            | 502.8                         | 419.1                            | 73.8              | 269.7               | 306.9      | 240.9      |
| 25.5          | 519.5             | 580.2                | 466.3                | 325.1              | 497.0                            | 504.9                         | 421.0                            | 74.0              | 270.1               | 307.6      | 241.0      |
| Ave           | 511.0             | 566.5                | 457.2                | 312.9              | 484.0                            | 492.4                         | 408.9                            | 71.7              | 265.4               | 299.4      | 241.9      |

### Forced Convection Calculations for 1.5 hr premium wood test in Harman P68

$$R = F + 459.67$$

$$T_{in} := 71.653^{\circ}\text{F} \quad T_o := 71.653^{\circ}\text{F}$$

$$T_{out} := 313.404^{\circ}\text{F}$$

$$C_p = .2432 \frac{\text{Btu}}{\text{lb} \cdot ^{\circ}\text{F}}$$

$$q_{\text{forced\_conv}} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

### From Dwyer Series 160 Data Sheet

$$P_B := 24.9$$

this is the barometric pressure in  
inches of mercury as measured

$$T_{\text{absF}} := 459.67 + T_o$$

this is absolute temperature of  
airflow past the pitot static tube

$$\rho := 1.325 \frac{P_B}{T_{\text{absF}}} \quad \rho = 0.062 \frac{\text{lb}}{\text{ft}^3} \quad \rho_1 := .062 \frac{\text{lb}}{\text{ft}^3}$$

### Calculate Air Velocity

$$P_v := 0.1 \quad \text{This is the velocity (or dynamic) pressure in inches of water, experimentally measured}$$

$$v := 1096.2 \sqrt{\frac{P_v}{\rho}} \quad v = 1.391 \times 10^3 \frac{\text{ft}}{\text{min}} \quad v_1 := 1.391 \times 10^3 \frac{\text{ft}}{\text{min}}$$

### Mass Flow Rate

$$d := \frac{4.25}{12} \text{ ft} \quad A_1 := \frac{\pi \cdot d^2}{4} \quad A_1 = 0.099 \text{ ft}^2$$

$$\dot{m}_{\text{dot1}} := \rho_1 \cdot A_1 \cdot v_1 \quad \dot{m}_{\text{dot1}} = 0.142 \frac{\text{lbm}}{\text{s}}$$

$$q_{\text{forced\_conv}} := \dot{m}_{\text{dot1}} \cdot c_p \cdot |T_{\text{out}} - T_{\text{in}}|$$

$$q_{\text{forced\_conv}} = 2.991 \times 10^4 \frac{\text{Btu}}{\text{hr}}$$

This is the heat output to the room due to forced convection at steady state operations

### Radiation Calculations

$$T_{\text{surface}} := \left( \begin{array}{l} 461.8036 + 459.67 \\ 270.6496 + 459.67 \\ 511.5607 + 459.67 \\ 265.6751 + 459.67 \end{array} \right)^R$$

Glass Plate  
Top Plate  
Side Plate  
Bottom Side Plate

$$T_{\text{surr}} := \begin{pmatrix} T_0 + 459.67 \\ T_0 + 459.67 \\ T_0 + 459.67 \\ T_0 + 459.67 \end{pmatrix} \text{R}$$

$$A_{\text{surface}} := \begin{pmatrix} 13.10 \\ 23.515 \\ 20.7513 \\ 9.7511.25 \end{pmatrix} \text{in}^2 \quad A_{\text{surface}} = \begin{pmatrix} 0.903 \\ 2.448 \\ 1.873 \\ 0.762 \end{pmatrix} \cdot \text{ft}^2$$

$$\varepsilon_{\text{xx}} := \begin{pmatrix} .95 \\ .17 \\ .18 \\ .17 \end{pmatrix} \begin{array}{l} \text{Glass Plate} \\ \text{Top Plate} \\ \text{Side Plate} \\ \text{Bottom Side Plate} \end{array}$$

$$\sigma := .1714 \cdot 10^{-8} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{R}^4} \quad \text{Stefan-Boltzmann Constant}$$

$$q_{\text{radglass}} := \varepsilon_0 \cdot A_{\text{surface}_0} \cdot \sigma \cdot \left[ (T_{\text{surface}_0})^4 - (T_{\text{surr}_0})^4 \right] \quad q_{\text{radglass}} = 942.704 \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radtop}} := \varepsilon_1 \cdot A_{\text{surface}_1} \cdot \sigma \cdot \left[ (T_{\text{surface}_1})^4 - (T_{\text{surr}_1})^4 \right] \quad q_{\text{radtop}} = 146.076 \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radside}} := \varepsilon_2 \cdot A_{\text{surface}_2} \cdot \sigma \cdot \left[ (T_{\text{surface}_2})^4 - (T_{\text{surr}_2})^4 \right] \quad q_{\text{radside}} = 468.188 \frac{\text{Btu}}{\text{hr}}$$

$$q_{\text{radbottom}} := \varepsilon_3 \cdot A_{\text{surface}_3} \cdot \sigma \cdot \left[ (T_{\text{surface}_3})^4 - (T_{\text{surr}_3})^4 \right] \quad q_{\text{radbottom}} = 43.749 \frac{\text{Btu}}{\text{hr}}$$

Total due to radiation is:

$$q_{\text{radtot}} := q_{\text{radglass}} + q_{\text{radtop}} + 2 \cdot q_{\text{radside}} + 2 \cdot q_{\text{radbottom}} \quad q_{\text{radtot}} = 2.113 \times 10^3 \frac{\text{Btu}}{\text{hr}}$$

### Total Heat Transfer

$$Q_{\text{total}} := q_{\text{radtot}} + q_{\text{forced\_conv}} = 3.202 \times 10^4 \frac{\text{Btu}}{\text{hr}}$$

### Fraction of Radiation:

$$\text{Rad} := \frac{q_{\text{radtot}}}{Q_{\text{total}}} \quad \text{Rad} = 0.067$$