Biomass Briquettes Pt. 2: Exploring Materials, Shape, and Heat Values

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Introduction

These experiments were part of Plant Chicago's ongoing research to examine the feasibility of creating a fuel source from waste materials produced by businesses at *The Plant*, centered around spent brewery grain. The goal is to produce biomass briquettes, or biobricks, which can be used as supplemental fuel in the wood-fired oven in Pleasant House Bakery. Based on recommendations from earlier tests, this phase of research was dedicated to ongoing experimentation with different material recipes and methods of biobrick production. Once a sufficient number of biobricks were produced, we conducted several test burns, including calorimetric tests, to assess how the heat value of the bricks compared with wood.

Goals

The goal of our ongoing research is to explore the feasibility and scalability of creating a fuel made from waste materials produced either locally or onsite. This phase focused on fine tuning the recipe developed by former Plant Chicago intern Liam Kenny, as well as producing enough briquettes to perform a larger scale burn in the bakery oven.

Materials

Materials used were largely identical to the previous phase of research, with the following exceptions:

- Coffee chaff from Four Letter Word Coffee was studied as a source of biomass rather than paper pulp.
- Several new molds were used to produce different shapes of brick, in the interest of testing the shape's impact on efficiency of production and drying. All of these consisted of PVC pipe set on top of a wooden board with a circular wooden cutout used as a plunger, and pressed with the hydraulic press. PVC diameters of 3, 4, and 6 inches were used. (6 inch mold pictured to the right.)
- An oven was used in place of the food dehydrator for drying the bricks, and a food processor was used in place of a spice grinder for milling the biomass.

It should be noted here that a hydraulic press was still used as the means of compressing and removing water from the biomass. The reason for this choice over a powered machine such as a pellet mill has to do with a number of factors. A pellet mill is significantly more costly than a manually operated press, and while it would produce briquettes (or pellets) more efficiently, non-renewable energy (electricity/diesel) would be consumed in their production. A machine would also remove the human element to a degree, turning the process into something that happens inside a 'black box,' potentially making it not as approachable.

Biobrick Recipe Assessments

Previous research had concluded that, of the recipes tested, a mixture of 50% sawdust and 50% spent grain produced the most stable brick and that using milled grain in the mixture produced a stronger brick than whole grain.

In this phase of research, we continued to test mixtures involving sawdust and spent grain, as well as experimenting with a new ingredient: coffee chaff. Chaff is a waste product of the coffee roastery in *The Plant*, Four Letter Word Coffee , consisting of the hulls (outer papery husk) of coffee beans.

Biobricks from a variety of mixtures and molds (from left to right): 50/50 milled grain and chaff (first 2), 65/35 milled grain and chaff, 100% whole chaff, 100% whole chaff from solid cylinder mold, 100% milled chaff, 50/50 milled chaff and sawdust.

A variety of recipes were tested using both the solid cylinder and hollow cylinder molds described in the previous report. Initial tests confirmed previous assessments that solid cylinders tend to be more delicate and dry more slowly. As a result, in later trials we primarily used the hollow cylinder mold to press a variety of recipes, including both whole and milled materials, in order to carry out comparative evaluation of different recipes.

The recipes tested were 100% whole chaff, 100% milled chaff, 50% milled chaff / 50% sawdust, 100% milled grain, 50% whole grain / 50% whole chaff, 50% milled grain / 50% sawdust, 65% milled grain / 35% milled chaff, 50% milled grain / 50% milled chaff (all percentages are by volume).

All bricks were then evaluated based on ease of removal from the mold, strength of the bricks before and after drying, and whether all the ingredients were produced within the building. Ease of removal was important because several mixtures could not be extracted from the mold by hand, instead needing to be pushed out using the hydraulic press - a process that drastically increased production time. Strength before and after drying was essential for handling and transport of the bricks. In-house ingredients were considered ideal because they would allow for material reuse from waste streams that already exist within the building, rather than requiring additional materials to be brought in, decreasing the overall energy necessary to produce the bricks. The results of this evaluation are summarized in Table 1.

Table 1 - Qualitative Evaluation of Biobrick Recipes

Material	Removal From Mold	Strength Pre-Drying	Strength Post-Drying	In-House Materials
100% Whole Chaff	Required Hydraulic Press	Very Delicate, often crumbles on removal from mold	Strong under compression, Tears under axial tension	Yes
100% Milled Chaff	Required Hydraulic Press	Very Delicate, often crumbles on removal from mold	Strong under compression, Tears under axial tension	Yes
50% Milled Chaff / 50% Sawdust	Required Hydraulic Press	Very Delicate, often crumbles on removal from mold	Weak - Light pressure causes it to crumble	No
100% Milled Grain	Done by Hand	Cannot be Moved	-	Yes
50% Whole Grain / 50% Whole Chaff	Done by Hand	Cannot be Moved	-	Yes
50% Milled Grain / 50% Sawdust	Done by Hand	Very Delicate, often crumbles on removal from mold	Weak - Light Pressure causes it to crumble	No
65% Milled Grain / 35% Milled Chaff	Done by Hand	Delicate, but Movable	Very Strong	Yes
50% Milled Grain / 50% Milled Chaff	Done by Hand	Delicate, but Movable (More Stable than 65/35 mix)	Very Strong	Yes

Based on these results, we selected a mixture of 50% milled grain / 50% milled chaff for further evaluation. This mixture had several advantages. Due to the moisture retained by the brewery grain, it required no added water to make the mixture hold its shape, minimizing additional resources necessary for manufacture. It required relatively little compression to form a stable wet brick, eliminating the need to reset the press midway through production, as detailed in the previous report, and thereby speeding up the production process. This mixture could also be easily removed from the mold by hand, compared with bricks made primarily of chaff, which expanded outwards when pressed, thereby requiring the hydraulic press for de-molding - a very slow process requiring adjustment to the setup. Both before and after drying, this mixture produced the most stable brick (while most of the recipes produced bricks that could still be easily broken with light pressure after drying, this recipe withstood the “dropkick test”, in which it was punted across the back yard without breaking.) Finally, it’s production relies entirely on materials produced within *The Plant*.

Initial Test Burns

Once the recipe was fixed, we carried out several small scale test burns in a log burning grill. The goal of these small scale burns was to establish heat values for the biobricks - how much energy we could expect to produce per pound of biobrick compared to an equal mass of wood. Due to the long production time of each brick (an average of 12-15 minutes for each quarter pound brick, not including drying time) we conducted these small scale burns in order to establish if the bricks produced enough heat, relative to wood, to make it worth scaling up production enough to test the bricks in the bakery oven.

These initial burns presented several challenges. The first attempted burn failed due to insufficient drying of the bricks. We had attempted to air dry the first batch in the feed storage room of the aquaponic farm, and while the bricks appeared dry on the outside, the density of this mixture made it such that moisture could not escape from the interior. Thus, every brick had a half inch band of wet material running through its center and had grown a substantial amount of mold. In order to get around this problem, we dried the second batch of biobricks in an electric oven. While the necessary energy input of this method makes it far from ideal, it succeeded in entirely drying the bricks (drying methods will be discussed further in the "Next Steps" section).

This drying method allowed us to conduct a successful test burn on our second attempt. In these trials, we attempted to compare the amount of energy produced by burning four biobricks - totalling 1.1 lbs - with the energy produced by burning an equal weight of wood. This was done by measuring the change in temperature of a litre of water sitting in a pot on the grill. Our ability to collect accurate calorimetric data was limited by several factors. First, the grill is poorly insulated, meaning not all the energy dispersed in burning went into heating the water. However, we assumed that, because both the wood and bricks were being burned under the same conditions, the results could be at least used for comparison, if not for a true heat calculation. Second, it is difficult to sustain such a small fire, and the necessity for intermittent relighting and adding of additional kindling certainly skewed any measurements of burn time and energy generated.

Despite these difficulties, it was possible to conclude from observation of the biobrick and wood burns that the biobrick had the potential to be a viable fuel source on a par with wood. Also, from the rough figures we collected - the biobricks raised the water temperature from 65 to 135 degrees Fahrenheit and burned for 30 minutes, the wood raised the water temperature from 70 to 120 degrees and burned for 45 minutes - it was possible to hypothesize that, in a large scale burn, the biobricks would burn faster and hotter than wood, likely due to their lower density and higher porosity.

Production Efficiency, Mold Designs, and Brick Shape Assessments

Having established the viability of biobricks as a fuel source the next major step in the experiment was to produce a large number of bricks and conduct another test burn in the bakery oven, ideally using a mass of biobricks equal to the mass of wood typically used to fire Pleasant House's oven.

After some calculation, we determined this was an infeasible goal. For a given day's burn, Pleasant House Bakery will use between 75 and 100 logs total, weighing an average of 3 pounds, for a total of between 225 and 300 pounds. At our current production rate of about 12 minutes per quarter pound biobrick, production of that scale would have taken a minimum of 180 hours (not including drying), so we decided to scale the large burn to 25 pounds of biobricks, and compare to an equal weight of wood.

This is the area where a pellet mill would be most beneficial, as this amount of biomass could be processed in a much shorter amount of time, with potentially even less residual moisture and thus a shorter drying time.

Even with this reduced production goal, it was apparent that improving production efficiency would be beneficial. The primary way this was achieved was through production of different shapes of bricks, listed in Table 2.

Table 2 - Shape and Dimensions of Biobricks (pictured above)

Shape	**Average Height (in)**	**Diameter (in)**	**Volume (cubic in)**
Hollow Cylinder	3.5	3 w/ 1" hole in center	21.99
Solid Cylinder	3.5	3	24.74
3" Puck	1.5	3	10.6
4" Puck	1.5	4	18.85
6" Puck	1.5	6	42.41

All molds used a similar design to the original hollow cylinder, a piece of pvc pipe set on a wooden board with a wooden plunger driven by the hydraulic press. The main advantage of the puck shapes was that material could be packed into the mold more quickly, due to a wide opening in the top of the mold rather than the small opening available in the hollow cylinder design (there is approximately 1" between the outside of the mold and the central tube). Additionally, the pucks could be removed from the mold more easily because there was no need to remove the central tube from the brick, as is the case with the hollow cylinder design.

All of the bricks tested (with the exception of the solid cylinder, confirming the problems of the previous experiments) maintained structural integrity and drying times roughly equivalent to the hollow cylinder. The puck designs could also be produced in around 8 minutes per brick, a 33% improvement on the hollow cylinder design. This improvement in production speed, along with the 6 inch puck being almost double the volume of the hollow cylinder meant this design could convert an equivalent weight of biomass into biobrick in one third the time, reducing the estimated production time for our 25 pound goal from 20 hours to just under 7 hours.

Wood Oven Test Burn

Once a sufficient quantity of biobricks had been produced, we were ready to conduct large scale burns using the bakery oven. These burns were conducted on two consecutive weekends, so that the residual heat bakery burns had as little impact on the results of each test burn as possible. The first burn used 25.5 pounds of biobricks, spread out across the various types we had produced (47 six-inch pucks, 7 hollow cylinders, 6 three-inch pucks, and 2 four-inch pucks). The second used 25.5 pounds of Post Oak wood (8 logs, plus wood scraps for kindling).

Pleasant House's oven consists of two chambers - the main hearth: the large upper chamber where their products are baked, and the auxiliary oven: a smaller chamber underneath the main hearth. Usually, wood will be fired in the main hearth, as it provides more space to burn the quantity of wood necessary to bring the oven up to temperature. However, given the smaller scale of our burns, we used the auxiliary oven (upper right). Using the smaller oven allowed for more accurate calorimetric measurements, as less heat could be dissipated to the surrounding air and masonry, from which it is harder to collect temperature measurements.

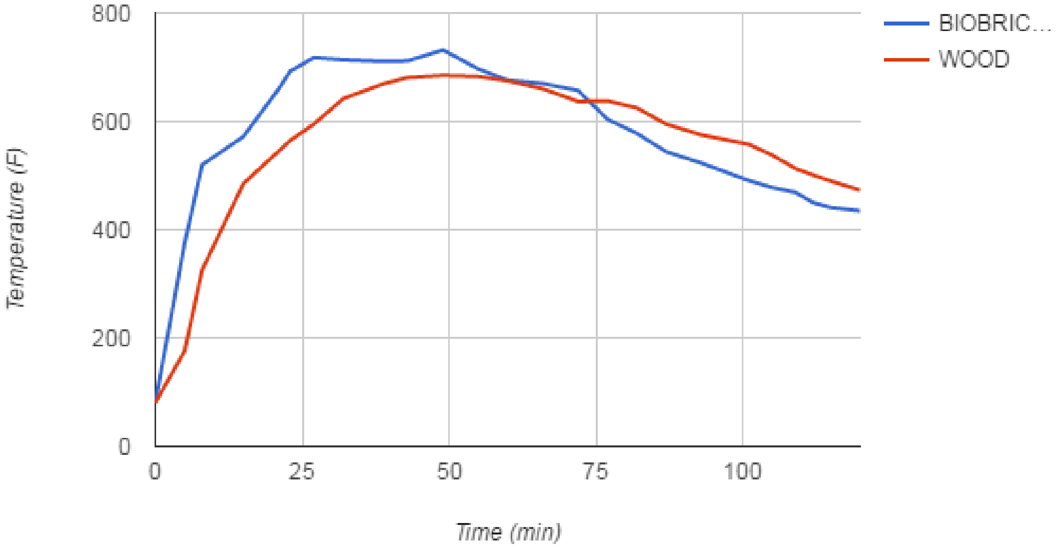
Temperature measurements were collected from the cast iron chimney (known as a Gueulard [goo-lahr] lower right) that connects the auxiliary oven to the main hearth. Although not a perfect source of measurement, due to unmeasured heat loss by convection from the chimney's outlet, this conductive bottleneck in the heat flow from auxiliary oven to the atmosphere represented the point where the heat released through burning could most directly be measured as a change in temperature. Given that the heat values of the biobricks and wood were measured under the same conditions, this technique still provides us with a solid basis for comparison. Additionally, the accepted heat value of Post Oak, established under more controlled circumstances, could be used to scale the results of both trials to account for unmeasured heat released during the burn.

Each burn was conducted over the span of two hours, using an infrared heat gun to collect temperature measurements of the chimney in five minute intervals. Due to the lower density of the biobricks, the auxiliary oven could not fit all 25.5 lbs simultaneously, so they were fed into the oven in batches over the first hour. The wood was all burned at once. The results are summarized in Figure 1, below.

Biomass Briquettes in the auxiliary oven

Post Oak logs in the auxiliary oven

Figure 1: Gueulard Temperature During Biobrick and Wood Burns



From the overall shape of the curves, it appears that our earlier hypothesis that the biobricks burn hotter and faster than wood holds true for a larger scale burn. During the biobrick burn, the gueulard reached peak temperatures between 27 and 49 minutes, with a maximum temperature of 732 degrees Fahrenheit. During the wood burn, the guelard reached peak temperatures between 40 and 60 minutes, with a max temperature of 685 degrees Fahrenheit. The wood burn experienced both a more gradual rise in temperature and more gradual fall. Had all of the biobricks been burned at once, it is likely that this difference would have been even more pronounced. The biobricks' energy would have been released even more quickly, creating a higher temperature peak earlier in the burn and more rapid temperature decline after combustion completed. This periodic addition of new biobricks is what accounts for the somewhat jagged representation of the biobrick temperature profile, as a sudden influx of heat caused the temperature of the Gueulard to rise dramatically.

Additionally, the flames from the wood fire went out after 93 minutes, as compared with the biobricks, which went out after 72 minutes. The biobricks also began to combust much more readily, requiring only an egg crate as kindling, compared to the wood which required an egg crate plus roughly half a pound of wood fragments before sustained combustion began.

Heat Value Analysis

Calculation of true heat values of the biobricks from these trials is an inexact process, as not all of the energy released by combustion is absorbed by the gueulard. The rate of energy transfer between two objects is proportional to the temperature difference between them. Thus, as the gueulard heated up, it absorbed less of the energy released from the fire and lost more heat to the surrounding oven. Also, as the fire burned down, there is a point at which the gueulard is hotter than the fire and is losing heat to the fire, rather than absorbing heat. All of these facts make it virtually impossible to draw a direct correlation between the temperature data collected and the heat values of the biobricks and wood.

However, because both the wood and biobricks were burned under the same conditions, it is possible to assume that a similar percentage of the total energy contained in each was absorbed by the gueulard before the temperature of the fire dropped below that of the gueulard and energy release could no longer be meaningfully measured.

Based on the temperature data obtained, we calculated that 2321.81 BTUs (British Thermal Unit) of heat were absorbed by the gueulard from the biobrick fire, and 2035.21 BTUs were absorbed from the wood fire (for details on the means of calculating these figures, see Appendix 1). Accepted values put the heat value of post oak at 23.7 MBTU (Million BTU)/cord, which translates to 6,196.1 BTU/lb, or 158,000 BTUs for the 25.5 lbs we burned. This means that about 1.3% of the energy released in combustion of the wood went into raising the temperature of the gueulard (such a low value is understandable, as the purpose of the gueulard is to channel heat to raise the temperature of the surrounding air and masonry in the oven). If a similar proportion of the heat from the biobrick fire was absorbed, then the heat value of the biobricks would be 7,004.0 BTU/lb, or 178,602 BTUs for the whole 25.5 lbs.

Based on these figures, the biobricks contain 13% more energy per pound than the post oak currently being burned. Although this is not enough to offset the differences in density discussed in the "Revised Goals" section (wood still contains 3x the number of BTUs per unit of volume), it does indicate that the biobricks have strong potential as a fuel source, meriting further investigation.

Revised Goals for Biobrick Use

The original intention of this project was to create biobricks that could be used entirely in place of wood when firing the oven. Currently, the oven is fired every other day with 60 logs, and then several hours later with an additional 20-40 logs in order to bring the oven to its peak temperature. The target is usually between 650 and 730 degrees Fahrenheit, and baking begins a few hours after the fire has finished burning.

Based on certain properties of the biobricks, we discussed revising their intended use with the bakers at Pleasant House. The primary concern with using the biobricks as an exact analog to wood is their density. Because the bricks are less dense than wood (.011 lbs/in^3 compared with .037 lbs/in^3), burning an equivalent mass would require nearly 3.5 times as much space. Given that the oven is near capacity when the first round of 60 logs are burned, this extra volume is infeasible.

However, because the oven is currently only fired every other day, it goes through wide temperature fluctuations, from about 350 to 780 degrees Fahrenheit. These wide fluctuations create limitations on when baking is possible, because the ideal range for baking is between 500 and 600 degrees. Currently, these limitations are acceptable, because baking takes place every other day. However, if production should increase, it would be necessary to maintain the oven's temperature in a more consistent range.

Based on our findings, the biobricks show great promise for this purpose. Because of their faster burn time, they can be burned between baking cycles in order to provide a quicker, smaller infusion of energy into the oven to help maintain its temperature in a more moderate range between the longer, larger burns using wood. Ideally this will diminish the overall quantity of wood that needs to be burned to return the oven to its highest temperatures, while preventing it from dropping to the lower temperature ranges that cannot be used for baking.

Next Steps

Based on the information collected during this phase of research, it will be necessary to continue to improve the efficiency of producing the biobricks. Although they are a viable fuel source for the oven, providing a similar amount of energy to wood, the amount of electricity and physical labor necessary to produce the bricks makes them prohibitive from an energy savings perspective.

The two major phases of production in which time and energy could be saved are in the milling and drying processes. In this phase of research, milling and mixing of the materials was carried out with an electric food processor. Because the grain/chaff mixture is sticky, the processor did not mill as effectively as it would if the mixture was more of a slurry. Adding more water however would then increase the drying time. The bowl of the processor would allow the milling of only two liters of material at one time. This process generally required about five minutes per two liters, which would produce enough material to press one six-inch diameter brick. Finding alternative means of milling, such as a hand powered feed grinder or food mill, that can more efficiently grind the material, be continuously fed, and not require electrical power would greatly benefit the process by both speeding up the milling and lowering the necessary electrical input.

Drying the bricks remains the most time and energy intensive part of the process. As discussed in the "Initial Test Burn" section, air drying is not feasible, as the bricks begin to grow mold long before their center is dry. Currently, bricks must be dried in an oven, a process requiring 8-12 hours, and limited by the space available in the oven. Experimentation with drying methods will be a key component of the next phase of this research.

Some proposed ideas include building a solar kiln or using 'waste' heat from the bakery oven. While these are unlikely to speed up the drying process, they would both dramatically reduce the energy input necessary to dry the bricks. Additionally, using 'waste' energy from the bakery would involve a key principle of the circular economy - capturing as much potential as possible from a process (in this case fuel combustion).

Another potential alternative is not pressing bricks at all, instead drying the raw materials enough for combustion, and shoveling the dried grain and chaff into the hearth to be burned. Drying the material in loose form increases the surface area exposed to the air, thereby not only improving the drying time, but also accelerating combustion. This would result in a hotter fire, but also a shorter burn time, potentially limiting the amount of heat transferred to the oven. Should combustion of the loose material prove effective, it would eliminate the need to mill the material or press the bricks while speeding up the drying, dramatically improving the efficiency of our biomass fuel production.

One other improvement to the process would be the incorporation of a pellet mill. This device would grind, press and extrude the material into small pellets that would potentially have much lower moisture values and a significantly shorter drying time. Under the greater pressures of a pellet mill, it is also conceivable that the pellets would approach the density levels of wood, reducing the storage space needed.

Stay tuned for updates as we continue our experimentation and seek to solve these issues!

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Appendix 1 - Calculating the Heat Values

The heat value calculations for the biobricks and wood are based on two equations.

First, the specific heat equation, $\Delta H = mc\Delta T$, which tells you the amount of energy (ΔH) that leaves or enters a substance of mass *m* with specific heat *c* in order to lower or raise its temperature by ΔT degrees.

Second, the overall heat transfer equation, $\frac{\Delta H}{\Delta t} = h_o A \Delta T$, which tells you the rate of heat transfer between two substances with overall heat transfer coefficient h_o , in contact with each other over surface area *A*, when the temperature difference between them is ΔT .

Combining these two equations, and assuming that the only two sources of heat flow into or out of the gueulard are the residual heat in the main oven and the fire in the auxiliary oven, we obtain the equation $\frac{mc\Delta T_g}{\Delta t} = h_o A (T_f - T_g) + h_o A (T_o - T_g)$

Where m = weight of the gueulard = 27.4 lbs

c = specific heat of iron = $0.11 \frac{BTU}{lb \cdot °F}$

ΔT_g = change in heat of the gueulard over certain amount of time, Δt

h_o = overall heat transfer coefficient between iron and air = $0.12 \times 10^{-4} \frac{BTU}{min \cdot in^2 \cdot °F}$

A = surface area of the gueulard = approximately 362.25 in^2 (calculated by approximating its shape as a rectangular prism with no bottom with dimensions 6”x10.5”x10.5”)

T_f = Temperature of the Fire in Auxiliary Oven

T_g = Temperature of the Gueulard

T_o = Temperature of the Main Oven = approximately 450°F (calculated as an average of temperatures at various points in the oven)

In simple terms, this equation tells us that the heat flow into the guelard ($\frac{mc\Delta T_g}{\Delta t}$) is equal to the sum of the heat flow from the fire to the gueulard ($h_o A (T_f - T_g)$) and the heat flow from the oven to the gueulard ($h_o A (T_f - T_g$). Either of the latter two heat flows can be reversed (heat moving from the gueulard to the firebox or the main oven) if T_g is greater than T_f or T_o.

A more useful form of this equation is $P_f = \frac{mc\Delta T_g}{\Delta t}$ - $h_o A (T_o - T_g$), where $P_f = h_o A (T_f - T_g)$, the rate of heat flow from the fire. The amount of heat absorbed by the gueulard from the fire will be found by integrating P_f with respect to time.

Filling in the numerical values above we get:

$P_f = \frac{(3.014)\Delta T_g}{\Delta t}$ - $(.042)(450 - T_g$)

At this point, it is necessary to replace T_g with some function of time, modelling the temperature data obtained during the test burn. We tried to create a continuous function for T_g out of a linear combination of polynomial, exponential, and sinusoidal functions, which would allow us to replace $\frac{\Delta T_g}{\Delta t}$ with derivative of T_g with respect to time, $\frac{dT_g}{dt}$, then integrate $P_f(t)$ over the interval t=0 min to t=120 min. However, we found that a piecewise function composed of 4 lines both created a better model of the temperature data, and was easier to work with than any of the continuous functions we were able to generate.

The four lines correspond roughly to four phases of the burn. Phase 1 is when the gueulard was taking in heat from both the fire and the oven, producing a rapid temperature increase. Phase 2 is when the gueulard is losing energy to the oven, but gaining more energy from the fire than it is losing, producing a slower temperature increase. Phase 3 corresponds to an equal energy gain from the fire and loss to the oven, resulting in a steady temperature. Phase 4 is when the gueulard is losing energy to both the fire and the oven, and was not considered in totalling the amount of energy received from the burning materials.

The functions used for $T_g(t)$ for the Biobricks were:
Phase 1: $0 \leq t \leq 8,\ T_g(t) = 55t + 80$
Phase 2: $8 \leq t \leq 27,\ T_g(t) = 10.5t + 436$
Phase 3: $27 \leq t \leq 49,\ T_g(t) = 719.5$
Phase 4: $49 \leq t \leq 120,\ T_g(t) = \ -4t + 915.5$

The functions used for $T_g(t)$ for the wood were:
Phase 1: $0 \leq t \leq 15,\ T_g(t) = 27t + 80$
Phase 2: $8 \leq t \leq 27,\ T_g(t) = 7.8t + 368$
Phase 3: $27 \leq t \leq 49,\ T_g(t) = 680$
Phase 4: $49 \leq t \leq 120,\ T_g(t) = \ -3.5t + 890$

With these equations, we can solve for the heat produced in each phase by plugging in the corresponding equations for T_g and their slopes for $\frac{\Delta T_g}{\Delta t}$ and integrating P_f with respect to time over the three intervals. (This process is shown in detail for the first equation.)

For Biobricks this gives us:

Phase 1: $\int_0^8 (3.014)\frac{\Delta T_g}{\Delta t} - (.042)\,(450 - T_g)\,dt =$

$$\int_0^8 (3.014)(55) - (.042)\,(450 - (55t + 80))\,dt = \int_0^8 2.31t + 157.765\,dt = 1336.04\ BTUs$$

Phase 2: $\int_8^{27} 0.441t + 31.059\,dt = 736.75\ BTUs$

Phase 3: $\int_{27}^{49} 11.319\,dt = 249.02\ BTUs$

Total: 2321.81 BTUs

For Wood:

Phase 1: $\int_0^{15} 1.134t + 65.838\,dt = 1115.15\ BTUs$

Phase 2: $\int_{15}^{40} 0.32761t + 20.0652\,dt = 726.86\ BTUs$

Phase 3: $\int_{40}^{60} 9.66\,dt = 193.2\ BTUs$

Total: 2035.21 BTUs

Works Consulted

Firewood Heat Value Comparison Charts:
https://chimneysweeponline.com/howood.htm

Overall Heat Transfer Coefficients:
http://www.engineeringtoolbox.com/overall-heat-transfer-coefficients-d_284.html

Specific Heats of Metals:
http://www.engineeringtoolbox.com/specific-heat-metals-d_152.html