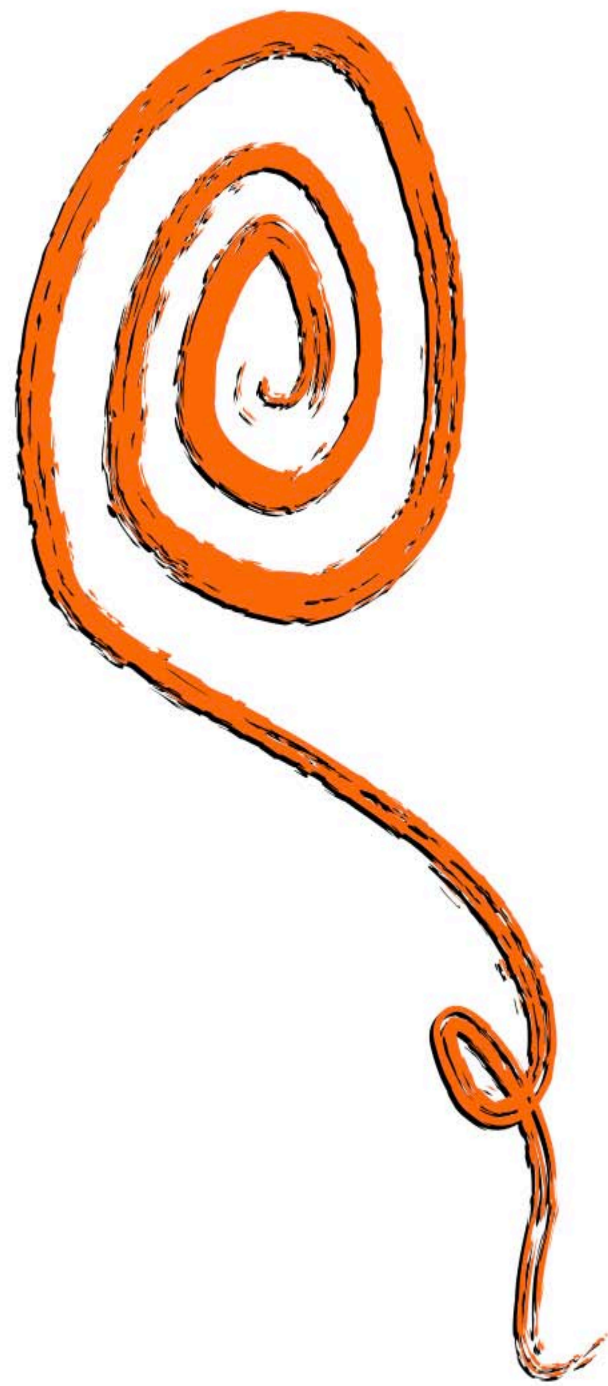
# Spiral Pine Needle Stove



D-Lab Design, Spring 2010

By four MIT students

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## Summary


**PROBLEM STATEMENT**

Design a cook stove that viably uses pine needles as an alternative fuel source for the AVANI community in Uttarakand, India; it must be as easy and efficient to use as their current cook stoves, involving minimal preprocessing of the needles.

**DESIGN SPECIFICATIONS**

The main design parameters we wanted our stove to concentrate on were durability, locally available materials, low cost, health and fire safety, control of heat for cooking, ease of use, efficiency, and pine needle processing. The design specifications that were most important was that the CO and particulate matter emissions could not exceed 10 ppm (50 ppm being the standard level of health hazard) and 0.150 mg/ $m^3$ , respectively, and needs to compete against 30-50% efficient wood stoves.

**PRIOR WORK**

Research was conducted into different types of stove designs (wood, charcoal, and brick) that could potentially be modified into stoves capable of using pine needles as the primary fuel source. Portable and permanent structure stoves were looked at. Of the stoves, the Anila gasification and Rocket Stoves were two of the more applicable stove designs to our design work. These two stoves became testing prototypes and points of comparison throughout our design process.

**CONCEPT EVALUATION**

The three major factors of a successful stove design guided our design process when trying to find the optimal way to tame the unruly nature of the pine needle burn; fuel, temperature, and air. We explored burning pine needles as a primary fuel in different forms- loose, compact, and “log” forms- with varying airflows. We also considered the use of pine needles as a secondary fuel, gasifying them to prolong the burn of a primary fuel. As we wanted to find a way to use pine needles as a sole alternative fuel without undergoing further processing, we pursued designs utilizing the pine needle as a primary fuel, meanwhile seeking to harness the volumes of fuel gas emitted to increase the efficiency of the burn. We used a fireplace and current charcoal stoves, and built prototypes of gasifiers and feed-mechanism-stoves, before focusing on the our final spiral design.

**PROPOSED SOLUTION**

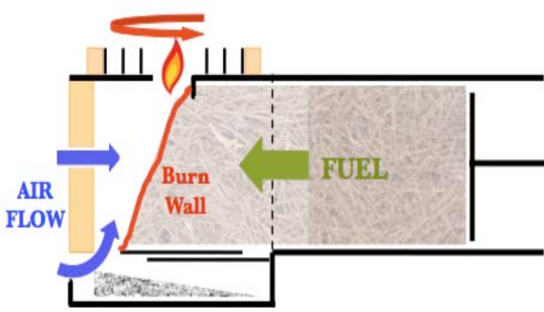
This stove design facilitates two burn stages—a primary burn in a firebox, and a secondary burn within a spiral. For the primary burn, unprocessed pine needles are compressed and fed into an insulated firebox. Strategically placed air inlets allow proper airflow. As the pine needles burn, gasification occurs. The flames and gases then travel upwards, entering the spiral via a central hole. The draft from the chimney pulls the gases around the spiral, and because the firebox heats the spiral from underneath, the gases ignite and a secondary burn ensues. The feeding system allows for a steady primary burn, while the spiral’s elongated burn path harnesses energy that is normally lost

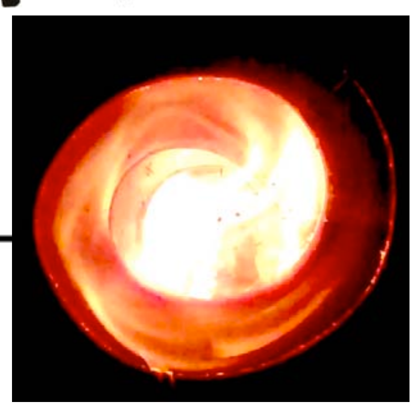
to gasification.

From current testing, the stove was determined to have an average efficiency of 23.75% during three cold starts with a maximum efficiency of 28.61%, and an average efficiency of 22.49% during three hot starts with a maximum efficiency of 24.90%. The time it took to boil 5L water ranged from 16-22 minutes, with an average of 20:08 minutes.

**FUTURE WORK**

Now that an effective burn method has been established, further work to be done on the stove includes optimizing the parameters at which the pine needles burn best in both the firebox and spiral. The parameters to be adjusted and tested for the spiral include its length, alignment, path width and height from the top of the firebox. The parameters to be adjusted and tested for the firebox include its size and shape, and that for the shoot include its length and opening size. Even though our cost analysis revealed only $0.85 above our original price, it would be valuable to lessen the amount of metal used in the design. As of now, there is excess metal as it is, with parts that could be made with a cheaper material. Once these parameters have been optimized this stove will be ready to be tested in the field.



## Prior Work

When we first began our research into using pine needles as a stove fuel, not many research or articles turned up. Pine needles had never really been tried successfully as a fuel source except in the form of charcoal briquettes. Therefore, in order to generate ideas for our stove design we researched current stove designs for developing countries to see if there were any current wood or charcoal stoves (in addition to existing pine needle fuel models) that could potentially be modified to burn pine needles.

### Portable Stove Designs

One of our team members was a part of the Dlab Peru team last semester, and since they had already done some research on portable improved cookstove design, we decided to start our search there. Two of the main types of stoves they worked with were a clay pot skirt/stand type of design, which involved making a clay combustion chamber which allowed for a pot to sit on top of it, the fuel is then put in at the bottom of the clay pot and lit, and the clay holder creates a combustion chamber that forces the heat upward to the pot, and the other design the team worked with was making an L-shaped combustion chamber out of bricks that are either stacked together or held together by an exterior container or adhesive. Both of these got good reception in the Amazonian community the Peru team was working with over IAP, and could be used for any form of pine needle fuel our team might develop. The clay and brick combustion chambers are shown below.

**Figure: Clay Pot Skirt Shown on the Left, Brick Combustion Chamber on Right**

The Nixtamalera stove, created by the Reinhardt Foundation, is a pot that uses an L-shaped combustion chamber, but instead of needing a certain size pot, they fix this chamber inside of a mixture of cement and gravel and surround it with an aluminum pot skirt so that as the bricks get hot all of these conduct heat from it to creating a one size fits all stove, for any shape pot.



**Figure: The Nixtamalera Stove**

Another stove design researched was the Anila gasifier stove. This stove model charcoalizes biomass such as pine needles through means of gasification of the particles as explained by the model shown below. We really liked this stove design and decided to test a stove model like this ourselves, the results of which are discussed in a later section.

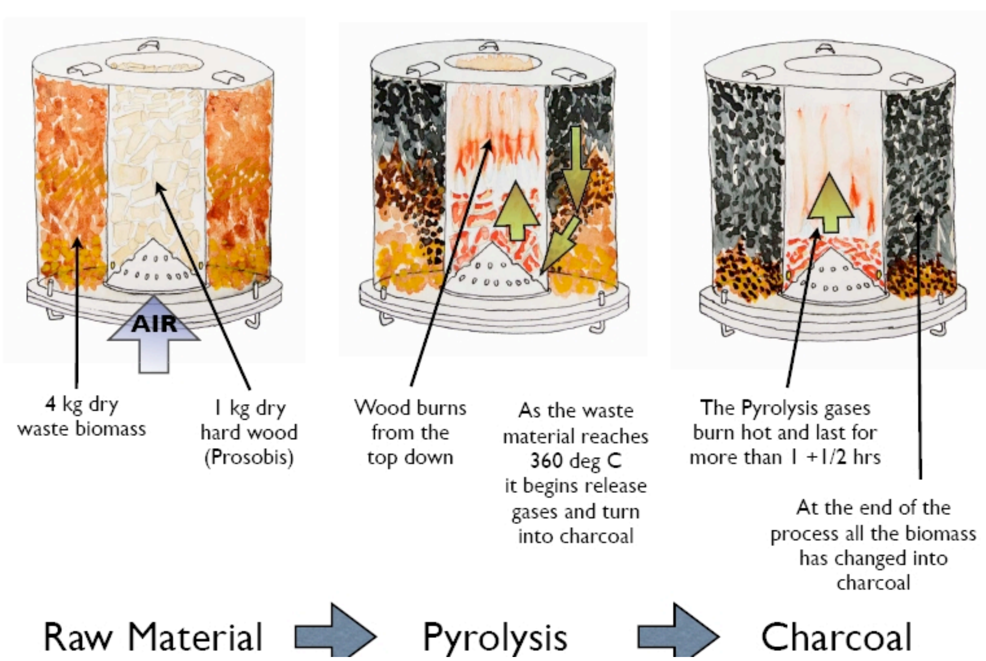



**Figure: Combustion Process for the Anila Stove**

The other main portable stove design we researched was the Rocket Stove. This stove design is an L-shape combustion chamber design with insulating material that is most notable for it's high efficiencies (around 55%). A schematic of this stove design is shown below.

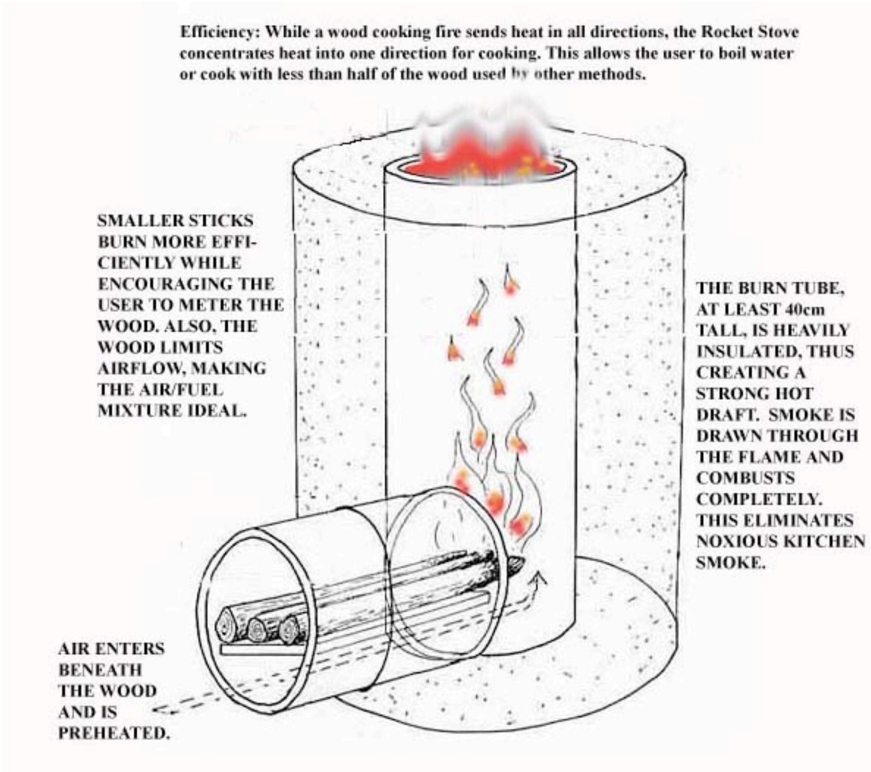



**Figure: Diagram of the Rocket Stove Combustion Process.**



### Permanent Stove Designs

We also looked into more permanent structure stoves for this project. We first looked at antique wood burning stoves, like those used in the 18th/19th/early 20th centuries in the US, as well as similar designs that have been created by the Reinhardt Foundation such as the Olin Stove. The Olin design is interesting in that it elongates the burn path for the wood smoke. Both designs incorporate a chimney system, which is very effective in reducing indoor air pollution for the community, and could be used indoors or outdoors depending on where the food is normally prepared within the community.





**Figure: Left: An antique wood stove. Right: The Onila woodburning stove**

Another design, that is currently being used in more southern India involves a more adobe/mud/clay stove, that is a permanent structure attachment to the home. Fuel is lit at one end of it, but the stove has multiple pot points so that you can cook directly over the flame, but keep things warm or simmering right off the flame as the heated smoke makes its way to the chimney.

**Figure: Southern Indian Mud Stove**



**DESIGN PARAMETERS**

- Designs for sustainability
  - Pine needles are a renewable energy source
  - Alternative to wood, which is a diminishing fuel

  - Fuel comes from "waste" that is harmful to the environment
  - Ability to change the ecosystem positively, by improving environment
- Design for affordability
  - Materials currently costs $15.85
  - Used a lot of metal, which is readily availability and is a specialized labor skill in the area
  - Simple design that minimizes volume and variation of material
  - Tools that were used were very simple: welding and hacksaw, die forming
- Design for failure
  - Does not have to be optimal conditions to function- allows for tolerance
  - (Warping is a problem)
  - Easy to replace and repair
    - The design is highly modular- you can replace just the parts that required
- Design for human use
  - Focused highly on minimizing the amount of attention required to keep the stove burning- compressed pine needles that needed to be inched in every 4 minutes. Shoot needed refilling after 10 minutes
  - Very quick start
  - Chimney ensured very low CO and particulate matter results
  - The air inlets allowed the user to easily monitor the fire without having to look at spiral
  - Added an ash drawer to easily remove ashes from the firebox
- Design for manufacturability
  - Used simple manufacturing processes: welding, hack sawing, dire forming
  - Community highly skilled in metal work that is required for the manufacturing for the stove.
  - Future step will include finding insulating materials more available to the community
- Design for assembly
  - Modular- requires simply bolts and welding to assemble
  - Currently, the stove can be used independently, however, in the future, if the stove is incorporated into the design of the house, certain materials required to hold the stove together could be eliminated if the stove was built in to the clay structure that is often seen in wood stoves.

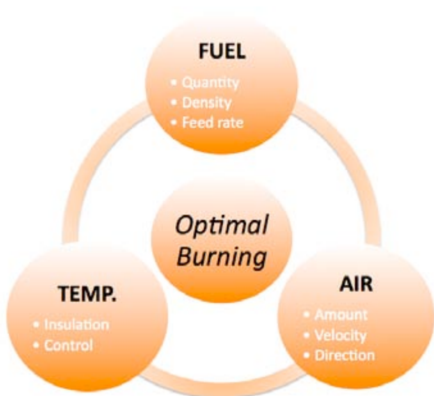
**DESIGN IDEAS**

The main design parameters we wanted our stove to concentrate on were durability, locally available materials, low cost, health and fire safety, control of heat for cooking, ease of use, efficiency, and pine needle processing. The design specifications that were most important was that the CO and particulate matter emissions could not exceed 10 ppm (50 ppm being the standard level of health hazard) and 0.150 mg/ $m^3$ , respectively, and needs to compete against 30-50% efficient wood stoves.

We first began our design process by exploring the burn properties of pine needles; familiarizing ourselves with the fuel we wanted to manipulate for our stove. We spent time discovering the characteristic behavior of pine needles and found that they burned very differently depending on the conditions. In the controlled environment of a fireplace, we burnt handfuls of tangled pine needles, pine needle “logs” tied together with string, packed pine needles in a pipe, chopped pine needles on a mesh grate, with varying airflow and volume. We found that the fire stays located (i.e. does not spread across the volume of the pine needles), especially with higher density, compact, volumes. The higher density the pine needles were burnt in, the more concentrated airflow was required to maintain the fire. The pine needles released a lot of gas in all cases, especially as the fire died and began smoldering. The pine needles caught fire quickly, but also lost its heat very rapidly (we were able to touch the ashes with our hands soon after the fire had extinguished without getting burnt). The fire needed to be tended to continuously, and for the loose pine needles, constant feeding was required. In many ways we could draw analogies with liquid burners, concerning the continuous fuel feed and air source meeting to create a burn.

Thereafter, we began the process of designing the stove that would successfully tame the wild nature of the pine needle burn and allow someone to practically use it for cooking. We discussed whether to place it inside or outside, and understood from our community partner that the most common place for cooking was inside, especially due to the cold climate it Uttakarand in the winter months. Keeping the design parameters mentioned in the introduction in mind, we brainstormed how to best apply the major three factors of a successful stove design to pine needles.

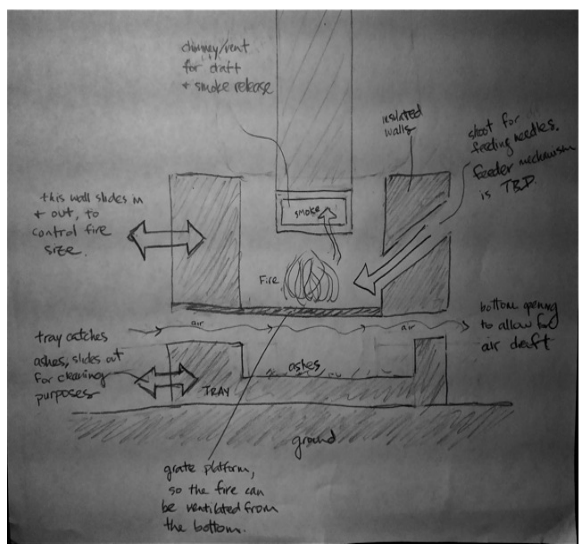
For fuel, we needed to determine the best form that the pine needles should be burnt, given our initial exploration of pine needle burn characteristics. Higher density meant a longer burn, more control, and less fuss but required more air, whereas loose pine needles needed less air but constant attention and feeding. Furthermore, we heavily discussed whether to use pine needles as a primary fuel source and/or as a secondary fuel source (i.e using the gas of the pine needles to sustain a burn created by another fuel). We essentially pursued four major different design ideas before we narrowed (or rather accidentally stumbled upon) our final design concept: using a normal charcoal stove with loose needles, “logs”, a feeder, and a gasifier.



**Loose needles**
We wanted to verify any possibility of using completely unprocessed needles with existing charcoal stoves and found quickly this was not a practical or viable option as the pine needles burnt uncontrollably, smoked greatly, and required constant attention. Below is a picture of one of the tests executed.

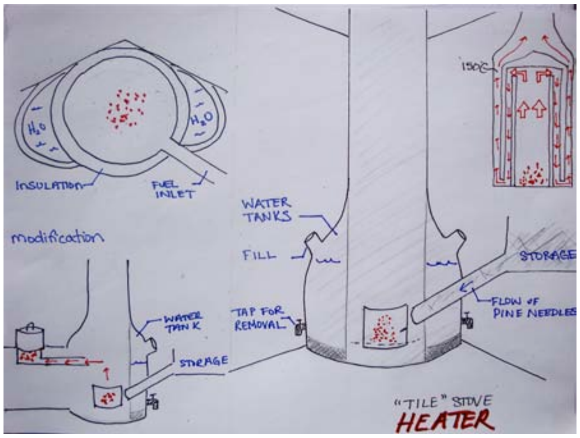
**Log stove**
Similarly, we wanted to test for same concept of using existing stove technologies and simulating a wooden log with the pine needles by aligning the pine needles and wrapping them with string. If the logs were placed in a TP, the would burn better because there was more air that could flow through, however, in general it was difficult to maintain the fire. We also wanted to shy away from having to process the pine needles into log forms.

**Feed stove**
We built a stove that fed unprocessed, loose pine needles into a shoot and burn them in a more controlled manner than the first design idea. Pine needles would have to be constantly fed, and realized that the manual feeder would have to be automated if we were to pursue this idea, which would add another dimension of complexity and cost. Due to the angled shoot, smoke would escape from the shoot and begin burning the supply along the tube. Even with a short chimney, there was not enough controlled airflow, and the gas released by the pine needles, was inefficiently being unused and escaped.



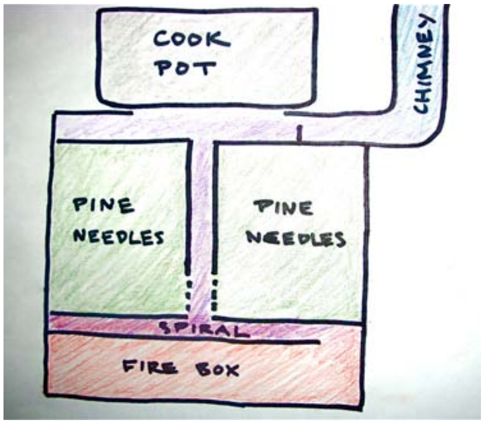

**Gasifier**
Finally we pursued the idea of using pine needles as a secondary fuel source in gasification. This spun from two sources: old technology of tile stoves, very popular in

Scandinavia, and existing biomass gasifiers in the field. Tile stoves use channels that maintain the gas released by burning fuel inside the system, which efficiently uses the gas released also a secondary fuel and retains the high temperature inside the stove before it is released. These stoves are able to use minimal fuel to heat up rooms and burn for a long time.



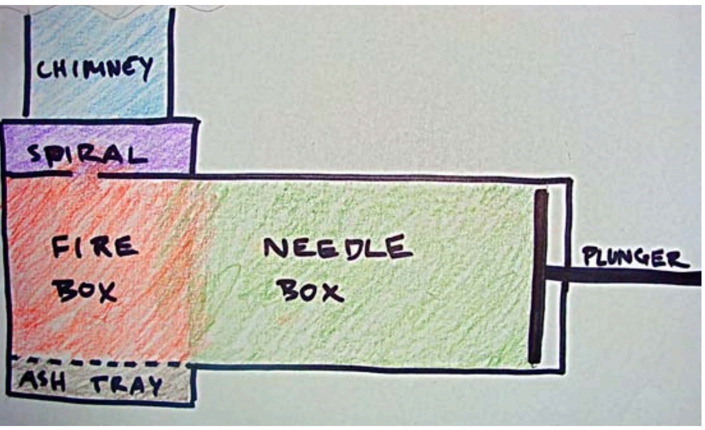

Courtesy of victorious felines on Flickr.

We prototyped the Anila gasifier stove in order to get a better understanding of pine needles' role as a secondary fuel. The main concept consisted of a primary fuel source created by wood, surrounded by a chamber of biomass (pine needles) that would begin to gasify at high temperatures and continuously reignite/feed the primary burn. This saved fuel and would yield high temperatures. Although this was a first pass at replicating the stove, we found some fundamental design flaws that stimulated our creativity and pushed us towards our final concept. Firstly, it would take too long of a time for the pine needles to begin gasifying and the stove was therefore an inefficient version of a woodstove for the largest part of the burn time. Moreover, the stove worked on a batch system, in that the stove needed to be loaded once before its use (by flipping it over, removing the base, and filling it with pine needles as seen by the left picture), and then would have to wait until the end of its use and for it to cool, before you could remove the biomass and reload.




We wanted therefore to tackle the problem of 1) decreasing the amount of time for it to gasify and 2) being able to feed pine needles during stove use.

In response to 1), we wanted to place the primary fuel underneath the biomass and then have a spiral structure (horizontal channel system) that would spread the fire underneath the entire bottom surface area of pine needles, and retain the heat in the system, like the tile stoves.




With that, we began thinking about removing the secondary chamber and simply keeping the firebox and the spiral on top, but using the pine needle as a primary fuel source and a secondary fuel source. The spiral would allow for the latter to occur, by elongating the burn path and creating a horizontal channel. The pine needles needed to be compacted to control the burn, but there was no pre-processing required.

We tested the idea and found that it clicked; it worked considerably better than all of our prior idea pursuits, required no processing, controlled the fire, incorporated a chimney into the design (a requirement we decided for), and used the principles of fuel vs. airflow, retained temperature, and gasification. We therefore decided to continue exploring this one and refine the air inlets and dimensions. The first rough prototype that convinced us is shown below.

## DESIGN DESCRIPTION

### Firebox

Critical to any good fire is the right balance of air, fuel, and temperature. The firebox provides a space where these three parameters can be adjusted to optimize the environmental conditions, thus facilitating a strong, primary burn. A steady source of compacted fuel enters the firebox via the fuel shoot; air flows into the firebox via adjustable air inlets, drawn by a chimney induced draft; and insulated walls keep the temperatures high within the firebox. After the class embodied energy exercise, we felt it was important to insulate the chamber as much as possible. Consequently, the firebox is made out of firebricks, held together by threaded rod and nuts.

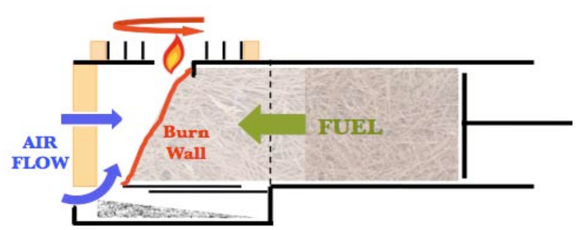



**Figure 1.** Schematic of a stove burn.

### Spiral

During the primary burn, a great deal of gasification occurs. The gases released by the fire get pulled up into and around the spiral, due to the draft from the chimney. In Figure 2a, one can see the central hole through which the flames and gases enter the spiral, and the chimney exit at the end of the spiral. Since the spiral is heated from the firebox below, the gases ignite and a secondary burn occurs. The flames extinguish before they reach the end of the spiral, once all the gases are burned up. This results in a clean burn with heat generated directly beneath the cook pot. The motivations behind this spiral design were to (1) elongate the burn path, (2) reheat the gases enough to cause a secondary burn, and (3) distribute heat evenly under the cook pot.

**Figure 2a.** Top view of the spiral component.
**Figure 2b.** Flames of the secondary burn traveling around the spiral.

### Chimney

A chimney is critical to this design, and generally speaking, chimneys play a significant role in reducing indoor air pollution from fire smoke. From the beginning, we wanted to incorporate a chimney for its health benefits. In this design, the chimney creates a strong draft that draws air into the firebox via the air inlets, and then up and around the spiral. Without the draw from the chimney, this system would not work. Currently, an acceptable chimney size for this stove is 4 inches in diameter, 9 to 12 feet in length.

### Air Inlets

Good airflow depends on both the chimney and the air inlets; however, it is much easier to manipulate air inlets than a chimney. This stove has four air inlets placed around the firebox, allowing the user to adjust the airflow to optimize conditions. Depending on the outside ambient conditions (the amount of wind, humidity, etc), and depending on the state inside the firebox (the temperature, the amount of fuel, if the fuel has turned into charcoal, etc), the fire requires different amounts of air, and sometimes air from different directions. The multiple inlets give the user control over the fire. Additionally, the air inlets serve as viewing portals into the firebox, allowing the user to monitor the primary burn. The ability to view into the firebox is very important in running the stove, because it provides visual queues for when the fire needs more fuel or air, or if ashes need to be cleared out.

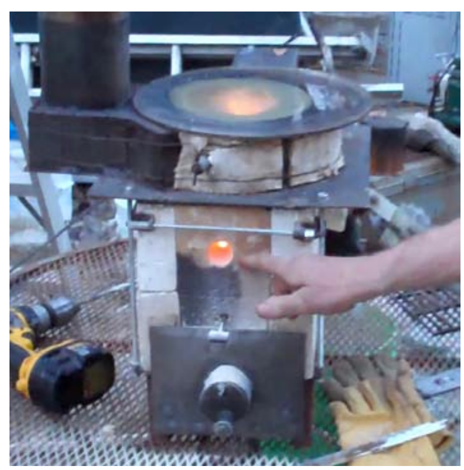


**Figure 4.** The hand in this photo is pointing at an air inlet. Below that is the ash tray.

**Fuel Shoot**

Pine needles are plunged into the firebox via the fuel shoot, with no preprocessing steps required. We found that for our purposes, pine needles burn best when compacted together—the burn relatively hot and controlled, so long as an adequate air supply is available. This plunging system allows the user to compact the needles appropriately into in the firebox. Furthermore, it allows the user to safely and easily add fuel without disturbing the burn and without releasing smoke or ashes into the room.

**Figure 5.** Plunging pine needles into the fuel shoot.

**Ash Tray**

As pine needles burn in the firebox, charcoal develops and eventually ashes form. The user needs to be able to clear out the firebox to make room for new fuel; if we consider the case in which the stove is run for several hours on end, one needs to be able to perform this clearing out process even when the stove is still running. Consequently, we designed an agitating floor into the firebox and placed an ash tray below it, so that the user can easily clear out the debris from the firebox as necessary. Additionally, the ash tray serves as an extra air inlet, allowing bottom-to-top airflow if ash drawer is left ajar.

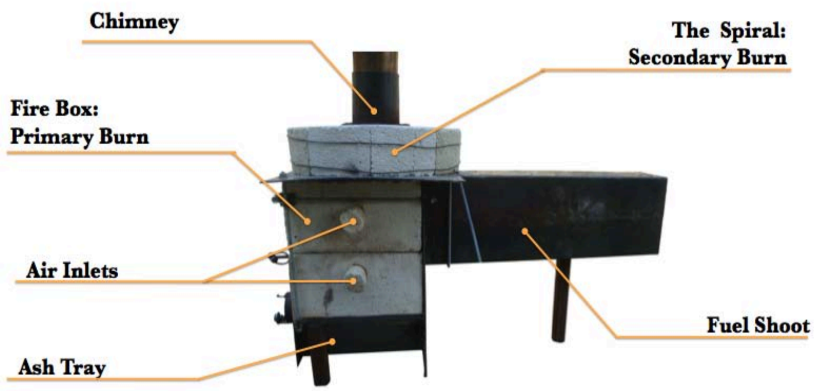



**Figure 6. Front view of the stove.**

## METHODOLOGIES AND RESULTS OF TESTS

### First Spiral Prototype

As we narrowed our design concept to a firebox with the spiral directly on top of it, we made a quick first prototype of this and used the method of stuffing the square of bricks underneath it with fire and lighting it. From this we were able to boil ***four cups of water in 13 minutes*****.** Although this result seemed promising, we realized that an easier method of feed the pine needles was needed for both safety purposes and ease of usability. We also realized that much of the flame that traveled around the spiral made its way into the chimney, thus making the chimney very hot, and this was problematic for two reasons. The first is in regards to safety—a hot chimney is not a great surface to be exposed to the user, and the second is that most of the heat is not concentrated where the pot would be placed. For this reason we elongated the spiral length for our next prototype.

### Second Spiral Prototype

Our second spiral prototype consisted on an enclosed firebox made of firebrick, a long shoot extended at one end, and the elongated spiral configuration located on top of the firebox with a chimney extended from the back in an L-shape. The height of the spiral was lowered by a few inches in this design so as to minimize the gap between the firebox and the pot. The firebox was also sealed more properly with a caulking gun at the cracks so that smoke could not easily escape. We initially tested this with a grate located underneath the area in which the pine needles would be pushed in, but to much dismay, found that this was of no help**.** From this, we decided to stick with a solid metal floor, and eventually moved into a floor that could be opened and closed for air circulation from underneath.

After running this stove a few times, there were a few problems that arose that led us our final prototype design. The first problem was that when the pine needles were pushed past the center spiral hole in the firebox, the fire would go out, as the center spiral hole was clogged with pine needles—the air had no way of getting through, which is what was keeping the fire aflame. Because of this, we added a small metal lip to the side of the spiral to keep the pine needles from directly clogging the hole, yet still allowing room for the pine needles to move into the firebox, creating a slightly slanted wall of fire. With the firebox being completely sealed off, it was difficult to access it and to evaluate what was happening with the burnt pine needles. The ashes of charcoal were thus cluttering the firebox, as the air inlet did not serve as ash and charcoal outlets. Because of this, we designed our third prototype to be modular. We shaped and fit the bricks closely together so that caulking was not necessary to keep the heat and smoke inside the firebox. We thus used long screws on the outside of the firebox to hold together the (now slightly warped) metal spiral and the firebox, and added a metal drawer to the bottom of the firebox to allow for easy removal of the ashes and charcoal.

**Third Spiral Prototype**

Before any quantitative testing was done, we first dealt with the ease of usability issues and smoke emissions issues through practice of running the stove and observing its behavior throughout the process. Through this method of testing our first two prototypes, we were able to refine our third prototype (given the time allowed), to have a smaller feeding shoot than the second, as we realized it was not necessary to have a four-foot long shoot full of pine needles, to have another air inlet was added opposite the direction in which the pine needles were being fed so as to better keep the flame going when needed, and to have an insulating layer (made of fiberfrax, then firebrick) on the outside of the outermost spiral so as to minimize heat loss, in addition to the other changes mentioned above.

It was with this third prototype that we did our most extensive quantitative testing. We began by performing a water boiling test, from both a cold and hot start, through which the stove's efficiency could also be calculated. We calculated the average efficiency of three cold starts to be 23.75%, with the highest efficiency to be 28.61%, and the average efficiency of three hot starts to be 22.49%, with the highest efficiency to be 24.90%. During this test, we also used three to four thermocouples, located at various places of the stove, in order to track the temperature profile at these locations during use. These locations include the end of the spiral, the center of the spiral, the base of the chimney, the center of the firebox, and the pot of water to be boiled. From these tests, we discovered that the temperature inside the chimney was lower than that at the center of the spiral, which was thus an improvement from our first spiral prototype—the elongated spiral path worked. We also discovered that the time it takes to boil 5L of water ranges from 16-22 minutes, with an average of 20:08 minutes. This range of boiling times was mainly dependent on the atmospheric conditions (i.e. wind, air temperature, etc.) of when the test was taken.

**Pine Needle Stove**

**EFFICIENCY DATA**

| Cold Start | Net Mass Used (g) | Time to Boil | Efficiency |
|---|---|---|---|
| 1 | 842 | 21:30 | **28.61%** |
| 2 | 673 | 21:56 | **19.39%** |
| 3 | 547 | 21:30 | **23.21%** |

| Hot Start | Net Mass Used (g) | Time to Boil | Efficiency |
|---|---|---|---|
| 1 | 594 | 19:47 | **22.05%** |
| 2 | 596 | 27:39:00 | **24.90%** |
| 3 | 584 | 16:00 | **20.53%** |

In addition to the water boiling test we performed a carbon monoxide (CO) emissions test, as well as a particulate test with a dust tracker. When running for thirty minutes, the CO emissions test revealed that the average value of CO was 2.96 ppm (parts per million), which was very good for a first test, considering that the standard level for being a health hazard is 50 ppm. When there was no cover on the spiral, the pure burning flame resulted in an average CO emission of 15.6ppm. The particulate test revealed the average value to be 0.251 $mg/m^3$, with three outliers that reach above 1.000 $mg/m^3$. Not considering the outlying values, the average particulate test gave a measure of 0.148 $mg/m^3$, which is under the 24 hour standards required for particulate matter; 0.150 $mg/m^3$. However it did go above during certain peaks (the outliers). These peaks of particulate emission coincided with the plunging of the pine needles into the firebox, and since then, we have learned to steadily push the needles in, rather than plunging them in with a lot of force at one time.

From these tests, we hope to continue to lower the value of the time it takes to lower water, as well as the CO and particulate emissions values. This will be done by continuing to optimize the shape and parameters of the firebox, spiral length and height, chimney height and diameter, and the feeding shoot.

## REFERENCES


Rajnish Jain (Avani NGO, India)

Ben Linder

Jic Davis

Brydem, et al. “Design Principles for Wood Burning Cook stoves,” Aprovecho Research Center, Shell Foundation, Partnership for Clean Indoor Air

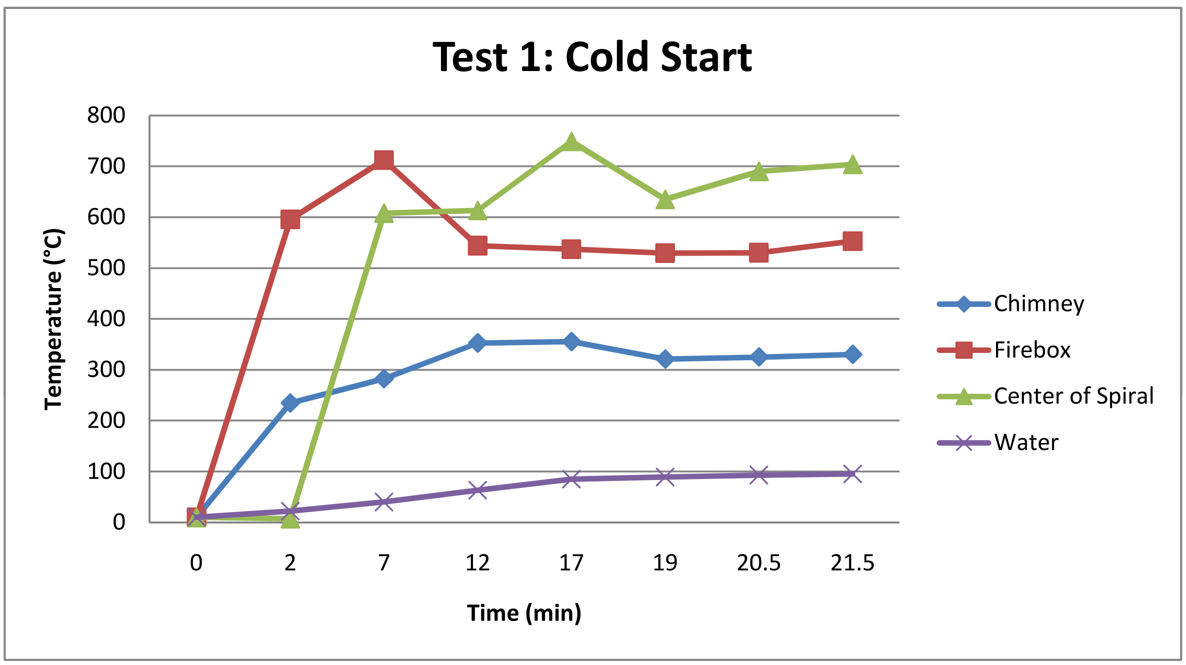
“Particulate Matter”, U.S. Environmental Protection Agency. Last updated April 16, 2010.

## APPENDIX: Charts and Graphs of Efficiency and Temperature Tests

**Test 1: Cold Start - 4/29/2010 (Thursday evening)**

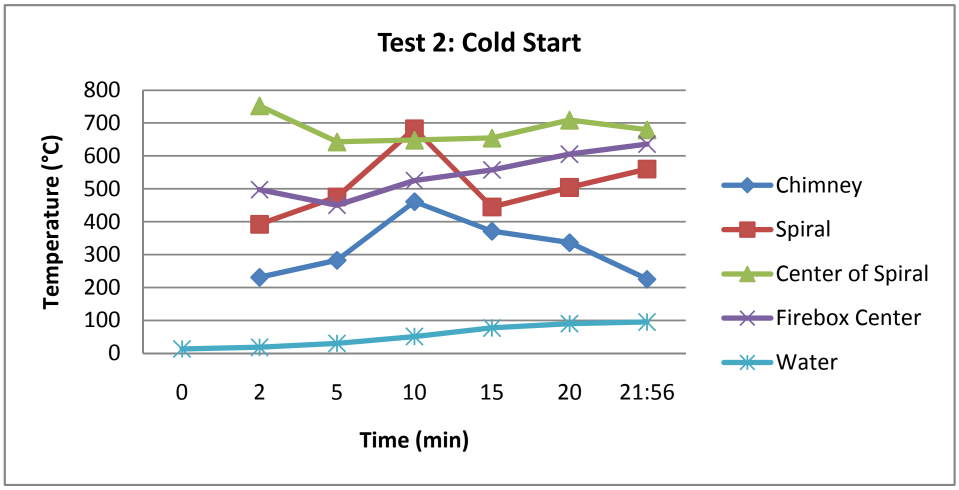
| | Chimney | Firebox | Center of spiral | Water |
|---|---|---|---|---|
| **Time** | **3** | **4** | **6** | **Water** |
| **0** | 10 | 9.9 | 9.8 | 10 |
| **2** | 234.4 | 595.9 | 7.26 | 22 |
| **7** | 282.2 | 712.2 | 608 | 40 |
| **12** | 352.6 | 544 | 613 | 63 |
| **17** | 355.1 | 537 | 748.8 | 85 |
| **19** | 320.7 | 529.1 | 635 | 89 |
| **20.5** | 324.9 | 530.1 | 690.1 | 93 |
| **21.5** | 330 | 553 | 704 | 95 |

* added more needles at 11 minutes



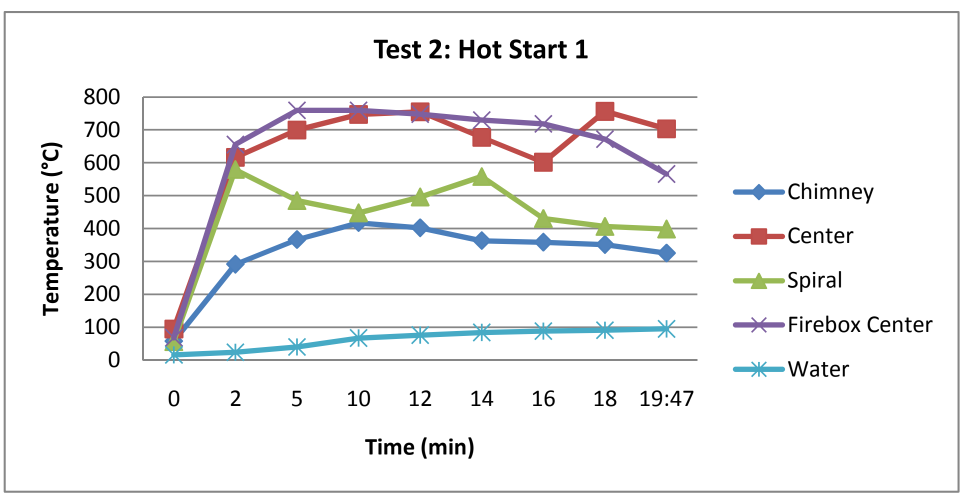
**Test 2: Cold Start - 5/1/2010 (Saturday morning)**

| | | Chimney | Center | Spiral | Firebox Center | Pot of |
|---|---|---|---|---|---|---|
| | **Time** | **3** | **4** | **5** | **6** | **Water** |
| 11:10am | 0 | | | | | 13 |
| 11:12 | 2 | 231 | 752.5 | 392.3 | 497.6 | 18 |
| 11:15 | 5 | 282.8 | 642.8 | 475.4 | 450.2 | 30 |
| 11:20 | 10 | 460.9 | 648.3 | 682.8 | 525.4 | 51 |
| 11:25 | 15 | 371.1 | 654.7 | 444.6 | 557.2 | 77 |
| 11:30 | 20 | 336.4 | 709.2 | 504.3 | 605.3 | 90 |
| 11:32 | 21:56 | 225.4 | 679.6 | 559.8 | 635.8 | 95 |

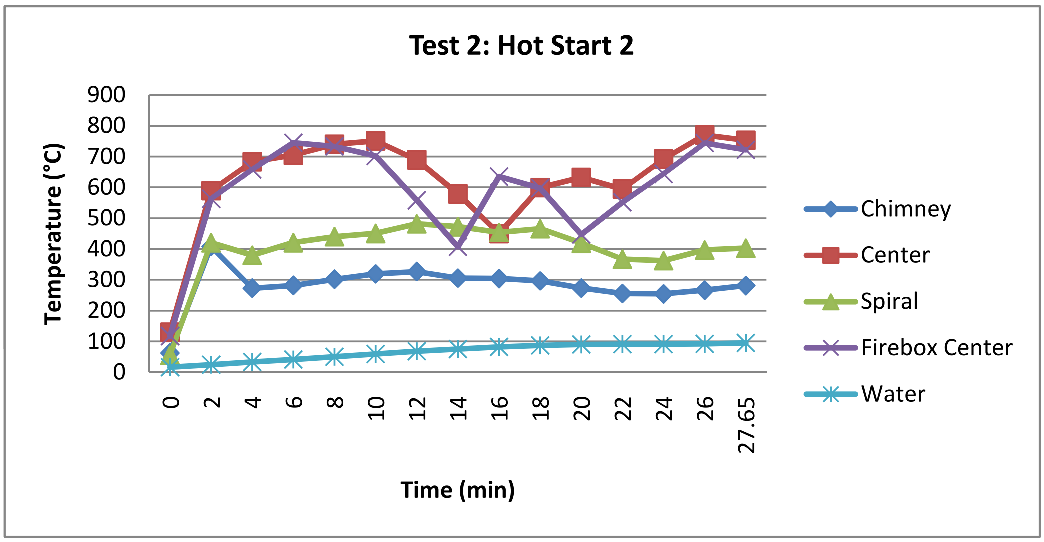



**Test 2: Hot Start 1 - 5/1/2010 (Saturday morning)**

| | | Chimney | Center | Spiral | Firebox Center | Pot of |
|---|---|---|---|---|---|---|
| | **Time** | **3** | **4** | **5** | **6** | **Water** |
| 11:56am | 0 | 57.7 | 94.5 | 56.1 | 68.0 | 16 |
| 11:58 | 2 | 291.3 | 616.7 | 579.3 | 655.3 | 24 |
| 12:01 | 5 | 366.2 | 699.3 | 484.8 | 759.4 | 40 |
| 12:06 | 10 | 417.4 | 747.1 | 447.7 | 759.2 | 67 |
| 12:08 | 12 | 402.1 | 755.2 | 495.9 | 748.1 | 76 |
| 12:10 | 14 | 362.9 | 677.3 | 557.9 | 729.7 | 84 |
| 12:12 | 16 | 358.4 | 601.6 | 430.3 | 718.3 | 88 |
| 12:14 | 18 | 351.2 | 756.3 | 406.3 | 672.0 | 91 |
| 12:15 | 19:47 | 325.1 | 703.2 | 398.4 | 565.8 | 95 |

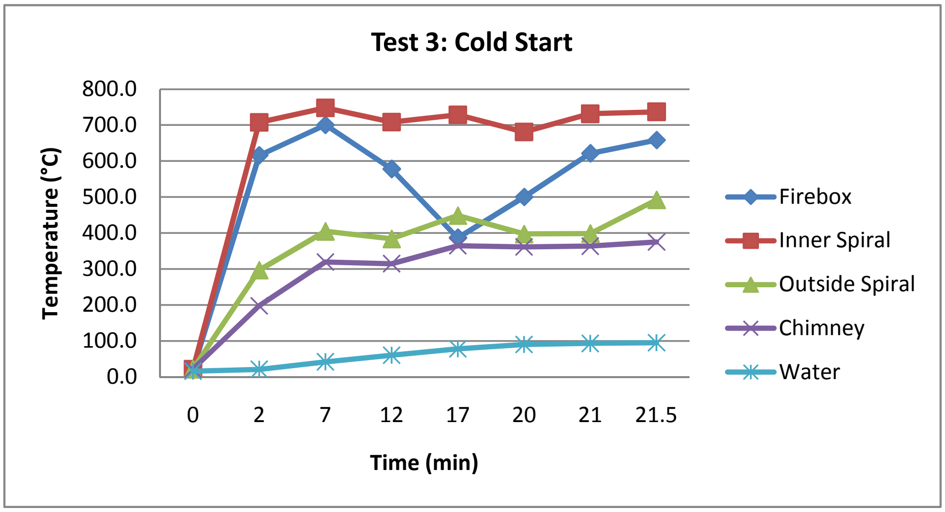


| Test 2: Hot Start 2 - 5/1/2010 (Saturday morning) | | | | | | |
|---|---|---|---|---|---|---|
| | | Chimney | Center | Spiral | Firebox Center | Pot of |
| | **Time** | **3** | **4** | **5** | **6** | **Water** |
| 12:37 | 0 | 62.5 | 129.7 | 55.5 | 117.3 | 16 |
| 12:39 | 2 | 407.8 | 589.2 | 420.4 | 563.2 | 24 |
| 12:41 | 4 | 272.8 | 683.2 | 380.1 | 658.4 | 33 |
| 12:43 | 6 | 281.9 | 704.8 | 420.9 | 745.2 | 41 |
| 12:45 | 8 | 301.8 | 740.1 | 440.4 | 732.8 | 50 |
| 12:47 | 10 | 319.3 | 751.3 | 450.8 | 702.1 | 59 |
| 12:49 | 12 | 326.6 | 689.6 | 481.9 | 558.2 | 68 |
| 12:51 | 14 | 305.4 | 579.2 | 472.7 | 407.2 | 75 |
| 12:53 | 16 | 304.1 | 449.9 | 454.1 | 634.9 | 82 |
| 12:55 | 18 | 296.4 | 599.3 | 465.8 | 598.0 | 87 |
| 12:57 | 20 | 273.1 | 632.1 | 418.7 | 447.2 | 90 |
| 12:59 | 22 | 255.5 | 595.0 | 367.2 | 551.4 | 91 |
| 1:01 | 24 | 254.3 | 691.9 | 362.3 | 643.9 | 91 |
| 1:03 | 26 | 266.2 | 769.8 | 396.8 | 743.8 | 92 |
| 1:04 | 27.65 | 281.2 | 753.2 | 402.8 | 722.2 | 95 |



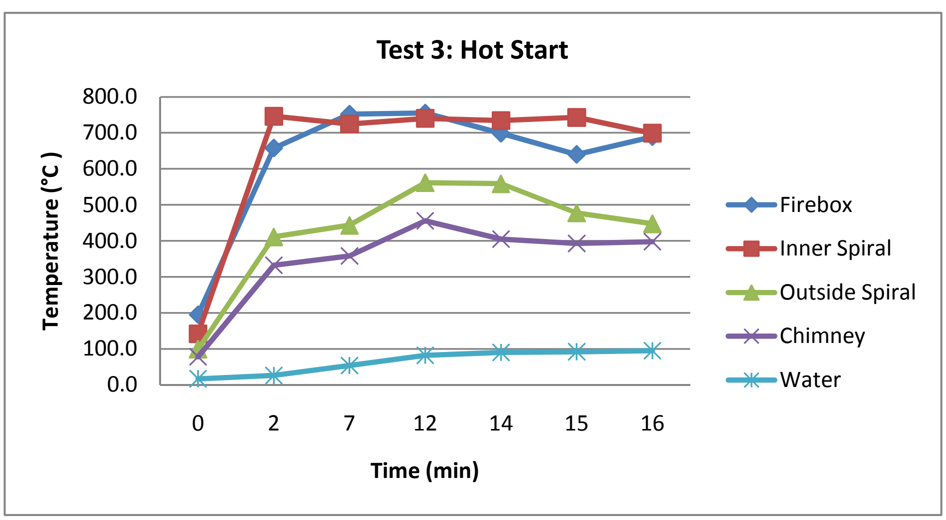
**Test 3: Cold Start - 5/3/2010 (Monday morning)**

| | Firebox | inner spiral | outside spiral | Chimney | Pot of |
|---|---|---|---|---|---|
| **Time** | **3** | **4** | **5** | **6** | **Water** |
| 0 | 21.5 | 21.6 | 21.7 | 21.3 | 16 |
| 2 | 616.0 | 707.9 | 296.7 | 197.7 | 21 |
| 7 | 700.0 | 747.8 | 404.7 | 319.3 | 42 |
| 12 | 577.9 | 708.3 | 383.7 | 314.9 | 60 |
| 17 | 386.6 | 728.4 | 448.6 | 364.7 | 78 |
| 20 | 500.1 | 680.9 | 397.3 | 361.3 | 90 |
| 21 | 621.3 | 731.5 | 398.7 | 363.4 | 93 |
| 21.5 | 658.2 | 737.1 | 492.2 | 375.0 | 95 |



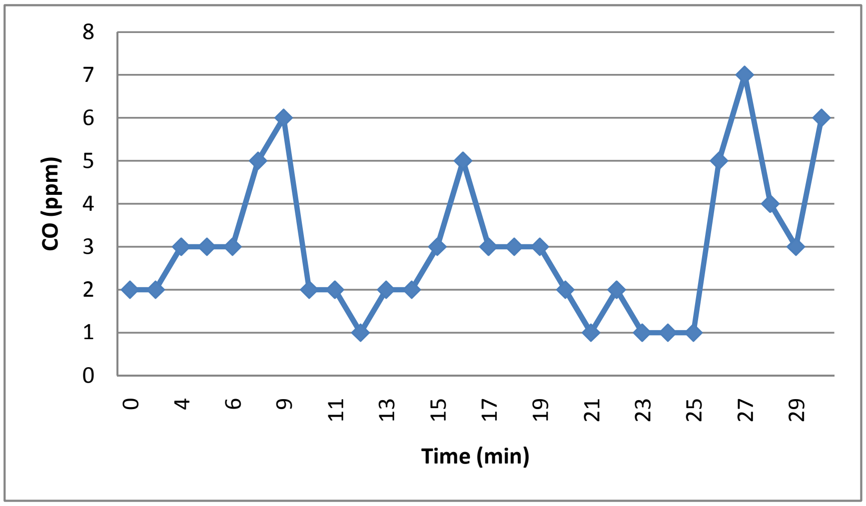

**Test 3: Hot Start - 5/3/2010 (Monday morning)**

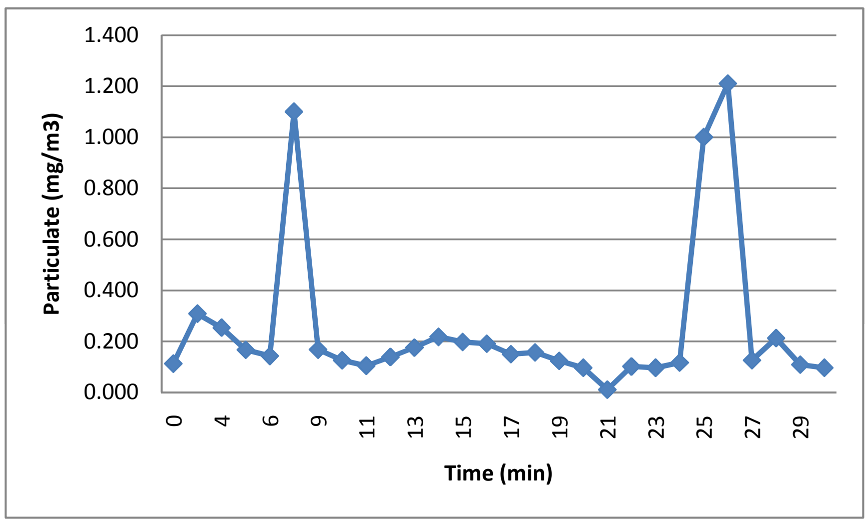
| | Firebox | inner spiral | outside spiral | Chimney | Pot of |
|---|---|---|---|---|---|
| **Time** | **3** | **4** | **5** | **6** | **Water** |
| 0 | 195.4 | 141.7 | 99.3 | 78.1 | 17 |
| 2 | 657.9 | 746.1 | 411.2 | 332.4 | 26 |
| 7 | 751.8 | 724.4 | 443.3 | 358.0 | 54 |
| 12 | 755.2 | 740.3 | 561.7 | 455.7 | 82 |
| 14 | 699.1 | 734.2 | 558.8 | 404.7 | 90 |
| 15 | 640.2 | 742.9 | 477.6 | 393.0 | 92 |
| 16 | 689.0 | 699.1 | 447.5 | 397.6 | 95 |



**Dust Tracker Data - 5/3/10 (Monday morning)**

| Time | CO (ppm) | DT (mg/m3) |
|---|---|---|
| 0 | 2 | 0.113 |
| 3 | 2 | 0.309 |
| 4 | 3 | 0.254 |
| 5 | 3 | 0.167 |
| 6 | 3 | 0.143 |
| 8 | 5 | 1.100 |
| 9 | 6 | 0.168 |
| 10 | 2 | 0.126 |
| 11 | 2 | 0.105 |
| 12 | 1 | 0.139 |
| 13 | 2 | 0.176 |
| 14 | 2 | 0.218 |
| 15 | 3 | 0.198 |
| 16 | 5 | 0.191 |
| 17 | 3 | 0.150 |
| 18 | 3 | 0.157 |
| 19 | 3 | 0.124 |
| 20 | 2 | 0.097 |
| 21 | 1 | 0.011 |
| 22 | 2 | 0.102 |
| 23 | 1 | 0.097 |
| 24 | 1 | 0.117 |
| 25 | 1 | 1.000 |
| 26 | 5 | 1.210 |
| 27 | 7 | 0.126 |
| 28 | 4 | 0.213 |
| 29 | 3 | 0.109 |
| 30 | 6 | 0.097 |



**COLD START 2** 5/1/2010

Given Parameters

| | |
|---|---|
| Local Boiling Point | 95 °C |
| Cp | 4.185 kJ/kg |
| L | 2260 kJ/kg |
| PN Energy Content | 18000 kJ/kg |

Conditions

| | |
|---|---|
| Air Temp | 25 °C |
| Outside | Warm but windy |

**EFFICIENCY DATA**

Pine Needles

| | |
|---|---|
| Mass Used | 1027 g |
| Mass Charcoal Left | 354 g |
| **NET MASS USED** | **673 g** |

Water

| | |
|---|---|
| Start Mass | 4914 g |
| End Mass | 4621 g |
| Mass Evapor. | 293 g |

| | |
|---|---|
| Start Temp | 13 °C |
| End Temp | 95 °C |
| Change in Temp | 82 °C |

**Time to Boil** **21 min 56 sec**

Efficiencies

| | |
|---|---|
| Ein | 12114 kJ |
| Eout | 2348.52 kJ |

**Efficiency** **19.39%**

**COLD START 1** 4/29/2010

Given Parameters

| | |
|---|---|
| Local Boiling Point | 95 °C |
| Cp | 4.185 kJ/kg |
| L | 2260 kJ/kg |
| PN Energy Content | 18000 kJ/kg |

Conditions

| | |
|---|---|
| Air Temp | 11 °C |
| Outside | Very cold and slightly windy |

**EFFICIENCY DATA**

Pine Needles

| | |
|---|---|
| Mass Used | 1060 g |
| Mass Charcoal Left | 218 g |
| **NET MASS USED** | **842 g** |

Water

| | |
|---|---|
| Start Mass | 4758 g |
| End Mass | 3588 g |
| Mass Evapor. | 1170 g |

| | |
|---|---|
| Start Temp | 10 °C |
| End Temp | 95 °C |
| Change in Temp | 85 °C |

**Time to Boil** **21min 30sec**

Efficiencies

| | |
|---|---|
| Ein | 15156 kJ |
| Eout | 4336.74 kJ |

**Efficiency** **28.61%**

**COLD START 3**

Given Parameters

| | |
|---|---|
| Local Boiling Point | 95 °C |
| Cp | 4.185 kJ/kg |
| L | 2260 kJ/kg |
| PN Energy Content | 18000 kJ/kg |

Conditions

| | |
|---|---|
| Air Temp | 25 °C |
| Outside | Humid, warm, no wind |

**EFFICIENCY DATA**

Pine Needles

| | |
|---|---|
| Mass Used | 801 g |
| Mass Charcoal Left | 254 g |
| **NET MASS USED** | **547 g** |

Water

| | |
|---|---|
| Start Mass | 5038 g |
| End Mass | 4764 g |
| Mass Evapor. | 274 g |

| | |
|---|---|
| Start Temp | 16 °C |
| End Temp | 95 °C |
| Change in Temp | 79 °C |

**Time to Boil** **21.5 min**

Efficiencies

| | |
|---|---|
| Ein | 9846 kJ |
| Eout | 2284.88 kJ |

**Efficiency** **23.21%**

**HOT START 2** 5/1/2010

Given Parameters

| | |
|---|---|
| Local Boiling Point | 95 °C |
| Cp | 4.185 kJ/kg |
| L | 2260 kJ/kg |
| PN Energy Content | 18000 kJ/kg |

Conditions

| | |
|---|---|
| Air Temp | 25 °C |
| Outside | Warm but windy |

**EFFICIENCY DATA**

Pine Needles

| | |
|---|---|
| Mass Used | 959 g |
| Mass Charcoal Left | 363 g |
| **NET MASS USED** | **596 g** |

Water

| | |
|---|---|
| Start Mass | 5066 g |
| End Mass | 4625 g |
| Mass Evapor. | 441 g |

| | |
|---|---|
| Start Temp | 16 °C |
| End Temp | 95 °C |
| Change in Temp | 79 °C |

**Time to Boil** **27 min 39 sec**

Efficiencies

| | |
|---|---|
| Ein | 10728 kJ |
| Eout | 2671.56 kJ |

**Efficiency** **24.90%**

**HOT START 3**

Given Parameters

| | |
|---|---|
| Local Boiling Point | 95 °C |
| Cp | 4.185 kJ/kg |
| L | 2260 kJ/kg |
| PN Energy Content | 18000 kJ/kg |

Conditions

| | |
|---|---|
| Air Temp | 25 °C |
| Outside | Humid, warm, no wind |

**EFFICIENCY DATA**

Pine Needles

| | |
|---|---|
| Mass Used | 969 g |
| Mass Charcoal Left | 385 g |
| **NET MASS USED** | **584 g** |

Water

| | |
|---|---|
| Start Mass | 5047 g |
| End Mass | 4821 g |
| Mass Evapor. | 226 g |

| | |
|---|---|
| Start Temp | 17 °C |
| End Temp | 95 °C |
| Change in Temp | 78 °C |

**Time to Boil** **16 min**

Efficiencies

| | |
|---|---|
| Ein | 10512 kJ |
| Eout | 2158.25 kJ |

**Efficiency** **20.53%**

**HOT START 1** 5/1/2010

Given Parameters

| | |
|---|---|
| Local Boiling Point | 95 °C |
| Cp | 4.185 kJ/kg |
| L | 2260 kJ/kg |
| PN Energy Content | 18000 kJ/kg |

Conditions

| | |
|---|---|
| Air Temp | 25 °C |
| Outside | Warm but windy |

**EFFICIENCY DATA**

Pine Needles

| | |
|---|---|
| Mass Used | 987 g |
| Mass Charcoal Left | 393 g |
| **NET MASS USED** | **594 g** |

Water

| | |
|---|---|
| Start Mass | 5052 g |
| End Mass | 4748 g |
| Mass Evapor. | 304 g |

| | |
|---|---|
| Start Temp | 16 °C |
| End Temp | 95 °C |
| Change in Temp | 79 °C |

**Time to Boil** **19 min 47 sec**

Efficiencies

| | |
|---|---|
| Ein | 10692 kJ |
| Eout | 2357.31 kJ |

**Efficiency** **22.05%**

EC.720J / 2.722J D-Lab II: Design
Spring 2010