Large Scale Analysis of Pit Fire Geometry

A Major Qualifying Project Submitted to the Faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree in Bachelor of Science in Mechanical Engineering and Chemical Engineering

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Introduction

In today's world, there is a significant amount of household waste generated each day. This waste contains food waste, packaging, old clothing, construction waste, and anything else that has been discarded (Nathanson, 2019). The quantity of waste generated varies greatly across world regions; in Canada it amounts to almost six pounds per person per day, while in developing countries it can be as low as one pound per day (Nathanson, 2019). In the United States, this trash is generally sent to landfills (EPA, 2019). In Sweden, garbage is incinerated to generate electricity in facilities with carefully regulated emissions (Yee, 2018). However, in areas of the world where there are little to no waste management systems in place, burning garbage in open outdoor fires is a common alternative (Wibbenmeyer, 2003). By burning garbage, the volume is reduced by up to 90 percent, significantly reducing the resources needed for disposal (Kirby, 1993). Due to this effectiveness, it is estimated that up to half of the garbage generated each year is burned (Hodzic, 2012). Burning of trash generates a lot of toxic smoke which contributes to worldwide environmental impacts (Hodzic, 2012) and it is also an immediate health hazard to those tending the fire, often resulting in burn injuries and inhalation of dangerous particulates (Woodall, 2012).

Research and small-scale tests have indicated that the combustion of these fires can be improved through burning the garbage in pits with an optimized geometry (Kimmerly, 2019). In order to further investigate the potential to create a cleaner way to burn trash, these small-scale tests must be scaled up to determine how benefits scale up with fire size. Potential benefits to burning trash in a pit instead of on open ground include reductions of burn injuries as the fire is contained in the pit, increased burning rate which would lead to less exposure to harmful smoke, and an increase in burn efficiency which would reduce the amount of harmful particulates in the smoke (Kimmerly, 2019). The goal of our project is to create a large-scale experimental set-up to effectively investigate if the positive effects of pit geometry persist as the fire is scaled up.

Background

Open air trash fires are heavily polluting to the environment and are unsafe for the person tending the fire. The goal of this research is to provide a free, easy, and effective way to make these fires more efficient, safer, and otherwise reduce the negative impacts of burning trash. The goal of this project is to design and build the setup and instrumentation for a larger scale test of the preliminary research for the effects of pit geometry on fire efficiency.

The pit fire is different from a ground fire in several ways. One of those ways is how the ground surrounding the pit changes the airflow into the pit. This air flow can be modeled as a backwards facing step. As seen in Figure 2, air coming over the edge of a backwards facing step creates a pocket of circulating air. There has not been significant research done to investigate the airflow effects of air flow into a pit, but there should be significant turbulent circulation within the pit. This circulation should, in theory, create better mixing between the air and the fuel, increasing the efficiency of the fire. This phenomenon has been noted in several pit fire experiments as depth is changed (Kimmerly, 2019). Our experiment was designed to test different pit depths, known as ullages, to explore changes in burning behavior. Ullage is defined as the distance from the top of the fuel to the opening in the "ground", as seen in Equation 1.

$$Ullage = \frac{Diameter}{Depth}$$

Equation 1

Where:

- Diameter is the diameter of the pit, and
- Depth is the distance from the ground to the surface of the fuel from the top of the fuel to the opening in the "ground".

We can also see from Figure 2 that the air flow approaching the backwards facing step is a well developed laminar flow. In order to develop the airflow in our experiment, we designed a square platform made from drywall that surrounds the experimental burn pit on all sides. The platform extends a minimum of 1 diameter. This is because the air must have room to develop flow but not become so turbulent so that it cannot experience the backwards step. This also creates a better model of the real-world application because the ground around a pit dug into dirt functionally acts as a semi-infinite plane.

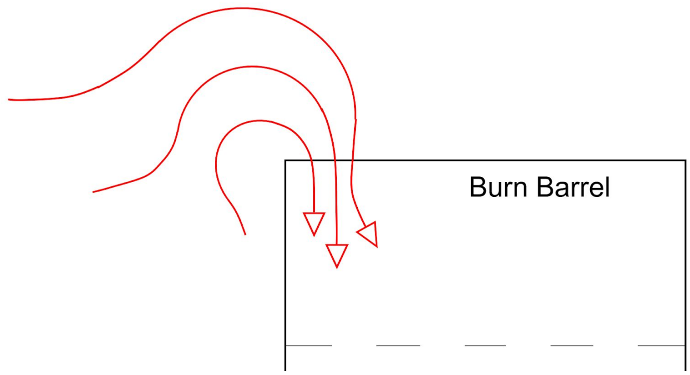

Figure 1: Air Flow into the Burn Barrel without Experimental Ground

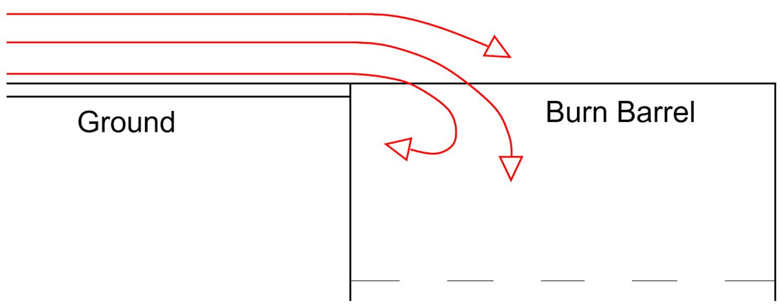

Figure 2: Air Flow into the Burn Barrel with Experimental Ground Demonstrating Flow Over a Backwards Facing Step

The purpose of the "ground" in the experimental set up is to create an air flow pattern that is characteristic of one found for a pit that is dug into the ground. Figure 1 above shows the flow of air into the barrel if there no experimental ground was constructed to develop the airflow. Figure 2 is the flow of air into the barrel with the experimental ground. This air flow is much more representative to one that would be found in a pit fire. The flow of air over our experimental ground can be modeled as flow over a flat plate. According to an aerodynamics study conducted in the California State University of Long Beach wind tunnel, the Reynolds

Number for the flow of air over a flat plate can be calculated using Equation 2 below (Gemba, 2007).

$$Re_\infty = \frac{\rho U_\infty L}{\mu} = \frac{U_\infty L}{\nu}$$

Equation 2

Where:

- Re is the Reynolds Number
- ρ is the density of the fluid
- U is the fluid velocity
- L is the length of the flat plate
- μ is the dynamic viscosity
- *v* is the kinematic viscosity

In the California State University of Long Beach's wind tunnel experiment, they found that the flow transition from laminar flow to turbulent flow occurred at roughly one meter from the edge of the flat plate (Gemba, 2007). The air velocity used in their experiment is 19.1 meters per second, or approximately 43 miles per hour. We can assume that the entrainment rate for our fire is less than 43 miles per hour, which is a very reasonable assumption. Under these conditions, we know that with an experimental ground that extends approximately one meter from the fire on all sides, the airflow will be laminar when it reaches the edge of the barrel. Our constructed ground, as shown in Figure 3, meets these requirements.

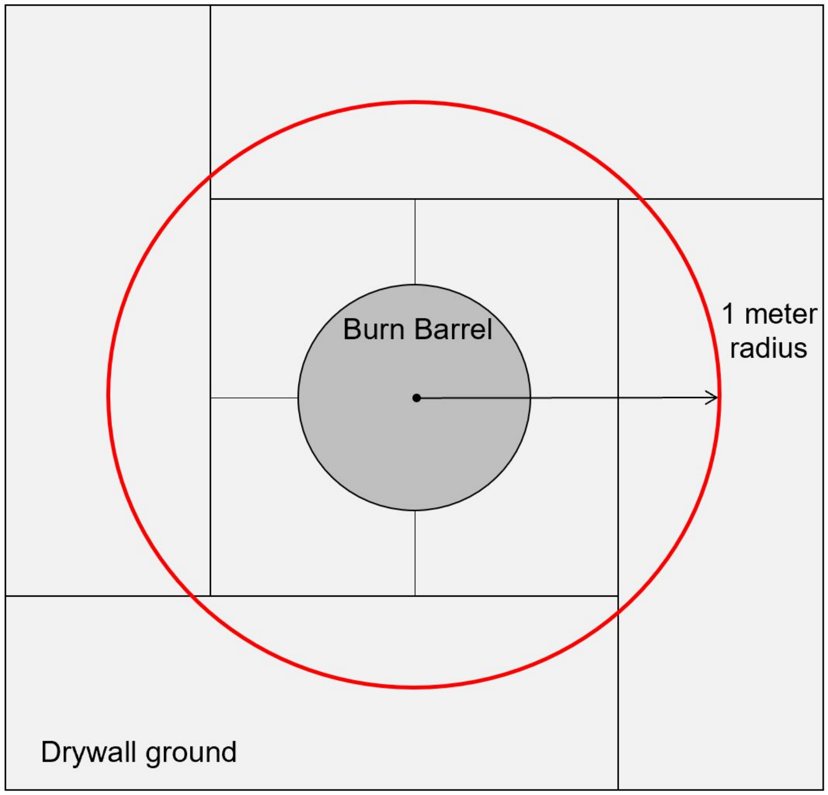

Figure 3: One Meter Radius Shown On Experimental Ground

Maximizing fire efficiency leads to both the fuel burning more quickly and at a higher temperature. By burning the fuel at a faster rate, the person tending the fire is exposed to the fumes for less time. Drysdale states that the dose is the important part in determining the toxicity of gasses, which can be expressed in terms of concentration and time (Drysdale, 2011). According to a study done by the World Bank's Urban Development Series, "Open-burning of waste is particularly discouraged due to severe air pollution associated with low temperature combustion." (Hoornweg, 2012). Small-scale research suggests that putting fire in a pit increases fire efficiency by increasing burn rate and burn temperature (Kimmerly, 2019).

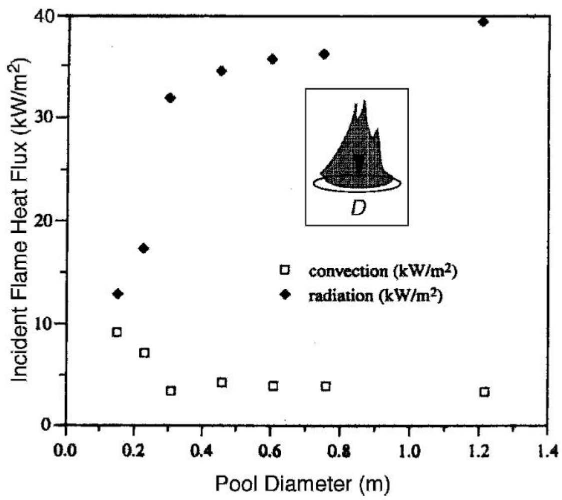

Figure 4: Incident Flame Heat Flux vs. Pool Diameter (Quintinere, 2006)

These small-scale tests do not fully and accurately represent a large scale fire, however. Figure 4 shows the incident flame heat flux as a function of pool diameter. A jump is seen at about 0.3 meters, showing a distinct gap in the heat lost by radiation of the fire with regards to fire size. In other words, the results of a small-scale test do not necessarily predict results on a larger scale because the heat flux from radiation increases at a very high rate compared to the increase in pool diameter. However, as shown in Figure 4 the incident flame heat flux levels out around 0.5 meters and does not increase significantly afterwards. To model a large-scale application we will be using a test pit with a diameter greater than 0.5 meters.

Methods

Materials

Materials for this project were sourced from a variety of vendors. For a detailed breakdown of materials, quantity, and source, please refer to Appendix 2.

Fuel Type

We chose to use kerosene as the test fuel. It is a low volatility hydrocarbon, meaning that it stays a liquid at room temperature, not allowing for gas clouds to form. It also does not burn very cleanly, and instead has a sooty, dirty flame (Fingas, 2016). This more accurately models the real-world equivalent of a solid fuel that does not burn cleanly. Most notably, kerosene is approved for use in large quantities in the WPI Performance Engineering Laboratory and is significantly cheaper and easier to acquire than fuels with similar properties, such as heptane.

We predicted fuel consumption for all trials before testing using a regression rate of 4 millimeters per minute. This number is based on previous experimental data. We conducted 6 burns that lasted approximately 15 minutes each (see "Experimental Process"), for a total of 90 minutes of burn time. With a safety factor of 1.25 to account for test trials, and an estimated 20 gallons needed throughout the system to maintain ullage in the final test, we found that we would require approximately 55 gallons of fuel. We purchased a total of 60 gallons.

The Ground

The ground is constructed from drywall. The drywall is set up in two portions consisting of an inner and outer ring. As drywall is exposed to heat it crumbles, so the inner ring that was exposed to the most heat was designed to be easily replaced in between experiments. This allowed us to maintain a simulated air flow along the ground for each experiment, while also minimizing the amount of material that was replaced each experiment. We constructed a frame of 8020 aluminum to hold the drywall, seen in Figure 5.

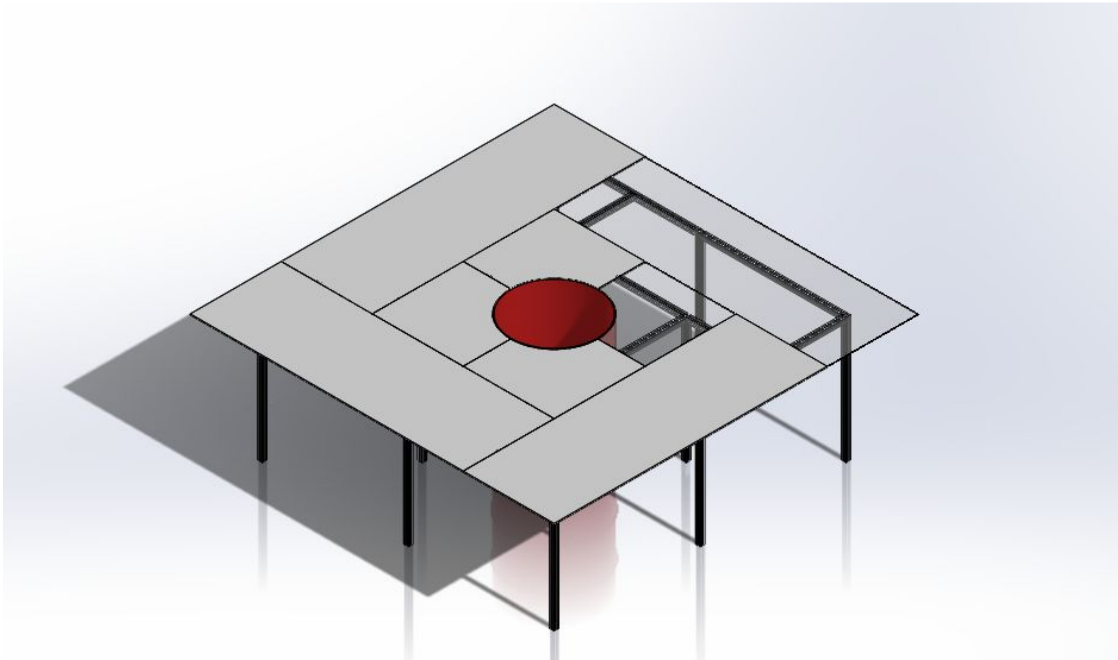

Figure 5: 8020 and Drywall Ground Diagram

Barrels

To create our Burn Pit, we used a 55-gallon steel drum. The drum is prefabricated, water-tight, and falls within the geometry requirements for our experimental pit. According to our given design specifications, the large scale test should be larger than 30 centimeters in diameter. The 55-gallon steel drum meets that requirement at 57.3 centimeters in diameter. Additionally, the drum's geometry allows testing of ullages up to 1.25 times the diameter. In initial small scale testing the optimized ullage fell between 0.75D and 1D (Kimmerly, 2019). With this prefabricated drum we can explore a range of ullages above and below this range. The drum additionally had prefabricated threaded holes 4 inches from the bottom, which we used for our fuel system. This reduced the number of holes we had to cut into the barrel to one. We insulated our burn pit with several layers of kaowool insulation. The kaowool insulation mimics the insulation that dirt would provide for a pit fire in the ground. A picture of the barrels used can be seen in Figure 6.

Figure 6: Middle and Reserve Barrels During Water Testing

Constantly Replenishing System

In this experiment, we test burning behavior at different ullages. As a liquid fuel burns, the level of the fuel lowers. That would cause the experiment to have a dynamic ullage for every trial, and this regression rate would change depending on the fire behavior and fuel consumption rate. In order to remedy this problem, we utilized a Constantly Replenishing System (CRS). Shown below in Figure 7, the CRS is made of three fuel reservoirs. The first reservoir is the "Burn Pit." It is explained in greater detail in the following section. The fuel level in the Burn Pit is maintained by the second reservoir, the "Middle Barrel", also referred to as the "Level Maintaining Barrel". The Middle Barrel has fuel entering from a peristaltic pump. It has fuel exiting from both an overflow pipe, and a pipe that feeds to the Burn Pit. The overflow pipe ensures that the fuel level in the Middle Barrel remains constant, as any fuel above this level will drain through the overflow pipe to the Reserve Barrel. The pipe between the Middle Barrel and the Burn Pit controls the ullage in the Burn Pit.

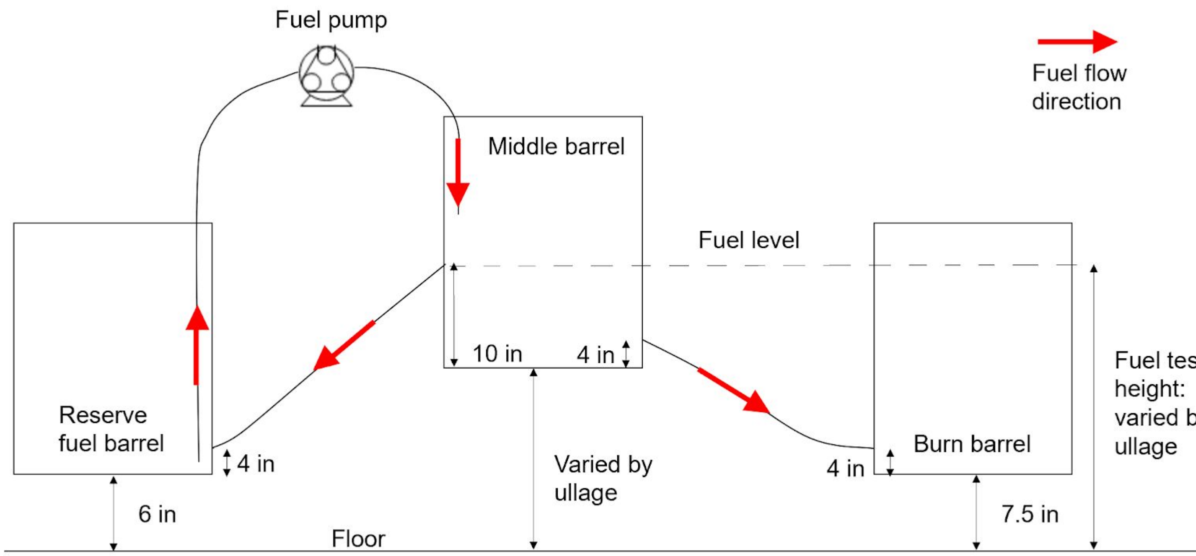

Figure7: Constantly Replenishing System (CRS) Diagram

The third and final reservoir is the Reserve Barrel. The overflow pipe from the Middle Barrel adds fuel to this reservoir, and the peristaltic pump removes fuel to be pumped into the Middle Barrel. We put a scale under the Reserve Barrel to measure the mass loss rate of the system. The Middle and Reserve Barrels, along with the pump and scale can be seen in action in Figure 8. Together, the three reservoirs and the pump maintain the system equilibrium.

Figure 8: Constantly Replenishing System at Ullage 0.75D

Incremental Testing

The 55-gallon drums being water tight is a large asset to our experiment. It would be detrimental to our graduation if we were to spill several gallons of burning kerosene on the floor of the WPI Performance Engineering Laboratory. In order to avoid that event, the input hose for the tank was carefully designed and attached to reduce the chance of leakage. During assembly of our experimental setup we tested for leaks using water. We also tested the 8020 frame for strength and stability to ensure that it could safely hold the drywall for the full extent of the testing.

After construction of the Constantly Replenishing System, it was tested with water. This allowed us to check for leaks and to test the functionality of the system without using any flammable elements. All weak connection points were sealed at this time. Additionally, the flow rate into the burn barrel was tested to ensure that it was sufficient to replace fuel at the rate it would be burnt. Finally, before starting test burns, we tested the process to achieve equilibrium for the kerosene level. This process was carefully monitored to ensure the fuel levels were as expected.

Experimental Process

Our first test was done at an ullage of 0 and was performed with a shallow pan in place of the CRS. A fire of this ullege is known as a "pool fire." Pool fires are well studied and predictable. Because pool fires are so well studied, this allowed us to treat the 0 ullage burn as a calibration burn. This test confirmed that the instrumentation, ground system, and extinguishing system worked as planned. It also confirmed our estimated fuel consumption rate. After the successful 0 ullage pool fire, we replaced the shallow pan with the CRS and moved to testing the next ullege.

Our next test was of the ullage of 0.25. At this ullage, the fuel in the barrel was 0.15 meters below the constructed drywall ground. We calibrated the fuel level in this system by elevating our Middle Barrel to a 0.65 meter height, and adjusting the lower thermocouple array to the fuel level within the barrel. At this point, all safety checks were performed, and the fire was lit. Once the fire reached a steady state, three sets of data were collected. This trial was allowed to burn for a total of approximately 15 minutes before extinguishment. The barrel was then allowed to cool for at least an hour before the system was adjusted to the next ullage.

Insulation

We wrapped several layers of kaowool insulation around the outside of the pit to simulate the insulation being underground would provide, as shown in Figure 9. This allowed us to model the pit walls as adiabatic, which is similar to how the walls of a dirt pit would behave. This assumption gave us the ability to apply these results to a wider range of real-life applications than if we did not insulate the ground. The insulation was shown to be effective, as shown in Figure 10.

Figure 9: Burn Barrel Wrapped in Kaowool Insulation

Figure 10: Glowing Steel Barrel Underneath Kaowool Insulation

Data Collection

Thermocouple tree

The bulk of our data was collected through two arrays of thermocouples. The upper array contains 24 K-type 32 gauge chromel-alumel thermocouples suspended above the pit. The array was positioned above the barrel as shown in Figures 11 and 12. This thermocouple array indicates flame behavior through region above the burn barrel. This array was supported by tensioned wires both above and below the thermocouples.

Figure 11: Upper Thermocouple Array

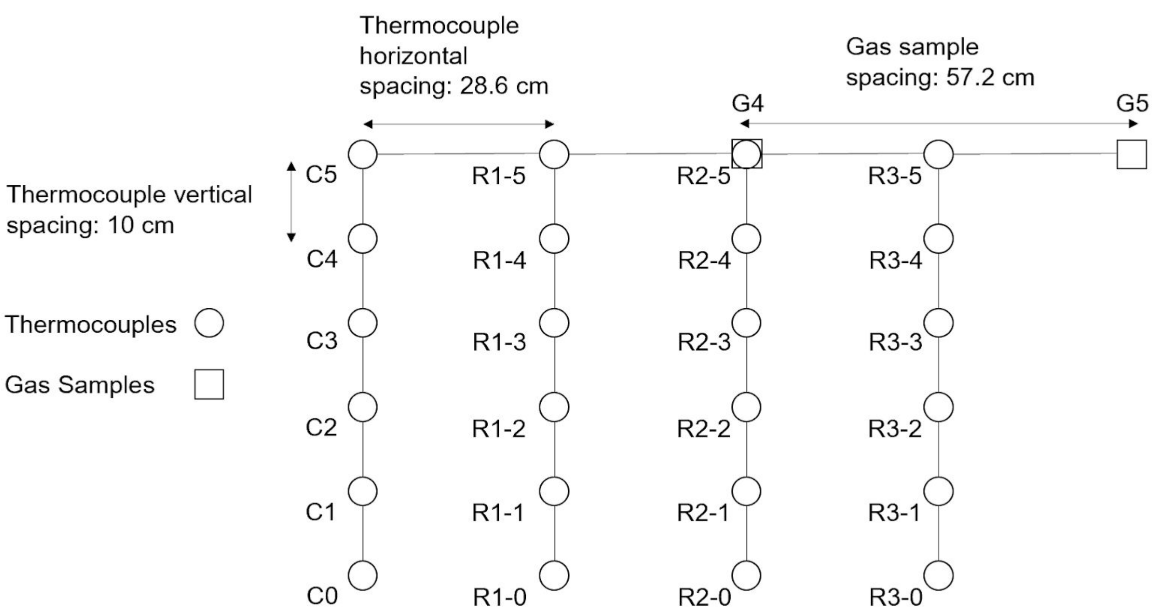

Figure 12: Upper Thermocouple Array Diagram

The lower array was mounted within the barrel and contains 8 K-type 32 gauge chromel-alumel thermocouples. These thermocouples were secured to the inside wall of our steel drum using Aluminum Tape, as seen in Figures 13. The group of thermocouples was stacked with 1 cm vertical spacing. Two thermocouples were submerged and the rest were above the fuel level, as shown in Figure 14.They were adjusted to each tested fuel level. During tests we recorded data at a sample rate of one hertz. The full instrumentation setup can be seen in Figure 15.

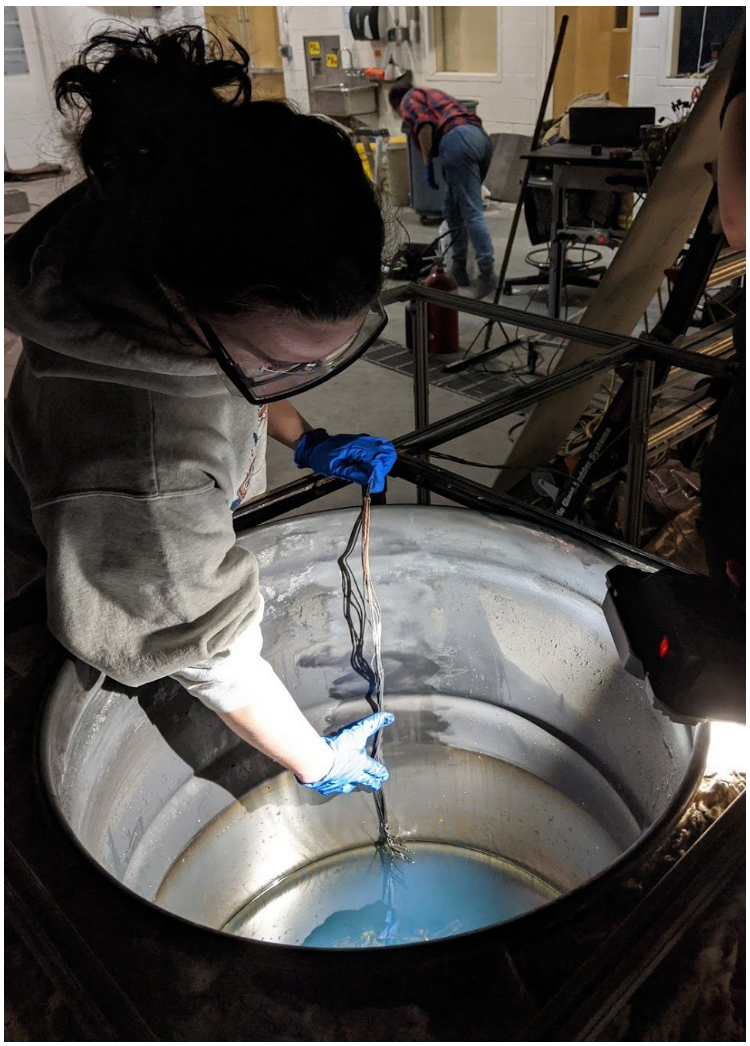

Figure 13: Lower Thermocouple Array Being Placed

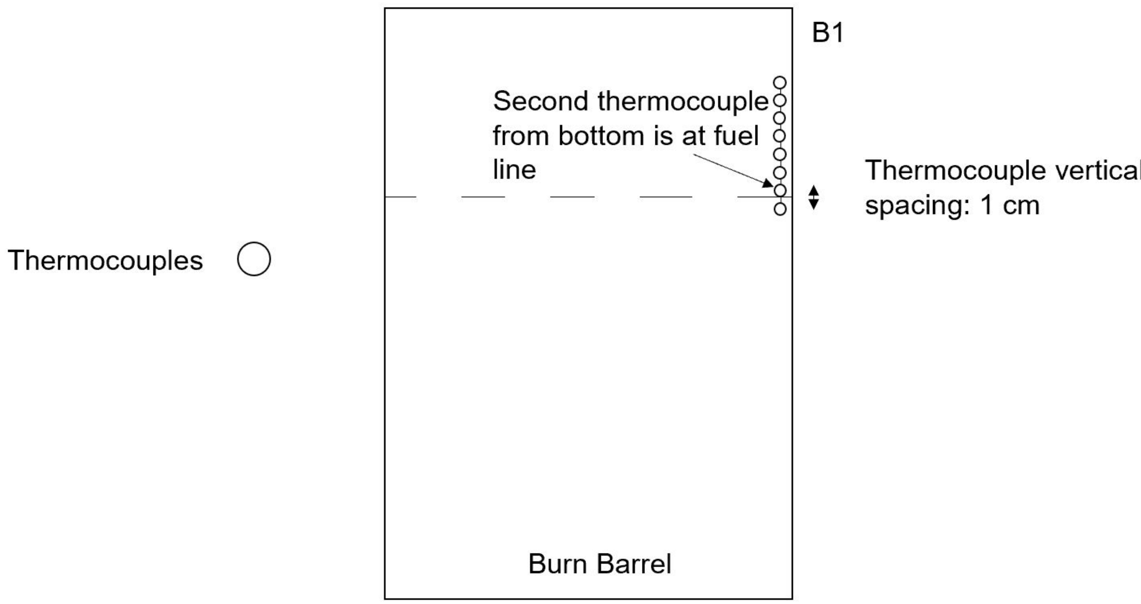

Figure 14: Lower Thermocouple Array Inside Burn Barrel

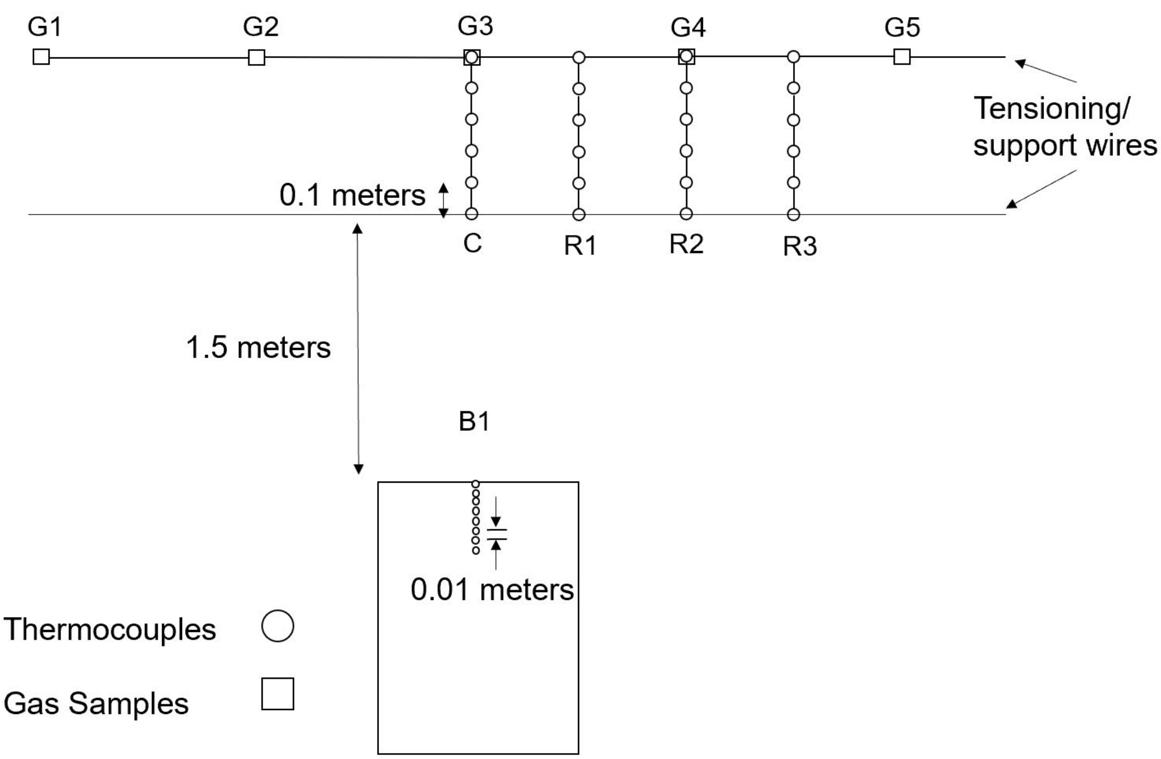

Figure 15: Full Instrumentation Setup Diagram

Imaging

We filmed our burn tests to get visual data on flame height and shape. We chose to film our burns from 2 different positions to get different perspectives while protecting the camera from heat and soot. One camera was mounted roughly fifteen feet high. This camera observed the fire from an overhead angle. The second camera was mounted to be even with the fabricated ground. This camera observed the flame height above the fabricated ground, as well as the flame shape. A view from each camera can be seen below in Figure 16 and 17.

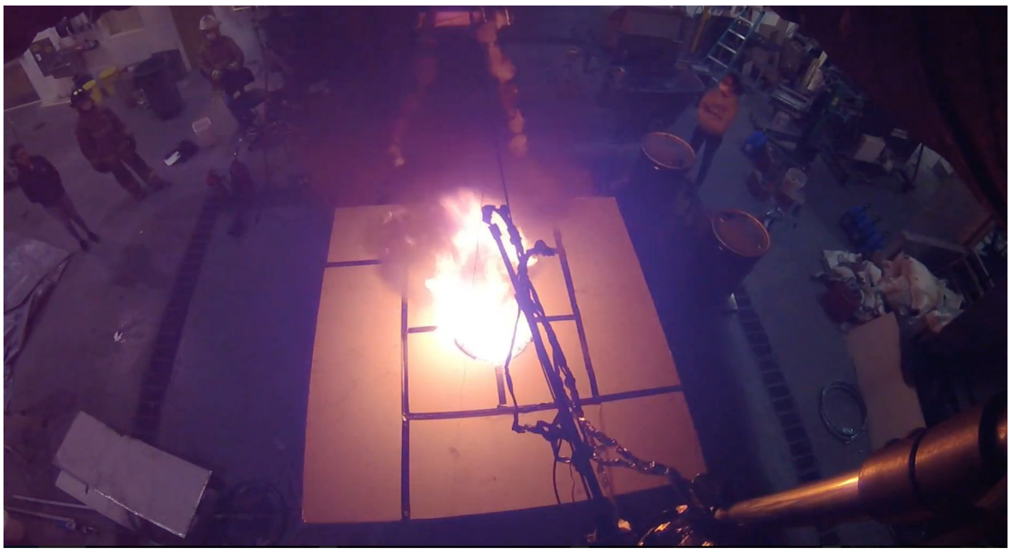

Figure 16: View From the Angled Overhead Camera

Figure 17: View From Camera at “Ground” Level

Gas Sampling

We considered collecting data on a gas analysis of the smoke put off by the fire during tests. This would have allowed us to see how the carbon monoxide, carbon dioxide, and other gas levels changed with ullage to evaluate the potential impact on the environment. However, the WPI Performance Engineering Laboratory was built with some inherent flaws that make gas sampling inaccurate. The exhaust pipes are significantly too short for laminar airflow to develop after smoke and fumes are removed via the large fume hood. This means that any samples taken are not a representative sample of the average composition of the airflow. The most accurate data readings have a margin of error of ± 40% as reported by the lab manager. This is too large of an uncertainty to functionally use this data to draw conclusions.

Under further consideration, we determined that gas sampling would not add much substance to the data regardless of accuracy. While it is a goal to reduce carbon monoxide percentage in the smoke, the overall exposure to fumes from standard daily operations such as cooking or being near running vehicles is a much greater risk to those affected by open-air trash fires (DeMarini, 2019). The goal of improving burn pit efficiency is more relevant and impactful when considering reducing the risk of bodily harm to the people tending the fire. Because of this, we chose to focus our efforts into other forms of data collection.

Our experiment was used as a preliminary test for a different method of gas sampling from various point sources. These sensors will be used in future testing by a PhD candidate, and were being tested for heat and soot tolerance. Five CO and CO_2 point sensors were mounted at increments of one diameter on the thermocouple suspension wire, as shown in Figure 15, above. However, the collected data will not be used for analysis of the setup.

Safety design

Due to the inherent risk of a fire scale-up experiment, safety was a major concern when designing our tests. We each did training in general lab safety and procedures through WPI Environmental Health and Safety as well as a lab-specific safety training through the Salisbury Combustion Lab and the Performance Engineering Laboratory. During each test, we had two people in turnout gear, as shown in Figure 18 below, a inch and a half diameter fire hose, a supervising lab manager, and several fire extinguishers in easy access points around the lab.

Figure 18: Turnout Gear in Use

Other elements of safety design are the features that reduced risk of an uncontrolled burn. After every test, we smothered the fire by pushing a piece of drywall over the top of the pit. This method allowed us to put out the fire while remaining a safe distance away from the flame. We also reduced the amount of fuel in the system by backfilling the bottom of the burn barrel with weighted buckets. To contain any potential spills, a tarp was spread underneath the whole system and a ring of granular sorbent was spread around the Burn Barrel. To remove the risk of the tubing between barrels melting, they were insulated in kaowool to protect them from the heat.

Results and Discussion

Instrumentation

The upper thermocouple array provided reasonable data through the entirety of the testing period. Sample data can be found later in this section. In the lower array, we lost one thermocouple to high temperatures within the barrel.

The video data was distinct and clearly showed flame height and shape, as seen in Figure 19. The overhead feed did not provide much substance to supporting the effects of depth on flame shape and height, but did show the relative symmetry of the fires and the sooty, dirty plume clearly, as seen in Figure 20.

Figure 19: Still from the Ground Level Video

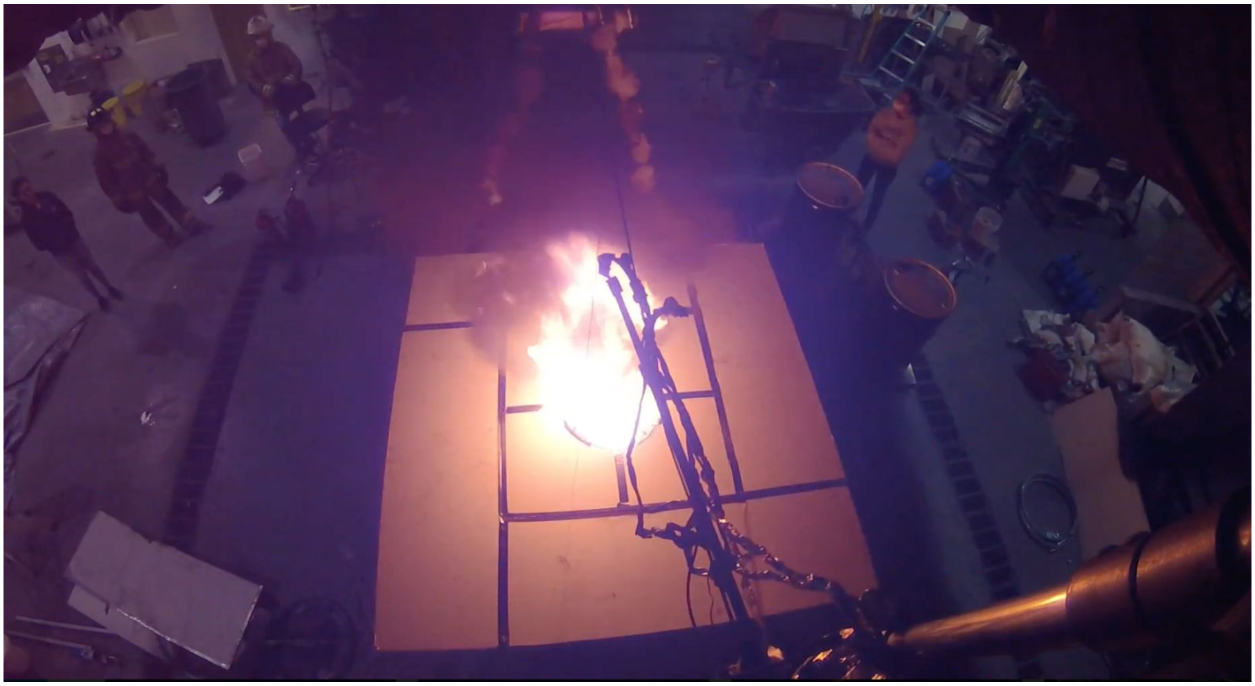

Figure 20: Still From the Angled Vertical Video

Overall, the quality of the data from the instrumentation varied by data collection method. The mass loss data is very inaccurate, due to the cyclical nature of the system discussed later in this section. The thermocouple data provided data that was consistent with the spacing and type of fire, and held up through all trials. The video data showed clearly the flame shape and height throughout the trials. Overall, the instrumentation design held up as expected through the entire testing period.

Ground

The ground was constructed with no significant adjustments to the original design. Our only edit to the original design was that we added additional supports to the legs to maintain stability during tests. Figure 21, below, shows a view of the ground in both the original design file and as constructed. These photos were taken before the pool fire test, which used a slightly smaller diameter pan, with the gap packed with kaowool. In all other trials, the edge of the drywall sat directly on top of the edges of the barrel.

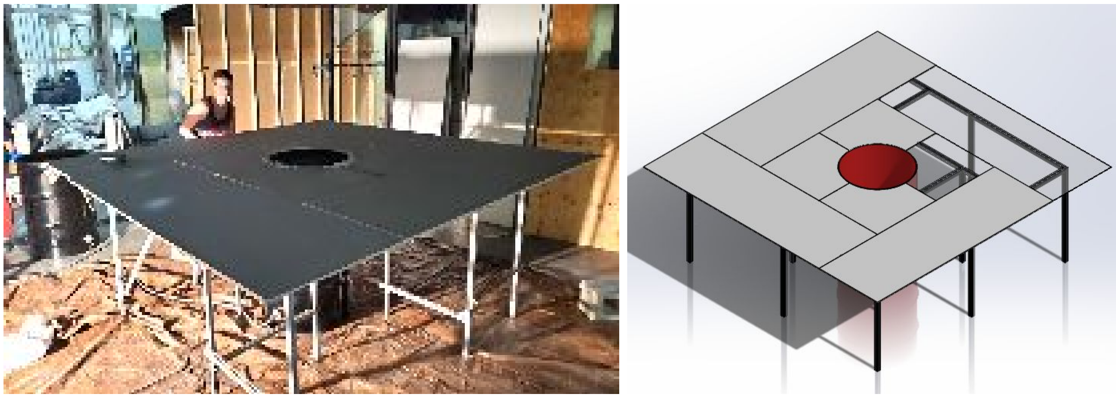

Figure 21: Models of Ground Compared to Fabricated Ground

As expected, the drywall on the inner circle crumbled at a much faster rate than the outside panels. We replaced these inner panels after every test. Only one of the outside panels had to be replaced, as the paper backing caught on fire during extinguishing. Figure 22, below, shows how the inner panels crumbled when removed after one of the tests. They maintained integrity before being moved, and did not crumble during the tests, maintaining a flat plane through the full test. This crumbling did, however, prove to be a major challenge when attempting to extinguish the fire. When we moved the cover over the top of the fire to smother it, the cover would break parts of the drywall off. The crumbled panels then created large gaps, which allowed air beneath the cover.

Figure 22: Charing of the Innermost Ground Panels, Post-Burn

We sealed the edges of the pit at the interface with the ground and the seams between panels with aluminum tape, shown in Figure 23. Similar to the inner panels, the tape maintained its seal despite heat damage until we tried to extinguish the fire, at which point it fell apart. Behind the tape, we packed the gap between the frame, drywall, and barrel with kaowool to help prevent drafts if the tape were to fail mid-test. This also helped to maintain a consistent wall condition.

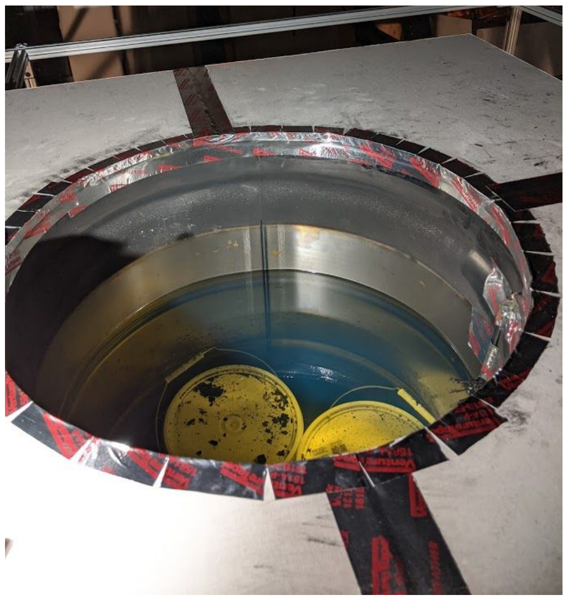

Figure 23: Seams Sealed with Aluminum Tape

Replenishing Pool

The constantly replenishing pool was constructed as shown below in Figure 24. The barrels were connected with high temperature kerosene safe half inch tubing, except for the line running through the pump, which used 5/16” polyurethane tubing.

Figure 24: Constantly Replenishing System In Use

The flow between the middle barrel (right in Figure 24) and the reserve barrel (left in Figure 24) was not consistent, meaning that the fuel level in the middle barrel fluctuated slightly over time. This did not affect the level in the burn barrel because the flow between those two barrels was relatively slow, but it did cause a significant amount of error in the mass loss data, seen in Figure 25 below.

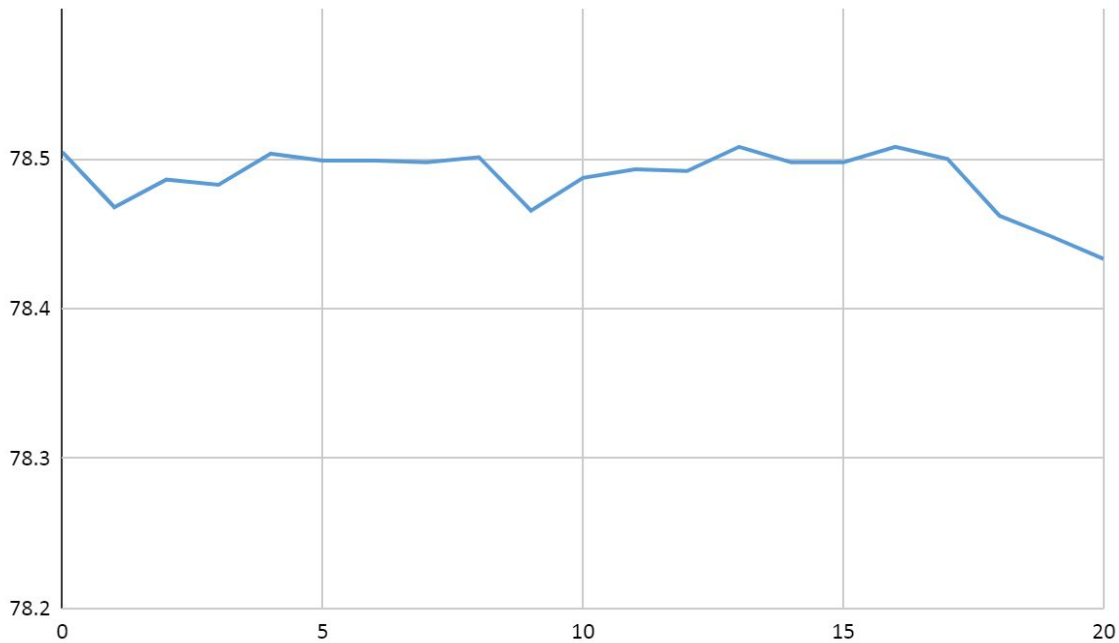

Figure 25: Mass Loss Data Graph From 0.5 Ullage Trial

This could have been fixed by using stiffer tubing between barrels. This cyclical pattern was caused by the tubing collapsing, getting enough back pressure to refill, draining, then collapsing again. By using stiffer tubing or larger tubing, we could have prevented the tubing from collapsing in the first place. We also had to remove the cutoff valve between the middle barrel and the burn barrel because it was limiting the flow too much to keep up with the required regression rate for the fuel. Despite these flaws, the system kept the flow between barrels very laminar in nature, maintaining very still, even surfaces and limited mixing of the fuel in the burn barrel.

To make sure the constantly replenishing pool system would be able to keep up with the expected regression rate even at the lowest ullage, we tested the system thoroughly with water. We allowed the system to reach equilibrium, then removed about 8 gallons of water from the system, dropping the water level in the burn barrel significantly. The system replenished at a rate of approximately 4.5 mm per minute, which was considered enough to keep up with the expected regression rate of 4 mm per minute. The theoretical maximum regression rate increased as the ullage decreased, because the potential between the barrels was higher.

Start-up and Shutdown

To maintain safe distance while lighting the fire, we attached a propane torch to a long rod, seen in Figure 26. Depending on the trial, it took between 15 to 45 seconds of holding the flame against the liquid surface and slowly "stirring" the flame around to heat the kerosene to its ignition temperature.

Figure 26: Ignition Torch

Once ignited, it took approximately 5 minutes to reach a thermal pseudo-steady state. The initial plan was to extinguish and re-ignite the fire after each trial, but after the first test, a simple pool fire (ullage of 0), we chose to instead leave the fire burning and collect data for at several different intervals during the burn. The first test showed that the extinguishment and re-ignition of the fire did not make any observable difference in the collected data, except for needing more time per trial to make sure the system was at thermal steady state. It also disturbed the drywall and tape around the edges of the barrel, opening holes for air to come up from underneath the ground surface. This broke the ground-developed flow we were hoping to achieve. Extinguishing and re-igniting the fire for each trial was also a safety concern, as it required us to interact with the fire more often. By modifying the tests to be a single ignition for each ullage, we created a more accurate data collection period and minimized experimental risk.

Extinguishing the fire was more challenging than expected. We had two extinguishing methods: the lid of the barrel attached to a rod, and sheets of drywall. We initially tried to use the lid of the barrel on the pole. The lid is a perfect fit for the top of the barrel, which should have correlated to a good seal when trying to smother the fire. It is also made of steel, which would have allowed heat to escape without letting air in. However, the drywall around the edge of the barrel crumbled and left large gaps between the edge of the lid and the top of the barrel, allowing air to continue fueling the fire. We instead used sheets of drywall to cover the opening of the barrel. These were much wider than the opening of the barrel, allowing for a better seal to be made between the ground, the barrel, and the air.

Even once we had established the more effective method of smothering the fire, we had significant trouble extinguishing the fire, especially at high ulleges. In high ulleges, more of the barrel was filled with air. This meant more oxygen was left inside the sealed barrel to fuel the fire. The walls of the barrel were also extremely hot, keeping heat in the system and encouraging the kerosene to vaporize and re-ignite. At the lowest depths, we displaced the air in the barrel with nitrogen from the building's nitrogen supply to help encourage the fire to go out. After we were confident that the fire had gone out in the barrel, we left the drywall on top for about 15 minutes to ensure that the kerosene wouldn't immediately re-ignite. Then we uncovered it slowly and left it to cool with an open top.

Conclusion and Recommendations

The goal of this project was to create a large-scale experiment for continuing the investigation of the effects of pit geometry on pit fires. This concept has impacts on the health and safety of trash fires that are common in areas with inadequate waste management systems. This experiment took research from 10 cm diameter "small scale" level tests to the scale of a 57.3 cm diameter, which is large enough to be considered a large-scale test. The experiment was overall a success and provided valuable data for further research.

For future tests, the following is recommended. First, a non-cyclical replenishing pool system should be implemented. This is important for obtaining real time, accurate mass loss data. To design a more effective CRS, calculations of flow rate and head loss should be done beforehand. The next recommendation is designing a more effective extinguishing method. This method should incorporate a guaranteed way to seal all airflow from the pit without relying on the integrity of drywall. Finally, the ground overall should be redesigned to be more airtight. The ground system was effective until heated, then the tape would crumble or melt, and the ground itself crumbled as well. The paper of the sheetrock itself additionally caught fire at some points, reducing its effectiveness and potentially affecting the data collected. The next step in this research should be to run a similar set of tests with an actual dirt pit and a solid fuel source.

Final Thoughts

"The control of fire by early humans was a turning point in the cultural aspect of human evolution. Fire provided a sense of warmth, protection, and a method for cooking food. These cultural advancements allowed for human geographic dispersal, cultural innovations, and changes of diet and behavior. Additionally, creating fire allowed the expansion of human activity to proceed into the dark and colder hours of the night." (McCavour, 2017)

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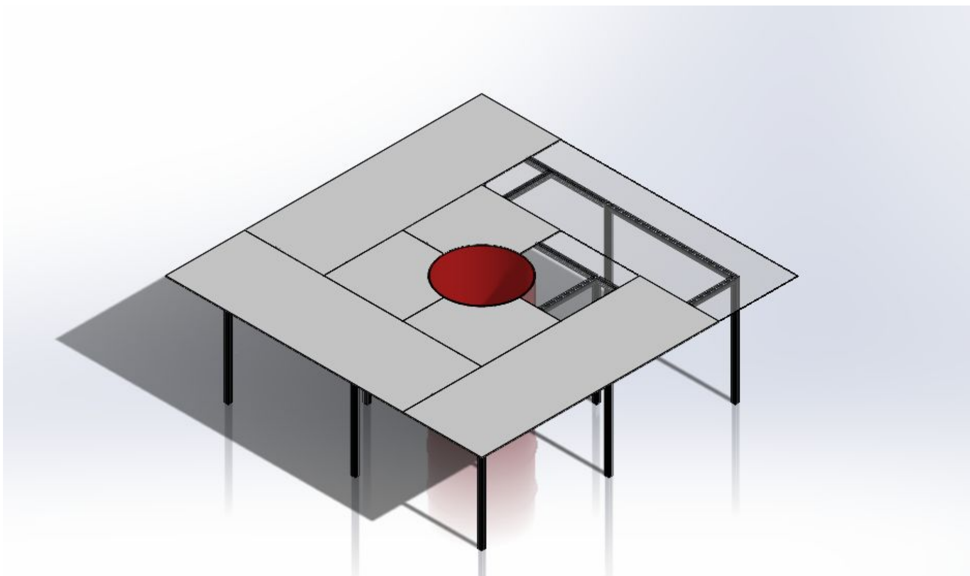
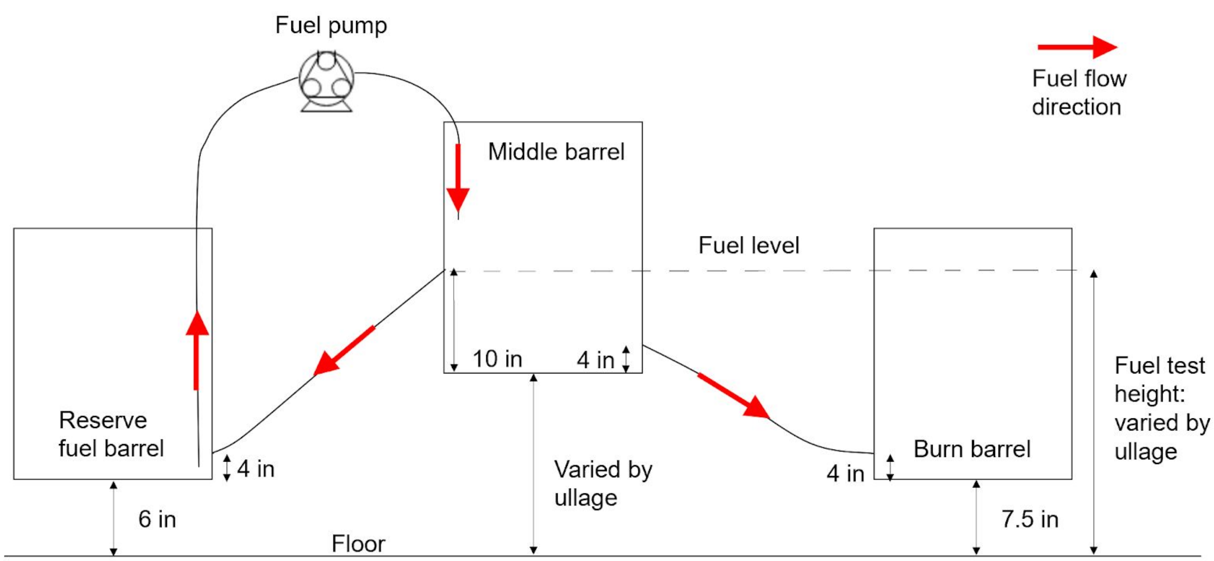
Appendix

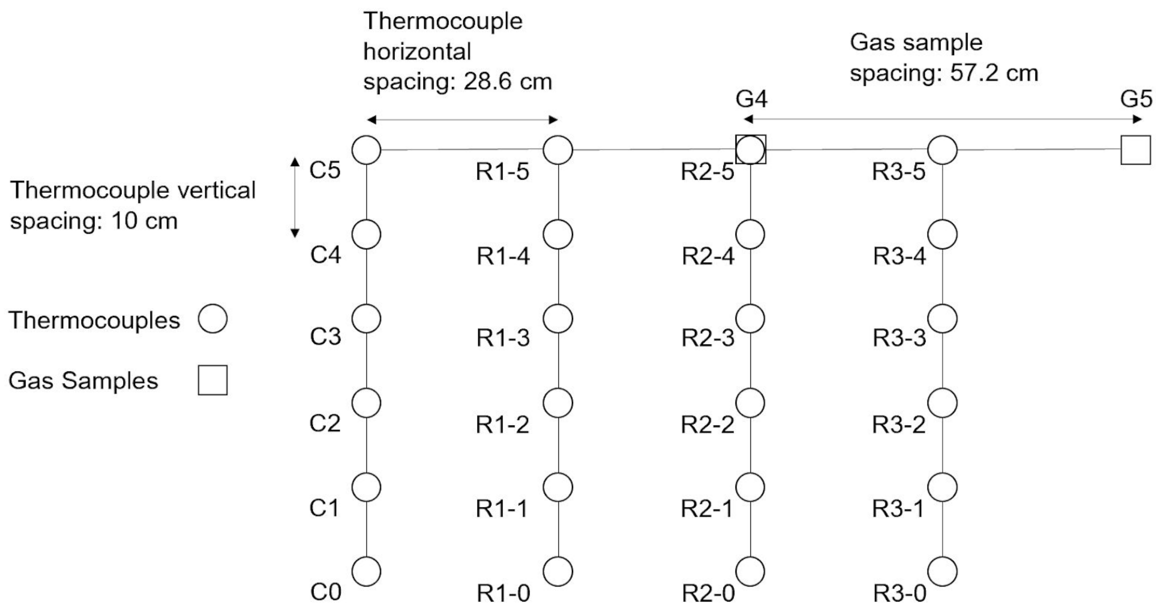
1. Technical Drawings and Diagrams



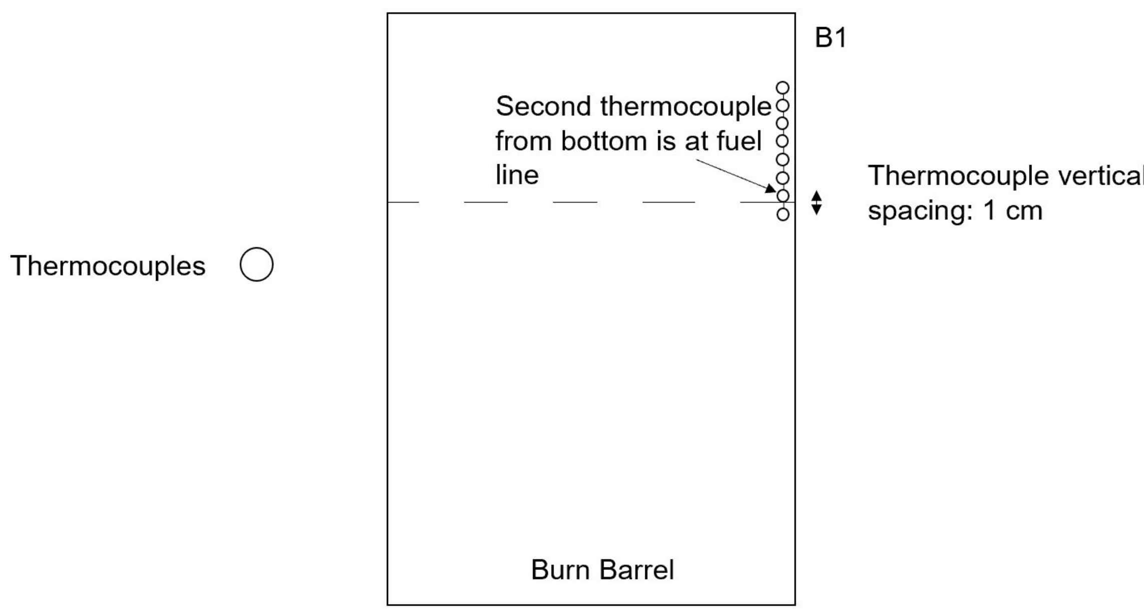
8020 and Drywall Ground Diagram



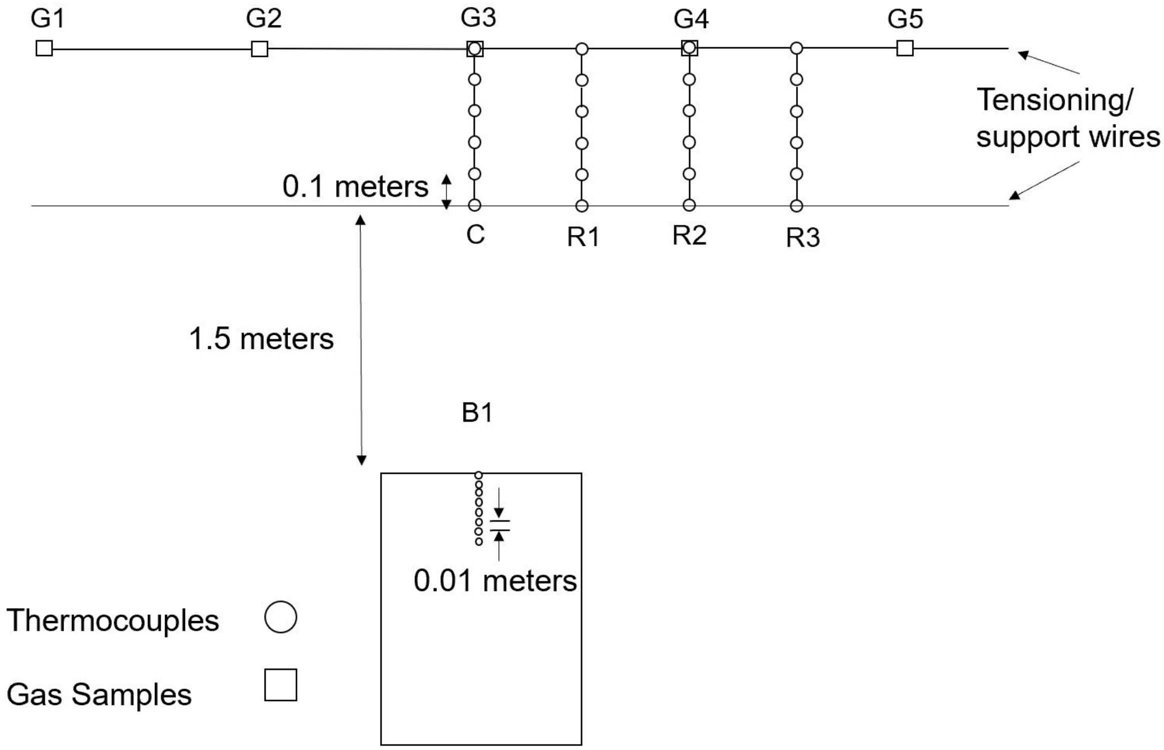
Constantly Replenishing Fuel System Diagram.



Upper Thermocouple Array Diagram.



Lower Thermocouple Array Inside Burn Barrel.



Full Instrumentation Setup Diagram.

2. Purchasing List With Costs and Sources

Item:	Units of purchase:	Quantity needed:	Cost per unit:	Total cost:	Source:
55 Gallon Drum	# of Drums	3	$125.00	$375.00	https://www.mcmaster.com/4115t24
8020	Ft	4, 6 ft segments 8, 8 ft segments	$266.28	$266.28	https://8020.net/1010.html
Fuel- Kerosene	Gal	60	$3.90	$234.00	Speedway: 1140 Main street, Worcester MA
Drywall	8 sheets	1	$118.58	$118.58	CNS Lumber
Duct Tape	3-pack	1	$8.88	$8.88	https://www.homedepot.com/p/Scotch-1-88-x-50-yd-48-mm-x-45-72-m-Utility-Duct-Tape-3-Pack-1950-3PK/308824310
Caulk	5.4 oz. Tube	1	$51.68	$51.68	https://www.rshughes.com/p/Momentive-RTV106-Adhesive-Sealant-Red-Paste-5-4-Fl-Oz-Cartridge-RTV106-RED-06S/rtv106_red_06s/?utm_source=rshgs&utm_campaign=RTV106%20RED%2006S&ef_id=Cj0KCQjw5rbsBRCFARIsAGEYRwdWmwOKAbtWBp3NQf2fg7wYYxGoEf6RdqRXUL73iHY3Le8CyqsADbUaAhGJEALw_wcB:G:s&s_kwcid=AL!4414!3!382998970219!!!g!329483791657!&gclid=Cj0KCQjw5rbsBRCFARIsAGEYRwdWmwOKAbtWBp3NQf2fg7wYYxGoEf6RdqRXUL73iHY3Le8CyqsADbUaAhGJEALw_wcB
Caulk 2	3 oz. Tube	1	$15.61	$15.61	https://www.homedepot.com/p/Permatex-3-oz-High-Temp-Red-RTV-Silicone-Gasket-Maker-75152/302774959
1/2" Tubing	Ft	50	$0.96	$48.00	https://www.mcmaster.com/standard-plastic-and-rubber-tubing%2f%3d66411207df9649a89d45eb86b2373c6dk2w0xwf8
5/16" Tubing	Ft	25	$2.09	$52.25	https://www.mcmaster.com/5792k22
Buckets	Sets of 3 buckets	2	$16.68	$33.36	https://www.homedepot.com/p/Leaktite-2-Gal-White-Plastic-Bucket-Pack-of-3-209331/203925043?MERCH=REC-_-pipsem-_-308875314-_-203925043-_-N
Kaowool	-	-	-	-	Owned by lab
Scale	# of scales	1	-	-	Owned by lab
River Rocks	-	-	-	-	Facebook Marketplace
Pump	# pumps	1	-	-	Owned by lab
Aluminum Tape	# rolls	2	-	-	Supplied by lab