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THE INTEGRATION OF PROPANE FLAMING AND MECHANICAL CULTIVATION FOR EFFECTIVE WEED CONTROL IN AGRICULTURE

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THE INTEGRATION OF PROPANE FLAMING AND MECHANICAL CULTIVATION FOR EFFECTIVE WEED CONTROL IN AGRICULTURE

by

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A THESIS

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THE INTEGRATION OF PROPANE FLAMING AND MECHANICAL CULTIVATION FOR EFFECTIVE WEED CONTROL IN AGRICULTURE

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University of Nebraska, 2012

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Flaming is a thermal weed control method that can kill weeds within or between crop rows using heat. Mechanical cultivation is another weed control method which undercuts weeds between crop rows to kill them. A combination flamer/cultivator implement was designed to take advantage of the good qualities of both flaming and cultivation to provide excellent organic weed control.

Flaming hoods were designed in the spring of 2010 and retrofitted on an existing row crop cultivator. The hoods were tested in corn and soybean field studies in the summer of 2010. Of the seven treatments tested, a treatment of flaming combined with cultivation applied twice during a season produced the highest weed control and crop yield, while maintaining low crop injury and weed dry matter.

The flaming hoods were redesigned in the spring of 2011 to be easier to manufacture. New torches were developed to replace the commercial torches previously used. A flow mixer enhanced heat transfer by reducing or eliminating film evaporation. Reducing the primary air intake decreased flame liftoff length and improved stability.
The new hoods and torches were tested in the same seven field treatments during the summer of 2011. Flaming combined with cultivation twice performed best overall again, although the actual values of the performance parameters were lower than in 2010. There are several factors which may have caused worse results in 2011 than in 2010. These include changes in weed composition and density, equipment, climate, and planting date.

Gas temperature measurements were conducted on three of the hood/torch configurations used in the field studies, as well as on open, unhooded torches. Thermocouple heat losses due to radiation were accounted for, and ranged from 0.9 percent to 29.4 percent. The hooded torches were far superior to the open torches, increasing the high-temperature region length by approximately 200 mm. The 2010 hood provided temperatures that were 36 percent higher at the hottest cross-section than the 2011 hood, but the latter performed better overall.
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Chapter 1. Introduction

1.1. History

1.1.1. History of Flaming

Contrary to belief of many, controlling weeds using flaming is not a new idea. The idea dates back over a century and a half to 1852, when John A. Craig of Arkansas patented and used a flaming machine. Oil and liquid propane gas (LPG) burners came into use for weed control on ditchbanks and other non-cultivated areas in the late 1930’s and soon were in extensive use, especially in southwestern states (Timmons, 2005). In 1935, Colonel Price C. McLemore of Alabama began using a flamer in his cotton fields. He continued using it, and by 1939 he filed for a patent titled “Method of Cultivation of Plants”, issued in 1943. Several other patents were granted in the early and mid-1940’s on schemes of flaming (Edwards, 1964). By the early 1940’s, flaming had caught on for use in cotton and other crops.

The use of butane, kerosene or other oils in the burners was dying out by 1944, when extensive work was begun on the use of LPG as the fuel for the flamer (Edwards, 1964). That same year, metal boxes were mounted on a cultivator at the Mississippi Delta Branch Agricultural Experiment Station, in order to block the cotton from the flame.

In the course of switching from fuel oil to LPG, new burners and vaporizers had to be designed to adapt to the differences in fuel properties. Harold T. Barr built the first
successful self-energizing burner, and by 1946 it was the accepted model for flamer manufacturers. The self-energizing burner is also known as the liquid type. The other type of burner is the vapor type. As separate vaporizers were improved, the vapor-type burner became more popular (Carter et al., 1960).

In 1948, Stewart Poole of the International Harvester Company designed a cast iron burner with an oval-cornered rectangular mouth opening. The key difference in the design was the nozzle, a standard flat fan-type spray orifice. It produced a relatively short, flat flame that was designed to operate at a much greater angle to the horizontal (Carter et al., 1960). Poole recommended setting the angle with the horizontal at 45°. This design was modified by J.K. Jones, who produced a sheet metal “flat” burner with a double-orifice fan spray nozzle. This was commonly known as the “Stoneville” burner. Another modification came in 1953 when Stanton created a horizontal combustion chamber followed by a 30°-angle deflector. This burner was commonly known as the “Arkansas” burner.

In 1962 came the first hooded burner designed to flame the crop inter-row space. The goal was to eliminate cultivation. By 1963 there were at least 20 states in which some research was being done by public and private research groups (Edwards, 1964). In 1964, when Edwards published his detailed history of flaming, there were an estimated 15,000 row crop flamers in use. The heyday of flaming did not last, though. After their introduction, herbicides took over the market (Storeheier, 1994). Seifert & Snipes (1996) and Laguë et al. (1997) said that flaming use declined in the 1970s due to both rising
LPG prices and the introduction of efficient, less expensive herbicides. Recent concerns due to the environmental effects of herbicides, higher worker protection standards, elevated herbicide prices, and the increased prevalence of herbicide-resistant weeds have renewed interest in flaming practice (Seifert & Snipes, 1996).

1.1.2. Cultivation

Kepner (1978) said that mechanical cultivation or tillage is still the most important method for controlling weeds. Though it is one of the oldest methods, its use is probably not nearly as widespread today as in 1978. Timmons (2005) looked at the history of mechanical weed control as part of the overall weed control history, and points out some major milestones along the way. The wheel cultivator with steel shovels was invented in 1848, followed by the straddle row cultivator in 1856 and the riding cultivator in the 1880’s. These were horse-drawn implements. The springtooth harrow and rotary hoe were two more horse-drawn implements developed along the way.

Other aspects of mechanical cultivation were developing as well. By 1899, Canadian extension work was addressing weed control. A series of 17 meetings was held in 1899 on control of weeds by tillage and crop competition (Timmons, 2005).

The rodweeder, developed in the Pacific Northwest during 1912 to 1914, was the first field implement to be designed exclusively, or even chiefly, for weed control (Timmons, 2005). Finally, the tractor-mounted cultivator was developed in the early 1920’s.
1.1.3. Combined Flaming and Cultivation

Flaming was combined with cultivation as early as 1900, when S. B. Jones of Illinois was granted a patent for an attachment to be mounted on a one-row cultivator. It consisted of a fuel tank and two burners, one on each side of the row. The principal claim for this machine was that of an insect destroyer (Edwards, 1964).

In 1943 there was a study at the Mississippi Delta Branch Agricultural Experiment Station comparing treatments with different combinations of cultivation, hoeing, and flaming in cotton. Table 1 reports the crop yield results for the four treatments as reported by Edwards (1964).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (lb/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivation—no hoeing—no flaming</td>
<td>1506</td>
</tr>
<tr>
<td>Cultivation—no hoeing—flaming</td>
<td>2130</td>
</tr>
<tr>
<td>No cultivation—no hoeing—flamed seven times</td>
<td>2033</td>
</tr>
<tr>
<td>Cultivation—hoeing—no flaming (plantation practice)</td>
<td>2140</td>
</tr>
</tbody>
</table>

The results in Table 1 show that combining cultivation and flaming in a weed control program can produce similar results to traditional plantation practice, which includes hoeing.
A research agricultural engineer in California in the 1940’s mounted burners up front on the cultivator gangs and shielded the burner and cultivator part in order to get better control in late season flaming of large irrigated cotton (Edwards, 1964). Similarly, in 1961, the Delta Branch station published a research paper on methods of mounting burners on individual cultivator gangs. Each burner floated independently of every other burner on the cultivator, and much better control of the flame was obtained (Edwards, 1964).

1.2. Overview of Current Technology

1.2.1. Current Flaming Technology

A common misconception about flaming is that weeds must be burned to a crisp in order to be controlled. In fact, the weeds should never be ignited during a flaming treatment. Thomas (1964) states that exposure times between 0.065 and 0.130 seconds were sufficient to control weeds. It is believed that Thomas used a temperature between 800°C and 900°C (Kang, 2001). The heat from the flame causes rupturing of the cell walls, which leads to water loss and plant death (Parish, 1990). Besides the benchmark from Thomas, another commonly used one is that plants can tolerate temperatures of 120°F to 140°F (Mayeux et al., 1968). Thus, it is important to keep the heat directed on the weeds but not the crop.

The dose of propane used in the full (broadcast) flamer for the studies considered here is 45 kg/ha (10 gal/acre (GPA)). This compares favorably with other researchers. Mutch et al. (2008) reported 8 to 10 GPA depending on application speed, while Laguë et al.
(1997) reported that Rahkonen and Vanhala (1993) used 4 to 15.7 GPA. Kang (2001) also reported that dosage rates above 40 kg/ha to be very effective.

The full flamer used in the field studies for this report is shown in Figure 1. It is a four-row unit, with two torches per row. Note that the torches are aligned parallel with the crop row, such that the flames flow along either side of the soybeans.

![Figure 1. Full flamer torch setup.](image)

Most of the past research on flaming has aligned the torches perpendicular to the crop row, with the flame hitting the ground a short distance from the base of the crop on the near side. The torches were staggered longitudinally to keep too much heat from building up in the crop and killing it. The parallel setup in Figure 1 has the distinct advantage of a symmetric temperature profile from left to right as one looks down a crop row. It is difficult to predict temperature profiles when there are torches pointing at the crop row from opposite directions and at different longitudinal differences. Carter et al. (1960) also found that vertical or sloping ridges on the sides of the crop row due to tillage have an adverse effect when the torches are set up perpendicular to the crop row. The flame is deflected upward by the ridge and into the crop.
The full flaming unit and flamer/cultivator used in this study both travel at a speed of 4.8 km/h (3 mi/h). For a four-row unit with eight torches, this means that it takes 40.8 minutes to cover 1 ha of 0.76-m (30-in) crop rows. Although flamers can control weeds as well as mechanical weed control if properly designed, they are usually slower than chemical weed control (Ascard et al., 2007).

There have been many successful studies that used some sort of flaming technique to control weeds without herbicides. Netland et al. (1994a) found two selective flame weedings using 50 kg propane/ha to give as good weed control in late white cabbage as two applications of propachlor, with no crop injury. Mutch et al. (2008) found similar yields in organic corn when using flaming or rotary hoe weed control treatments. Flaming can also have the advantage of being able to be applied when the field is too wet for cultivation.

Flaming is not the complete answer for all types of weeds, though. Weeds with protected growing points, such as grasses and perennials, are stunted by flaming but eventually recover (Wszelaki et al., 2007). Ulloa et al. (2010a) also found that foxtail species were more tolerant to flaming, in general, than pigweed species. Fortunately, large broadleaf species, such as pigweed, are the bigger threat to crop productivity, as they were shown to be more competitive than most grasses and smaller broadleaf weeds (Canner et al., 2002).
There have been a couple of other suggestions from researchers on the application of flaming. Ulloa et al. (2012) found that plants were more susceptible to flaming in the afternoon than in the morning, possibly due to daily variation in leaf relative water content. Thomas (1964) suggested that flame penetration in dense weeds is improved by using higher operating pressures.

There have been environmental concerns about products of combustion contributing to pollution. Ascard et al. (2007) found that propane combustion is relatively clean when compared with other fossil fuels. Ulloa et al. (2011) calculated that broadcast flaming produces nearly twice the carbon dioxide emissions that banded herbicide spraying does, while banded flaming produces about 8 percent fewer emissions than banded herbicide spraying.

1.2.2. Current Cultivation Technology

There are numerous types of equipment available for mechanical weed control. For post-planting tillage, types include, but are not limited to, rotary hoes, flex-tine weeders, spike-tooth harrows, spring-tooth harrows, row crop cultivators, and rolling cultivators. Pictures of some of these types of implements are shown in Figure 2 - Figure 4.
Figure 2. A flex-tine weeder.

Figure 3. A row-crop cultivator.

Figure 4. A rolling cultivator.
Row crop cultivators work by cutting weeds at the soil surface and throwing dirt towards the crop row to cover weeds close to the crop. Jones et al. (1995, 1996) as cited in Bond & Grundy (2001) found burial to 1-cm depth and cutting weeds at the surface to be most effective. How should the cultivator be set up to accomplish such results? The operating depth of the cultivator sweeps in the studies considered in this project was approximately 1 inch, as recommended by Bowman (2002). Increasing the working depth does little to improve weed kill (Bond & Grundy, 2001).

Like any weed control treatment, there are advantages and disadvantages to row crop cultivation. Schweizer et al. (1994) found that standard row crop cultivators are most effective on weeds that are 15 cm tall or less. Thus the importance of cultivating early in the growing season cannot be overemphasized. In addition, inter-row cultivation does not significantly reduce plant population (Mulder & Doll, 1993). There is concern about the effects of cultivation on soil compaction and erosion. However, Mulder & Doll (1993) found that soil compaction is not increased by multiple cultivations over that compaction due to the first cultivation. Finally, it was mentioned earlier that flaming and herbicide spraying both produce significant carbon dioxide emissions. The only contribution to carbon dioxide emission from cultivation is from the diesel fuel consumed by the tractor, a 76 percent reduction over banded flaming (Ulloa et al., 2011).

1.3. Why Combine Flaming and Cultivation?

Traditional mechanical cultivation methods, despite their advantages, are ineffective in providing satisfactory season-long weed control. They do a good job in the inter-row space, but a strip of weeds remains within the crop row after cultivation. Thus the weeds
nearest the crop row present the greatest challenge in mechanical cultivation, as they
directly influence crop performance (Mulder & Doll, 1993). A combination of methods
is therefore necessary to maintain good weed control throughout the season.

Flaming has the potential to remove weeds within the crop row without significantly
damaging the crop. In that sense, flaming can be thought of as a non-selective herbicide.
It has been shown that herbicide use can be reduced 50 to 75 percent by integrating
banded herbicide spraying with mechanical cultivation (Mulder & Doll, 1993). Forcella
(2000) also found that rotary hoeing can replace 67 percent of the label rate of the
herbicide acetochlor. Instead of using the banded herbicide spraying, why not substitute
banded flaming? Indeed, Wszelaki et al. (2007) proposed that “combining flaming with
mechanical cultivation and hand-weeding may be an effective integration to optimize
weed control.”

In one year of the studies by Wszelaki et al. (2007) there was a shift in weed composition
and height. They concluded that such an occurrence speaks to the need to have several
weed control methods on hand in any given year. Even as early as 1964, Thomas (1964)
called flaming a “supplementary weed control measure”, while herbicide forms the basis
of most weed control programs, and that concerted efforts were being made to replace
flaming. Carter et al. (1960) found it impossible in many cases to completely control
weeds with flaming alone. Ulloa et al. (2010b) also advised that flaming should not be
the only method for non-chemical weed control.
It was mentioned earlier that banded flaming produces 8 percent fewer carbon dioxide emissions than herbicide spraying (Ulloa et al, 2011). Thus, the same benefits as banded herbicide could be realized by combining flaming with cultivation, with an 8 percent reduction in carbon dioxide emissions! It should be mentioned that while they are effective tools when used together, flaming and cultivation are just two tools in the toolbox of integrated weed management.
Chapter 2. Design of First Flamer/Cultivator Prototype

Throughout the course of working on this project, the name for the new implement has interchangeably been flamer/cultivator or flamer-cultivator (note the slash and hyphen between the two versions). After reading a significant amount of literature on flaming, it seems least confusing to call it the flamer/cultivator, as this emphasizes the dual nature of the machine. There are several mentions of a “flame cultivator” in the literature, which actually refers to a dedicated flaming unit with no mechanical cultivation.

2.1. Modifications to Noble Cultivator

The original Noble Row-Runner cultivator utilized in this project was purchased used from a farm auction, and brought to the University of Nebraska-Lincoln (UNL) Haskell Agricultural Laboratory in Concord, NE. Figure 5 shows what the cultivator looked like before any modifications were made to it.

![Figure 5. Noble Row-Runner cultivator before any modifications were made to it.](image)

Figure 6 shows a close-up view of one of the gangs, or arms that hangs off of the main toolbar. Note that there are five sweeps per gang. Although they are obscured by the grass in the picture, the sweeps on the cultivator at that time were fairly narrow, around 4 inches wide, and varied from front to back of the gang.
The first step in modifying the cultivator was to remove two of the tines from each gang, and replace the narrow sweeps with larger, 7-1/2-inch-wide sweeps. A picture of this first modification is shown in Figure 7, with the terminology used in this report.
The sweeps were now of uniform width across the cultivator, for they had not been prior to modifications. The one-piece sweep undercuts the weeds. The edge-bent S-tine shanks vibrate to shake weed roots free from clinging soil. The operating depth of the sweeps is about 1 inch. The gang mainbeam profiles up and down with the contour of the ground using the gauge wheel and parallel linkage system. The toolbar is always at a fixed position relative to the tractor. The stabilizing coulter serves to keep the cultivator moving as straight as possible. The cultivator is mounted on the tractor using a three-point hitch. The Noble cultivator was set for 0.76-m (30-in) -wide rows. The shovel beams are 2-inch square steel tubing. The term “shovel beam” is not technically standard, but no other single term has been found to be used.

2.2. Advantages of Using Flaming Hoods

One feature that can be added to row crop flaming equipment is hoods to cover the burners, or torches. The idea behind using hoods is to keep the heat produced by the torches close to the ground, where the weeds are. Storeheier (1994) said that hooded torches are far more effective than open ones. In addition, Storeheier (1994) found that torches under a shield are more tolerant to variations in torch angle with the ground.

Bruening (2009) completed a field study comparing the level of plant injury obtained with an open torch and a hood/torch combination. He tested two crop species and four weed species. The length of the flaming hood used in the experiment was 1.2 m (4 ft). Five propane doses were used, including an untreated control. The results indicate that the same level of weed control can be obtained with the hood/torch configuration with an
average of 50 percent less propane than with the open torch configuration. The results are useful, but remain yet to be proven on a large scale.

In addition to increasing the energy efficiency of a flaming operation, hoods also provide safety and more consistent treatments. The hoods provide safety by keeping the flames and heat down on the ground and away from the tractor operator. The hoods provide more consistent treatments by blocking much of the effect of wind during a treatment. As a general rule, full flaming or flaming/cultivation treatments were not conducted for the field studies considered here if the wind was blowing more than 16 km/h (10 mi/h).

2.3. Design of Original Flamer/Cultivator Hood

When performing flaming and cultivation simultaneously, consideration must be given as to which operation a plant is subjected to first. Flaming needs to be the first operation applied to the weeds, to rupture the cell walls and cause water loss, before the cultivator sweeps pass through. If the cultivation were to happen before flaming, the weeds would be partially covered by soil, and would be insulated from the heat produced by the torches. The weeds could then potentially grow back through the loose soil. Thus, the flaming operation would be much less effective if preceded by cultivation. The type of cultivator that is converted to a flamer/cultivator would limit the length of the flaming hood adopted.

The hood used on the first flamer/cultivator prototype was not made entirely from scratch. As mentioned, there was a 1.2-m hood used during the field study of Bruening (2009), known as the 4-ft hood. There was also a 0.6-m hood tested during Bruening’s
work on temperature measurements, known as the 2-ft hood. It is basically a shorter version of the 4-ft hood, with other features remaining the same. This was the size of hood adopted for the flamer/cultivator, based on the length of the Noble cultivator gangs. Figure 8 shows the 2-ft hood sitting on the ground between two cultivator gangs.

The hood length is of course 2 ft, and the hood width is 1 ft. The height of the hood at its inlet is 12 in, with a 30°-sloping section, and levels off at a 4.5-in outlet height. This design is consistent with the recommendations of Storeheier (1994), who found the optimum shield height to be 100 mm (~4 in.), and that a backwards-sloping shield keeps sufficient oxygen supply up front while forcing hot gases downwards at the rear end.

There were two major design challenges from here. One was to find a way to mount this hood on the cultivator. Second, because this flamer/cultivator implement was scheduled to be used on both early and late growth stages of the crops, it was decided that a gap must be allowed for in the middle of the hood so that the crop can pass through the hood when it is tall without getting knocked down. A picture of the resulting hood, mounted on the cultivator, is shown in Figure 9.
The hood was mounted on the cultivator using a piece of 2.5-inch square tube, cut 3 inches long, which can slide back and forth on the shovel beams, as seen in Figure 9. It can be fixed in place by a set screw on the back side. To this piece was welded a vertical 1.25-inch square tube. Inside this tube, a smaller, 1-inch square tube can slide up and down. A rendering of the assembly is shown in Figure 10. This inner vertical tube was then welded to the side of the hood, and the two vertical tubes were locked together using a squared retainer snap safety pin. There are holes drilled at 1-inch increments on the inner vertical tube to allow for height adjustment. An earlier version of this was used on an all-terrain vehicle at Haskell Ag Lab for flaming research.
To meet the second design challenge, the hood was designed not as one piece, but as two separate halves. During late-season flaming, the crop will be tall and will need to pass through an opening between the two halves of the hood. A removable cover creates this opening. Each half of the hood covers one torch and passes next to the crop row. During broadcast flaming, the crop will be either preemergent or slightly emerged. At this point, the entire hood can pass over the crop without knocking it down. To improve fuel efficiency, the removable cover for broadcast flaming was designed to enclose the two halves of the hood. The hood assembly for late-season flaming, with the covers removed, is shown in Figure 11 on a different cultivator tested in summer 2010.
Figure 11. Flamer/cultivator hood assembly for late-season flaming, with a gap for taller crops.

Each half of the hood covers one 3-in wide cylindrical torch purchased from Flame Engineering, Inc. The torches are at a 30° angle with the ground, parallel to the slope of the hood. This falls within the 22.5° - 45° range recommended by Storeheier (1994). Storeheier also mentioned that burner angle does significantly influence performance for round burners (such as the ones used in this hood). The Flame Engineering torches were calibrated, and it was determined that operation at 15 psig provided the desired application rate of 20 kg/ha (4 GPA) when the tractor speed is 4.8 km/h (3 mi/h).

The gap between the hoods for late-season flaming was designed to be 3 inches. The shape of the hood roof at its inlet was designed to funnel the crop into the gap between the hoods, and allow for the operator to drive at a moderate speed even with the narrow 3-in gap. With a total hood width of 12 inches, each half of the hood then has a width of 4.5 inches.

The torches have street elbow pipe fittings at their inlets. Between the hose and the street elbow is a porous brass filter that cleans debris out of the propane stream before it enters
the torch. This filter also serves as a flame arrester, protecting against lightback to the tank. The manual pressure regulator, large filter, and master ball valve are mounted on a piece of angle iron which is bolted to the cultivator mast. This setup can be seen in Figure 12. The propane tank used is a forklift-style tank, which can hold approximately 30 lb of propane. The mount is a common mount used to mount propane tanks onto forklifts. This tank mount is directly bolted to the cultivator toolbar.

![Figure 12. Plumbing system leading from the tank to the regulator and to the manifolds.](image)

### 2.4. Radiation Shields

The adiabatic flame temperature of a stoichiometric propane-air mixture at constant pressure with reactants at 298 K and no dissociation is calculated to be 2394 K. A flame in an actual reaction has a lower temperature than that, but the hood walls can still reach relatively high temperatures. A risk is then present that the rubber gauge wheels can receive significant heat transfer by radiation from the high-temperature hoods. This heat could potentially melt the gauge wheels or damage their bearings.

The solution is to install radiation shields about midway between the hood and the gauge wheel. It is a simple design, just a sheet of steel welded to a piece of 2.5-inch square tube, so it is able to slide back and forth just like the hood mount. It is held in place by a set screw. The shields can be seen most clearly in Figure 9, hanging on the shovel beam between the hood mounts and the gauge wheels.
2.5. Adjustments Made to Original Design

The flamer/cultivator built during Summer 2010 was a first prototype, and the design was not perfect. A few minor adjustments were made to the original design in the course of attaching the hoods to the cultivator. As can be seen in Figure 7, each gang mainbeam has one sweep at the back. The three middle mainbeams each have one “rear sweep” positioned on the left side towards the back, and one “forward sweep” on the right side near the front, next to the gauge wheel. The two end mainbeams each have two sweeps. The hoods were mounted on the shovel beams toward the front of the gang mainbeams, where the forward sweep is also mounted. The hood mounts interfered with the forward sweeps, causing them to be out of position and not cover enough inter-row area. Because the vertical tube is biased to one side of the mount, as shown in the rendering of Figure 10, a simple solution was to swap the left and right side hood mounts so the extra length of the hood mount would be next to the hood, not interfering with the sweeps. In the course of making this change, the 18-in shovel beams on the three middle gang mainbeams were replaced with 24-in shovel beams.

After the system was mounted on the cultivator, the cultivator was taken to the field for a “cool run” without igniting the torches. It was unexpectedly found that having a sweep right between the hood and radiation shield causes that area to plug up with dirt very quickly. So, the forward sweeps were moved back parallel with the rear sweeps and that problem was solved. For the reasons of mounting the hoods and avoiding the plugging up of dirt, it seems that sweeps must not be mounted next to the flaming hoods in the future.
The original radiation shields were designed to be rectangular, with a triangular cutout at one bottom corner to allow the shield to glide over the dirt. As can be seen in Figure 9, a large triangular piece was cut out of the top corner to avoid contact with the edge-bent S-tine shanks. Finally, an extra nut was added above the torch itself when mounting to allow for extra room between the torch and roof of the hood. The practical implication is that future torch mounts should be designed about an inch lower.

2.6. Alloway Flamer/Cultivator

In addition to the Noble Row-Runner cultivator used in Concord, NE, a second flaming project was conducted during the summers of 2010 and 2011 at the UNL High Plains Agricultural Laboratory in Sidney, NE. The purpose of having a project there was to test flaming under a different, drier climate. The crew at Sidney provided an Alloway row crop cultivator for mounting of the same hood/torch mounting system used at Concord. Due to the extreme distance of Sidney from Concord and Lincoln, measurements of the Alloway cultivator were obtained from the crew in Sidney, and it was determined that copies of the Noble flamer/cultivator equipment would most likely fit the Alloway cultivator.
Indeed, the flaming equipment fit perfectly on the Alloway row crop cultivator. The Alloway flamer/cultivator can be seen in Figure 13. There are some key differences between this and the Noble cultivator that makes the Alloway more suitable for flaming. The front shovel beams on the Alloway cultivator are 22 inches long, rather than the 18-inch beams on the Noble cultivator. Recall that three of those 18-inch beams were replaced with 24-inch beams to make room for the hood mounts. So the 22-inch beams on the Alloway cultivator are perfect. Also, the beams for the rear sweeps are staggered such that they are out of the way of the flaming hood but pose no threat for getting clogged with dirt because of being right next to each other. Although having both the sweeps in the back on the Noble cultivator did not pose a problem during testing here, an expert on cultivation said it is usually best to have them staggered, just in case.
There are half-inch increments marked on the gauge wheel adjustment posts, which make it easy to adjust all wheels to the same height. The gauge wheels are located farther forward on the gang mainbeams than on the Noble cultivator. The wheels are then less likely to melt due to radiation from the hoods. In fact, the radiation shields, which were the same design as for the Noble cultivator, were flipped backwards to effectively shield the gauge wheels which were so far forward. Finally, the tank mount is of the forklift type as on the Noble cultivator, and it was purchased from a local Caterpillar dealer. Instead of being bolted directly to the toolbar, these mounts are bolted to two sets of 2-inch steel square tube, which clamp on top and bottom of the toolbar. Thus holes did not need to be drilled into the cultivator for any part of the Alloway flamer/cultivator assembly.
Chapter 3. 2010 Field Study

Two similar field studies were conducted during the summer of 2010 to test the flamer/cultivator at the UNL Haskell Agricultural Laboratory in Concord, NE. One was in corn and the other was in soybean. These studies will be discussed separately.

3.1. Corn 2010 Field Study

3.1.1. Corn Materials and Methods

In corn, eight treatments were compared that involved cultivation, flaming, or a combination of the two, as well as weed-free and weedy-season-long control plots. The treatments were arranged in a randomized complete block design (RCBD) with four replications. The treatments were conducted once or twice during a season, and were applied at specific growth stages. The vegetative growth stages are designated by a “V” followed by the number of the uppermost leaf whose leaf collar is visible, such as V1, V2, V3, etc. (Ritchie, 2008). The list of treatments conducted is given below, along with the growth stage(s) at which they were conducted.

1. Weed-free control
2. Cultivation once (V3)
3. Cultivation twice (V3 & V6)
4. Flaming + cultivation once (V3)
5. Flaming + cultivation twice (V3 & V6)
6. Full flaming once (V3)
7. Full flaming twice (V3 & V6)
8. Weedy season-long

The row spacing used in the treatments was 0.76 m (30 in). The seed planted was an organic corn hybrid. Conventional soil was used in this study, but it did not receive any herbicide during the year of the study. The soil type is Baltic silty clay, occasionally
flooded (Soil Survey Staff, 2012). The field preparations included one disking and one field cultivation. The study was planted on May 19 at a rate of 24,650 seeds/acre.

The plots were 13.7 m (45 ft) long by 3.05 m (10 ft) wide, which meant there were four rows in each plot. The harvesting was done by hand, and was taken from 4-m lengths in each of the two middle rows of each plot, for a total of 8 m harvested. The samples were threshed using an ALMACO thresher, and the moisture content was taken using a Dickey-John GAC 2000 Grain Analysis Computer.

For treatment 1, the plots were maintained by hand weeding, a common practice by many organic farmers. The equipment used for treatments 2-5 was the Noble flamer/cultivator, shown in Figure 14, mounted on a tractor using a three-point hitch. For treatments 2 and 3, with cultivation only, the torches were not running. Approximately 0.48 m (19 in) of the inter-row space was cultivated in these treatments. For treatments 4 and 5, with flaming + cultivation, the torches were running. This is a banded treatment, such that 0.30 m (12 in) of the inter-row space was flamed and 0.48 m (19 in) was cultivated, with 2.5 cm (1 in) of overlap between the two operations. Treatment 8, weedy season-long, was left alone; nothing was done to it the entire season.
The equipment used for treatments 6 and 7 was the so-called “full flamer”, which is shown in Figure 15. It has two parallel torches per crop row, one on each side of the row, similar to the flamer/cultivator. The torches are larger, cowbell-shaped torches from Flame Engineering, Inc. It should be noted the torches were not set perpendicular to the crop row as recommended by Flame Engineering. Rather, they were set parallel to the row so that the temperature profile was uniform across the inter-row space and the weeds are exposed to the entire flame length in the direction of travel. They are spaced farther apart than on the flamer/cultivator because their flame coverage area is much wider. The larger hoods are closed for the early-growth-stage treatment. The individual hoods slide left and right, and can be opened to a 6-inch gap for the late-growth-stage treatments, allowing the taller crop to pass through, as shown on the right in Figure 15.
The operating speed for both of the implements used was 4.8 km/h (3 mi/h). The propane dose applied differs between treatments. Treatments 6 and 7, which utilize the full flaming unit for broadcast flaming, use a rate of 45 kg/ha (10 GPA). Treatments 4 and 5 use cultivation combined with banded flaming, which only flames a 0.6-m (1 ft) band centered on each crop row. Because these treatments cover only 0.6 m out of the 0.76 m of row spacing, the propane dose can be reduced from that of the full flamer. The flaming + cultivation treatments use a rate of 19 kg/ha (4 GPA). The mass flowrate of each torch was measured indoors in the lab. The flowrate, coverage area, and operating speed were used to determine the values of the application rates. The treatments at the V3 stage were conducted on June 9, and the V6 treatments were conducted on June 24.

The treatments were evaluated based on four performance parameters. Visual ratings of weed control and crop injury were taken 1, 7, 14, and 28 days after treatment (DAT). DAT refers to the number of days after the last application of a treatment in a plot. For example, this is days after the first application for treatments 2, 4, and 6, which have only one application, while this is days after the second application for treatments 3, 5, and 7, which have two applications. The ratings used a scale of 0-100%, where 0% means no
crop injury or weed control, and 100% means plant death, as illustrated in Figure 16. Weed dry matter was collected on a single day for the entire study, from a 0.5-m² quadrat in the middle two rows of each plot, at approximately 60 days after the final treatment applications in the study. Thus, it was 60 DAT for treatments 3, 5, and 7, and 75 DAT for treatments 2, 4, and 6. Finally, crop yields were taken at harvest, using the procedure mentioned previously.

![Figure 16. Weeds showing 0% damage (left) and 100% damage (right).](image)

### 3.1.2. 2010 Corn Results

An analysis of variance (ANOVA) was performed on the two years of data, 2010 and 2011, using SAS statistical software. Prior to performing the analysis, the four data points in each treatment per year were subjected to the Tukey robust outlier test. In this method, any value greater than the 75th percentile plus 1.5 times the interquartile distance, or less than the 25th percentile minus 1.5 times the inter-quartile distance, is treated as an outlier and is discarded (Shoemaker, 1999). The data was significantly different between the two years at the $\alpha = 0.05$ significance level, and could not be pooled. Error bars on the plots show the standard error of the means. The weed control ratings for corn at 7 and 28 DAT are shown in graphical form in Figure 17.
The best treatments for weed control appear to be treatments 5 and 7, which are flaming + cultivation twice and full flaming twice, respectively. Of these, treatment 5 is the best, with nearly 100 percent weed control at 7 and 28 DAT. Treatment 7 is not far behind, with 90 percent weed control at 7 DAT, and dropping only to 85 percent at 28 DAT. Both of the flaming + cultivation treatments are significantly better than cultivation alone. Thus, a simple flaming kit that can be retrofitted on a row crop cultivator can make a weed control tool that is only partially effective become very effective.

It should be noted that the cultivation treatments were conducted differently than how many farmers conduct it. Farmers often use a cultivator with large sweeps that throw a lot of dirt toward the intra-row space to cover the weeds. Due to the use of only one cultivator for both the cultivation-only and flaming + cultivation treatments, not as much dirt was thrown with this unit. Such a cultivation treatment with a lot of dirt thrown toward the crop row may be more effective than the method used in this study.
Visual ratings of the corn injury were taken at the same times and the ratings for this are shown in Figure 18.

![Figure 18. 2010 crop injury ratings for corn.](image)

Treatment 1 is the weed free control plot and does not present corn injury. Likewise, treatments 2 and 3 were cultivation alone and did not present corn injury. These treatments are not shown in Figure 18. For all of the treatments shown, the level of corn injury is highest at 7 DAT compared to 28 DAT. The highest level of injury among the flamer/cultivator treatments, 4 and 5, is approximately 17 percent. By 28 DAT, the corn recovers and the injury has been reduced to 5 percent. Due to further recovery with time, the level of visual injury later in the season is likely to be very small, if any. Thus the flamer/cultivator does not significantly impact the corn growth. The best treatment in terms of crop injury is treatment 7, full flaming twice, showing less than 3 percent injury at 28 DAT. However, the difference in crop injury between treatments 7 and 5 is minimal.
The results for weed dry matter are shown in Figure 19. Treatment 8, weedy season-long, is shown to have the largest amount of dry matter, 201 g/m², as expected.

The clear winner among these treatments is treatment 5, flaming + cultivation twice. The amount of weed dry matter is very small, only 2 g/m². Treatment 7 is the next best, with 12 g/m². The cultivation-only treatments, 2 and 3, have significantly higher amount of weed dry matter than the treatments containing flaming. This shows the advantage of flaming being able to kill weeds within the crop row. These weeds would be impossible to cut with a row crop cultivator without destroying the crop. However, a cultivator with throws a lot of dirt toward the crop row would help this problem, as mentioned previously.

From an economic standpoint, the most important result is yield, and the results of the corn yield are shown in Table 2. The letters in the last column represent the statistical grouping of the treatments. Those treatments that contain the same letter are not
statistically different at the $\alpha = 0.05$ significance level. The yield results correspond to the trends shown in the weed control, crop injury, and weed dry matter ratings.

Treatment 7, which is full flaming twice, gave the best yield of 12.31 t/ha (196.1 bu/ac). Treatment 5, which is flaming + cultivation twice, gave the second best yield of 11.98 t/ha (190.8 bu/ac). These yields are even better than the hand-weeded control, treatment 1, which yielded 11.08 t/ha (176.5 bu/ac). Treatments 7 and 5 are statistically similar (both contain A in their grouping). Besides weedy season-long, the treatments with cultivation alone (3 and 2) were the worst in terms of yield, giving 9.88 and 9.44 t/ha, respectively.

### Table 2. 2010 yield results for corn.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (t/ha)</th>
<th>Yield (bu/ac)</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>12.31</td>
<td>196.1</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>11.98</td>
<td>190.8</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>11.08</td>
<td>176.5</td>
<td>B</td>
</tr>
<tr>
<td>4</td>
<td>10.71</td>
<td>170.6</td>
<td>B C D</td>
</tr>
<tr>
<td>6</td>
<td>10.65</td>
<td>169.7</td>
<td>C D</td>
</tr>
<tr>
<td>3</td>
<td>9.88</td>
<td>157.3</td>
<td>D</td>
</tr>
<tr>
<td>2</td>
<td>9.44</td>
<td>150.4</td>
<td>D E</td>
</tr>
<tr>
<td>8</td>
<td>8.48</td>
<td>135.1</td>
<td>E</td>
</tr>
</tbody>
</table>

Regarding the smaller yield of treatment 1 as compared to treatments 7 and 5, the removal of weeds in treatment 1 was done either by hand weeding (pulling weeds) or by hand hoeing. It is possible that pulling weeds, especially large ones, and/or hand hoeing causes damage to the roots of the crop which can lead to smaller yield. Treatment 7 has the advantage over cultivation treatments of retaining all soil moisture. Studies have shown that approximately one inch of water is lost per cultivation. These are some of the considerations that need to be employed, among others, not discussed, to understand the
yield ranking of the different treatments presented in Table 2. Of course, the limited number of replications is also a major consideration.

### 3.2. Soybean 2010 Field Study

#### 3.2.1. Soybean Materials and Methods

In soybean, seven treatments were compared that involved cultivation, flaming, or a combination of the two, as well as weed-free and weedy-season-long control plots. The treatments were arranged in a randomized complete block design (RCBD) with four replications. The treatments are conducted once or twice during a season, and are applied at specific growth stages.

The vegetative growth stages are designated by a “V” followed by the leaf designation. The cotyledon growth stage, the first one after emergence, is designated by VC. In this stage, the two cotyledons are closed and protect the growing point. This is the recommended stage for early flaming. It is short-lived, however, lasting only 2-4 days. It is followed by the unifoliate stage, designated VU. Ulloa et al. (2010b) found this to be the most susceptible stage for flaming, and that flaming at this stage will cause high crop injury and yield loss. The remaining vegetative growth stages are designated by the number of trifoliate leaves as V1, V2, etc. The list of treatments conducted is given below, along with the growth stage(s) at which they were conducted.
1. Weed-free control
2. Weedy season-long
3. Flaming once at VC, followed by cultivation at V4
4. Flaming + cultivation once (VC)
5. Flaming + cultivation twice (VC & V4)
6. Full flaming once at (VC)
7. Full flaming twice at (VC & V4)

The row spacing used in the treatments was 0.76 m (30 in). The seed planted was an organic soybean hybrid. Conventional soil was used in this study, but it did not receive any herbicide during the year of the study. The soil type is Moody silty clay loam, 6 to 11 percent slopes (Soil Survey Staff, 2012). The field preparations included one disking and one field cultivation. The study was planted on May 19 at a rate of 179,742 seeds/acre.

The plots were 13.7 m (45 ft) long by 3.05 m (10 ft) wide, which meant there were four rows in each plot. The harvesting was done by hand, and was taken from 4-m lengths in each of the two middle rows of each plot, for a total of 8 m harvested. The samples were threshed using an ALMACO thresher, and the moisture content was taken using a Dickey-John GAC 2000 Grain Analysis Computer.

The equipment used was the same as described in the corn study. For treatment 1, the plots were maintained by hand weeding, a common practice by many organic farmers. Treatment 2, weedy season-long, was left alone; nothing was done to it the entire season. For treatment 3, the full flamer was used at the VC stage, as shown in Figure 15. The Noble flamer/cultivator was used at the V4 stage of treatment 3, with the torches not running, as shown in Figure 14. Approximately 0.48 m (19 in) of the inter-row space
was cultivated in this treatment. For treatments 4 and 5, with cultivation + flaming, the Noble flamer/cultivator was used with torches running. This is a banded treatment, such that 0.30 m (12 in) of the inter-row space was flamed and 0.48 m (19 in) was cultivated, with 2.5 cm (1 in) of overlap between the two operations. The equipment used for treatments 6 and 7 was the full flamer.

The operating speed for both of the implements used was 4.8 km/h (3 mi/h). The propane dose applied differs between treatments. Treatments 6 and 7, which utilize the full flaming unit for broadcast flaming, use a rate of 45 kg/ha (10 GPA). Treatments 4 and 5 use cultivation combined with banded flaming, which only flames a 0.6-m (1 ft) band centered on each crop row. Because these treatments cover only 0.6 m out of the 0.76 m of row spacing, the propane dose can be reduced from that of the full flamer. The flaming + cultivation treatments use a rate of 19 kg/ha (4 GPA). The mass flowrate of each torch was measured indoors in the lab. The flowrate, coverage area, and operating speed were used to determine the values of the application rates. The treatments at the VC stage were conducted on June 15, and the V4 treatments were conducted on July 7.

The treatments were evaluated based on four performance parameters. Visual ratings of weed control and crop injury were taken 1, 7, 14, and 28 days after treatment (DAT). DAT refers to the number of days after the last application of a treatment in a plot. For example, this is days after the first application for treatments 2, 4, and 6, which have only one application, while this is days after the second application for treatments 3, 5, and 7, which have two applications. The ratings used a scale of 0-100%, where 0% means no
crop injury or weed control, and 100% means plant death, as illustrated in Figure 16. Weed dry matter was collected on a single day for the entire study, from a 0.5-m\(^2\) quadrat in the middle two rows of each plot, at approximately 60 days after the final treatment applications in the study. Thus, it was 60 DAT for treatments 3, 5, and 7, and 82 DAT for treatments 2, 4, and 6. Finally, crop yields were taken at harvest, using the procedure mentioned previously.

3.2.2. 2010 Soybean Results

The ANOVA procedure and Tukey outlier analysis was conducted on the data, as mentioned above in the corn study. Error bars on the plots show the standard error of the means. The weed control ratings for soybean are shown in graphical form in Figure 20.

![Figure 20. Weed control ratings for soybean.](image)

Treatment 5, with flaming + cultivation twice, shows the most consistently high weed control, with 71 percent at 28 DAT. However, treatment 6, with full flaming once, shows a much higher level of weed control at 7 DAT (78 percent) than at 28 DAT (11 percent).
Note that the level of weed control at 28 DAT is much higher for flaming + cultivation (treatments 4 and 5) than for full flaming (treatments 6 and 7).

Looking at the equipment differences between treatments 4 and 6, which both have high levels of weed control at 7 DAT, treatment 4 has flaming hoods with top and sides on them, whereas treatment 6 only has hoods with the top steel sheet on them. Having all sides on the flamer/cultivator hood seems to cause a better treatment. Then it makes sense that in the treatment 7, with full flaming, the weeds have a complete recovery after the first application, and the second application does not produce good weed control ratings, even at 7 DAT.

The soybean injury ratings were taken at the same times, and the results are shown in graphical form in Figure 21. Treatments 1 and 2 did not present any injury and are not shown in Figure 21.
Only one of the treatments (7) shows more than 10 percent injury at 7 DAT. The soybean crop then recovers and injury is reduced to near zero at 28 DAT in all cases. Note that the soybean injury sustained in treatment 3 is only from the broadcast flaming at the cotyledon growth stage, as cultivation at the V4 stage does not present any soybean injury.

The results for weed dry matter in soybean are shown in graphical form in Figure 22.
Figure 22. Weed dry matter results in soybean.

Treatment 5 clearly has the most weed dry matter reduction, with 10 g/m$^2$ remaining, as compared to 321 g/m$^2$ for treatment 2. The full flaming treatments left weed matter in the 167 - 171 g/m$^2$ range.

Economically, the most important results for soybean, as for corn, are the yield values. The yield values for soybean are presented in Table 3.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (t/ha)</th>
<th>Yield (bu/ac)</th>
<th>Grouping</th>
</tr>
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<tbody>
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<td>1</td>
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<tr>
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<td>20.0</td>
<td>C</td>
</tr>
</tbody>
</table>
The yield results for soybean show similar trends to those of corn. The most notable difference is that the weed-free control treatment gave the best yield, 3.37 t/ha. This is to be expected and makes more sense than the corn results. Treatment 5, flaming + cultivation twice, is the next best treatment yielding 3.34 t/ha, followed by treatment 7, full flaming twice, with 2.79 t/ha. The worst treatment besides the weedy season-long is treatment 6, full flaming once, with 1.52 t/ha.

### 3.3. 2010 Field Study Conclusions

It is apparent from the 2010 field results that the best weed control treatments among those tested are flaming + cultivation twice and full flaming twice. Flaming + cultivation twice provided high levels of weed control and weed dry matter reduction with little crop injury or yield loss. This was true in both corn and soybean. Although flaming + cultivation twice (70-95% weed control) outperformed full flaming twice (10-90% weed control) in both cases, full flaming twice can be an important alternative for rainy seasons in which the soil is too wet to cultivate. Note that the weed control was less than 10 percent at 28 DAT with full flaming twice in soybean, whereas it performed much better in corn. It is also clear from the 2010 field results that a single weed control treatment per season cannot provide sufficient weed control. Finally, cultivation alone has proven to be insufficient for season-long weed control, confirming one of the hypotheses made in the introduction.

Looking at both corn and soybean yield results, the top two treatments besides the weed-free control were flaming + cultivation twice and full flaming twice, which both had the following characteristics:
a. They contained two applications.

b. They were the only ones that included intra-row flaming in both applications.

Thus, these are characteristics which must be included with any successful weed control treatment.
Chapter 4. Design of Second Flamer/Cultivator Prototype

During spring 2011, the flamer/cultivator hood and torch mounting system was redesigned. There were some shortcomings in the first design that were modified upon assembly, as mentioned in Chapter 2. These were addressed in the second design. Ease of manufacture was also taken into consideration. Finally, new torches were designed in 2011 to replace the cylindrical Flame Engineering torches, and the new hood design was built around these new torches.

4.1. U-bolt Mounting System

The first prototype had a set screw holding the hood mount in place on the shovel beams. It was determined that these mounts inevitably rattle and shake loose, causing the operator to tighten the set screws before each treatment. The new system, shown in Figure 23, has two square U-bolts that clamp each hood mount in place. The height adjustment is the same as before; a 1-inch square tube slides up and down and has seven holes drilled 1 inch apart for a squared retainer snap safety pin to hold it in place.

Figure 23. New flamer/cultivator hood and torch mounting system.
4.2. New Crop Guides

The old flamer/cultivator hoods had a flat piece of sheet steel above the torch, parallel to the ground, which funneled the crop between the hood halves during flaming at late growth stages. There were two major problems with this design. First, the old crop guides extended 36.8 cm (14.5 in) behind the hood inlet, sometimes interfering with the three-point hitch. Second, there was no extra room between the top of the old torches and the crop guide. In fact, the new torches designed in 2011 did not fit underneath the old crop guide at all. The solution, shown in Figure 23, was to replace the piece of sheet steel on top with a 6.35-mm (1/4-in) thick steel strap that bends around the torch. The steel strap is removable, and bolts to the side and top of the hood. The strap is removable because it fits tightly around the torch, and must be removed when installing or uninstalling the torches.

4.3. Continuously Sloping Hood Roof

The roof of the old flamer/cultivator hoods had two portions, as shown in Figure 9. One portion sloped down at a 30° angle from the hood inlet, and the other was a horizontal portion at 11.4 cm (4.5 in) above the bottom of the hood that led to the hood exit. The new hood design has just one flat piece of sheet steel, and it slopes continuously from the top of the hood inlet, 30 cm (12 in) from the bottom, to the hood exit, 11.4 cm (4.5 in) from the bottom, as shown in Figure 24. Thus the hood roof slopes at a 17° angle. Having one flat piece for the roof makes manufacturing and assembly easier. It allows the hood roof and side wall to be made from one sheet of steel, with a single bend made by a press brake.
4.4. New Torch Mounts

The first prototype design used an angle iron which cantilevered from the sidewall to hang the cylindrical torches from. The new torches designed for 2011, which will be discussed in Chapter 5, are box-shaped. To reduce the number of parts, the new torches had bolts welded to the side and were directly bolted to the side wall of the flamer/cultivator hood. This meant that the torches must be designated left or right, depending on which side of the torch the bolts were welded to. The holes drilled in the hood side wall are such that the torches make a 30° angle with the ground as before. These can be seen best in Figure 23.

4.5. Wider Gap

The new flamer/cultivator hoods still have a removable cover which can be removed during flaming at late growth stages when the crop is tall. The old hood design called for a 7.62-cm (3-in) gap. This was problematic when flaming on side hills; the crop grew straight up despite the side slope and got caught in the hoods which followed the hill slope. The new hood design calls for a 10.2-cm (4-in) gap, as shown in Figure 25. Each
hood half is also 10.2 cm (4 in) wide. Thus the total width of the hood is 30 cm (12 in), the same as in the original design.

Figure 25. New flamer/cultivator hoods in late flaming setup.

4.6. Results and Discussion

These new flamer/cultivator hoods have been built and tested, and most of the changes have worked well. In particular, the U-bolt clamping system provides a nice, tight hold that does not need to be adjusted often. An issue that was not anticipated was warping of the hood sidewalls due to the torch being mounted directly onto them. The heat produced by the torches is quite significant, and the warping of the hoods due to this heat can cause the torches to point slightly to the side. The abilities of the old and new hood designs to keep heat close to the weeds are addressed in the temperature measurements in Chapter 7.
Chapter 5. Torch Design

The original flamer/cultivator prototype used 3-in wide cylindrical LT 3-12 T torches purchased from Flame Engineering, Inc. Each half of the hood covers one torch, and there is one torch passing by each side of the crop row. These torches performed well and produced very stable flames. However, it was desired to improve on certain aspects of the torch. To accomplish this and better understand the propane vaporization process, new torches were designed as part of this research project.

5.1. Literature Review

Before discussing the characteristics of torches, the definition of a flame must be established. Turns (2000) defines a flame as a “self-sustaining propagation of a localized combustion zone at subsonic velocities.” Another way a flame is described is the location where the equivalence ratio, $\Phi$, is equal to 1. The equivalence ratio is the ratio of the stoichiometric air-fuel ratio, $(A/F)_{stoic}$, to the actual air-fuel ratio, $A/F$.

$$\Phi = \frac{(A/F)_{stoic}}{(A/F)}$$ (1)

Thus when $\Phi > 1$, the mixture is fuel-rich, and when $\Phi < 1$, the mixture is fuel-lean.

Harris et al. (1969) said that flame stability and performance depends on two processes, primary air entrainment and propagation of the combustion wave. In the Flame Engineering (FE) torches, the primary air comes in through the two oval-shaped openings at the back of the torch, as shown in Figure 26. If this primary air is not sufficient for combustion, secondary air can diffuse into the reaction zone from outlet end of the torch, where the long vaporizer rod sticks out.
Pritchard et al. (1977) provided a thorough evaluation of the different types of burners (torches) available today and the design process for each type. The torches used for the flamer/cultivator fall under the category of atmospheric aerated burners. The fuel in vapor state emerges from an orifice and enters a mixture tube. “Primary air is entrained by momentum sharing between this jet and the surrounding air. The amount of air induced in this way is generally about 50 to 70 [percent] of the stoichiometric air requirement” (Pritchard et al., 1977). The remaining air necessary for combustion is the secondary air and is gathered at the burner port.

For the conditions that are utilized in the weed flaming torches, the type of flame is a diffusion, or nonpremixed, flame. This means that the fuel and oxidizer diffuse toward each other and meet in a flame. As will be seen in the torch prototype photos, propane is a very clean-burning fuel, producing little soot. The result is a long blue flame. There are four major design issues that Turns (2000) discusses for turbulent nonpremixed flames:

- Flame shape and size
- Flame holding and stability
- Heat transfer
- Pollutant emissions
The first three issues are of greatest concern in these weed flaming torches. The flame shape and size turned out to have a greater impact on weed control in the studies considered here than initially thought. Turns (2000) states that the width of the “flame zone” increases with downstream distance. As for the flame length, many definitions and techniques for measuring it exist, but no single one is accepted as preferred. For the torch prototype testing, a flame length is defined in Section 5.5.3. As the fuel flowrate increases and the flow transitions from laminar to turbulent, flame lengths become significantly dependent on initial jet diameter and less dependent on the gas injection velocity (Turns, 2000).

If the fuel flowrate is low, the base of a jet flame is close to the nozzle, and the flame is said to be attached. As the flowrate increases, holes increasingly form in the flame sheet at the base of the flame, and at a sufficiently high flowrate, there is no continuous flame close to the nozzle. This condition is called liftoff (Turns, 2000). The distance from the nozzle to the start of the flame is the liftoff length, and within this distance, a substantial amount of air is entrained (Bergstrand et al., 2002). This liftoff length increases approximately linearly with the gas injection velocity. With sufficiently high gas injection velocity, the flame could be extinguished (which is called blowout), and the same can occur in the case with a too low gas injection velocity (Bergstrand et al., 2002).

Bergstrand et al. (2002) also found in their experimental work that the flame liftoff length increases with an increase in nozzle orifice diameter. Turns (2000) said that liftoff should be avoided to maintain a stable flame, and that operation near the blowout limit
should be avoided as well. Blowout leads to a room filled with a raw fuel-air mixture, creating “an immense hazard.” There are three theories of blowout that are discussed by Turns (2000). The first has origins that date back to 1949 and will be presented here. This theory says that the liftoff length occurs when the local flow velocity at the position where the laminar flame speed is a maximum matches the turbulent burning velocity of a premixed flame.

5.2. Old Torch

The FE torches previously used were fed by a liquid LP gas (also known as propane) supply. The inlet end of the torch is shown in the right end of the left photo in Figure 26. The propane enters the inner of two concentric cylinders. The outer cylinder is the long vaporizer rod which protrudes 12.1 cm (4.75 in) from the exit of the housing as shown. When the liquid propane reaches the end of the vaporizer rod, it exits the inner cylinder, makes a 180° turn, and flows back toward the torch housing within the annulus inside the vaporizer rod. This vaporizer rod uses heat from direct flame contact to vaporize the liquid LP gas inside. After traveling back into the torch housing through the annulus, the propane, which is now vaporized, makes another 180° turn and exits through the twin pinhole burners shown in Figure 27.

Figure 27. Twin pinhole burners seen in an end view of the FE torch.
During the 2010 field study, an operating pressure of 15 psig was used with this torch, to deliver LP gas at a rate of 1.07 g/s. When traveling at 4.8 km/h (3 mi/h) through crop rows with 0.76-m (30-in) spacing, this produces the 19 kg/ha (4 GPA) application rate desired.

5.3. Goals of New Design

The vaporizer rod on the Flame Engineering (FE) torch tended to be in the way when flaming soybeans. The hood/torch system sometimes needs to be lowered during soybean treatment. The long rod often interferes with the ground. Also, it was desired to eliminate direct flame contact with the vaporizer rod. Thus the rod needed to be moved on top of the housing, away from the flame. Second, it was desired to have the torch operate at a higher pressure than the FE torch. A higher operating pressure would mean that the LP gas travels through the plumbing network at a higher temperature, lessening the frost buildup on the plumbing network. Third, the new torch was to have a single nozzle rather than twin pinhole burners. Fourth, the new torch must also have sufficient space for the operator to reach in and change the nozzle if needed.

In the course of testing the old and new torches, it was seen that some housing designs allowed the flame to anchor on the bottom plate, causing the housing to glow red hot in spots. Such effects were undesirable and had to be eliminated. Finally, this torch needed to have the capability to be integrated into an electronic ignition system. An electronic ignition system allows the operator to light the torches with the flick of a switch from the driver’s seat, rather than dangerous lighting by hand with a blowtorch. Such a system should also be able to detect if a flame has extinguished in a torch, and relight that torch.
5.4. Bending the New Vaporizer Tube

The vaporizer tube for the new flamer/cultivator torch was originally designed for another torch within the Propane Flame Weeding research group. That other torch is for broadcast flaming applications and has a cowbell shape. Henceforth it shall be called the UNL 5 prototype, as the final design was the fifth prototype tested. The vaporizer for the UNL 5 torch also needed to be moved out of the housing, just like the cylindrical torch. An initial vaporizer was designed which wrapped outside and inside one side wall of the housing. It was determined that 0.953-cm (3/8-in) steel tubing was the largest size which would give a reasonable bending radius for use in the torch housing. A hand tube bender was purchased, along with some 0.953-cm (3/8-in) steel tube stock. A crudely bent tube was made in the laboratory, and a hand tube flaring tool was used to make gas-tight connections for the LP gas hose and nozzle. The tube is shown in Figure 28.

![Figure 28. First crudely bent tube with flare fittings on each end.](image1)

![Figure 29. Second crudely bent tube clamped to FE cowbell torch housing.](image2)
A longer tube was made, and was clamped to a FE cowbell housing with the vaporizer rod removed, as shown in Figure 29. An LP gas source was attached to the vaporizer and the torch was run at 10 and 20 psig with an H ¼ VV-8008 nozzle from Spraying Systems Company. This nozzle will henceforth be referred to as the “8008”, and similarly with other nozzles from this supplier, such as 8006, 1506, and 0006. In the Spraying Systems Company naming convention, the first two digits represent the spray angle of the nozzle (80° in this case). The last two digits represent the water flow capacity of the nozzle at 40 psig. For example, the “08” in this nozzle represents a water flow capacity of 0.8 gpm at 40 psig. At 10 psig, the torch in Figure 29 was stable and appeared to be completely vaporizing for the first 1 minute, 45 seconds. After that, frost built up on the vaporizer and the LP gas did not completely vaporize. The flame got larger and orange, as shown in Figure 30. Also, when the nozzle and tube were moved forward into the middle of the housing, the flame became unstable.

![Figure 30. Large orange flame resulting from incomplete vaporization of LP gas.](image)

The flame transferred a significant amount of heat to the torch housing, as it was much too hot to handle right after the test. However, the amount of heat transferred from the housing to the tube was insufficient to vaporize the LP gas. One reason for this was that there was only line contact between the tube and housing. The next step was to design a
torch housing with a vaporizer tube welded to the top. The weld area would greatly increase the heat transfer area, and would hopefully provide sufficient heat for LP gas vaporization. During vaporization, a layer of film vapor is formed on the inside of the vaporizing tube. This vapor has a large thermal resistance, further increasing the amount of heat needed to completely vaporize the liquid propane supply.

5.5. Testing Prototypes

5.5.1. Breakthroughs from the UNL 5 Torch

The UNL 5 torch developed in the Propane Weed Flaming research group is pictured in Figure 31. It is 2.54 cm (1 in) longer than the old FE cowbell torch, and is made of a thicker, 0.318-mm (1/8 in) sheet steel. A great deal was learned in the course of the design, testing, and re-design of these large torch prototypes. The two major breakthroughs that were applied to the design of the new flamer/cultivator torch are discussed next.

Figure 31. UNL 5 torch during testing in the lab.
The weld area used initially turned out to be insufficient when tested. Several different methods were tried to increase the length of the tube or the weld contact area, and none of them completely vaporized the liquid LP gas. Bursts of liquid spray resulted in pulsing orange flames, similar to that shown in Figure 30, at pressures as low as 10 psig. It was necessary to eliminate the propane film vapor with some type of a flow mixer to complete the vaporization of the liquid propane.

Two 1.6-mm (1/16-in) diameter wires were inserted inside the vaporizer tube of the UNL 5 torch. One was inserted at the start of the final U-bend, and the other was inserted at the start of the second 90° bend. There was no liquid pulsing at pressures tested up to 20 psig. Various other forms of flow mixers were tried with varying success. By far the best flow mixer was made up of two 27.9-cm (11-in)-long compression springs with an outer diameter of 5.33 mm (0.21 in). They were large enough to fill most of the tube’s inner diameter, but loose enough to slide around by hand inside the tube. There was no liquid pulse with either the 8006 or 8008 nozzles, up to 70 psig.

The second major breakthrough relates to keeping the torch housing temperatures low. Several of the designs allowed the flame to anchor on the bottom plate, causing it to glow red hot, as shown in Figure 32. In an earlier version of the UNL 5 torch, shown in Figure 32, the top and bottom plates are parallel. The solution was to tilt the bottom plate downwards adequately so that the flame passed over it and did not anchor to it. An angle of tilt of 8° was adequate (see Figure 31).
5.5.2. FC 1 Torch Prototype

Coming off of the success of designing the UNL 5 torch, the box-shaped torch for the flamer/cultivator was created by modifying the UNL 5 design. The flaming hood used for the flamer/cultivator is shown in Figure 24. The total hood is 30 cm (12 in) wide, with each “half” of the hood being 10.2 cm (4 in) wide and joined by a flat plate in the middle. The new torches for this hood must be narrow enough to fit underneath the 10.2-cm (4-in) width of each hood half.

The old FE torches were cylindrical in shape, but it was decided to try a box-shaped torch to remain as similar to the UNL 5 torch as possible. The first prototype, known as FC 1, essentially took the UNL 5 torch and cut off the sides that flare out, as shown in Figure 33. The side walls on FC 1 were parallel. The top was perpendicular to the side walls, and the bottom plate was tilted downward by 8°, the same as UNL 5.
The total width of the vaporizer tube, which is also the same as on UNL 5, is 8.26 cm (3.25 in). The FC 1 torch was made 8.89 cm (3.5 in) wide so that the torch was as narrow as possible. This made welding the vaporizer tube to the top difficult, and so the vaporizer tube was bent a bit narrower to fit on the torch.

The first test conducted with the FC 1 torch was with an 8006 nozzle, the same as the final UNL 5 design. It was hypothesized before the experiment that the spray angle would be much too large, but it would give a baseline to start from. The torch operated beautifully during this first test. The flame produced was stable, and remained the same width as the housing, that is, the parallel sides did not allow the visible flame to spread out when it left the housing. The major problem with the 8006 nozzle was that the flame was shooting at the inside walls of the housing, causing them to glow bright red, as shown in Figure 34 at 20 psig.
The results from this test were encouraging, however, as the flame hit the ground and spread out nicely, as seen in Figure 34. The propane mass flow rates were very close to those of the UNL 5 torch. The torch needed a nozzle with a much smaller spray angle.

The next test run with the FC 1 housing was with an H \( \frac{1}{4} \) VV-1506 nozzle, referred to as the 1506, shown at 20 psig in Figure 35. This nozzle has the same flow rate as an 8006 nozzle, but with a 15° spray angle. The smaller spray angle produced a dramatic difference in the housing temperature, as it was not glowing red at all. At 5 psig, the torch produced a nice stable flame. At 10 psig, however, the torch extinguished after 3.5 minutes. At this point, it was decided to bend the tube so that the nozzle was more biased toward the top plate of the torch. It was then 19 mm from the top. The flame was once again stable at 5 psig. The stability was improved by covering various amounts of the air intake area with small plates. This also decreased the visible flame liftoff length.
From the work of Bergstrand et al. (2002), it is known that increasing the entrainment increases the liftoff length, and makes the flame leaner. Thus, it makes sense that decreasing the primary air entrainment area with plates would decrease entrainment and decrease the liftoff length.

Another option for testing was a H ¼ U-0006 nozzle with a 0° spray angle, that is, a circular orifice, referred to as 0006. This test was conducted, starting with an operating pressure of 5 psig. It was quickly discovered that this setup was unstable, as the torch extinguished within 30 seconds. It was also tried at pressures up to 40 psig. The torch again extinguished at 10 and 15 psig. At 20 and 30 psig the torch did not extinguish but was not very stable. Covering various amounts of the air intake did not fix the problem sufficiently. So the 0006 nozzle was discarded, and the 1506 was kept.

According to the Spraying Systems Company Catalog 70 (2010), both the 8006 and 1506 nozzles have an equivalent orifice diameter of 0.061 in. The 0006 nozzle, however, has an equivalent orifice diameter of 0.058 in, which is 4.9 percent smaller than the others.
This smaller orifice would logically have a greater flame liftoff length due to the higher velocity at which fuel emerges from the orifice. Therefore, this flame was less stable. Bergstrand et al. (2002) also normalized the flame liftoff length with orifice diameter, finding a relatively larger liftoff length with a smaller orifice diameter. They claim this would be beneficial to air entrainment. One might conclude that this additional air entrainment is causing the instability of the flame.

5.5.3. FC 1B Torch Prototype

Rather than building an entirely new housing, the torch housing of FC 1 was modified. Two small plates were welded over the air intake area to make the intake smaller. The remaining opening was 3/4 inch wide by 2 inches tall. The modified torch was operated with the 1506 nozzle for the next trial, shown in Figure 36 at 30 psig. At 5 psig, the torch produced a nice, stable, blue flame. The results looked just as good at 10, 20, 30, and 40 psig. The housing temperatures, which were already low with the original FC 1 configuration, were even lower with this FC 1B configuration.

Figure 36. FC 1B torch during testing in the lab with a 1506 nozzle.
The test was run a total of four times, each with different 1506 nozzles, to check if the nozzle itself varied significantly. The plot of the LP gas mass flowrates of the four nozzles (A, B, C, and D) is given in Figure 37.

![Graph showing LP gas mass flowrates](image)

**Figure 37. Variance of the LP gas mass flow rate in four different 1506 nozzles in FC 1B.**

The visible flame length was also measured for each nozzle at each operating pressure. The reported value is actually a horizontal projection of the flame on the test bench, starting directly below the torch exit. The flame length measurement setup is shown in Figure 38. The visible flame lengths for the FC 1B prototype are shown in Figure 39. There is some variance in these quantities at the higher pressures, but overall the nozzles seem to be reasonably similar.

![Schematic profile view of flame length measurement](image)

**Figure 38. Schematic profile view of flame length measurement.**
5.5.4. FC 2 Torch Prototype

After seeing the results of the FC 1B torch, it was decided to finalize the changes and wrap them all up into a new housing. The FC 2 torch can be seen in Figure 40. FC 2 was built slightly wider, 9.53 cm (3.75 in) instead of 8.89 cm (3.5 in). This allowed the vaporizer used on UNL 5 to be welded to the top without sacrificing weld area. The air intake area was 2.54 cm (1 in) wide by 5.08 cm (2 in) tall, and the plates covering the back area were based on the two combined plates on FC 1B. New permanent fixtures for the LP gas inlet and nozzle outlet were welded to the tube. In addition, a rigid mount on the back of the torch fixed the nozzle position and direction. The vaporizer tube was also made shorter in the back to save on space and material.
The results of the test were excellent, as the same stable, blue flame was produced by this torch. The housing temperatures were also quite low. Like the FC 1B torch, FC 2 was tested four times, each with a different 1506 nozzle. The agreement among nozzles was even better for this torch, as shown for LP gas mass flowrate and visible flame length in Figure 41 and Figure 42, respectively. A layer of fire bricks was added to protect the test bench soil pans for these trials. The new height of the torch above the testing surface was 4.6 in, so the flame lengths may not be directly comparable to those for the FC 1B torch.

Figure 41. Variance of LP gas mass flow rate for four different 1506 nozzles in FC 2.
The final test for this prototype to prove its durability was a 2-hour endurance test. The torch was set at the desired operating pressure of 25 psig, and run constantly for 2 hours. The mass flow rate, housing temperature, visible flame length, and other data were recorded at 5, 10, and 15 minutes, and every 15 minutes following that. The data was very steady, and the LP gas mass flowrate hovered at 1.00 g/s for the entire 2 hours.

**5.6. Final Torch Fabrication**

Once the endurance test for FC 2 was completed and everything met the design requirements, the design was given to a local fabrication company, TMCO, to build a set of torches for use on the flamer/cultivator research units. They produced the model shown in Figure 43. Note that a circular port was added on top for a spark plug to be threaded into. This allows for the future installation of an electronic ignition system.

The bolt on top allows for the torch to be hung from the top as before. Later, bolts were welded to one side of the torches to allow them to be directly bolted to the left and right side walls of the flamer/cultivator hoods. Finally, the vaporizer tube was made as long as
it originally was on FC 1 and 1B, in order to have one common vaporizer size for manufacturing UNL 5 and FC 2.

Figure 43. Final version of flamer/cultivator torch produced by TMCO.

Figure 44 shows the torches installed on the new flamer/cultivator hoods. Note that they are bolted to the hood side walls.

Figure 44. New torches mounted on the flamer/cultivator hoods.

After installing the new torches and hoods on the flamer/cultivator, the torches were run at night so that the blue flames were easily visible. The flame width was equal to the width of the torch housing, as mentioned earlier, and there was a noticeable gap in between the two visible flames under each hood. This observation is shown in Figure 45.
At the end of the summer, it was noticed that several of the plots treated by the flamer/cultivator had a strip of grasses left within the crop row. It is thought that perhaps the gap between the visible flames under each hood is also leaving a strip within the crop row where the temperatures are not sufficiently high to kill weeds. Temperature measurements were made in the fall of 2011 to test this hypothesis, and are discussed in Chapter 7.
Chapter 6. 2011 Field Study

After reviewing the promising results from the 2010 field studies, it was decided to repeat the studies to make a stronger case for the data. The main differences from the 2010 field study were that different fields were used due to crop rotation, and the new torches and hoods were used on the flaming equipment. In addition, weather is an ever-present variable which cannot be controlled. The corn and soybean results will once again be discussed separately.

6.1. Corn 2011 Field Study

6.1.1. Corn Materials and Methods

In corn, the same eight treatments as in 2010 were compared that involved cultivation, flaming, or a combination of the two, as well as weed-free and weedy-season-long control plots, as listed below.

1. Weed-free control
2. Cultivation once (V3)
3. Cultivation twice (V3 & V6)
4. Flaming + cultivation once (V3)
5. Flaming + cultivation twice (V3 & V6)
6. Full flaming once (V3)
7. Full flaming twice (V3 & V6)
8. Weedy season-long

The row spacing used in the treatments was 0.76 m (30 in). The seed planted was the same organic corn hybrid as in 2010. Conventional soil was used in this study, but it did not receive any herbicide during the year of the study. The soil type is Moody silty clay loam, 6 to 11 percent slopes (Soil Survey Staff, 2012). The field preparations included
one disking and one field cultivation. The study was planted on June 1 at a rate of 25,677 seeds/acre.

The plots were 13.7 m (45 ft) long by 3.05 m (10 ft) wide, which meant there were four rows in each plot. The harvesting was done by hand, and was taken from 4-m lengths in each of the two middle rows of each plot, for a total of 8 m harvested. The samples were threshed using an ALMACO thresher, and the moisture content was taken using a Dickey-John GAC 2000 Grain Analysis Computer.

For treatment 1, the plots were maintained by hand weeding, a common practice by many organic farmers. The equipment used for treatments 2-5 was the Noble flamer/cultivator, shown in Figure 46 with the new hoods and torches, mounted on a tractor using a three-point hitch. For treatments 2 and 3, with cultivation only, the torches were not running. For treatments 4 and 5, with cultivation + flaming, the torches were running. Treatment 8, weedy season-long, was left alone; nothing was done to it the entire season.

![Figure 46. Noble flamer/cultivator used in the 2011 field study.](image-url)
The equipment used for treatments 6 and 7 was the so-called “full flamer”, which is shown in Figure 47. The torches are the larger torches known as UNL 5 and shown in Figure 31.

![Image: Full flamer in the early flaming setup (left) and late flaming setup (right).](image)

The operating speed for both of the implements used was 4.8 km/h (3 mi/h). The propane dose applied differs between treatments. Treatments 6 and 7, which utilize the full flaming unit for broadcast flaming, use a rate of 45 kg/ha (10 GPA). Treatments 4 and 5 use cultivation combined with banded flaming, and a rate of 19 kg/ha (4 GPA). The mass flowrate of each torch was taken from the data in Chapter 5. The flowrate, coverage area, and operating speed were used to determine the values of the application rates. The treatments at the V3 stage were conducted on June 19, and the V6 treatments were conducted on July 4.

The treatments were evaluated based on four performance parameters. Visual ratings of weed control and crop injury were taken 1, 7, 14, and 28 days after treatment (DAT). DAT refers to the number of days after the last application of a treatment in a plot. For example, this is days after the first application for treatments 2, 4, and 6, which have only
one application, while this is days after the second application for treatments 3, 5, and 7, which have two applications. The ratings used a scale of 0-100%, where 0% means no crop injury or weed control, and 100% means plant death, as illustrated in Figure 16. Weed dry matter was collected on a single day for the entire study, from a 0.5-m² quadrat in the middle two rows of each plot, at approximately 60 days after the final treatment applications in the study. Thus, it was 60 DAT for treatments 3, 5, and 7, and 75 DAT for treatments 2, 4, and 6. Finally, crop yields were taken at harvest, using the procedure mentioned previously.

6.1.2. 2011 Corn Results

An ANOVA analysis was performed on the two years of data, 2010 and 2011, using SAS statistical software. Prior to performing the analysis, the four data points in each treatment per year were subjected to the Tukey robust outlier test. In this method, any value greater than the 75th percentile plus 1.5 times the interquartile distance, or less than the 25th percentile minus 1.5 times the inter-quartile distance, is treated as an outlier and is discarded (Shoemaker, 1999). The data was significantly different between the two years at the $\alpha = 0.05$ significance level and could not be pooled. Error bars on the plots show the standard error of the means. The weed control ratings for corn at 7 and 28 DAT are shown in graphical form in Figure 48.
The best treatment for weed control is treatment 5, which is flaming + cultivation twice, with over 75 percent weed control at 28 DAT. This was also the best weed control treatment in 2010. The second best treatment is harder to determine. Full flaming twice, treatment 7, was the second best in 2010 but has fallen behind in 2011. Treatment 2, cultivation once, has a slight edge for second best. However, the weed control level is less than satisfactory.

Visual ratings of the corn injury were taken at the same times and the ratings for this are shown in Figure 49.
Treatment 1 is the weed free control plot and does not present corn injury. Likewise, treatments 2 and 3 were cultivation alone and did not present corn injury. These treatments are not shown in Figure 49. For all of the treatments shown, the level of corn injury is highest at 7 DAT compared to 14 and 28 DAT. The highest level of injury from the flamer/cultivator (treatments 4 and 5) is approximately 38 percent at 7 DAT, more than double the injury in 2010. By 28 DAT, the corn injury has been reduced to 14 percent for treatment 5. Treatments 5 and 7 show very similar crop injury, and can be considered the best in this category.

The results for weed dry matter in corn are shown in Figure 50.
The clear winner among these treatments is treatment 5, flaming + cultivation twice, with 39 g/m$^2$. On the other hand, treatment 4, flaming + cultivation once, has the most weed dry matter with 245 g/m$^2$. Recall that treatment 5 only had 2.1 g/m$^2$ of weed dry matter in 2010. Also, the weed control level was somewhat reduced in 2011, with only 75 percent control compared to 98 percent control in 2010. Why is there such a difference?

There could be many reasons:

a) The torches used in 2010 had an operating pressure of 15 psig, whereas the new torches designed and used in 2011 had an operating pressure of 25 psig for the same propane flowrate. Increased pressure also increases the gas jet velocity, which can decrease the time of contact of the gas with the soil (Storeheier, 1994). If the weeds are in contact with the hot gas for a little less time, they have less chance of becoming hot enough to wilt. Thus it seems that time of exposure at high temperature, not propane flowrate, is the most important factor in plant
damage. In addition, operating the torches at a different pressure leads to different flame shape and size.

b) The weed composition is also dramatically different between 2010 and 2011. The weed dry matter data was broken down by weed species, and the total percentage of grasses and broadleaf weeds were determined for each year. The totals are shown in Table 4. This only measures the weed species left at 60 DAT. However, since it is known that grasses are very difficult to kill by flaming (Ulloa et al., 2010a), it can be inferred that the 2011 field had a much higher percentage of grasses to begin with than the 2010 field. Thus, the 2011 reduction in weed control may be simply a reflection of the higher grass percentage.

Table 4. Species breakdown of weed dry matter at 60 DAT in corn.

<table>
<thead>
<tr>
<th>Year</th>
<th>% Broadleaves</th>
<th>% Grasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>78</td>
<td>22</td>
</tr>
<tr>
<td>2011</td>
<td>36</td>
<td>64</td>
</tr>
</tbody>
</table>

From an economic standpoint, the most important result is yield, and the results of the corn yield are shown in Table 5.

Table 5. 2011 yield results for corn.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (t/ha)</th>
<th>Yield (bu/ac)</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.81</td>
<td>156.3</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>9.16</td>
<td>146.0</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>8.46</td>
<td>134.7</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>8.27</td>
<td>131.7</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>7.99</td>
<td>127.3</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>7.96</td>
<td>126.7</td>
<td>A</td>
</tr>
<tr>
<td>7</td>
<td>7.77</td>
<td>123.7</td>
<td>B</td>
</tr>
<tr>
<td>8</td>
<td>7.40</td>
<td>117.9</td>
<td>B</td>
</tr>
</tbody>
</table>
The letters in the last column represent the statistical grouping of the treatments. Those treatments that contain the same letter are not statistically different at the $\alpha = 0.05$ significance level. The yield results correspond to the trends shown in the weed control, crop injury, and weed dry matter ratings. The weed-free control had the best yield, with 9.81 t/ha. Treatment 5, which is flaming + cultivation twice, gave the best yield of the weed control treatments, with 9.16 t/ha. Note that all of the treatments other than the weed-free control are statistically similar, being in the “B” grouping. Although treatment 5 is the best, full flaming treatments are not significantly lower in yield.

6.2. Soybean 2011 Field Study

6.2.1. Soybean Materials and Methods

In soybean, the same seven treatments as in 2010 were compared that involved cultivation, flaming, or a combination of the two, as well as weed-free and weedy-season-long control plots, as listed below.

1. Weed-free control
2. Weedy season-long
3. Flaming once at VC, followed by cultivation at V5
4. Flaming + cultivation once (VC)
5. Flaming + cultivation twice (VC & V5)
6. Full flaming once at (VC)
7. Full flaming twice at (VC & V5)

The soybean plants were too short at the V4 stage in 2011 for flaming, so it was completed at V5 instead. The row spacing used in the treatments was 0.76 m (30 in). The seed planted was the same organic soybean hybrid as in 2010. Conventional soil was used in this study, but it did not receive any herbicide during the year of the study. The
soil type is Alcester silt loam, 2 to 6 percent slopes (Soil Survey Staff, 2012). The field preparations included one disking and one field cultivation. The study was planted on June 11 at a rate of 149,000 seeds/acre. The soybeans emerged on June 18.

The flaming and harvesting equipment used was the same as described in the corn study. The operating speed for both of the implements used was 4.8 km/h (3 mi/h). The propane dose applied differs between treatments. Treatments 6 and 7, which utilize the full flaming unit for broadcast flaming, use a rate of 45 kg/ha (10 GPA). Treatments 4 and 5 use cultivation combined with banded flaming, and a rate of 19 kg/ha (4 GPA). The mass flowrate of each torch was taken from the data in Chapter 5. The flowrate, coverage area, and operating speed were used to determine the values of the application rates. The treatments at the VC stage were conducted on June 19, and the V5 treatments were conducted on July 18.

The treatments were evaluated based on four performance parameters. Visual ratings of weed control and crop injury were taken 1, 7, 14, and 28 days after treatment (DAT). DAT refers to the number of days after the last application of a treatment in a plot. For example, this is days after the first application for treatments 2, 4, and 6, which have only one application, while this is days after the second application for treatments 3, 5, and 7, which have two applications. The ratings used a scale of 0-100%, where 0% means no crop injury or weed control, and 100% means plant death, as illustrated in Figure 16. Weed dry matter was collected on a single day for the entire study, from a 0.5-m² quadrat in the middle two rows of each plot, at approximately 60 days after the final treatment.
applications in the study. Thus, it was 60 DAT for treatments 3, 5, and 7, and 89 DAT for treatments 2, 4, and 6. Finally, crop yields were taken at harvest, using the procedure mentioned previously.

6.2.2. 2011 Soybean Results

The ANOVA procedure and Tukey outlier analysis were conducted on the data, as mentioned above in the corn study. Error bars on the plots show the standard error of the means. The weed control ratings for soybean are shown in graphical form in Figure 51.

![Figure 51. 2011 weed control ratings for soybean.](image)

The results of this study are fairly consistent with 2010 data. Treatment 5, flaming + cultivation twice, clearly has the highest weed control, with 83 percent at 28 DAT. Treatments 3 and 4 have reversed positions from 2010. Treatment 3, flaming at VC + cultivation at V5, now has the second best weed control. It makes sense that a single-pass treatment like flaming + cultivation only once (treatment 4) is not sufficient for weed control.
The soybean injury ratings were taken at the same times, and the results are shown in graphical form in Figure 52. Treatments 1 and 2 did not present any injury and are not shown in Figure 52.

![Figure 52. 2011 crop injury ratings for soybean.](image)

The soybean injury trends between treatments are also somewhat consistent with the 2010 data. However, actual crop injury percentages are much higher than in 2010. Treatment 4, flaming + cultivation once, has the lowest soybean injury, with 4 percent at 28 DAT. Treatment 6 is also low, with 6 percent. It should be noted that although these treatments presented the lowest crop injury, which should be minimized in a treatment, they have proven to be ineffective at weed control, which is the primary goal of performing the treatment. Flaming + cultivation twice came in with 21 percent soybean injury. The main reason for the higher injury may be due to the shorter height of the plants in 2011. Also, any difference in moisture between the two years may have affected the relative water content in the crop.
The results for weed dry matter in soybean are shown in graphical form in Figure 53.

![Figure 53. 2011 weed dry matter results in soybean.](image)

Once again, treatment 5 has the most weed dry matter reduction, with 42 g/m² remaining at the time of measurement, as compared to 251 g/m² for the weedy season-long treatment, #2. The full flaming treatment applied once (treatment 6) had even more remaining weed dry matter, with 291 g/m². Again, why is the weed control so much less in 2011?

As discussed in corn, the torches used in 2010 had a higher operating pressure of 15 psig, compared to 25 psig in 2011 for the same propane flowrate. Increased pressure also increases the gas jet velocity, which can increase the time of contact of the gas with the soil (Storeheier, 1994). The lower contact time of the flame and the plants may be a factor in the lower weed control. It appears that weed composition does not have as large
an effect in soybean as in corn, as the weed dry matter was split nearly evenly between grasses and broadleaf weeds in 2011.

Economically, the most important results for soybean, as for corn, are the yield values. The yield values for soybean are presented in Table 6.

Table 6. 2011 yield results for soybean.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (t/ha)</th>
<th>Yield (bu/ac)</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.68</td>
<td>39.9</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>2.26</td>
<td>33.7</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>2.25</td>
<td>33.5</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>1.75</td>
<td>26.1</td>
<td>B</td>
</tr>
<tr>
<td>2</td>
<td>1.68</td>
<td>25.0</td>
<td>B</td>
</tr>
<tr>
<td>7</td>
<td>1.61</td>
<td>24.0</td>
<td>B</td>
</tr>
<tr>
<td>6</td>
<td>1.35</td>
<td>20.2</td>
<td>B</td>
</tr>
</tbody>
</table>

The yield results for soybean show some similarities to the 2010 results. The weed-free control treatment gave the best yield, 2.68 t/ha. This is to be expected. Treatment 5, flaming + cultivation twice, gave the next best result, yielding 2.26 t/ha. Treatment 3, flaming at VC followed by cultivation at V5, is the other treatment which is statistically similar to the first two at the $\alpha = 0.05$ significance level, performing better than in 2010. This is very consistent with the weed dry matter result. It seems that flaming alone is not enough in soybean; cultivation must also be part of the weed control strategy.

6.3. 2011 Field Study Conclusions

The 2011 field study results support the 2010 result that the best weed control treatment among those tested is flaming + cultivation twice. This treatment provided the highest levels of weed control and weed dry matter reduction, behind the weed-free control. The
crop injury was not the lowest in 2011 for flaming + cultivation twice, but it was lower than full flaming twice. This was more true in soybean than in corn.

The next best treatment is a much more difficult matter to determine. The crop injury was fairly uniform across treatments in corn, whereas treatments 3, 4, and 6 in soybean had much lower injury than the others in soybean. Soybean treatment 3, flaming at VC followed by cultivation at V5, was the second best treatment in the weed control, dry matter, and yield results. Note that this treatment is not found in the corn study. More replications may be needed to fully differentiate between treatments. The trends suggest that cultivation must be a part of weed control in some form; flaming alone for two applications during a season does not provide complete weed control.

Another issue is why the performance parameters seem to be generally worse in 2011 than 2010. One possible reason mentioned is that the weed composition of is different in the fields used in 2010 than in those used in 2011. The composition was dramatically different in corn between the two years. The difference was less in soybean. Another factor that changed between the two years was the flaming hoods and torches themselves. The torches in 2011 used a higher operating pressure to give the same propane dose. This causes the hot gas jet velocity to be higher, decreasing the contact time between the gas and the weed/soil system. This effect would be more significant for the torches on the full flamer, which operated at 65 psig in 2011. Laguë et al. (1997) found that increasing operating pressure above 60 psig does not generate higher temperature rises
than lower pressures. The flaming hoods need to be tested for temperature differences between the two years, and those results follow in Chapter 7.

Note that the weed-free treatment yield in soybean is 20 percent lower in 2011 than in 2010. Also, the weed-free corn treatment has 11 percent lower yield in 2011 than in 2010. This result suggests that some environmental factors were one cause of the overall lower performance of the crops in 2011 than in 2010, such as moisture or temperature differences. Further, the studies were planted 2-3 weeks later in 2011 than in 2010. For any of these reasons, the soybeans were shorter in 2011 than in 2010 and had to be flamed at the V5 stage rather than at V4. Thus, changes in climate, planting date, equipment, and weed composition and density all need to be considered when interpreting the differences between the 2010 and 2011 field results.
Chapter 7. Temperature Measurements

The performance of the flamer/cultivator hood/torch system has been proven in the field with two-year studies in corn and soybean. Now it is time to look at the mechanisms of how the flamer/cultivator achieved the best weed control. The benchmark used by Thomas (1964) of 800°C gas temperature for 0.1 seconds is one of the few published benchmarks available for flaming equipment design. Taking temperature measurements of the combustion gases inside the flaming hoods will confirm whether the equipment designed here is meeting this benchmark, and if so, by how much. Different hood/torch configurations will be compared to gain further insight into the advantages of using flaming hoods, and which hood configuration is the best.

7.1. Measurement Materials and Methods

7.1.1. Propane Flame Weeding Test Bench

The Combustion Research Laboratory at the University of Nebraska-Lincoln was utilized for temperature measurements. It is equipped with a propane flame weeding test bench and exhaust system, shown in Figure 54.
On top of the bench are stainless steel soil pans which simulate the field conditions in which the flamer/cultivator is used. Also, the soil acts as an insulator to keep heat away from the operator underneath the bench. Underneath the soil pans is an air gap, below which is a layer of residential ceramic tile, as further means of insulation. Between the soil pans are gaps in the bench top for thermocouple probes to be inserted, as shown in Figure 55.

Figure 54. Propane weed flaming test bench for temperature measurements.

Figure 55. Thermocouple probes poking through the gaps between soil pans.
7.1.2. Thermocouple Probes and DAQ

The thermocouple probes are K-type Super OMEGACLAD XL probes. They have a proprietary metallic sheath on the outside to resist high temperatures and chemical reaction (OMEGA, n.d.a.). These probes are used in differential mode with an OMB-DAQ-54 USB Data Acquisition Module, referred to as a DAQ. These thermocouples provide an accuracy of ± 0.4°C at 600°C when using a “very slow” sample rate (OMEGA, n.d.b.). Because OMEGA recommends using a “very slow” sample rate for steady-state measurements to provide greater resolution and greater accuracy, a sample rate of 0.5 Hz was used. A measurement time period of 20 seconds was used, thus there were 11 values recorded by the DAQ for each location. The average of these 11 values was used for the analysis.

The DAQ was connected to an HP laptop using a USB cable. This DAQ can monitor up to five channels at a time, has a built-in cold-junction compensator, and has a reading accuracy of 0.015% (OMEGA, n.d.b.). The DAQ comes with Personal DaqView software for real-time monitoring of the temperatures on the five channels. This software was used to determine when the thermocouples had reached steady-state, and then it also recorded a set of temperature readings upon manual trigger and wrote them to disk files.

The thermocouple probes were clamped in between two horizontal metal strips and hooked into a pulley system, as shown in Figure 56. The pulley system was designed by Evan Hilgemann, an undergraduate researcher working in the lab. The thermocouple probes could then be moved up and down easily to measure at any vertical location. The
pulley system was mounted in a rigid stainless steel frame which could be moved to any of the set positions along the length of the bench, which are 200 mm apart.

![Figure 56. Pulley system and frame used to move thermocouple probes.](image)

### 7.1.3. Hood Configurations

Four different hood configurations were tested in these temperature measurements. The first setup, 2011 Closed Hood (2011CH), utilized the redesigned cultivator hood used in 2011 with the removable cover fastened in place, as shown in Figure 57. This configuration simulates the early season flaming when the crop, corn or soybean, is short enough to leave the cover on the flaming hood.

![Figure 57. 2011 Closed Hood configuration.](image)

The second configuration, 2011 Partially Open Hood (2011PO), also utilized the new hoods from the 2011 field testing. This configuration, however, had the top cover
removed so the 10.2-mm (4-in) gap between the hood halves was exposed. Two sets of thin steel strips were bolted to the hood halves to keep them upright and spaced at 10.2 mm in the absence of the removable cover, as shown in Figure 58. These steel strips were assumed to have negligible influence on the heat transfer and air entrainment in this setup. This configuration simulates flaming at late growth stages, when the crop is tall and the cover is removed to let the crop flow through.

![Figure 58. 2011 Partially Open Hood configuration.](image)

The third setup is the 2011 Open Torch (2011OT) configuration. This setup does not utilize any hoods. Rather, the two torches, the type used during the 2011 field study, are mounted on a bar so that they are at the same height and orientation as they are when bolted to the hood, as shown in Figure 59. This configuration was used to quantify the benefits of using hoods to concentrate heat close to the weeds, as opposed to leaving the torches open to the environment.

![Figure 59. 2011 Open Torch configuration.](image)
The final setup is the 2010 Closed Hood (2010CH) configuration. As was shown in results of the field studies, the flamer/cultivator performed better in 2010 than in 2011. Among several variables that changed between the two years, some major ones included the redesign of the hoods and the use of the newly designed UNL torches. Also it was noted that a strip of grasses remained uncontrolled in the crop row in 2011. The 2010CH configuration was chosen to see if there were temperature reasons why the flamer/cultivator performed better that year. It utilizes the original flamer/cultivator hood with the broadcast flaming cover on, as shown in Figure 60.

![Figure 60. 2010 Closed Hood configuration.](image)

The 2011CH, 2011PO, and 2011OT configurations all utilized the new FC2 torches designed in this research group, as detailed in Chapter 5. The operating pressure was 25 psig, the actual pressure used in the field. This corresponds to a propane flowrate of 1.93 g/s total for the two torches. The 2010CH configuration utilized the cylindrical LT 3-12 T torches from Flame Engineering, Inc. The operating pressure was 15 psig, the actual pressure used in the field. This corresponds to a propane flowrate of 1.83 g/s total for the two torches. The flowrate was measured using a stopwatch and an OHAUS Defender 3000 Series scale.
7.1.4. Pyrometer

In addition to the thermocouple readings being recorded in the combustion gas stream, hood surface temperature measurements were taken using an infrared pyrometer. The model used was an Extech High Temperature InfraRed Thermometer, Model 42542. It has an accuracy of (2.0% of reading + 2°C) in the range of 200 to 538°C, and (3.5% of reading + 5°C) in the range of 538 to 1000°C (Extech, 2007). The pyrometer has a laser pointer which allows the user to easily see which spot they are measuring. The meter’s field of view is 30:1, i.e., holding it 30 cm away from the target means the diameter of the target must be at least 1 cm. The surface temperature was measured at every longitudinal and vertical location along the side of the hood where thermocouple measurements were taken, as shown in Figure 61. The hoods were painted with flat black paint so that the emissivity value could be set at a known value of 0.98 (Incropera et al., 2007).

![Figure 61. Taking hood surface temperature readings with the pyrometer.](image)

7.2. Measurement Locations

The axes for measurement were such that the z-axis lies along the length of the test bench, as shown in Figure 62. The hood inlet was set parallel with z = 0 mm, so that the first measurement takes place at the air intake. The remaining measurement locations are spaced apart along the z-axis. The hood exit is at z = 600 mm, and the locations at z =
800 mm and 1000 mm are outside of the hood entirely. The same measurement locations were used for all four hood/torch configurations.

![Diagram](image)

**Figure 62. Measurement locations along the z-axis.**

Within each z-location there lies a grid of measurement points in the xy-plane. This plane is shown in Figure 63. The origin is located at the ground plane of the hood, centered left-to-right. The y-measurements are taken in steps of 20 mm starting at the ground plane. The x-measurements are spaced 40 mm apart with the exception of the origin (x=0 mm). Because the DAQ only has five channels, the x-locations were split up into two measurement sessions. In one session, measurements at all y and z locations were taken at x = -140, -60, 0, 60, and 140 mm. In the other session, measurements at all y and z locations were taken at x = -100, -20, 0, 20, and 100 mm. The x = 0 mm location was kept for both sessions to keep the flow pattern symmetric, and the values at x = 0 mm were averaged between the two sessions.
The measurement locations chosen also match well with useful data ranges found by previous researchers. Seifert & Snipes (1996) found that temperatures decreased approximately 25 to 30% between the soil surface and a height of 100 mm during flaming. Carter et al. (1960) found that the temperature above a 102 mm height approaches atmospheric temperature very rapidly.

7.3. Temperature Corrections

The temperatures recorded by the thermocouples are not the actual gas temperature. The thermocouple junction temperature is less than the actual gas temperature due to radiation losses to the thermocouple’s surroundings. After the lab measurements were complete, corrections were made to account for radiation losses and find the actual gas temperature.

There have been a wide variety of approaches to temperature corrections made by those studying flame weeding. Wszelaki et al. (2007) and Laguë et al. (1997), for example,
made no mention of corrections in their temperature measurements. Storeheier (1994) admits that the temperature measured in their work is not the temperature of the plant environment, but that of a plant having equal mass and thermal conductivity properties to the thermocouples. Harris et al. (1969) called correcting thermocouple readings for environmental errors “a highly speculative effort and for this reason corrections were not made.” Mayeux et al. (1968) admitted that their thermocouples were not shielded against radiation, but thought the error was minimal due to lack of complete flame transparency.

The corrections used here are largely based on the work of Bruening (2009). He took temperature measurements in the same lab using very similar flaming hoods. He assumed that all of the radiation from the thermocouple probe either went to the hood or to the lab walls, depending on whether the probe was at a location inside the hood or outside the hood, respectively. Thus the view factor was assumed to be unity between the thermocouple and hood or the thermocouple and walls. Unfortunately, Bruening did not have a method for measuring the hood wall temperature directly. He used an iterative method where a gas temperature was guessed, and this was used to calculate the hood temperature assuming that the only heat transferred to the hood wall was through convection from the gas. A new gas temperature was computed, and an iteration was made. More details of his analysis can be found in the appendix.

Two major improvements were made over the temperature corrections of Bruening (2009). First, the hood temperatures were measured directly using a pyrometer, eliminating the iterative procedure. Second, the view factor between the thermocouple...
and lab walls was evaluated at each measurement location inside the hood, since in reality the thermocouple sees both the lab walls and the hood at these locations, and the view factor is less than one. Thus a three-body thermal radiation circuit could be utilized between the thermocouple, hood, and lab walls. The details of the calculation can be found in the appendix.

The view factors from the thermocouple to the lab walls were calculated using the single area integration method (1AI) described by Walton (2002) in the case of obstructed view factors. Although Walton described several methods for calculating view factors, this 1AI method seemed most appropriate for this situation because the needed vectors could readily be calculated from the geometry of the test bench and lab. Walton based his solution on a contour integration method from Hottel & Sarofim (1967) of a view factor $F_{dA_1 \rightarrow A_2}$ for an infinitesimal area $dA_1$ radiating to a finite polygonal area $A_2$:

$$F_{dA_1 \rightarrow A_2} = \frac{1}{2\pi} \sum_i d\gamma_i \cdot n_1$$

(2)

where $\gamma_i$ is a vector of magnitude given by the angle subtended by a side of the polygon at point P, and of direction normal to the plane passing through that side and P. The unit vector $n_1$ is a unit vector normal to area $dA_1$. The geometry is illustrated in Figure 64. The angles $g_i$ shown represent $\gamma_i$. Note that $n_1$ is normal to infinitesimal area $dA_1$. 
Walton (2002) re-wrote Equation (2) in the form

$$F_{dA_1 \rightarrow A_2} = \frac{1}{2\pi} \sum_{i=1}^{E_2} \left( \frac{c_i \cdot n_1}{e_i} \left[ \frac{\pi}{2} - \tan^{-1} \frac{d_i}{e_i} \right] \right)$$  \hspace{1cm} (3)$$

where the summation is around all of the edges of $A_2$. If $\mathbf{a}$ and $\mathbf{b}$ are vectors from point $P$ to two consecutive vertices of $A_2$, then

$$\mathbf{c} = \mathbf{a} \times \mathbf{b}$$  \hspace{1cm} (4)$$

$$e = |\mathbf{c}|$$  \hspace{1cm} (5)$$

and

$$d = \mathbf{a} \cdot \mathbf{b}$$  \hspace{1cm} (6)$$

In the case where there is a third object between $dA_1$ and $A_2$ which casts a shadow on $A_2$ as viewed from $dA_1$, the summation in Equation (3) is only around the unshaded portions of $A_2$ that $dA_1$ sees. In the case of the flaming lab test bench, $dA_1$ is the infinitesimally small area of the thermocouple junction, and $A_2$ is the lab walls. The hood is an obstruction which casts shadows on the wall when viewed from the thermocouple junction. Thus the view factors are computed separately for each wall and then summed together to give a view factor from the thermocouple to the lab walls at a given location.
Details of the calculation and program code can be found in the appendix. The average view factors from the thermocouple junction to the lab walls at the four locations of Case 1 are shown in Table 7.

Table 7. Average view factor to the lab walls at each hood cross section for Case 1.

<table>
<thead>
<tr>
<th>z (mm)</th>
<th>Average View Factor to Lab Walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.969</td>
</tr>
<tr>
<td>200</td>
<td>0.554</td>
</tr>
<tr>
<td>400</td>
<td>0.557</td>
</tr>
<tr>
<td>600</td>
<td>0.882</td>
</tr>
</tbody>
</table>

Thus the measurement locations fall into two categories. In Case 1, the thermocouple is inside the hood, and the view factor analysis mentioned above is applied. This includes measurement locations at z = 0, 200, 400, and 600 mm for the 2011CH, 2011PO, and 2010CH configurations. In Case 2, the thermocouple is outside of the hood, and the thermocouple can be assumed to only exchange radiation with the lab walls. This covers all of the measurement locations in the 2011OT configuration, plus z = 800 and 1000 mm for the 2011CH, 2011PO, and 2010CH configurations.

7.4. Measurement Results and Discussion

The significance of the temperature corrections is illustrated with a few selected measurement points shown in Table 8. Recall that in Case 1, the thermocouple junction exchanges radiation with both the hood and lab walls, while in Case 2 the junction only exchanges radiation with the lab walls. The gas temperatures are all some percentage higher than the measured junction temperatures, and this is the error shown in the table.
Table 8. Comparison of junction and gas temperatures at selected locations.

<table>
<thead>
<tr>
<th>Junction Temperature (°C)</th>
<th>Gas Temperature (°C)</th>
<th>Case 1</th>
<th>Error (%)</th>
<th>Case 2</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>102</td>
<td>0.9</td>
<td>102</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>185</td>
<td>189</td>
<td>2.0</td>
<td>189</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>398</td>
<td>417</td>
<td>4.7</td>
<td>419</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>598</td>
<td>635</td>
<td>6.2</td>
<td>658</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>924</td>
<td>15.5</td>
<td>941</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td>1021</td>
<td>1306</td>
<td>27.9</td>
<td>1321</td>
<td>29.4</td>
<td></td>
</tr>
</tbody>
</table>

At the low end of junction temperatures, 101°C, the error is very similar for both cases, resulting in only 1°C difference between the gas and junction temperatures. The error is also similar for the two cases at 185°C. At the 398°C junction temperature, the thermocouple is becoming hot enough relative to the lab walls that radiation losses are significant, and so the two cases start to diverge. The error for Case 2 is now greater than Case 1. At the 598°C junction temperature, the hood and junction temperatures are now approximately equal. The error due to radiation losses to the lab walls is now about 4 percent larger for Case 2 than Case 1.

When the thermocouple junction reaches a temperature of 800°C, it is now significantly warmer than the hood. However, for some reason, the difference in error is now smaller than before. Finally, at the 1021°C junction temperature, the error is now 1.5 percent higher for Case 2 than Case 1. At this high temperature, the measurement location was right near the flame, at (x, y, z) coordinates of (-140, 100, 200) mm, and the junction’s view factor to the lab walls was 0.51, one of the lowest among the locations. Also,
radiation directly from the flame was not considered. These may help explain why the error difference decreases at these high temperatures.

All of the gas flow temperature results are shown as color contour plots in Figure 65 - Figure 70. The same results are also presented in Appendix C in a different format. They are shown by z - location, as defined in Figure 62. Looking first at the contour plots at z = 0 mm (Figure 65), it is seen that the gas has not heated up that much yet. The 2011CH and 2011PO configurations are at nearly uniform temperatures between 100° - 200°C. The measurement locations here are below the flame jet emerging from the torch, which has not hit the ground yet. The 2011OT configuration is even cooler, between 0° - 100°C, which is not surprising since there is no hood that can contain the hot air to elevate the temperatures at z = 0 mm. One interesting point is that the 2010CH configuration shows higher temperatures in the upper third, between 200° - 300°C. This upper third is closest to the torches. This result is a preview of a hotter trend for the 2010CH configuration, as will be shown shortly.

A dramatic change is seen at z = 200 mm (Figure 66), where the highest temperatures in the hood can be found. There are also very steep temperature gradients, as the high temperatures are very localized at this point, staying confined to the areas directly in front of the two torches. Not much gas mixing along the x-direction is evident at this point. Although the high temperature regions look very similar between the four cases, there are other important differences to note. The main difference between the 2011CH and 2011PO configuration is the space between the two torches. The 2011CH plot shows
temperatures between 500° - 600°C, while the 2011PO configuration only reaches 400° - 500°C over most of this region. Thus, the average temperature of the region between the torches for 2011PO is 18% lower than that of 2011CH. The 2011OT configuration is similar to the 2011PO configuration.

Finally, note that the best mixing at z = 200 mm occurs in the 2010CH configuration, with the lowest temperatures here coming in at 700° - 800°C. This is 36% higher than the average temperature of the region between the torches in the 2011CH configuration. This may be due to the steeper slope of the 2010 hood, among other things, such as different torches and nozzles that lead to different flame sizes and shapes. The lower middle temperatures for the 2011 hood may also partially explain why the 2011 hood was leaving a strip of grass down the middle of the crop row.

At the next location, z = 400 mm (Figure 67), there is much more horizontal mixing of the gases. There are still distinct high temperatures regions on the left and right sides, but the middle temperatures have rapidly increased to the 900° - 1000°C range. The maximum temperatures have dropped from their high of almost 1600°C to the 1100° - 1200°C range. This location is the most telling for the advantages of hoods over open torch. The 2011OT plot shows that the gas in the upper third of the plot is already cooling off before the lower gases have not even completely mixed. This gives a distinct advantage to 2011CH for weeds that are over 60 mm tall.
A look at the 2010CH plot at $z = 400$ mm shows that this still has a clear advantage over the 2011CH configuration. The $900^\circ$ - $1000^\circ$C range extends all the way up to the top of the measuring area, unlike the other configurations. The mixing is also much more uniform along the x-direction. This location falls in the part of the 2010 hood where the roof is parallel to the ground, so it is not surprising that the hot gases are confined lower. This may better control weeds of all heights.

The next location, $z = 600$ mm (Figure 68), is located just inside the hood exit for the three hooded configurations. At this point, one cannot tell that there are two torches producing heat; the gases have completely mixed horizontally. The main difference between the 2011CH and 2011PO configurations here is that the upper fifth of the area has dropped below $800^\circ$C, the benchmark from Thomas (1964). This cooling is attributable to the gap between hood halves in the 2011PO configuration, and unavoidable convection losses. The 2011OT configuration is cooling off more noticeably, with only a small center core being above $800^\circ$C. The 2010CH configuration is now becoming quite similar to the 2011CH, with the majority of the region in the $900^\circ$ - $1000^\circ$C range. Any of the hooded configurations should be killing weeds effectively at this point. The 2011CH configuration has an advantage over the 2010CH configuration. It will still better treat small weeds (less than 2 cm) since the 2010CH experiences a thicker cool zone close to the ground.

Moving downstream to $z = 800$ mm (Figure 69), all of the configurations are now at locations where the thermocouples are outside the hood. The gases are no longer
confined by the hood, resulting in rapid cooling for all configurations. The high-
temperature core above 800°C has shrunk to only the middle region in the three hooded
configurations. The gases are cooled by convection of the bottom, left, and right sides.
The three hooded configurations are all similar at this point, with the 2011CH having a
substantial edge. The advantage of 2011CH over 2010CH noted at z = 600 mm is even
more pronounced here. The 2011CH has an obvious edge due to the sloping hood at the
exit, which creates a flow of gases exiting at an angle towards the ground. Thus, the cool
zone is thinner for 2011CH than 2010CH, which has a horizontal roof at the exit. The
OT configuration is rapidly becoming too cool to be effective here.

At the final measurement location of z = 1000 mm (Figure 70), things have cooled down
to the point where it is unknown whether conditions are hot enough to kill weeds. Only
the 2011CH has temperatures above 800°C, located in a small core near the top fourth of
the region. The other three configurations have cooled off further from the bottom, left,
and right sides, with the OT configuration cooling off to less than 600°C everywhere.
The hot gases are rising and so that is where the highest temperatures are found. The
clear advantage of the 2011CH configuration over the 2010CH configuration continues
here, as the temperature field of 2010CH (hot gases exiting horizontally) has cooled off
enough that it closely resembles that of the 2011OT configuration. 2011CH (hot gases
exiting at an angle toward the ground) has maintained high temperatures the longest.
Figure 65. Temperature contour plots for $z = 0$ mm.
$z = 200\text{ mm (7.9 in)}$

**2011 Closed Hood**

**2011 Partially Open Hood**

**2011 Open Torch**

**2010 Closed Hood**

Figure 66. Temperature contour plots for $z = 200$ mm.
Figure 67. Temperature contour plots for $z = 400$ mm.
Figure 68. Temperature contour plots for $z = 600$ mm.
Figure 69. Temperature contour plots for $z = 800$ mm.
Figure 70. Temperature contour plots for $z = 1000$ mm.
7.5. Temperature Measurement Conclusions

The test bench in the Combustion Research Laboratory at the University of Nebraska-Lincoln worked well for temperature measurements. Gas temperature corrections due to radiation losses from the thermocouple junction were able to be calculated based on the geometry of the room and the test setup. These corrections showed significant differences compared with the junction temperatures. Case 1, where the thermocouple junction emitted radiation to both the hood and lab walls, was calculated based on view factors from the method of Walton (2002). The corrections ranged from 0.9% at 101°C to 27.9% at 1021°C for Case 1. Case 2 assumed radiation was that of a two-body enclosure, between the junction and the lab walls, which acted as a blackbody. The corrections ranged from 1.2% at 101°C to 29.4% at 1021°C. Thus Case 2 showed higher radiation losses due to the cooler temperature of the lab walls compared with the hood.

There were several interesting conclusions drawn from the gas temperature contour plots. First, the gap between the hood halves in the 2011PO configuration reduced temperatures between the two flame regions at z = 200 mm by 100°C, or 18%, compared with the 2011CH configuration. It should be noted, though, that in field operation, the presence of the crop flowing through this gap should reduce the convective heat losses substantially, moving the temperatures closer to those of a fully closed hood.

On the other hand, the 2010CH configuration raised temperatures between the flames by 200°C, or 36%, compared with the 2011CH configuration at z = 200 mm. The lower temperatures in the middle of the 2011CH configuration may partially explain why a strip
of grasses was left uncontrolled in the crop row in 2011. However, 2011CH maintains temperatures that are hotter and closer to the ground for larger z values than the 2010CH configuration.

The z = 400 mm location shows the advantage of the hood over the open torch setup most clearly. The hot gases are still mixing in the x- and y-directions for the two closed hood configurations. However, for the 2011OT configuration, the upper third of the measurement area is already cooling, even though the hot gases in the lower two-thirds have not completely mixed in the x- and y-directions. Thus, weeds up to 100 mm are exposed to the high-temperature core longer with the closed hood configurations than with an open torch. It would logically follow that hooded torches provide more effective weed control than open torches on the flamer/cultivator.

Based on the temperatures at z = 600 mm, the gases have completely mixed along the x-direction and all three hooded configurations should be effective at killing weeds. At z = 800 and 1000 mm, there is rapid cooling on the bottom, left and right sides in all configurations. However, the high-temperature zone for 2011CH is much larger than that of the other configurations, due to the sloped roof at the hood exit, which creates a flow of hot gases exiting at an angle toward the ground. Only the 2011CH configuration has temperatures above 800°C at this point. However, the benchmark of 800°C exposure for 0.1 s by Thomas (1964) needs to be tested on a basic plant response level before this can be completely used to judge flamer performance. It is concluded that the three hooded
configurations, 2011CH, 2011PO, and 2010CH, all produce temperatures high enough for a long enough length to kill weeds effectively.
Chapter 8. Conclusions

1. The original flamer/cultivator hoods designed in 2010 were very effective and fit well on two different brands of row crop cultivator. They provided a solid baseline to improve upon in the 2011 design.

2. The U-bolt clamping system and steel strap crop guides on the redesigned flamer/cultivator hoods performed better structurally than on the first prototype.

3. The continuously sloping hood roof was easier to manufacture than the two-part roof on the first prototype, and maintained a high level of weed control.

4. Torches bolted directly to the hood cause warping issues.

5. A flow mixer is needed on the torch design for effective vaporization of propane, and a tilted bottom keeps torch housing temperatures from being red hot.

6. Decreasing the primary air intake on the flamer/cultivator torch decreases the liftoff length and makes it more stable.

7. Thermocouples located inside the hood had errors due to radiation losses ranging from 0.9% at 101°C to 27.9% at 1021°C, whereas thermocouples outside the hood had errors ranging from 1.2% at 101°C to 29.4% at 1021°C.

8. The gap between hood halves in the 2011 Partially Open Hood configuration reduced temps between the flames by 100°C, or 18%, below the 2011 Closed Hood configuration at z = 200 mm.

9. The 2010 Closed Hood configuration raises temps between the flames by 200°C, or 36%, compared with the 2011 Closed Hood configuration at z = 200 mm, perhaps explaining why grasses within the crop row were less controlled in 2011.
10. Although it has lower temperatures between the flames at \( z = 200 \text{ mm} \), the 2011 Closed Hood configuration provides the best temperature field overall because it maintains high temperatures for larger \( z \) values than the 2010 Closed Hood configuration. The sloped roof at the hood exit creates a flow of hot gases exiting at an angle toward the ground.

11. The 2011 Open Torch configuration already begins cooling off at 400 mm from the torch outlet, providing less effective weed control than any of the hooded configurations.

12. All three hooded configurations tested produced temperatures high enough for a long enough length to kill all weeds effectively.

13. Flaming + cultivation twice was the best weed control treatment of those tested in 2010 and 2011, in both corn and soybean.

14. In 2010, cultivation alone was shown to be insufficient as a season-long weed control treatment.

15. In 2011, flaming alone appeared to be insufficient as a season-long weed control treatment; some cultivation is needed as well.

16. There are several factors which may have caused worse results in 2011 than in 2010. These include changes in weed composition and density, equipment, climate, and planting date.

17. Integrating propane flaming and mechanical cultivation has proven to be an effective tool for weed control in corn and soybean.
References


Appendix A. Temperature Correction Procedure

Thermocouples are often used to measure gas temperatures, as was the case in this study. The temperature measured at the thermocouple junction in the lab is not the same as the gas temperature. The gas transfers heat to the junction by convection, but the junction loses some of that heat by radiating it to the surroundings. The surroundings in this case include the hood walls and the lab walls. Knowledge of heat transfer is needed to determine the actual gas temperature from the junction temperature readings. The differences between the thermocouple junction temperature and gas temperature can be large, especially at high temperatures. The procedure that was used to determine the gas temperature follows.
## A.1. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>Surface area of spherical thermocouple junction with diameter $D_1$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_2$</td>
<td>Surface area of hood</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_3$</td>
<td>Surface area of lab walls</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Cross-sectional area of hood outlet</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$c_{pa}$</td>
<td>Specific heat of air</td>
<td>kJ/kg*K</td>
</tr>
<tr>
<td>$c_{pf}$</td>
<td>Specific heat of fuel</td>
<td>kJ/kg*K</td>
</tr>
<tr>
<td>$D_1$</td>
<td>Diameter of thermocouple probe</td>
<td>m</td>
</tr>
<tr>
<td>$E_{b1}$</td>
<td>Total emissive power of a blackbody at same temperature as the thermocouple junction</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>$E_{b2}$</td>
<td>Total emissive power of a blackbody at same temperature as the hood</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>$E_{b3}$</td>
<td>Total emissive power of a blackbody at same temperature as the lab walls</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>$F_{12}$</td>
<td>View factor from the thermocouple junction to the hood</td>
<td>-</td>
</tr>
<tr>
<td>$F_{13}$</td>
<td>View factor from the thermocouple to the lab walls</td>
<td>-</td>
</tr>
<tr>
<td>$F_{23}$</td>
<td>View factor from the hood to the lab walls</td>
<td>-</td>
</tr>
<tr>
<td>$H$</td>
<td>Height of the hood outlet</td>
<td>m</td>
</tr>
<tr>
<td>$h_a$</td>
<td>Enthalpy of the air</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>$h_1$</td>
<td>Convective heat transfer coefficient for gas flow over spherical thermocouple junction</td>
<td>W/m$^2$*K</td>
</tr>
<tr>
<td>$J_1$</td>
<td>Radiosity of thermocouple junction</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>$J_2$</td>
<td>Radiosity of hood</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>$J_3$</td>
<td>Radiosity of lab walls</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>$k_a$</td>
<td>Thermal conductivity of air</td>
<td>W/m*K</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value of propane (water remains in vapor form)</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>$\dot{m}_f$</td>
<td>Mass flowrate of fuel</td>
<td>kg/s</td>
</tr>
<tr>
<td>$\dot{m}_a$</td>
<td>Mass flowrate of air</td>
<td>kg/s</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Total mass flowrate of combustion gases exiting hood</td>
<td>kg/s</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
<td>-</td>
</tr>
<tr>
<td>$p_{op}$</td>
<td>Torch operating pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
<td>-</td>
</tr>
<tr>
<td>$\dot{q}_1$</td>
<td>Heat transfer rate from gas to thermocouple junction (Case 1)</td>
<td>W</td>
</tr>
<tr>
<td>$\dot{q}_2$</td>
<td>Heat transfer rate from gas to hood (Case 1)</td>
<td>W</td>
</tr>
<tr>
<td>$\dot{q}_3$</td>
<td>Heat transfer rate from thermocouple junction to hood (Case 1)</td>
<td>W</td>
</tr>
<tr>
<td>$\dot{q}_5$</td>
<td>Heat transfer rate from gas to thermocouple junction to lab walls (Case 2)</td>
<td>W</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>$\dot{q}_6$</td>
<td>Heat transfer rate from thermocouple junction to the lab walls (Case 1)</td>
<td>W</td>
</tr>
<tr>
<td>$R_1$</td>
<td>Thermal resistance between gas and thermocouple junction</td>
<td>K/W</td>
</tr>
<tr>
<td>$R_2$</td>
<td>Thermal resistance between gas and hood (Case 1)</td>
<td>K/W</td>
</tr>
<tr>
<td>$R_3$</td>
<td>Thermal resistance between thermocouple junction and hood (Case 1)</td>
<td>K/W</td>
</tr>
<tr>
<td>$R_4$</td>
<td>Thermal resistance between hood and ambient air (Case 1)</td>
<td>K/W</td>
</tr>
<tr>
<td>$R_5$</td>
<td>Thermal resistance between thermocouple junction and lab walls (Case 2)</td>
<td>K/W</td>
</tr>
<tr>
<td>$R_6$</td>
<td>Thermal resistance between thermocouple junction and lab walls (Case 1)</td>
<td>K/W</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td>-</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Temperature of the primary air entering the hood intake</td>
<td>K</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Temperature of the fuel injected into the torch housing</td>
<td>K</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Temperature of combustion gases flowing through the measurement zone</td>
<td>K</td>
</tr>
<tr>
<td>$T_h, T_2$</td>
<td>Temperature of the hood</td>
<td>K</td>
</tr>
<tr>
<td>$T_{gm}$</td>
<td>Mean temperature of combustion gases, averaged over the entire hood</td>
<td>K</td>
</tr>
<tr>
<td>$T_{j1}$</td>
<td>Temperature of the thermocouple junction</td>
<td>K</td>
</tr>
<tr>
<td>$T_{jm}$</td>
<td>Mean temperature of the thermocouple junction, averaged over the entire hood</td>
<td>K</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Surface temperature - the average of mean gas flow and mean thermocouple junction temperatures</td>
<td>K</td>
</tr>
<tr>
<td>$T_{\infty}, T_3$</td>
<td>Ambient air and lab wall temperature</td>
<td>K</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity of gas flow through hood and over the spherical thermocouple junctions</td>
<td>m/s</td>
</tr>
<tr>
<td>W</td>
<td>Width of the hood outlet</td>
<td>m</td>
</tr>
<tr>
<td>z</td>
<td>Distance from hood inlet along hood’s longitudinal axis</td>
<td>m</td>
</tr>
<tr>
<td>$\varepsilon_1$</td>
<td>Emissivity of thermocouple junction</td>
<td>-</td>
</tr>
<tr>
<td>$\varepsilon_2$</td>
<td>Emissivity of hood</td>
<td>-</td>
</tr>
<tr>
<td>$\varepsilon_3$</td>
<td>Emissivity of lab walls</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity of air at mean gas temperature</td>
<td>N*s/m²</td>
</tr>
<tr>
<td>$\mu_s$</td>
<td>Dynamic viscosity of air at surface temperature</td>
<td>N*s/m²</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of air</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant (value = 5.67x10⁻⁸)</td>
<td>W/m²*K⁴</td>
</tr>
</tbody>
</table>
A.2. Problem Setup

A schematic of the experimental setup is shown in Figure 71. The setup shown is for the 2011 Closed Hood (2011CH) configuration, but is valid for all four configurations tested. The propane fuel flows into the torches at a temperature $T_f$ and with a mass flowrate $\dot{m}_f$. The primary air is drawn into the hood inlet, or drawn into the flame area for the 2011 Open Torch (2011OT) configuration, at a temperature $T_a$ and with a mass flowrate $\dot{m}_a$. The stream exiting the hood is a combination of air and combustion gases at a temperature $T_g$, with a total mass flowrate $\dot{m}$, and a velocity $V$. The ambient air and surroundings are quiescent at a temperature $T_\infty$. The ventilation system in the lab keeps $T_\infty$ at an average value of 298 K.

![Figure 71. Schematic of hood/torch device operation in the lab.](image)

Important hood dimensions used in the calculations are defined in Figure 72.
Figure 72. Important hood dimensions used in the temperature correction calculations.

The thermocouple measurement locations are divided into two cases:

1. The thermocouple probe is inside the hood.

2. The thermocouple probe is outside the hood.

In Case 1, the thermocouple junction exchanges radiation with both the hood walls and the lab walls. The view factor from the junction to the lab walls was evaluated at every location within Case 1. This case applies to the locations $z = 0, 200, 400,$ and $600$ mm in the 2011 Closed Hood (2011CH), 2011 Partially Open (2011PO) and 2010 Closed Hood (2010CH) configurations. In Case 2, the junction exchanges radiation only with the lab walls, so the view factor is assumed to be 1. This case applies to all the 2011 Open Torch (2011OT) measurement locations, as well as the locations $z = 800$ and $1000$ mm in the 2010CH, 2011PO, and 2010CH configurations.

The present work is based largely on that of Bruening (2009). He took measurements in the same lab with very similar flaming hoods. He divided the measurement locations into the two cases as noted above. His work made the assumption that in Case 1, the junction
only exchanges radiation with the hood walls, thus the view factor from the junction to the hood walls was 1. Bruening constructed a thermal circuit based on his assumptions and setup for Case 1, and that circuit can be seen in Figure 73.

Bruening (2009) did not measure the hood temperature, $T_h$, but rather guessed a gas temperature, $T_g$, and used this to calculate $T_h$ by leaving the switch in the lower arm open. This is equivalent to assuming that heat transfer from the gas to the hood only occurs by convection, through thermal resistance $R_2$. The hood temperature was then used with heat rate $\dot{Q}_1$ and a closed switch to calculate a new value of $T_g$, and iterations of this process continued until the gas temperature converged.

The present work makes two major improvements over the temperature corrections of Bruening (2009). First, the hood wall temperature was measured directly using a pyrometer, eliminating the iterative procedure. Second, the thermocouple junction in Case 1 is now assumed to exchange radiation with both the hood wall and lab wall. Thus the view factor between the junction and hood is less than 1, and must be calculated at each measurement location. The new thermal circuit used in this analysis is shown in Figure 74. The switch on the lower arm has been removed, as the iterative procedure is no longer needed. Also, there are now two paths of radiation heat transfer from the
thermocouple junction temperature $T_j$. Heat transfer rate $\dot{q}_3$ represents radiation from the junction to the hood wall. Heat transfer rate $\dot{q}_6$ represents radiation from the junction to the lab walls.

![Thermal circuit used in the present work for Case 1.](image)

The heat transfer rates $\dot{q}_3$ and $\dot{q}_6$ must be found by considering a separate radiation network. As mentioned, it is a three-body enclosure since the junction simultaneously radiates to the hood walls and the lab walls. Example 13.3 in Incropera et al. (2007) provides exactly the type of three-body network that is applicable here. The three bodies in this case are numbered 1-3 as shown in Figure 75.

![Numbering system for three-body radiation enclosure.](image)

The lab walls act as a surface which is large relative to all other surfaces under consideration, and thus can be treated as a blackbody (Incropera et al., 2007). This can
be seen in the fact that even though the lab walls might reflect some irradiation incident upon it, it will likely reach another part of the wall. Then all irradiation incident upon the wall will be absorbed by the wall eventually. The radiation network can be drawn as shown in Figure 76, with the radiosities $J_i$ as driving potentials.

$$E_{b3} = \sigma T_3^4$$

$$\frac{1 - \epsilon_3}{\epsilon_3 A_3} \rightarrow 0$$

$$J_3$$

$$(A_1 F_{13})^{-1}$$

$$(A_2 F_{23})^{-1}$$

$$\frac{1 - \epsilon_1}{\epsilon_1 A_1}$$

$$(A_1 F_{12})^{-1}$$

$$\frac{1 - \epsilon_2}{\epsilon_2 A_2}$$

$$E_{b1} = \sigma T_1^4$$

$$E_{b2} = \sigma T_2^4$$

Figure 76. Radiation network for the three-body enclosure.

For Case 2, where the thermocouple junction is outside of the hood, the thermal circuit is simple and is the same as the one Bruening (2009) used for Case 2. This circuit is shown in Figure 77.

$$T_y$$

$$R_1$$

$$T_j$$

$$R_5$$

$$T_\infty$$

$$\dot{q}_5$$

Figure 77. Thermal circuit used for Case 2.
A.3. Assumptions

The following assumptions were used in the problem solution:

1. The entering fuel was considered to be superheated vapor at the ambient temperature.

2. The measuring junction of the thermocouple probe can be treated as a sphere having the same diameter as the probe.

3. The temperature of the thermocouple sheath was equal to the junction temperature.

4. Conduction along the thermocouple probe was negligible.

5. Effects from catalytic reaction on the thermocouple sheath were negligible.

6. At measurement locations inside the hood (Case 1), the thermocouple junction emits radiation to the hood and lab walls simultaneously.

7. At measurement locations outside the hood (Case 2), the thermocouple junction only emits radiation to the lab walls.

8. The radiation from the thermocouple probe did not affect the temperature of the hood.

9. The soil working surface was a perfect thermal insulator; there was no heat flux through the soil.

10. The inside and outside surfaces of the hood were the same temperature.

11. The properties of the combustion gases flowing through the hood were very similar to air at the same temperature.

12. The lab walls act as a blackbody.

13. Each measurement was taken at steady state.
14. The hood and thermocouple junction are gray, diffuse surfaces with uniform radiosity and uniform irradiation.

15. The air is a nonparticipating medium.

16. The properties of the LP gas are accurately estimated by those of pure propane (Williams and Lom, 1974).

A.4. Solution: Case 1

The temperatures $T_j$, $T_h$, and $T_\infty$ are known from direct measurement. To find the gas temperature $T_g$, the heat transfer rates (or “currents”) can be summed at the node representing $T_j$ in Figure 74.

$$\dot{q}_1 = \dot{q}_3 + \dot{q}_6 \quad (7)$$

The heat transfer rate $\dot{q}_1$ can be replaced by the temperature difference and thermal resistance $1$:

$$\frac{T_g - T_j}{R_1} = \dot{q}_3 + \dot{q}_6 \quad (8)$$

Rearranging Equation (8), the gas temperature can be solved for.

$$T_g = R_1 (\dot{q}_3 + \dot{q}_6) + T_j \quad (9)$$

The area of the lab walls, $A_3$, is large, so the geometrical resistance between $E_{b3}$ and $J_3$ in Figure 76 goes to zero. Thus $J_3 = E_{b3}$, consistent with the blackbody assumption. This helps tremendously, reducing the number of unknown radiosities from three to two. Two equations can be written for the sum of radiation heat transfer rates, or “currents”, at the $J_1$ and $J_2$ nodes as follows.

$$\frac{\sigma T_1^4 - J_1}{(1 - \varepsilon_1)/\varepsilon_1 A_1} = \frac{J_1 - J_2}{(A_1 F_{12})^{-1}} + \frac{J_1 - \sigma T_3^4}{(A_1 F_{13})^{-1}} \quad (10)$$
The emissivity of the thermocouple probe sheath material was determined from a data sheet from Monarch Instruments. The material is best represented by a heavily oxidized aluminum at 504°C (Monarch, 2008), so \( \varepsilon_1 = 0.31 \). The emissivity of the hood can be found easily because it was painted with flat black paint. The emissivity of flat black paint is given in Incropera et al. (2007) as \( \varepsilon_2 = 0.98 \).

The view factor \( F_{13} \) from the thermocouple junction to the lab walls was determined at each location using the program described in Appendix B. Because this is a three-body enclosure, the view factor from the junction to the hood, \( F_{12} \), is given by

\[
F_{12} = 1 - F_{13}
\] (12)

The area \( A_2 \) includes the inside and outside surface area of the hood. The inside of the hood was assumed to exchange radiation only with the junction, and the outside of the hood was assumed to exchange radiation only with the lab walls, thus \( F_{23} = 0.5 \) everywhere. Equations (10) and (11) can be written in matrix form and easily solved for \( J_1 \) and \( J_2 \) by inverting the 2 x 2 coefficient matrix. Once \( J_1 \) and \( J_2 \) are found, the radiation heat transfer rates are given by

\[
\dot{q}_3 = A_1 F_{12} (J_1 - J_2)
\] (13)

\[
\dot{q}_6 = A_1 F_{13} (J_1 - \sigma T_3^4)
\] (14)

These radiation heat transfer rates can be substituted into Equation (9) for the gas temperature. Next, thermal resistance 1 must be determined. Thermal resistance 1 is due
to convection between the gas and the thermocouple junction, and so the resistance can be written as

\[ R_1 = \frac{1}{h_1 A_1} \]  \hspace{1cm} (15)

The heat transfer coefficient \( h_1 \) can be found using a correlation for external flow over a sphere (Assumption #2). The diameter of the probe is \( 4.76 \times 10^{-3} \) m, therefore the surface area of the sphere would be \( 7.12 \times 10^{-5} \) m\(^2\).

The velocity of the gas was needed next to find the heat transfer coefficient. The velocity was not measured directly, but a reasonable approximation can be found using an energy balance, following the method of Bruening (2009). Knowing the fuel mass flow rate, the cross-sectional area of the hood exit, and the average gas temperature across that section, the mass flow rate of primary air entering the hood can be found using an energy balance.

From Figure 71, the total energy entering the hood must equal the total energy exiting the hood. The energy entering the hood included the initial enthalpies of the fuel and air, as well as the chemical energy stored in the fuel. The energy exiting the hood included the enthalpy of the combustion gases. It is assumed that radiative, conductive, and convective losses through the hood are neglected.

\[ \dot{m}_f (c_{pf} T_f + LHV) + \dot{m}_a c_{pa} T_a = \dot{m} c_{pa} T_g \]  \hspace{1cm} (16)

Also, by conservation of mass at steady state, the mass flowrate of combustion gases exiting the hood was equal to the sum of the flowrates of the two entering streams.

\[ \dot{m} = \dot{m}_f + \dot{m}_a \]  \hspace{1cm} (17)
Combining and rearranging Equations (16) and (17), the mass flowrate of entering air can be solved for.

\[ \dot{m}_a = \dot{m}_f \left( \frac{c_{pf} T_f + LHV - c_{pa} T_g}{c_{pa} (T_g - T_a)} \right) \quad (18) \]

The following values were obtained by direct measurements:

\[ \dot{m}_f = 1.93 \times 10^{-3} \text{ kg/s} @ p_{op} = 0.17 \text{MPa (25 psi)} \text{ for the 2011 torches} \]

\[ \dot{m}_f = 1.83 \times 10^{-3} \text{ kg/s} @ p_{op} = 0.10 \text{MPa (15 psi)} \text{ for the 2010 torches} \]

\[ T_\infty = 298 \text{ K (76.7°F)} \]

\[ T_g = 1144 \text{ K (1600°F)} \]

\[ T_f = T_\infty \rightarrow \text{Assumption #1} \]

The following values were taken from Turns (2000):

\[ LHV = 46,357 \frac{kJ}{kg} \]

\[ c_{pf} = 1.6650 \frac{kJ}{kg \cdot K} \]

\[ h_a(T_\infty) = c_{pa} T_a = 300.1 \frac{kJ}{kg} \]

\[ h_a(T_g) = c_{pa} T_g = 1334 \frac{kJ}{kg} \]

The exit gas temperature and corresponding enthalpy above were first determined from the temperature correction program described later, using Bruening’s result (2009) of \( h_1 = 132.4 \frac{W}{m^2 \cdot K} \), and then iterating later to find \( h_1 \) for each case. Substituting the above values into Equation (18), the air/fuel ratio was determined.

\[ \frac{\dot{m}_f}{\dot{m}_a} = 53.4 \quad (19) \]

The gas velocity can be determined by the definition of the exit gas mass flowrate.

\[ \dot{m} = \rho V A_c \quad (20) \]
Combining Equations (19) and (20), the gas velocity is given by

\[ V = \frac{53.4m_f}{\rho A_c} \] (21)

The density of air, \( \rho_a \), was taken to be that at a temperature of 1000 K.

\[ \rho = \rho_a = 0.3482 \text{ kg/m}^3 \]

The cross-sectional area of the hood, \( A_c \), was the hood width times the exit height.

\[ A_c = W \times H = 3.48 \times 10^{-2} \text{ m}^2 \]

The gas velocity was then determined using Equation (21) to be

\[ V = 8.50 \text{ m/s (19.0 mph)} \]

The Nusselt number was evaluated using the Whitaker correlation for external flow over a sphere found in Incropera et al. (2007) Equation 7.56.

\[ \overline{Nu_D} = \frac{h_1 D_1}{k_a} = 2 + \left( 0.4Re_D^{1/2} + 0.06Re_D^{2/3} \right) Pr^{0.4} \left( \frac{\mu}{\mu_s} \right)^{1/4} \] (22)

The Reynolds number is given by

\[ Re_D = \frac{\rho V D_1}{\mu} \] (23)

All gas properties were evaluated at the mean gas temperature of 993 K, averaged over the entire inside of the hood, except for \( \mu_s \), which was evaluated at the mean surface temperature, \( T_s \). \( T_s \) is the average of the mean gas temperature and the mean junction temperature of 881 K:

\[ T_s = \frac{T_{gm} + T_{jm}}{2} = 937 \text{ K} \] (24)

The following gas properties were taken from Incropera et al. (2007) Table A.4:

\[ \rho = \rho_a = 0.3482 \text{ kg/m}^3 \]
\[ \mu = 422.6 \times 10^{-7} \text{ N} \cdot \text{s/m}^2 \]
\[ \mu_s = 407.8 \times 10^{-7} \text{ N} \cdot \text{s/m}^2 \]
The Reynolds number, Nusselt number, heat transfer coefficient, and thermal resistance could now be evaluated.

\[
Pr = 0.726
\]

\[
k_a = 66.4 \times 10^{-3} \text{ W/m} \cdot \text{K}
\]

The Reynolds number, Nusselt number, heat transfer coefficient, and thermal resistance could now be evaluated.

\[
Re_D = 333
\]

\[
\overline{Nu}_D = 11.0
\]

\[
h_1 = 154 \text{ W/m}^2 \cdot \text{K}
\]

\[
R_1 = 91.5 K/W
\]

The updated value of heat transfer coefficient, \(h_1\), was substituted back into the temperature correction program for each case, and the true value of the heat transfer coefficient was found for each case:

\[
h_1 = 154 \text{ W/m}^2 \cdot \text{K} \text{ for the 2011 Closed Hood case}
\]

\[
h_1 = 156 \text{ W/m}^2 \cdot \text{K} \text{ for the 2011 Partially Open Hood case}
\]

\[
h_1 = 164 \text{ W/m}^2 \cdot \text{K} \text{ for the 2011 Open Torch case}
\]

\[
h_1 = 154 \text{ W/m}^2 \cdot \text{K} \text{ for the 2010 Closed Hood case}
\]

Thermal resistance 1 could now be computed for each case using Equation (15). The gas temperature was then solved at each measurement location using Equation (9), using the Fortran program found in Appendix B.

**A.5. Solution: Case 2**

The thermal circuit in Figure 77 can be used to find the heat transfer rate \(\dot{q}_5\).

\[
\dot{q}_5 = \frac{T_g - T_j}{R_1} = \frac{T_j - T_\infty}{R_5}
\]  \(25\)
The special case of a two-body enclosure in which one body (the lab walls) can be considered to be a blackbody leads to the following relation.

\[
\frac{T_j - T_\infty}{R_s} = \epsilon_1 \sigma A_1 (T_j^4 - T_\infty^4)
\]  \tag{26}

Combining Equations (25) and (26) and rearranging allows one to solve for the gas temperature, \(T_g\).

\[
T_g = T_j + \epsilon_1 \sigma A_1 R_1 (T_j^4 - T_\infty^4)
\]  \tag{27}

Substituting the property values found earlier, this becomes

\[
T_g = T_j + 1.069 \times 10^{-10} [T_j^4 - (298 \, K)^4]
\]  \tag{28}

which can be solved using a spreadsheet for each measurement location in Case 2. Note that in the OT case, the gas flow is not actually channeled by a hood, so the actual velocity would be somewhat lower than what was found using Equation (21). Thus the temperature correction for Case 2 would be somewhat underestimated due to this fact.
Appendix B. Temperature Correction Fortran Program

The floor plan below shows important dimensions in the Combustion Research Laboratory where the flaming hood sits on the test bench, that were used in the following program to calculate the view factors and temperature corrections. All dimensions are in inches.
PROGRAM temp_corrections

!Purpose: This program calculates the view factors to the lab walls and hood walls from the thermocouple used for temperature measurements in the propane flaming lab.
! This program is for the 2ft. hood.
! This program then calculates the gas temperature.

! Record of revisions:
! Date Programmer Description of change
! ==== ================ ===============
! 9-8-10 Brian Neilson Original code
! 10-24-11 Brian Neilson Changed hoodto9 distance
! 10-25-11 Brian Neilson Changed vectors to relative
! 11-11-11 Brian Neilson Added IF statements to Wall 9
! 3-13-12 Brian Neilson Changed z3 on Walls 2&4, east
! 3-13-12 Brian Neilson Changed x3 IF on Wall 9
! 3-17-12 Brian Neilson Changed y1 and y4 to = 0
! 3-18-12 Brian Neilson Deleted y1 statements
! 3-18-12 Brian Neilson Changed hood inlet to 12 in
! 3-18-12 Brian Neilson Changed thermocouple locations
! 3-18-12 Brian Neilson Updated room dimensions
! 3-18-12 Brian Neilson Removed debugging code
! 3-19-12 Brian Neilson Added radiation calculations

IMPLICIT NONE

! Data dictionary: declare variable types & definitions
REAL, PARAMETER :: rhw = 111.5  !Room half-width in inches
REAL, PARAMETER :: hoodlength = 48  !Hood length in inches
REAL, PARAMETER :: hoodto9 = 237  !Hood to wall 9 (in.)
REAL, PARAMETER :: bhw = 24  !Bench half-width in inches
REAL, PARAMETER :: zwest = 170.5 !Hood inlet to west wall (in.)
REAL, PARAMETER :: itbe = 80.5  !Hood inlet to bench end (in.)
INTEGER :: x, y, z  !Thermocouple coordinates(cm.)
REAL, DIMENSION(3) :: r1, r2, r3, r4  !Position vectors
REAL :: x1, x2, x3, x4, y1, y2, y3, y4, z1, z2, z4
REAL :: xcopy, ycopy, zcopy!Thermocouple coordinates(in.)
REAL, PARAMETER :: frontend = 15.5 !Hood inlet to bench end in
INTEGER, PARAMETER :: size = 3  !size of vectors
REAL :: f12e, f12w, f13, f14e, f14w, f19 !walls' view factors
REAL :: f1_labwalls  !Total view factor to lab walls
REAL :: xnorth !Thermocouple coordinates (in.) wall 4
INTEGER, PARAMETER :: unit=3  !Output unit
INTEGER :: iostat, iostat2, iostat3  !I/O status
REAL :: znear  !Near point on wall 2, west
REAL, PARAMETER :: ceiling=127 ! from bench to ceiling (in.)
REAL, PARAMETER :: bht=69 ! from bench to floor (in.)
INTEGER, PARAMETER :: TC=4 ! TC temp file unit
INTEGER, PARAMETER :: hood=5 ! Hood temp file unit

! Define variables for radiation loss calculation.
REAL, PARAMETER :: sigma=5.67E-8 ! Stefan-Boltzmann, W/m^2*K^4
REAL :: T1 ! TC temp, deg C
REAL, PARAMETER :: eps1 = 0.31 ! TC emissivity
REAL, PARAMETER :: A1 = 7.12E-5 ! TC area, m^2
REAL, PARAMETER :: T3 = 298 ! Lab wall temp, K
REAL :: F1_hood ! View factor from TC to hood
REAL :: T2 ! Hood temp, deg C
REAL, PARAMETER :: eps2 = 0.98 ! Hood emissivity
REAL, PARAMETER :: A2 = 0.938 ! Hood surface area, m^2
REAL, PARAMETER :: F23 = 0.5 ! View factor hood to lab wall
REAL, DIMENSION(2,2) :: A ! Coefficient matrix
REAL, DIMENSION(2,2) :: B ! Nonhomogeneous column vector
REAL, DIMENSION(2,2) :: AI ! Inverse of matrix A
REAL, DIMENSION(2) :: J ! Radiosity solution vector
REAL :: inverter ! Multiplier used to invert A
REAL :: detA ! Determinant of matrix A
REAL :: q3 ! Heat transfer rate TC to hood
REAL :: q6 ! Heat transfer rate TC to wall
REAL, PARAMETER :: h1 = 154 ! HT coefficient from gas to TC
REAL :: Tg ! Gas temp, deg C
INTEGER :: s, t ! Loop indices

! Open output file.
OPEN (UNIT=unit, FILE='TEMP_CORRECTIONS.DAT', &
  STATUS='REPLACE', ACTION='WRITE', IOSTAT=iostat)

! Open thermocouple temp input file.
OPEN (UNIT=TC, FILE='TC_temp.DAT', &
  STATUS='OLD', ACTION='READ', IOSTAT=iostat2)

! Open hood temp input file.
OPEN (UNIT=hood, FILE='hood_temp.DAT', &
  STATUS='OLD', ACTION='READ', IOSTAT=iostat3)

! Write column headers.
WRITE(unit, 109) 'x', 'y', 'z', 'F1_lab_walls', 'Tg'
109 FORMAT (1X, A1, T8, A1, T13, A1, T16, A12, T25, A2)

! Do loops for various coordinates
outer: DO z= 0, 1200, 200
middle: DO x = -140, 140, 20

! Skip unneeded x-coordinates
IF ( (x == -120) .OR. (x == -80) .OR. (x == -40) .OR. (x == 40) .OR. (x == 80) .OR. (x == 120)) CYCLE middle

inner: DO y = 0, 100, 20

! Convert thermocouple coordinates to inches
xcopy = (REAL(x))/25.4
ycopy = (REAL(y))/25.4
zcop y = (REAL(z))/25.4

! Wall 2, east

znear = zcopy - ((rhw - xcopy)*((zcop y)/(6 - xcopy)))

IF (znear <= -(hoodto9 + zcopy)) THEN
   f12e = 0
ELSE

   y2 = (rhw - xcopy)*((12 - ycop y)/(6 - xcopy))
   IF (y2 > ceiling) THEN
      y2 = ceiling
   END IF

   z2 = -(rhw - xcopy)*((zcop y)/(6 - xcopy))

   r1(1) = rhw - xcopy
   r1(2) = 0
   r1(3) = z2
   r2(1) = rhw - xcopy
   r2(2) = y2
   r2(3) = z2
   r3(1) = rhw - xcopy
   r3(2) = y2
   r3(3) = -1*(hoodto9 + zcopy)
   r4(1) = rhw - xcopy
   r4(2) = 0
   r4(3) = -1*(hoodto9 + zcopy)

   CALL contour_integral(r1, r2, r3, r4, size, f12e)
END IF

! Wall 2, west
znear= zcopy + ((rhw-xcopy)*((hoodlength-zcopy)/(6-xcopy)))

if1: IF (znear >= zwest) THEN
    f12w = 0
ELSE if1
    z1= (rhw-xcopy)*((hoodlength-zcopy)/(6-xcopy))
y2= (z1-zcopy)*((4.5-ycopy)/(hoodlength-zcopy))
r1(1)= rhw-xcopy
r1(2)= 0
r1(3)= z1
r2(1)= rhw-xcopy
r2(2)= y2
r2(3)= z1
r3(1)= rhw-xcopy
r3(2)= y2
r3(3)= zwest-zcopy
r4(1)= rhw-xcopy
r4(2)= 0
r4(3)= zwest-zcopy

    CALL contour_integral(r1, r4, r3, r2, size, f12w)
END IF if1

!Wall 3

x1= (zwest-zcopy)*((6-xcopy)/(hoodlength-zcopy))
IF (x1 > (rhw-xcopy)) THEN
    x1 = rhw-xcopy
END IF

y2= (zwest-zcopy)*((4.5-ycopy)/(hoodlength-zcopy))
IF (y2 > ceiling) THEN
    y2 = ceiling
END IF
x3= -(zwest-zcopy)*((6+xcopy)/(hoodlength-zcopy))
IF (x3 < -(rhw+xcopy)) THEN
    x3 = -(rhw+xcopy)
END IF

r1(1)= x1
r1(2)= 0
r1(3)= zwest-zcopy
r2(1)= x1
r2(2)= y2
r2(3)= zwest-zcopy
r3(1)= x3
CALL contour_integral(r1, r4, r3, r2, size, f13)

!Wall 4, east
	xnordt = -1*xcopy
znear = zcopy - ((rhw - xnorth)*((zcory)/(6-xnorth)))

IF (znear <= -(hoodto9+zcopy)) THEN
   f14e = 0
ELSE

   y2 = (rhw - xnorth)*((12-ycopy)/(6-xnorth))
   IF (y2 > ceiling) THEN
      y2 = ceiling
   END IF

   z2 = -(rhw - xnorth)*((zcory)/(6-xnorth))

   r1(1) = -(rhw - xnorth)
   r1(2) = 0
   r1(3) = z2
   r2(1) = -(rhw - xnorth)
   r2(2) = y2
   r2(3) = z2
   r3(1) = -(rhw - xnorth)
   r3(2) = y2
   r3(3) = -1*(hoodto9+zcopy)
   r4(1) = -(rhw - xnorth)
   r4(2) = 0
   r4(3) = -1*(hoodto9+zcopy)

   CALL contour_integral(r1, r2, r3, r4, size, f14e)
END IF

!Wall 4, west

znear = zcopy + ((rhw - xnorth)*((hoodlength-zcopy)/(6-xnorth)))

if3: IF (znear >= zwest) THEN
   f14w = 0
ELSE if3
  z1 = (rhw-xnorth)*((hoodlength-zcopy)/(6-xnorth))
  y2 = (z1-zcopy)*((4.5-ycopy)/(hoodlength-zcopy))
  r1(1) = -(rhw-xnorth)
  r1(2) = 0
  r1(3) = z1
  r2(1) = -(rhw-xnorth)
  r2(2) = y2
  r2(3) = z1
  r3(1) = -(rhw-xnorth)
  r3(2) = y2
  r3(3) = zwest-zcopy
  r4(1) = -(rhw-xnorth)
  r4(2) = 0
  r4(3) = zwest-zcopy

  CALL contour_integral(r1, r4, r3, r2, size, f14w)
END IF if3

!Wall 9

x1 = -(hoodto9+zcopy)*((6+xcopy)/(zcopy)))
IF (x1 < -(rhw+xcopy)) THEN
  x1 = -(rhw+xcopy)
END IF

y2 = (hoodto9+zcopy)*((12-ycopy)/(zcopy))
IF (y2 > ceiling) THEN
  y2 = ceiling
END IF

x3 = (hoodto9+zcopy)*((6-ycopy)/(zcopy))
IF (x3 > (rhw-ycopy)) THEN
  x3 = (rhw-ycopy)
END IF

r1(1) = x1
r1(2) = 0
r1(3) = -(hoodto9+zcopy)
r2(1) = x1
r2(2) = y2
r2(3) = -(hoodto9+zcopy)
r3(1) = x3
r3(2) = y2
r3(3) = -(hoodto9+zcopy)
r4(1) = x3
r4(2) = 0
r4(3) = -(hoodto9+zcopy)

CALL contour_integral(r1, r4, r3, r2, size, f19)

! Sum the contributions from the lab walls
f1_labwalls = f12e + f12w + f13 + f14w + f14e + f19

! Correct view factors slightly greater than 1.
IF (f1_labwalls > 1.0) THEN
    f1_labwalls = 1.0
END IF

! Read thermocouple and hood temps at given location.
READ(TC,*) T1  ! TC temp, degrees Celsius
READ(hood,*) T2  ! hood temp, degrees Celsius

! Convert temps to Kelvin.
T1 = T1 + 273.15
T2 = T2 + 273.15

! Calculate the view factor from the thermocouple to the hood.
F1_hood = 1 - f1_labwalls

! Initialize the elements of the coefficient matrix.
A(1,1) = ((eps1*A1)/(1-eps1))+(A1*F1_hood)+(A1*f1_labwalls)
A(1,2) = -A1*F1_hood
A(2,1) = -A1*F1_hood
A(2,2) = ((eps2*A2)/(1-eps2))+(A1*F1_hood)+(A2*F23)

! Initialize the elements of the nonhomogeneous column vector.
B(1) = ((sigma*(T1**4)*eps1*A1)/(1-eps1))&
    + (sigma*(T3**4)*A1*f1_labwalls)
B(2) = ((sigma*(T2**4)*eps2*A2)/(1-eps2))+(sigma*(T3**4)*A2*F23)

! Check to see if matrix A is invertible.
detA = (A(1,1)*A(2,2))-(A(1,2)*A(2,1))
invert: IF (detA == 0) THEN
    WRITE(unit, *) 'Matrix A not invertible.'
ELSE invert

! Invert the coefficient matrix.
inverter = 1.0/detA
A1(1,1) = inverter*A(2,2)
A1(1,2) = -inverter*A(1,2)
A1(2,1) = -inverter*A(2,1)
AI(2,2) = inverter*A(1,1)
END IF invert

!Call matrix multiplier to solve system of equations.
CALL multiply (2, AI, B, J)

!Solve for the heat transfer rates.
q3 = A1*F1_hood*(J(1)-J(2))
q6 = A1*f1_labwalls*(J(1)-(sigma*(T3**4)))

!Solve for the gas temperature at the given point.
Tg = ((q3+q6)/(h1*A1)) + T1 - 273.15

!Write the result.
WRITE(unit, 110) x, y, z, f1_labwalls, Tg
110 FORMAT (1X, I4, 1X, I3, 1X, I4, 1X, F7.5, 1X, F7.2)

END DO inner
END DO middle
END DO outer

CLOSE (UNIT=hood)
CLOSE (UNIT=TC)
CLOSE (UNIT=unit)

END PROGRAM temp_corrections
Appendix C. Temperature Plots as Line Graphs

\( z = 0 \text{ mm} \)

2011
Closed Hood

2011
Partially Open Hood

2011
Open Torch

2010
Closed Hood

Figure 78. Temperature line graph for \( z = 0 \text{ mm} \).
Figure 79. Temperature line graph for $z = 200$ mm.
Figure 80. Temperature line graph for $z = 400$ mm.
Figure 81. Temperature line graph for $z = 600$ mm.
Figure 82. Temperature line graph for $z = 800$ mm.
Figure 83. Temperature line graph for $z = 1000$ mm.