Barbeque Grill Temperature Distribution Design Improvement

California Polytechnic State University
San Luis Obispo, CA 93407

Mechanical Engineering
Phone: 805-756-1334
Fax: 805-756-1137
me.calpoly.edu

June 6, 2013

Sponsor:

Bull Outdoor Products
2483 West Walnut Ave
Rialto, CA 92376

Faculty Advisor:

Dr. James LoCascio

Team Members:

Peter Gobell pgobell@calpoly.edu
Connor McGill cmcgill@calpoly.edu
Thomas Willson tjwillso@calpoly.edu
Barbeque Grill Temperature Distribution Design Improvement

by

Peter Gobell

Thomas Willson

Connor McGill

Project Advisor: Dr. LoCascio

Instructor’s Comments:

Instructor’s Grade: ______________

Date: __________________________
Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>5</td>
</tr>
<tr>
<td>Introduction</td>
<td>6</td>
</tr>
<tr>
<td>Background</td>
<td>6</td>
</tr>
<tr>
<td>Objectives</td>
<td>8</td>
</tr>
<tr>
<td>Management Plan</td>
<td>8</td>
</tr>
<tr>
<td>Test Design Development</td>
<td>9</td>
</tr>
<tr>
<td>Background Research</td>
<td>9</td>
</tr>
<tr>
<td>Concepts</td>
<td>11</td>
</tr>
<tr>
<td>Final Test Fixture Selection</td>
<td>14</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>15</td>
</tr>
<tr>
<td>Fabrication</td>
<td>15</td>
</tr>
<tr>
<td>Detailed Analysis</td>
<td>18</td>
</tr>
<tr>
<td>Total System and Fuels</td>
<td>18</td>
</tr>
<tr>
<td>Grill Surface</td>
<td>20</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>22</td>
</tr>
<tr>
<td>Results - Unmodified System</td>
<td>23</td>
</tr>
<tr>
<td>Discussion - Unmodified System</td>
<td>25</td>
</tr>
<tr>
<td>Results – Briquettes</td>
<td>25</td>
</tr>
<tr>
<td>Discussion – Briquettes</td>
<td>27</td>
</tr>
<tr>
<td>Design - Modified Flame Tamers</td>
<td>27</td>
</tr>
<tr>
<td>Results – Modified Flame Tamers</td>
<td>27</td>
</tr>
<tr>
<td>Discussion – Modified Flame Tamers</td>
<td>34</td>
</tr>
<tr>
<td>Conclusion</td>
<td>34</td>
</tr>
<tr>
<td>References</td>
<td>35</td>
</tr>
<tr>
<td>Appendices</td>
<td>36</td>
</tr>
</tbody>
</table>
Abstract

Team License to Grill set out to assess Bull Outdoor Products, Inc.’s barbecues and quantify the apparent uneven temperature distribution or “hot spots” and “cold spots” across the grill. This testing was accomplished with the design and fabrication of a test fixture allowing for accurate and repeatable temperature collection across the barbecue. With results that matched the sponsor’s claims of hot and cold spots, an engineering model was made using heat transfer and thermodynamic equations. Once the model somewhat resembled the experimental data, it was used to suggest different modifications that would allow for better temperature distribution. It was discovered that the flame tamers have a large role in controlling heat going to the grill bars. This led to testing modified flame tamers to control temperature differences across the barbecue. It was found that greater air flow through the top of the flame tamers resulted in a more uniform temperature of the grill. The final iteration of the modified flame tamers incorporated larger holes that allowed for more hot gas to heat the front of the grill giving a slightly better front-to-back temperature distribution than before.
Introduction

Barbequing has become a popular and social method of outdoor food preparation. Through this popularity, barbeque grills have come to utilize various fueling methods – common fuels being charcoal, natural gas, and propane. Additional advances have been made in recent years that allow users to further control the cooking process. Other heating methods, such as infrared grilling, have been integrated with these conventional fuels. Even with all of these advances, however, there exists room for improvement, such as moderating the temperature distribution across the grilling surface.

For this project, Bull Outdoor Products has requested analysis of two of their high-end barbeque grill systems (using both natural gas and propane fuel). The goal is to obtain a greater understanding of their heat transfer characteristics affecting temperature distribution across the grill surface. Specific optimizations include even temperature distribution across the grilling surface and what changes can be made with minimal impact to manufacturing and overall cost.

Temperature distribution data for both Bull grills and competitor grills of similar sizes are not currently available. Bull Outdoor Products does not have a way to measure the differential temperature across the grill easily and accurately. As such, our initial goal was to develop a model with a set of theoretical and empirical thermodynamic and heat transfer equations that predict temperatures on the grill surface. We then constructed a test apparatus to collect temperature data to verify our model and to confirm that any changes we made in the barbeque result in an even temperature distribution.

Background

Bull Outdoor Products manufactures a wide range of high-end grills that are offered in many styles and sizes. Grilling has become a predominant method for Americans to prepare a variety of foods. To produce foods that contain the perfect amount of juices, flavor and texture requires knowledge of tools that are used to produce these foods, including the grill. The modern barbecue grill has made advancements in recent years and has become a science itself.

As with any complex system, there must be an understanding of the general process and components which make up the system as a whole and how they interact. Barbecue grilling is a process that takes stored energy in the form of a combustible fuel and uses it to cook food such as meat. The cooking process in its many forms results in the breakdown of fats, proteins and carbohydrates into a product that is both flavorsome and safe to consume (“The Thermodynamics of cooking and how different cooking methods work”).

There are three heat transfer modes that cook food through combustion of fossil fuels. The first mode is convection, which involves heating up a working fluid surrounding the food – air in this case – to
transfer energy to the food. The second is conduction and utilizes direct contact of an intermediate material such as a grilling grate that is heated up and transfers energy to the food through this contact. This can be seen with any food that has grill marks. The third is radiation, which transmits energy via electromagnetic waves. Many grills now utilize direct radiation in the form of Infrared waves that are produced from an infrared burner (IR). IR cooking adds intense heat to allow the user to produce chef-quality sears.

There are many forms of stored energy, but the most economical and readily available fuels for grilling are in the form of either compressed gas or compressed liquid. We will be focusing our studies on propane and natural gas.

Propane is extremely common in the US and is a very effective fuel source. Propane has about 2.44 times the BTU output of natural gas ("Propane vs. Natural Gas"). Propane used for a barbeque is purchased in pressurized tanks in liquid form by weight. There are 3 different grades of propane available in the US. The grade quality is determined by the percentages of its composing elements. Grade HD5 – the highest and most commonly used – is composed of at least 90% propane, no more than 5% propylene and the remainder is a combination of butane, iso-butane and methane ("Propane vs. Natural Gas"). The filler gases that are present other than propane have to fall within the prescribed limits but may vary within them depending on the process used to refine and manufacture. The other two grades are HD10 and commercial.

Natural gas, an alternative to propane, is measured differently than propane because it cannot be easily compressed into a liquid, and is measured in cubic feet. As mentioned before natural gas does not have the BTU per pound-mass output that propane has, but can be cheaper than propane depending on the location. Natural gas composition is about 70-90% methane, 0-20% ethane or propane or butane and 0-5% nitrogen or nitrogen sulfide ("Propane vs. Natural Gas"). There may be traces of rare gas as well but these percentages can vary depending on the refining process. Two main drawbacks are associated with the use of natural gas. The first requires a direct connection between the gas company and your grilling unit. This requires professional installation to be done correctly and safely if none currently exists. The second centers around the difference between the burner components and other associated hardware that deals with the fuel. Most commercially available gas grills come with stock propane set-ups unless otherwise specified, however most manufacturers sell aftermarket conversion kits.

There are several claims that competitors make as to why and how they have a more even temperature distribution across their grilling surface. Some of the more expensive varieties incorporate a ceramic briquette system. Bull outdoor products sent a panel of the briquette system to test and compare against their current flame tamer design. The results can be found in the result section.
Objectives

Bull Outdoor Products has asked team License to Grill to focus on one central concern they have deemed important. The problem of uneven temperature distribution across the grilling surface is a recurring issue that our team plans to investigated theoretically and empirically in order to offer solutions. To address these concerns, our team built, tested, and evaluated procedures that lead us to conclusive results that Bull Outdoor products can implement in future designs and manufacturing in regards to their outdoor gas grills.

The first objective was to perform theoretical analysis to develop a model of the grill systems as they currently exist. The next objective was to build a test apparatus to measure and record temperature profiles of the grills. The ultimate objective was to combine the results of both methods to make final recommendations to address these concerns.

Management Plan

In order to maximize efficiency of the team, tasks were delegated to each team member such that multiple tasks progressed simultaneously. These tasks reflected the particular strong skill sets of each member. All team members have had a part in the research of current grilling technology and documentation.

**Responsibilities**

**Mr. Willson**
- Communication with Bull Outdoor Products.
- Computational modeler
- Heat transfer analyst
- Thermodynamics analyst
- Data collection expert

**Mr. McGill**
- Communication with workspace facility personnel
- Budget
- Solid modeling
- Test checker, for accurate procedures and repeatable results

**Mr. Gobell**
- Shop tech
- Pretest, test mock up, and fabrication expert
- Solid modeling
Mr. Willson, Mr. McGill, and Mr. Gobell shared some responsibilities equally. These included, but were not limited to:

- Product-related research
- Problem calculations and modeling
- Test procedure generation
- Design ideation
- Document write-up

With these responsibilities, both individual and shared, License to Grill was able to maximize the time used to improve the grill design for Bull Outdoor Products. A Gantt chart detailing past and future project tasks may be found in Appendix L.

**Test Design Development**

**Background Research**

Based on the details of the problem from Bull Outdoor Products, License to Grill has conducted background research relating to barbeque technology as a whole. Having a thorough grasp of what is out in the market will aid in making the necessary conceptual designs to develop the best possible solution to the problem. This includes looking into infrared burner technology, natural gas and propane fuels, burner configurations, hood design, etc.

Accurate and repeatable temperature collection was the primary focus during the testing fixture design phase. These temperatures produced the necessary data to make informed design changes on the barbeque itself. In order to collect temperature data for multiple points inside the Brahma and Angus (models sent from Bull) a temperature Data Acquisition system (DAQ) simultaneously collected all the needed temperature points. The most reliable and cost effective way to measure multiple temperatures at once is with thermocouples hooked up to the DAQ. The DAQ sends the information to a computer that can plot in real-time the temperature distribution of the barbeque.

Professor Kim Shollenberger of Cal Poly is an expert in heat transfer and fluid mechanics. Her experience with temperature acquisition pointed us to a DAQ from Measurement Computing Corporation (MCC) with a 32 thermocouple input capability. She also recommended software that allows for numerous inputs to the computer (which we found satisfied by TracerDAQ Pro, also from MMC).

Choosing the correct thermocouple to use for the most reliable and accurate results required much research and comparison of various types. Table N-1 in Appendix N gives a comprehensive overview of which thermocouple type was best suited for the test environment. In the end, the thermocouple that was chosen had to be reliable in the anticipated temperature range.
results must also be achievable or comparing a design improvement to the old design becomes a moot point. At our predicted maximum grill temperature of around 1000°F, oxidation and thermocouple insulation material become especially relevant concerns. Type N thermocouples with glass braid (GG) insulation, although expensive, were chosen to address these two concerns. From Table N-4 in Appendix N, the temperature range for the glass braid insulation can be seen to hold our predicted maximum temperature.

**Application**

License to Grill has determined three types of insulation for type N thermocouples that are suitable and cost effective for the desired application. These types vary in the amount of sheathing that surrounds and protects the wiring inside. Each have been rated for certain range of temperature that they will best relay accurate data. The thermocouple temperature rating is between 200 and 2300 degrees Celsius (Watlow, pg.25). This is almost identical to type K thermocouple wiring, however, research showed that type N wire would better handle the cyclic temperature pattern of testing.

Other considerations that were thought to be related and important in their own right were the stiffness of each type and the ability to minimize quantity by reducing the diameter of each wire. Attaching the thermocouples to the test fixture as well as to any other point on the grill is another important consideration. The stiffness of the wire became a factor when considering how the thermocouple would make contact with the grill. The wires had to be stiff enough to spring back after being dragged across a bar, but not too stiff to hinder movement over the bar completely.

**Thermocouple Types**

The following is a summary that our team has developed to streamline the process of selection and underline all the important parameters associated with the selection process found in Appendix N of this report.

**Testing**

Before any physical data was taken, the thermocouple and insulation selected was tested to determine if it was suitable for the rigorous testing to follow. The testing procedure outlined in Appendix S and P specifies the exact method and procedure as well as the safety procedure in Appendix R.


**Concepts**

The main goal in the first quarter of our project was to conceptualize and develop tests as well as a test fixture that would be able to handle the many different types of experiments our team would like to carry out. The primary test centered on collecting temperature data across the entire grilling surface to determine the temperature distribution.

The team developed a set of criteria that would set guidelines. The tests and test fixture need to have these qualities at a minimum:

- Reliable
- Fast
- Accurate
- Repeatable
- Adjustable
- Presentable
- Applicable
- Reasonable /Relevant
- Safe
- Logical

After laying out the basic criteria that would guide the concept generating process License to Grill began producing theoretical test procedures and test apparatus solutions. Below are the details of the two concepts. A safety procedure before any test begins is in Appendix R.

**Test**

The types of test that our team developed were broken into two categories. The first was the primary testing goals. Primary tests deal directly with temperature and data acquisition on or surrounding the grill surface. This was the first priority because it was the main subject in the initial problem statement. The tests associated with this category needed to be detailed and offer considerable insight into to exactly what occurs from combustion to heat transfer. The tests run, in regards to this category, guided most of our design. See Appendix Q for the general testing procedure followed.

Next secondary tests served to offer background information and a more detailed analysis of areas that did not involve the grilling surface such as air temperatures at the vents and outer surfaces such as knobs and hood.

Categorizing these tests placed priority on areas that allowed the team to gather data to further our understanding of what is occurring in the grill. These experiments were refined and evaluated throughout the project timeline so that data remained pertinent and or relevant.
Test Fixture

The test fixture is a product and a physical representation of the tests we as a team planned to execute. Following the basic criteria discussed above served as a guide to what was included and how it was achieved involving data acquisition. The following features took into account while designing the test fixture:

- Structure dimensions
- Thermocouple mounts
- Thermocouple mounting system
- Thermocouple wiring accommodations
- Structure positioning/constraining
- Moving components
- Thermal Expansion
- Actuating/Indexing thermocouples
- Servicing/maintenance

This leaves room for many designs that can accomplish this goal and final decisions can be evaluated on other aspects such as manufacturability, cost and time associated with set up/running tests. A need to have temperature readings in equal fixed distances in the entire inside area of the grill dictated how the basic structure would function. From this, the structure was designed to accommodate several different thermocouple mounts and mounting systems.

Following the initial structural design, many considerations needed to be processed to develop a data collection device that would not skew the result or alter the natural mechanisms that occur in the grill while in operation. Design considerations were as follows:

- Mass of test fixture
- Temperatures in and around grill
- Convection disruption
- Grill modifications
- Thermocouple placement and position
- Conduction/Material choice
- Manufacturing
- Data Acquisition
- Cost

These considerations further placed constraints on the final design of our test fixture. An important note to make is that this device has few mechanical parts but must be able to perform several temperature reading tests. To reduce the potential for human error, the design was kept simple with the intention of allowing for consistent tests. A visual of our final design can be seen in Figure 1 and previous iterations can be seen in Appendix I.
Test Fixture Selection

The next obstacle was to choose a solution that accomplished all the requirements stated above. Initial considerations for design selection included manufacturability and material availability. This was a factor in deciding how and with what could be used to build the test fixture. Implementation and actual data collection was the primary goal and the sooner testing could begin the better. The resources that were available to the team include the machine shops on campus and local and online vendors. Accessing all the resources available to our team gave us a realistic picture needed to complete our goals. One of the main resources that our team had access to was Cal Poly faculty and technicians. Their insight was highly valued and greatly appreciate - helped guide the design selection process. The approved budget totaled $5,400.00 and allowed License to Grill to allocate a large percentage of our budget to a Data Acquisition System. The type of system, number of readings and sensitivity all played a role in determining the setup and operation of the test fixture. A structure with the most reliable and accurate method of data capturing made the final cut. A detailed breakdown of the budget is in Appendix K.
Final Test Fixture Selection

The selection described in the “Test Fixture” section incorporates all the design criteria and the ability to be flexible to allow the team to perform various tests. The apparatus went through several iterations. Appendix J shows a structural strength calculation to ensure the structure could handle the loads at the elevated temperatures. The final selection closely follows the criteria established in the initial selection but with an emphasis on reduction of the thermal mass.

Keeping the background research in mind, we conducted tests to first increase our basic understanding of the underlying issues in relation to Bull’s particular grills. Once we had preliminary data, we began to formulate design changes to the current systems.

After data was collected, the early computer models of the grill system were updated (Appendices B through H) to ensure that they are representative of the grills. This helped in determining the effects of any proposed changes made in the following design iteration of the barbeque.

After testing was completed and the results were analyzed to pinpoint the problem area(s), License to Grill brainstormed concept designs to address the concerns. The unrestricted brainstorming process allowed all concepts to have an equal and fair chance to be considered before making a final decision. The team wanted to have ample ideas and then weed out the infeasible ones. Simple analysis was done on the concepts and proof of concept models were created for those which held promise. Once we received the unmodified barbeques, our team was able to streamline ideas and make more informed decisions in regards to fixture design.

Figure 2. Design process to be followed during the early stages of this project.
Manufacturing

The main objective and emphasis of the project is to offer a viable solution to the problem of uneven temperature distribution throughout the grill surface. This requires intensive testing and evaluations of these tests.

Resources/Capabilities

The design constraints associated with our project mentioned above served as a launch point along with the initial test fixture concept. The final design includes input from a manufacturing point of view and was factored into the design long before construction began. Understanding the resources and limitations associated with the manufacturing capabilities was key to producing a quality test structure. The facilities that were available to our team include the following:

Basic wood- and metal-working tools

- Drill Presses, chop saws, bench grinders
- Manual lathes and mills
- Vertical CNC machine
- MIG Welder
- Spot welder
- TIG Water cooled welder
- Brazing Equipment
- General Machine shop Equipment

Fabrication

The most important piece of equipment for experimentation is the test apparatus. After flushing out the final design, basic drawings were generated and taken to the machine shop to communicate important design details. A fabrication plan was developed that detailed manufacturing steps to ensure our fabrication went smoothly and stayed on schedule this is in Appendix O.

For definitions of test fixture terminology used, see Appendix A.

Design 1

The first design used the team’s initial concepts and was an attempt to put into practice what our team felt was a good starting point. There was some uncertainty in the design, and as such, we allowed for modifications should they cause problems during the testing. As stated before the wire and pulley system was our initial design strategy to moving the slider bar. After constructing the basic rectangular test structure, the slider bar with thin steel wire attached to each end of the wire and joined in the middle to create a Y-junction. The single end of the Y-junction was routed along pulleys
to the rotisserie port elevation, which it could be pulled manually to move the slider bar across the grill surface. The design also incorporated a tabbed indexing system that would allow the slider bar to stop at each prescribed point where it would remain for a short amount of time that would allow for data collection. The indexing points on the fixture were machined as described in Appendix O and seen in Appendix I. It became very apparent after assembling the components and testing the system that this method was both unreliable and inaccurate. The slider bar would bind, pull over designated marks and performance at operational temperatures was a major concern. Our team took this failure as a learning opportunity and began to generate ideas that would solve the encountered problems. This first design allowed valuable insight to improve on the next design.

**Design 2**

The second design had many advantages over the first and helped make it past the initial testing phase and used in collecting data. As mentioned in the previous paragraph, there was a need for a more accurate and reliable method to move the thermocouples along the grill surface. Many ideas were generated; borrowing concepts related to how basic CNC machines are controlled gave our team a new way to position the slider bar. A lead screw would solve the major issue of travel. This design called for 5/16” diameter all-thread, a rod that is threaded its entire length. This in conjunction with the appropriately sized nut would allow for controlled movement in either direction. At the same time, our team did not want to alter the grill in anyway. The transmission, can be seen in Appendix I, allows the user to control movement manually via a hand crank. The crank arm is routed through the rotisserie port that is already in place. Inside the grill, the crank arm is attached to a sprocket, which is connected via a chain to an identical sprocket that is attached to the lead screw. The transmission is on the outside of the test fixture but on the inside of the grill. This allows the unit to fit inside the grill. This can be seen in Appendix I in greater detail.

After testing commenced using design 2 several minor issues arose that were addressed along the way. The first was there were small ports for ceramic feet on the bottom side of the test fixture but do to a communication error the feet were not made to the correct dimensions and did not fit into the prescribed holes. Metallic feet were not welded given that conduction through the feet might skew future data. This caused the test fixture to move and wedge itself in between grill bars. This situation would allow the fixture to be slightly tilted and cause the thermocouples to contact the bars at different places depending on the location in the grill. This was primarily because the thermocouple wiring that our team had selected was stiffer than anticipated even at elevated temperatures. This would not have been such a problem however this factor was multiplied 31 times given the number of thermocouple that were on the slider bar. This caused the stiffness of the system to behave much different than previously thought. This caused the test fixture to move rather than the slider bar at times and
allowed for some shifting to occur. This was quickly solved by taking some of the excess thermocouple wire (rated for our exact temperature range) and tying the test fixture down in all four corners. This method worked for the most part however at times it made quick changes more difficult and inserting modified flame tamers very difficult. Among other issues were transmission issues that caused the system to become unusable until the problems were resolved. Lubrication and operation at elevated temperatures such as 700°F adds considerable complexity to any system. This was best managed with high temperature cutting lubricant. The second designed test fixture was built specifically for the Brahma model grill and because of this it could only be used when testing that specific model. This was what our team had intended to do from the start so that the next fixture that was built that was for the smaller Angus model would have some of the improvements that our team felt would have the most influence.

Overall, our team was very pleased with the test fixtures performance and felt that with a few further modifications the design would be considered sound. The modifications that were made and the reasoning behind them are explained below. The second design made great advancements as compared to the first and much was learned in the process. At this point, the team took all the knowledge that we had gathered and design three is a culmination of this knowledge. Build descriptions and schematics can be found in Appendices O and I, respectively.

Design 3

Design 3 is an iteration of Design 2 with additional modifications to enhance its functionality. The first being that all-thread, as mentioned above, was not an ideal component to transfer linear motion and in its place our team went with a larger half inch diameter ACME threaded rod. To reduce the number of components, our team decided to forego the transmission and implement a direct drive system that makes use of an electric motor (electric drill) to move the slider bar. Two slots were cut on each side of the grill to allow the shaft to slide through, and the shaft can be chucked up in the drill. The testing previous to this showed that there was heat loss occurring through gaps on either side of the grill hood. As the slots that we made are considerably smaller than these pre-existing gaps, the slots should not cause a significant change in heat loss through the sides. In addition to the improvement of using ACME thread over regular thread, the lead screw was fixed to the fixture on each end using radial ball bearings. These bearings helped to reduce friction and keep the slider bar aligned over the guide rails. The bearings were installed in plates machined to have an interference fit of 0.001”. Locating the bearings this way allowed for accurate location and greater ease of use. The other option that was discussed was to install the bearings by welding them in place but this could lead to damage or warping due to the high heat that they would be subjected to. This was realized because the first test fixture warped during welding. The press fit worked well and held the bearings in place enough to let them smoothly roll, while still tight enough to not let the bearings move or fall out during testing. The final
addition to the third design was welding on thin feet to the fixture so it would not fall in between the grill bars. All of these improvements allowed for rapid collection of more accurate data, leading to stronger confidence in the results.

**Detailed Analysis – Total System and Fuels**

The team has assembled various simulations using Engineering Equation Solver (henceforth referred to as “EES”) for the grilling process in order to give a platform to vet potential alterations to the grills in the future. Factors such as the volumetric flow rate of air through the system, excess air with regards to combustion were tested for and ultimately approximated in order to get the simulations as representative of the system as we could. The simulations were not able to exactly predict the temperature profile of the grill surface, but they were able to predict trends such as the lower temperature “cold spots” being located immediately above the flame tamer and the higher temperature “hot spots” being located between burners. *Appendix M* has the initial test data which served to give us some idea about temperatures we could anticipate see on the grill.

The initial EES programs computed the complete combustion of the fuels entering the barbecue grills. The composition of natural gas was obtained from the gas supplier, PG&E. The composition of propane was found online in a Material Safety Data Sheet (“Safety Services of Suburban Propane”), but was assumed to be primarily propane. The adiabatic flame temperature for complete combustion of propane was approximately 3600°F. The adiabatic flame temperature for natural gas was approximately 3200°F. *Appendix C* contains the EES program for propane combustion, and *Appendix D* contains the EES program for natural gas combustion.

Early on in our calculations, through these programs, we determined that the effects of humidity could be neglected from future calculations, as the effects that they had on heat transfer were small. *Table 1* shows values for heat transfer based on humidity (the variable “a” representing relative humidity between approximately 0 and 80%). Please see *Appendix C* for the EES program.
Table 1. Effects of humidity on the heat transfer.

<table>
<thead>
<tr>
<th>a</th>
<th>$\dot{Q}_{cv}$ [Btu/hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00356</td>
<td>-10120</td>
</tr>
<tr>
<td>0.00712</td>
<td>-10116</td>
</tr>
<tr>
<td>0.01068</td>
<td>-10111</td>
</tr>
<tr>
<td>0.01424</td>
<td>-10107</td>
</tr>
<tr>
<td>0.01780</td>
<td>-10103</td>
</tr>
<tr>
<td>0.02136</td>
<td>-10098</td>
</tr>
<tr>
<td>0.02492</td>
<td>-10094</td>
</tr>
<tr>
<td>0.02848</td>
<td>-10089</td>
</tr>
<tr>
<td>0.03204</td>
<td>-10085</td>
</tr>
<tr>
<td>0.03560</td>
<td>-10081</td>
</tr>
</tbody>
</table>

The programs following were an attempt to model the internal temperature distribution. We then turned to developing our model of the overall system with the First Law of Thermodynamics. Our control volume is shown in Figure 3. Values such as the measured temperatures mentioned early in the “GIVEN/MEASURED” section of the EES program (see Appendix B) were found through testing with all of the burners set to their “medium” setting.

![Figure 3. Control volume of grill. CAD file courtesy of Bull Outdoor Products.](image-url)
From this program, we were able to approximate the amount of excess (non-combusting) air (shown in the program as “air_multiplier”) through known and approximated temperatures and the average time it takes for the grill to reach steady-state. The percent excess air was thus found to be approximately 400% (see Appendix B for First Law of Thermodynamics calculations).

**Detailed Analysis – Grill Surface**

The next simulation was for transient nodal analysis of the grill surface. Nomenclature used for descriptions and the numbering system used for the nodes are described in Appendix A. The purpose of this simulation is to be able to see the temperature distribution across the grill surface over time. Convection, conduction, and radiation modes of heat transfer are included in the analysis. Appendix E contains an explanation of the equations used, Appendix F contains the spreadsheet output from Microsoft Excel where the calculations took place, Appendix G shows a sample calculation, and Appendix H has the EES code used to find the thermodynamic properties used in the calculations.

The simulation (for propane with all burners on the “medium” setting) is shown in Figure 4.
### Simulation

<table>
<thead>
<tr>
<th>Bar Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>379</td>
<td>362</td>
<td>341</td>
<td>321</td>
<td>300</td>
<td>420</td>
<td>452</td>
<td>480</td>
<td>501</td>
<td>501</td>
<td>480</td>
<td>452</td>
<td>420</td>
<td>400</td>
<td>380</td>
</tr>
<tr>
<td>2</td>
<td>398</td>
<td>386</td>
<td>366</td>
<td>346</td>
<td>326</td>
<td>346</td>
<td>366</td>
<td>386</td>
<td>406</td>
<td>406</td>
<td>386</td>
<td>366</td>
<td>346</td>
<td>326</td>
<td>306</td>
</tr>
<tr>
<td>3</td>
<td>417</td>
<td>408</td>
<td>388</td>
<td>368</td>
<td>348</td>
<td>368</td>
<td>388</td>
<td>408</td>
<td>428</td>
<td>428</td>
<td>408</td>
<td>388</td>
<td>368</td>
<td>348</td>
<td>328</td>
</tr>
<tr>
<td>5</td>
<td>455</td>
<td>446</td>
<td>426</td>
<td>406</td>
<td>386</td>
<td>406</td>
<td>426</td>
<td>446</td>
<td>466</td>
<td>466</td>
<td>446</td>
<td>426</td>
<td>406</td>
<td>386</td>
<td>366</td>
</tr>
<tr>
<td>6</td>
<td>474</td>
<td>464</td>
<td>444</td>
<td>424</td>
<td>404</td>
<td>424</td>
<td>444</td>
<td>464</td>
<td>484</td>
<td>484</td>
<td>464</td>
<td>444</td>
<td>424</td>
<td>404</td>
<td>384</td>
</tr>
<tr>
<td>7</td>
<td>493</td>
<td>483</td>
<td>463</td>
<td>443</td>
<td>423</td>
<td>443</td>
<td>463</td>
<td>483</td>
<td>503</td>
<td>503</td>
<td>483</td>
<td>463</td>
<td>443</td>
<td>423</td>
<td>403</td>
</tr>
<tr>
<td>8</td>
<td>512</td>
<td>502</td>
<td>482</td>
<td>462</td>
<td>442</td>
<td>462</td>
<td>482</td>
<td>502</td>
<td>522</td>
<td>522</td>
<td>502</td>
<td>482</td>
<td>462</td>
<td>442</td>
<td>422</td>
</tr>
<tr>
<td>9</td>
<td>531</td>
<td>521</td>
<td>501</td>
<td>481</td>
<td>461</td>
<td>481</td>
<td>501</td>
<td>521</td>
<td>541</td>
<td>541</td>
<td>521</td>
<td>501</td>
<td>481</td>
<td>461</td>
<td>441</td>
</tr>
</tbody>
</table>

### Temperature [°F]

**Figure 4. Temperature profile of the entire grill surface after 10 minutes.**
It was also found that the relationship between the relative influences of radiation and convection were directly influenced by the grill bar temperature. This relationship is shown in Figure 5 for a simulation conducted for constant combustion product temperature and flame temperatures. As can be seen, the system will reach its steady-state temperature when the ratio between the radiation and convection is equal to -1, which indicates that the convection causes energy loss in the grill bars equivalent to the energy gain through radiation. The terms described as the radiation and convection influences are shown in Appendix F as equations [4] and [5], respectively.

Figure 5. Ratio of convection to radiation influence as a function of the grill bar node 14 temperature.

Results and Discussion

The results in the following section were accomplished by following a strict test procedure that was outlined earlier. This said, testing a barbeque outside has inherent variability that can consequently skew the data. The effect of a strong wind was to cool off the barbeque, thus lowering the grill bar temperatures. Similarly, when the humidity differed from day to day there were differences in the temperatures across the grill. This could have been avoided if testing was performed a completely isolated and controlled environment. However, the team did not have access to a large enough fume hood system that would allow for testing to be conducted indoors. The temperature profiles were difficult to duplicate because the test environment could not be controlled. Fortunately, as we were testing at in the same location at about the same time of day (for greater consistency of radiation from
the sun, which was otherwise not considered), we were able to get close temperature profiles for repeated tests. The wind however, can skew certain portion of the data as it was generally not constant and gusted from time to time. There were precautions made to reduce this, but again the barbeque could not be fully enclosed for safety reasons and there is always going to be some variability though small.

There were many more tests done on the propane fueled Brahma barbeque then the natural gas Angus barbeque. This is attributed to the similarities that were found between the two gas types. It will be shown below that both fuel types produce the same uneven temperature pattern across the grill. Due to similar results seen between the two fuels, the decision was made to primarily run our tests on the Brahma grill.

**Results – Unmodified System**

Tests were conducted at three different burner settings - “medium”, the lowest possible, and the highest possible. Very few tests were conducted at the highest possible temperature, as the temperatures nearly exceeded 1000 °F and were thus deemed impractical for general consumer grilling.

**Figure 6** shows collected data for the same settings as the simulation results shown previously in **Figure 5**. The test fixture needed to be attached to the grill surface, and as a result, only the temperatures of 36 of the 45 grill bars were recorded, as shown in **Figure 6**. **Figure 7** shows the comparison between the simulation and measured temperatures across the grill for the 7th node of each bar. While the measured and simulated temperatures were clearly not the same, the overall temperature profiles were of similar shape. Shifts in the peak locations is a result of the grill bar sets sliding around during testing.
<table>
<thead>
<tr>
<th>Bar Set</th>
<th>Hot Node</th>
<th>Temperature [°F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>626 357 365</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>655 375 401</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>602 397 421</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>631 415 441</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>660 439 473</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>699 468 513</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>738 507 551</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>777 536 580</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>816 585 629</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>855 624 668</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>894 663 708</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>933 702 746</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>972 741 785</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1011 774 818</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1050 842 886</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1089 887 931</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>1128 955 1000</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>1167 1034 1078</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>1206 1091 1135</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1245 1154 1198</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>1284 1223 1267</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>1323 1298 1332</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>1362 1337 1371</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>1401 1376 1415</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1440 1415 1459</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>1479 1454 1498</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>1518 1493 1537</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>1557 1532 1576</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>1596 1571 1615</td>
</tr>
</tbody>
</table>

*Figure 6. Measured temperature distribution.*
Discussion – Unmodified System

From the results shown in Figures 6 and 7 there are “hot and cold” spots on the grill that can lead to inconsistent grilling. The results validated the qualitative data given by Bull Outdoor Products stating that they were perceiving the “hot and cold” spots and the general unequal nature of the temperature of the grill. One of the more intriguing points to make is that the highest temperatures are found not directly over the burner, as one might expect, but rather directly in between the burners. After much discussion and consultation with the heat transfer text, it was determined that the flame tamers geometry and location could play a major role in the varying the temperature of the grill surface. It was first theorized that the flame tamer blocked the radiation that was directly coming from the flame to the center of the burner. It was also hypothesized that the very geometry of the flame tamer trapped hot gasses underneath it and pushed them out toward the side. This would increase the grill temperature between the burners through both the radiation and convective terms of heat transfer. The bars in between the burner are able to see the flames from both burners leading to the much higher radiation term. These hypotheses were tested in the model and proven to be a solid basis for the team to start designing new flame tamers based of this insight.

Results – Briquettes

As mentioned before, Bull Outdoor Products sent us a briquette system (shown in Figure 8 placed above the center burner) to compare to their current flame tamers. For the comparison, our team conducted a test with the two different systems with a single burner directly below the sample set to “medium”. The results may be seen in Figure 9.
**Figure 8.** Ceramic briquette system used by some of Bull Outdoor Products, Inc.’s competitors.

**Figure 9.** Temperature distribution from a single burner for two systems. Average ambient temperature of 71 [°F] for the ceramic briquette test and 68 [°F] for the flame tamer test.
**Discussion – Briquettes**

From **Figure 9**, it can be seen that the temperatures of the grill bars with the briquette system reach a higher temperature, but this comes at the cost of a greater temperature difference between the lowest temperature of a bar and the highest temperature of the same bar. For instance, looking at grill bar 7 of bar set 3 on both systems, the temperature difference for the briquette system is approximately 30°F higher than with the flame tamer system. With this in mind, the briquette system did not appear to be a solution to the uneven temperature distribution.

**Design – Modified Flame Tamers**

As it was noted that the current flame tamers blocked both radiation and a portion of the convection heat transfer directly above the burner, the first flame tamer redesign was a simple proof of concept trial. It was the exact same geometry as the original flame tamer, but had 1/4” holes drilled down either side of the top crown in an attempt to increase both the hot air travel up to the bars and line of sight the bars had to the flames. After each flame tamer was tested more design changes were made. There was not more than one variable changed at a time to control the experiment and eliminate any question as to what caused the results.

**Results – Modified Flame Tamer**

Tests of the modified flame tamers were all conducted on the same day in order to try to eliminate as many uncontrollable variables as possible (such as wind conditions, pressure, etc.). Due to manufacturing and cost restrictions, only one of each modified tamer was made rather than a full set of 5. Temperatures were taken directly over the flame tamer being tested with three burners set to “medium” - the burner directly below the flame tamer and the two adjacent burners using the standard flame tamers. The use of the adjacent burners was to ensure consistency of the results previously determined on the full grill surface test with all of the burners on - specifically the “hot spots” being seen between burners and the “cold spots” being directly above each burner.

**Figure 10** shows the unmodified flame tamers currently used within the grills. As a baseline comparison, we conducted a test with this flame tamer to compare to the modified flame tamers. For further reference, we tested without a flame tamer. The comparison between the setup without the flame tamer and the baseline may be seen in **Figure 14**.

The temperature profiles shown in **Figures 11, 12, and 13** for the modified flame tamer is proof of concept. The comparison to the baseline for each of these modified flame tamers may be seen in **Figures 15, 16, and 17**.
Figure 10. Stock (unmodified) flame tamer.

Figure 11. Modified flame tamer ("Type A"), which has an additional 30° added to the bend as well as 34 evenly-spaced ¼” holes.
**Figure 12.** Modified flame tamer (“Type B”), which has two rows of staggered evenly-spaced $\frac{1}{4}$” holes (34 holes in each row).

**Figure 13.** Modified flame tamer (“Type C”), which has two rows of staggered evenly-spaced holes (34 holes in each row) with all of the holes $\frac{1}{4}$” except for the last six on the higher row closest to the front of the grill, with are $\frac{3}{8}$”.
### Table 1: Temperature Distribution Comparison

<table>
<thead>
<tr>
<th>System</th>
<th>Standard Flame Tamer</th>
<th>No Flame Tamer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Set</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bar Not.</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

**Figure 14.** Temperature distribution comparison over a single burner for the standard unmodified flame tamer and no flame tamer.
<table>
<thead>
<tr>
<th>System</th>
<th>Standard Flame Tamer</th>
<th>30 Degree Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Set</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bar Node</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

**Figure 15.** Temperature distribution comparison over a single burner for the standard unmodified flame tamer and the “Type A” modification (additional 30° bend and holes).
<table>
<thead>
<tr>
<th>System</th>
<th>Standard Flame Tamer</th>
<th>Two Rows of Holes Staggered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Set</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bar Node</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>47</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>57</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 16.** Temperature distribution comparison over a single burner for the standard unmodified flame tamer and the “Type B” modification (staggered hole pattern).
<table>
<thead>
<tr>
<th>System</th>
<th>Standard Flame Tamer</th>
<th>Two Rows of Holes, Big Holes in the Front</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Set</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 17.** Temperature distribution comparison over a single burner for the standard unmodified flame tamer and the “Type C” modification (staggered hole pattern with larger holes in the front).
**Discussion – Modified Flame Tamers**

As we had been seeing with our other tests, the temperature distribution for the standard flame tamers contained “hot spots” and “cold spots” both laterally and longitudinally across the grill surface. Laterally, the grill was hottest in the back. In the longitudinal direction, the coolest grill bars were those that were directly above the flame tamers.

Without the flame tamers, the temperatures were fairly high all across the grill surface (as shown in Figure 11), but this would be impractical for consumer use as flare-ups from grease drips would likely become problematic. This does, however, indicate that we are headed in the right direction to try to increase the radiation and convection heat transfer to the grill bars immediately above the burners.

The “Type A” modification as shown in Figure 12 was seen to improve the temperature distribution for the bars above the burner, but minimal change to the temperature distribution towards the front or back of the grill (shown in Figure 13). Due to the change in the angle, however, changes would be need to be made to the overall shape of either the front and end of this flame tamer or the grill box such that it could rest stably as the unmodified flame tamers rest on a lip in the grill box.

The “Type B” modification shown in Figure 14 improved the temperature distribution for the bars above the burner and towards the back, but saw minimal change to the temperature distribution to the lateral temperature profile, as can be seen in Figure 15.

The final modification tried, “Type C”, shown in Figure 16 showed the most improvement in all three of the areas of interest (shown in Figure 17). The larger holes in the front appear to have served their purpose of allowing for more heat transfer to the front section of the grill bars, without introducing issues with heating the control surface.

**Conclusion**

Team License to Grill set out to assess Bull Outdoor Products barbecues and quantify the apparent uneven temperature distribution across the grill. The results have shown that the flame tamers play a large role in controlling the heat distribution across the grill bars. The flame tamers with modified holes at the top showed improvement with lateral temperature distribution. The final flame tamer design incorporating larger holes towards the front showed an improvement in both the lateral as well as longitudinal, or front to back and side-to-side temperature distributions. There is much that can be built on this study to further improve the temperature distribution and control other parameters such as flare-ups at the same time and will be subject for future research.
References

ANSI and IEC Color Codes for Thermocouples, Wire and Connectors. Omega Engineering Inc.  


SAF 5152 MATERIAL SAFETY DATA SHEET. Safety Services of Suburban Propane.  
www.suburbanpropane.com/safety (Accessed December 1, 2012)

The Thermodynamics of cooking and how different cooking methods work. AmazingRibs, Inc.  


Appendix A

An Explanation of Terms Used

Figure A-1. Nomenclature for external grill parts.

Figure A-2. Nomenclature for key internal grill parts.

Terminology for the test fixture:
- **Slider Bar** - square steel tube that contains 31 thermocouples in roughly \( \frac{1}{2} \) " increments and forms a “brush” that moves across the grill surface.
- **Lead Screw** - threaded rod that spins relative to the slider bar nut and is used to actuate the slider bar back and forth across the grill surface.
- **Slider Bar Nut** - an internal threaded nut that threads over the lead screw and allows the slider bar to move by remaining stationary.
- **Test Fixture** - physical structure that the slider bar, lead screw and transmission are fixed to.
- **Transmission** - the second design calls for a small transmission which is comprised of two spur gears and chain.
- **Rotisserie Ports** - physical cavities on either side of the grill that are used for a rotisserie but are used in our case for routing thermocouple wiring and power transmission.
Figure A-3. Numbering system used to describe the grill bars as used in calculations.
Appendix B

The following pages contain the EES code for applying the First Law of Thermodynamics to the barbeque grill system.
Grill Box - First Law - Propane

Assuming:
-see assumptions list in APPENDIX E

- - - - - GIVEN/ASSUMED - - - -

\[ m_{steel} = 200 \text{ [lbm]} \]

mass of barbeque steel - approximated

\[ T_{amb} = 62 \text{ [F]} \]

measured approx ambient temperature

\[ T_{air,ave} = 550 \text{ [F]} \]

measured average air temperature leaving vent

\[ T_{steel,inside} = 550 \text{ [F]} \]

approximate temperature of inside hood surface

\[ T_{steel,outside} = 220 \text{ [F]} \]

approximate temperature of outside hood surface

\[ \text{molarmass}_{C3H8} = 44.09 \text{ [lbm/lbmol]} \]

molar mass of propane

\[ \text{molarmass}_{O2} = 32 \text{ [lbm/lbmol]} \]

molar mass of oxygen

\[ \text{molarmass}_{N2} = 28 \text{ [lbm/lbmol]} \]

molar mass of nitrogen

\[ \dot{m}_{propane} = 2.7 \text{ [lbm/hour]} \]

mass flowrate of propane - measured

\[ \Delta t = 25 \text{ [min]} \cdot 60 \text{ [s/min]} \]

average measured time to steady-state

CALCULATIONS

\[ c_{steel} = c\left(\text{Stainless AISI304}, \frac{T_{steel,outside}+T_{steel,inside}}{2}\right) \]

specific heat of 304 stainless steel

\[ c_{p\ air} = C_p(Air,T=T_{air,ave}) \]

specific heat of air for constant pressure

\[ \dot{m}_{dot\ air} = (\text{air multiplier}) \cdot \frac{\dot{m}_{propane}}{\text{molarmass}_{C3H8}} \cdot (5 \cdot \text{molarmass}_{O2} + 3.76 \cdot \text{molarmass}_{N2}) \]

mass flowrate of air

\[ m_{steel} \cdot c_{steel} \cdot \frac{T_{steel,outside} - T_{steel,inside}}{\Delta t \cdot \text{convert(s,hour)}} + \dot{m}_{dot\ air} \cdot c_{p\ air} \cdot \frac{T_{air,ave} - T_{amb}}{0} = 0 \]

first law - steady state
\[ c_{\text{steel}} = c \left( \text{Stainless AISI304} \right) \left( \frac{T_{\text{steel,outside}} + T_{\text{steel,inside}}}{2} \right) \text{ specific heat of 304 stainless steel} \]

\[ c_{p,\text{air}} = c_{p} \left( \text{Air}, T = T_{\text{air,ave}} \right) \text{ specific heat of air for constant pressure} \]

\[ \dot{m}_{\text{air}} = \text{air multiplier} \cdot \frac{\dot{m}_{\text{propane}}}{\text{molarmass}_{\text{C}_3\text{H}_8}} \cdot 5 \cdot \left[ \text{molarmass}_{\text{O}_2} + 3.76 \cdot \text{molarmass}_{\text{N}_2} \right] \text{ mass flowrate of air} \]

\[ m_{\text{steel}} \cdot c_{\text{steel}} \cdot \left[ \frac{T_{\text{steel,outside}} - T_{\text{steel,inside}}}{\Delta t \cdot 0.00277778 \cdot \text{hour/s}} \right] + \dot{m}_{\text{air}} \cdot c_{p,\text{air}} \cdot \left[ T_{\text{air,ave}} - T_{\text{amb}} \right] = 0 \text{ first law - steady state} \]

**SOLUTION**

**Unit Settings: Eng F psia mass deg**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{air multiplier} )</td>
<td>3.925</td>
</tr>
<tr>
<td>( c_{p,\text{air}} )</td>
<td>0.2489 ( \text{[Btu/lbm-R]} )</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>1500 ( \text{[s]} )</td>
</tr>
<tr>
<td>( \text{molarmass}_{\text{C}_3\text{H}_8} )</td>
<td>44.09 ( \text{[lbm/lbmol]} )</td>
</tr>
<tr>
<td>( \text{molarmass}_{\text{O}_2} )</td>
<td>32 ( \text{[lbm/lbmol]} )</td>
</tr>
<tr>
<td>( \text{molarmass}_{\text{N}_2} )</td>
<td>28 ( \text{[lbm/lbmol]} )</td>
</tr>
<tr>
<td>( \dot{m}_{\text{air}} )</td>
<td>165 ( \text{[lbm/hour]} )</td>
</tr>
<tr>
<td>( \dot{m}_{\text{propane}} )</td>
<td>2.7 ( \text{[lbm/hour]} )</td>
</tr>
<tr>
<td>( T_{\text{air,ave}} )</td>
<td>550 ( \text{[F]} )</td>
</tr>
<tr>
<td>( T_{\text{amb}} )</td>
<td>62 ( \text{[F]} )</td>
</tr>
<tr>
<td>( T_{\text{steel,inside}} )</td>
<td>550 ( \text{[F]} )</td>
</tr>
<tr>
<td>( T_{\text{steel,outside}} )</td>
<td>220 ( \text{[F]} )</td>
</tr>
</tbody>
</table>

No unit problems were detected.
Appendix C

The following pages contain the EES code for the combustion of liquid propane.
"Combustion of Propane"

Assuming:
- ideal gas behavior
- complete combustion
- steady state
- 10% excess air
- negligible work, kinetic, potential energy

\[
\text{C}_3\text{H}_8 + (5 + \text{excess})(\text{O}_2 + 3.76(\text{N}_2)) + a(\text{H}_2\text{O}(g)) \rightarrow 3(\text{CO}_2) + (4 + a)(\text{H}_2\text{O}(g)) + (5 + \text{excess})(3.76)(\text{N}_2) + (5 + \text{excess})(\text{O}_2)
\]

"- - - GIVEN/ASSUMED - COMBUSTION - - -"

flow=2.7 [lbm/hr] "mass flowrate of propane"
T_propane= -60 [F] "input propane temperature"
T_ambient=77 [F] "ambient temperature"
P_in=14.7 [lbf/in^2] "input pressure"
P_out=P_in "output pressure"
molarmass_C3H8=44.09 [lbm/lbmol] "molar mass of propane"
n_dot_propane=flow/molarmass_C3H8 "lbmols of propane per hour"
a=0 "humidity ratio prior to combustion"
excess_percent=400 "percent of excess air"
excess_percent=(excess/5)*100

n_C3H8=1 "lbmol percentage propane"
n_O2=5*n_C3H8 "lbmole percentage oxygen"
n_CO2=3*n_C3H8 "lbmole percentage carbon dioxide"
n_H2O=4*n_C3H8 "lbmole percentage water vapor"
n_O2_ex=excess*n_C3H8 "lbmol percentage of excess oxygen"
n_N2=(5+excess)*3.76*n_C3H8 "lbmole percentage nitrogen"

"- - - LOOKUP/CALCULATIONS - - -"

h_bar_C3H8_form=ENTHALPY(C3H8,T=converttemp(C,F,25 [C])) "enthalpy of formation for propane"
h_bar_O2_form=ENTHALPY(O2,T=converttemp(C,F,25 [C])) "enthalpy of formation for oxygen"
h_bar_CO2_form=ENTHALPY(CO2,T=converttemp(C,F,25 [C])) "enthalpy of formation for carbon dioxide"
h_bar_H2O_form=ENTHALPY(H2O,T=converttemp(C,F,25 [C])) "enthalpy of formation for dihydrogen monoxide"
h_bar_N2_form=ENTHALPY(N2,T=converttemp(C,F,25 [C])) "enthalpy of formation for nitrogen"

h_bar_CO2_ref=ENTHALPY(CO2,T=T_propane) "specific enthalpy of carbon dioxide at ref temperature"
h_bar_CO2_out=ENTHALPY(CO2,T=T_out) "specific enthalpy of output carbon dioxide"

h_bar_O2_in=ENTHALPY(O2,T=T_ambient) "specific enthalpy of input oxygen"
h_bar_O2_ref=ENTHALPY(O2,T=T_propane) "specific enthalpy of oxygen at ref temperature"
h_bar_O2_out=ENTHALPY(O2,T=T_out) "specific enthalpy of output (excess) oxygen"

h_bar_H2O_pre=ENTHALPY(H2O,T=T_ambient) "specific enthalpy of water vapor in the air prior to combustion"
h_bar_H2O_ref=ENTHALPY(H2O,T=T_propane) "specific enthalpy of water vapor at ref temperature"
h_bar_H2O_out=ENTHALPY(H2O,T=T_out) "specific enthalpy of output water vapor"

h_bar_N2_ref=ENTHALPY(N2,T=T_propane) "specific enthalpy of nitrogen at ref temperature"
h_bar_N2_out=ENTHALPY(N2,T=T_out) "specific enthalpy of output nitrogen"
h_bar_N2_pre=ENTHALPY(N2,T=T_ambient) "specific enthalpy of input nitrogen"

DELTAh_bar_C3H8=0 [Btu/lbmol] "difference of enthalpy of propane referencing input temperature"
DELTAh_bar_O2=h_bar_O2_in-h_bar_O2_ref "difference of enthalpy of oxygen referencing input temperature"
DELTAh_bar_O2_ex=h_bar_O2_out-h_bar_O2_ref "difference of enthalpy of oxygen referencing input temperature"
DELTAh_bar_CO2=h_bar_CO2_out-h_bar_CO2_ref "difference of enthalpy of carbon dioxide referencing input temperature"
DELTAh_bar_H2O=h_bar_H2O_out-h_bar_H2O_ref "difference of enthalpy of water vapor referencing input temperature"
DELTAh_bar_H2O_p=h_bar_H2O_pre-h_bar_H2O_ref "difference of enthalpy of water vapor in air referencing input temperature"
DELTAh_bar_N2=h_bar_N2_out-h_bar_N2_ref "difference of enthalpy of nitrogen referencing input temperature"
DELTAh_bar_N2_p=h_bar_N2_pre-h_bar_N2_ref "difference of enthalpy of nitrogen in air referencing input temperature"
Combustion of Propane

- - - - Assumes: - - - -
- ideal gas behavior
- complete combustion
- steady state
- 10% excess air
- negligible work, kinetic, potential energy

\[ \text{C}_3\text{H}_8 + (5+\text{excess})(\text{O}_2 + 3.76\text{(N}_2) \rightarrow 3(\text{CO}_2) + (4+a)(\text{H}_2\text{O}(g)) + (5+\text{excess})(3.76)(\text{N}_2) + (5+\text{excess})(\text{O}_2) \]

- - - - GIVEN/ASSUMED - COMBUSTION - - - -

flow = 2.7 [lbm/hr] mass flowrate of propane

\[ T_{\text{propane}} = -60 \text{ [F]} \] input propane temperature

\[ T_{\text{ambient}} = 77 \text{ [F]} \] ambient temperature

\[ P_{\text{in}} = 14.7 \text{ [lbf/in}^2 \] input pressure

\[ P_{\text{out}} = P_{\text{in}} \] output pressure

\[ \text{molarmass}_{\text{C}_3\text{H}_8} = 44.09 \text{ [lbm/lbmol]} \] molar mass of propane

\[ n_{\text{propane}} = \frac{\text{flow}}{\text{molarmass}_{\text{C}_3\text{H}_8}} \text{ lbmols of propane per hour} \]

a = 0 humidity ratio prior to combustion

excess\_percent = 400 percent of excess air

\[ \text{excess\_percent} = \frac{\text{excess}}{5} \cdot 100 \]

\[ n_{\text{C}_3\text{H}_8} = 1 \text{ lbmol percentage propane} \]

\[ n_{\text{O}_2} = 5 \cdot n_{\text{C}_3\text{H}_8} \text{ lbmole percentage oxygen} \]

\[ n_{\text{CO}_2} = 3 \cdot n_{\text{C}_3\text{H}_8} \text{ lbmole percentage carbon dioxide} \]

\[ n_{\text{H}_2\text{O}} = 4 \cdot n_{\text{C}_3\text{H}_8} \text{ lbmole percentage water vapor} \]

\[ n_{\text{O}_2,\text{ex}} = \text{excess} \cdot n_{\text{C}_3\text{H}_8} \text{ lbmole percentage of excess oxygen} \]

\[ n_{\text{N}_2} = (5 + \text{excess}) \cdot 3.76 \cdot n_{\text{C}_3\text{H}_8} \text{ lbmole percentage nitrogen} \]
- - - - LOOKUP/CALCULATIONS - - - -

\[ \bar{h}_{\text{C}_3\text{H}_8,\text{form}} = h \left( \text{'C}_3\text{H}_8', T = \text{ConvertTemp} \ (C, F, 25 \ [C]) \right) \text{enthalpy of formation for propane} \]

\[ \bar{h}_{\text{O}_2,\text{form}} = h \left( \text{'O}_2', T = \text{ConvertTemp} \ (C, F, 25 \ [C]) \right) \text{enthalpy of formation for oxygen} \]

\[ \bar{h}_{\text{CO}_2,\text{form}} = h \left( \text{'CO}_2', T = \text{ConvertTemp} \ (C, F, 25 \ [C]) \right) \text{enthalpy of formation for carbon dioxide} \]

\[ \bar{h}_{\text{H}_2\text{O},\text{form}} = h \left( \text{'H}_2\text{O}', T = \text{ConvertTemp} \ (C, F, 25 \ [C]) \right) \text{enthalpy of formation for dihydrogen monoxide} \]

\[ \bar{h}_{\text{N}_2,\text{form}} = h \left( \text{'N}_2', T = \text{ConvertTemp} \ (C, F, 25 \ [C]) \right) \text{enthalpy of formation for nitrogen} \]

\[ \bar{h}_{\text{CO}_2,\text{ref}} = h \left( \text{'CO}_2', T = T_{\text{propane}} \right) \text{specific enthalpy of carbon dioxide at ref temperature} \]

\[ \bar{h}_{\text{CO}_2,\text{out}} = h \left( \text{'CO}_2', T = T_{\text{out}} \right) \text{specific enthalpy of output carbon dioxide} \]

\[ \bar{h}_{\text{O}_2,\text{in}} = h \left( \text{'O}_2', T = T_{\text{ambient}} \right) \text{specific enthalpy of input oxygen} \]

\[ \bar{h}_{\text{O}_2,\text{ref}} = h \left( \text{'O}_2', T = T_{\text{propane}} \right) \text{specific enthalpy of oxygen at ref temperature} \]

\[ \bar{h}_{\text{O}_2,\text{out}} = h \left( \text{'O}_2', T = T_{\text{out}} \right) \text{specific enthalpy of output (excess) oxygen} \]

\[ \bar{h}_{\text{H}_2\text{O},\text{pre}} = h \left( \text{'H}_2\text{O}', T = T_{\text{ambient}} \right) \text{specific enthalpy of water vapor in the air prior to combustion} \]

\[ \bar{h}_{\text{H}_2\text{O},\text{ref}} = h \left( \text{'H}_2\text{O}', T = T_{\text{propane}} \right) \text{specific enthalpy of water vapor at ref temperature} \]

\[ \bar{h}_{\text{H}_2\text{O},\text{out}} = h \left( \text{'H}_2\text{O}', T = T_{\text{out}} \right) \text{specific enthalpy of output water vapor} \]

\[ \bar{h}_{\text{N}_2,\text{ref}} = h \left( \text{'N}_2', T = T_{\text{propane}} \right) \text{specific enthalpy of nitrogen at ref temperature} \]

\[ \bar{h}_{\text{N}_2,\text{out}} = h \left( \text{'N}_2', T = T_{\text{out}} \right) \text{specific enthalpy of output nitrogen} \]

\[ \bar{h}_{\text{N}_2,\text{pre}} = h \left( \text{'N}_2', T = T_{\text{ambient}} \right) \text{specific enthalpy of input nitrogen} \]

\[ \Delta \bar{h}_{\text{C}_3\text{H}_8} = 0 \text{ [Btu/lbmol]} \text{ difference of enthalpy of propane referencing input temperature} \]

\[ \Delta \bar{h}_{\text{O}_2} = \bar{h}_{\text{O}_2,\text{in}} - \bar{h}_{\text{O}_2,\text{ref}} \text{ difference of enthalpy of oxygen referencing input temperature} \]

\[ \Delta \bar{h}_{\text{O}_2,\text{ex}} = \bar{h}_{\text{O}_2,\text{out}} - \bar{h}_{\text{O}_2,\text{ref}} \text{ difference of enthalpy of oxygen referencing input temperature} \]

\[ \Delta \bar{h}_{\text{CO}_2} = \bar{h}_{\text{CO}_2,\text{out}} - \bar{h}_{\text{CO}_2,\text{ref}} \text{ difference of enthalpy of carbon dioxide referencing input temperature} \]

\[ \Delta \bar{h}_{\text{H}_2\text{O}} = \bar{h}_{\text{H}_2\text{O},\text{out}} - \bar{h}_{\text{H}_2\text{O},\text{ref}} \text{ difference of enthalpy of water vapor referencing input temperature} \]

\[ \Delta \bar{h}_{\text{H}_2\text{O},\text{p}} = \bar{h}_{\text{H}_2\text{O},\text{pre}} - \bar{h}_{\text{H}_2\text{O},\text{ref}} \text{ difference of enthalpy of water vapor in air referencing input temperature} \]

\[ \Delta \bar{h}_{\text{N}_2} = \bar{h}_{\text{N}_2,\text{out}} - \bar{h}_{\text{N}_2,\text{ref}} \text{ difference of enthalpy of nitrogen referencing input temperature} \]

\[ \Delta \bar{h}_{\text{N}_2,\text{p}} = \bar{h}_{\text{N}_2,\text{pre}} - \bar{h}_{\text{N}_2,\text{ref}} \text{ difference of enthalpy of nitrogen in air referencing input temperature} \]

\[ \bar{W}_{cv} = 0 \text{ [Btu/hour]} \text{ negligible work} \]

\[ \dot{Q}_{cv} = -15000 \text{ [Btu/hour]} \text{ heat transfer} \]

\[ \Sigma = n_{\text{CO}_2} \cdot \left[ \bar{h}_{\text{CO}_2,\text{form}} + \Delta \bar{h}_{\text{CO}_2} \right] + \left[ n_{\text{H}_2\text{O}} + a \right] \cdot \left[ \bar{h}_{\text{H}_2\text{O},\text{out}} + \Delta \bar{h}_{\text{H}_2\text{O}} \right] + n_{\text{N}_2} \cdot \left[ \bar{h}_{\text{N}_2,\text{form}} + \Delta \bar{h}_{\text{N}_2} \right] + n_{\text{O}_2,\text{ex}} \]
\[
\sum_{\text{in}} = n_{C_3H_8} \cdot \left[ \overline{\Delta h}_{C_3H_8\text{,form}} + \overline{\Delta h}_{C_3H_8\text{,ex}} \right] + n_{O_2} \cdot \left[ \overline{\Delta h}_{O_2\text{,form}} + \overline{\Delta h}_{O_2\text{,ex}} \right] + n_{N_2} \cdot \left[ \overline{\Delta h}_{N_2\text{,form}} + \overline{\Delta h}_{N_2\text{,p}} \right] + a \cdot \left[ \overline{\Delta h}_{H_2O\text{,form}} + \overline{\Delta h}_{H_2O\text{,p}} \right]
\]

\[
\frac{\Delta_{cv}}{n_{\text{propane}}} - \frac{W_{cv}}{n_{\text{propane}}} = \Sigma_{\text{out}} - \Sigma_{\text{in}} \quad \text{energy balance}
\]
Appendix D

The following pages contain the EES code for the combustion of natural gas.
Combustion of Natural Gas

Assuming:
- ideal gas behavior
- complete combustion
- steady state
- no excess air (will be added later)
- negligible work, kinetic, potential energy

Assumed Composition
- 95.5% Methane
- 2.75% Ethane
- 1% Nitrogen
- 0.75% Carbon Dioxide

\[
(0.955(CH_4) + 0.0275(C_2H_6) + 0.01(N_2) + 0.0075(CO_2)) + (2.00625+\text{excess})(O_2) + 3.76(N_2) + a(H_2O(g)) \rightarrow 1.0175(CO_2) + (1.9925+a)(H_2O(g)) + (7.5435+(3.76\text{excess})N_2)+(\text{excess}O_2) + \text{heat}
\]

"GIVEN/ASSUMED"

- \(Q_{\text{dot cv}}=0\) [Btu/hour] "set heat transfer to 0 to find adiabatic flame temperature"
- \(W_{\text{dot cv}}=0\) [Btu/hour] "negligible work"
- \(T_{\text{nat gas}}=77\) [F] "input propane temperature"
- \(T_{\text{ambient}}=77\) [F] "ambient temperature"
- \(P_{\text{in}}=14.7\) [lbf/in^2] "input pressure"
- \(P_{\text{out}}=P_{\text{in}}\) "output pressure"
- flow=2 [lbm/hour] "mass flowrate of propane"
- molarmass_CH4=16.04 [lbm/lbmol] "molar mass of methane"
- molarmass_CO2=44.01 [lbm/lbmol] "molar mass of carbon dioxide"
- molarmass_C2H6=30.07 [lbm/lbmol] "molar mass of ethane"
- molarmass_N2=28.01 [lbm/lbmol] "molar mass of nitrogen"

\[
\text{input mass}=n_{CH_4}\text{molarmass}_CH_4+n_{C_2H_6}\text{molarmass}_C_2H_6+n_{N_2\_fuel}\text{molarmass}_N_2+n_{CO_2\_r}\text{molarmass}_CO_2
\]

\[
n_{\text{dot nat gas}}=\frac{\text{flow}}{\text{input mass}} "lbmols of propane per hour"
\]

- a=0 "humidity ratio prior to combustion"
- excess_percent=10 "percent of excess combustion air"
- excess_percent=(excess/5)*100
- \(n_{\text{nat gas}}=1\) "lbmol percent propane"
- \(n_{CH_4}=0.955n_{\text{nat gas}}\) "lbmol percent methane"
- \(n_{C_2H_6}=0.0275n_{\text{nat gas}}\) "lbmol percent ethane"
- \(n_{N_2\_fuel}=0.01n_{\text{nat gas}}\) "lbmol percent nitrogen fuel input"
- \(n_{CO_2\_r}=0.0075n_{\text{nat gas}}\) "lbmol percent carbon dioxide"
- \(n_{N_2\_r}=2.00625*3.76n_{\text{nat gas}}\) "lbmol percent nitrogen from air"

- \(n_{O_2}=(2.00625+\text{excess})n_{\text{nat gas}}\) "lbmole percent oxygen"
- \(n_{CO_2}=1.0175n_{\text{nat gas}}\) "lbmole percent carbon dioxide"
- \(n_{H_2O}=1.9925n_{\text{nat gas}}\) "lbmole percent water vapor"
- \(n_{N_2}\_p=(7.5435+3.76\text{excess})n_{\text{nat gas}}\) "lbmole percent nitrogen product"
- \(n_{O_2}\_ex=\text{excess}n_{\text{nat gas}}\) "lbmole percent of excess oxygen"

"LOOKUP VALUES"

- \(h_{\text{bar CH4 form}}=\text{ENTHALPY}(\text{CH4},T=\text{converttemp}(\text{C,F,25}[\text{C}]))\) "enthalpy of formation for methane"
- \(h_{\text{bar C2H6 form}}=\text{ENTHALPY}(\text{C2H6},T=\text{converttemp}(\text{C,F,25}[\text{C}]))\) "enthalpy of formation for ethane"
- \(h_{\text{bar O2 form}}=\text{ENTHALPY}(\text{O2},T=\text{converttemp}(\text{C,F,25}[\text{C}]))\) "enthalpy of formation for oxygen"
- \(h_{\text{bar CO2 form}}=\text{ENTHALPY}(\text{CO2},T=\text{converttemp}(\text{C,F,25}[\text{C}]))\) "enthalpy of formation for carbon dioxide"
- \(h_{\text{bar H2O form}}=\text{ENTHALPY}(\text{H2O},T=\text{converttemp}(\text{C,F,25}[\text{C}]))\) "enthalpy of formation for water vapor"
- \(h_{\text{bar N2 form}}=\text{ENTHALPY}(\text{N2},T=\text{converttemp}(\text{C,F,25}[\text{C}]))\) "enthalpy of formation for nitrogen"
formation for nitrogen

\[ h_{\text{bar, CO}_2\text{ ref}} = \text{ENTHALPY(CO}_2, T=T_{\text{ambient}}) \quad \text{"specific enthalpy of input carbon dioxide"} \]
\[ h_{\text{bar, CO}_2\text{ out}} = \text{ENTHALPY(CO}_2, T=T_{\text{out}}) \quad \text{"specific enthalpy of output carbon dioxide"} \]
\[ h_{\text{bar, O}_2\text{ in}} = \text{ENTHALPY(O}_2, T=T_{\text{ambient}}) \quad \text{"specific enthalpy of input oxygen"} \]
\[ h_{\text{bar, O}_2\text{ ref}} = \text{ENTHALPY(O}_2, T=T_{\text{nat gas}}) \quad \text{"specific enthalpy of output oxygen"} \]
\[ h_{\text{bar, O}_2\text{ out}} = \text{ENTHALPY(O}_2, T=T_{\text{out}}) \quad \text{"specific enthalpy of output excess oxygen"} \]
\[ h_{\text{bar, H}_2\text{O in}} = \text{ENTHALPY(H}_2\text{O}, T=T_{\text{ambient}}) \quad \text{"specific enthalpy of water vapor in the air prior to combustion"} \]
\[ h_{\text{bar, H}_2\text{O ref}} = \text{ENTHALPY(H}_2\text{O}, T=T_{\text{nat gas}}) \quad \text{"specific enthalpy of output water vapor"} \]
\[ h_{\text{bar, H}_2\text{O out}} = \text{ENTHALPY(H}_2\text{O}, T=T_{\text{out}}) \quad \text{"specific enthalpy of input water vapor"} \]
\[ h_{\text{bar, N}_2\text{ ref}} = \text{ENTHALPY(N}_2, T=T_{\text{nat gas}}) \quad \text{"specific enthalpy of output nitrogen"} \]
\[ h_{\text{bar, N}_2\text{ out}} = \text{ENTHALPY(N}_2, T=T_{\text{out}}) \quad \text{"specific enthalpy of input nitrogen"} \]
\[ h_{\text{bar, N}_2\text{ in}} = \text{ENTHALPY(N}_2, T=T_{\text{ambient}}) \quad \text{"specific enthalpy of input nitrogen"} \]

"CALCULATIONS"
\[- - - - - - - - - -]
\[ \Delta h_{\text{bar, CH}_4\text{ r}} = 0 \quad \text{[Btu/lbmol]} \quad \text{"difference of enthalpy of methane referencing input temperature"} \]
\[ \Delta h_{\text{bar, C}_2\text{H}_6\text{ r}} = 0 \quad \text{[Btu/lbmol]} \quad \text{"difference of enthalpy of ethane referencing input temperature"} \]
\[ \Delta h_{\text{bar, CO}_2\text{ r}} = 0 \quad \text{[Btu/lbmol]} \quad \text{"difference of enthalpy of input carbon dioxide referencing input temperature"} \]
\[ \Delta h_{\text{bar, N}_2\text{ r fuel}} = 0 \quad \text{[Btu/lbmol]} \quad \text{"difference of enthalpy of nitrogen in input air referencing input temperature"} \]
\[ \Delta h_{\text{bar, N}_2\text{ r}} = h_{\text{bar, N}_2\text{ in}} - h_{\text{bar, N}_2\text{ ref}} \quad \text{"difference of enthalpy of nitrogen in input air referencing input temperature"} \]
\[ \Delta h_{\text{bar, H}_2\text{O r}} = h_{\text{bar, H}_2\text{O in}} - h_{\text{bar, H}_2\text{O ref}} \quad \text{"difference of enthalpy of water vapor in input air referencing input temperature"} \]
\[ \Delta h_{\text{bar, O}_2\text{ r}} = h_{\text{bar, O}_2\text{ in}} - h_{\text{bar, O}_2\text{ ref}} \quad \text{"difference of enthalpy of oxygen referencing input temperature"} \]
\[ \Delta h_{\text{bar, CO}_2\text{ p}} = h_{\text{bar, CO}_2\text{ out}} - h_{\text{bar, CO}_2\text{ ref}} \quad \text{"difference of enthalpy of carbon dioxide referencing input temperature"} \]
\[ \Delta h_{\text{bar, H}_2\text{O p}} = h_{\text{bar, H}_2\text{O out}} - h_{\text{bar, H}_2\text{O ref}} \quad \text{"difference of enthalpy of water vapor referencing input temperature"} \]
\[ \Delta h_{\text{bar, N}_2\text{ p}} = h_{\text{bar, N}_2\text{ out}} - h_{\text{bar, N}_2\text{ ref}} \quad \text{"difference of enthalpy of nitrogen referencing input temperature"} \]
\[ \Delta h_{\text{bar, O}_2\text{ ex}} = h_{\text{bar, O}_2\text{ out}} - h_{\text{bar, O}_2\text{ ref}} \quad \text{"difference of enthalpy of oxygen referencing input temperature"} \]
\[ \Sigma_{\text{out}} = n_{\text{CO}_2\text{ p}}(h_{\text{bar, CO}_2\text{ form}} + \Delta h_{\text{bar, CO}_2\text{ p}}) + (n_{\text{H}_2\text{O}} + a)^*(h_{\text{bar, H}_2\text{O form}} + \Delta h_{\text{bar, H}_2\text{O p}}) + n_{\text{N}_2\text{ p}}(h_{\text{bar, N}_2\text{ form}} + \Delta h_{\text{bar, N}_2\text{ p}}) + n_{\text{O}_2\text{ ex}}(h_{\text{bar, O}_2\text{ form}} + \Delta h_{\text{bar, O}_2\text{ ex}}) \]
\[ \Sigma_{\text{in}} = n_{\text{CH}_4\text{ p}}(h_{\text{bar, CH}_4\text{ form}} + \Delta h_{\text{bar, CH}_4\text{ p}}) + n_{\text{C}_2\text{H}_6\text{ p}}(h_{\text{bar, C}_2\text{H}_6\text{ form}} + \Delta h_{\text{bar, C}_2\text{H}_6\text{ p}}) + n_{\text{N}_2\text{ r fuel}}(h_{\text{bar, N}_2\text{ form}} + \Delta h_{\text{bar, N}_2\text{ r fuel}}) + n_{\text{CO}_2\text{ r}}(h_{\text{bar, CO}_2\text{ form}} + \Delta h_{\text{bar, CO}_2\text{ r}}) + n_{\text{O}_2\text{ r}}(h_{\text{bar, O}_2\text{ form}} + \Delta h_{\text{bar, O}_2\text{ r}}) + n_{\text{N}_2\text{ r}}(h_{\text{bar, N}_2\text{ form}} + \Delta h_{\text{bar, N}_2\text{ r}}) + (a)^*(h_{\text{bar, H}_2\text{O form}} + \Delta h_{\text{bar, H}_2\text{O r}}) \]
\[ Q_{\text{dot cv}}/n_{\text{dot nat gas}} - W_{\text{dot cv}}/n_{\text{dot nat gas}} = \Sigma_{\text{out}} - \Sigma_{\text{in}} \quad \text{"energy balance"} \]

Combustion of Natural Gas

Assuming:
- ideal gas behavior
- complete combustion
- steady state
- no excess air (will be added later)
- negligible work, kinetic, potential energy

Assumed Composition

95.5% Methane
2.75% Ethane  
1% Nitrogen   
0.75% Carbon Dioxide

\[
\begin{align*}
(0.955(CH_4) + 0.0275(C_2H_6) + 0.01(N_2) + 0.0075(CO_2)) + (2.00625 + \text{excess})(O_2 + 3.76(N_2)) + a(H_2O(g)) \rightarrow 1.0175(CO_2) \\
+ (1.9925 + a)(H_2O(g)) + (7.5435 + 3.76 \times \text{excess})(N_2) + (\text{excess})(O_2) + \text{heat}
\end{align*}
\]

**GIVEN/ASSUMED**

* \( \dot{Q}_{cv} = 0 \) [Btu/hour] set heat transfer to 0 to find adiabatic flame temperature

* \( W_{cv} = 0 \) [Btu/hour] negligible work

* \( T_{nat, gas} = 77 \) [F] input propane temperature

* \( T_{ambient} = 77 \) [F] ambient temperature

* \( P_{in} = 14.7 \) [lbf/in²] input pressure

* \( P_{out} = P_{in} \) output pressure

* flow = 2 [lbm/hour] mass flowrate of propane

* \( \text{molarmass}_{CH_4} = 16.04 \) [lbm/lbmol] molar mass of methane

* \( \text{molarmass}_{CO_2} = 44.01 \) [lbm/lbmol] molar mass of carbon dioxide

* \( \text{molarmass}_{C_2H_6} = 30.07 \) [lbm/lbmol] molar mass of ethane

* \( \text{molarmass}_{N_2} = 28.01 \) [lbm/lbmol] molar mass of nitrogen

* input mass = \( n_{CH_4} \cdot \text{molarmass}_{CH_4} + n_{C_2H_6} \cdot \text{molarmass}_{C_2H_6} + n_{N_2,\text{fuel}} \cdot \text{molarmass}_{N_2} + n_{CO_2,\text{r}} \cdot \text{molarmass}_{CO_2} \)

* \( n_{nat, gas} = \frac{\text{flow}}{\text{input mass}} \) lbmols of propane per hour

* \( a = 0 \) humidity ratio prior to combustion

* \( \text{excess percent} = 10 \) percent of excess combustion air

* \( \text{excess percent} = \frac{\text{excess}}{5} \cdot 100 \)

* \( n_{nat, gas} = 1 \) lbmol percent propane

* \( n_{CH_4} = 0.955 \cdot n_{nat, gas} \) lbmol percent methane

* \( n_{C_2H_6} = 0.0275 \cdot n_{nat, gas} \) lbmol percent ethane

* \( n_{N_2,\text{fuel}} = 0.01 \cdot n_{nat, gas} \) lbmol percent nitrogen fuel input

* \( n_{CO_2,\text{r}} = 0.0075 \cdot n_{nat, gas} \) lbmol percent carbon dioxide
\[ n_{N_2,r} = 2.00625 \cdot 3.76 \cdot n_{\text{nat, gas}} \text{ lbmol percent nitrogen from air} \]

\[ n_{O_2} = \left[ 2.00625 + \text{excess} \right] \cdot n_{\text{nat, gas}} \text{ lbmole percent oxygen} \]

\[ n_{CO_2,p} = 1.0175 \cdot n_{\text{nat, gas}} \text{ lbmole percent carbon dioxide} \]

\[ n_{H_2O} = 1.9925 \cdot n_{\text{nat, gas}} \text{ lbmole percent water vapor} \]

\[ n_{N_2,p} = \left[ 7.5435 + 3.76 \cdot \text{excess} \right] \cdot n_{\text{nat, gas}} \text{ lbmole percent nitrogen product} \]

\[ n_{O_2,ex} = \text{excess} \cdot n_{\text{nat, gas}} \text{ lbmole percent of excess oxygen} \]

**LOOKUP VALUES**

\[ \bar{h}_{\text{CH}_4,\text{form}} = \bar{h} \left[ \text{CH}_4, T = \text{ConvertTemp} \left( C, F, 25 \ \text{[C]} \right) \right] \text{ enthalpy of formation for methane} \]

\[ \bar{h}_{\text{C}_2\text{H}_6,\text{form}} = \bar{h} \left[ \text{C}_2\text{H}_6, T = \text{ConvertTemp} \left( C, F, 25 \ \text{[C]} \right) \right] \text{ enthalpy of formation for ethane} \]

\[ \bar{h}_{O_2,\text{form}} = \bar{h} \left[ \text{O}_2, T = \text{ConvertTemp} \left( C, F, 25 \ \text{[C]} \right) \right] \text{ enthalpy of formation for oxygen} \]

\[ \bar{h}_{CO_2,\text{form}} = \bar{h} \left[ \text{CO}_2, T = \text{ConvertTemp} \left( C, F, 25 \ \text{[C]} \right) \right] \text{ enthalpy of formation for carbon dioxide} \]

\[ \bar{h}_{H_2O,\text{form}} = \bar{h} \left[ \text{H}_2\text{O}, T = \text{ConvertTemp} \left( C, F, 25 \ \text{[C]} \right) \right] \text{ enthalpy of formation for water vapor} \]

\[ \bar{h}_{N_2,\text{form}} = \bar{h} \left[ \text{N}_2, T = \text{ConvertTemp} \left( C, F, 25 \ \text{[C]} \right) \right] \text{ enthalpy of formation for nitrogen} \]

\[ \bar{h}_{CO_2,\text{ref}} = \bar{h} \left[ \text{CO}_2, T = T_{\text{ambient}} \right] \text{ specific enthalpy of input carbon dioxide} \]

\[ \bar{h}_{CO_2,\text{out}} = \bar{h} \left[ \text{CO}_2, T = T_{\text{out}} \right] \text{ specific enthalpy of output carbon dioxide} \]

\[ \bar{h}_{O_2,\text{in}} = \bar{h} \left[ \text{O}_2, T = T_{\text{ambient}} \right] \text{ specific enthalpy of input oxygen} \]

\[ \bar{h}_{O_2,\text{ref}} = \bar{h} \left[ \text{O}_2, T = T_{\text{nat, gas}} \right] \text{ specific enthalpy of output oxygen} \]

\[ \bar{h}_{O_2,\text{out}} = \bar{h} \left[ \text{O}_2, T = T_{\text{out}} \right] \text{ specific enthalpy of output excess oxygen} \]

\[ \bar{h}_{H_2O,\text{in}} = \bar{h} \left[ \text{H}_2\text{O}, T = T_{\text{ambient}} \right] \text{ specific enthalpy of water vapor in the air prior to combustion} \]

\[ \bar{h}_{H_2O,\text{ref}} = \bar{h} \left[ \text{H}_2\text{O}, T = T_{\text{nat, gas}} \right] \text{ specific enthalpy of output water vapor} \]

\[ \bar{h}_{H_2O,\text{out}} = \bar{h} \left[ \text{H}_2\text{O}, T = T_{\text{out}} \right] \text{ specific enthalpy of input water vapor} \]

\[ \bar{h}_{N_2,\text{ref}} = \bar{h} \left[ \text{N}_2, T = T_{\text{nat, gas}} \right] \text{ specific enthalpy of output nitrogen} \]

\[ \bar{h}_{N_2,\text{out}} = \bar{h} \left[ \text{N}_2, T = T_{\text{out}} \right] \text{ specific enthalpy of input nitrogen} \]

\[ \bar{h}_{N_2,\text{in}} = \bar{h} \left[ \text{N}_2, T = T_{\text{ambient}} \right] \text{ specific enthalpy of input nitrogen} \]

**CALCULATIONS**

\[ \Delta \bar{h}_{\text{CH}_4,r} = 0 \text{ [Btu/lbmol]} \text{ difference of enthalpy of methane referencing input temperature} \]
\[ \Delta h_{C2H6,r} = 0 \text{ [Btu/lbmol]} \text{ difference of enthalpy of ethane referencing input temperature} \]
\[ \Delta h_{CO2,r} = 0 \text{ [Btu/lbmol]} \text{ difference of enthalpy of input carbon dioxide referencing input temperature} \]
\[ \Delta h_{N2,r,fuel} = 0 \text{ [Btu/lbmol]} \text{ difference of enthalpy of nitrogen in input air referencing input temperature} \]
\[ \Delta h_{N2,r} = \bar{h}_{N2,in} - \bar{h}_{N2,ref} \text{ difference of enthalpy of nitrogen in input air referencing input temperature} \]
\[ \Delta h_{H2O,r} = \bar{h}_{H2O,in} - \bar{h}_{H2O,ref} \text{ difference of enthalpy of water vapor in input air referencing input temperature} \]
\[ \Delta h_{O2,r} = \bar{h}_{O2,in} - \bar{h}_{O2,ref} \text{ difference of enthalpy of oxygen referencing input temperature} \]
\[ \Delta h_{CO2,p} = \bar{h}_{CO2,out} - \bar{h}_{CO2,ref} \text{ difference of enthalpy of carbon dioxide referencing input temperature} \]
\[ \Delta h_{H2O,p} = \bar{h}_{H2O,out} - \bar{h}_{H2O,ref} \text{ difference of enthalpy of water vapor referencing input temperature} \]
\[ \Delta h_{N2,p} = \bar{h}_{N2,out} - \bar{h}_{N2,ref} \text{ difference of enthalpy of nitrogen referencing input temperature} \]
\[ \Delta h_{O2,ex} = \bar{h}_{O2,out} - \bar{h}_{O2,ref} \text{ difference of enthalpy of oxygen referencing input temperature} \]

\[ \Sigma_{out} = n_{CO2,p} \cdot \left[ \bar{h}_{CO2,form} + \Delta h_{CO2,p} \right] + \left[ n_{H2O} + a \right] \cdot \left[ \bar{h}_{H2O,form} + \Delta h_{H2O,p} \right] + n_{N2,p} \cdot \left[ \bar{h}_{N2,form} + \Delta h_{N2,p} \right] \]
\[ + n_{O2,ex} \cdot \left[ \bar{h}_{O2,form} + \Delta h_{O2,ex} \right] \]

\[ \Sigma_{in} = n_{CH4} \cdot \left[ \bar{h}_{CH4,form} + \Delta h_{CH4,r} \right] + n_{C2H6} \cdot \left[ \bar{h}_{C2H6,form} + \Delta h_{C2H6,r} \right] + n_{N2,r,fuel} \cdot \left[ \bar{h}_{N2,form} + \Delta h_{N2,r} \right] + n_{CO2,r} \cdot \left[ \bar{h}_{CO2,form} + \Delta h_{CO2,r} \right] + n_{O2} \cdot \left[ \bar{h}_{O2,form} + \Delta h_{O2,r} \right] + n_{N2,r} \cdot \left[ \bar{h}_{N2,form} + \Delta h_{N2,r} \right] + a \cdot \left[ \bar{h}_{H2O,form} + \Delta h_{H2O,r} \right] \]

\[ \frac{\dot{Q}_{cv}}{\dot{n}_{nat,gas}} = \frac{\dot{W}_{cv}}{\dot{n}_{nat,gas}} = \Sigma_{out} - \Sigma_{in} \text{ energy balance} \]

**SOLUTION**

**Unit Settings: Eng F psia molar deg**

\[ a = 0 \]
\[ \Delta h_{C2H6,r} = 0 \text{ [Btu/lbmol]} \]
\[ \Delta h_{CH4,r} = 0 \text{ [Btu/lbmol]} \]
\[ \Delta h_{CO2,r} = 39735 \text{ [Btu/lbmol]} \]
\[ \Delta h_{N2,r} = 0 \text{ [Btu/lbmol]} \]
\[ \Delta h_{H2O,r} = 31752 \text{ [Btu/lbmol]} \]
\[ \Delta h_{N2,r,fuel} = 0 \text{ [Btu/lbmol]} \]
\[ \Delta h_{O2,ex} = 25727 \text{ [Btu/lbmol]} \]
\[ \Delta h_{O2,r} = 0 \text{ [Btu/lbmol]} \]
\[ \text{excess} = 0.5 \]
\[ \text{excesspercent} = 10 \]
\[ \text{flow} = 2 \text{ [lbm/hour]} \]
\[ \bar{h}_{C2H6,form} = -36047 \text{ [Btu/lbmol]} \]
\[ \bar{h}_{CH4,form} = -32070 \text{ [Btu/lbmol]} \]
\[ \bar{h}_{CO2,form} = -169169 \text{ [Btu/lbmol]} \]
\[ \bar{h}_{H2O,form} = -103960 \text{ [Btu/lbmol]} \]
\( \dot{\text{H}_{2}O,_{in}} = -103960 \) [Btu/lbmol]
\( \dot{\text{H}_{2}O,_{out}} = -72208 \) [Btu/lbmol]
\( \dot{\text{H}_{2}O,_{ref}} = -103960 \) [Btu/lbmol]
\( \dot{\text{N}_{2,form}} = 0 \) [Btu/lbmol]
\( \dot{\text{N}_{2,_{in}} = 0} \) [Btu/lbmol]
\( \dot{\text{N}_{2,_{out}} = 24388} \) [Btu/lbmol]
\( \dot{\text{N}_{2,_{ref}} = 0} \) [Btu/lbmol]
\( \dot{\text{O}_{2,form}} = 0 \) [Btu/lbmol]
\( \dot{\text{O}_{2,_{in}} = 0} \) [Btu/lbmol]
\( \dot{\text{O}_{2,_{out}} = 25727} \) [Btu/lbmol]
\( \dot{\text{O}_{2,_{ref}} = 0} \) [Btu/lbmol]
\( \text{inputmass} = 16.76 \) [lbm/lbmol]
\( \text{molarmass}_{\text{C}_{2}H_{6}} = 30.07 \) [lbm/lbmol]
\( \text{molarmass}_{\text{CH}_{4}} = 16.04 \) [lbm/lbmol]
\( \text{molarmass}_{\text{CO}_{2}} = 44.01 \) [lbm/lbmol]
\( \text{molarmass}_{\text{N}_{2}} = 28.01 \) [lbm/lbmol]
\( n_{\text{C}_{2}H_{6}} = 0.0275 \)
\( n_{\text{CH}_{4}} = 0.955 \)
\( n_{\text{CO}_{2,p}} = 1.018 \)
\( n_{\text{CO}_{2,r}} = 0.0075 \)
\( \dot{n}_{\text{nat,~gas}} = 0.1194 \) [lbmol/hour]
\( \dot{n}_{\text{H}_{2}O} = 1.993 \)
\( \dot{n}_{\text{N}_{2,p}} = 9.424 \)
\( \dot{n}_{\text{N}_{2,r}} = 7.544 \)
\( \dot{n}_{\text{N}_{2,r,fuel}} = 0.01 \)
\( \dot{n}_{\text{nat,~gas}} = 1 \)
\( n_{\text{O}_{2}} = 2.506 \)
\( n_{\text{O}_{2,ex}} = 0.5 \)
\( P_{\text{in}} = 14.7 \) [lbf/in\(^2\)]
\( P_{\text{out}} = 14.7 \) [lbf/in\(^2\)]
\( \dot{Q}_{cv} = 0 \) [Btu/hour]
\( \Sigma_{\text{in}} = -32887 \) [Btu/lbmol]
\( \Sigma_{\text{out}} = -32887 \) [Btu/lbmol]
\( T_{\text{ambient}} = 77 \) [F]
\( T_{\text{nat,~gas}} = 77 \) [F]
\( T_{\text{out}} = 3169 \) [F]
\( W_{cv} = 0 \) [Btu/hour]

No unit problems were detected.
Appendix E

Equations in parenthesis are from “Introduction to Heat Transfer, Sixth Edition”, equations in brackets are derived.

See Appendix A for further nomenclature explanation.

Assumptions:
- negligible work, kinetic and potential energies
- no mass accumulation
- 2D grill bar broken up into 30 nodes for nodal analysis
- grill box sides are treated as isothermal and in direct contact with each bar’s nodes 1 and 30
- Explicit transient finite method (unknown nodal temperatures for new times are determined exclusively by known nodal temperatures at the previous time)
- constant properties across control surfaces
- burner flames treated as 30 rectangular black bodies with two sets of 30 per burner ("An Introduction to Flame Dynamics, Third Edition" Section 2.4.3 – supports the use of visible flames as black bodies)
- adiabatic flame temperature ~3600 F (see Appendix C)
- grill bar ends are only conducting to the grill box and not to each other
- air/combustion products exhibit ideal gas behavior
- air escaping same temperature as combustion products
- laminar boundary layer given Ra less than 10^12 (see Appendix H)
- grill is symmetrical about bar set 3, bar 5
- 400% excess air (beyond that needed for complete combustion) (see Appendix C)

Additional Notes:
- all three modes of heat transfer (conduction, convection and radiation) are accounted for
- thermodynamic properties obtained through EES
- ‘Grill Bar Model ver [latest version]’ EES code handles computations, constants, properties
### Table E-1. Variable descriptions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>ft$^2$</td>
<td>bar node cross-sectional area</td>
</tr>
<tr>
<td>$A_{burn}$</td>
<td>ft$^2$</td>
<td>burner flame surface area</td>
</tr>
<tr>
<td>$D$</td>
<td>ft</td>
<td>grill bar diameter</td>
</tr>
<tr>
<td>$k_{air}$</td>
<td>lbf/(s-R)</td>
<td>thermal conductivity of air</td>
</tr>
<tr>
<td>$F_{ij}$</td>
<td>-</td>
<td>total view factor</td>
</tr>
<tr>
<td>$F_0$</td>
<td>-</td>
<td>Fourier Number (Appendix H)</td>
</tr>
<tr>
<td>$g$</td>
<td>ft/s$^2$</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>$h$</td>
<td>Btu/(hr-R-ft$^2$)</td>
<td>convection heat transfer coefficient</td>
</tr>
<tr>
<td>$k_{steel}$</td>
<td>Btu/(hr-ft-R)</td>
<td>thermal conductivity of steel</td>
</tr>
<tr>
<td>$L$</td>
<td>ft</td>
<td>vertical distance from bar to flame</td>
</tr>
<tr>
<td>$L_{bar}$</td>
<td>ft</td>
<td>total grill bar length</td>
</tr>
<tr>
<td>$Pr$</td>
<td>-</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$q_{conv}$</td>
<td>Btu/hr</td>
<td>heat transfer rate due to convection</td>
</tr>
<tr>
<td>$q_{rad}$</td>
<td>Btu/hr</td>
<td>heat transfer rate due to radiation</td>
</tr>
<tr>
<td>$r$</td>
<td>ft</td>
<td>grill bar radius</td>
</tr>
<tr>
<td>$Ra$</td>
<td>-</td>
<td>Rayleigh Number</td>
</tr>
<tr>
<td>$T_{air}$</td>
<td>R</td>
<td>air/combustion products temperature</td>
</tr>
<tr>
<td>$T_{flame}$</td>
<td>R</td>
<td>flame temperature</td>
</tr>
<tr>
<td>$T_{P,m,b}$</td>
<td>R</td>
<td>bar temperature at time P, node number m, bar set b</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>ft$^3$/s</td>
<td>thermal diffusivity of steel – Appendix H</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1/R</td>
<td>thermal expansion due to free convection of air</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>s</td>
<td>time step</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>ft</td>
<td>node spacing in x-direction</td>
</tr>
<tr>
<td>$\nu$</td>
<td>ft$^2$/s</td>
<td>kinematic viscosity of air</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Btu/(hr-R$^2$-ft$^2$)</td>
<td>Stephen-Boltzman constant</td>
</tr>
</tbody>
</table>

**Figure E-1.** View factor variable information.
Appendix E

Transient finite-difference – conduction:
\[
T_{m,b}^{p+1} = F_{o} \left[ T_{m-1,b}^{p} + T_{m+1,b}^{p} \right] + (1 - 2F_{o})T_{m,b}^{p}
\]
(Equation 5.81)
\[
F_{o} = \frac{a\Delta t}{(\Delta x)^2}
\]
(Equation 5.80)

Transient finite-difference – conduction and radiation:
\[
T_{m,b}^{p+1} = F_{o} \left[ T_{m-1,b}^{p} + T_{m+1,b}^{p} + \frac{q_{rad}\Delta x}{k_{A}} \right] + (1 - 2F_{o})T_{m,b}^{p}
\]
Combining these equations:
\[
T_{m,b}^{p+1} = F_{o} \left[ T_{m-1,b}^{p} + T_{m+1,b}^{p} + \frac{A_{burn}^{F_{ij}}\sigma \left( (T_{\text{flame}})^{4} - (T_{m,b}^{p})^{4} \right)}{k_{\text{steel}} \Delta x} \right] + (1 - 2F_{o})T_{m,b}^{p}
\]

Further equations going into the above:
For the view factor for a cylinder (grill bar) and parallel rectangle (assumed shape of blackbody flame assumption):
\[
F_{ij} = \frac{r}{s_{1} - s_{2}} \left[ \tan^{-1} \left( \frac{s_{1}}{L} \right) - \tan^{-1} \left( \frac{s_{2}}{L} \right) \right]
\]
(Table 13.1)
\[
F_{ij} = F_{\text{own}} + F_{\text{far own}} + F_{\text{next burner}}
\]
A further addition to this model is breaking the parallel rectangle into 30 elements. This allows for more representative view factors for the bar nodes not near the center of the burner.

Transient finite-difference – conduction, radiation, and convection:
\[
Ra_{D} = \frac{g \beta (T_{m,b}^{p} - T_{\text{air}})}{\nu \alpha}
\]
(Equation 9.23)
\[
\bar{N}_{u_{D}} = \frac{0.60 + \frac{0.387 Ra_{D}^{1/3}}{\left( 1 + (0.550 Pr^{-9/8})^{8/27} \right)^{8/27}}}{k_{air}}
\]
(Equation 9.34)

Combine equations to find \( \bar{h} \):
\[
\bar{h} = \frac{k_{air}}{D} \left( 0.60 + \frac{0.387 \left( \frac{g \beta (T_{m,b}^{p} - T_{\text{air}})}{\nu \alpha} \right)^{1/3}}{\left( 1 + (0.550 Pr^{-9/8})^{8/27} \right)^{8/27}} \right)^{2}
\]
\[
q_{\text{conv}} = \bar{h} A (T_{\text{air}} - T_{m,b}^{p})
\]
(Equation 6.8)
\[
T_{m,b}^{p+1} = F_{o} \left[ T_{m-1,b}^{p} + T_{m+1,b}^{p} + \frac{q_{rad}\Delta x}{k_{\text{steel}}A} + \frac{q_{\text{conv}}(\Delta x)^{2}}{k_{air} A_{\text{bar}}} \right] + (1 - 2F_{o})T_{m,b}^{p}
\]
Appendix E

Combining these equations for the final node temperature after a single time step [1]:

\[
T_{m,b}^{p+1} = F_0 \left[ T_{m-1,b}^p + T_{m+1,b}^p + \frac{A_{\text{burn}F,i,p} \left( \frac{(T_{\text{flame}})^4 - (T_{m,b}^p)^4}{k_{\text{steel}A}} \right) \Delta x}{L_{\text{bar}D}} + \left( \frac{(T_{\text{air}} - T_{m,b}^p)(\Delta x)^2}{1 + \left( \frac{0.559}{Pr} \right)^{9/16}} \right) \right] + (1 - 2F_0)T_{m,b}^p
\]

For the nodes in contact with the grill box sides (approximately) [2]:

\[
T_{m,b}^{p+1} = F_0 \left[ T_{m-1,b}^p + T_{m+1,b}^p + \frac{A_{\text{burn}F,i,p} \left( \frac{(T_{\text{flame}})^4 - (T_{m,b}^p)^4}{k_{\text{steel}A}} \right) \Delta x}{L_{\text{bar}D}} + \left( \frac{(T_{\text{air}} - T_{m,b}^p)(\Delta x)^2}{1 + \left( \frac{0.559}{Pr} \right)^{9/16}} \right) \right] + (1 - F_0)T_{m,b}^p
\]
Appendix F

Sample Calculation for a single temperature step of a bar node not in contact with the grill box sides using equation [1] derived in Appendix E:

\[
T_{m,b}^{P+1} = F_0 \left[ T_{m-1,b}^P + T_{m+1,b}^P + \frac{A_{burn} F_{ij} \sigma \left[(T_{\text{flame}})^4 - (T_{m,b})^4\right]\Delta x}{k_{\text{steel}} A} + \left(\frac{(T_{\text{air}} - T_{m,b})\Delta x}{L_{\text{bar}} D}\right) \left(0.60 + \frac{0.387 \left(\frac{g \beta (T_{m,b} - T_{\text{air}}) D^3}{\nu \alpha}\right)^{1/6}}{1 + \left(0.559 \frac{9}{416}\right)^{8/27}}\right)^2 \right] + (1 - 2F_0)T_{m,b}^P
\]

Where, to allow for easy comparison between radiation and convection terms, simplifying to a set of equations of:

\[ T_{m,b}^{P+1} = F_0 \left[ T_{m-1,b}^P + T_{m+1,b}^P + T_{\text{rad}} + T_{\text{conv}} \right] + (1 - 2F_0)T_{m,b}^P \]  

\[ T_{\text{rad}} = \frac{A_{burn} F_{ij} \sigma \left[(T_{\text{flame}})^4 - (T_{m,b})^4\right]\Delta x}{k_{\text{steel}} A} \]  

\[ T_{\text{conv}} = \left(\frac{(T_{\text{air}} - T_{m,b})\Delta x}{L_{\text{bar}} D}\right) \left(0.60 + \frac{0.387 \left(\frac{g \beta (T_{m,b} - T_{\text{air}}) D^3}{\nu \alpha}\right)^{1/6}}{1 + \left(0.559 \frac{9}{416}\right)^{8/27}}\right)^2 \]

General:

\[ T_{\text{flame}} = 1600 \text{ [R]} \]
\[ T_{\text{air}} = 1250\text{[R]} \]
\[ \sigma = \left(5.67 \cdot 10^{-8} \frac{W}{K^4 \text{m}^2}\right) \cdot \left(0.0302 \frac{\text{Btu}}{\text{hr} \cdot \text{R}^4 \cdot \text{ft}^2}\right) \]
\[ \sigma = 1.712 \cdot 10^{-9} \left(\frac{1}{\text{Btu}} \frac{\text{hr} \cdot \text{R}^4 \cdot \text{ft}^2}{W^4 \cdot \text{K}^4}\right) \]
\[ g = 32.2 \left[\frac{\text{ft}}{\text{s}}\right] \]
\[ \Delta t = 10 \text{[s]} \]

For this case:

\[ L_{\text{bar}} = 2.0625 \text{[ft]} \]
\[ L_{\text{perp}} = 6.667 \cdot 10^{-2} \text{[ft]} \]
\[ L_{\text{width}} = 0.25 \text{[ft]} \]
\[ m = 14 \]
\[ b = 1 \]
\[ L = 0.3542 \text{[ft]} \]
\[ T_{13,3} = 550 \text{[R]} \]
\[ T_{14,3} = 550 \text{[R]} \]
\[ T_{15,3} = 550 \text{[R]} \]

Geometry:

\[ \Delta x_r = 0.825 \text{[in]} \]
\[ \Delta x_r = (0.825 \text{[in]} \cdot \frac{1}{12} \text{[in]}) \]
\[ \Delta x_b = 6.875 \cdot 10^{-2} \text{[ft]} \]
\[ \Delta x_b = 0.619 \text{[in]} \]
\[ \Delta x_b = (0.619 \text{[in]} \cdot \frac{1}{12} \text{[in]}) \]
\[ \Delta x_b = 5.156 \cdot 10^{-2} \text{[ft]} \]
\[ D = \left(\frac{5}{16} \text{[in]} \cdot \frac{1}{12} \text{[ft]}\right) \]
\[ D = 0.026 \text{[ft]} \]
\[ r = 1.302 \cdot 10^{-2} \text{[ft]} \]
Appendix F

$$A = \frac{\pi D^2}{4} \text{ grill bar cross-section}$$

\[
A = \pi (0.026 \text{[ft]})^2 \\
A = 5.326 \cdot 10^{-4} \text{[ft}^2]\]

$$A_{burn} = (1 \text{[in]}^2) \cdot \left( \frac{1}{114} \text{[in}^2] \right) \left( \frac{1}{10} \right)$$

$$A_{burn} = 6.944 \cdot 10^{-3} \text{[ft}^2]\]

flame surface area (see assumptions)

Thermal Properties (from EES):

\[
k_{steel} = 12.11 \text{ [Btu} \text{hr}^{-1} \text{ft}^{-1} \text{R}^{-1}] \text{ thermal conductivity of steel}
\]

\[
k_{air} = 6.335 \cdot 10^{-3} \text{ [Btu} \text{hr}^{-1} \text{ft}^{-1}] \text{ thermal conductivity of air}
\]

\[
Pr = 0.684 \text{ Prandtl number for air}
\]

\[
\rho = 475.6 \text{ [lbm} \text{ft}^{-3}] \text{ density of steel}
\]

\[
c = 0.1444 \text{ [Btu} \text{lbm}^{-1} \text{R}^{-1}] \text{ specific heat capacity of steel}
\]

\[
\alpha = \frac{k_{steel}}{\rho c} \text{ thermal diffusivity of steel}
\]

\[
\alpha = \frac{(12.52 \text{ [Btu} \text{hr}^{-1} \text{ft}^{-1} \text{R}^{-1}] )}{(475.6 \text{ [lbm} \text{ft}^{-3}]) \left( 0.1444 \text{ [Btu} \text{lbm}^{-1} \text{R}^{-1}] \right)}
\]

\[
\alpha = 0.2084 \text{ [ft}^2 \text{hr}]\]

\[
\beta = \frac{1}{\tau_{air}} \text{ thermal expansion due to free convection for air}
\]

\[
\beta = \frac{1}{1250 \text{ [R]}}
\]

\[
\beta = 8.132 \cdot 10^{-4} \text{ [R]}\]

\[
\nu = 6.855 \cdot 10^{-4} \text{ [ft}^2 \text{]} \text{ kinematic viscosity of air}
\]

View factor calculations done iteratively in EES (see Appendix T). A sample calculation segment follows for the 14
th grill bar node of a set for the first node of the burner:

$$Fo = \frac{a\Delta t}{(\Delta x)^2} \text{ Fourier number}$$

\[
Fo = \frac{(0.2084 \text{ [ft}^2 \text{hr}])(10 \text{[s]})(\frac{1 \text{[in]}^2}{3600 \text{[s]}})}{(6.875 \cdot 10^{-2} \text{[ft]}^2)}
\]

\[
Fo = 0.109 \text{ less than 0.5, so } 1D \text{ modeling acceptable}
\]

\[
L_{horiz,own,1} = |\Delta x_p n_p - \Delta x_r n_r| \text{ horizontal distance from grill bar to burner}
\]

\[
L_{horiz,own,1} = |(5.156 \cdot 10^{-2} \text{[ft]})(1) - (6.875 \cdot 10^{-2} \text{[ft]})(14)|
\]

\[
L_{horiz,own,1} = 0.9109 \text{ [ft]}\]

\[
S_{1,own,1} = \sqrt{L_{perp}^2 + L_{horiz,own,1}^2} \text{ view factor long distance, own burner, near}
\]

\[
S_{1,own,1} = \sqrt{(6.667 \cdot 10^{-2} \text{[ft]}^2) + (0.9109 \text{[ft]})^2}\]

\[
S_{1,own,1} = 0.9134 \text{[ft]}\]

\[
S_{2,own,1} = S_{1,own,1} - \frac{1}{12} \text{[ft]} \text{ view factor short dist, assumes 1" flame block}
\]

\[
S_{2,own,1} = 0.9134 \text{[ft]} - \frac{1}{12} \text{[ft]}
\]

\[
S_{2,own,1} = 0.8300 \text{[ft]}\]

\[
S_{2,own,2} = \sqrt{L_{perp}^2 + (L_{horiz,own,1} + L_{width})^2} \text{ view factor long distance, own burner, far}
\]

\[
S_{2,own,2} = \sqrt{(6.667 \cdot 10^{-2} \text{[ft]}^2) + (0.9109 \text{[ft]} + 0.25 \text{[ft]})^2}\]

\[
S_{2,own,2} = 1.1629 \text{[ft]}\]

\[
S_{2,own,2} = S_{1,own,2} - \frac{1}{12} \text{[ft]} \text{ view factor short dist, assumes 1" flame block}
\]

2 of 4
Appendix F

\[ s_{2,\text{own},2} = 1.1629 \ [ft] - \frac{1}{12} \ [ft] \]
\[ s_{2,\text{own},2} = 1.0800 \ [ft] \]

\[ s_{1,\text{adj}} = \sqrt{(L_{\text{perp}} + L_{\text{horiz,adj}})^2 + L_{\text{horiz,own},1}^2} \] view factor long distance, adjacent burner

\[ s_{1,\text{adj}} = \sqrt{(6.667 \cdot 10^{-2} \ [ft] + 0.9109 \ [ft])^2 + (0.9109 \ [ft])^2} \]
\[ s_{1,\text{adj}} = 1.3362 \ [ft] \]

\[ s_{2,\text{adj}} = s_{1,\text{adj}} - \frac{1}{12} \ [ft] \] view factor short dist, assumes 1° flame block

\[ s_{2,\text{adj}} = 1.3362 \ [ft] - \frac{1}{12} \ [ft] \]
\[ s_{2,\text{adj}} = 1.2529 \ [ft] \]

\[ F_{ij,\text{own}1} = \frac{r}{s_{1,\text{own}1} - s_{2,\text{own}1}} \left[ \tan^{-1} \left( \frac{s_{1,\text{own}1}}{L} \right) - \tan^{-1} \left( \frac{s_{2,\text{own}1}}{L} \right) \right] \left( \frac{1}{30} \right) \] view factor for own burner, near

\[ F_{ij,\text{own}1} = \frac{(1.302\cdot10^{-2} \ [ft])}{(0.9134 \ [ft])-(0.8300 \ [ft])} \left[ \tan^{-1} \left( \frac{(0.9134 \ [ft])}{(0.3542 \ [ft])} \right) - \tan^{-1} \left( \frac{(0.8300 \ [ft])}{(0.3542 \ [ft])} \right) \right] \left( \frac{1}{30} \right) \]
\[ F_{ij,\text{own}1} = 0.0099 \]

\[ F_{ij,\text{own}2} = \frac{r}{s_{1,\text{own}2} - s_{2,\text{own}2}} \left[ \tan^{-1} \left( \frac{s_{1,\text{own}2}}{L} \right) - \tan^{-1} \left( \frac{s_{2,\text{own}2}}{L} \right) \right] \left( \frac{1}{30} \right) \] view factor for own burner, far

\[ F_{ij,\text{own}2} = \frac{(1.302\cdot10^{-2} \ [ft])}{(1.1629 \ [ft])-(1.0800 \ [ft])} \left[ \tan^{-1} \left( \frac{(1.1629 \ [ft])}{(0.3542 \ [ft])} \right) - \tan^{-1} \left( \frac{(1.0800 \ [ft])}{(0.3542 \ [ft])} \right) \right] \left( \frac{1}{30} \right) \]
\[ F_{ij,\text{own}2} = 0.0063 \]

\[ F_{ij,\text{adj}} = \frac{r}{s_{1,\text{adj}} - s_{2,\text{adj}}} \left[ \tan^{-1} \left( \frac{s_{1,\text{adj}}}{L} \right) - \tan^{-1} \left( \frac{s_{2,\text{adj}}}{L} \right) \right] \left( \frac{1}{10} \right) \] view factor for adjacent burner

\[ F_{ij,\text{next}} = \frac{(1.302\cdot10^{-2} \ [ft])}{(1.3362 \ [ft])-(1.2529 \ [ft])} \left[ \tan^{-1} \left( \frac{(1.3362 \ [ft])}{(0.3542 \ [ft])} \right) - \tan^{-1} \left( \frac{(1.2529 \ [ft])}{(0.3542 \ [ft])} \right) \right] \left( \frac{1}{30} \right) \]
\[ F_{ij,\text{next}} = 0.0049 \]

\[ F_{ij} = F_{ij,\text{own}1} + F_{ij,\text{own}2} + F_{ij,\text{next}} \] total view factor for the single burner node

\[ F_{ij} = 0.0099+0.0063+0.0049 \]
\[ F_{ij} = 0.0211 \]

From "view factors ver 2.EES" file, it was found that the total view factor for this node is 0.116.

Plugging all of these values back in to the original equations:

\[
T_{\text{rad}} = \frac{\Delta x}{k_{\text{steel}}} \left[ (T_{\text{flame}})^4 - (T_{\text{m,b}})^4 \right] \]

\[
T_{\text{rad}} = \frac{(6.944 \cdot 10^{-3} \ [ft^2])(0.116) \left( 1.712 \cdot 10^{-9} \left( \frac{Btu}{hr \cdot R^4 \cdot ft^2} \right) \cdot [(1600 \ [R])^4 - (550 \ [R])^4](6.875 \cdot 10^{-2} \ [ft^2]) \right)}{12.11 \left( \frac{Btu}{hr \cdot ft \cdot R} \right)(5.625 \cdot 10^{-3} \ [ft^2])} \]

\[ T_{\text{rad}} = 9.0 \ [R] \]

\[
T_{\text{conv}} = \left( \frac{(T_{\text{air}}-T_{\text{m,b}})(\Delta x)^2}{l_{\bar{b}ar}D} \right) \left( 0.60 + \frac{0.387 \left( \frac{\rho(T_{\text{m,b}}-T_{\text{air}})\alpha^4}{\nu} \right)^{1/6}}{1 + \left( \frac{0.559 \rho}{\nu} \right)^{9/16}} \right)^{2} \]

\[ T_{\text{conv}} = \left( (T_{\text{air}}-T_{\text{m,b}})(\Delta x)^2 \right) \left( 0.60 + \frac{0.387}{(1 + \left( \frac{0.559 \rho}{\nu} \right)^{9/16})^{8/27}} \right)^{2} \]
Appendix F

\[
T_{\text{conv}} = \left( \frac{(1250 \ [R] - 550 \ [R]) (6.875 \cdot 10^{-2} \ [ft])^2}{(2.0625 \ [ft])(0.026 \ [ft])} \right) 0.60 + \\
0.387 \left( \frac{32.2}{S^2} \right) \left( 8 \cdot 10^{-4} \left( \frac{1}{R} \right) \right) \left( \frac{1250 \ [R] - 550 \ [R]) (0.026 \ [ft])^3}{(6.855 \cdot 10^{-4} \left( \frac{t}{S} \right) \left( 0.2084 \left( \frac{t}{R} \right) \right)} \right)^{\frac{1}{2}} \\
+ \left( 1 + \left( \frac{0.559}{0.684} \right)^{\frac{8}{27}} \right)^{\frac{8}{27}} \right)^\frac{9}{16}
\]

\[
T_{\text{conv}} = 56.2 \ [R]
\]

\[
T_{m,b}^{P+1} = F_0 \left[ T_{m-1,b}^P + T_{m+1,b}^P + T_{\text{rad}} + T_{\text{conv}} \right] + (1 - 2F_0)T_{m,b}^P \tag{3}
\]

\[
T_{14,3}^{P+1} = (0.109)(550 \ [R]) + (550 \ [R]) + (9.0 \ [R]) + (56.2 \ [R]) + (1 - 2(0.109))(550 \ [R])
\]

\[
T_{14,3}^{P+1} = 557.1 \ [R]
\]
### Table G-1. Variables used for transient nodal analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Fo} )</td>
<td>0.109</td>
<td>-</td>
<td>Fourier number</td>
</tr>
<tr>
<td>( \text{A} )</td>
<td>5.33E-04</td>
<td>ft(^2)</td>
<td>&quot;node&quot; cross-sectional area</td>
</tr>
<tr>
<td>( \text{A}_{\text{burn}} )</td>
<td>6.94E-03</td>
<td>ft(^2)</td>
<td>burner flame surface area</td>
</tr>
<tr>
<td>( \text{k}_{\text{steel}} )</td>
<td>12.52</td>
<td>Btu/(hr-ft-R)</td>
<td>thermal conductivity</td>
</tr>
<tr>
<td>( r )</td>
<td>1.30E-02</td>
<td>ft</td>
<td>grill bar radius</td>
</tr>
<tr>
<td>( \text{sigma} )</td>
<td>1.71E-09</td>
<td>Btu/(hr-R(^4)-ft(^2))</td>
<td>Stephen-Boltzman constant</td>
</tr>
<tr>
<td>( \text{delta}_x )</td>
<td>6.88E-02</td>
<td>ft</td>
<td>node spacing in x-direction</td>
</tr>
<tr>
<td>( \text{L} )</td>
<td>0.354</td>
<td>ft</td>
<td>distance from bar to flame (vert)</td>
</tr>
<tr>
<td>( \text{T}_{\text{flame}} )</td>
<td>1600</td>
<td>R</td>
<td>flame temperature</td>
</tr>
<tr>
<td>( \text{Pr} )</td>
<td>0.684</td>
<td>-</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>( g )</td>
<td>32.2</td>
<td>ft/s(^2)</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>( \text{Beta} )</td>
<td>8.0E-04</td>
<td>l/R</td>
<td>thermal expansion due to free convection</td>
</tr>
<tr>
<td>( \text{T}_{\text{air}} )</td>
<td>1250</td>
<td>R</td>
<td>air/combustion products temperature</td>
</tr>
<tr>
<td>( \text{D} )</td>
<td>0.026</td>
<td>ft</td>
<td>grill bar diameter</td>
</tr>
<tr>
<td>( \text{nu} )</td>
<td>6.86E-04</td>
<td>ft(^2)/s</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>( \text{alpha} )</td>
<td>5.79E-05</td>
<td>ft(^2)/s</td>
<td>thermal diffusivity</td>
</tr>
<tr>
<td>( \text{k}_{\text{air}} )</td>
<td>6.34E-03</td>
<td>lbf/(s-R)</td>
<td>thermal conductivity of air</td>
</tr>
<tr>
<td>( \text{T}_{\text{amb}} )</td>
<td>550</td>
<td>R</td>
<td>ambient air temperature</td>
</tr>
<tr>
<td>( \text{T}_{\text{front}} )</td>
<td>550</td>
<td>R</td>
<td>grill box front temperature</td>
</tr>
<tr>
<td>( \text{T}_{\text{back}} )</td>
<td>550</td>
<td>R</td>
<td>grill box back temperature</td>
</tr>
</tbody>
</table>

The following pages contain the nodal analysis for time steps of 10 seconds.
Appendix H

The following pages contain the EES code for calculating property values for use with the transient nodal analysis shown in Appendices E, F, and G.
"Grill Bar Model (version 1) - Propane

Assuming:
- see assumptions list in APPENDIX E

"- - - GIVEN/ASSUMED - CONDUCTION - - -"

Temperature=800 [F] "input air temperature"
DELTAx=0.825 [in] "distance between nodes"
DELTAt=10 [sec] "elapsed time - determined from Fourier number stability"
c=c_('Stainless_AISI304', Temperature) "specific heat capacity of steel"
k=k_('Stainless_AISI304', Temperature) "thermal conductivity"
rho=rho_('Stainless_AISI304', Temperature) "density"
alpha=k/(rho*c) "thermal diffusivity (Section 2.2.2)"
Fo=alpha*(DELTAx*convert(sec,hour))/((DELTAx*convert(in,ft))^2) "Fourier number (less than 0.5 for 1D)"
sigma=(5.67E-8 [W/(K^4*m^2)])*convert(W/(K^4*m^2),Btu/(hr^-R^-4*ft^2)) "Stephen-Boltzman constant"

D=((5/16) [in])*convert(in,ft) "grill bar diameter"
BETA=1/T_air "volumetric thermal expansion coefficient - ideal gas"
g=32.2 [ft/s^2] "acceleration due to gravity"
nu=(38.79E-6 [m^2/s])*convert(m^2,ft^2) "kinematic viscosity (Table A.4 for 500 [K])"
T_air=converttemp(F,R,Temperature) "air/propane products temperature"
T_s=converttemp(F,R,400 [F]) "grill bar surface temperature"
(T_s=converttemp(F,R,350 [F]) "grill bar surface temperature"

Ra_D=-(g*BETA*(T_s-T_air)*(D^3))/(nu*alpha*convert(s,hour)) "Rayleigh number (Equation 9.25)"

k_air=Conductivity(Air,T=Temperature)*convert(Btu/hr-ft-R,lbf/s-R) "Thermal conductivity of air"

Grill Bar Model (version 1) - Propane

Assuming:
- see assumptions list in APPENDIX E

Temperature = 800 [F] input air temperature

\[ \Delta x = 0.825 \text{ [in]} \quad \text{distance between nodes} \]

\[ \Delta t = 10 \text{ [sec]} \quad \text{elapsed time - determined from Fourier number stability} \]

\[ c = c\left(\text{Stainless}_{\text{AISI304}}, \text{Temperature}\right) \quad \text{specific heat capacity of steel} \]

\[ k = k\left(\text{Stainless}_{\text{AISI304}}, \text{Temperature}\right) \quad \text{thermal conductivity} \]

\[ \rho = \rho\left(\text{Stainless}_{\text{AISI304}}, \text{Temperature}\right) \quad \text{density} \]

\[ \alpha = \frac{k}{\rho \cdot c} \quad \text{thermal diffusivity (Section 2.2.2)} \]
\[ F_0 = \alpha \cdot \frac{\Delta t}{\Delta x} \cdot \left( \frac{0.00277778 \text{ hour}}{\text{sec}} \right)^2 \]

**Fourier number (less than 0.5 for 1D)**

\[ \sigma = 5.67 \times 10^{-8} \left[ \frac{\text{W}}{\text{K}^4 \text{m}^2} \right] \cdot \frac{0.030197216 \cdot \frac{\text{Btu}}{\text{hr} \cdot \text{R}^4 \text{ft}^2}}{\left[ \frac{\text{W}}{\text{K}^4 \text{m}^2} \right]} \]

**Stephen-Boltzman constant**

\[ D = \frac{5}{16} \cdot 1 \text{ [in]} \cdot \frac{0.083333333 \cdot \text{ft}}{\text{in}} \]

**grill bar diameter**

\[ \beta = \frac{1}{T_{\text{air}}} \]

**volumetric thermal expansion coefficient - ideal gas**

\[ g = 32.2 \left[ \frac{\text{ft}}{\text{s}^2} \right] \]

**acceleration due to gravity**

\[ \nu = 0.0003879 \left[ \frac{\text{m}^2}{\text{s}} \right] \cdot 10.76 \cdot \left( \frac{\text{ft}^2}{\text{m}^2} \right) \]

**kinematic viscosity (Table A.4 for 500 [K])**

\[ T_{\text{air}} = \text{ConvertTemp} [\text{F}, \text{R}, \text{Temperature}] \]

**air/propane products temperature**

\[ T_s = \text{ConvertTemp} [\text{F}, \text{R}, 400] \left[ \text{F} \right] \]

**grill bar surface temperature**

\[ \frac{\text{Ra}_D}{D^3} = \frac{-g \cdot \beta \cdot (T_s - T_{\text{air}}) \cdot D^3}{\nu \cdot \alpha \cdot \left( \frac{0.00277778 \left( \frac{\text{hr}}{\text{s}} \right)}{\text{sec}} \right)} \]

**Rayleigh number (Equation 9.25)**

\[ k_{\text{air}} = k \left[ \text{Air}, T = \text{Temperature} \right] \cdot \left( 0.21615814 \cdot \frac{\text{lbf/s-R}}{\text{Btu/hr-ft-R}} \right) \]

**Thermal conductivity of air**

**SOLUTION**

**Unit Settings: Eng F psia mass deg**

\[ \alpha = 0.1864 \left[ \frac{\text{ft}^3}{\text{hr}} \right] \]

\[ c = 0.136 \left[ \frac{\text{Btu}}{\text{lbmol-R}} \right] \]

\[ \Delta t = 10 \left[ \text{sec} \right] \]

\[ F_0 = 0.1096 \]

\[ k = 12.25 \left[ \frac{\text{Btu}}{(\text{hr-ft-R})} \right] \]

\[ \nu = 0.0004175 \left[ \frac{\text{ft}^2}{\text{s}} \right] \]

\[ \rho = 483 \left[ \frac{\text{lbmol}}{(\text{ft}^3)} \right] \]

**Temperature = 800 \left[ \text{F} \right]**

**T_s = 859.7 \left[ \text{R} \right]**

\[ \beta = 0.0007939 \left[ \frac{1}{\text{R}} \right] \]

\[ D = 0.02604 \left[ \text{ft} \right] \]

\[ \Delta x = 0.825 \left[ \text{in} \right] \]

\[ g = 32.2 \left[ \frac{\text{ft}}{\text{s}^2} \right] \]

**k_{\text{air}} = 0.006454 \left[ \frac{\text{lbf/s-R}}{\text{Btu/hr-ft-R}} \right] \]

\[ \text{Ra}_D = 8351 \]

**No unit problems were detected.**
Appendix I

The following figures illustrate details of the test fixture and flame tamer designs.

Figure I-1. Preliminary test fixture setup sketch.
Appendix I

**Figure I-2.** Details of a possible test fixture base and slider mechanism.

The following figures (Figures I-3 through Figure I-6) show the chosen fixture geometry for the Angus grill test fixture.
Figure I-3. Pictorial reference for the Angus grill test fixture.
Figure I-4. Pictorial reference for the Angus grill test fixture inside the Angus grill.
Figure I-5. Test fixture structure geometry.
Figure I-6. Test fixture sliding thermocouple support bar geometry.
Figure I-7. The second iteration of the test fixture incorporating a chain and all-thread.
Figure I-8. The final test fixture design using an acme thread along with two roller bearings.
Figure I-9. First modified flame tamer design
Figure I-10. Second flame tamer design incorporating two rows of offset holes
Figure I-9. Final Flame Tamer Design with differing hole sizing
Appendix J

The maximum anticipated temperature to be seen by the test fixture will be around 1000°F ≈ 540°C.

Assumed 5lbf uniform force from attached alligator clips and all 500 ft of thermocouple wire with a linear density of 9lbf per 1000ft.
Appendix J

From Table 2-9 (effect of temperature on the material strength) in Shigley’s 9th Edition Mechanical Engineering Design, at 540°C for 1020 Steel, $S_y = 0.7S_y$ and $S_{ult} = 0.71S_{ult}$.

From Table:

- $S_y' = 30$ [kpsi] yield strength for 1020 HR Steel
- $S_{ult}' = 53$ [kpsi] ultimate yield strength for 1020 HR Steel

From Table 2-9 (effect of temperature on the material strength) in Shigley’s 9th Edition Mechanical Engineering Design, at 540°C: $S_y = 0.7S_y'$ and $S_{ult} = 0.71S_{ult}'$.

- $S_y = 0.7(30$ [kpsi]) adjusted yield strength
  - $S_y = 21$ [kpsi]
- $S_{ult} = 0.71(53$ [kpsi]) adjusted ultimate yield strength
  - $S_{ult} = 39$ [kpsi]

For the following geometry, find the static moment of area and the moment of inertia:

For the hollow rectangle:

\[ I = \frac{bh^3}{12} \]

\[ I_{\text{large}} = \frac{bh^3}{12} \]

\[ I_{\text{empty}} = \frac{bh^3}{12} \]

\[ I_{\text{actual}} = (0.15625 \text{ [in}^3]) - (0.006332 \text{ [in}^3]) \]

\[ I_{\text{actual}} = 0.009295 \text{ [in}^3] \]

\[ Q = \frac{b}{2} (c^2 - y_1^2) \]

\[ Q_{\text{large}} = \frac{b}{2} (c^2 - y_1^2) \]

\[ Q_{\text{empty}} = \frac{b}{2} (c^2 - y_1^2) \]

\[ Q_{\text{actual}} = Q_{\text{large}} - Q_{\text{empty}} \]

\[ y_1 = 0 \]

Distance away from center of mass to location of interest in the cross section (set to 0 for max shear)

Static moment of area

Static moment of area for a 0.5” square block

Static moment of area for a 0.37” square block

Static moment of area for the hollow rectangle

Moment of inertia

Moment of inertia for a 0.5” square block

Moment of inertia for a 0.37” square block
Appendix J

\[ I_{\text{actual}} = I_{\text{large}} - I_{\text{empty}} \]
\[ I_{\text{actual}} = (0.005208 \text{[in}^4\text{])} - (0.001562 \text{[in}^4\text{])} \]
\[ I_{\text{actual}} = 0.003647 \text{[in}^4\text{]} \]

Using the maximum shear strength criteria:

\[ \tau_{\text{max}} = \frac{S_2 - S_1}{2} = \frac{S_y}{2n} \]

Find \( \tau_{\text{max}} \):

\[ \tau_{\text{max}} = \frac{VQ}{I}\tau \]
\[ \tau_{\text{max}} = \frac{(2.5 \text{[lb]})(0.009293 \text{[in}^2\text{])}}{(0.003647 \text{[in}^4\text{])}(0.063 \text{[in]})} \]
\[ \tau_{\text{max}} = 12.7 \text{[lb]} \text{[in]}^2 \]

Plugging the maximum shear into the maximum shear strength criteria to find the factor of safety, \( n \):

\[ n = \frac{S_y}{2\tau_{\text{max}}} \]
\[ n = \frac{2110^3 \text{[psi]}}{2(12.7 \text{[psi]})} \]
\[ n = 827 \]

There is so little force from the thermocouples’ weight and the weight of the system itself that there is no need to worry about high-temperature strength issues. The material selected far exceeds minimum acceptable factors of safety, but will be used due to its availability and machinability.
## Appendix K

**Table K-1. Budget breakdown for the entire project**

*Note: This does not include a computer to install the software on and run the tests.*

<table>
<thead>
<tr>
<th>Item</th>
<th>Estimated</th>
<th>Actual</th>
<th>With tax</th>
<th>Cash flow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>License to Grill Budget</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Item</strong></td>
<td><strong>Quantity</strong></td>
<td><strong>Cost</strong></td>
<td><strong>Subtotal</strong></td>
<td><strong>With tax</strong></td>
</tr>
<tr>
<td>Overhead</td>
<td>1</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
</tr>
<tr>
<td>Natural gas line install</td>
<td>1</td>
<td>$837.40</td>
<td>$837.40</td>
<td>$837.40</td>
</tr>
<tr>
<td>Propane empty tanks</td>
<td>2</td>
<td>$30.00</td>
<td>$60.00</td>
<td>$64.80</td>
</tr>
<tr>
<td>Propane refill</td>
<td>10</td>
<td>$20.00</td>
<td>$200.00</td>
<td>$216.00</td>
</tr>
<tr>
<td>16 Temperature input DAQ</td>
<td>1</td>
<td>$1,099.00</td>
<td>$1,099.00</td>
<td>$1,186.92</td>
</tr>
<tr>
<td>16 Temperature expansion</td>
<td>1</td>
<td>$649.00</td>
<td>$649.00</td>
<td>$700.92</td>
</tr>
<tr>
<td>TraverDAQ Pro (software to read data)</td>
<td>1</td>
<td>$199.00</td>
<td>$199.00</td>
<td>$214.92</td>
</tr>
<tr>
<td>High Temperature thermocouple wire in ft</td>
<td>500</td>
<td>$0.54</td>
<td>$270.00</td>
<td>$291.60</td>
</tr>
<tr>
<td>Thermocouple connector (Male@Female)</td>
<td>32</td>
<td>$4.13</td>
<td>$132.16</td>
<td>$142.73</td>
</tr>
<tr>
<td>Thermocouple connector (Male)</td>
<td>32</td>
<td>$1.85</td>
<td>$59.20</td>
<td>$63.94</td>
</tr>
<tr>
<td>Box fan for wind tests</td>
<td>3</td>
<td>$15.96</td>
<td>$47.88</td>
<td>$51.71</td>
</tr>
<tr>
<td>Wood for wind tests</td>
<td>1</td>
<td>$50.00</td>
<td>$50.00</td>
<td>$54.00</td>
</tr>
<tr>
<td>Steel tubing for thermocouple fixture</td>
<td>1</td>
<td>$28.74</td>
<td>$28.74</td>
<td>$31.04</td>
</tr>
<tr>
<td>Test fixture material</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>McMaster Carr purchases for second structure</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel for new flame tamers</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TriTip for Senior Expo</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Proposed Money left*
Appendix K

**Figure K-1.** DAQ and data collection software (shown source: Measurement Computing Corporation).

**Figure K-2.** Thermocouple parts cost (shown source: Omega Engineering Inc.).
Appendix L

The following page details the schedule we have been following throughout the project.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliverables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intro Letter</td>
<td>Tue 9/18/12</td>
<td>Thu 6/6/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project Proposal</td>
<td>Tue 9/25/12</td>
<td>Mon 10/22/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDR</td>
<td>Fri 11/23/12</td>
<td>Mon 12/8/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Presentation</td>
<td>Mon 11/26/12</td>
<td>Mon 11/26/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second Report</td>
<td>Mon 1/7/13</td>
<td>Tue 1/29/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second Presentation</td>
<td>Tue 1/29/13</td>
<td>Tue 1/29/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Report Document</td>
<td>Thu 5/30/13</td>
<td>Thu 6/6/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Presentations</td>
<td>Tue 5/28/13</td>
<td>Thu 5/30/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sponsor Presentation</td>
<td>Tue 5/28/13</td>
<td>Tue 5/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Senior Project Expo</td>
<td>Thu 5/30/13</td>
<td>Thu 5/30/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer Models</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion Models</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure O2 Propane</td>
<td>Thu 10/4/12</td>
<td>Fri 10/26/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Propane (no excess)</td>
<td>Wed 10/17/12</td>
<td>Tue 10/23/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Nat Gas (no excess)</td>
<td>Tue 10/23/12</td>
<td>Fri 10/26/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodal Analysis</td>
<td>Sun 10/28/12</td>
<td>Tue 11/6/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodal Analysis</td>
<td>Sun 10/28/12</td>
<td>Tue 11/6/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Law Model</td>
<td>Thu 11/8/12</td>
<td>Wed 11/14/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary Tests</td>
<td>Thu 11/8/12</td>
<td>Thu 11/8/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary Models</td>
<td>Thu 11/8/12</td>
<td>Wed 11/14/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grill Temperature</td>
<td>Mon 1/7/13</td>
<td>Mon 1/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conduction</td>
<td>Mon 1/7/13</td>
<td>Mon 1/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>Mon 1/7/13</td>
<td>Mon 1/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convection</td>
<td>Mon 1/7/13</td>
<td>Mon 1/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>Mon 10/22/12</td>
<td>Fri 6/7/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Documentation</td>
<td>Wed 11/14/12</td>
<td>Tue 1/8/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What to test for</td>
<td>Wed 11/14/12</td>
<td>Mon 11/26/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Procedure</td>
<td>Mon 11/26/12</td>
<td>Tue 1/8/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Fixture</td>
<td>Mon 10/22/12</td>
<td>Mon 1/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grill Setup, Prelim Tests</td>
<td>Mon 10/22/12</td>
<td>Thu 11/8/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary Designs</td>
<td>Wed 11/14/12</td>
<td>Mon 11/26/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Selection</td>
<td>Mon 11/26/12</td>
<td>Fri 11/30/12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed Design</td>
<td>Tue 11/27/12</td>
<td>Mon 1/7/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype Construction</td>
<td>Tue 1/8/13</td>
<td>Mon 1/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td>Mon 1/28/13</td>
<td>Fri 6/7/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Tests</td>
<td>Mon 1/28/13</td>
<td>Tue 3/12/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Tests</td>
<td>Mon 1/13/13</td>
<td>Sun 6/2/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Processing</td>
<td>Mon 4/1/13</td>
<td>Fri 6/7/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Presentations</td>
<td>Tue 5/28/13</td>
<td>Thu 5/30/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sponsor Presentation</td>
<td>Tue 5/28/13</td>
<td>Tue 5/28/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Senior Project Expo</td>
<td>Thu 5/30/13</td>
<td>Thu 5/30/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure M-1. Preliminary test data collected for use of a single burner on November 8th, 2012 using a type K thermocouple. Conducted by C. McGill, P. Gobell, and T. Willson.
### Table N-1. Comprehensive thermocouple selection table (using the cited tables below)

<table>
<thead>
<tr>
<th>Thermocouple type</th>
<th>Temperature Range °F</th>
<th>Cost/ft¹</th>
<th>Sensitivity²</th>
<th>Stable at 400°F-1500°F</th>
<th>Upper Temp limit for 20 gauge wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>200 -- 1400</td>
<td>0.37</td>
<td>±0.75%(T-32)</td>
<td>degrades quick</td>
<td>900°F</td>
</tr>
<tr>
<td>K</td>
<td>-330 -- 2300</td>
<td>0.54</td>
<td>±0.75%(T-32)</td>
<td>accuracy degrades</td>
<td>1800°F</td>
</tr>
<tr>
<td>E</td>
<td>-330 -- 1650</td>
<td>0.54</td>
<td>±0.5%(T-32)</td>
<td>accuracy degrades</td>
<td>1000°F</td>
</tr>
<tr>
<td>N</td>
<td>200 -- 2700</td>
<td>0.66</td>
<td>±0.75%(T-32)</td>
<td>most stable</td>
<td>1800°F</td>
</tr>
</tbody>
</table>

1. Cost for a 500 foot order from omega.com
2. Sensitivity at operating temperatures ~500°F-1000°F

Table N-2. Thermocouple types and their respective temperature ranges and tolerances by class (data source: Thermometrics Corporation).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>-200' to -67'</td>
<td>±1.5% T</td>
<td>±0.9% T*</td>
<td>-328' to -85'</td>
<td>±1.5% (T-32)</td>
<td>±0.8% (T-32)*</td>
</tr>
<tr>
<td></td>
<td>-67' to -62'</td>
<td>±1'</td>
<td>±0.8% T*</td>
<td>-88' to -80'</td>
<td>±1.8'</td>
<td>±0.8% (T-32)*</td>
</tr>
<tr>
<td></td>
<td>-62' to 125'</td>
<td>±1'</td>
<td>±0.5'</td>
<td>205' to 272'</td>
<td>±1.8'</td>
<td>±0.9'</td>
</tr>
<tr>
<td></td>
<td>125' to 133'</td>
<td>±1'</td>
<td>±0.4% T</td>
<td>272' to 700'</td>
<td>±0.75% (T-32)</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td></td>
<td>133' to 370'</td>
<td>±0.75% T</td>
<td>±0.4% T</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>0' to 275'</td>
<td>±2.2'</td>
<td>±1.1'</td>
<td>32' to 527'</td>
<td>±3.96'</td>
<td>±1.98'</td>
</tr>
<tr>
<td></td>
<td>275' to 293'</td>
<td>±2.2'</td>
<td>±0.4% T</td>
<td>527' to 560'</td>
<td>±3.96'</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td></td>
<td>293' to 760'</td>
<td>±0.75% T</td>
<td>±0.4% T</td>
<td>760' to 1400'</td>
<td>±0.75% (T-32)</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td>E</td>
<td>-200' to -170'</td>
<td>±1% T</td>
<td>±1'</td>
<td>-328' to -274'</td>
<td>±1% (T-32)</td>
<td>±1.8*</td>
</tr>
<tr>
<td></td>
<td>-170' to 250'</td>
<td>±1.7'</td>
<td>±1'</td>
<td>-274' to 482'</td>
<td>±3.06'</td>
<td>±1.8*</td>
</tr>
<tr>
<td></td>
<td>250' to 340'</td>
<td>±1.7'</td>
<td>±0.4% T</td>
<td>482' to 644'</td>
<td>±3.06'</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td></td>
<td>340' to 870'</td>
<td>±0.5% T</td>
<td>±0.4% T</td>
<td>644' to 1600'</td>
<td>±0.5% (T-32)</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td>K</td>
<td>-200' to -110'</td>
<td>±2% T</td>
<td>—</td>
<td>-328' to -166'</td>
<td>±2% (T-32)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>-100' to 0'</td>
<td>±2.2'</td>
<td>—</td>
<td>-166' to 32'</td>
<td>±3.96'</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>0' to 275'</td>
<td>±2.2'</td>
<td>±1.1'</td>
<td>32' to 527'</td>
<td>±3.96'</td>
<td>±1.98'</td>
</tr>
<tr>
<td></td>
<td>275' to 293'</td>
<td>±2.2'</td>
<td>±0.4% T</td>
<td>527' to 560'</td>
<td>±3.96'</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td></td>
<td>293' to 1260'</td>
<td>±0.75% T</td>
<td>±0.4% T</td>
<td>560' to 2300'</td>
<td>±0.75% (T-32)</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td>N</td>
<td>0' to 275'</td>
<td>±2.2'</td>
<td>±1.1'</td>
<td>32' to 527'</td>
<td>±3.96'</td>
<td>±1.98'</td>
</tr>
<tr>
<td></td>
<td>275' to 293'</td>
<td>±2.2'</td>
<td>±0.4% T</td>
<td>527' to 560'</td>
<td>±3.96'</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td></td>
<td>293' to 1260'</td>
<td>±0.75% T</td>
<td>±0.4% T</td>
<td>560' to 2300'</td>
<td>±0.75% (T-32)</td>
<td>±0.4% (T-32)</td>
</tr>
<tr>
<td>R or S</td>
<td>0' to 1260'</td>
<td>±1.5'</td>
<td>±0.5'</td>
<td>32' to 1112'</td>
<td>±2.7'</td>
<td>±1.08'</td>
</tr>
<tr>
<td></td>
<td>1260' to 1480'</td>
<td>±0.25% T</td>
<td>±0.1% T</td>
<td>1112' to 2700'</td>
<td>±0.25% (T-32)</td>
<td>±0.1% (T-32)</td>
</tr>
<tr>
<td></td>
<td>1480' to 1700'</td>
<td>±0.5% T</td>
<td>±0.25%</td>
<td>1600' to 3100'</td>
<td>±0.5% (T-32)</td>
<td>±0.25% (T-32)</td>
</tr>
<tr>
<td>B</td>
<td>870' to 1700'</td>
<td>±0.5% T</td>
<td>±0.25%</td>
<td>1600' to 3100'</td>
<td>±0.5% (T-32)</td>
<td>±0.25% (T-32)</td>
</tr>
<tr>
<td>C&quot;</td>
<td>0' to 426'</td>
<td>±4.4'</td>
<td>—</td>
<td>32' to 860'</td>
<td>±8'</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>426' to 2315'</td>
<td>±1% T</td>
<td>—</td>
<td>800' to 4200'</td>
<td>±1% (T-32)</td>
<td>—</td>
</tr>
</tbody>
</table>
**Appendix N**

**Table N-3.** Temperature ranges for different thermocouple types (Thermocouples. Watlow)

<table>
<thead>
<tr>
<th>Thermocouple Type</th>
<th>Useful/General Application Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1600-3100°F (870-1700°C)</td>
</tr>
<tr>
<td>E*</td>
<td>200-1650°F (95-900°C)</td>
</tr>
<tr>
<td>J</td>
<td>200-1400°F (95-760°C)</td>
</tr>
<tr>
<td>K*</td>
<td>200-2300°F (95-1260°C)</td>
</tr>
<tr>
<td>N</td>
<td>200-2300°F (95-1260°C)</td>
</tr>
<tr>
<td>R</td>
<td>32-2700°F (0-1480°C)</td>
</tr>
<tr>
<td>S</td>
<td>32-2700°F (0-1480°C)</td>
</tr>
<tr>
<td>T*</td>
<td>32-660°F (0-350°C)</td>
</tr>
</tbody>
</table>

*Also suitable for cryogenic applications from -328 to 32°F (-200 to 0°C)*
**Table N.4** Comparing Thermocouple Insulation (ANSI and IEC Color Codes for Thermocouples)

<table>
<thead>
<tr>
<th>Code</th>
<th>Conductor</th>
<th>Overall Conductors</th>
<th>Solvent</th>
<th>Acid Base</th>
<th>Frame</th>
<th>Ease of Framing</th>
<th>Insulation Resistance</th>
<th>Abrasion Resistance</th>
<th>Flexibility</th>
<th>Submersion Water</th>
<th>Resistance To:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PP</strong> Polyvinyl Chloride (PVC)</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>FX</strong> FEP Teflon or Neoflon</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>TT</strong> PFA Teflon or Neoflon</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>KK</strong> Kapton</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>TG</strong> Glass Braid</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>GG</strong> Glass Braid</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Fair</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>HH</strong> High Temp Glass Braid</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>XR</strong> Refrasil Braid</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor*</td>
<td>Excellent</td>
<td>Good*</td>
<td>Good*</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor*</td>
<td>Poor*</td>
</tr>
<tr>
<td><strong>XC</strong> Nextel Braid</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td><strong>XS</strong> Silica</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>TFE</strong> TFE Teflon</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

* denotes to 35˚C (800°F) -267 to 260˚C (-450 to 500°F)
Appendix O

Introduction

Tables O-1, 2 and 3 are detailed practical application spreadsheets of the fabrication that our team “License to Grill” has generated. The test fixture has been designed so that it can accommodate and perform the many tests that our team has developed to offer insight and information that can serve as a guide to grill modifications. The sheets are broken down into designs that differ by the indicated notes and are broken up into tasks and the details involved with each task number. The times for each task are approximations and may have varied slightly.

Design 1

Notes:
- Wire/Pulley Actuated
- Clamp Thermocouple Method
- Not actually used for any real data collection

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Description</th>
<th>Equipment Required</th>
<th>Est. Time (hrs.)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inspect raw material</td>
<td>none</td>
<td>0.1</td>
<td>1/2 x1/2 x 5 ft pieces x5</td>
</tr>
<tr>
<td>2</td>
<td>Measure and mark raw material for cutting</td>
<td>tape measure and soap stone</td>
<td>0.2</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>Cut raw material</td>
<td>chop saw, face shield</td>
<td>0.5</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>Deburr and wire brush all measured pieces</td>
<td>file, wire brush wheel</td>
<td>0.5</td>
<td>clean up all sides of tubing and all cut edges</td>
</tr>
<tr>
<td>5</td>
<td>Mill set-up</td>
<td>Bridgeport mill, mill kit, horizontal vises x 2</td>
<td>0.75</td>
<td>square both vices to 0.001” Tol.</td>
</tr>
<tr>
<td>6</td>
<td>Machine indexing points</td>
<td>vertical mill, mill kit, ¼” end mill</td>
<td>2.0</td>
<td>square both vices to 0.001” Tol., re-jig piece</td>
</tr>
<tr>
<td>7</td>
<td>Mill clean up</td>
<td>Shop vacuum</td>
<td>0.3</td>
<td>Clean off all chips and debris</td>
</tr>
<tr>
<td>8</td>
<td>Deburr and wire brush all machined components</td>
<td>file, wire brush wheel</td>
<td>0.5</td>
<td>clean off all oils and assemble structure</td>
</tr>
<tr>
<td>9</td>
<td>Welder prep and inspection</td>
<td>Miller TIG welder, weld kit</td>
<td>0.5</td>
<td>check amperage, torch configuration</td>
</tr>
<tr>
<td>10</td>
<td>Welder set-up</td>
<td>magnetic squares, vice</td>
<td>0.1</td>
<td>place and fit all pieces to be welded</td>
</tr>
<tr>
<td>11</td>
<td>Weld test fixture</td>
<td>3/32 filler rod, 1/16th tungsten</td>
<td>3.0</td>
<td>water cooled TIG out of service</td>
</tr>
</tbody>
</table>
## Appendix O

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Description</th>
<th>Equipment Required</th>
<th>Est. Time (hrs.)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Clean and inspect welds</td>
<td>wire brush, grinding wheel</td>
<td>0.1</td>
<td>look for evidence of lack of shielding gas</td>
</tr>
<tr>
<td>13</td>
<td>Slider bar fabrication</td>
<td>hand grinder, 90 degree air tool</td>
<td>0.75</td>
<td>Check for clearance tolerances</td>
</tr>
<tr>
<td>14</td>
<td>Attach slider bar and calibrate indexing equipment</td>
<td>Phillips screwdriver, crescent wrench</td>
<td>0.75</td>
<td>Correct for misalignment</td>
</tr>
</tbody>
</table>

### Details
The specifics of fabrication and any deviations from our plans have been noted and the table above is meant to be a step by step guide that takes you through each process. As standard practice it is always advisable to calculate the required time needed for welding as well as other major fabrication methods and multiplying the minimum time by 3. This is done so as to get an accurate amount of time that will be required and can be expected so quality does not suffer. The procedure as stated above was followed exactly however the only deviation was the fact that in task 9 the water cooled Miller TIG machine was found to have corrosion and build up in the coolant lines and reservoir and was rendered unusable. The air cooled Miller TIG machine was not supplying adequate shielding gas and was used for a small portion of the welds. The Miller MIG machine was used to finish the required welding and provided reliable clean welds. This process of switching from machine to machine did eat some time and is reflected in the estimated time column. The dynamic portion of the test apparatus being the slider bar, as noted has not yet been completed and is in currently in the process of being developed.

### Design 2
Notes:
- Lead Screw Actuated (all-thread design)
- Through-hole Thermocouple Method
- Spur Gear Transmission
- Hand-crank
### Appendix O

#### Table O-2. Plan of Manufacture of Second Iteration

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Description</th>
<th>Equipment Required</th>
<th>Est. Time (hrs.)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inspect raw material</td>
<td>none</td>
<td>0.1</td>
<td>1/2 x1/2 x 5 ft pieces x5</td>
</tr>
<tr>
<td>2</td>
<td>Measure and mark raw material for cutting</td>
<td>tape measure and soap stone</td>
<td>0.2</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>Cut raw material</td>
<td>chop saw, face shield</td>
<td>0.5</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>Deburr and wire brush all measured pieces</td>
<td>file, wire brush wheel</td>
<td>0.5</td>
<td>clean up all sides of tubing and all cut edges</td>
</tr>
<tr>
<td>5</td>
<td>Deburr and wire brush all machined components</td>
<td>file, wire brush wheel</td>
<td>0.5</td>
<td>clean off all oils and assemble structure</td>
</tr>
<tr>
<td>6</td>
<td>Welder prep and inspection</td>
<td>Miller TIG welder, weld kit</td>
<td>0.5</td>
<td>check amperage, torch configuration</td>
</tr>
<tr>
<td>7</td>
<td>Welder set-up</td>
<td>magnetic squares, vice</td>
<td>0.1</td>
<td>place and fit all pieces to be welded</td>
</tr>
<tr>
<td>8</td>
<td>Weld test fixture</td>
<td>3/32 filler rod, 1/16th tungsten electrode</td>
<td>3.0</td>
<td>water cooled TIG out of service</td>
</tr>
<tr>
<td>9</td>
<td>Clean and inspect welds</td>
<td>wire brush, grinding wheel</td>
<td>0.1</td>
<td>look for evidence of lack of shielding gas</td>
</tr>
<tr>
<td>10</td>
<td>Slider bar fabrication</td>
<td>hand grinder, 90 degree air tool</td>
<td>1.5</td>
<td>Check slots for rail clearance</td>
</tr>
<tr>
<td>11</td>
<td>Drill Holes for lead screw</td>
<td>Drill press</td>
<td>0.5</td>
<td>Align both holes</td>
</tr>
<tr>
<td>12</td>
<td>Configure transmission</td>
<td>Metric /English Allen wrenches</td>
<td>0.5</td>
<td>Check all set screws, align spur gears</td>
</tr>
<tr>
<td>13</td>
<td>Assemble and test transmission</td>
<td>Metric/English Allen wrenches</td>
<td>0.5</td>
<td>Adjust chain tension</td>
</tr>
<tr>
<td>14</td>
<td>Attach slider bar and calibrate indexing equipment</td>
<td>Phillips screwdriver, crescent wrench</td>
<td>1.0</td>
<td>Check for full range of slider bar motion</td>
</tr>
<tr>
<td>15</td>
<td>Attach thermocouples and bundle wiring</td>
<td>small gage wire, pliers</td>
<td>0.75</td>
<td>Number and record position of each thermocouple</td>
</tr>
<tr>
<td>16</td>
<td>Test apparatus in grill with heat</td>
<td>grill</td>
<td>1.0</td>
<td>Test through full range of motion</td>
</tr>
</tbody>
</table>
Appendix O

Design 3

Notes:

- Lead Screw Actuated (ACME thread design)
- Through-hole Thermocouple Method
- Direct Drive Transmission
- Electric motor Driven
- Minor modification to grill sides

Table O-3. Plan of Manufacture of Final Iteration

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Description</th>
<th>Equipment Required</th>
<th>Est. Time (hrs.)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inspect raw material</td>
<td>none</td>
<td>0.1</td>
<td>1/2 x 1/2 x 5 ft pieces x 5</td>
</tr>
<tr>
<td>2</td>
<td>Measure and mark raw material for cutting</td>
<td>tape measure and soap stone</td>
<td>0.2</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>Cut raw material</td>
<td>chop saw, face shield</td>
<td>0.5</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>Deburr and wire brush all measured pieces</td>
<td>file, wire brush wheel</td>
<td>0.5</td>
<td>clean up all sides of tubing and all cut edges</td>
</tr>
<tr>
<td>5</td>
<td>Deburr and wire brush all machined components</td>
<td>file, wire brush wheel</td>
<td>0.5</td>
<td>clean off all oils and assemble structure to be welded</td>
</tr>
<tr>
<td>6</td>
<td>Welder prep and inspection</td>
<td>Miller TIG welder, weld kit</td>
<td>0.5</td>
<td>check amperage, torch configuration</td>
</tr>
<tr>
<td>7</td>
<td>Welder set-up</td>
<td>magnetic squares, vice</td>
<td>0.1</td>
<td>place and fit all pieces to be welded</td>
</tr>
<tr>
<td>8</td>
<td>Weld test fixture</td>
<td>3/32 filler rod, 1/16th tungsten electrode</td>
<td>3.0</td>
<td>water cooled TIG out of service</td>
</tr>
<tr>
<td>9</td>
<td>Clean and inspect welds</td>
<td>wire brush, grinding wheel</td>
<td>0.1</td>
<td>look for evidence of lack of shielding gas</td>
</tr>
<tr>
<td>10</td>
<td>Set up manual mill</td>
<td>Mill kit</td>
<td>0.5</td>
<td>Fix and square vice to within 0.001” tolerance</td>
</tr>
<tr>
<td>11</td>
<td>Mill slots in slider bar</td>
<td>Vice, manual mill</td>
<td>0.75</td>
<td>Check speeds and feeds for 4 flute 0.5” end mill</td>
</tr>
<tr>
<td>12</td>
<td>Wire brush slider bar</td>
<td>Wire brush wheel</td>
<td>0.1</td>
<td>Check slots for rail clearance</td>
</tr>
</tbody>
</table>
### Appendix O

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Description</th>
<th>Equipment Required</th>
<th>Est. Time (hrs.)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Measure material for bearing plates</td>
<td>Tape measure, sharpie</td>
<td>0.1</td>
<td>Measure plate thickness</td>
</tr>
<tr>
<td>14</td>
<td>Cut Bearing plates</td>
<td>Chop saw, face shield</td>
<td>0.05</td>
<td>None</td>
</tr>
<tr>
<td>15</td>
<td>Set up manual mill</td>
<td>Mill kit</td>
<td>0.5</td>
<td>Fix and center rotary table</td>
</tr>
<tr>
<td>16</td>
<td>Drill holes in bearing plates</td>
<td>Manual mill, rotary table</td>
<td>1.0</td>
<td>¼” 2-flute end mill</td>
</tr>
<tr>
<td>17</td>
<td>Clean up mill</td>
<td>Shop vacuum</td>
<td>0.5</td>
<td>Clean all chips off machine and ways</td>
</tr>
<tr>
<td>18</td>
<td>Wire brush bearing plates</td>
<td>Wire brush wheel</td>
<td>0.10</td>
<td>Remove all burrs and debris</td>
</tr>
<tr>
<td>19</td>
<td>Press bearings into bearing plates</td>
<td>Bearing press, lubricant</td>
<td>0.10</td>
<td>Lubricate and locate</td>
</tr>
<tr>
<td>20</td>
<td>Weld bearing plates</td>
<td>TIG welder</td>
<td>1.0</td>
<td>Align with lead screw in place</td>
</tr>
<tr>
<td>21</td>
<td>Cut brackets for locating nuts</td>
<td>Electric cut off wheel, face shield</td>
<td>0.75</td>
<td>x4 brackets</td>
</tr>
<tr>
<td>22</td>
<td>Wire brush bearing brackets</td>
<td>Wire brush wheel</td>
<td>0.10</td>
<td>Remove all burrs and debris</td>
</tr>
<tr>
<td>23</td>
<td>Size 5/8⁴ᵗʰ nuts and bolts to brackets</td>
<td>Drill press</td>
<td>0.10</td>
<td>Lubricate and locate</td>
</tr>
<tr>
<td>24</td>
<td>Weld nuts to brackets and brackets to fixture</td>
<td>TIG welder</td>
<td>1.0</td>
<td>Align with side wall planes</td>
</tr>
<tr>
<td>25</td>
<td>Chase threads</td>
<td>Tapping set</td>
<td>0.5</td>
<td>Check thread for loose clearance</td>
</tr>
<tr>
<td>26</td>
<td>Align lead screw</td>
<td>None</td>
<td>0.1</td>
<td>Check for proper clearance</td>
</tr>
<tr>
<td>27</td>
<td>Attach slider bar and calibrate indexing equipment</td>
<td>Power Drill with ½” chuck</td>
<td>0.2</td>
<td>Check for full range of slider bar motion</td>
</tr>
<tr>
<td>28</td>
<td>Attach thermocouples and bundle wiring</td>
<td>small gage wire, screw driver</td>
<td>0.75</td>
<td>Number and record position of each thermocouple</td>
</tr>
<tr>
<td>29</td>
<td>Slots on side walls of grill</td>
<td>Electric cut off wheel</td>
<td>1.0</td>
<td>Check location and dimensions of each slot</td>
</tr>
<tr>
<td>30</td>
<td>Deburr slots</td>
<td>Hand file</td>
<td>0.2</td>
<td>Check for sharp edges/cuts</td>
</tr>
<tr>
<td>26</td>
<td>Test apparatus in grill with heat</td>
<td>Grill</td>
<td>1.0</td>
<td>Test through full range of motion</td>
</tr>
</tbody>
</table>
Appendix P

Bull Outdoor Products Senior Project: Thermocouple Testing Preparation

Purpose

The following procedure is a detailed step by step guide to preparing and implementing thermocouple testing and temperature acquisition.

Note: The IECEE CTL Operation Procedure (CTL-OP 108) Laboratory Procedure for Preparation, Attachment, Extension and Use of Thermocouples was referenced.

Procedure

1. Clip all thermocouple wiring to be used to the required length and inspect to ensure no there is no damage to outer sheath or actual wire.
2. The end that is to be used for testing should have its inner insulation stripped back approximately 1.5 mm (.06 in.) from tip.
3. Outer insulation, if there is any, should be stripped back approximately 15 mm (0.6 in.) from tip.
4. The tip is to be welded by a single point weld, any other acceptable method that is able to achieve a consistent and concise material joining can be used.
5. After junction has cooled cold water bath or other reliable testing methods should be used to ensure the thermocouple is working properly.

Placement

The thermocouple should be placed in the optimal position so as to accurately read the temperature of the material in question without exceeding the limitations of the physical thermocouple or associated equipment. Areas of thermocouple contact other than the tip should be properly insulated to eliminate additional conduction.

Attachment

The tip of the thermocouple should be placed in direct and consistent contact with the material to be tested and the method in which this is done should ensure the minimization of material and movement.

Securing of Thermocouples

Several methods of attaching thermocouple junctions exist however finding the best application method may depend on several factors such as cost, time and material limitations. It is up to the test designer to select the appropriate method so that accurate and reliable data can be collected.

These methods include tying, cementing adhesive, peening, and welding, soldering and mechanical pressure.

Tying

Tying using thread or other typical flexible materials can be utilized for securing thermocouples to round items.

Cement

Kaolin powder mixed with sodium silicate solution mixed in equal portions with respect to volume is one such mixture. Advantages include better thermal bond and offers larger surface area to contact junction and material. Cementing reduces the surface
Appendix P

area of the junction and leads exposed to air and therefore eliminate a different temperature that can be introduced.

Soldering
This method is useful for attaching thermocouples to copper or other metal surfaces in which soldering materials will adhere. Soldering offers better thermal conductivity and better mechanical security over cementing a joint. The following equipment will be required:

- Leather gloves
- Tongs or Pliers
- Safety glasses
- Wire cutters
- Pen
- Plastic sandwich bags
Appendix Q

Bull Outdoor Products Senior Project: General Testing Procedure

Note: Before performing the following steps the safety procedure check list should be followed to ensure safe and accurate test results can be obtained.

Note: A schematic, definitions of terminology and specifics on the test units are provided in Appendix A.

Grill Surface Test Experiment

1. Power up all data collection devices and ensure that all thermocouples are connected to their correct ports and that data collection software is loaded up.
2. Test apparatus is inspected for defects and all thermocouple clips are working and in the proper location.
3. Verify that the test apparatus is in working condition and properly positioned.
4. Make note of ambient conditions which may affect testing, such as wind speed and direction.
5. Lock one or more of the wheels on the carts in the position you plan to test.
6. If wind shields are to be used, note their placements and be sure to be consistent in their use and set up.
7. Verify that the test area is clear of debris and other objects.
8. Test one or more of the thermocouples in and ice bath to ensure the integrity and accuracy of the equipment.
9. Place thermocouple slider bar and test apparatus frame into the starting position and ensure each thermocouple is in contact with ONE grill bar at around the same distance along the grill bars.
10. Check fuel line connections, then open fuel line valves and check for leaks.
11. Fire up grill and ensure that proper ignition is achieved for all burners concerned.
12. Wait until grill reaches desired temperature range for data collection.
13. Record placement (ratchet position) and temperature of each thermocouple.
14. Move the contact bar to the next grill bar and repeat step 14.
15. Note if the hood is opened for any reason and for how long.
16. Refer to the shut down procedure to safely conclude testing.
Appendix R

Bull Outdoor Products Senior Project: BBQ Safety Procedure

Start Up

Note: The following is a strict guideline of procedures and precautions that should be implemented at the beginning of each experiment to ensure safety of those performing the tests and the safety of the equipment. The equipment may cause serious harm if not used properly as stated below. They are as follows:

Ensure the following requirements have been met before testing:

1. Determine the area in which you plan to test has proper first aid and emergency medical materials such as eye and skin wash as well as burn kit.
2. There is proper ventilation in the area and that fire protection is available such as fire extinguishers.
3. If testing is being performed after dark, ensure that there is adequate light for safe operations.
4. Remove cover from the grill and place it in a safe place away from the testing area.
5. Inspect the grill for any foreign objects and remove them.
6. Secure all loose clothing, long hair, and flammable items.
7. Inspect gas lines or any connections that provide fuel to grills and pay close attention to irregularities in equipment condition or abnormal smells due to leakage of fuel.
8. Always perform test with a partner present and never leave the grill unattended while in operation.
9. When all the conditions stated above have been met, the safety procedure has been concluded and testing may commence.

Shut Down Procedure

Note: The following is a safety procedure that should be followed at the end of an experimentation period before grill units are to be stored for any amount of time.

Ensure the following criteria have been met:

1. All the burner knobs are in the off position and there is no visible flame in any of the burners.
2. The main gas cut-off valve is in the closed position.
3. Be cautious of all hot surfaces and allow grill unit to cool until all surfaces including the hood are cool enough to touch.
4. Clean up surrounding area and inspect for any parts that may have come loose or fallen off during testing.
5. Place covers on grills and store grills in designated area, ensuring that they do not block paths or doors.
Appendix S

Bull Outdoor Products Senior Project: Thermocouple Sample Test

The following equipment will be required:

- Leather gloves
- Tongs or Pliers
- Safety glasses
- Wire cutters
- Pen
- Plastic sandwich bags

Note: The following is a procedure that outlines the set up and test procedure associated with testing a wide range of thermocouple samples at varying temperatures. They are as follows:

Ensure the following requirements have been met before testing:

1. Follow the safety start up procedure outlined previously to ensure grill is safely brought to the correct temperature given the current wind and pressure conditions.

2. Prepare all samples to be tested by inspecting for damage and debris and cutting into 3 or 4 inch segments.

3. Organize and label all samples according to their type such as J,K,N, etc. and specific ID number and set aside.

4. Set the temperature knobs to max temperature allowed and wait until the grill arrives at steady state (no temperature fluctuation).

5. Place single thermocouple wire completely in grill in a designated area that appears to have the relatively best heat distribution and close hood.

6. Wait 5 minutes and lift hood to inspect sample, remove sample and reattach label and ID number and place on steel side workspace to cool.

7. Repeat steps 4 and 5 until all samples have been tested and removed.

8. Follow the safety shut down procedure to ensure grill is safely shut down and stored for later testing.

9. After all samples are cool enough to handle closely inspect each sample for indication of failure. These might be excessive sheath fraying, exposed wire or burned/melted portions of wire.

10. Record all findings immediately and file findings to be referenced in later analysis and report.
Appendix T

The following pages contain the EES code for calculating the view factors for each node along a single bar. Values were output into a file, and then copied into the Excel transient calculation sheet (shown in Appendix G).
**View Factors**

Assuming:
- see assumptions list in APPENDIX E

**FUNCTION VIEW(bar_set, bar_number, r_node)**

```
F_tot_own_1 := 0
F_tot_own_2 := 0
F_tot_adj := 0
b_node := 1
b_width := 0.25 [ft]
b_to_b_dist := (0.8*9) [in] * convert(in, ft)
```

REPEAT
perp_dist_in := 0.8 [in]
IF (bar_number = 1) OR (bar_number = 9) THEN
mod := 1
ENDIF
IF (bar_number = 2) OR (bar_number = 8) THEN
mod := 2
ENDIF
IF (bar_number = 3) OR (bar_number = 7) THEN
mod := 3
ENDIF
IF (bar_number = 4) OR (bar_number = 6) THEN
mod := 4
ENDIF
IF (bar_number = 5) THEN
mod := 5
ENDIF
mod_ft := (0.8 [in]) * mod * convert(in, ft)
perp_dist_ft := perp_dist_in * mod * convert(in, ft)
DELTA_x_r := (0.825 [in]) * convert(in, ft)
DELTA_x_b := DELTA_x_r * .75
r := (5/16) [in] * convert(in, ft)
burner_dist := abs(delta_x_b * b_node - delta_x_r * r_node)
L := (4.25 [in]) * convert(in, ft)
s_1_o_1 := sqrt((perp_dist_ft)^2 + burner_dist^2)
s_2_o_1 := s_1_o_1 - (1 [in]) * convert(in, ft)
F_own_1 := (r / (s_1_o_1 - s_2_o_1)) * (arctan(s_1_o_1 / L) - arctan(s_2_o_1 / L))
s_1_o_2 := sqrt((perp_dist_ft + mod_ft)^2 + burner_dist^2)
s_2_o_2 := s_1_o_1 - (1 [in]) * convert(in, ft)
F_own_2 := (r / (s_1_o_2 - s_2_o_2)) * (arctan(s_1_o_2 / L) - arctan(s_2_o_2 / L))
s_1_a := sqrt((perp_dist_ft + mod_ft)^2 + burner_dist^2)
s_2_a := s_1_a - (1 [in]) * convert(in, ft)
F_adj := (r / (s_1_a - s_2_a)) * (arctan(s_1_a / L) - arctan(s_2_a / L))
```

b_node := b_node + 1
```
go to next node
```
F_tot_own_1 := F_tot_own_1 + F_own_1
F_tot_own_2 := F_tot_own_2 + F_own_2
F_tot_adj := F_tot_adj + F_adj
```

UNTIL (b_node = 31)
```
each view factor from 1/30 an area of the burner
```
F_tot_own_1_mod := F_tot_own_1 / 30
F_tot_own_2_mod := F_tot_own_2 / 30
F_tot_adj_mod := F_tot_adj / 30
```
each view factor from 1/30 an area of the burner
```
$EXPORT /A 'G:\Senior Project\Comparative Simulations\data3.csv' bar_set, bar_number, r_node, F_tot_own_1_mod, F_tot_own_2_mod, F_tot_adj_mod
```

VIEW := 1
```
return a random value to please EES
```
END
```
set the bar set number
```
bar_set := 1
Feedback := VIEW(bar_set, bar_number, r_node)
```
```
call VIEW function defined above
```
View Factors

Assuming:
- see assumptions list in APPENDIX E

Function VIEW (bar_set, bar_number, r_node)

\[
\text{declare function}
\]

\[
F_{\text{tot,own},1} := 0 \quad \text{declare variable}
\]

\[
F_{\text{tot,own},2} := 0 \quad \text{declare variable}
\]

\[
F_{\text{tot,adj}} := 0 \quad \text{declare variable}
\]

\[
b_{\text{node}} := 1 \quad \text{initial burner node number}
\]

\[
b_{\text{width}} := 0.25 \quad \text{[ft]} \quad \text{burner width}
\]

\[
b_{\text{bt,b.dist}} := 0.8 \cdot 9 \cdot 1 \quad \text{[in]} \cdot \left| 0.083333333 \cdot \frac{\text{ft}}{\text{in}} \right| \quad \text{burner to burner distance}
\]

Repeat loop until b_{node} variable goes through last burner node

\[
\text{perp}_\text{dist,in} := 0.8 \quad \text{[in]}
\]

If \((\text{bar_number} = 1) \) or \((\text{bar_number} = 9)\) Then

\[
\text{mod} := 1
\]

If \((\text{bar_number} = 2) \) or \((\text{bar_number} = 8)\) Then

\[
\text{mod} := 2
\]

If \((\text{bar_number} = 3) \) or \((\text{bar_number} = 7)\) Then

\[
\text{mod} := 3
\]

If \((\text{bar_number} = 4) \) or \((\text{bar_number} = 6)\) Then

\[
\text{mod} := 4
\]

If \((\text{bar_number} = 5)\) Then

\[
\text{mod} := 5
\]

\[
\text{mod}_h := 0.8 \quad \text{[in]} \cdot \text{mod} \cdot \left| 0.083333333 \cdot \frac{\text{ft}}{\text{in}} \right|
\]

\[
\text{perp}_\text{dist,ft} := \text{perp}_\text{dist,in} \cdot \text{mod} \cdot \left| 0.083333333 \cdot \frac{\text{ft}}{\text{in}} \right| \quad \text{perpendicular distance from bar to burner}
\]

\[
\Delta_{x,r} := 0.825 \quad \text{[in]} \cdot \left| 0.083333333 \cdot \frac{\text{ft}}{\text{in}} \right| \quad \text{rod node spacing}
\]
\[ \Delta x,b := \Delta x,r \cdot 0.75 \quad \text{burner node spacing} \]

\[ r := \frac{5}{16} \cdot 1 \quad \text{[in]} \cdot \frac{0.083333333 \cdot \text{ft}}{\text{in}} \quad \text{rod radius} \]

\[ \text{burner}_\text{dist} := |\Delta x,b \cdot b\_\text{node} - \Delta x,r \cdot r\_\text{node} | \quad \text{distance along burner away from rod node} \]

\[ L := 4.25 \quad \text{[in]} \cdot \frac{0.083333333 \cdot \text{ft}}{\text{in}} \quad \text{view factor height (Table 13.1)} \]

\[ s_{1,o,1} := \sqrt{\text{perp}_{\text{dist,ft}}^2 + \text{burner}_{\text{dist}}^2} \quad \text{long distance for view factor (Table 13.1)} \]

\[ s_{2,o,1} := s_{1,o,1} - 1 \quad \text{[in]} \cdot \frac{0.083333333 \cdot \text{ft}}{\text{in}} \quad \text{short distance for view factor (Table 13.1)} \]

\[ F_{\text{own,1}} := \left[ \frac{r}{s_{1,o,1} - s_{2,o,1}} \right] \cdot \left[ \arctan \left( \frac{s_{1,o,1}}{L} \right) - \arctan \left( \frac{s_{2,o,1}}{L} \right) \right] \quad \text{view factor (Table 13.1)} \]

\[ s_{1,o,2} := \sqrt{\left[ \text{perp}_{\text{dist,ft}} + \text{b}_{\text{width}} \right]^2 + \text{burner}_{\text{dist}}^2} \quad \text{long distance for view factor (Table 13.1)} \]

\[ s_{2,o,2} := s_{1,o,1} - 1 \quad \text{[in]} \cdot \frac{0.083333333 \cdot \text{ft}}{\text{in}} \quad \text{short distance for view factor (Table 13.1)} \]

\[ F_{\text{own,2}} := \left[ \frac{r}{s_{1,o,2} - s_{2,o,2}} \right] \cdot \left[ \arctan \left( \frac{s_{1,o,2}}{L} \right) - \arctan \left( \frac{s_{2,o,2}}{L} \right) \right] \quad \text{view factor (Table 13.1)} \]

\[ s_{1,a} := \sqrt{\left[ \text{perp}_{\text{dist,ft}} + \text{mod}_{\text{ft}} \right]^2 + \text{burner}_{\text{dist}}^2} \quad \text{long distance for view factor (Table 13.1)} \]

\[ s_{2,a} := s_{1,a} - 1 \quad \text{[in]} \cdot \frac{0.083333333 \cdot \text{ft}}{\text{in}} \quad \text{short distance for view factor (Table 13.1)} \]

\[ F_{\text{adj}} := \left[ \frac{r}{s_{1,a} - s_{2,a}} \right] \cdot \left[ \arctan \left( \frac{s_{1,a}}{L} \right) - \arctan \left( \frac{s_{2,a}}{L} \right) \right] \quad \text{view factor (Table 13.1)} \]

\[ b\_\text{node} := b\_\text{node} + 1 \quad \text{go to next node} \]

\[ F_{\text{tot,own,1}} := F_{\text{tot,own,1}} + F_{\text{own,1}} \quad \text{build up the total view factor for close own burner} \]

\[ F_{\text{tot,own,2}} := F_{\text{tot,own,2}} + F_{\text{own,2}} \quad \text{build up the total view factor for far own burner} \]

\[ F_{\text{tot,adj}} := F_{\text{tot,own,1}} + F_{\text{adj}} \quad \text{build up the total view factor for adjacent burner} \]

Until \[ b\_\text{node} = 31 \]

\[ F_{\text{tot,own,1,mod}} := \frac{F_{\text{tot,own,1}}}{30} \quad \text{each view factor from 1/30 an area of the burner} \]

\[ F_{\text{tot,own,2,mod}} := \frac{F_{\text{tot,own,2}}}{30} \quad \text{each view factor from 1/30 an area of the burner} \]

\[ F_{\text{tot,adj,mod}} := \frac{F_{\text{tot,adj}}}{30} \quad \text{each view factor from 1/30 an area of the burner} \]

\[ \text{VIEW} := 1 \quad \text{return a random value to please EES} \]
End  VIEW

bar_set  =  1  set the bar set number

Feedback  =  VIEW[bar_set , bar_number , r_node ]  call VIEW function defined above