BBQ Grill Temperature Uniformity Study

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May 27, 2016

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Abstract

Bull Outdoor Products, Incorporated, a barbeque grill and outdoor kitchen manufacturer, sponsored this project with the intent of improving the temperature uniformity across the surface of their barbecue grills. For this project, the Cal Poly team of mechanical engineering students, Monty Dodge Jr. and Samuel Melo, used the Brahma grill head model with setups for both natural gas and propane. In order to determine exactly what the uniformity across the grill surface was, the student team designed a testing apparatus which would measure a grid of temperature locations one inch apart spanning an area 16 by 36 inches. Developing a testing method which produced accurate results was done over five separate tests, at which point the team began testing various geometrical configurations of flame guards (flame tamers) to determine how these geometries affected the overall temperature uniformity. Across all of the tests, the results clearly showed that temperature in the back of the grill was consistently higher than the front. It was also found that approximately half of the propane grill, on the left side, was significantly lower temperature than the right. Upon further investigation, and bench testing a propane manifold for pressure at each valve, it was determined the cause of the discrepancy in temperature from left to right was the result of a pressure drop in the manifold. Recommendations were then made to Bull Outdoor Products with regard to how this might be improved. The student team did, in the end, design a set of louvers which would direct heat flow from the back to the front of grill. These new louvers did improve the temperature distribution from front to back, however, the most valuable deliverable was the actual design of the test apparatus, the test method, and method of data analysis used.

Introduction

Backyard barbequing has become a tradition among households all across America. Naturally, as it has become more of a staple among American homes, it has led to a market for improving barbeque technology. Every grill master is actually a master of reading the grill, in other words, knowing the hot spots and the cold spots. A barbeque master is able to shuffle food on the grill in a way that equalizes cooking time and ensures everything comes off the grill cooked to perfection. The goal of Bull Outdoor Products, Inc., is to make every owner of a grill with ReliaBull technology become a natural grill master, by minimizing the difference in temperature across the entire grilling surface.

With the help of California Polytechnic State University (Cal Poly) Mechanical Engineering seniors Monty Dodge and Samuel Melo, henceforth referred to as Brazing Bull, this goal has come closer to reality. The endeavor fulfills a senior design project requirement for obtaining a Bachelor of Science degree in Mechanical Engineering at Cal Poly, San Luis Obispo. Brazing Bull was responsible for defining the rubric used to measure a successful design and develop a quantifiable measure of improved temperature distribution. These specifications were based upon the desired outcome described by Bull Outdoor Products as “consistent temperature distribution from left to right and front to back of the grilling surface.” This goal was achieved without any change to the outside dimensions of the grill head and without changing the location of the burner manifold.

To achieve an optimum temperature distribution, Brazing Bull will began by reproducing the results of a previous Cal Poly team of engineering students. Using the results, along with addition data collected by Brazing Bull, a statistical analysis was performed to define clear and measurable specifications that quantify a successful project and greater improvement of consistency in temperature distribution.

The statistical analysis was used to determine whether the temperature data obtained consisted of a normal distribution, in which the representative bell curve is unimodal, and to define the resulting standard deviation of the data. When performing a brief statistical analysis of the previous team’s data, Brazing Bull saw trends that appeared to be bi-modal, although this analysis was not reliable due to the lack of certainty regarding how their data was obtained and organized. It was useful, however, in experimenting with potential statistical models to be applied to data collected by Brazing Bull’s improved data acquisition (DAQ) system, which was built and used in temperature data collection.

With improved reliability of temperature data and a statistical model in place to validate any improvements in temperature distribution, Brazing Bull experimented with modified burners, varying inner barbecue head geometries, and additional alterations to flame tamers developed by the previous Cal Poly ReliaBull team.

Sponsor Background and Needs

Bull Outdoor Products, Inc. has been developing the ReliaBull technology with the help of Cal Poly mechanical engineering students since the 2012/13 academic year. The previous team of students, License to Grill, developed a fixture which traveled across the grill, with thermocouples mounted at even spacing, and connected to a DAQ system in order to measure temperature distribution. Brazing Bull located what is left of the system and determined which components were salvageable, and which aspects of the system could be improved to acquire more reliable data.

Bull Outdoor Products, Inc., intends to integrate the ReliaBull Technology into all of the barbeques in the Bull product line. After conducting some research, Brazing Bull has found other barbeque technologies that have digital temperature monitoring systems as well as automatic temperature control systems. However, the consistent temperature distribution technology like that of ReliaBull seems to be unique to Bull Outdoor Products, Inc.

Objective

Originally, the project was presented to Brazing Bull with the goal of improving the performance of grills already in production. This posed an issue because there was not an official problem definition. Therefore, Brazing Bull developed their own problem definition.

The ultimate objective for this project was to design, develop, and implement a testing method for Bull Outdoor Products, with the purpose of increasing the performance of their grills, specifically the distribution of heat across the grill surface, creating as constant temperature as possible. Brazing Bull used said testing method to develop results for several different grill configurations, and devleoped recommendations for Bull Outdoor Products based on those results.

Brazing Bull initially wanted to develop the testing apparatus in a way which provided flexibility to gather temperature distribution data from all of the barbeques in the Bull Outdoor Products line. However, this goal proved to be unfeasible with the amount of time and manufacturing required to accomplish it. The DAQ system will still be a valuable asset to future research conducted by Bull Outdoor Products on their Brahma thirty-eight inch or larger barbeques as well as provide a means of conducting in-house competitor benchmarking on similar grills. This will give Bull Outdoor Products the ability to validate ratings established by Consumer Reports and other product review organizations, as well as understand what areas of the grill technology will result in the highest return of investment from future grill enhancements.

With measurable parameters defined, phase two involved designing a reasonable method of evenly distributing the heat produced by the grill over the cooking surface. Ideally, this was done without altering the outside dimensions of the grill head, and with minimal amount of design alterations to hardware already in production. This included QFD as well as ideation processes normally being completed at the beginning of the design process. Bull Outdoor Products gave adequate freedom to change the design of their grills, however, the goal was to create something that will achieve the ultimate objective without large manufacturing costs or large design alterations.

Background

Existing Products

Based on consumerreports.org reviews of the Bull Urban Islands 21151 5-Burner gas grill sold at Costco, and compared to other gas grills in the same price range, the Bull product leads the competition in size and BTU output. However, when it comes to the high and low temperature evenness ratings the Bull unit receives a "good" and "fair" rating, respectively. Some of the competitor products outperform Bull in this category according to the testing standards used with the Kenmore Elite receiving "excellent" ratings in both evenness categories, and the Napoleon Mirage receiving "very good" ratings in both categories. These and other comparisons may be seen in Table A1 of Appendix A.

It is important to note that the testing methods for these review comparisons is not well defined. For the evenness testing at high and low temperature, quantitative data indicating the temperatures across the grid is not known; the information provided merely states that the temperatures were measured with thermocouples. In addition, the heat output, number of burners, and size varies from grill to grill among those outlined in Table A1 of Appendix A.

The results found during this research certainly allow room for improvement and provide additional motivation for Brazing Bull to "turn up the heat" with this design challenge. As Brazing Bull moves forward with testing, additional research will be conducted in order to determine quantifiable measures of a successful design, including a detailed look at team License to Grill's results and temperature distribution data.

Current State of the Art

Currently, Bull Outdoor Products sells grills using two fuel types of various sizes. They provided Brazing Bull with two Brahma grill heads as seen in Figure 1. One configured for propane fuel, and the other for natural gas fuel. Other than the gas regulator used on each grill head for different fuel types, the grill heads are identical. The Brahma head is their thirty eight inch model, meaning the grilling surface is 38" wide. The Brahma head consists of five cast stainless burners, spaced evenly from left to right across the grill, and stretching from the manifold, located at the front of the grill, to the rear of the grill. Each of the smaller grills in the Bull Outdoor Products line use the same left to right spacing of the burners. Therefore, data collected for the Brahma head should be accurate for smaller versions of the grill.

Figure 1: *"Brahma" Bull barbeque head, the model provided by Bull Outdoor Products for analysis.*

In conducting background research, Brazing Bull has found that the testing apparatus used by the previous Cal Poly ReliaBull Senior Project team is unique for the task of measuring temperature distribution. Therefore, team License to Grill's design was used as a benchmark for comparison in choosing design features of the new apparatus, based on three categories: motion of array, indexing of array, and material selection. The previous apparatus is no longer available, and based on team License to Grill's report and feedback from shop techs at Cal Poly's Mustang 60 machine shop, further improvements will be made. The decisions made based on background research of the testing apparatus will be further outlined in the Design Development section.

Other than the DAQ receiver and thermocouple wires, the previous team's apparatus has since been discarded, therefore, Brazing Bull rebuilt and improved the DAQ system for a reliable assessment of the current grill configuration. Some of the improvements that were made to the previous system include: drive system (ball screw), indexing method, and material, all of which were decided upon using a decision matrix technique outlined in Appendix C. In addition to these improvements, the method of attaching thermocouples to the array was improved by machining slots into a solid aluminum bar in order to precisely control the location and orientation of each individual thermocouple; the previous DAQ simply had thermocouple wires wrapped around a steel bar numerous times as seen in Figure 2. While inspecting the remaining thermocouple wires, Brazing Bull also determined that it would improve the longevity of the DAQ by enclosing the thermocouple wires in a heat resistant flexible wrap. During the production of the new DAQ, additional enhancements were made using the design, build, test methodology which will be outlined in detail later in this report.

Figure 2: *Team License to Grill's testing apparatus*
Highlighting the method of attaching thermocouples.

Manufacturer Grill Specifications

Bull Outdoor Products provides the following list of specifications for their Brahma grill head:

- 90,000 BTU's
- 304, 16 Gauge Stainless Steel Construction
- 5 Cast Stainless Burners
- Infrared back burner 15,000 BTU's
- Single Piece Dual Lined Hood
- Piezo igniters/Zinc Knobs
- Solid Stainless Steel Grates
- Heavy Duty Thermometer
- Warming Rack 266 Sq. In.
- Stainless Steel Rotisserie Motor
- Twin Lighting System
- Cooking Surface 1026 Sq. In.
- CSA Approved

Most of the provided specification data was not needed by Brazing Bull, however, it has been included for reference.

Design Development

Method of Approach

Due to the unique nature of the ReliaBull project, Brazing Bull's method of approach broke slightly away from the typical "design, build, test" model. In order to gain a more complete understanding of the needs and technical specifications, Brazing Bull began by building a revised testing apparatus to collect accurate and complete data for Bull Outdoor Product's grill design. After collection of necessary data and developing a full analysis of the experimental temperature distribution, experimentation of different configurations that meet the goals of the project begun. Therefore, the solution process followed a "design, build, test, experiment" approach.

In the past, Bull Outdoor Products, Inc. has teamed with Cal Poly mechanical engineering student groups to improve temperature distribution with the development of ReliaBull technology. Due to lack of access to the previous team's raw data files, and changes to grill components, Brazing Bull needed to obtain detailed information about the performance of the grills. This information included:

- Temperature distribution over the entire grill surface to determine:
    - Locations where heat is concentrated or weak
    - Average temperature
    - Greatest difference in temperature
    - Statistical representation of temperature data
    - Standard deviation of grill surface temperatures

This was accomplished by building a DAQ system apparatus using a linear array of N-type thermocouples and a frame on which to move the thermocouples to desired locations across the grilling surface. The DAQ recorded numerous temperature data points across the entire surface so that Brazing Bull could develop a temperature distribution map across the provided Brahma barbecue head. Once the data was obtained, Brazing Bull had the ability to determine locations on the grill where the heat is, or is not, distributed uniformly. Furthermore, the acquired data enabled Brazing Bull to determine what maximum and minimum temperatures the grills produced and how the range of heat between those temperatures was statistically distributed.

Once sufficient data was collected, a quantifiable set of engineering specifications was defined at which point the experimentation process for improving ReliaBull Technology began. Before quantifiable and measurable technical specifications were established, only broad goals were able to be set, such as, "create an even temperature distribution". Therefore, the technical specifications and detailed problem statement defined by Brazing Bull was fully developed after the completion of the initial testing phase.

Project sponsor, Bull Outdoor Products, Inc., has large scale manufacturing capabilities and agreed to assist in manufacturing some of the final components in cooperation with Brazing Bull. When feasible, machine shops and other resources provided by Cal Poly were utilized by Brazing Bull in order to manufacture and test newly developed grill configurations. Due to the unconventional nature of the ReliaBull design project, Brazing Bull focused on the development of experimental configurations later in the academic year, and tried multiple approaches while simultaneously performing statistical and engineering analysis in order to keep the project on schedule.

The DAQ system developed by Brazing Bull was influential in investigating the source(s) of hot and cold spots across the grill. Each set of data helped direct further configuration iterations, as well as developing the most accurate method of collecting data.

Conceptual Designs

Brazing Bull used several methods in order to make decisions pertaining to materials and operation of the testing apparatus which they built. These methods will be covered in detail in the next section titled "Concept Selection". However, before any of these methods were used, Brazing Bull sketched and brainstormed several ideas, using License to Grill's basic design as inspiration.

Appendix D shows the initial sketches and ideation of the testing apparatus. The sketches also show how the mechanical method of testing was developed into the final drawings presented in Appendix E. Page one of Appendix D demonstrates the original idea of using a linear array of thermocouples with a machined bar that organizes the wires into bundles. However, this first idea used a motor to rotate a screw which would result in a powered, or automated, testing system. In the end, a manual method was selected, as it would have required additional funds, programing, and time to achieve an automated system. The decision matrix in Appendix C demonstrates this decision as well. Page two of Appendix D demonstrates the initial idea for the indexing knob which was developed to precisely control the location of the ball screw in equal increments as it rotates. The remainder of Appendix D displays various ideas of how to build the frame and fixture the apparatus. Final frame design was chosen to utilize the rotisserie slots already cut into the side of the grill body and hood, to align the ball screw. Only slight enlargement of the rotisserie hole on one side of the grill (left side) was required to accommodate the final testing apparatus.

During manufacturing, various components of the design were altered slightly, however, the operation of the apparatus remained unchanged. The back frame rail was moved forward two inches so that the thermocouple array wouldn't have to be redesigned for clearance at the back of the grill. Furthermore, a support was welded in across the apparatus to add rigidity to the frame, and keep the bushings from trying to advance on the ball screw.

Concept Selection

Brazing Bull used various brainstorming techniques and comparisons to the testing apparatus designed and used by team License to Grill in order to choose key components of the new design. Since the overall function of the apparatus served the same purpose, some components are similar, however, many parts of the design were improved upon. It is the desire of Bull Outdoor Products for this apparatus to be used on their barbeque heads for years to come, and with that in mind, Brazing Bull applied the decision matrix technique to compare three aspects of the design with various criterion to the previously used apparatus. The results of the three categories, listed in Table 1, may be found in Appendix C.

Table 1: *Categories of interest for various aspect of testing apparatus design.*

Motion of Array	Indexing of Array	Material Selection
Repeatability	Repeatability	Cost
Cost	Cost	Durability
HMI Simplicity	HMI Simplicity	Strength
Durability	Durability	Manufacturability
Accuracy	Accuracy	
Manufacturability	Manufacturability	

Preliminary Analysis

In addition, the engineering justification for the criterion listed in Table 1 may be found in Appendix F of this report including temperature effect on material properties, stress analysis of the testing apparatus components, and indexing dial manufacturing based on pitch of selected lead screw. Values for some material properties were found using Shigley's Mechanical Engineering Design, Ninth Edition. The calculations performed, which are shown in Appendix F of this report, found the bending stress in the apparatus rails to be less than 5% of the yield strength for stainless steel resulting in a maximum deflection of 0.0022 inches. Brazing Bull determined these were acceptable results, which led them to select the parts and materials that ended up being used.

Proof of Concept

Aside from engineering calculations, Brazing Bull proved the concepts they chose by putting them to the test. A full description of how the final testing method was developed is detailed further in this report under the section titled "Test Method Development". However, after initial testing began, Brazing Bull understood that the design and function of the apparatus would ultimately work as planned. Brazing Bull's first testing attempt was at high valve setting on the natural gas grill. After being exposed to temperatures up to, and exceeding, 900 degrees Fahrenheit for over two hours, Brazing Bull felt it was safe to assume this would be the most extreme conditions the apparatus would ever encounter. Aside from a few repairable flaws in the apparatus that arose under these conditions, the apparatus worked as designed. Modifications were made to fix the issues that arose under the most extreme conditions, and thus, Brazing Bull felt the chosen concept had proven itself in the intended environment and operation.

The apparatus was designed to withstand the high temperature environment it is subject to inside the barbeques, and still retain accuracy for future testing. For each barbeque, the testing apparatus took at least six series of data, meaning six complete testing procedures, each taking almost two hours to complete. In the case of the ReliaBull Heat Technology project, the testing is designed more so to determine the distribution of temperatures across the Brahma grill head from Bull Outdoor Products rather than the durability or functionality of the apparatus itself. After each test was conducted, the components of the test apparatus were verified to ensure they are still in their original operating condition. This verification included ensuring frame geometry remained unchanged, thermocouple insulation remained intact, and all ball screw assembly components were still aligned and operating within their rated tolerances. A description of this design verification can be seen in Appendix K.

Final Design

Overall description

In order to convert Bull Outdoor Products' given problem statement into quantifiable terms, a method was needed to define the current operating conditions of their grill. The focus of the original problem statement was on temperature distribution, so an apparatus to test and record temperatures at the surface of the grill was created. Although there is heat throughout the entire barbeque box, it was assumed that the most critical location for obtaining even temperatures was at the surface, where food will rest during cooking. Therefore the apparatus was designed to collect air temperatures as close as possible to this surface. Initially, Brazing Bull's objective was to create an apparatus that would be able to test the entire line of Bull barbeques, as well as competitor's barbeques. However, as time and restraints began closing in, it was decided that the apparatus would be built only for the Brahma 38" grill head. The final design after all alterations is shown, with labels, in Figure 3.

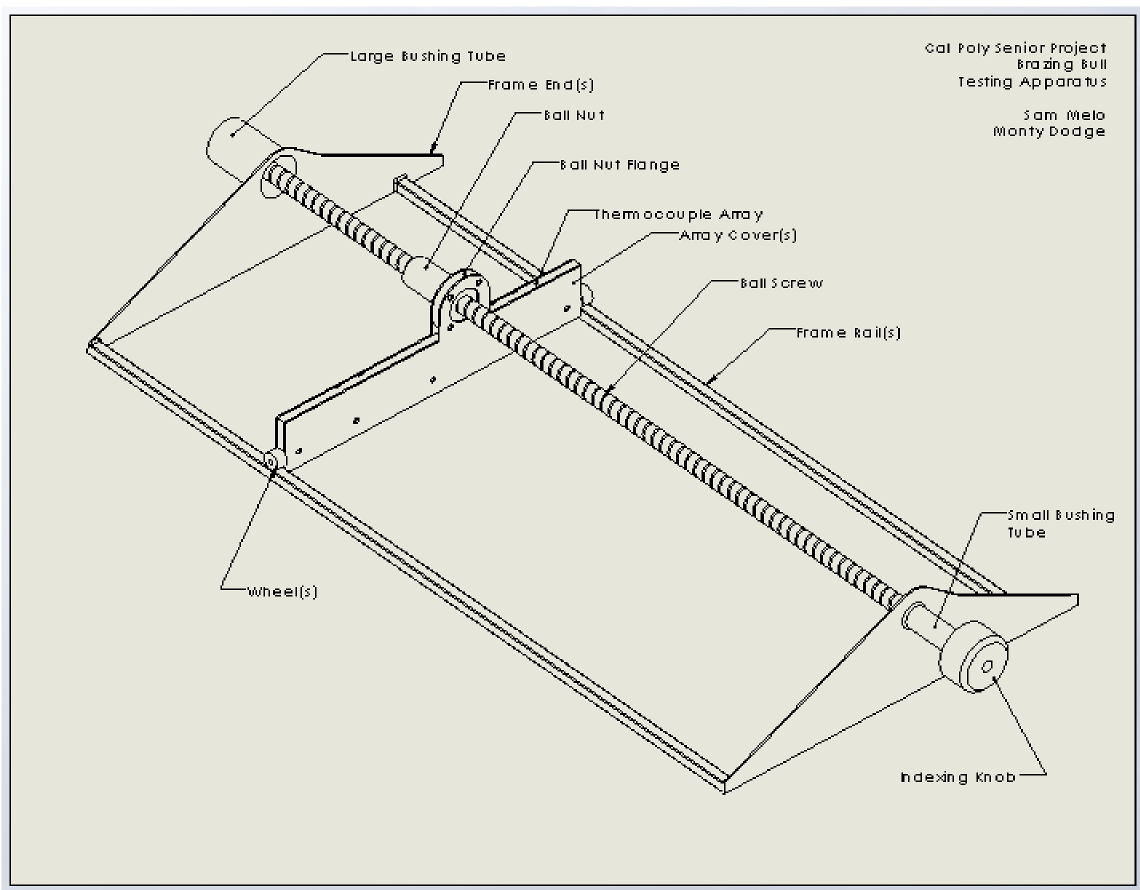


Figure 3: Full assembly drawing of the Brazing Bull testing apparatus after all alterations. ***This drawing represents the final apparatus after manufacturing, and does not completely match the original design.***

Detailed design description

The testing apparatus assembly consists of three sub-assemblies containing twenty-one total manufactured components. The three subassemblies are the frame, ball screw, and thermocouple array.

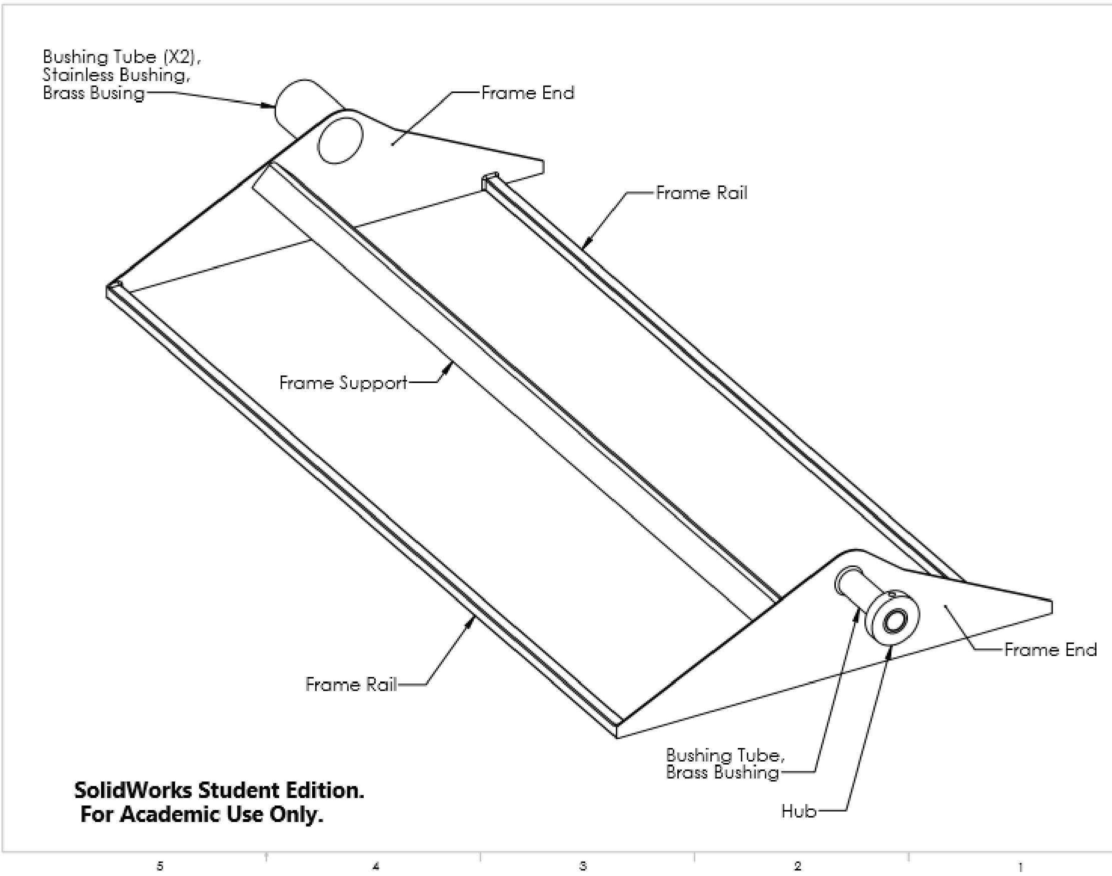


Figure 4. *Frame assembly labeled drawing.*

The frame, as shown in Figure 4, is the largest subassembly and serves as a method of rigidly locating the ball screw ends and providing a flat path for the thermocouple array to move over, while simultaneously locating the array's height over the grill surface. Eleven components make up the frame; two stainless steel frame ends, two stainless frame rails, three stainless bushing tubes of different diameter, two brass bushings, one stainless bushing, and one aluminum hub.

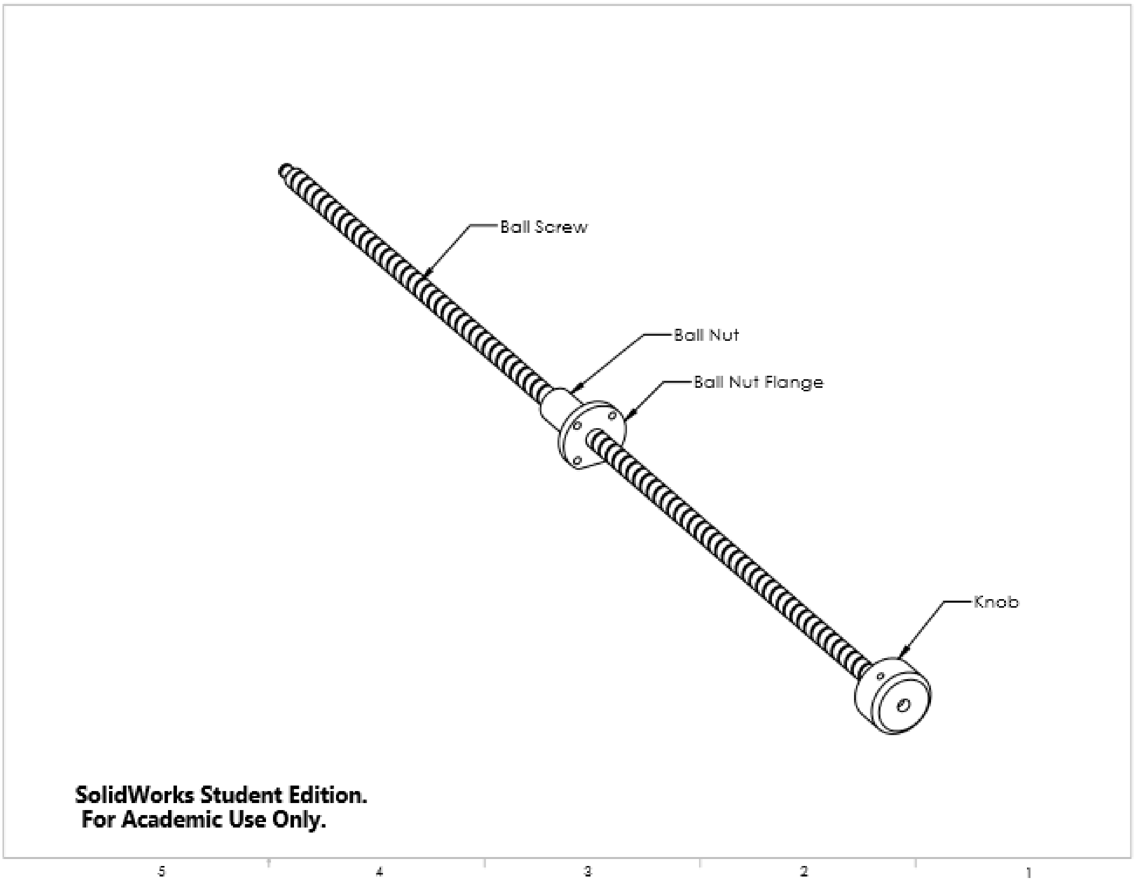


Figure 5. *Ball screw subassembly labeled drawing.*

The ball screw subassembly serves as a method of converting manual rotational input motion from the knob, to linear translation of the thermocouple array across the grill. It is made up of five components; one ball screw, one ball nut (which contains 148 recirculating steel balls), one flange, one knob, and one handle. All ball screw subassembly components are shown in Figure 5.

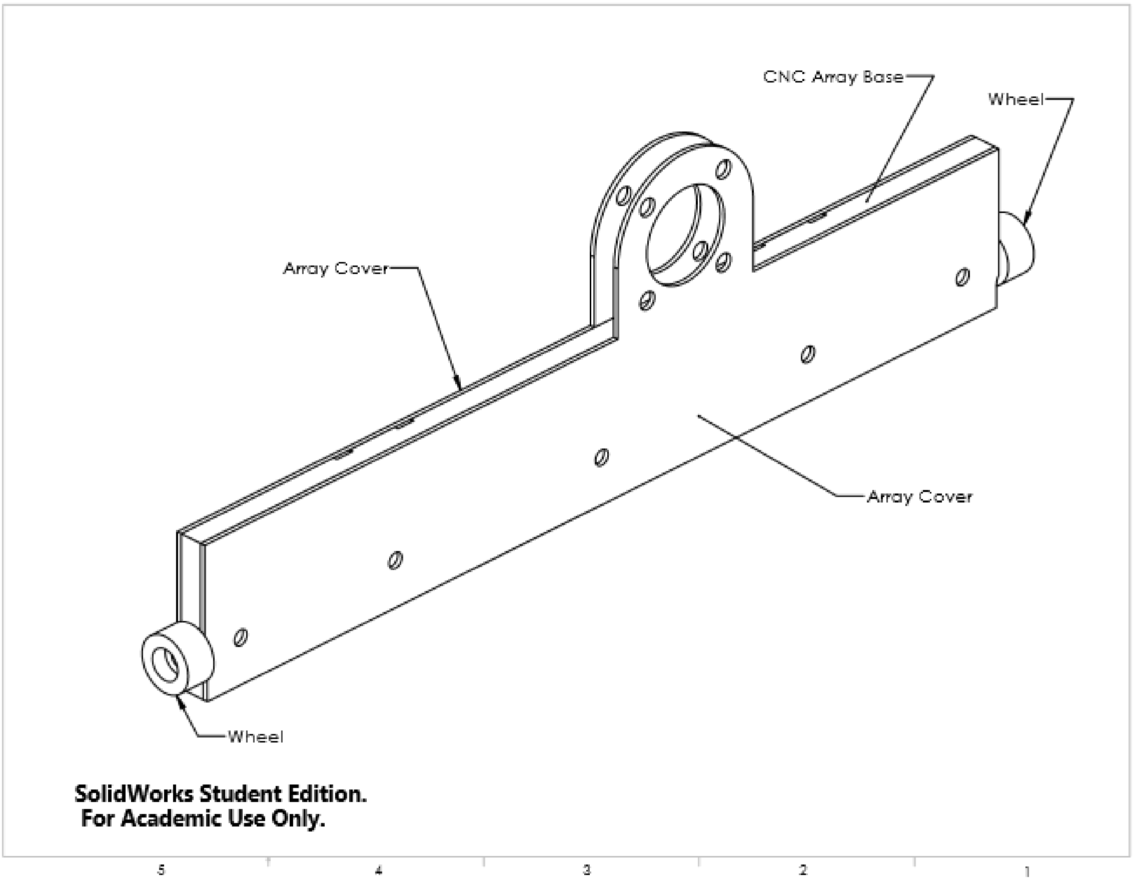


Figure 6. Thermocouple array subassembly labeled drawing.

Finally, the thermocouple array subassembly, shown in Figure 6, consists of five components including two stainless array covers, one aluminum CNC machined array base, and two stainless steel wheels. This subassembly rigidly connects sixteen N-type thermocouples of equal spacing to the ball screw nut in a linear fashion spanning the grilling surface from front to back. Please refer to Appendix E for a detailed drawing of the array base that shows the slots which accommodate the thermocouple wires.

The testing apparatus and its components were designed with the purpose of moving the thermocouple array tips across the grill while also keeping them all evenly spaced .050" above the grill grates. An overview of the full apparatus assembly can be seen in Figure 3, while full drawings of all critical components are compiled into drawing sheets in Appendix E. Each part belongs to one of the three subassemblies, and is labeled accordingly with a two letter acronym corresponding to the subassembly, followed by a three digit number. The indicating letters are FR, for the frame assembly, BS, for the ball screw assembly, and AR, for the thermocouple array assembly.

Extensive care was taken during manufacturing of the apparatus so that thermocouple tip location would be as accurate and repeatable as possible. One main objective during the design phase of the apparatus was to ensure that every time it was used, it would always be recording temperatures in the same locations as the previous test, or as close as possible with minimal uncertainty. This is why the thermocouple array was machined using a CNC method, and an accurate indexing method was implemented in the knob.

A solid model of every component and the entire assembly was created using Solidworks, then converted to technical drawings with dimensional and geometric callouts. Machining and fabrication took place on Cal Poly's campus at several locations including the Mustang 60' Machine Shop, the Hangar, and the IME department machine shop.

Fabrication of the frame consisted of cutting stainless steel square tubing to length for use as frame rails, then machining the ends so that each rail was exactly the same length and square. The stainless frame ends were cut using an optical plasma CAM, which traces a 1:1 scale printout of a two dimensional shape, then translates a plasma cutting tip through a path generated by the system based on the drawing. This method was chosen due to the dynamic shape of the frame ends. Most common cutting tools either cut in a straight line, or are too difficult to accurately create identical shapes by hand. Bushing tube locating holes were cut into the frame ends using a simple drill press and whole saw, which produced excellent cut quality and dimensional tolerance. The frame rails and frame ends were simultaneously attached to a flat surface using temporary fixtures to ensure proper location and meet tolerances for flatness, square, and parallel. Throughout the process of mounting to fixtures, the components were repeatedly checked for square before being welded together using a TIG welding process. Each bushing tube was faced on a manual lathe to ensure they were proper length and that the ends were perpendicular to their length. Then the respective bushings were precision machined on the lathe and pressed into the correct tubes. The bushings were made of brass, and act as the final locating method for the ball screw, as well as being a friction type bearing that allows for the ball screw to be rotated while still retaining its position in the frame. Since one bushing tube needed to be oversized to accommodate for the ball nut retracting into it, an additional stainless bushing and tube needed to be manufactured in order to locate the smaller brass bushing inside of the larger diameter tube. With both tubes completed, and their respective bushings pressed in place, they were aligned using the ball screw and attached using fixtures to the frame ends located by the previously cut holes. Once in place and checked for perpendicularity, the tubes were welded to the frame, again using a TIG process. The tubes were not welded completely around in order to avoid warping of the frame, thus causing misalignment of the bushings. The last component to be added to the frame was a hub, which the knob on the ball screw would rotate around. This part was turned and bored on a lathe, then drilled and pressed onto the small diameter bushing tube. Finally, as the result of a decision to make the frame accommodate auxiliary fixed position temperatures, holes were drilled into the sides of the frame rails to allow extra thermocouples to protrude through the frame without interfering with the operation of the apparatus.

The ball screw subassembly consisted of the simplest components to manufacture, as most were ordered from a supplier ready to use. However, to fit our design, the components needed some modification. The ball screw itself needed to be machined on both ends to the proper diameters for fitting into bushings on both ends and the knob. Then the larger bushing end was machined for a snap ring and the knob end was machined to accept a set screw to rigidly locate the knob onto the ball screw. The knob was machined from aluminum to fit on the end of the ball screw and around the hub of the frame with considerable clearance. All of the above operations were performed on a manual lathe except for the set screw slot which was performed on a vertical mill. As a safety precaution, a handle was tapped and threaded into the knob so that heat conducted from the grill through the apparatus would not harm the operator as they turned the knob. Lastly, the ball nut flange came from the supplier too thick for the design, therefore it was trimmed down on a vertical mill to match the thickness of the thermocouple array base.

Manufacturing of the thermocouple array required two types of automation. First was another operation of the optical plasma CAM used to cut the array covers from a sheet of stainless steel. Second, HSMworks was used through Solidworks to create a G&M code compatible with the IME department's Haas VF2 CNC three axis vertical milling machine. This machining operation cut precisely spaced grooves into an aluminum bar, which when sandwiched by the array covers, contains the sixteen thermocouple wires. Finally, the proper holes were transferred to the array covers and drilled with both a standard twist drill bit, and a boring bit on a vertical mill for larger holes. When assembled, holes in the array base and cover are aligned with bolts that clamp the assembly together, and in doing so, clamp the thermocouple wires into the groves in the array base.

Assembly of all the components was designed to be simple and repeatable. Creating the final apparatus required only thirty-five pieces of hardware which include machine screws, lock washers, hex nuts, snap ring, set screw, and sheet metal screws. It requires only a few simple common hand tools to assemble and disassemble so that any future work or alteration needed on the apparatus could be done simply, and by anyone without specific knowledge of the original design. The most difficult task in assembly of the apparatus, and probably the most critical, is ensuring proper thermocouple wire placement in between the array and array covers. However, this was completed by placing a rigid straight edge the proper distance from the bottom of the array, and placing all the wires in the array's grooves so that the tips protruded out just far enough to touch the straight edge. This positions the wires correctly and evenly across the entire array. The final manufactured testing apparatus as drawn in Figure 3 can be seen in Figure 4.

Figure 7: Completed testing apparatus with insulated wires in the provided natural gas grill.

Cost analysis

Funding for the project was broken into two parts, testing apparatus build, and testing phase. An original list of needed materials was compiled for building the testing apparatus. This budget was approved during fall quarter of 2015 and $2000 was provided to Brazing Bull by Bull Outdoor Products, which covered the approved budget with extra funds. Funding came in the form of two $1000 VISA gift cards which could be used just like debit cards to make purchases at stores as well as online. Vendors were sourced for all needed materials for the apparatus and purchased using the gift cards. All transactions were recorded by Brazing Bull to keep an up to date record of remaining funds and budget. At the completion of the testing apparatus, Brazing Bull has spent $1887.00 of the provided $2000, leaving a remainder of $113.00 in the budget, as seen in Table 2. Due to unforeseen expenses, this amount is $242.26 over the original proposed budget, but still under the provided amount. The materials list and budget sheet can be seen in Table G1 of Appendix G and reflects all purchases made up to the completion of the testing apparatus.

Table 2: *Budget review up to apparatus completion.*

Proposed Budget	$1644.74
Provided	$2000.00
Spent	$1887.00
Remaining	$113.00

After the apparatus was completed, phase two of the project began which included testing of the grills. For this phase of the project, Bull Outdoor Products provided Brazing Bull with a check for $2000. These funds were placed in a joint Chase checking account with access by both team members. These funds were used for all expenses related to testing and the senior expo. A review of all expenses during phase two can be seen in Table G2 of Appendix G. All remaining funds were returned to Bull Outdoor Products via cashier's check, and the account was closed.

Safety considerations

The operation of a barbeque grill is normally safe for the average consumer, however, Brazing Bull wanted to ensure that testing of the grill heads was as safe as possible. During testing, Brazing Bull discovered that the knob was able to conduct enough heat to cause discomfort and small burns to the hands of the operator. To remedy this, a handle was installed on the knob of the apparatus to give the operator something to hold onto further away from the heat produced by the grill. Since the handle can still conduct some heat to the operator, Brazing Bull also recommends using adequate leather welding gloves, or other comparable hand protection, such as an oven mitt, to rotate the knob and advance the thermocouple array. The advancement knob protruding from the grill is the only part of the apparatus that requires operator interaction. Therefore, Brazing Bull simply suggests the operator use standard caution during testing, as if they were using the grill normally to cook food, and that they avoid contact, and be aware of, potentially hot surfaces.

Additional safety concerns arose when considering the use of pressurized flammable gasses to produce heat through combustion. Brazing Bull urges that special care be taken when connecting all fuel lines, and that all testing be performed in well ventilated areas. Whenever a new connection is made, it should always be checked for leaks using a soap and water solution. When sprayed onto connects under pressure, the soapy water will bubble, indicating a leak. If any connection fails this test, the fuel must be shut down immediately, and connections be fixed for further operation. Furthermore, it is important to remember to close all valves completely when testing has completed. This includes the five valves on the manifold controlling flow to each burner, and the valve on the bottle of propane or the valve from a constant source for natural gas.

Under no circumstances should holes in the burners be blocked when operating the grills for testing. Blockages in the burners cause fuel to escape around the valve and out of the grill head through the control knob. When this occurs, there is a high risk of ignition and subsequent flames being directed at the operator's hands.

Maintenance and repair considerations

The apparatus designed and used by Brazing Bull was able to provide excellent and useable data. However, there were some repairs that were necessary after initial testing began, as well as a few recommendations for any further iterations of the apparatus. Thorough engineering calculations were done prior manufacturing the apparatus to ensure its operation would be possible, but

Brazing Bull learned that under real world conditions, the apparatus needed a few minor changes.

After the inaugural test of the natural gas grill, with the burners set to high, Brazing Bull understood that high valve setting tests would no longer be completed because of the extreme effects that prolonged exposure to high heat had on both the testing apparatus and the grill head itself. During that first test, the apparatus experienced temperatures over 900 degrees Fahrenheit, well above the necessary temperature for cooking food. However, Brazing Bull was still able to complete an entire test run under these conditions, so the apparatus design proved to be a success as a whole. After a cool down period, the apparatus was inspected and the following flaws were noted:

- Interference between the frame rails and ends of the thermocouple array, causing traces of aluminum to transfer from the array to the rails due to heat and friction as the array advanced across the grill.
- Deformation of the aluminum wheels due to temperatures approaching the melting point of aluminum combined with friction during advancement.
- Decline of wheel bearing performance due to enclosed grease being completely burned away during testing.
- Velcro attached, from the factory, to the heat wrap protecting the thermocouple wires could not withstand heat inside the grill and melted before turning to ash inside the grill.
- The snap ring retaining the ball screw within the apparatus was experiencing too much axial load when turning the ball screw and would occasionally break or be forced out of its groove.
- Significant flex was noticed in the frame ends when advancing the array.
- There were many aluminum shavings visibly falling out of the knob between the knob and hub, indicating friction between the two components.
- The indexing ball occasionally becomes lodged in its hole in the hub, thus locking the knob in place and making it unable to be turned by the operator. Similarly, friction from the ball rubbing the inside of the knob has created a groove and notches in the original detent, making it out of tolerance, and difficult for the ball to plunge in and out the detent properly.

In order to remedy the interference between the thermocouple array and frame rails, the apparatus was semi-deconstructed, leaving the thermocouple array covers still intact with the base. By doing this, the entire array assembly was able to be modified without removing or disturbing the precisely located thermocouple wires. The array assembly was placed on a vertical milling machine and .100” was removed from each end, as well as an additional .050” removed from the area of the thermocouple array directly next to the frame rails. This gave the array a total of .300” clearance between the frame rails when the apparatus is cold, which is an adequate amount to compensate for thermal expansion of the thermocouple array assembly.

Entirely new wheels were manufactured for the ends of the thermocouple array to fix both the wheel deformation problem, as well as the bearing grease problem. Brazing Bull decided that the use of greased bearings was not necessary because the wheels do not experience enough load to justify their use when considering how difficult it would be to keep them adequately greased.

Instead, stainless steel wheels were machined to be located with only the mounting screw, and no bearing. Since stainless steel has a much higher melting temperature than aluminum, machining the wheels from stainless steel solved the wheel deformation problem. Brazing Bull decided it would be adequate to rigidly fix the wheels to the array without the ability to rotate because they would still be able to slide across the frame rails easily, while still locating the height of the array off of the cooking surface.

Although the heat wrap purchased from Jeggs.com claimed to be heat resistant to 2000 degrees Fahrenheit, the included Velcro used to attach the shielding could not withstand the temperatures that the shielding experienced. Fortunately, any Velcro which melted inside the grill was completely turned to ash and disintegrated before the test was complete, thus avoiding a troublesome mess. To avoid future issues, and smoke caused by burning plastic, all Velcro was cut away from the shielding and discarded. Instead, thick wire was coiled around the shielding to secure it to the thermocouple wires coming out of the thermocouple array. This method allowed Brazing Bull to tightly bind the wires together in an organized and durable fashion, without melting anything inside the grill.

Due to the snap ring's small size and flexible nature, a solution to the snap ring failure did not come from altering the design and dimensions of the groove in the ball screw, or the snap ring itself. Instead, Brazing Bull was able to secure the snap ring in place by binding together the snap ring ends using wire threaded through the holes in the snap ring, normally used for assembly and disassembly. When twisted together and trimmed, the wire bound the ends of the snap ring, thus restricting the ring's expansion under load. The snap ring was no longer able to expand out of its groove. Brazing Bull recommends that future iterations of the testing apparatus either use a similar method of restraining the snap ring, or opt to use a heavier duty snap ring if available.

During operation of the apparatus, Brazing Bull noticed that the bushing tubes would wiggle in and out of the grill while the knob was being rotated. This indicated the presence of flex in the frame ends, possibly due to axial force applied by the ball screw threads gripping the brass bushings. To better support the frame ends, a piece of stainless steel angle bar was welded in place between the frame ends running parallel to the ball screw, and spanning the entire apparatus. Further operation of the apparatus with this support bar in placed produced minimal visible flex within the frame, however, Brazing Bull recommends possibly adding additional support to further stiffen the frame for future iterations. The current condition of the frame works well, but could be improved with additional stability.

Aluminum shavings visible around the knob after the initial testing procedure meant that there was friction between the aluminum knob and hub. The knob was machined on a lathe without the proper boring bar, so the finish was rough. To solve issues with friction, the knob was revisited with the proper boring bar, machined smooth on the inside, and given additional clearance around the hub. Cleaning up the knob in this manner, combined with light sanding of the hub cleared the apparatus of friction within the knob.

Currently, there are still issues with the operation of the ball, spring, and detent. Originally, the indexing system worked well. However, prolonged use under high temperatures has caused some deformation of the detent notch inside the knob. Occasionally, the ball will get stuck and not retract into the hole properly to allow continued rotation of the knob and ball screw. To fix this, the operator must remove the knob and lightly sand the inside rim and detent notch. This combined with applying some grease usually allows the indexing system to work properly through an entire testing procedure. When the dimensions are proper, the system works well, therefore it is Brazing Bull's recommendation that the knob be re-manufactured using stainless steel to the same dimensions. Since stainless steel is a harder metal than aluminum, the hardened steel ball should not deform the inside rim of the knob due to the force applied to it by the spring. Brazing Bull also recommends experimenting with different springs installed within the hub. By changing the spring, the operator can adjust how firmly the ball seats into the detent notch in the knob. As the knob is rotated, the ball should have a definite "click" as it engages the detent notch, and should be able to be felt by the operator through the handle. If the operator cannot hear or feel the ball engage the detent notch, a stronger spring is required. Different springs will also contribute to how difficult it is to turn the knob and disengage if from the indexing position. If the operator has too much difficulty turning the knob, or cannot disengage the knob from one indexing location to the next, a weaker spring should be used. It is possible to adjust spring strength simply by trimming off a few coils, or by exploring alternate spring options at a hardware store. It is important to keep in mind that under normal testing conditions, the spring will heat up and thus not feel as strong to the operator relative to how it might have felt under cold conditions.

Grill Performance Study

Temperature Parameters

The primary purpose of this project is to obtain temperature data for the grilling surface of the Brahma grill head model made by Bull Outdoor Products. This will be accomplished by measuring a grid of temperatures over a surface of the grill measuring 16 by 36 inches, approximately 89 percent of the grill surface. The remaining 11 percent will not be measured due to limitations of the grill geometry or the test apparatus itself. The temperature grid will be measured using 16 N-type, glass insulated, thermocouples spaced evenly one inch apart and fixed to the thermocouple array which spans from the front to the back of the grilling surface. The thermocouple array advances across the grill from left to right reading temperatures from all 16 thermocouples for approximately two minutes and fifteen seconds at 36 locations also spaced evenly one inch apart. This grid of temperatures is the most important data obtained throughout the duration of testing; however, there are some concerns as to the validity of the method in which this data is obtained.

The primary concern for the validity of the method used to measure temperatures across the grilling surface is the possibility of there being a time dependence on the data. This concern has been addressed in two ways. First, we have made sure to adequately preheat the grill with the lid closed in order to eliminate the possibility of skewed data obtained at different times of the temperature ramping up during preheat. Second, we have placed four thermocouples at fixed locations on the frame of the test apparatus. These four fixed thermocouples allow us to monitor temperatures at these locations throughout the duration of each test run. The fixed thermocouple data is compiled in a spreadsheet titled Steady State-Single and the data obtained from these thermocouples is then plotted in order to verify a steady state operation of the grill. In all test runs, we were able to verify steady state operation and therefore validate the testing method used to measure the 16 by 36 inch grid of temperatures mentioned above.

Initially, we had thought we would be employing some theoretical models of the grill performance, namely thermodynamic, fluid flow, and heat transfer models. In order to aid in employing these models, we also measured ambient temperature approximately five feet from the grill, exhaust temperature at the main exhaust location on the top back side of the grill, and finally, we also measured the temperature at the analog temperature gage probe on the lid of the grill heads. This location served a dual purpose as a potential boundary temperature for a thermodynamic model as well as a means of verifying the analog gage reading.

The final thermocouple used was submerged in an ice bath contained within multiple stacked Styrofoam cups for insulation. The only purpose of measuring the temperature within the ice bath was as an experimental control since this is a theoretically known temperature of 32˚F. Monitoring the temperature within the ice bath also provides confidence that the DAQ box is properly calibrated. At times during the experiments, we did see the ice bath temperature rise minimally, however, this was always fixed by adding more ice or stirring.

Pressure Parameters

Although the main objective of this project focuses on temperature distribution, it cannot be assumed that trying to "fix" temperatures is the only method for a successful design. There could be other factors that affect temperatures at the grill surface. Therefore, it is important to consider the source of energy that creates heat at the surface, the fuel. The grills run on two different fuels; natural gas and propane. This is a fixed variable, which means that it is beyond the scope or purpose of this project to experiment or design fuels that provide more even heating in the barbeques. Instead, the properties of the incoming fuel must be analyzed to obtain a thorough investigation of what might be causing uneven heating. This is cause for the analysis of fuel flow into the grill, and flow of combusted fuel exiting the grill.

Each grill is provided with a regulator that controls fuel pressure to the grill's manifold. This pressure should always be constant as long as fuel is flowing, and should be at the manufacturer's specifications. Brass fittings, which consisted of ball valves connected to tees, were installed in each grill between the pressure regulators and burner manifolds. A flexible tube from the valve runs to a u-tube manometer which measures pressure with respect to ambient air in units of inches of water. When testing is not being done, the ball valves can be closed and the tubes removed, allowing for normal, safe, operation of the grills. Pressure measured after the regulator will be recorded as fuel inlet pressure and will be taken at each thermocouple array test position. The manometer is a visual tool, so it will be inspected and recorded manually each time a reading is required.

In addition to the fuel pressure, exit exhaust and air inlet pressures were also desired. However, these flows do not occur in a closed tube, and are therefore unable to be measured with a simple in-line gauge of any kind. Instead, a professor of fluid mechanics in Cal Poly's Mechanical Engineering department has provided a pitot-static tube with digital readout device, which is capable of measuring static and dynamic air pressure in air flow. This data will be useful in the fluid flow analysis, however, measuring the pressure at the exhaust could prove to be a difficult task due to turbulent conditions. During testing of the grill, an operator will hold the pitot tube in the exhaust vent and an air inlet location at the start of data collection for each indexed position of the thermocouple array. These various pressures will be recorded with the objective of aiding in the engineering analysis of the grills' performance, since it is suspected that the temperature distribution may be greatly affected by the flow of fuel and air through the barbeque.

Update: Due to inconsistent pressure gradients in the turbulent exhaust flow and numerous immeasurable inlet flows, the inlet and outlet flow pressures were omitted from the testing method. The inlet regulated fuel pressures were measured for each test run and found to remain constant.

Miscellaneous Parameters

Temperature and pressure have been discussed as variables being recorded during testing that need specialized equipment in order to record. However, there are several other parameters which must be noted during testing that don't require complex methods of recording.

The locations of the data recorded are not necessarily a test variable, but are very important in order to create an accurate model. Therefore, the sixteen thermocouples in the array are lettered from A to P, from back to front. The letters correspond to Y axis positioning. Similarly, the testing locations are numbered from 1 to 36, starting from the far left of the grill ending at the far right. The numbers correspond to X axis positioning. This creates an imaginary (X, Y) coordinate grid across a plane lying on the surface of the grill, with the origin at the back left of the grill, at position (1, A). The grid is an essential testing parameter that will identify which areas of the grill are too hot or too cool based on the coordinates of temperatures collected in those areas.

There are other testing parameters that were recorded based simply on setup. These include: fuel type, burner valve position, flame tamer configuration, preheat location, and time stamps. Each of these variables was recorded manually and attached to the data for labeling purposes.

Test Method Development Overview

In order to create an accurate representation of the performance of the grill provided by Bull Outdoor Products various parameters needed to be recorded, the most important being the grid of temperatures across the grill surface. However, in order to validate the recorded temperature data, several other variables were tracked and recorded for reference. A set of instructions for how to use the testing apparatus, including the set up for measuring all additional parameters can be found in Appendix I.

Although barbeques are generally assumed to be safe and reliable pieces of equipment, there are still pressurized and combusting gasses causing high temperatures which create a possibly dangerous environment if the proper precautions are not taken. Therefore a safety sheet was created as an outline for such precautions. For example, the gas lines must be checked for leaks prior to operation, and the barbeque must be used in a well ventilated area. A complete list of warnings and safety precautions can be seen in Appendix H.

After manufacturing of the apparatus was complete, the exact testing method needed to be determined. Originally, Brazing Bull planned to operate the apparatus by preheating the grill with the thermocouple array at location 1 (far left), then advancing it one inch at a time to location 36 (far right) after a steady state condition was recorded by the four fixed location thermocouples. However, after a few tests completed in this manor, it was discovered that the resulting data presented what appeared to be an increasing temperature profile from left to right over a large portion of the grill surface, as if it was still heating up to a steady state condition. However, the fixed position thermocouples showed that steady state condition had already been reached prior to test commencement. The data then pointed to the possibility that either there was a fuel pressure drop off on the low temperature side of the grill, or there might be an issue with the preheating procedure. Since testing for pressure would require an entirely new set up and procedure, Brazing Bull decided to perform an identical test, but move the thermocouple array from right to left instead of left to right. If the results were identical to the previous method, it could be determined that the grill was in fact gradually colder on one side. However, the resulting data from the right to left experiment showed a mirrored distribution from that of the left to right experiment. This meant that the preheating and data taking sequence needed to be modified.

Next, Brazing Bull attempted to run a test procedure with the thermocouple array at position 6.5 during preheat. This would position the array in between two of the fixed position thermocouples so that the temperatures recorded by thermocouples A and P would match the two fixed thermocouples. This would prove that both the fixed thermocouples and array thermocouples had reached steady state before the test commenced. The resulting data from this method improved slightly as a ramping up profile could still be seen. Finally, a sequenced testing procedure was experimented with that would shuffle the outermost ten testing locations on each side of the grill. This method allowed the array to travel in and out of known hotter regions of the grill to maintain the array at a constant internal temperature. This method, combined with preheating the grills with the apparatus at position 6.5 led to the best results, and was used for all remaining official tests.

Progression of Testing Method

The initial test plan is outlined in the first draft of the DVPR provided in Appendix K. This included testing at high and low valve settings, between and above grill grates, and ramp up tests to measure preheat. After the first test run, it became apparent that this plan was not adequate, and the testing method evolved over the first five test runs using the natural gas grill. Once the test method was established, Brazing Bull conducted a battery of tests under identical conditions for both the natural gas and propane grill setups. Both the development of the test method, and the results from each test will be described within this section of the report.

Test Run-1_Natural Gas

This test was performed with the valves for all five burners set to the high setting which resulted in temperatures as high as 912˚F and caused damage to the test apparatus outlined within the Maintenance and Repair Considerations section of this report. This was the only test performed at high valve setting, and moving forward Brazing Bull recommends that the grill not be used for prolonged periods of time with all valves set to high. Another problem discovered in this test was that the grill was not adequately pre-heated as seen in Figure 8 below. This can be determined by the ramp up section of the test data for the first 800 to 1000 temperature readings. Please also note that in this test, the grill was preheated with the thermocouple array resting at location 1 (far left side of grill) and was advanced one location at a time across the 36 locations from left to right.

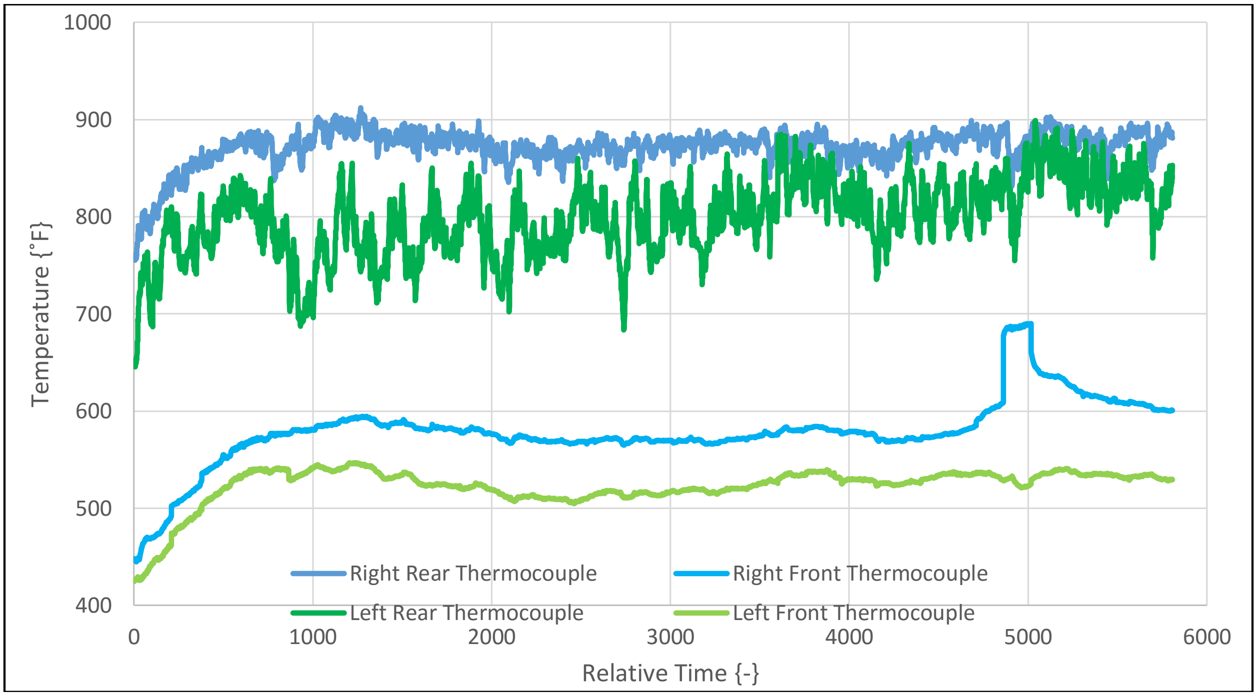


Figure 8: Steady state temperature plot using temperature data from fixed thermocouples for Test Run-1.

In addition to observing the steady state operation of the grill for Test Run-1, we used a program called JMP pro 12 to plot the temperature distributions at each location in 3 dimensions (3D Scatterplot), where two dimensions represent the physical locations of each point, and the third dimension is temperature. This plot can be seen below, and was useful for comparing to the next test conducted in order to validate performing all of the tests at the low valve setting. The 3D Scatterplot from this test run can be seen in Figure 9. It can be seen that the left side of the plot is at significantly lower temperatures than the rest, which directly correlates to the steady state data plotted in Figure 8. It is important to note that the data from Figure 8 and Figure 9 are obtained from different thermocouples, and the fixed thermocouple data in Figure 8 is primarily used to validate steady state operation. Additionally, the data used in Figure 9 was obtained by the 16 thermocouples fixed to the thermocouple array and every column seen in the 3D Scatterplot is representative of the temperature distribution for the corresponding location. The usefulness of this information will be described later in this report, for now the focus is on the fact that the method used did not produce reliable data for the heat study.

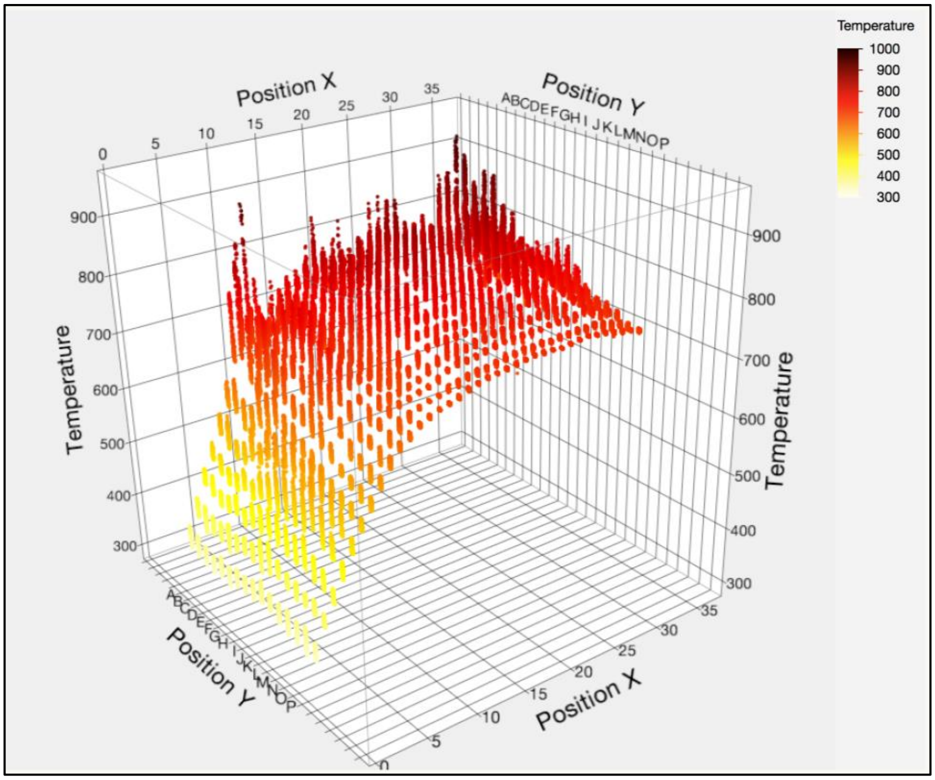


Figure 9: 3D Scatterplot of Test Run-1.

With the analysis done thus far on Test Run-1, it was able to be determined that the grill preheat was not adequate, and that all future tests would be performed with the valve setting at low. For the comparison of the overall temperature profile from high to low valve setting excel was used to calculate average temperatures at each location, and MATLAB to produce a 3D mesh plot of those averages for comparison. These results can be seen in Figure 10 and Figure 11 respectively.

373	420	468	512	555	604	703	747	720	717	729	743	748	762	774	772	767	768	777	777	782	793	800	803	799	795	793	791	790	821	849	836	810	786	757	729
367	412	462	500	545	609	744	762	722	712	728	745	752	776	808	782	779	771	780	776	800	806	814	815	805	801	797	792	787	805	859	881	806	775	742	704
361	408	452	488	529	589	690	713	713	721	732	746	748	769	791	781	782	780	784	787	814	815	807	811	806	802	801	798	798	794	822	854	805	782	757	730
356	407	453	489	531	590	671	686	705	721	732	741	737	761	772	776	785	780	784	795	817	806	798	803	804	801	799	802	803	791	808	840	798	776	752	720
365	411	463	502	558	633	715	698	734	746	749	749	728	762	758	784	819	791	800	824	839	815	795	805	811	811	809	820	825	797	812	867	798	766	734	691
360	409	453	495	552	621	679	686	731	742	742	738	721	742	752	770	808	784	791	816	827	801	793	794	797	798	798	815	823	799	803	832	794	772	753	725
369	420	467	514	579	639	671	696	747	751	741	734	709	729	750	761	801	785	791	827	834	793	787	789	789	791	797	822	825	792	788	821	795	768	750	720
368	420	467	518	577	618	643	680	726	731	725	723	703	718	745	754	779	774	776	806	800	776	776	776	776	778	784	804	800	778	775	792	783	765	757	731
371	428	471	528	584	612	637	678	715	720	713	712	697	706	738	752	771	766	767	790	775	767	767	768	771	772	779	795	788	778	768	783	779	761	761	733
372	436	473	539	586	599	640	690	713	707	701	703	694	702	727	763	754	757	751	762	753	756	759	756	760	760	768	782	773	766	756	774	769	755	762	737
370	426	464	529	575	587	625	670	696	696	699	698	692	696	707	743	737	741	738	742	740	746	746	746	749	751	757	767	759	751	744	763	760	743	746	727
365	418	460	532	577	576	604	640	666	679	691	691	691	691	699	716	728	734	731	733	734	739	743	740	744	747	748	754	750	744	739	754	751	733	730	716
361	414	467	554	574	564	586	615	640	663	677	681	686	689	694	703	714	726	722	721	725	727	731	730	735	736	734	738	736	731	733	748	743	725	723	712
360	410	453	527	548	554	578	606	633	656	673	679	683	688	692	699	709	715	714	717	721	723	727	728	726	727	727	729	730	729	730	738	728	720	718	709
358	409	447	499	534	549	571	596	621	643	660	670	678	683	687	691	696	702	704	706	709	712	714	716	714	717	715	717	718	719	718	719	713	709	706	697
352	399	434	471	507	536	565	594	621	641	652	665	673	679	683	688	696	700	704	706	709	711	714	716	715	715	713	715	717	718	715	714	711	708	704	698

Figure 10: *Grid of average temperatures with color mapping for visual representation of Test Run-1.*

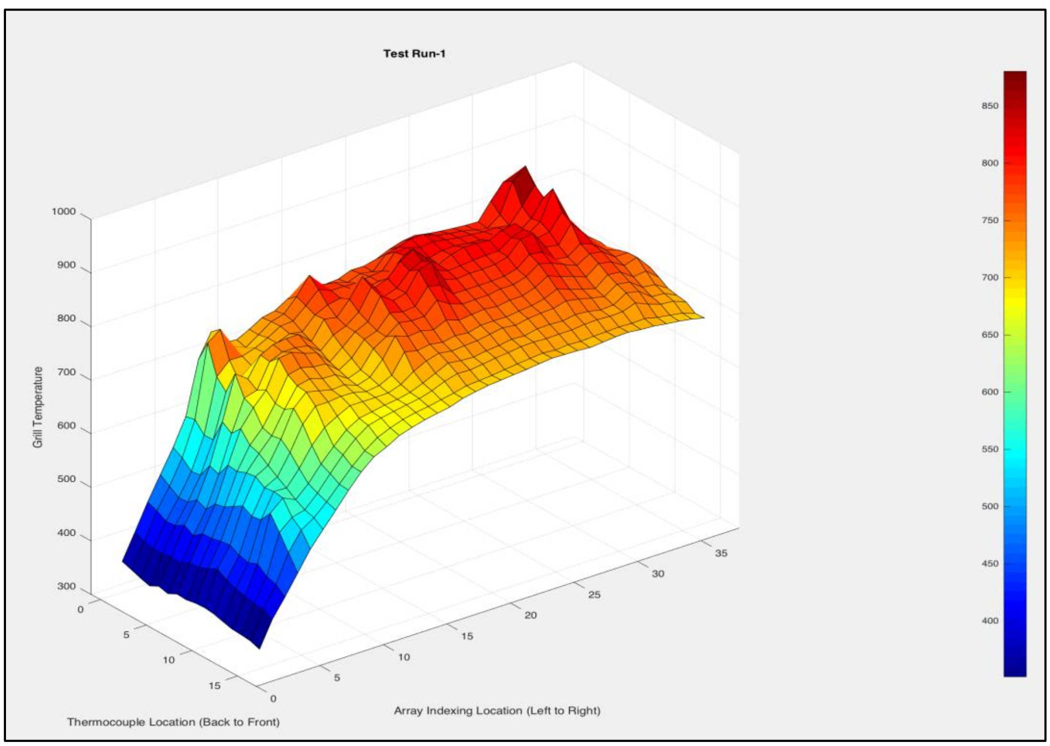


Figure 11: 3D mesh plot of average temperature grid produced using MATLAB for Test Run-1.

Test Run-2_Natural Gas

In Test Run-2, all test parameters, configurations, and methods used were identical to Test Run-1, except the valves for all five burners were set to the low position. The following figures were produced using the same methods used to produce the corresponding figures from Test Run-1. It can be seen, in Figure 12, that the pre-heat was adequate, and a steady state was reached for the test. However, in Figure 13 it can be seen that there is a significantly lower trend in temperatures again at the left most side of the grill on the 3D Scatterplot. After conducting this test, it was suspected there was a pressure drop within the manifold resulting in a smaller gas flow at the left side of the manifold. Brazing Bull came to this conclusion because of the trend in the data and also knowing that the manifold was supplied from the right hand side. Despite the fact that the pre-heat was not adequate for Test Run-1, it was determined that the average temperatures plotted in the 3D mesh plot of Figure 15 resembled the profile of the same plot from Test Run-1 closely enough that conducting future tests at the low valve setting was justified. The overall shape of the plot is very similar, differing primarily in magnitude as expected. Due to the continuing trend in lower temperatures at the left side of the grill, it was decided to investigate this in Test Run-3 to determine if it was attributed to a potential manifold pressure issue or if it was attributed to a flaw in the testing method being used.

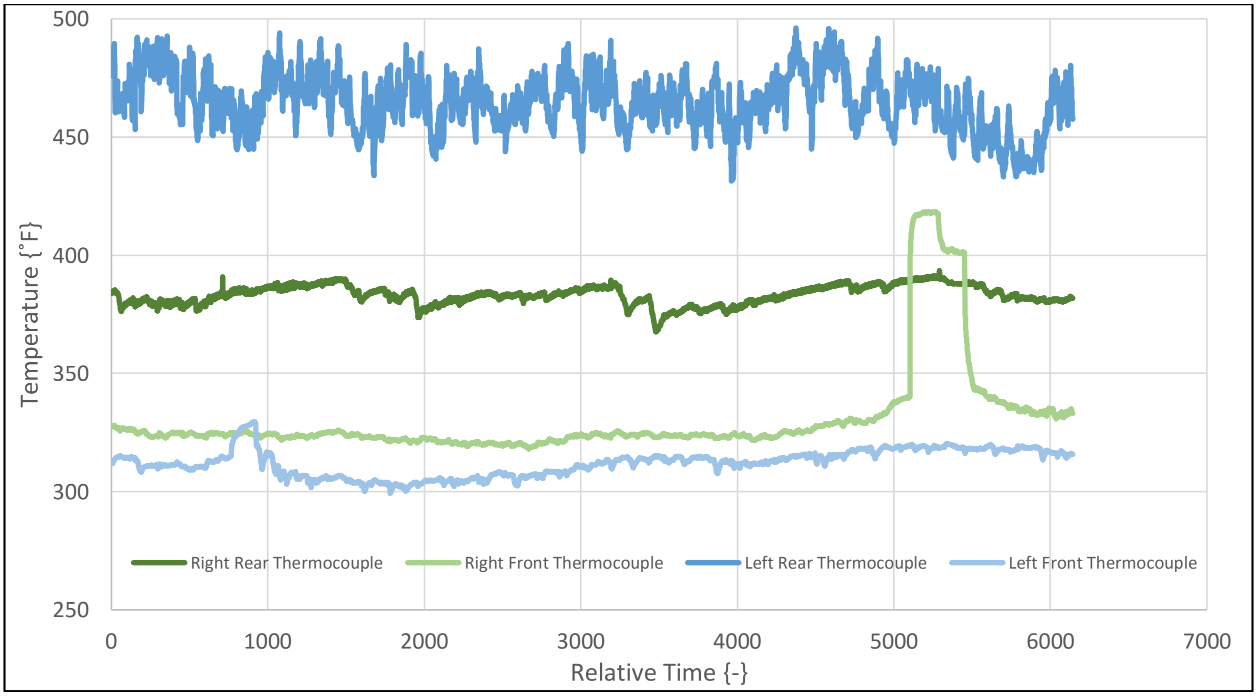


Figure 12: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-2.*

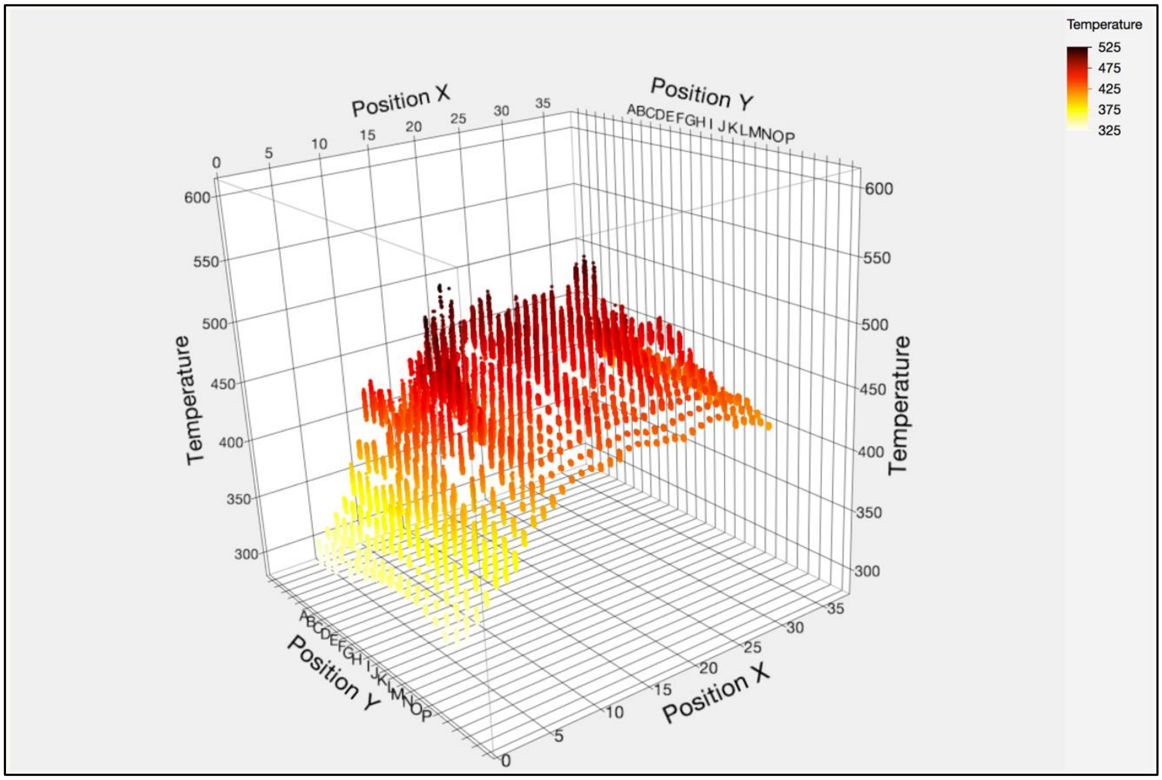


Figure 13: *3D Scatterplot of Test Run-2.*

325	343	347	360	377	403	437	436	424	416	428	459	460	459	454	448	457	475	482	459	458	460	465	463	466	475	464	453	447	471	497	467	443	424	414	405
325	343	347	360	373	403	442	440	425	420	429	460	469	465	455	444	455	478	483	457	456	466	474	470	466	478	465	455	450	470	498	466	442	426	417	408
328	343	349	361	372	407	442	443	430	429	441	466	487	478	472	445	456	479	491	461	458	470	484	476	464	482	469	458	454	466	488	470	448	430	420	411
338	347	353	363	374	401	422	429	430	437	446	457	479	462	460	449	456	471	481	465	460	465	472	470	461	474	469	461	457	460	467	464	452	438	429	420
330	339	348	362	379	420	434	434	442	458	458	458	472	444	439	444	454	477	486	464	456	456	464	469	456	477	474	461	452	453	459	464	450	428	420	411
339	343	354	367	384	414	424	429	451	463	453	450	444	441	443	450	454	472	478	469	460	453	455	463	457	473	474	467	456	453	455	461	454	437	430	421
339	339	355	373	395	418	427	437	472	475	454	446	430	426	433	446	455	475	476	468	459	445	440	456	453	474	477	470	460	448	450	462	462	428	420	415
345	343	359	377	395	410	422	439	477	472	449	441	431	428	433	448	455	473	470	466	454	444	443	451	453	469	473	467	463	450	449	463	466	432	424	419
347	345	359	375	392	405	416	440	472	464	444	437	430	429	435	447	453	469	461	458	449	442	440	445	449	464	467	460	455	448	447	462	464	432	427	420
348	344	356	370	391	403	413	447	464	458	440	436	428	429	435	442	450	464	453	450	446	441	439	441	445	460	461	454	447	445	445	461	460	429	425	420
349	347	356	367	388	402	405	428	438	446	438	434	426	429	433	437	446	457	444	443	443	440	434	437	441	456	454	447	442	441	441	455	446	421	419	418
348	348	354	365	382	399	394	405	415	430	434	432	426	429	432	436	440	451	440	440	441	439	436	436	439	450	446	442	439	439	440	447	436	420	415	415
348	350	354	367	388	393	384	390	403	422	435	433	427	429	431	434	439	450	441	438	439	438	436	435	441	451	443	440	438	438	441	446	436	422	419	415
346	347	349	357	371	376	375	383	397	411	428	428	425	428	430	432	435	444	438	437	438	437	435	434	438	439	436	437	437	437	439	438	430	425	423	417
342	340	343	349	358	366	369	379	392	403	414	418	420	423	424	426	426	430	430	431	432	430	427	428	426	429	430	431	432	432	432	427	422	419	417	411
335	333	339	342	351	362	366	374	387	396	402	407	413	418	420	421	419	421	424	427	427	425	423	423	422	419	422	425	427	427	424	415	417	414	410	404

Figure 14: *Grid of average temperatures with color mapping for visual representation of Test Run-2.*

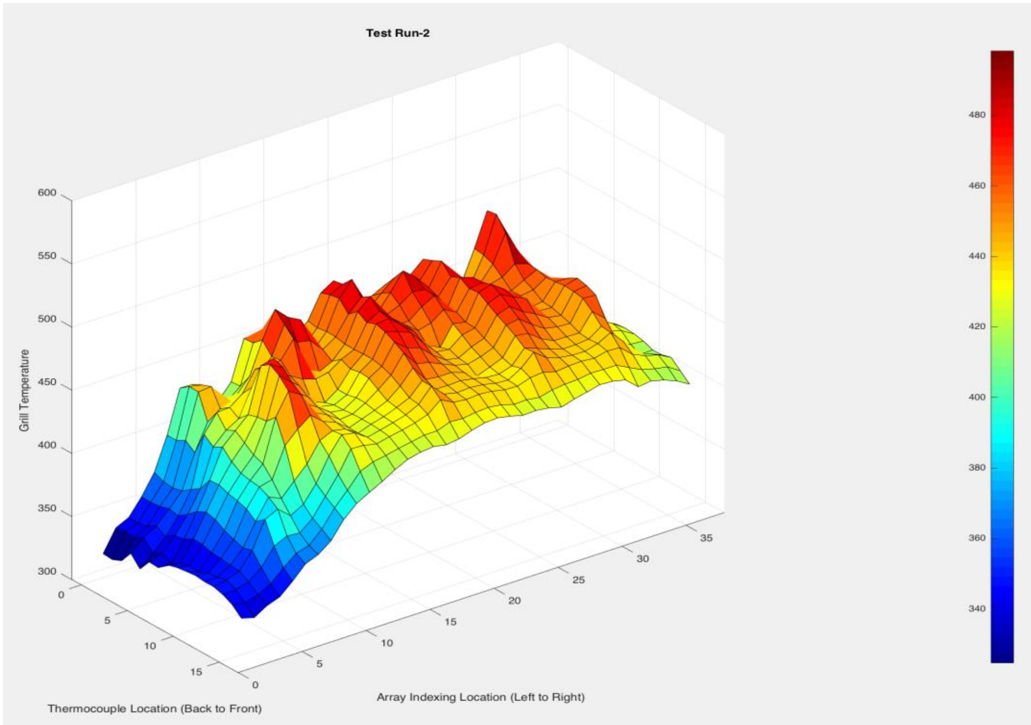


Figure 15: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-2.*

Test Run-3_Natural Gas

In order to investigate the trend in lower temperatures at the left side of the grill, Test Run-3 was performed using the exact same parameters and configurations of Test Run-2, except that the order which we advanced the thermocouple array was reversed. Instead of preheating with the thermocouple array at location 1 and advancing left to right until reaching location 36, the preheat was performed with the thermocouple array at location 36 and advanced the thermocouple array from right to left until reaching location 1. This test eliminated the suspicion of a pressure gradient within the manifold, because as seen in Figure 17, the trend in lower temperatures was now occurring at the right hand side of the grill. This test was very useful in proving that the issue was in fact with the method being used to measure the grid of temperatures. Again, with this test run, the steady state temperature condition was reached as seen by the fixed thermocouple data plot of provided in Figure 16. In the interest of giving a complete look at each test leading to the final method used for all subsequent tests, Figure 18 and Figure 19 are representative of average temperature values over the 16 inch by 36 inch area of the grill for which temperature data was obtained. However, this data remains somewhat irrelevant until Test Run-5 at which point the final test method was established.

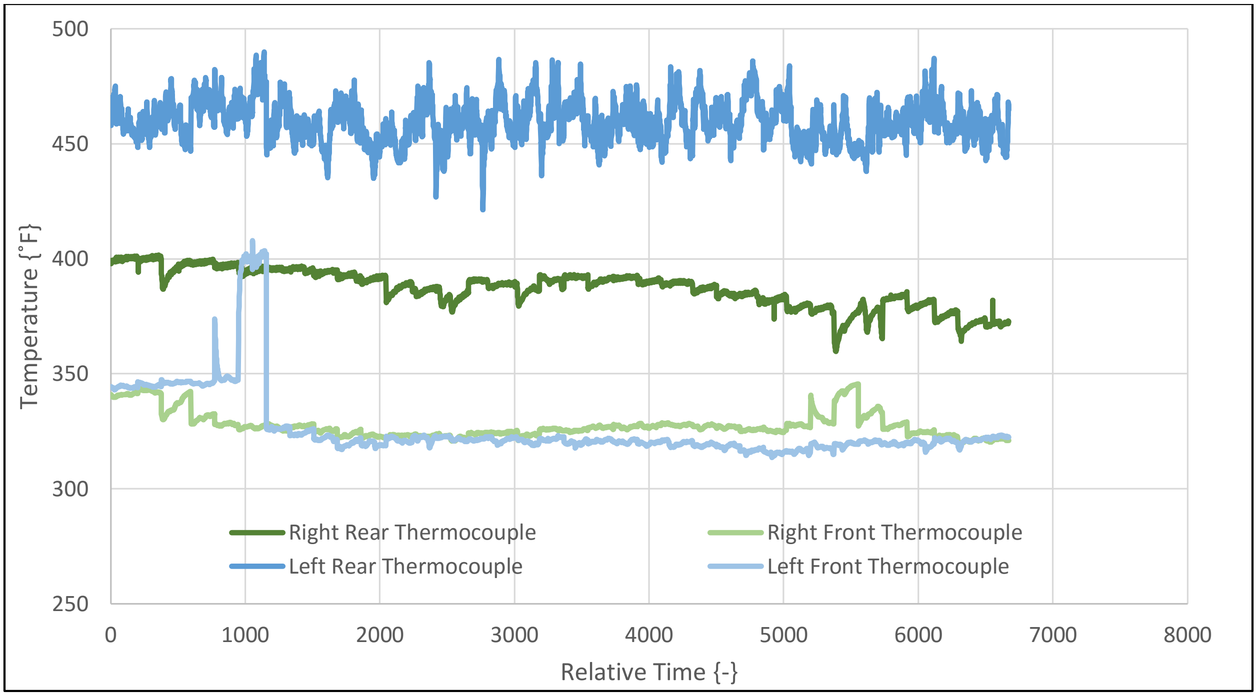


Figure 16: Steady state temperature plot using temperature data from fixed thermocouples for Test Run-3.

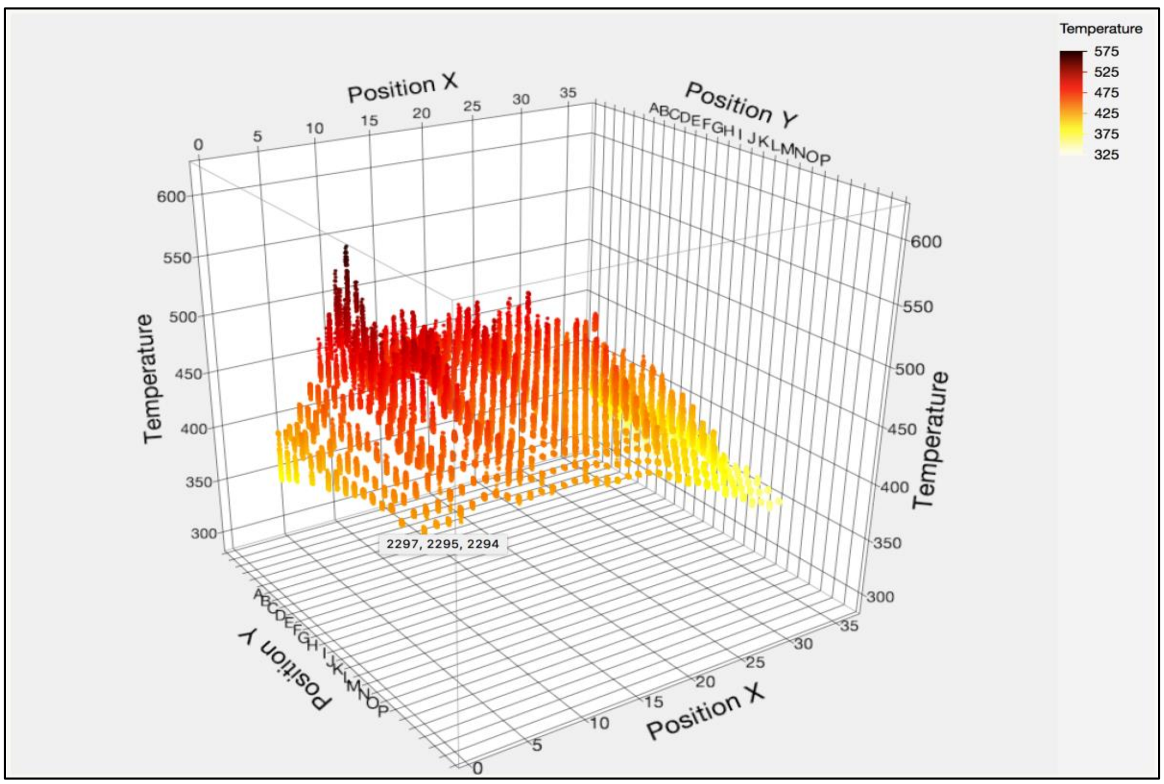


Figure 17: *3D Scatterplot of Test Run-3.*

403	422	438	454	470	496	495	463	461	471	471	467	472	471	470	468	475	478	472	454	453	458	459	456	456	453	430	422	436	453	428	395	380	366	351	332
408	427	440	454	474	518	527	474	463	471	474	475	477	471	468	468	477	478	466	446	450	456	463	458	456	456	427	420	432	455	430	397	377	364	350	333
409	423	440	455	476	513	513	473	467	475	481	496	486	478	469	473	485	484	469	451	452	452	467	459	458	464	432	424	431	468	431	403	380	368	355	340
426	437	451	465	483	503	489	473	472	477	482	493	478	474	469	473	477	474	462	453	451	448	457	453	452	454	435	425	423	426	417	400	380	370	360	351
410	422	436	459	490	517	484	475	479	488	489	493	469	469	470	476	483	480	462	447	444	436	451	451	457	470	451	429	421	429	429	419	384	367	355	341
425	434	445	468	495	503	480	487	486	491	478	472	462	465	473	477	477	473	454	449	445	439	443	447	451	463	451	433	420	419	420	417	388	373	364	355
415	425	442	473	495	488	477	507	498	498	467	459	453	457	470	473	479	474	452	443	437	428	431	442	450	468	453	437	421	427	423	429	396	373	361	354
422	432	449	474	482	472	479	510	501	492	463	456	450	452	465	470	474	466	447	442	433	425	427	435	446	460	442	433	421	416	420	425	398	375	366	361
423	435	450	470	466	464	478	505	496	481	457	452	448	448	460	465	467	458	442	436	430	422	425	432	442	452	430	424	418	412	415	420	396	376	369	364
425	435	448	464	458	458	482	498	491	473	452	449	445	445	455	459	460	451	438	432	430	423	425	429	440	446	422	418	414	409	414	420	392	376	370	364
428	433	443	458	453	449	470	479	478	466	447	445	443	442	448	449	452	445	435	429	428	425	424	427	437	437	415	412	408	407	411	416	386	374	368	364
428	432	439	453	454	450	456	461	464	461	445	443	443	442	445	445	446	440	433	429	428	426	426	426	433	425	409	406	402	400	406	406	379	370	365	362
429	433	443	455	454	452	453	452	456	462	447	442	442	442	443	442	444	437	432	430	428	427	425	425	430	421	406	403	400	396	405	403	378	369	365	363
432	437	440	446	449	448	451	449	450	457	449	440	440	440	440	440	439	434	430	428	426	425	424	421	420	409	404	400	396	390	394	387	370	366	362	360
427	431	430	432	438	440	444	443	441	442	437	433	434	434	434	433	430	429	425	423	421	421	419	415	412	405	400	396	391	384	383	375	367	363	359	358
418	423	426	425	430	433	437	436	432	426	427	428	428	428	428	427	423	421	418	419	418	417	414	409	404	399	395	391	385	379	376	368	360	358	353	353

Figure 18: *Grid of average temperatures with color mapping for visual representation of Test Run-3.*

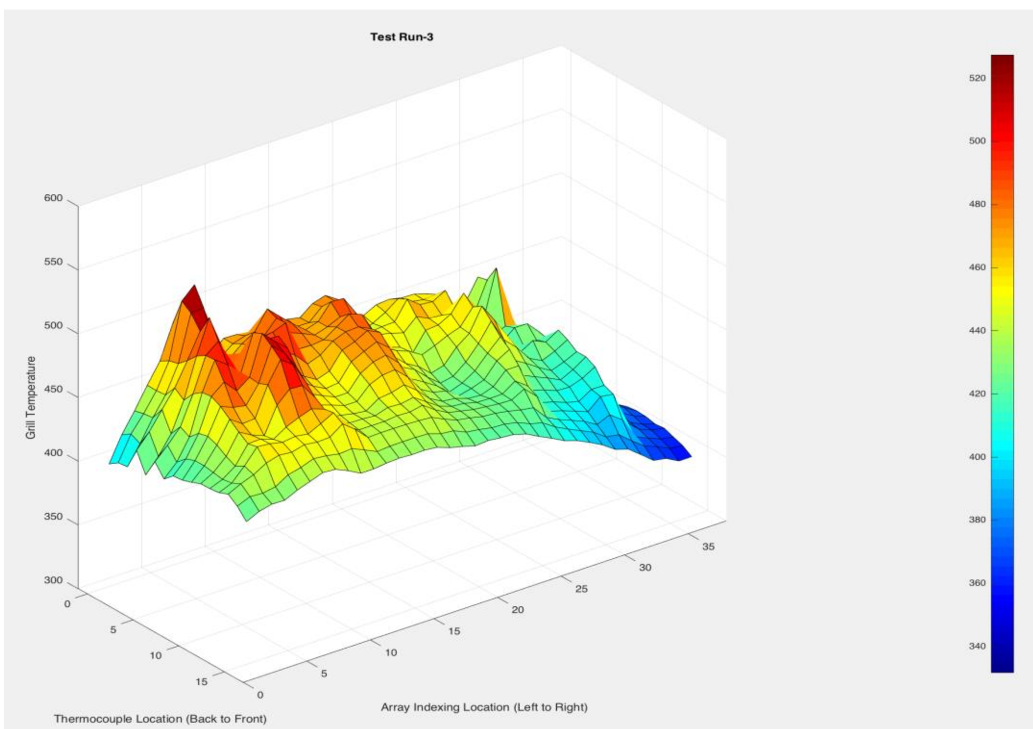


Figure 19: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-3.*

Test Run-4_Natural Gas

At this point in the development of the testing method, it had been determined that the low temperatures at the starting location of the test runs were not attributed to some pressure gradient within the manifold. Although it was not definitively proven given the tools and available time for the scope of this project, Brazing Bull suspects that this is due to a bias from the large aluminum and stainless steel bar of which the 16 array thermocouples are attached. The suspicion is that this bias comes from stored heat being transferred via radiation to the thermocouples of which the welded ends are only .200 inches away. For all intents and purposes, Brazing Bull feels that this bias does not have a significant negative effect on the overall measure of temperature uniformity across the grill surface. With Test Run-4, Brazing Bull attempted to embrace this bias and find a way to give the temperature data obtained from all locations the same bias. After all, it is the goal to compare the temperature from each location to that of all other locations, and if the magnitude of temperatures has an equal bias across the entire surface it will suffice for determining the overall uniformity across the surface. With this new goal in mind, it was chosen to conduct the pre-heat with the thermocouple array aligned with the fixed thermocouples on the left hand side, which is associated with array location 6.5 (halfway between location 6 and location 7). Once preheat was completed, Brazing Bull continued by beginning the measurements with the thermocouple array at location one and advancing from left to right in the same manner as previous test runs.

As seen in Figure 20, steady state was successfully reached for Test Run-4. Also it can be seen from the 3D Scatterplot in Figure 21, that performing the pre-heat with the thermocouple array at location 6.5, some of the problem was alleviated associated with the radiating heat from the thermocouple array support bar, however, because for the first few inches the array is over a portion of the grill that is less effected by burners, a slight drop can still be seen before the trend in temperature begins rising again from left to right.

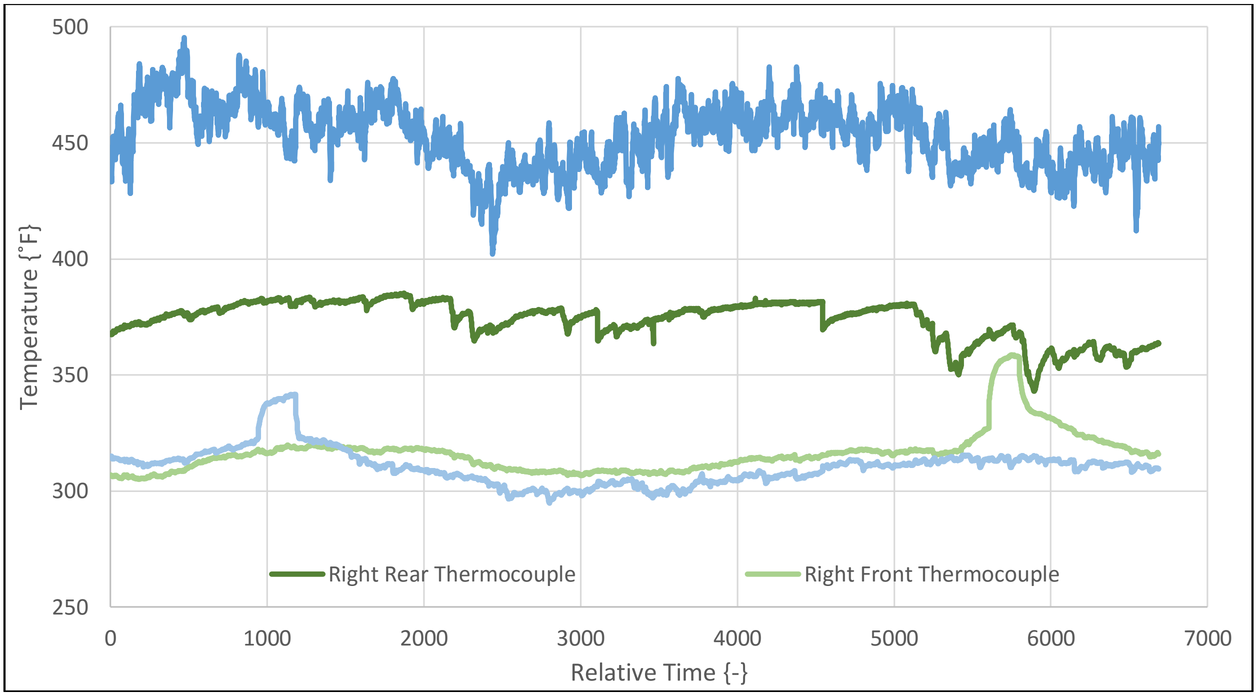


Figure 20: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-4.*

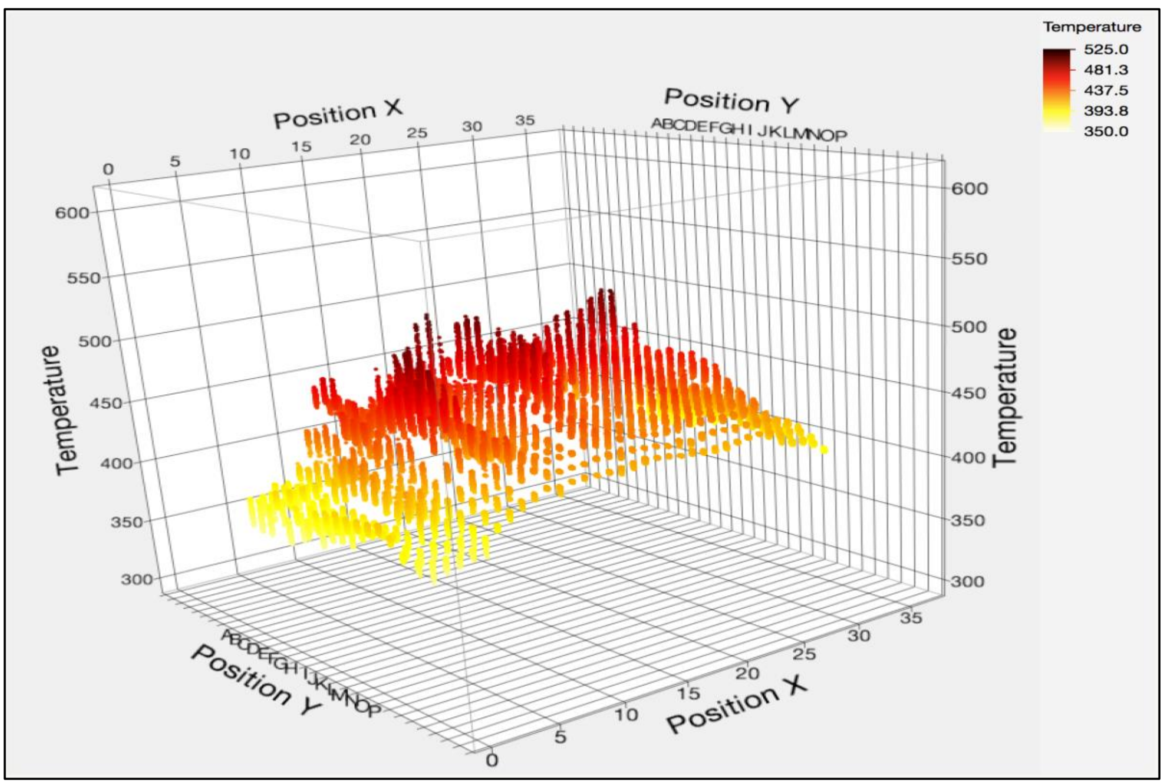


Figure 21: *3D Scatterplot of Test Run-4.*

381	387	394	390	402	427	458	450	442	431	429	447	451	453	452	448	450	462	478	458	453	454	453	453	458	453	450	433	433	470	483	450	428	410	396	391
379	388	394	388	403	428	465	453	442	435	434	448	456	459	454	443	446	464	481	457	451	457	455	456	463	455	451	438	438	474	486	450	427	414	398	393
379	385	393	388	406	432	464	452	443	441	445	457	464	468	472	442	448	465	484	459	452	460	455	460	470	461	455	445	442	469	484	453	433	416	401	396
398	397	400	398	409	429	443	443	445	448	453	456	456	452	458	446	450	460	471	461	455	456	454	457	465	461	456	449	446	453	462	451	437	426	414	407
375	377	387	391	412	448	446	444	454	458	466	457	446	441	439	439	450	468	478	462	450	450	451	461	474	468	460	447	442	448	458	453	432	414	403	395
391	387	394	404	418	445	436	446	453	466	462	447	438	442	442	442	452	466	470	462	451	446	448	456	464	464	461	453	447	446	449	453	438	425	418	408
385	378	388	413	426	446	436	455	459	479	460	442	427	432	434	432	455	472	471	462	445	438	426	449	457	460	463	456	447	442	444	456	443	416	411	402
394	385	394	419	425	434	434	464	463	478	454	439	428	430	434	433	457	472	462	457	444	438	437	444	449	453	461	457	449	445	443	456	447	421	415	406
398	388	396	418	418	422	431	463	464	467	443	431	425	425	432	441	453	466	450	447	440	435	435	438	442	448	457	452	447	443	440	453	446	421	414	406
401	388	395	413	412	414	430	465	479	468	445	432	428	426	431	440	449	459	442	440	436	432	434	435	436	444	453	448	442	440	437	449	443	420	413	406
401	392	395	407	408	409	422	446	464	462	445	434	428	428	431	434	444	450	435	435	434	431	422	432	432	440	446	441	435	435	435	441	434	413	407	404
404	395	396	405	407	404	412	425	434	447	443	435	430	429	431	431	440	442	431	433	433	431	429	430	430	439	439	435	431	433	433	433	425	410	403	401
405	397	396	409	410	402	405	414	419	436	440	433	429	428	429	429	437	439	430	431	431	430	428	429	431	440	435	432	428	430	432	429	422	411	405	401
408	399	393	403	400	396	399	408	414	426	437	432	428	427	427	428	432	434	430	430	430	429	427	428	431	432	429	429	427	428	429	424	418	413	410	404
402	391	385	389	387	387	392	403	409	416	426	426	422	421	422	422	424	425	423	424	423	423	420	422	419	422	423	422	422	422	422	414	410	407	406	398
393	384	381	381	380	383	388	397	404	409	412	416	413	417	417	416	417	416	417	419	419	418	415	417	414	414	414	415	417	417	416	409	404	403	399	391

Figure 22: *Grid of average temperatures with color mapping for visual representation of Test Run-4.*

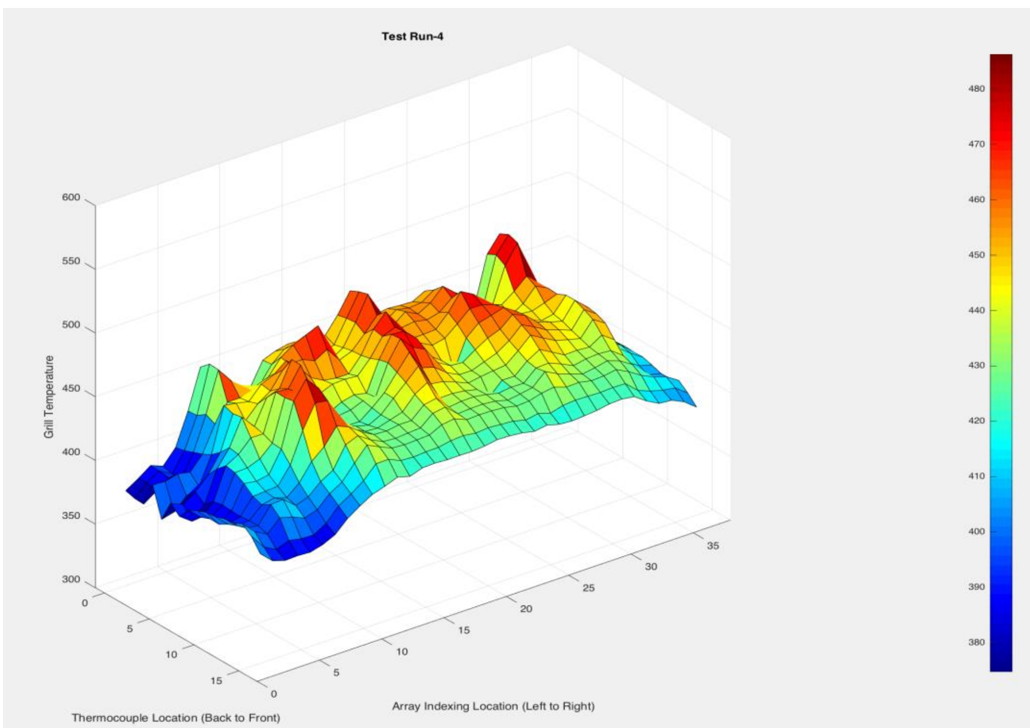


Figure 23: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-4.*

Test Run-5_Natural Gas

In Test Run-5, Brazing Bull finally landed upon a testing method that provided reliable data that reflected temperature profiles one might expect across the surface of a barbeque. This test became the reference for all future tests and the subsequent methods remained the same, however in the tests that followed Brazing Bull began to experiment with various configurations of flame tamers and geometries within the grill heads. For this test (Test Run-5), however, all grill configurations were kept the same as previous tests, and instead modified the order in which temperature data was recorded. Similar to Test Run-4, the pre-heat was performed with the thermocouple array support bar located at location 6.5. Alternatively, instead of recording temperatures beginning at location 1 and traveling left to right to location 36, the data was recorded with a sequencing pattern at the beginning and end the test run as follows: 6, 1, 7, 2, 8, 3, 9, 4, 10, 5, 11-25, 31, 26, 32, 27, 33, 28, 34, 29, 35, 30, 36. Using this sequence, there was not enough time at any end location for the thermocouple support bar to cool off and skew the data in any significant way. This sequence was used for all remaining test runs, on both natural gas and propane grill heads.

Moving forward it is more important to note that what is changing is actually the flame tamer configurations, fuel type, and in one case the type of burner. Test Run-5 was performed using the new style of flame tamers (Flame Tamers with Holes) developed by a previous Cal Poly Mechanical Engineering Senior Project group. The configuration can be seen in Figure 24.

Because the testing method was established with this test run Brazing Bull began using the population standard deviation of the mean temperatures across the entire grilling surface as a measure of overall temperature uniformity, referred to henceforth as uniformity measure. For Test Run-5, the uniformity measure was 22˚F. Data obtained from the 3D Scatterplot is more valuable for targeting problem areas on the grill but the uniformity measure provides a quick and easy way of comparing a magnitude of overall uniformity, where smaller values equate to more even temperatures.

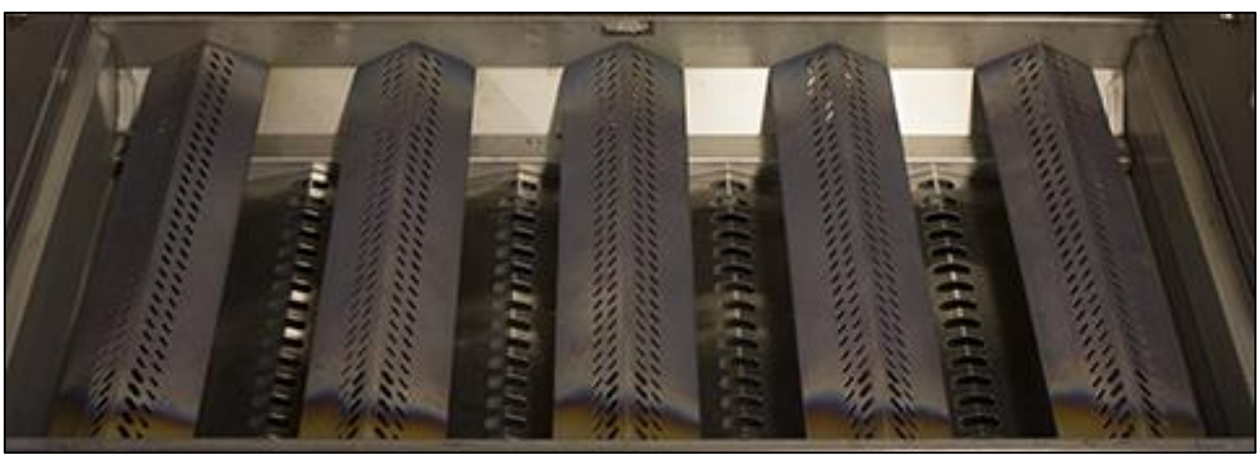


Figure 24: *Flame Tamer Configuration described as 'Flame Tamers w/ Holes'.*

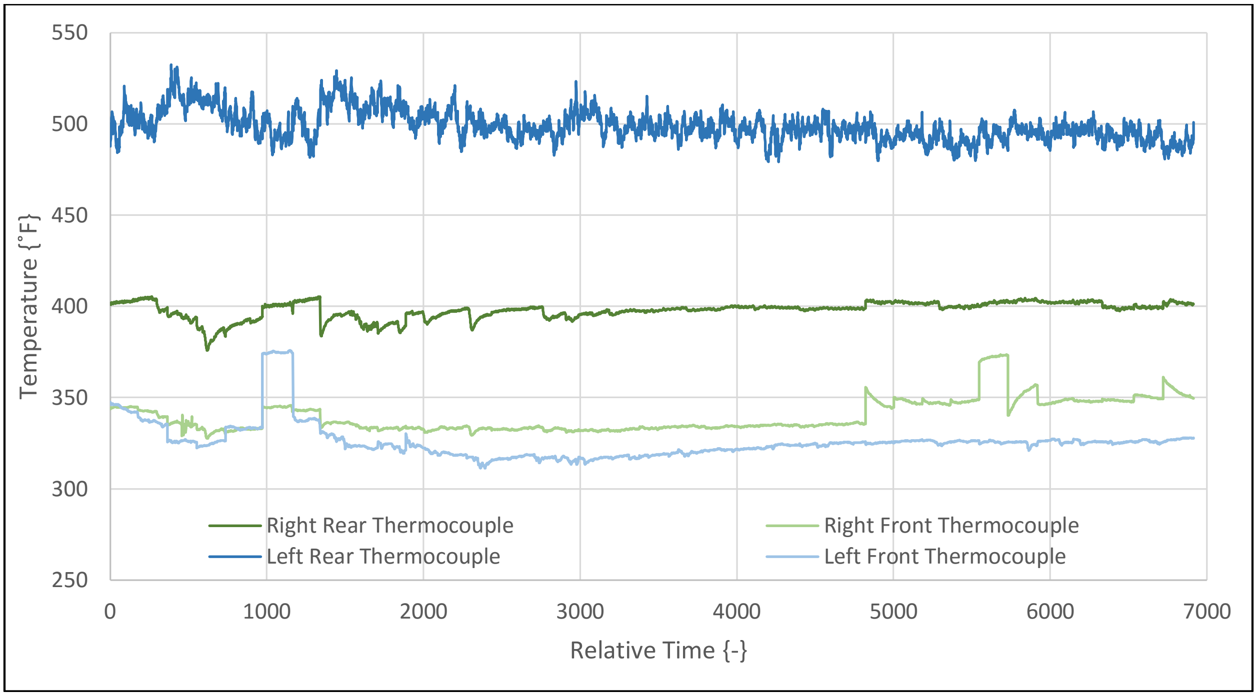


Figure 25: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-5.*

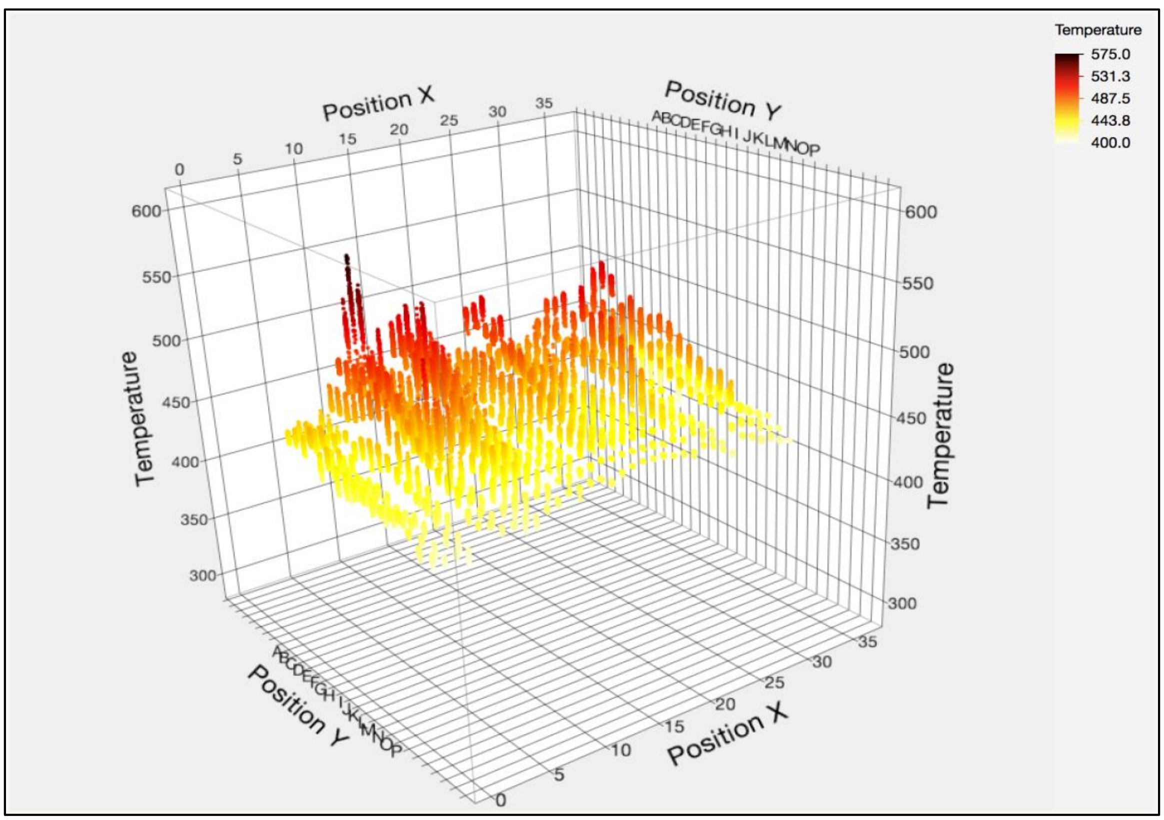


Figure 26: *3D Scatterplot of Test Run-5.*

448	448	446	452	465	491	510	472	461	471	500	487	482	474	470	466	472	505	495	474	468	468	464	468	483	493	467	461	455	485	505	463	452	447	437	428
451	453	446	450	466	488	538	479	460	471	507	489	484	471	469	464	471	510	492	468	463	463	465	467	484	498	464	458	457	494	515	468	457	448	439	427
448	450	445	449	466	490	529	476	460	474	517	497	488	471	462	468	476	519	495	472	466	465	465	466	483	504	467	460	459	492	511	473	459	451	440	425
458	457	451	452	468	494	493	464	460	471	496	484	479	469	468	469	474	496	486	473	468	467	465	464	473	492	471	461	456	469	491	477	463	454	444	437
440	438	434	445	480	504	500	459	463	488	516	487	474	463	464	466	472	507	485	462	461	462	457	458	475	508	477	460	454	467	495	482	458	446	434	416
450	446	441	451	480	500	478	459	462	483	497	479	470	462	463	465	468	491	477	465	462	463	460	457	470	494	484	466	453	455	477	483	464	451	441	432
436	431	427	453	485	497	465	457	466	493	495	472	460	449	454	457	465	487	471	457	453	452	452	452	470	494	488	468	449	447	466	487	464	444	434	423
439	434	431	455	473	485	460	456	466	487	475	464	453	442	451	454	464	478	465	459	451	445	443	451	468	484	478	463	447	446	459	483	465	444	434	426
439	434	433	451	458	472	465	456	464	478	459	455	446	439	451	452	465	471	460	454	446	439	444	449	465	475	465	453	444	443	454	475	461	442	433	426
438	431	429	446	443	462	480	468	465	472	450	448	440	436	448	450	463	465	454	448	437	435	446	450	462	470	454	446	439	439	450	470	457	439	432	426
435	426	425	440	434	454	466	466	460	462	444	442	437	437	444	446	458	458	448	441	433	430	440	446	459	459	447	442	437	427	446	464	450	435	428	422
434	427	425	436	431	447	445	442	449	453	442	440	439	440	443	443	451	452	447	442	438	435	442	443	453	447	441	438	434	430	444	458	444	435	428	423
435	430	426	435	427	445	438	432	443	453	444	440	438	441	442	442	451	450	446	443	442	442	443	445	453	445	441	438	433	429	444	460	446	433	428	424
439	432	423	430	423	439	435	429	435	440	437	437	435	439	440	441	446	446	444	444	443	443	443	442	446	438	441	438	432	427	443	450	438	433	428	424
431	423	413	418	412	430	429	422	426	427	426	429	429	433	434	436	436	439	437	438	438	437	437	435	437	434	437	433	427	421	431	433	431	426	420	418
421	413	409	411	406	427	424	418	417	418	415	422	425	428	429	431	430	425	430	432	434	433	433	430	429	426	431	428	422	417	428	425	420	420	414	411

Figure 27: *Grid of average temperatures with color mapping for visual representation of Test Run-5.*

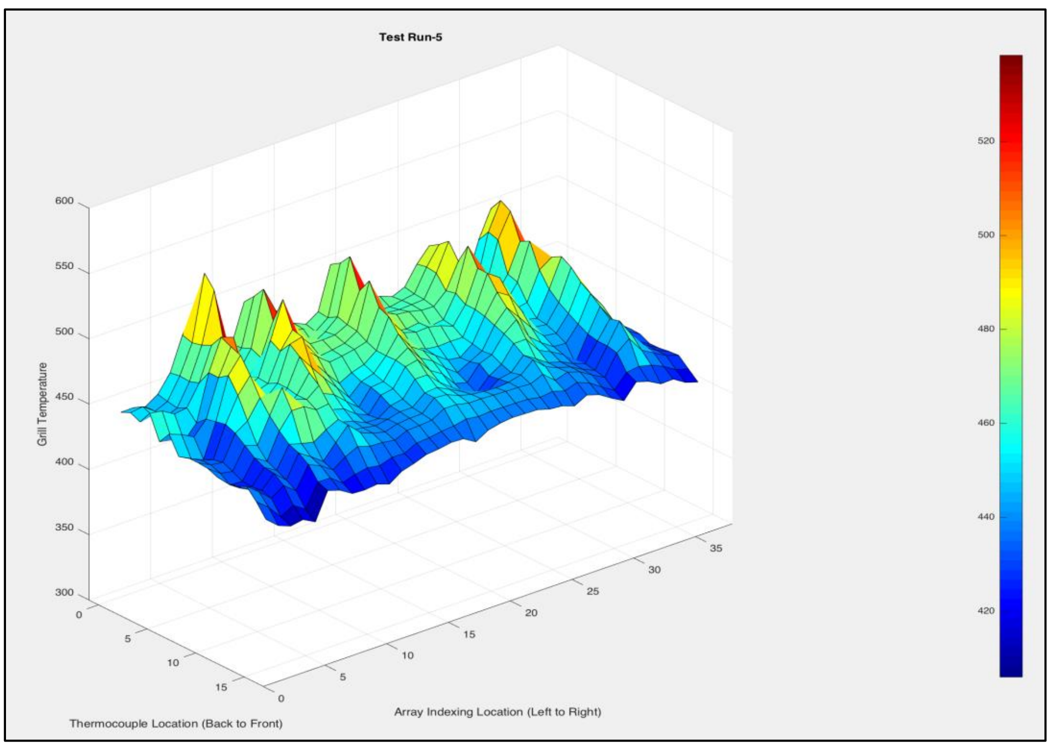


Figure 28: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-5.*

Test Run-6_Natural Gas

For Test Run-6, the modification made was to the flame tamer configuration. On this test run, the old style of flame tamers (Flame Tamers without Holes) were used. All other parameters were held constant and the following figures are the results obtained from the test in the same order as described in the above sub-section for Test Run-5_Natural Gas. Figure 29 shows an image of the configuration using the 'Flame Tamers without Holes'.

The data for this test run actually shows a smaller value for uniformity measure, meaning that the original flame tamers without holes actually perform better than the new configurations. The value of uniformity measure for this configuration is 19˚F, an improvement from Test Run-5 configuration of 3˚F. This does not necessarily mean that adding holes to the flame tamers is a bad way of improving uniformity, but rather that the layout of the holes has potential for optimization.

As stated above, the uniformity measure is good as a quick way of comparing overall uniformity of the grill surface, however it is useful to note the difference in characteristics seen in the 3D Scatterplot shown in Figure 31. Although the majority of the grill appears to be more uniform, more drastic spikes in temperature throughout can be seen. It is also worth noting that these spikes have shifted from the position they were at in the Test Run-5 3D Scatterplot. For Test Run-6 the temperature spikes have shifted from directly over the flame tamers to in between the flame tamers. Remember, the columns in the 3D Scatterplot are a visual representation of temperature distribution at each individual measurement location, and these larger spikes may be attributed to a more turbulent flow as a result of the fluids made up of excess air and combustion products rolling around and over the flame tamers without holes.

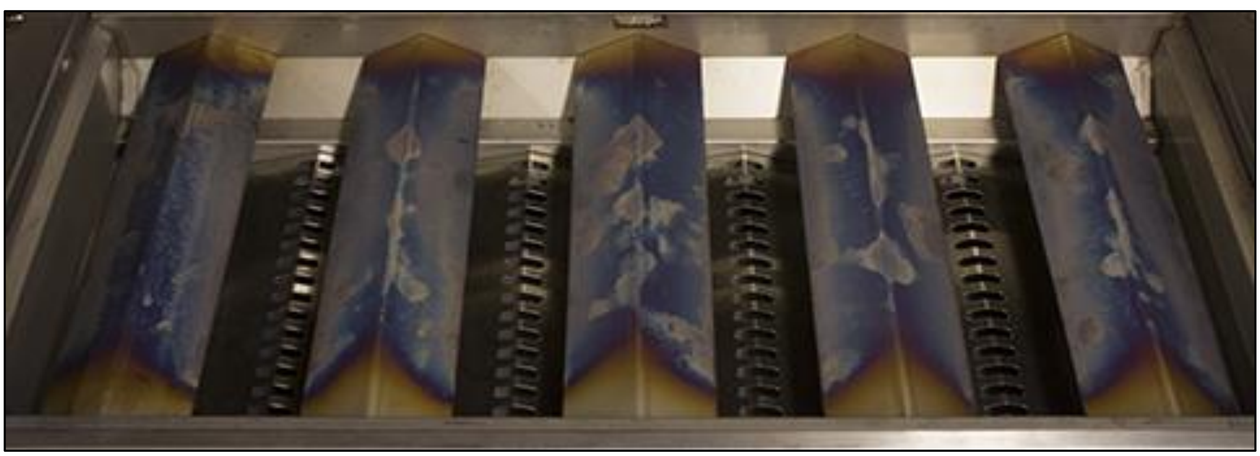


Figure 29: *Flame Tamer Configuration described as 'Flame Tamers w/o Holes'.*

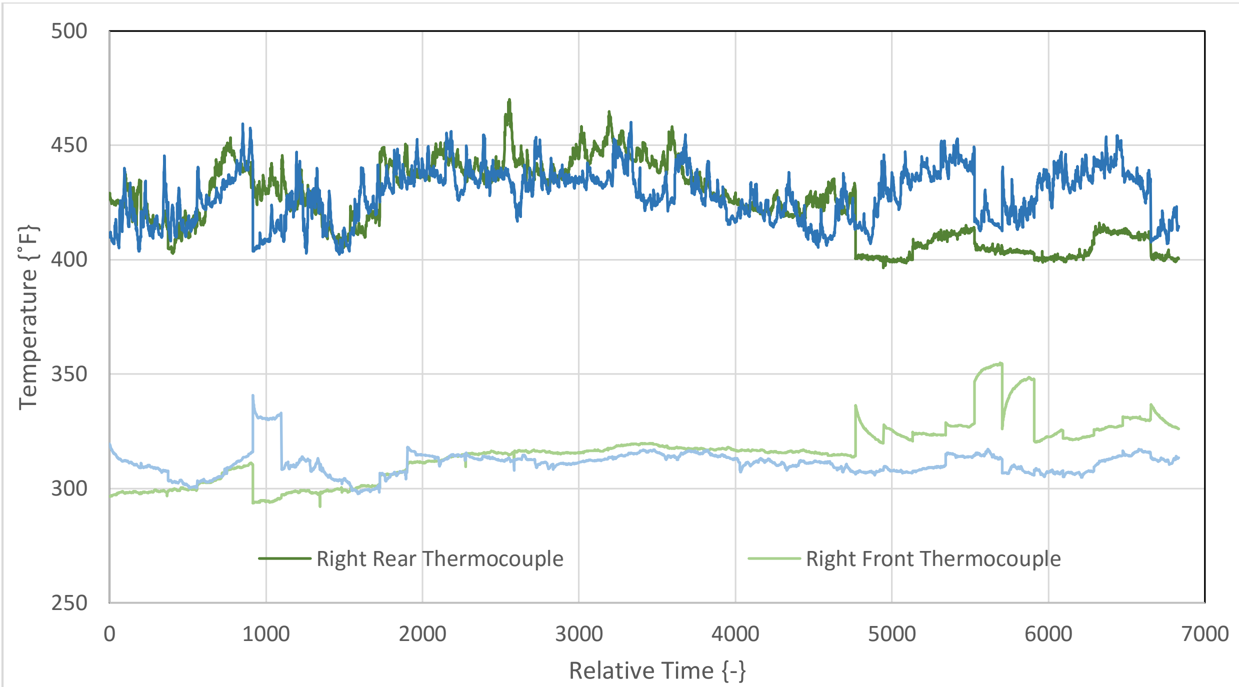


Figure 30: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-6.*

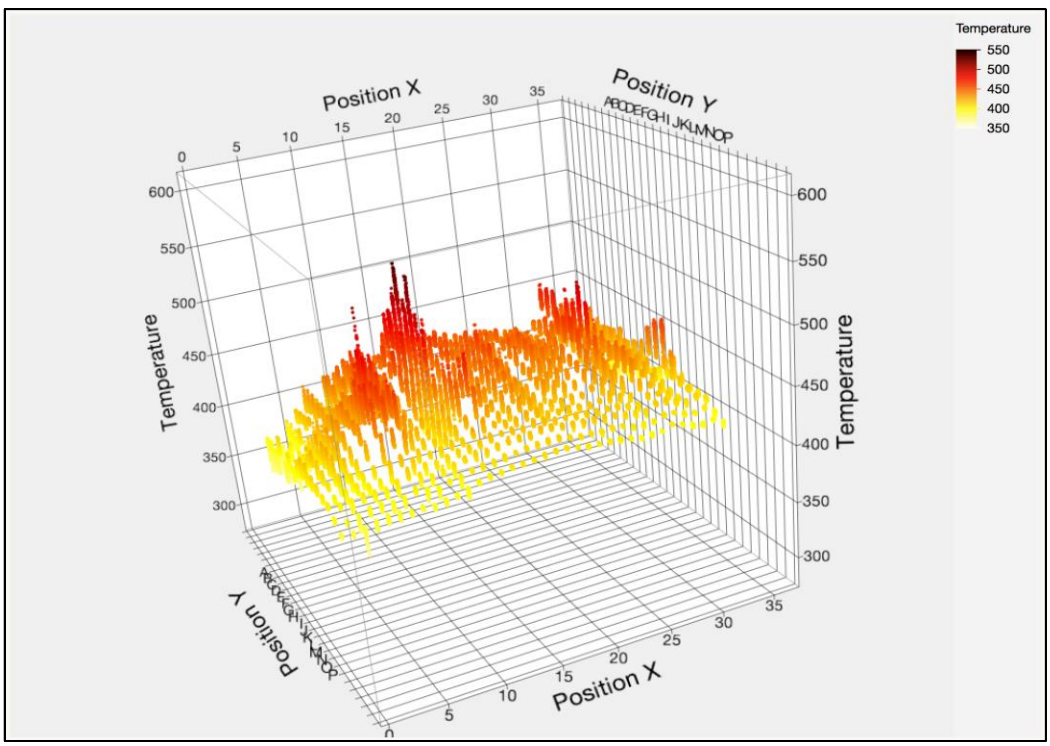


Figure 31: *3D Scatterplot of Test Run-6.*

385	369	397	413	420	416	432	434	439	439	433	446	455	462	452	453	456	456	449	444	446	444	445	440	439	438	433	441	464	429	441	428	422	427	403	391
383	368	398	416	422	414	434	440	440	441	433	447	467	477	458	451	456	452	443	442	445	442	445	438	439	436	432	441	466	431	446	428	425	427	405	393
383	371	397	415	422	416	431	437	444	446	439	454	478	499	464	453	458	453	443	450	450	444	449	445	443	438	435	447	464	436	448	430	427	426	408	395
403	397	409	421	426	423	424	425	437	439	437	447	459	468	448	450	452	448	445	449	448	441	444	445	443	439	436	444	447	430	442	432	430	430	421	407
384	374	393	412	419	423	431	438	453	448	443	458	457	466	432	443	452	446	444	450	443	434	442	451	443	439	438	461	461	432	442	427	423	421	407	393
399	391	405	418	425	430	429	443	444	440	436	446	436	446	431	438	444	442	445	448	441	433	439	447	441	439	438	458	463	429	440	431	426	426	422	407
394	393	403	414	427	434	436	463	449	441	431	438	422	430	424	434	439	437	444	448	437	423	434	441	438	436	439	461	475	426	438	429	423	418	425	401
404	410	413	417	428	436	442	464	447	434	426	428	417	421	433	437	437	434	442	444	435	424	434	435	434	434	438	451	465	427	435	432	424	420	438	405
409	416	415	416	423	433	447	457	446	429	421	422	412	418	442	449	437	431	436	438	431	423	431	430	431	431	437	437	443	425	435	431	424	419	444	410
407	409	412	412	415	428	454	456	453	425	418	417	412	418	437	459	436	427	429	432	426	420	428	424	426	425	432	429	430	424	435	431	421	415	445	413
406	407	408	407	408	419	444	451	450	419	415	414	413	417	425	438	428	422	423	427	424	419	419	418	420	421	425	422	421	420	430	426	416	409	427	411
405	407	405	404	403	408	424	431	426	411	411	412	414	414	418	422	422	420	419	422	421	418	418	417	417	417	418	418	415	413	421	420	413	408	415	408
404	400	402	403	401	402	410	418	412	407	407	409	413	413	414	417	419	418	417	420	419	417	417	416	416	415	415	414	412	410	417	416	412	408	414	407
403	401	399	402	401	401	404	411	405	404	406	407	411	412	412	414	416	417	416	419	418	417	416	415	415	414	414	412	410	409	414	414	411	408	411	406
397	392	390	396	398	395	398	403	399	398	403	403	407	408	408	410	411	413	413	414	414	412	410	410	409	410	409	406	405	405	409	408	404	403	405	399
390	388	385	388	392	392	392	393	392	394	395	397	401	404	405	406	407	408	409	410	410	408	406	406	406	404	403	401	401	401	405	403	399	397	399	393

Figure 32: *Grid of average temperatures with color mapping for visual representation of Test Run-6.*

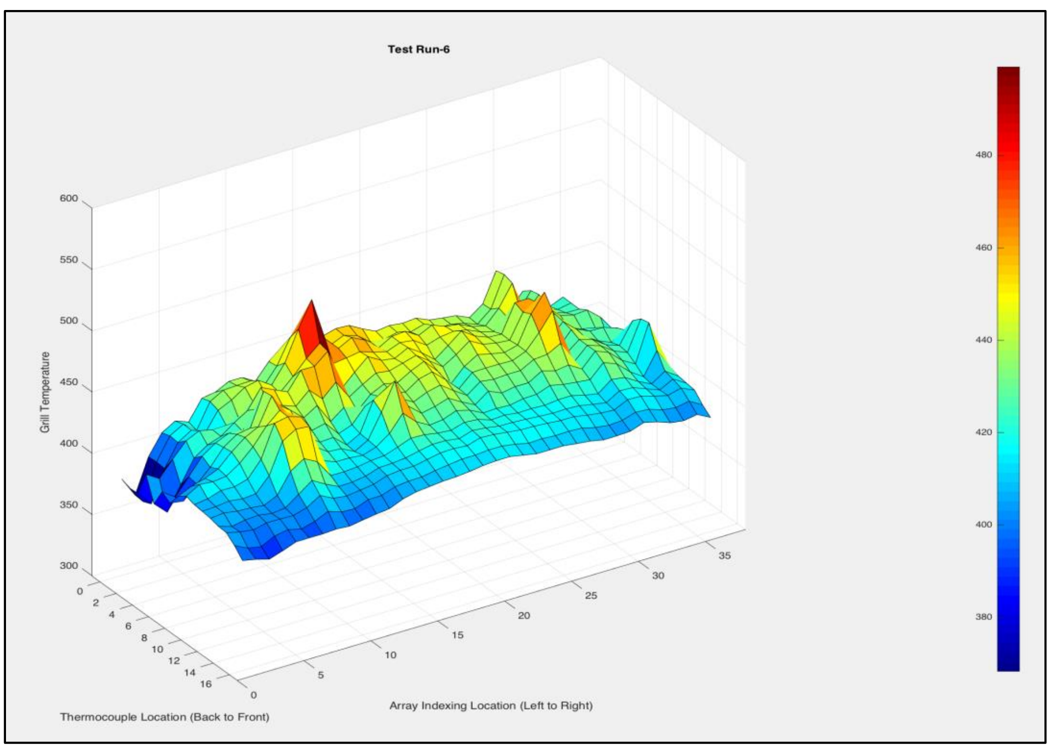


Figure 33: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-6.*

Test Run-7_Natural Gas

For these battery of tests performed on each of the grill heads, Brazing Bull did not want to limit testing to existing configurations of flame tamers. In the case of Test Run-7, Brazing Bull cut 1/3 off of a set of flame tamers without holes and used them to cover the back 1/3 of holes in the new flame tamers with holes. The motivation to target covering the back 1/3 of holes is based upon the consistently higher temperatures in the back portion of the grill. This modified configuration can be seen in Figure 34.

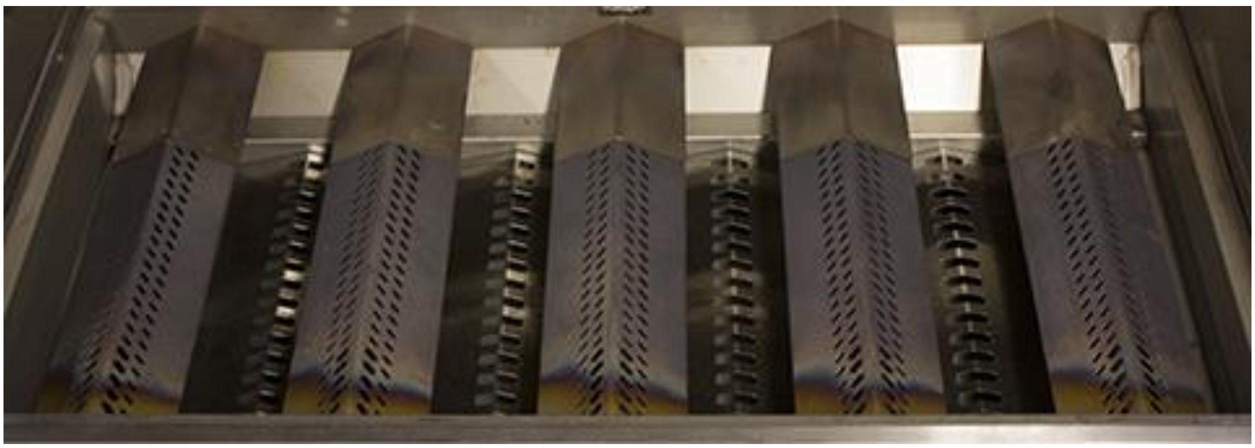


Figure 34: *Flame Tamer Configuration described as 'Rear 1/3 Flame Tamers w/o Holes'.*

This experimental flame tamer configuration resulted in a uniformity measure of 19˚F, equal to that of Test Run-6. Some differences can be seen in the 3D Scatterplot of Figure 36. With a closer look at the spiked temperature columns it can be seen that the spiked columns were decreased over the rear 1/3 of the grill surface. Despite the taming of these spikes, the uniformity measure remains the same, due to larger temperature distributions at the point of transition where the larger temperature spikes occur.

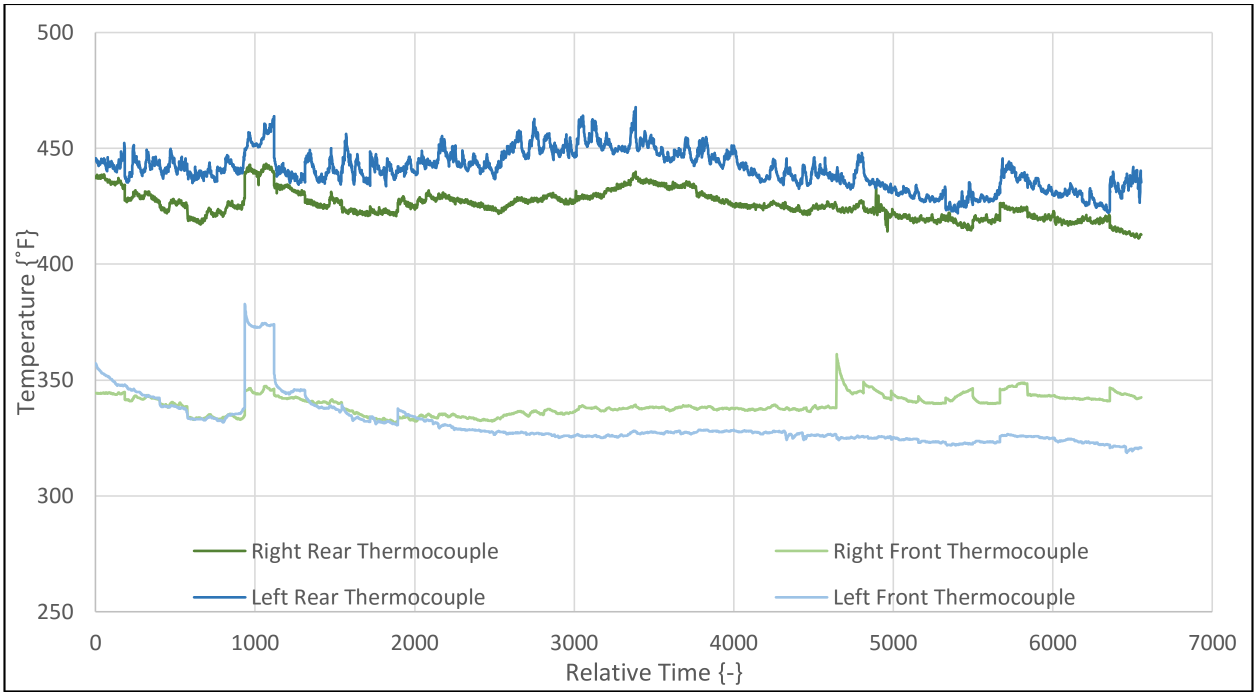


Figure 35: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-7.*

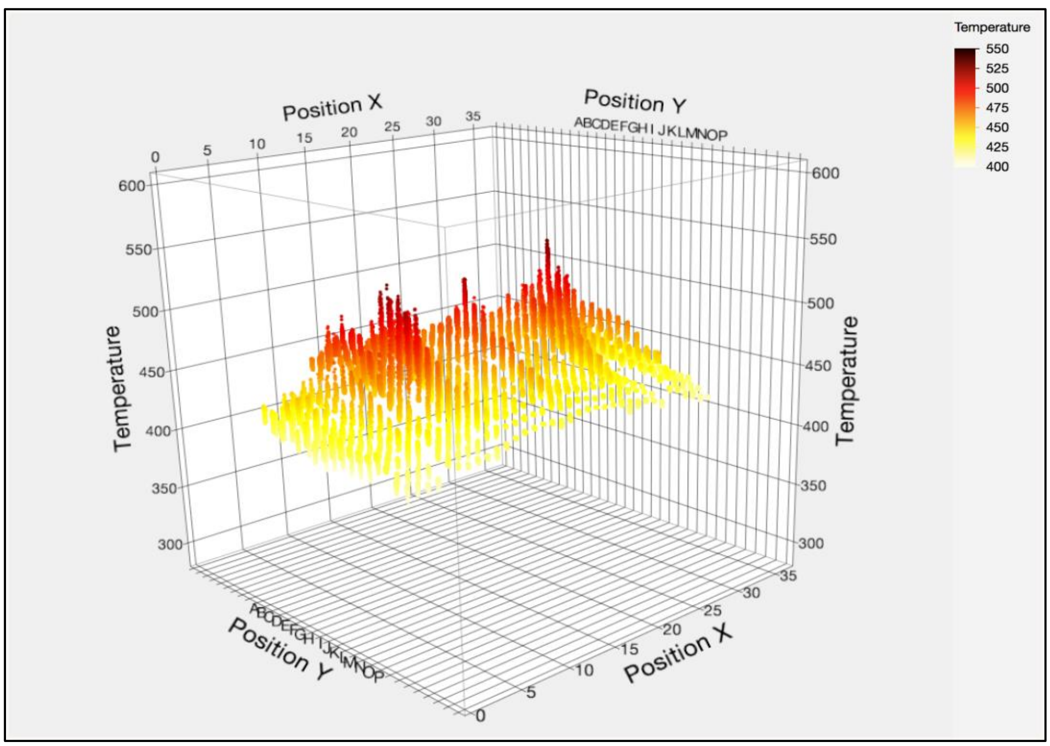


Figure 36: *3D Scatterplot of Test Run-7.*

435	428	437	438	441	466	467	469	452	452	459	470	467	463	462	460	465	467	470	469	465	464	459	454	458	458	458	454	452	472	467	455	448	436	431	416
431	432	437	440	444	465	477	473	454	453	460	472	468	462	461	459	465	467	470	471	464	462	460	455	463	458	456	454	450	477	481	459	451	442	436	420
426	428	436	440	444	475	482	470	456	459	468	480	474	462	462	458	468	475	479	477	470	463	455	459	467	466	459	461	453	483	506	473	455	443	435	418
445	442	445	446	453	484	477	458	460	465	472	476	467	460	461	459	466	476	486	478	469	463	460	459	462	470	467	464	459	460	487	473	458	449	442	430
423	425	433	440	453	495	486	460	475	493	493	482	459	451	458	453	468	486	503	479	464	458	456	455	459	477	482	479	474	450	486	476	459	440	434	420
430	431	437	445	459	493	473	454	473	489	485	473	457	452	459	454	464	479	490	473	463	457	458	456	456	470	479	484	479	446	465	470	461	445	440	429
419	419	429	441	462	493	468	455	476	494	488	468	444	441	450	444	462	477	482	464	455	447	438	451	451	466	479	485	479	442	453	467	467	435	431	421
424	421	433	443	460	480	462	462	480	485	477	459	439	437	444	444	459	473	467	459	451	444	446	449	450	463	473	472	456	439	449	461	467	437	432	423
429	423	433	441	451	466	456	475	484	476	468	453	434	434	439	446	456	472	458	454	447	441	446	447	447	461	466	457	442	436	448	456	465	436	431	423
429	421	431	438	443	454	455	495	490	472	463	448	431	432	435	445	453	473	451	450	442	438	445	445	443	459	460	448	436	432	445	450	461	434	429	423
430	422	429	432	437	447	447	478	471	460	456	445	432	434	434	442	450	469	445	446	441	437	432	442	440	455	453	440	433	428	442	447	454	427	427	425
430	422	428	430	433	441	437	445	444	445	450	444	435	437	437	441	446	460	440	443	441	438	438	439	440	448	446	438	432	426	440	446	446	425	423	422
430	425	427	438	435	440	432	431	433	439	450	442	437	437	439	441	445	457	442	442	441	440	438	439	441	450	442	436	431	426	439	447	445	425	423	420
435	427	425	429	430	438	428	427	428	431	441	438	438	438	439	440	442	452	440	442	442	441	439	438	438	441	437	435	431	426	439	447	435	426	425	421
428	419	417	416	417	427	421	421	423	423	430	431	432	433	434	435	436	440	436	436	436	435	433	433	433	431	431	429	426	422	433	434	425	422	419	415
418	413	413	410	411	423	418	416	418	418	419	422	426	428	429	430	429	426	428	430	431	430	428	428	427	421	423	423	421	417	427	424	417	416	411	409

Figure 37: *Grid of average temperatures with color mapping for visual representation of Test Run-7.*

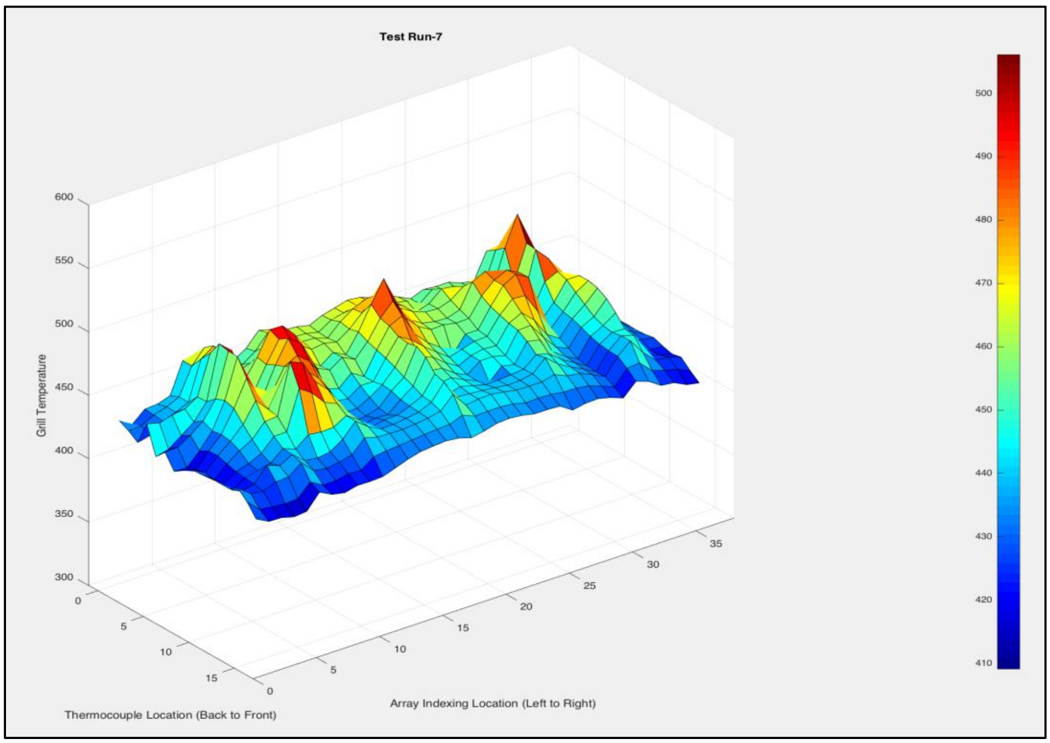


Figure 38: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-7.*

Test Run-8_Natural Gas

The configuration used in Test Run-8 was similar to that of Test Run-7 however rather than covering the back 1/3 of holes on the flame tamers, the back ½ of holes were covered as seen in Figure 39.

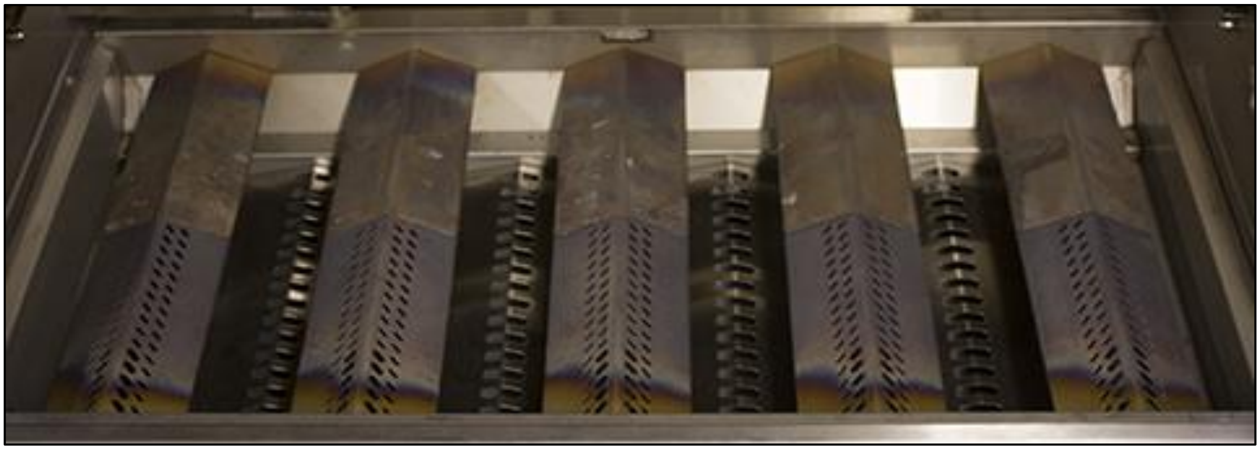


Figure 39: *Flame Tamer Configuration described as 'Rear 1/2 Flame Tamers w/o Holes'.*

Using this configuration resulted in a further shift forward of the spiked temperature areas discussed in Test Run-7 section above. Covering the back ½ of the holes resulted in a 1˚F improvement in the uniformity measure at a value of 18˚F.

As seen in Figure 42, and Figure 43, the average temperature heat map and 3D mesh plot appear to be more uniform, and the largest spike corresponds with the location of the largest spike in the 3D Scatterplot of Figure 41. Once again, this spike has occurred closer to the front side of the grill and corresponds to the point at which the holes in the flame tamers are exposed.

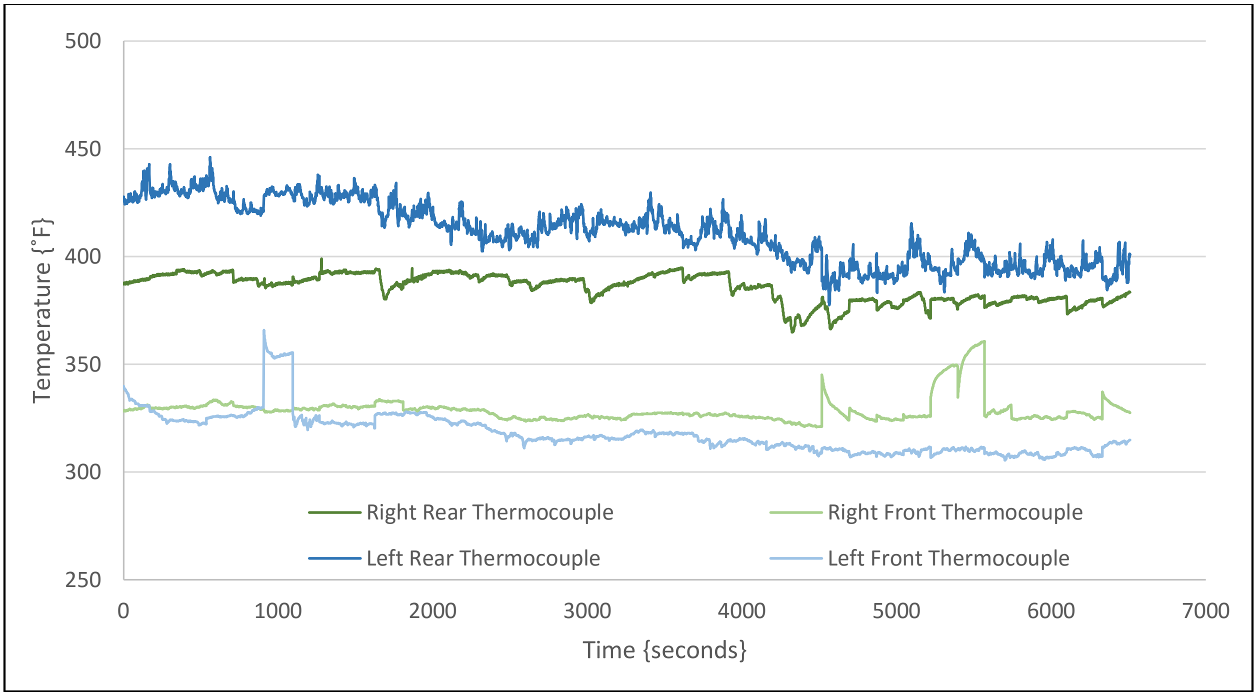


Figure 40: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-8.*

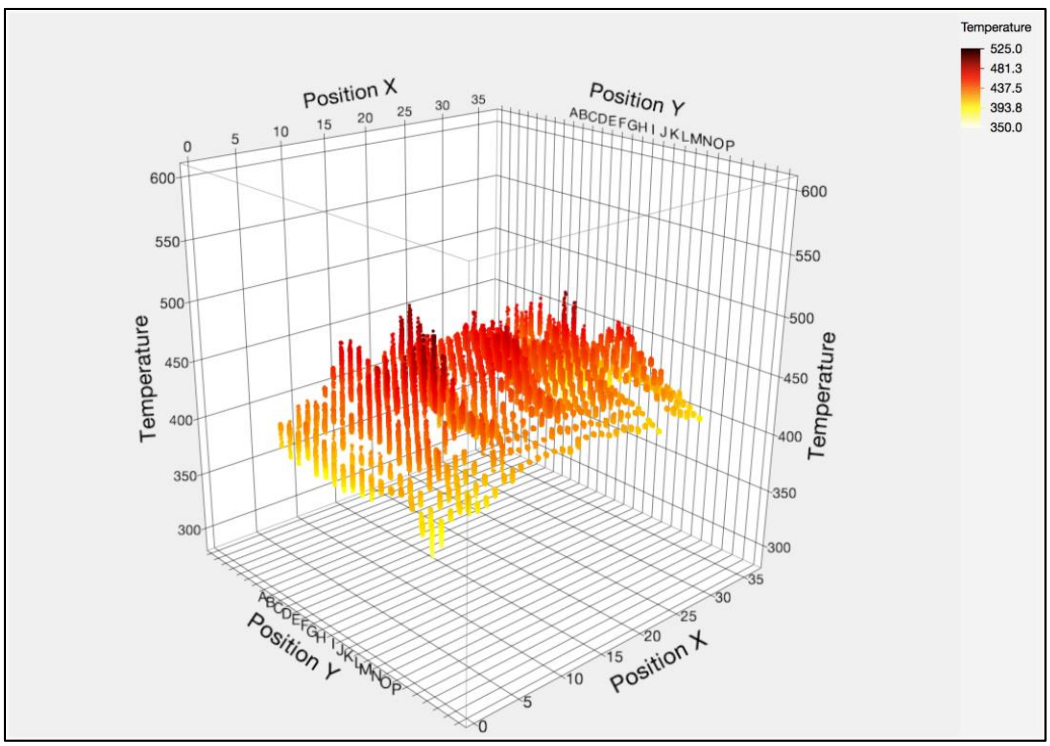


Figure 41: *3D Scatterplot of Test Run-8.*

419	413	422	424	425	439	450	464	454	426	431	443	450	454	451	449	453	453	451	445	450	450	451	448	442	434	425	421	433	427	440	425	413	405	389	373
419	412	420	426	430	436	453	466	455	432	432	444	455	461	451	447	453	452	447	445	452	451	454	446	442	434	425	423	433	427	448	426	417	415	393	376
415	406	419	426	429	438	452	466	453	435	437	450	473	478	454	449	455	454	450	453	460	455	460	453	447	437	430	429	434	434	451	430	420	416	396	377
428	419	428	434	436	448	447	448	446	440	443	450	466	459	449	448	453	452	451	457	457	452	458	454	449	441	435	433	432	429	448	435	428	425	413	399
409	398	413	424	432	452	453	451	454	447	447	454	461	448	438	442	452	449	449	460	456	448	460	453	447	439	438	438	433	427	444	431	421	417	403	382
418	409	421	432	443	462	453	444	450	453	447	449	445	443	439	445	449	450	453	459	455	446	456	453	448	440	442	446	447	423	443	436	426	424	418	400
406	397	412	436	451	473	459	446	452	464	449	443	430	431	425	436	449	456	460	462	456	439	440	446	447	439	447	456	464	419	437	435	428	424	414	399
409	403	416	442	454	470	454	450	455	472	449	438	430	426	427	434	452	463	464	464	455	437	442	441	448	441	449	458	467	423	438	441	443	442	423	408
413	406	418	440	447	458	446	456	464	472	445	434	428	422	432	443	451	462	459	458	447	433	438	437	444	438	447	453	457	424	437	442	454	444	431	411
413	407	417	436	439	446	443	476	486	469	442	432	429	421	433	445	450	460	452	448	439	429	433	432	437	436	444	447	445	424	436	441	460	442	432	413
413	409	416	429	434	437	437	469	478	460	440	432	429	424	430	436	446	452	441	439	435	428	421	429	432	433	440	438	432	415	432	440	457	431	424	410
415	410	415	426	432	430	424	437	442	450	440	432	430	428	430	434	440	446	435	433	433	430	427	427	429	432	434	431	424	418	430	437	446	420	415	409
416	412	414	435	435	425	416	420	423	445	442	433	430	430	431	433	439	446	435	432	433	431	427	426	431	435	431	428	422	416	430	437	443	421	414	410
420	411	409	425	427	419	412	414	417	437	442	431	429	429	429	431	435	443	434	432	432	430	427	426	429	431	425	424	420	413	429	437	434	418	415	410
413	399	398	410	412	408	403	408	412	424	429	427	425	424	425	426	427	428	426	426	426	424	420	420	420	422	418	418	415	407	425	425	420	411	410	404
401	390	394	402	406	406	401	402	407	414	413	418	419	420	420	420	419	415	420	421	421	419	415	415	416	413	409	410	409	401	418	414	410	406	404	397

Figure 42: *Grid of average temperatures with color mapping for visual representation of Test Run-8.*

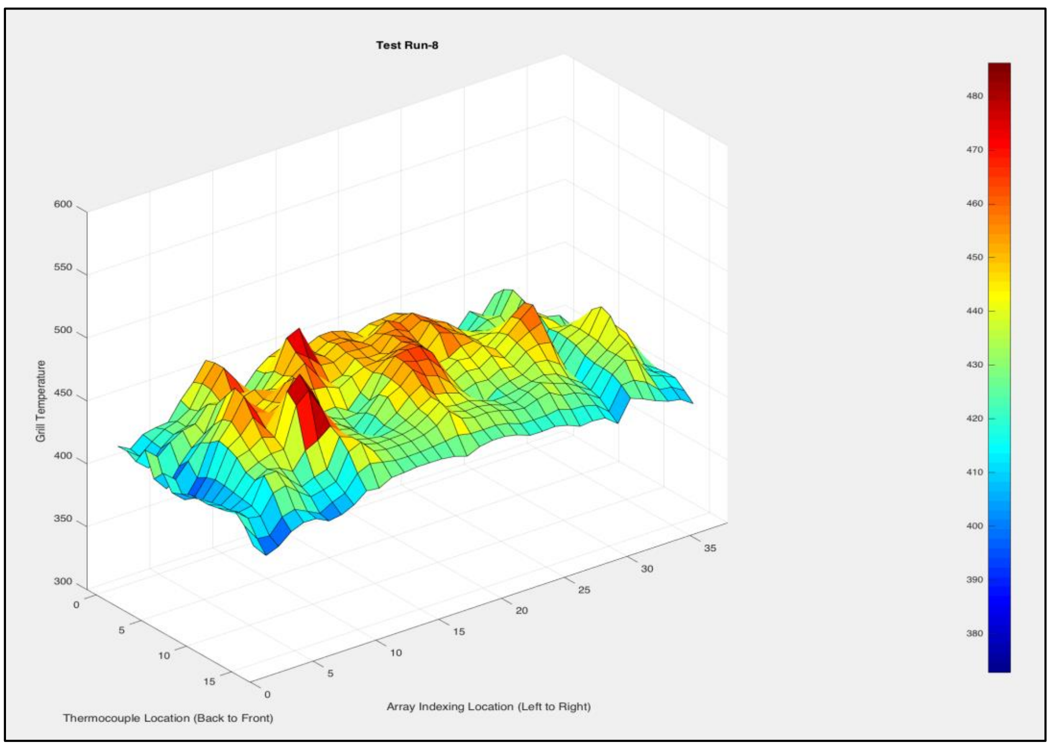


Figure 43: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-8.*

Test Run-9_Natural Gas

The configuration of Test Run-9 was a further progression of modification to the flame tamer configuration of Test Run-7 and Test-Run-8. In this test run the rear 2/3 of holes in the flame tamers were covered, as seen below in Figure 44. The results of this test have shown this configuration provided the most ideal uniformity measure of all tests performed at a value of 16˚F, an improvement of 2˚F from the previous best. This configuration improved the uniformity measure of the new flame tamers with holes currently in production at Bull Outdoor Products by 6˚F, and 4˚F from the previous flame tamers without holes.

Figure 44: *Flame Tamer Configuration described as 'Rear 2/3 Flame Tamers w/o Holes'.*

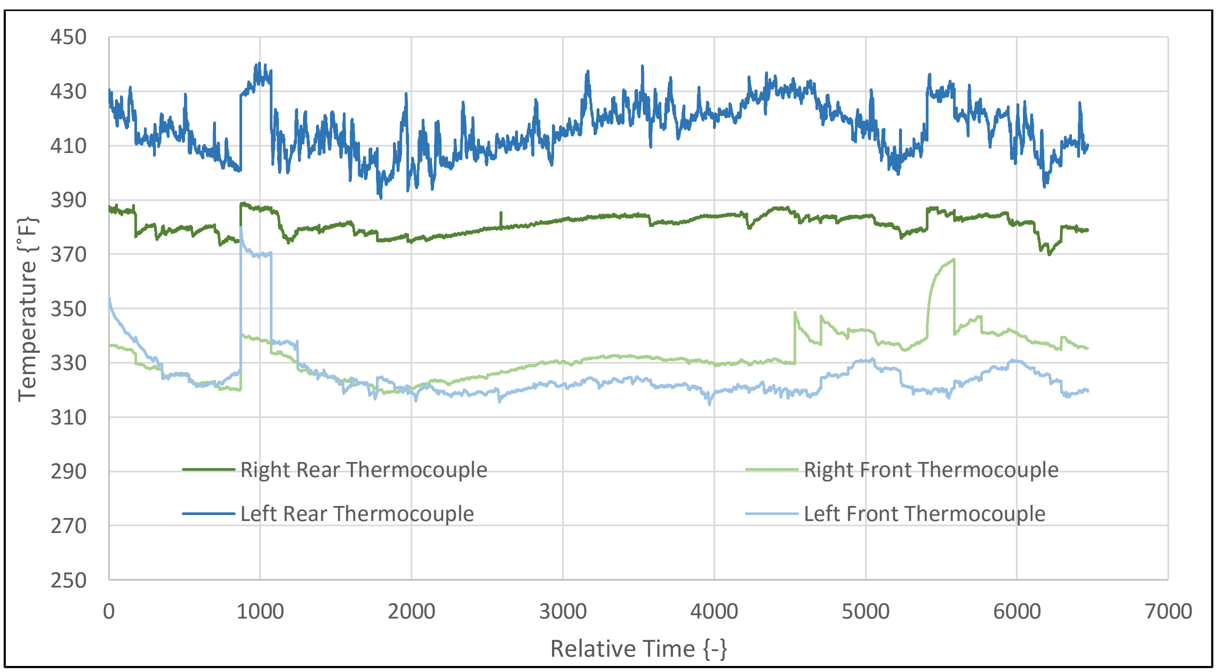


Figure 45: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-9.*

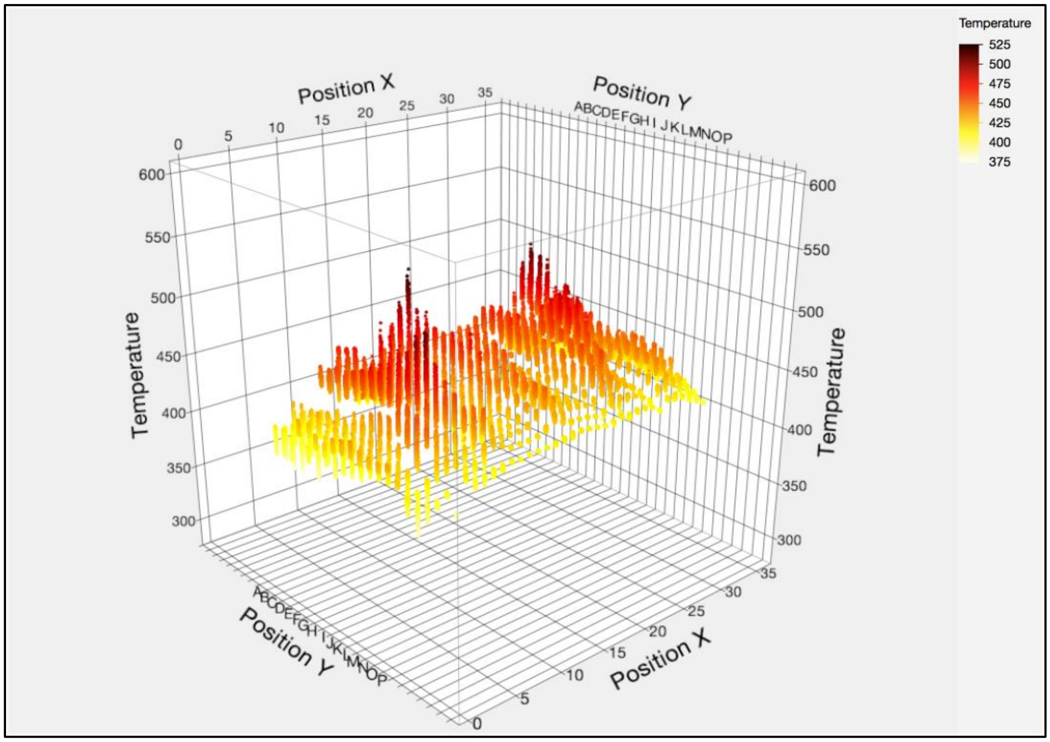


Figure 46: *3D Scatterplot of Test Run-9.*

402	403	407	414	410	446	441	456	441	420	422	435	445	455	449	446	456	456	449	445	446	448	447	451	452	454	453	440	439	476	468	451	437	418	410	417
401	405	408	418	415	445	444	458	442	426	424	437	457	469	449	445	457	454	446	443	445	449	446	454	454	453	452	439	441	487	471	452	438	421	415	422
400	401	406	417	413	445	446	463	444	434	428	442	473	490	448	449	462	457	447	449	449	452	442	458	457	454	452	446	440	481	477	456	441	422	417	420
424	418	421	426	423	454	446	446	443	440	433	441	456	463	440	446	455	451	448	451	447	448	444	452	452	451	453	448	439	452	465	457	444	431	427	427
406	399	406	415	413	450	451	452	457	448	435	441	453	447	431	440	455	448	448	449	441	444	440	451	452	450	454	457	444	453	470	460	437	420	419	419
420	410	417	422	424	458	451	449	453	446	434	436	438	433	434	440	448	444	447	448	440	442	441	447	447	449	455	465	452	444	459	458	440	429	426	425
418	403	412	417	426	460	457	455	458	444	432	431	428	422	423	438	444	441	442	447	434	436	431	442	442	445	457	472	461	436	451	455	436	421	418	418
425	409	418	422	433	464	459	458	461	440	429	427	425	420	420	441	442	439	439	446	432	434	433	439	439	443	456	467	460	430	446	450	436	427	422	418
429	413	420	425	434	463	460	463	459	437	428	425	417	417	425	443	442	438	436	439	428	430	432	436	436	443	450	456	451	425	441	446	437	432	423	417
430	415	420	427	435	460	469	482	467	440	428	424	411	416	427	439	442	441	436	434	424	426	433	435	438	449	448	450	444	423	437	444	443	435	423	416
428	417	419	427	444	455	467	483	467	449	432	425	412	419	421	431	441	447	437	431	424	422	425	433	438	451	444	442	436	422	432	443	447	431	418	415
427	417	419	428	445	449	450	451	445	447	436	426	419	422	423	428	437	445	433	428	425	424	422	429	436	444	439	436	429	421	431	440	443	426	415	412
428	419	421	443	446	445	436	430	429	440	439	428	423	423	424	426	435	446	435	428	427	426	424	428	439	447	436	432	427	420	430	440	446	428	416	411
432	421	418	435	447	442	430	423	422	434	444	428	424	423	423	424	431	444	431	427	427	426	424	426	433	435	431	429	425	418	428	437	434	426	418	413
423	408	407	413	424	429	423	415	416	422	428	423	419	419	419	420	424	430	425	422	421	421	418	420	424	426	425	423	419	413	423	425	423	418	413	406
415	400	402	402	407	425	416	409	410	412	411	414	413	414	414	414	415	416	417	418	417	416	414	415	417	414	416	416	414	409	417	416	414	413	407	401

Figure 47: *Grid of average temperatures with color mapping for visual representation of Test Run-9.*

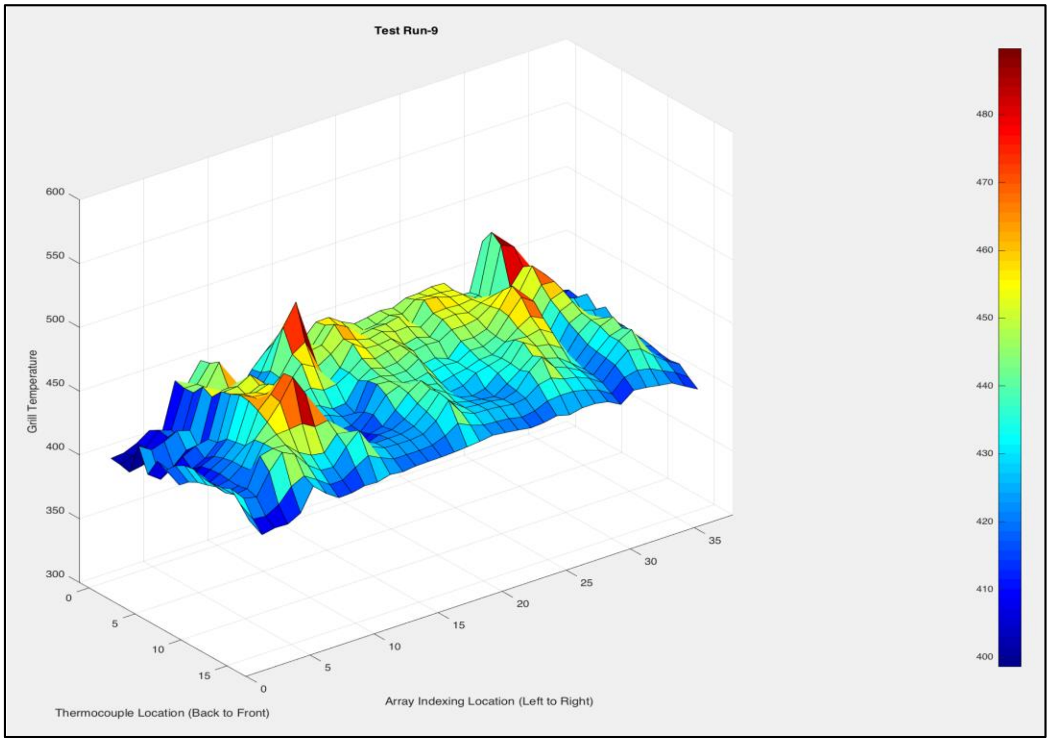


Figure 48: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-9.*

Test Run-10_Natural Gas

The configuration used in Test Run-10 was the final configuration used for testing on the natural gas model and paved the framework for the battery of testing to be conducted on the propane models. In speaking with the sponsor contact, Frank Mello, Brazing Bull came up with the idea to modify some of the new flame tamers such that they would rest upside down in between a set of old flame tamers without holes as seen below in Figure 49. It was predicted that this would help with calming some of the turbulent flow and improve the distribution, however this configuration resulted in a uniformity measure of 26˚F, significantly greater than any other configuration. This is in part due to larger gradients from front to back, and very high temperature spikes at the ends of the grill where more heat is being forced to flow out. These results can be seen in Figure 51, Figure 52, and Figure 53.

Figure 49: *Flame Tamer Configuration described as 'Blanks up Holes Down'.*

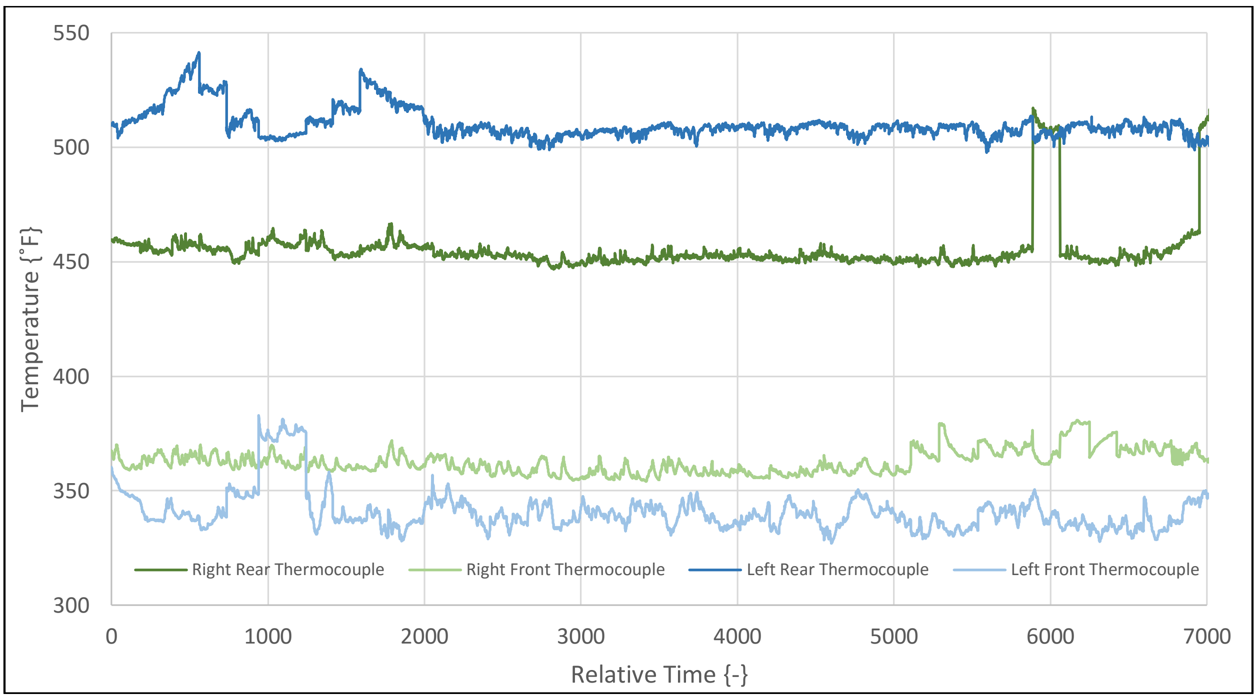


Figure 50: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-10.*

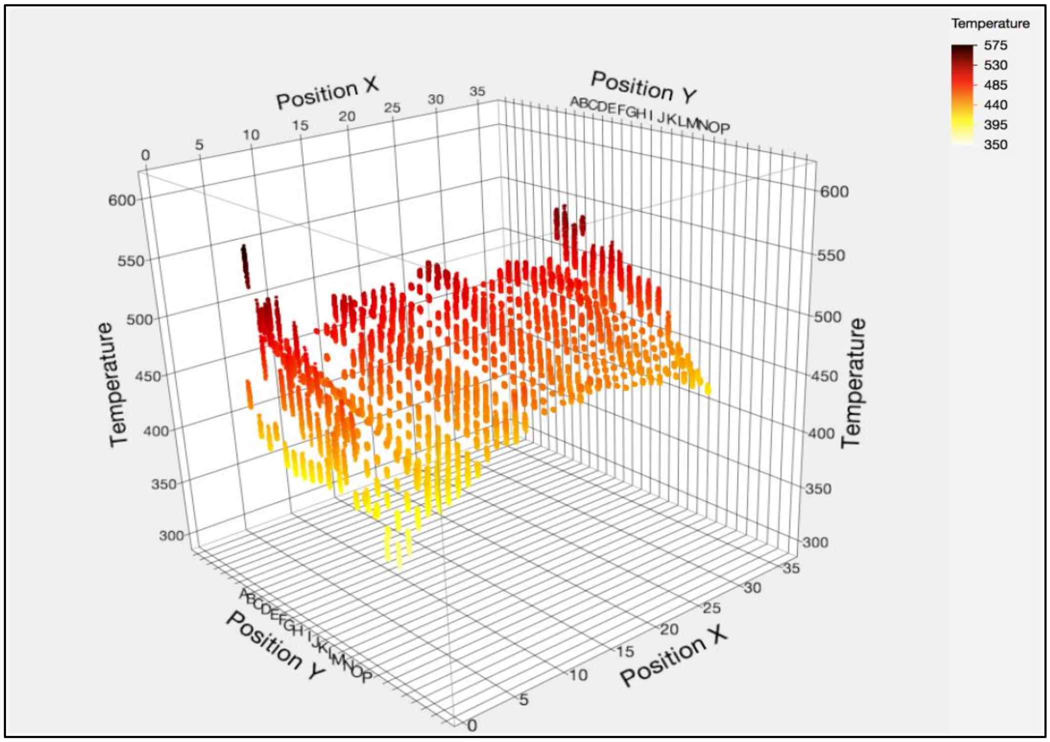


Figure 51: *3D Scatterplot of Test Run-10.*

455	562	514	488	487	471	461	493	491	510	507	507	508	506	506	500	501	508	518	522	511	508	499	491	490	492	491	497	501	495	493	485	484	492	527	522
431	500	518	481	483	468	457	473	490	509	501	503	500	496	497	494	497	508	519	521	508	502	492	487	488	491	491	498	502	494	492	483	482	487	517	504
423	521	515	480	483	468	457	496	491	509	502	504	496	490	491	490	496	504	513	518	507	500	486	487	489	492	490	497	504	500	497	483	483	488	513	530
436	467	487	472	477	463	450	464	475	485	486	489	485	481	480	481	486	491	496	501	496	492	485	484	484	486	483	484	490	493	490	482	480	483	497	486
417	471	504	472	475	460	450	469	480	484	489	490	481	470	467	471	483	491	494	503	494	489	479	477	481	486	482	481	492	500	495	480	479	483	508	477
416	457	486	466	471	458	447	462	470	472	479	481	478	467	465	468	477	483	485	493	489	486	477	476	478	482	478	478	486	497	494	479	476	478	505	482
417	456	479	463	467	455	447	462	467	468	476	479	473	458	455	459	474	482	481	489	484	480	467	470	474	478	475	475	483	499	496	475	473	475	510	499
417	445	459	458	463	452	446	456	460	463	470	473	469	456	454	456	471	479	478	483	479	476	467	468	473	475	473	472	479	487	483	472	470	472	494	491
419	432	452	453	458	449	443	449	453	456	464	467	464	455	452	455	469	474	474	478	474	471	463	465	470	471	469	469	474	477	474	468	466	467	483	484
422	430	449	447	454	445	438	443	446	448	458	461	458	454	448	453	465	469	469	473	469	466	459	460	466	467	464	465	469	469	468	463	462	463	474	483
444	466	442	440	448	439	433	437	440	442	454	456	454	457	450	452	462	465	466	469	466	462	453	458	463	462	461	462	465	462	454	456	457	458	465	480
435	458	429	433	442	433	426	431	434	436	449	451	451	454	444	449	458	461	461	464	463	459	452	453	459	458	457	458	460	458	455	452	453	454	457	459
412	408	417	426	437	428	422	427	430	432	445	448	449	447	436	442	454	457	459	461	458	453	447	448	456	456	454	455	454	449	451	449	451	451	450	437
418	405	412	420	433	424	418	424	426	429	442	445	447	436	431	439	452	455	457	459	449	447	446	444	455	453	452	453	450	444	449	449	449	449	447	435
410	391	399	411	427	416	413	421	424	424	437	442	447	436	429	439	450	452	455	456	445	443	446	446	453	449	449	449	448	442	445	440	443	441	435	425
382	374	385	401	415	413	413	417	420	422	432	437	448	467	468	457	448	447	451	453	457	461	457	453	449	444	445	444	443	440	443	438	435	430	425	415

Figure 52: *Grid of average temperatures with color mapping for visual representation of Test Run-10.*

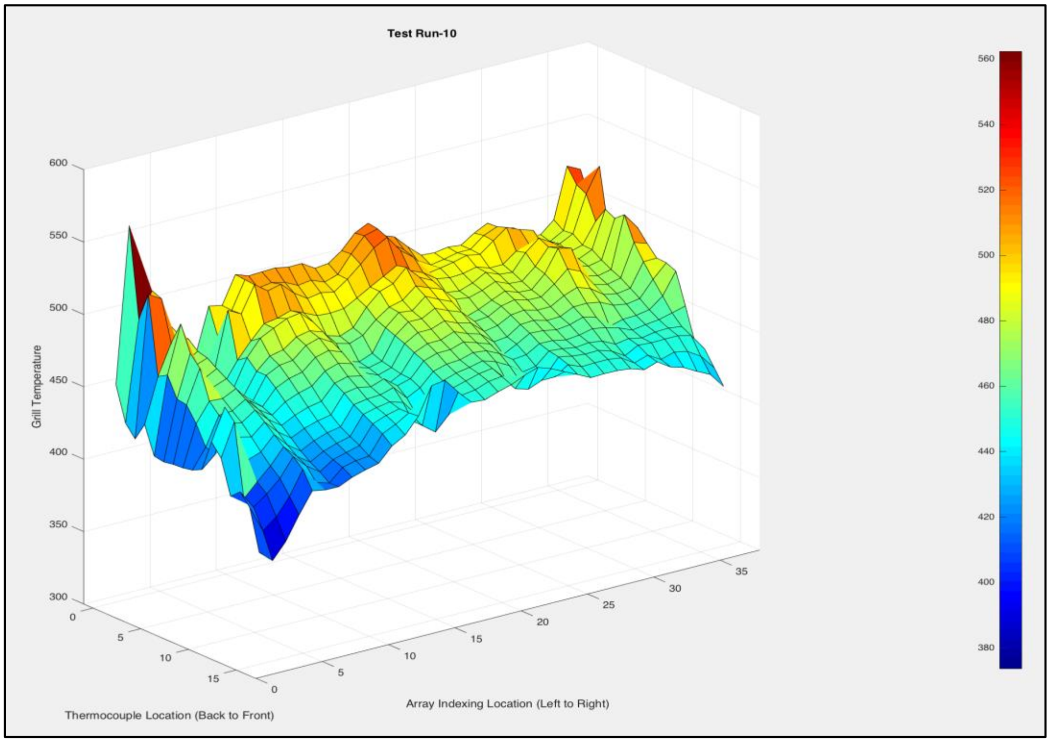


Figure 53: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-10.*

Propane Tests

The series of testing performed on the propane models was done using the same method implemented on Test Run-5 through Test Run-10 on the natural gas models, and using the same exact configurations where Test Run-1(Propane) is equal to Test Run-5(Natural Gas), and so on.

All of the results from the propane tests are attached in Appendix J of this report, however a discrepancy was found that effected the results on all of the tests. It can be seen in all of the 3D Scatterplots, average temperature heat maps, and average temperature 3D mesh plots in Appendix J that there is clearly a drop in temperature beginning at the second burner from the right and to the left hand side of the grill. This result was clear in every test performed and resulted in uniformity measures ranging between 18˚F and 30˚F.

Due to this discrepancy, we have determined that this data is not useful in judging the uniformity of the propane grills. We suspected that this was likely due to a pressure drop within the burner manifold because the manifold is supplied with fuel from the right hand side where the highest temperatures occurred. In order to test this theory, we requested that our sponsor send us a propane manifold in order to perform some bench testing and verify if there was in fact a correlation between pressure and the steep temperature drop on the left half of the grill surface. The results of this pressure test can be seen in Table 3 below.

Table 3: *Results of pressure bench test on separate propane burner manifold.*

Burner Pressure {in-H_2O}					
Burner Number (Right to Left)	1	2	3	4	5
Pressure [in of H_2O]	7.0	7.2	5.8	5.6	4.8
% Diff	N/A	2.86%	-17.14%	-20.00%	-31.43%

In Table 3, burner number 1 is the rightmost burner because it is closest to the fuel inlet, and burner 5 is the leftmost burner since it is the farthest from the fuel inlet. The percent difference is calculated based on percent difference of the rightmost burner pressure. It can be seen here that there is a 19 percent decrease in pressure from burner 2 to burner 3, which may be a side effect of having the rear infared burner supplied from the manifold from that location. Overall there is a 31 percent decrease in pressure across the length of the manifold and the gradient seen by these results closely resembles the results obtained from the temperature test.

Brazing Bull recommends that Bull Outdoor Products address the pressure drop issue in the manifold, and perform the temperature tests with all the configuration used for this project again in order to make a more direct comparison to the natural gas results. Until this issue is addressed, the data obtained from the test results is flawed and not useful for determining a uniformity measure across the gill surface.

Meat Tests

As a more qualitative performance test, Brazing Bull designed a test by cooking tri tips at various locations and recording the amount of time required for the tri tips at each location to reach 160˚F internally. Each test used 6 tri tips, and aside from test 2, all of the tri tips were within 0.1lbs of the same weight. The location numbers can be seen with relation to their actual location on the grill in Figure 54 below.

Figure 54: *Tri Tip Locations with respect to grill surface.*

The results from these meat tests were not only delicious, but they also showed similar results in that the most optimum flame tamer configuration again was the rear 2/3 of the flame tamer holes covered. All meat tests were performed on the natural gas model during temperature tests on the propane model.

Table 4: *Results from meat tests on Natural Gas grill head.*

Meat Test Results (Cook Time to Reach 160˚F at 6 Locations)								
Configuration	Test Run		Tri Tip Location					
			1	2	3	4	5	6
Blanks Up Holes Down	1	Weight {lbs}	unknown	unknown	unknown	unknown	unknown	unknown
		Time {min}	37.00	52.00	38.00	40.00	50.00	60.00
Rear 1/3 Covered	2	Weight {lbs}	3.87	2.87	2.87	2.87	2.89	2.89
		Time {min}	66.00	53.00	57.00	71.00	57.00	85.00
Rear 1/2 Covered	3	Weight {lbs}	2.5	2.49	2.67	2.5	2.61	2.56
		Time {min}	45.00	55.00	46.00	54.00	43.00	63.00
Rear 2/3 Covered	4	Weight {lbs}	2.61	2.34	2.58	2.33	2.53	2.18
		Time {min}	58.00	8.00	49.00	54.00	53.00	53.00

Bread Tests

In addition to performing meat tests, Brazing Bull thought it might be interesting to also perform what is referred to as a bread test, on the natural gas grill. The purpose of the bread test was to provide a visual representation of the results obtained in the temperature tests, and ideally these results would be easy for someone with no technical background to understand. After all, not everyone understands statistical analysis or 3 dimensional plots of 120,000 temperature readings, but everyone understands burnt toast.

Brazing Bull welded expanded steel purchased at Home Depot to a frame made of ½ inch steel square tubing with handles so that they could cover the entire area of focus with bread simultaneously and remove all the bread simultaneously as well. This way, it would be able to be seen how the discoloration of the bread would match up to the actual data for the various configurations used in testing.

In the figures below, the 3D Scatterplots have been overlaid on top of the toasted bread for the various different configurations used and these results have shown that the temperature data obtained is actually quite accurate with regard to uniformity or evenness across the grill surface.

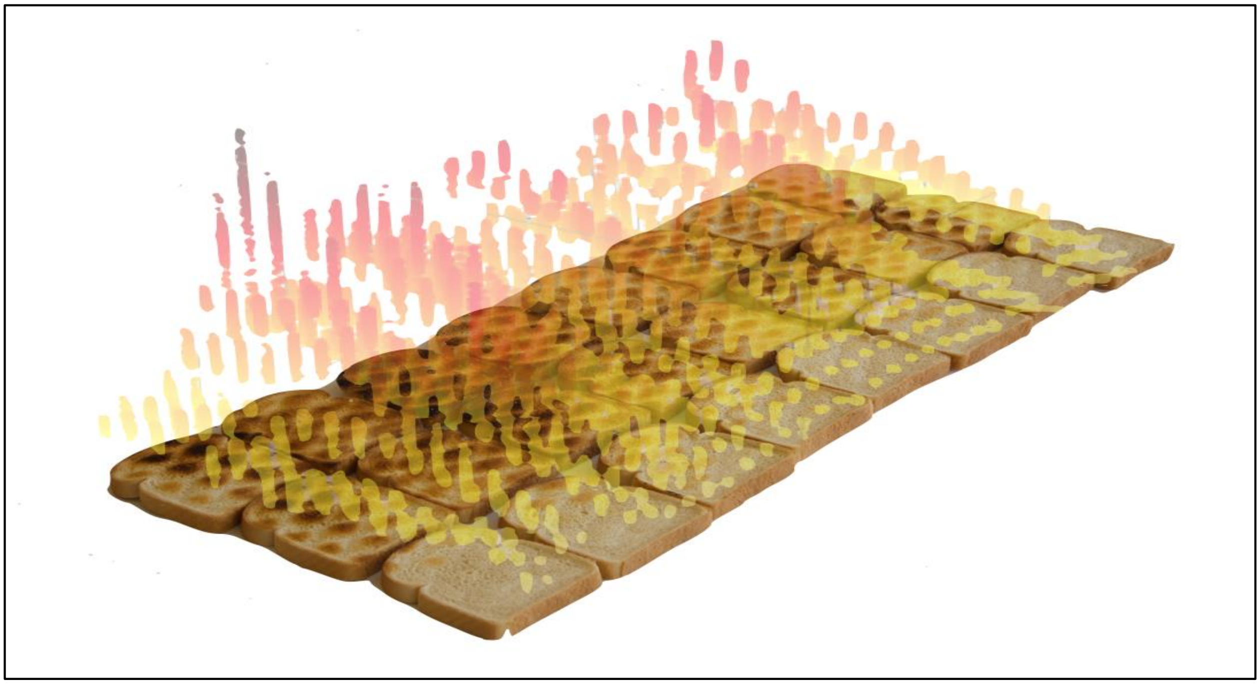


Figure 55: *Overlay of temperature data onto image from bread test with configuration of flame tamers with holes.*

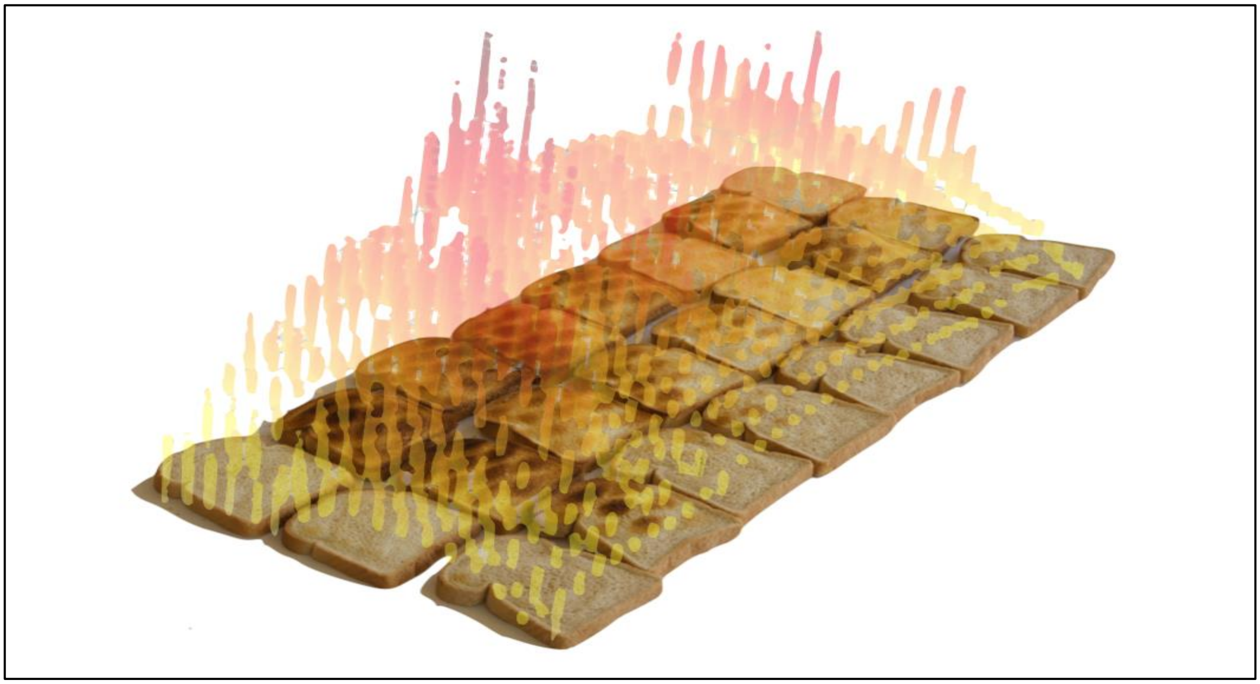


Figure 56: *Overlay of temperature data onto image from bread test with configuration of flame tamers without holes.*

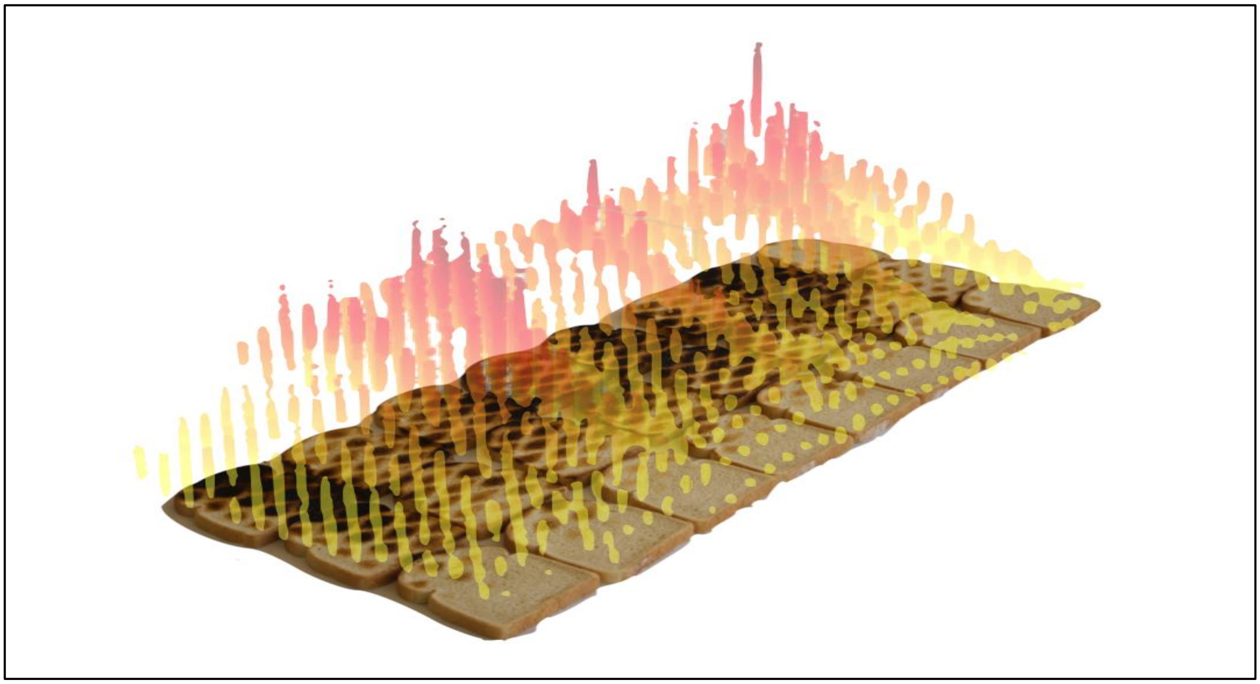


Figure 57: *Overlay of temperature data onto image from bread test with configuration of rear 1/3 flame tamers w/o holes.*

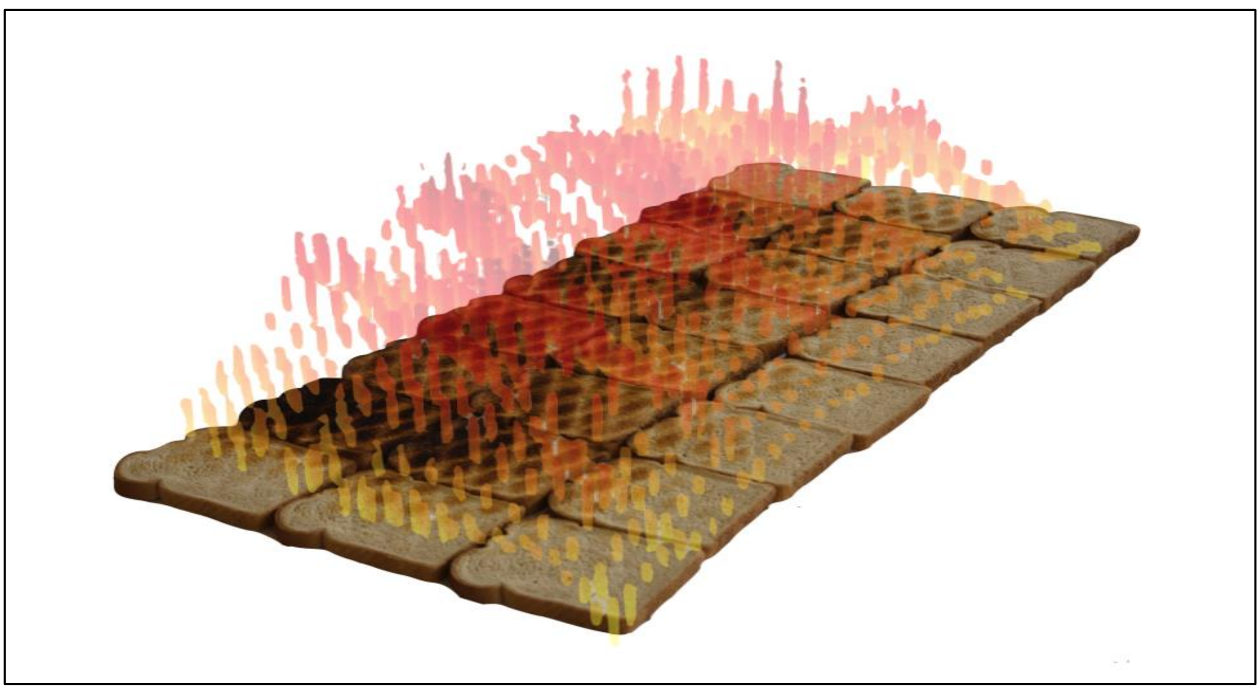


Figure 58: *Overlay of temperature data onto image from bread test with configuration of rear ½ flame tamers w/o holes.*

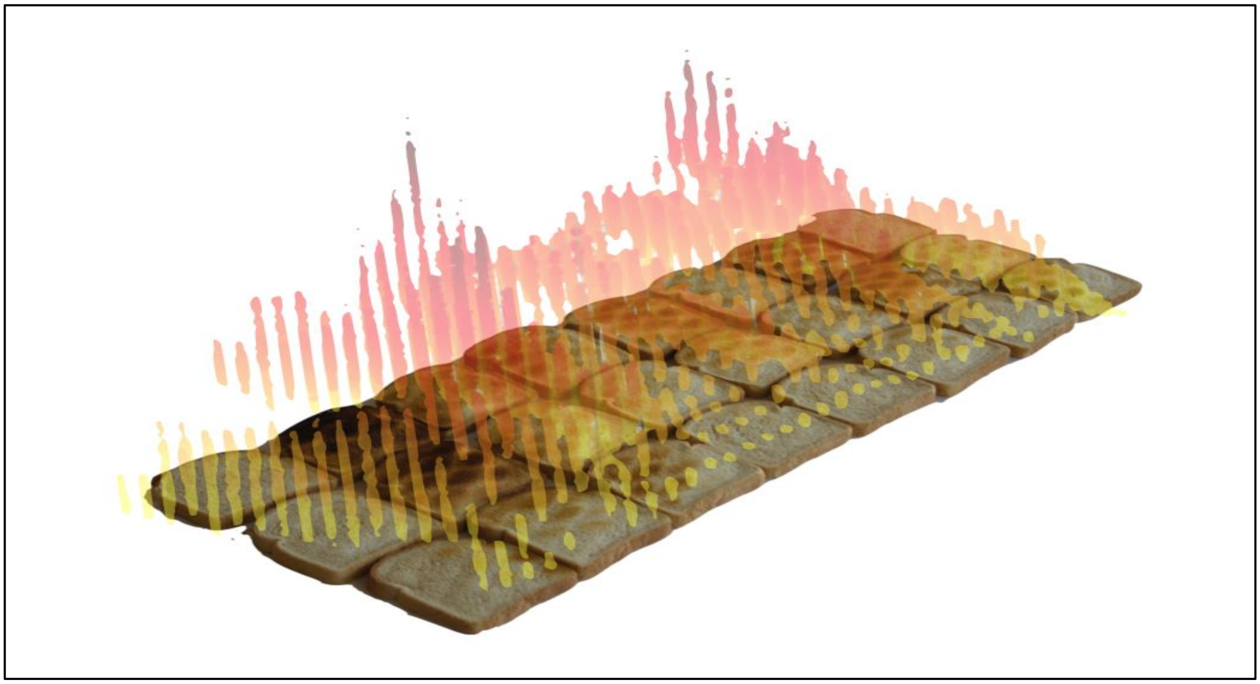


Figure 59: *Overlay of temperature data onto image from bread test with configuration of rear 2/3 flame tamers w/o holes.*

Lessons Learned (Testing Methods)

Overall, Brazing Bull is pleased with the testing method developed over the first five test runs, and the methodology for settling on the final test method is described in the Progression of Testing Method section above. Some of the most important lessoned learned in developing the test method were as follows:

- Monitoring preheat to ensure steady state is reached. This requires a minimum of 45 minutes preheat
- Preheat with thermocouple array in line with fixed thermocouple (approximately location 6.5)
- Use the sequencing method at each end as described in Test Run-5 section above.
- Do not use high valve setting.
- One tank of propane is adequate for a total of 3 test runs, be sure to have a spare on hand.

It is also important to note that in order to acquire reasonable and reliable or “ReliaBull” data on the propane grill, the testing should be repeated once the manifold pressure drop issue is addressed.

Conclusions and Recommendations

In all, Brazing Bull completed 30 tests between the two Brahma model grills provided by Bull Outdoor Products. This includes 19 tests completed using the uniquely designed temperature testing apparatus, one pressure test of the propane manifold, 6 bread tests on the natural gas grill, and 4 tri tip roast test also completed on the natural gas grill. Combined, this provided Bull Outdoor Products with extensive information about the performance of their grills. However, more can be done.

Based on the data collected by Brazing Bull, one configuration was chosen to be the best for producing the most uniform heating of the grill surface. The best profile was produced when the rear two thirds of the flame tamers with holes in them were covered. Therefore, based simply on Brazing Bull's research, Bull Outdoor Products should consider manufacturing their flame tamers with holes only in the front one third portion.

However, Brazing Bull does not recommend taking the aforementioned conclusion as the best possible solution. Brazing Bull created the testing apparatus to be durable and reliable so that testing can continue at Bull Outdoor Products own facility, in the hopes that they will be able to continue research and continue developing the greatest grill design possible. Therefore the most valuable result of this project is a proven and accurate method of collecting data from the grills, and being able to assess the performance of any design changes within the grills. With this in mind, Brazing Bull has many ideas and recommendations for Bull Outdoor Products to explore.

After extensive testing, it is understood that the flame tamers play a significant role in the heat distribution of the grills. For the duration of this project, mostly hole configurations in the flame tamers were altered and tested. Brazing Bull acknowledges that there are many other aspects that can be altered in order to produce different results. Some things to consider changing and testing are the angles in which the flame tamers sit from front to back of the grill, the angle bent into the flame tamer itself, the sizes and location of holes within the flame tamers, the overall width of the flame tamers, etc. It is well known that heat rises, and therefore, Brazing Bull hypothesizes that making the flame tamers rest higher in the front of the grill than the rear might cause more heat to be directed forward in the grill. Changing the dimensions of the flame tamers, such as width and bend angle may cause heat to be spread out further, or it may not. Brazing Bull feels these are aspects worth testing, but cannot say for certain whether or not these types of changes will in fact increase the performance of the grills.

The Brahma grill head come in both propane and natural gas configurations, and even though the grills are otherwise identical, Brazing Bull does not feel comparisons can be made between the two grills, even for the same flame tamer configurations. This is because of the pressure issue discovered within the propane manifold. After a bench test of the propane manifold, it was found to have a significant pressure drop from right to left, causing a considerable bias of heat to be on the right side of all propane configurations. This problem did not arise for the natural gas grill, causing it to have far superior heat uniformity. Therefore, the propane pressure issue needs to be remedied before comparing testing results to that of the natural gas grill. Bull Outdoor

Products sells both grill types with identical hardware inside the head, and if they wish to continue to do so, they must improve the propane manifold's ability to deliver adequate pressure to each burner as the natural gas grill does. By doing this, they can configure the grill inserts to be identical between the grills, and only alternate regulator and manifolds need to be installed on different models. Once this is done, Brazing Bull recommends that the propane tests performed in this study be reproduce, then compared to the natural gas grill. Once the results are truly comparable, Bull Outdoor Products can see if configurations are consistent in their performance across fuel types.

Some observers of the project have suggested that different sized burners be used across the grill. Brazing Bull does not recommend this solution because it would require the user to ensure that each burner is always installed in its proper location. If the end user mistakenly installs a burner which allows more gas on the right side of the grill, it is possible to produce an unsafe product expelling a dangerous amount of heat. Furthermore, it would be more difficult for Bull Outdoor Products to manufacture and organize several different configurations of essentially the same part. As their production exists currently, all of the available gas powered grills use identical burners, only changing the quantity of burners installed. Most importantly, each burner needs to produce the manufacturer specified amount of BTUs. Although all tests done by Brazing Bull had all burners turned on to equal positions, not all grill users operate their grills in this manner. There are situations in which only one, or some, of the burners are turned on, while others are turned off. Once again, having different burner sizes could produce dangerous conditions for this situation, as there would not be the same pressure drop recorded in this study, if not all of the burners were turned on. Instead, Brazing Bull recommends possibly implementing a manifold pipe of a larger diameter to reduce frictional losses within the manifold.

Towards the end of the time allotted for this project, Brazing Bull received modified baffled burners and some prototyped louvers from Bull Outdoor Products' manufacturing facility. The modified burners are a continuing development from Bull Outdoor Products with baffles welded to the interior of the burner, while the louvers were design by Brazing Bull. Since the parts were received late in the final weeks of the project, extensive testing was not able to be done on both grills with these setups. Each part received one data test on the propane grill with the flame tamers with all holes exposed. Even though there was still significant right side bias in these propane tests, both prototypes produced better results than with just the standard flame tamers alone. Therefore, Brazing Bull suspects that a grill with both designs implemented might produce considerably improved heat distribution. It is recommended that flame tamer configurations continue to be explored combined with the implementation of the new louvers and burners. By mixing and matching these components, Bull Outdoor Products should be able to determine a path to a significantly improved gas barbeque grill.

Brazing Bull has validated their data and testing method in many ways, including a test method development process, visual validation in toasting bread, and qualitative validation in cooking meat. Brazing Bull is confident that all supplied data and analysis is accurate and provides an in depth look into the performance of the Brahma grill heads. Possibly the greatest outcome is an understanding that there is considerable potential for experimenting with different configurations. Brazing Bull hopes that Bull Outdoor Products will use this study and method to continually develop their barbeques for years to come so they may produce the best gas powered grills on the market.

Appendix A (Background Research)

Table A1: *Table of rating comparisons as determined by consumerreports.org.*

Consumer Reports Rating Comparison									
Product	# of Burners	Pre-heat Performance	Indirect Cooking	High Temp Evenness	Low Temp Evenness	Temperature Range	Convenience	Cost	Heat Output
Bull Urban Island	5	3	4	2	3	5	2	$1,700.00	90,000 BTU
Kenmore Elite	5	4	4	5	5	4	4	$1,800.00	84,000 BTU
Napoleon Mirage	4	4	5	4	4	4	3	$1,799.00	90,500 BTU
Napoleon Prestige Pro	5	4	5	4	5	5	3	$2,600.00	91,000 BTU
Vermont Castings Signature Series	4	4	5	4	4	4	4	$1,700.00	84,000 BTU
Saber	4	3	4	4	4	3	4	$1,600.00	50,000 BTU
Fervor Icon	6	3	4	2	2	3	3	$1,800.00	81,000 BTU
Weber Summit	4	4	4	3	4	4	4	$1,899.00	82,000 BTU

Appendix B (Timeline Goals)

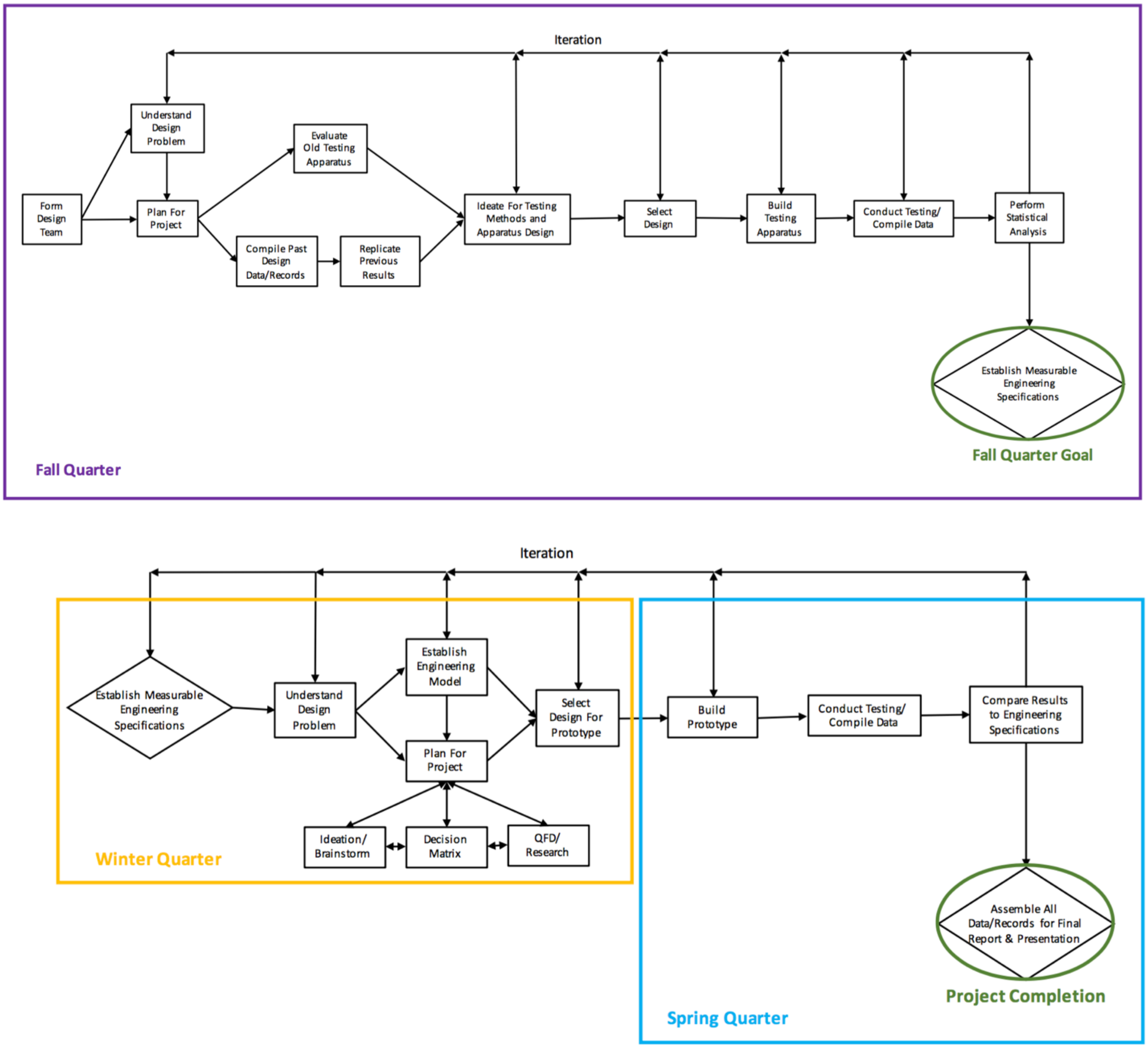


Figure B1: *Flowchart of design process specific to ReliaBull technology senior design project.*

Team Brazing Bull

0

Sponsor: **Bull Outdoor Products, Inc.**

Project: **ReliaBull Technology**   Today's Date: 11/8/15 Sunday

(vertical red line)

Project Lead(s): Monty Dodge/ Sam Melo

Start Date: 9/28/15 Monday

First Day of Week (Mon=2): 2

WBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining
1	**Meet n Greet**	All	9/29/15	9/30/15	1	100%	2	1	0
1.1	Contact Sponsor (Intros)	All	9/30/15	10/5/15	5	100%	4	5	0
2	**Project Proposal**	All	9/30/15	10/27/15	28	100%	20	28	0
2.1	Deliver to Sponsor	Monty	10/27/15	10/27/15	1	100%	1	1	0
2.1.1	Deliver to Advisor	Monty	10/23/15	10/23/15	1	100%	1	1	0
2.1.1.1	Introduction	Monty	10/7/15	10/9/15	3	100%	3	3	0
2.1.1.2	Background	All	10/8/15	10/15/15	8	100%	6	8	0
2.1.1.3	Method of Approach	Monty	10/9/15	10/13/15	5	100%	3	5	0
2.1.1.4	Objectives	Sam	10/10/15	10/19/15	10	100%	6	10	0
2.1.1.5	Management Plan	Monty	10/10/15	10/10/15	1	100%	0	1	0
2.1.1.6	Works Cited	All	10/21/15	10/22/15	2	100%	2	2	0
2.1.1.7	Appendices	All	10/21/15	10/22/15	2	100%	2	2	0
2.1.1.8	Edit	All	10/21/15	10/22/15	2	100%	2	2	0
3	**Build Testing Apparatus**	All	10/7/15	11/20/15	45	45%	33	20	25
3.1	Order Materials	Sam	10/28/15	10/28/15	0	0%	1	0	0
3.1.1	Calculate Budget	Sam	10/17/15	10/23/15	7	100%	5	7	0
3.1.2	Submit Budget to Sponsor	Sam	10/23/15	10/23/15	1	100%	1	1	0
3.1.3	Create Materials List	All	10/23/15	10/29/15	7	100%	5	7	0
3.2	Design Testing Apparatus	All	10/7/15	11/3/15	28	35%	20	9	19
3.2.1	Product Review	Monty	10/7/15	10/10/15	4	90%	3	3	1
3.2.1.1	Ideation	All	10/23/15	10/27/15	5	50%	3	2	3
3.2.1.2	Conceptual Design	All	10/27/15	10/31/15	5	0%	4	0	5
3.2.1.3	3D Model	Sam	10/30/15	11/3/15	5	0%	3	0	5
3.3	Assembly	All	11/14/15	11/20/15	6	0%	5	0	6
3.4	Manufacture Components	All	11/4/15	11/20/15	17	35%	13	5	12
4	**Conduct Testing**	All	11/23/15	11/26/15	3	0%	4	0	3
4.1	Test 1		11/23/15	11/23/15	1	0%	1	0	1
4.1.1	Sub Task Test 1		11/23/15	11/23/15	1	0%	1	0	1
4.1.1.1	Sub Task Test 1		11/23/15	11/23/15	1	0%	1	0	1
4.2	Test 2		11/23/15	11/23/15	1	0%	1	0	1
4.2.1	Sub Task Test 2		11/23/15	11/23/15	1	0%	1	0	1
4.2.1.1	Sub Task Test 2		11/23/15	11/23/15	1	0%	1	0	1
4.3	Test 3		11/24/15	11/24/15	1	0%	1	0	1
4.3.1	Sub Task Test 3		11/24/15	11/24/15	1	0%	1	0	1
4.3.1.1	Sub Task Test 3		11/24/15	11/24/15	1	0%	1	0	1
4.4	Test 4		11/25/15	11/25/15	1	0%	1	0	1
4.4.1	Sub Task Test 4		11/25/15	11/25/15	1	0%	1	0	1
4.4.1.1	Sub Task Test 4		11/25/15	11/25/15	1	0%	1	0	1
5	**Perform Analysis**	All	11/27/15	11/30/15	3	0%	2	0	3
5.1	Analysis 1		11/23/15	11/26/15	3	0%	4	0	3
5.1.1	Sub Task Analysis 1		11/23/15	11/23/15	1	0%	1	0	1
5.1.1.1	Sub Task Analysis 1		11/23/15	11/23/15	1	0%	1	0	1
5.2	Analysis 2		11/23/15	11/26/15	3	0%	4	0	3
5.2.1	Sub Task Analysis 2		11/23/15	11/23/15	1	0%	1	0	1
5.2.1.1	Sub Task Analysis 2		11/23/15	11/23/15	1	0%	1	0	1
5.3	Analysis 3		11/25/15	11/28/15	3	0%	3	0	3
5.3.1	Sub Task Analysis 3		11/25/15	11/25/15	1	0%	1	0	1
5.3.1.1	Sub Task Analysis 3		11/25/15	11/25/15	1	0%	1	0	1
5.4	Analysis 4		11/26/15	11/29/15	3	0%	2	0	3
5.4.1	Sub Task Analysis 4		11/26/15	11/26/15	1	0%	1	0	1
5.4.1.1	Sub Task Analysis 4		11/26/15	11/26/15	1	0%	1	0	1

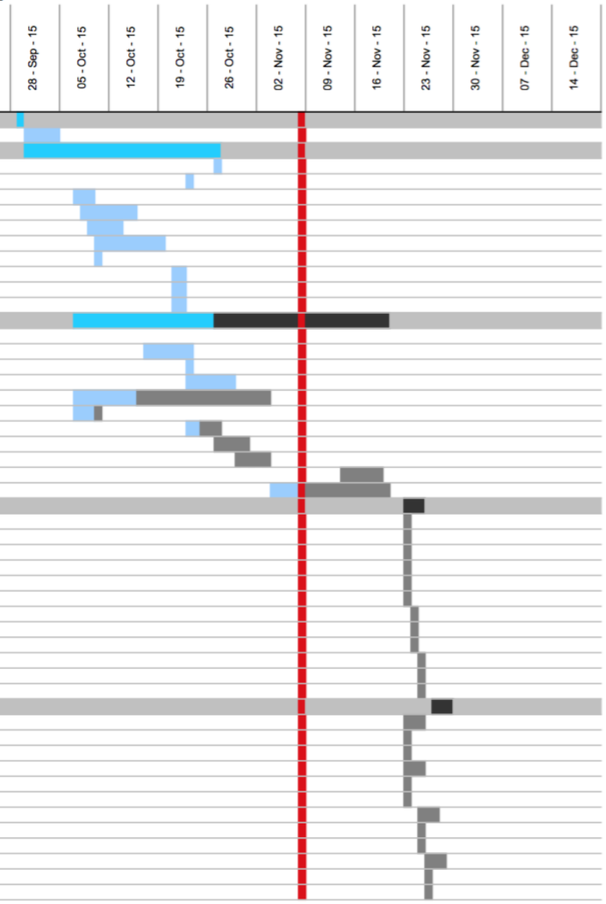


Figure B2: *Gantt chart outlining design of testing apparatus and initial test runs.*

Appendix C (Decision Matrix Results)

Table C1: *Decision matrix applied to motion of array.*

		Motion of Array							
Decision Model		**All Thread-Power Drill**		**Lead Screw-Motorized**		**Lead Screw-Manual**		**Linear Motion-Manual**	
Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Repeatability	5	0	0	1	5	2	10	1	5
Cost	1	0	0	-2	-2	1	1	2	2
HMI Simplicity	3	0	0	0	0	2	6	1	3
Durability	3	0	0	1	3	2	6	2	6
Accuracy	5	0	0	1	5	2	10	1	5
MFG Ability	2	0	0	2	4	1	2	2	4
Total		**0**	**0**	**3**	**15**	**10**	**35**	**9**	**25**

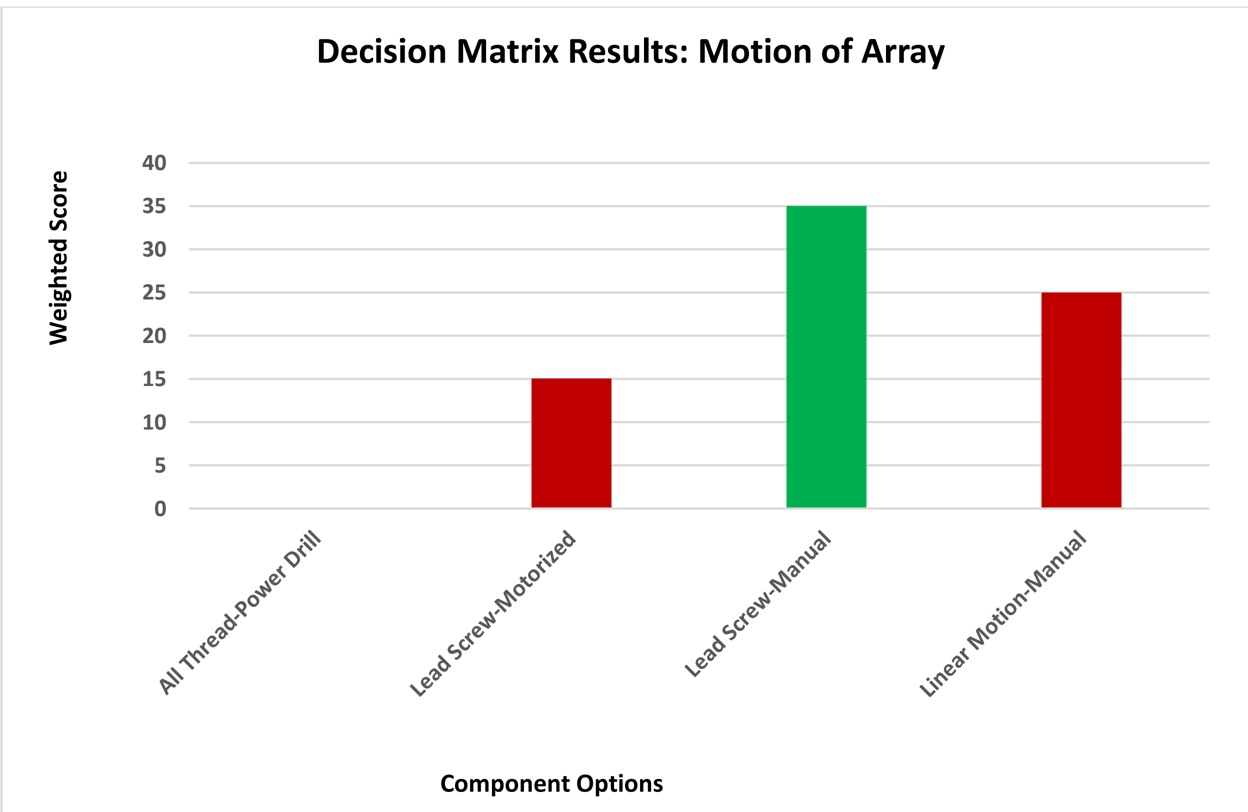


Figure C1: *Bar chart representing results of decision matrix from Table C1.*

Appendix C (continued)

Table C2: *Decision matrix applied to indexing of array.*

Decision Model		Indexing of Array							
		Ratchet System		Dial Index		Notch & Detent (Dial)		Linear Scale	
Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Repeatability	5	0	0	1	5	2	10	1	5
Cost	1	0	0	0	0	0	0	0	0
HMI Simplicity	3	0	0	1	3	2	6	1	3
Durability	3	0	0	1	3	2	6	-1	-3
Accuracy	5	0	0	0	0	1	5	1	5
MFG Ability	2	0	0	0	0	1	2	1	2
Total		**0**	**0**	**3**	**11**	**8**	**29**	**3**	**12**

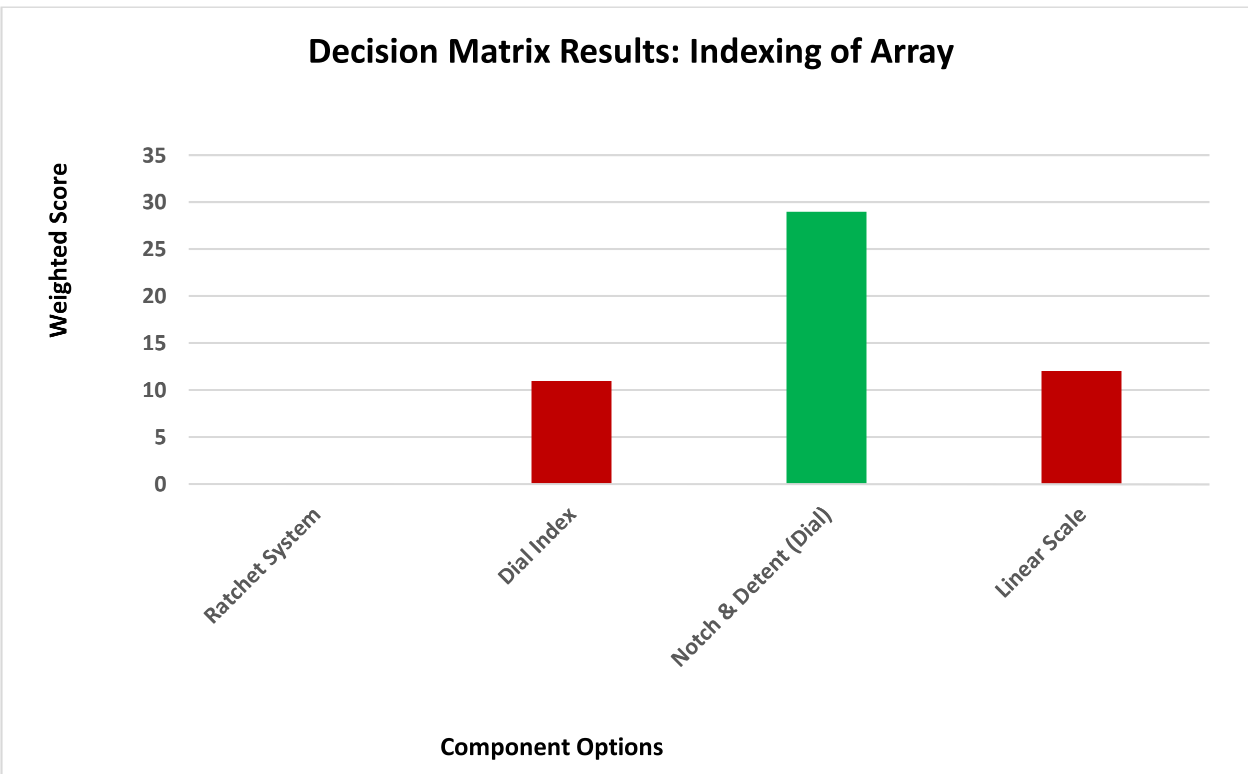


Figure C2: *Bar chart representing results of decision matrix from Table C2.*

Appendix C (continued)

Table C3: *Decision matrix applied to material selection of testing apparatus.*

Decision Model		Material Selection					
		Steel		Aluminum		Stainless Steel	
Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Cost	4	0	0	-1	-4	-2	-8
Durability	4	0	0	-2	-8	2	8
Strength	3	0	0	-2	-6	1	3
MFG Ability	2	0	0	2	4	-1	-2
Total		**0**	**0**	**-3**	**-14**	**0**	**1**

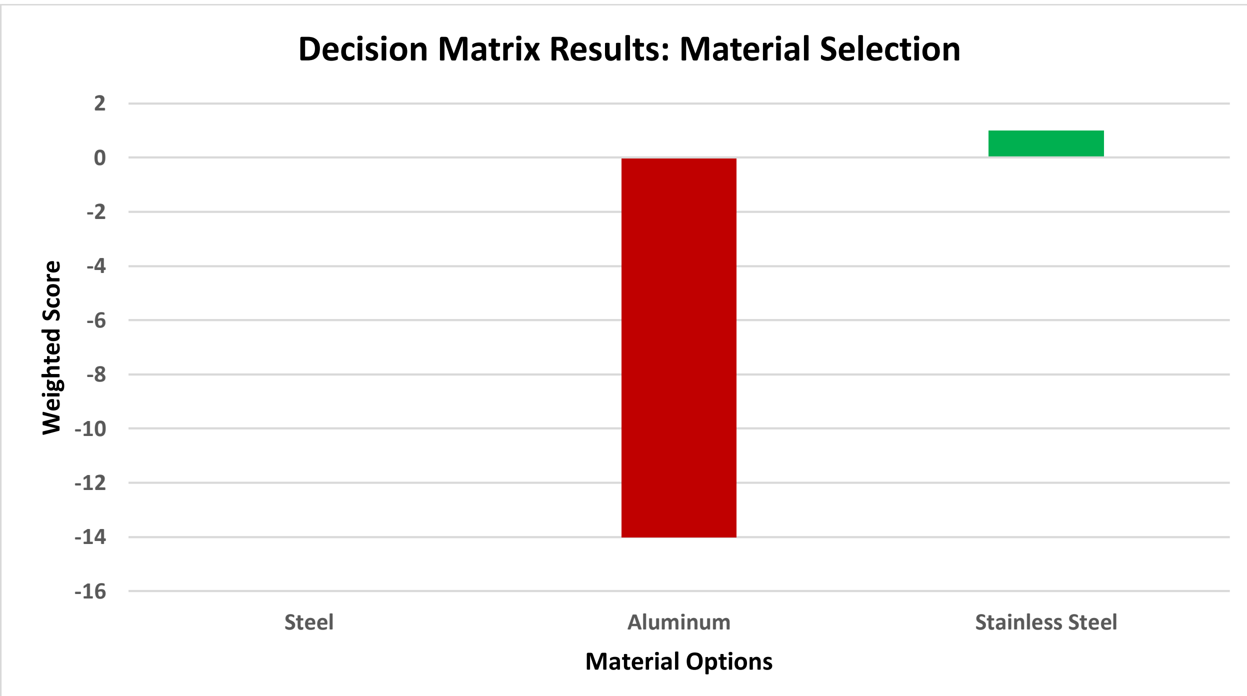


Figure C3: *Bar chart representing results of decision matrix from Table C3.*

Appendix D (Initial Sketches/Model)

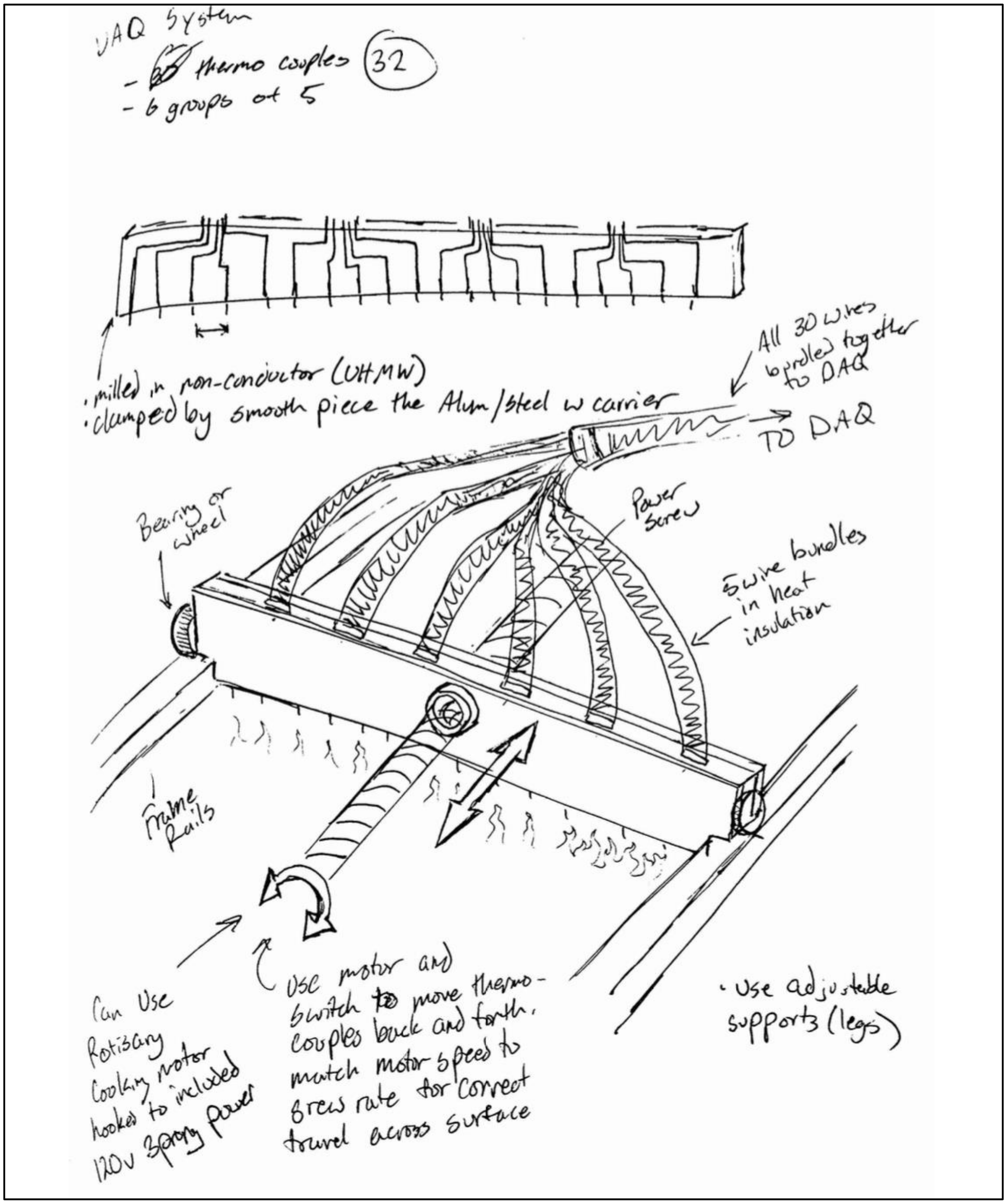


Figure D1: *Initial design sketch showing general apparatus concept and thermocouple layout.*

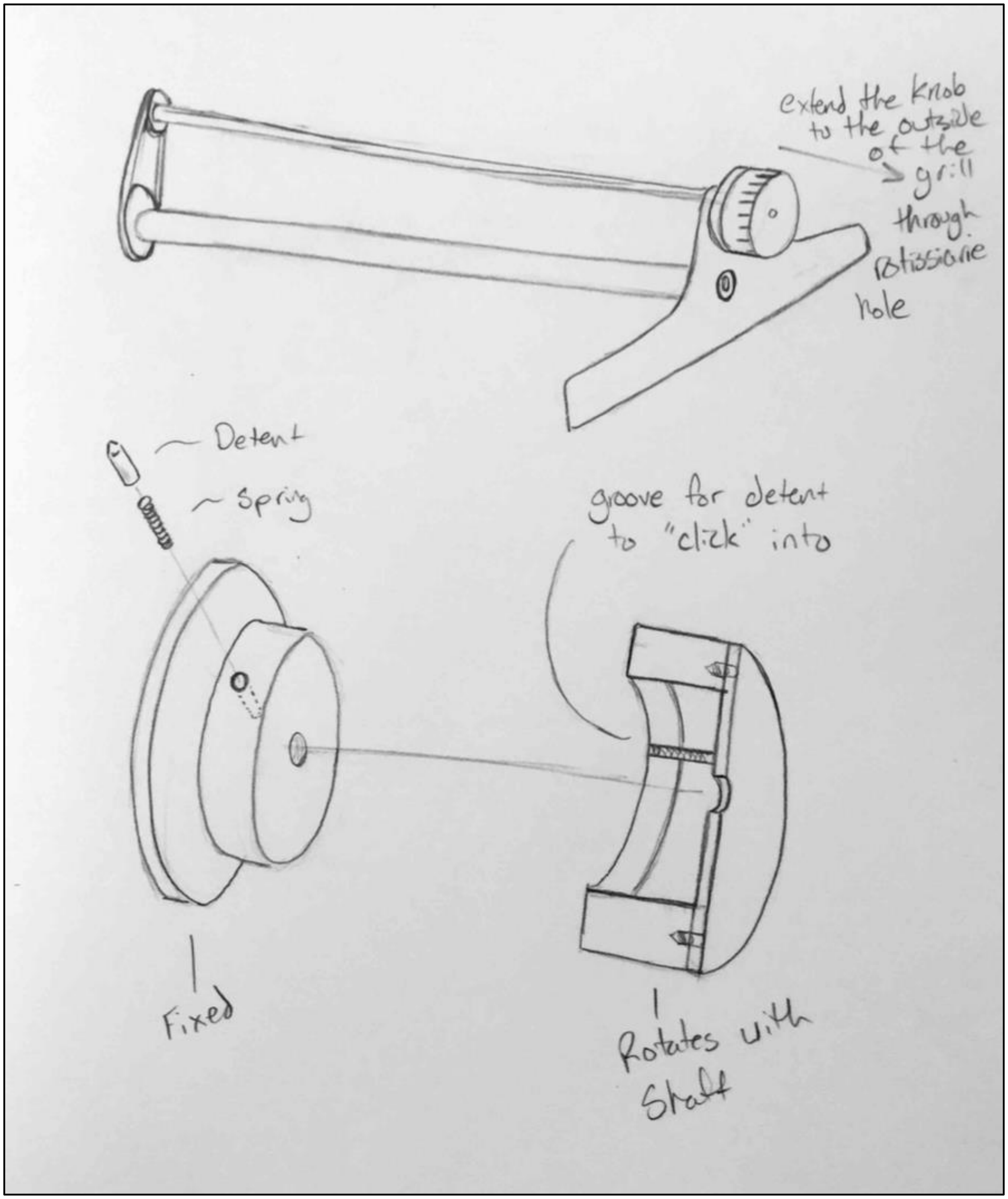


Figure D2: *Initial design sketch showing dial index design concept.*

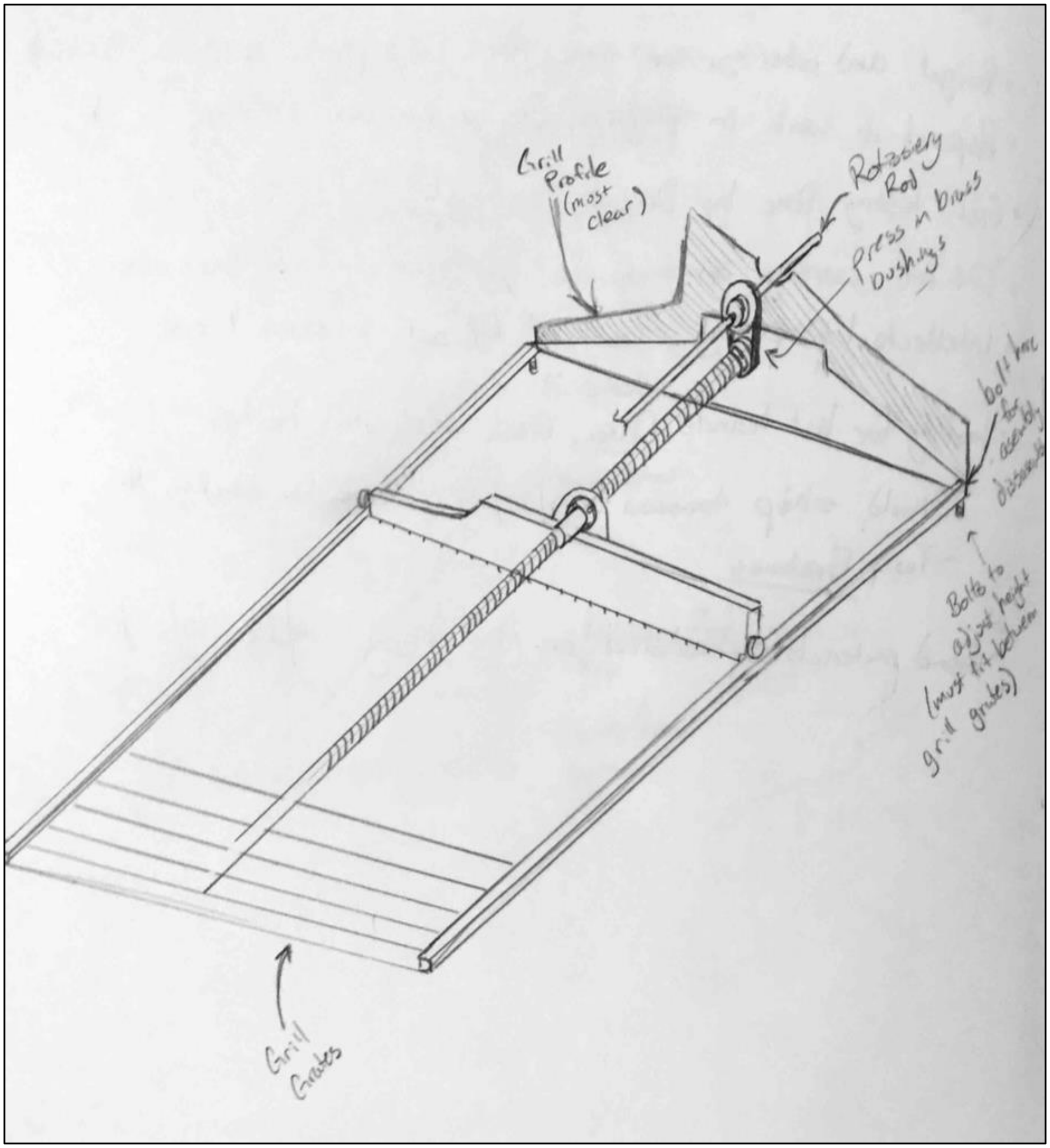


Figure D3: *Initial design sketch showing general apparatus concept.*

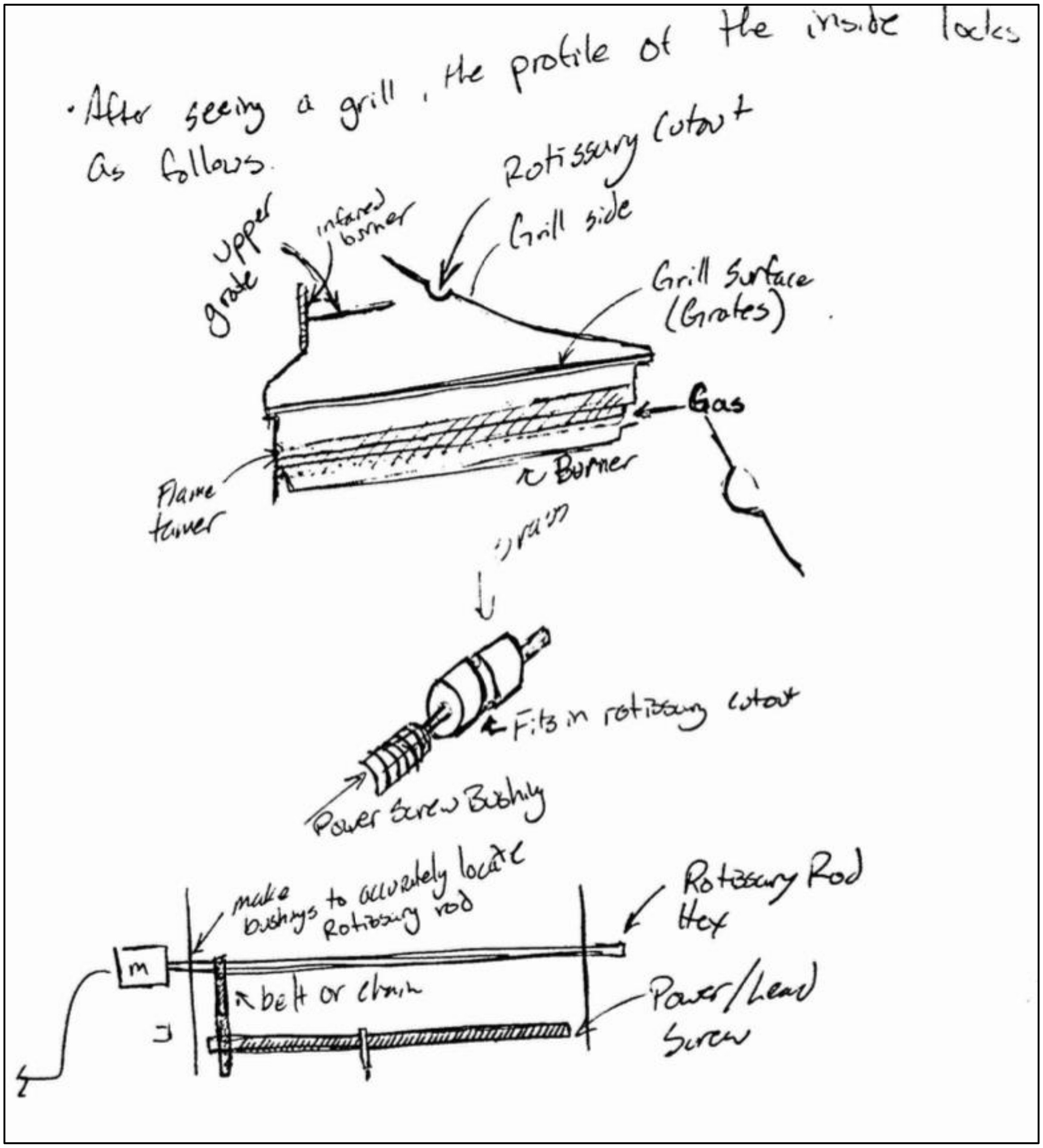


Figure D4: *Initial design sketch showing method of transferring motion from indexing dial to power screw.*

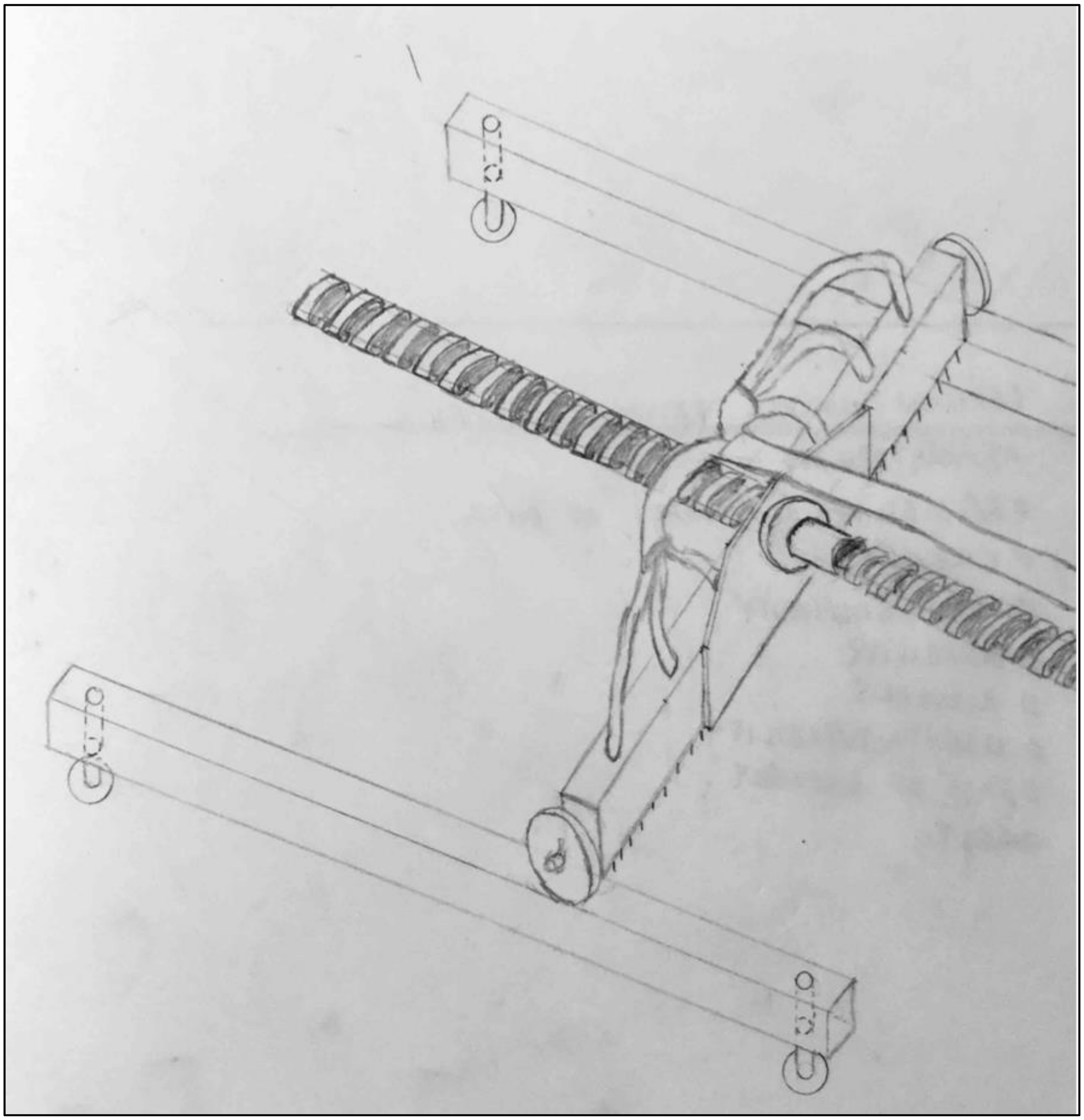
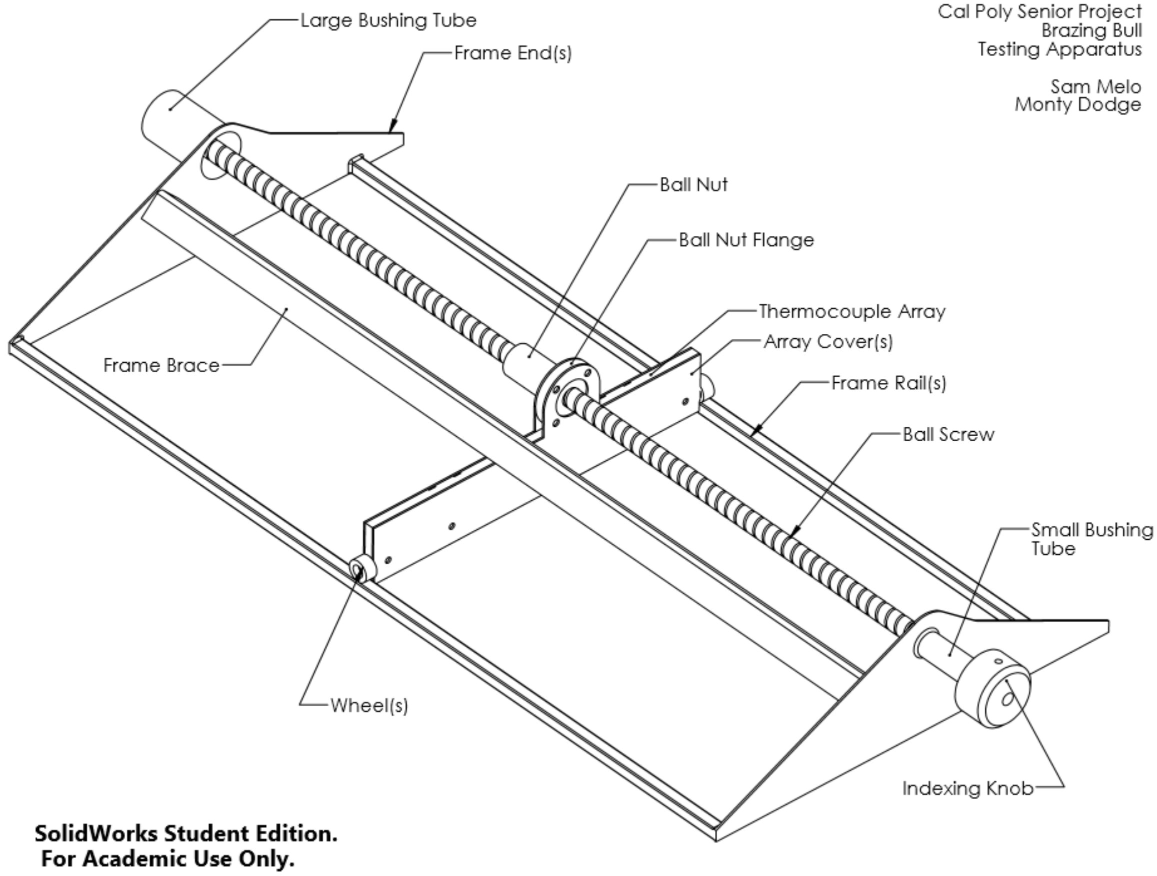
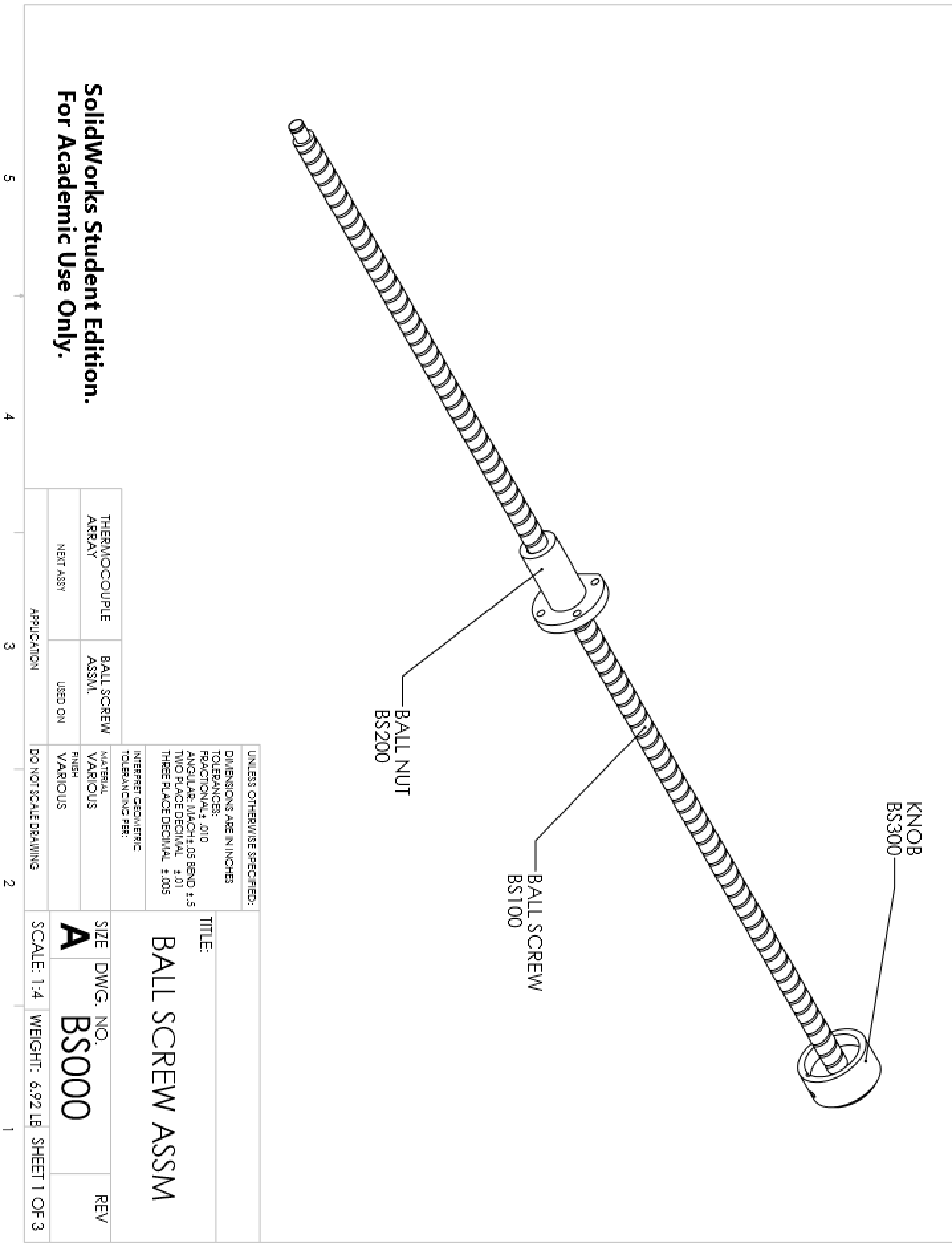


Figure D5: *Initial design sketch showing general apparatus concept and thermocouple layout.*

Appendix E (Technical Component Documents)





KNOB
BS300
BALL SCREW
BS100
BALL NUT
BS200
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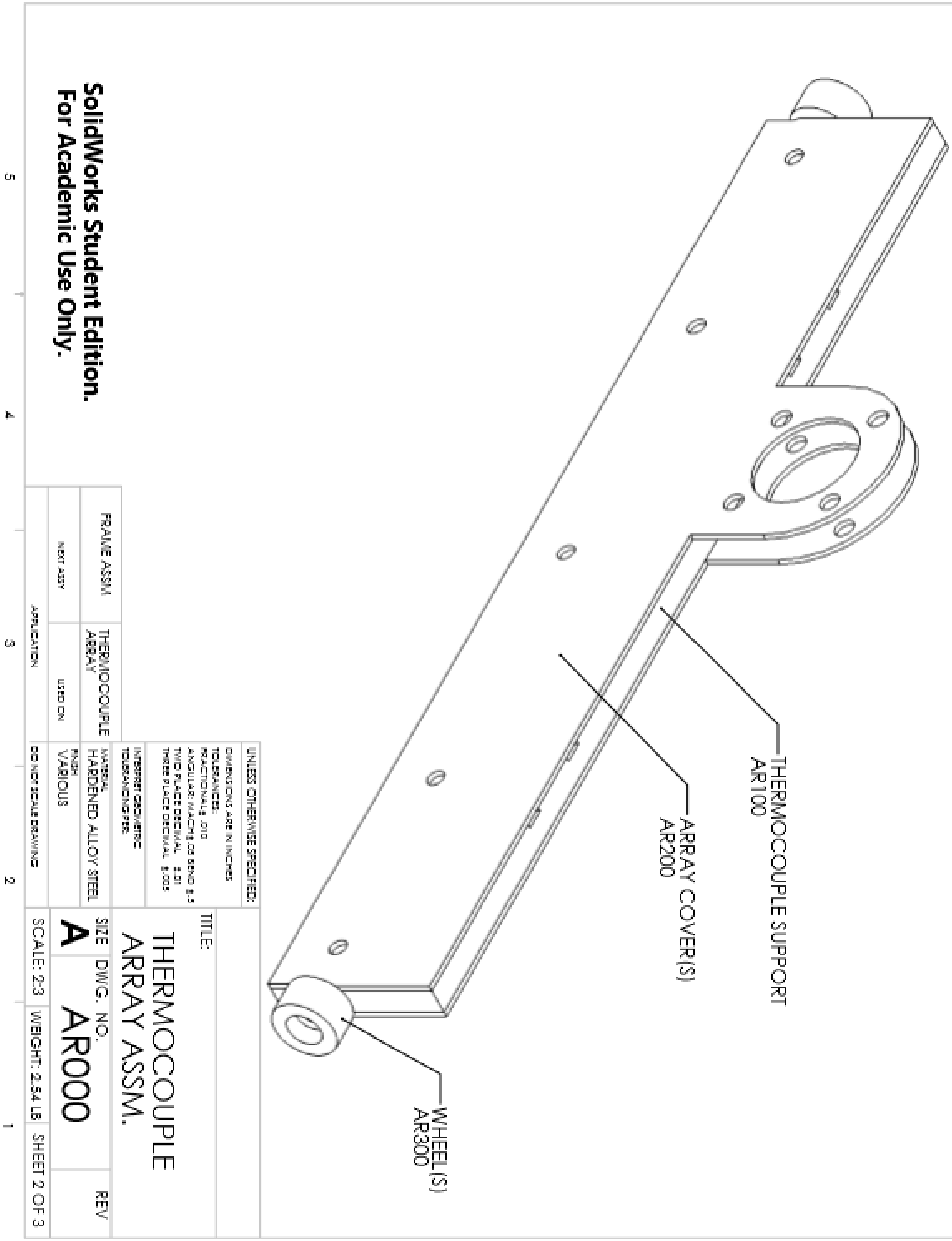
NEXT ASSY
BALL SCREW ASSM.
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .010
ANGULAR: MACH ±.05 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
VARIOUS
FINISH
VARIOUS
DO NOT SCALE DRAWING
TITLE:
BALL SCREW ASSM
SIZE
A
DWG. NO.
BS000
REV
SCALE: 1:4
WEIGHT: 6.92 LB
SHEET 1 OF 3
5
4
3
2
1


THERMOCOUPLE SUPPORT
AR100
ARRAY COVER(S)
AR200
WHEEL(S)
AR300
SolidWorks Student Edition.
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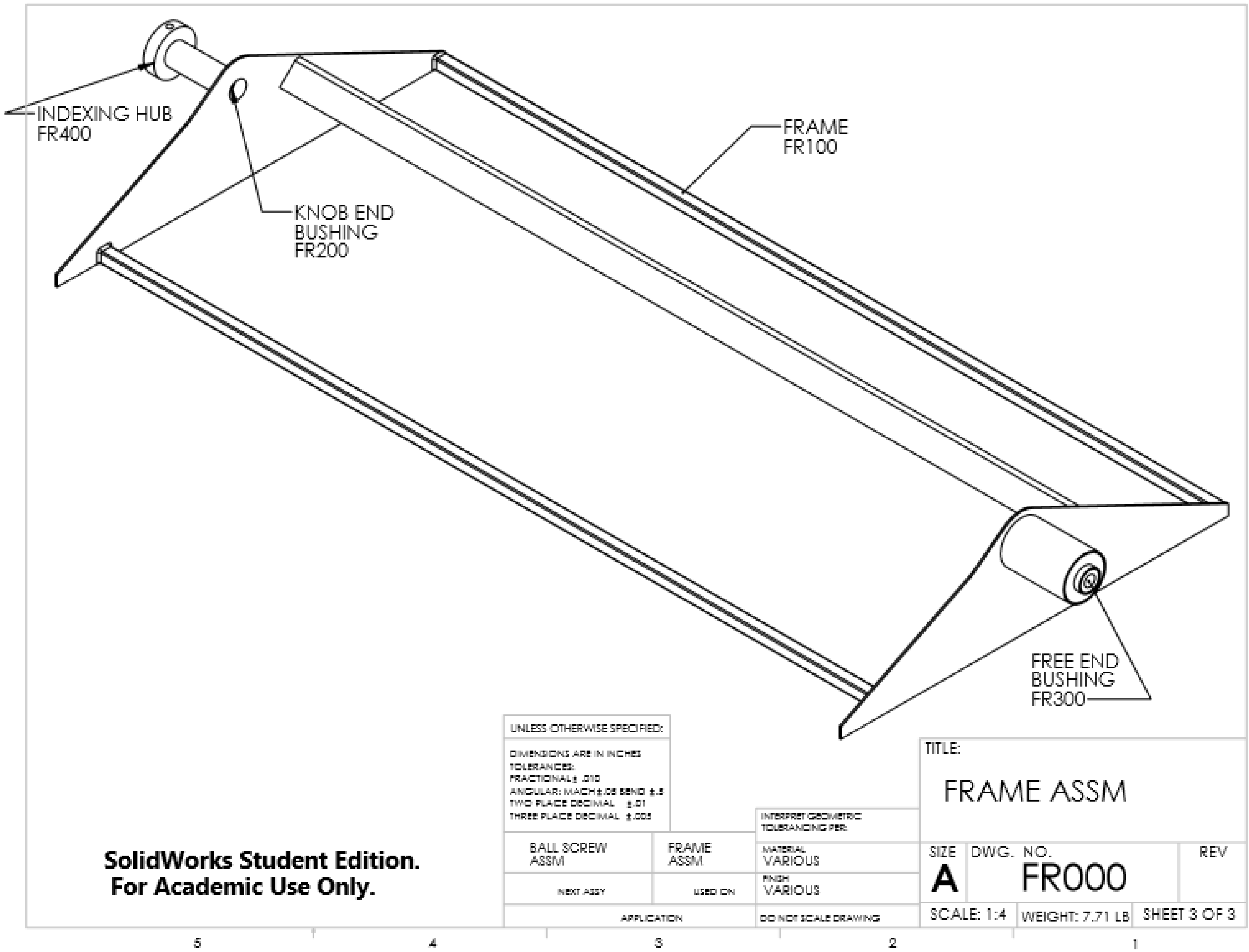
FRAME ASSM
THERMOCOUPLE ARRAY
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
MATERIAL
HARDENED ALLOY STEEL
FINISH
VARIOUS
DO NOT SCALE DRAWING
TITLE:
THERMOCOUPLE
ARRAY ASSM.
SIZE
A
DWG. NO.
AR000
REV
SCALE: 2:3
WEIGHT: 2.54 LB
SHEET 2 OF 3


INDEXING HUB
FR400
KNOB END
BUSHING
FR200
FRAME
FR100
FREE END
BUSHING
FR300
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .010
ANGULAR: MACH ±.05 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC
TOLERANCING PER:
BALL SCREW ASSM
FRAME ASSM
NEXT ASSY
USED ON
APPLICATION
MATERIAL
VARIOUS
FINISH
VARIOUS
DO NOT SCALE DRAWING
TITLE:
FRAME ASSM
SIZE
A
DWG. NO.
FR000
REV
SCALE: 1:4
WEIGHT: 7.71 LB
SHEET 3 OF 3
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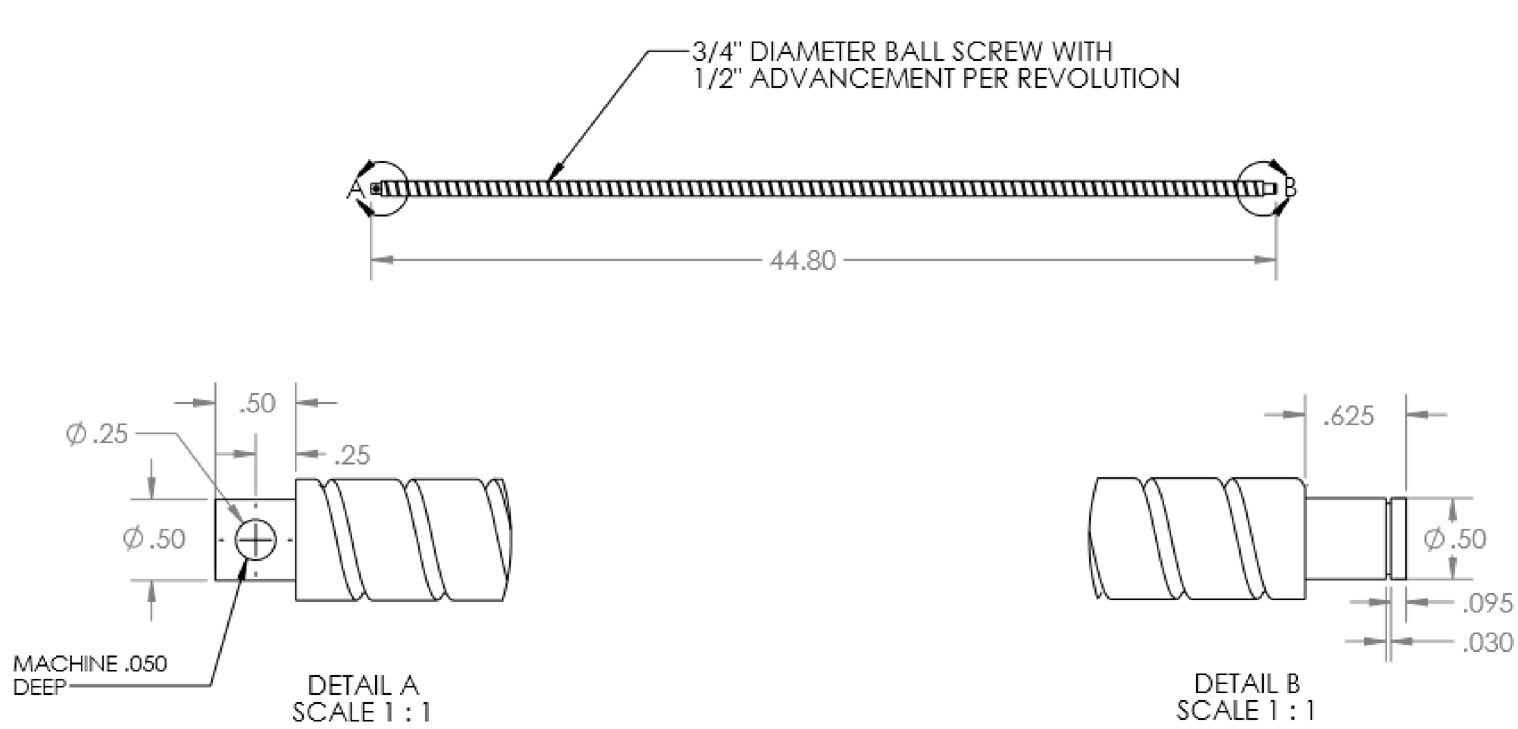
5
4
3
2
1



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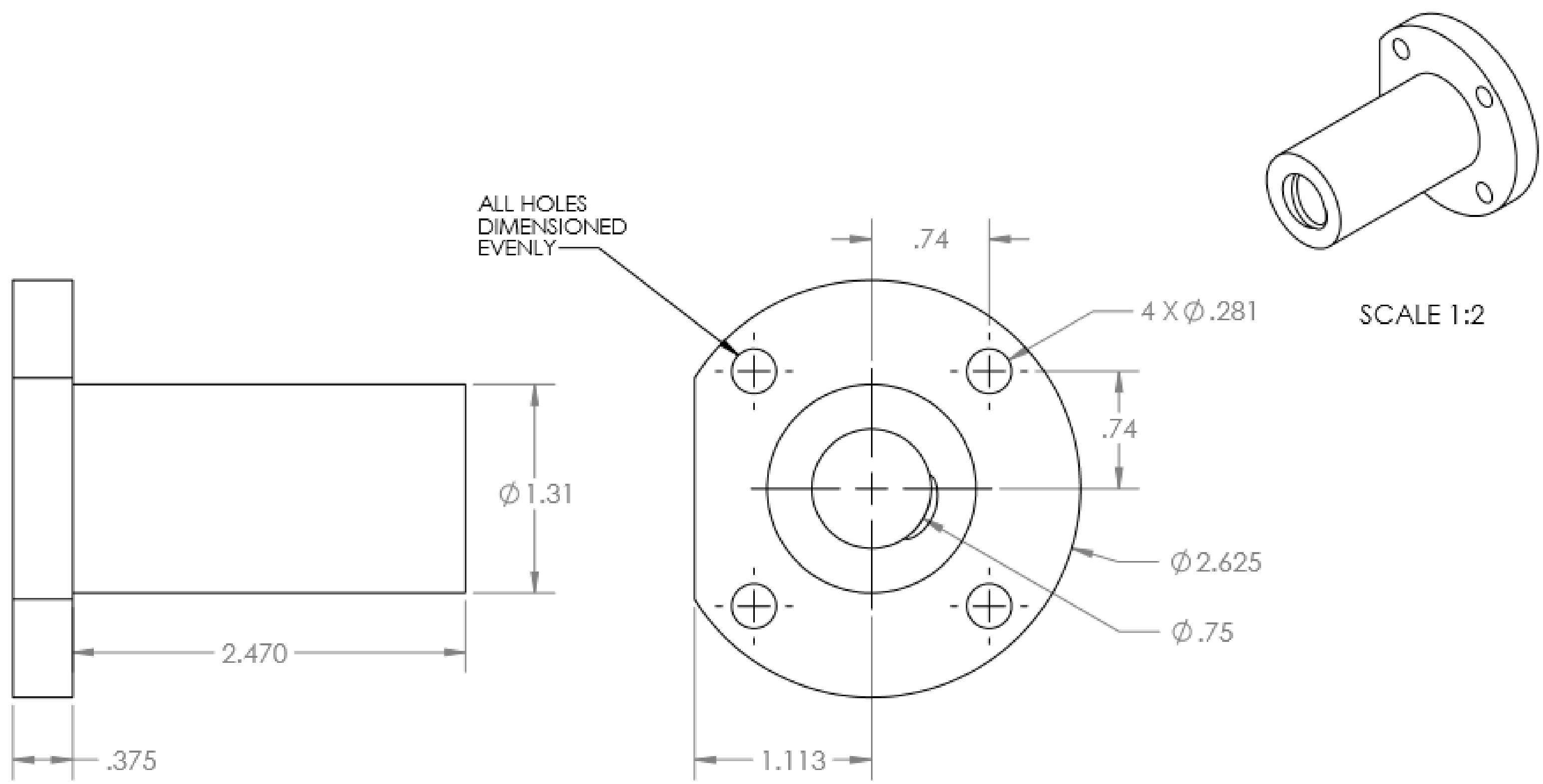
THERMOCOUPLE ARRAY — NEXT ASSY
BALL SCREW ASSM. — USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .010
ANGULAR: MACH ±.05 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: HARDENED ALLOY STEEL
FINISH: MACHINE ROLLED
DO NOT SCALE DRAWING

TITLE: BALL SCREW

SIZE: A
DWG. NO.: BS100
REV
SCALE: 1:8
WEIGHT: 5.34 LB
SHEET 1 OF 10

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± .010 ANGULAR: MACH±.05 BEND ±.5 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005	TITLE: BALL NUT & FLANGE		
INTERPRET GEOMETRIC TOLERANCING PER:			
MATERIAL HARDENED ALLOY STEEL	SIZE A	DWG. NO. BS200	REV
FINISH END MILL / FILED			
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: 1.11 LB	SHEET 2 OF 10

THERMOCOUPLE ARRAY	BALL SCREW ASSM.
NEXT ASSY	USED ON
APPLICATION	

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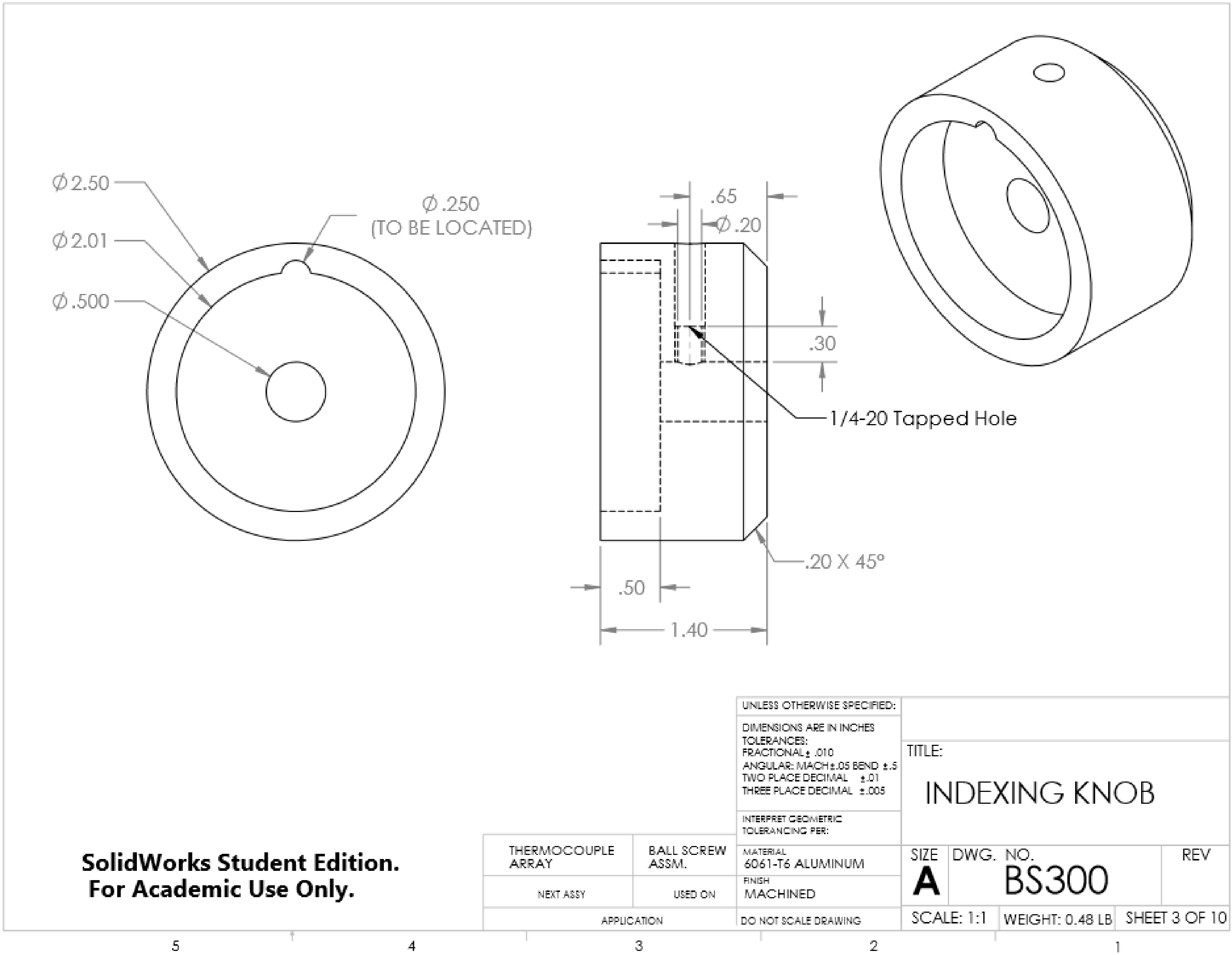
5 4 3 2 1



Ø 2.50
Ø 2.01
Ø .500
Ø .250
(TO BE LOCATED)
.65
Ø .20
.30
1/4-20 Tapped Hole
.20 X 45°
.50
1.40
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .010
ANGULAR: MACH ± .05 BEND ± .5
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6 ALUMINUM
FINISH
MACHINED
DO NOT SCALE DRAWING
THERMOCOUPLE ARRAY
BALL SCREW ASSM.
NEXT ASSY
USED ON
APPLICATION
TITLE:
INDEXING KNOB
SIZE
A
DWG. NO.
BS300
REV
SCALE: 1:1
WEIGHT: 0.48 LB
SHEET 3 OF 10
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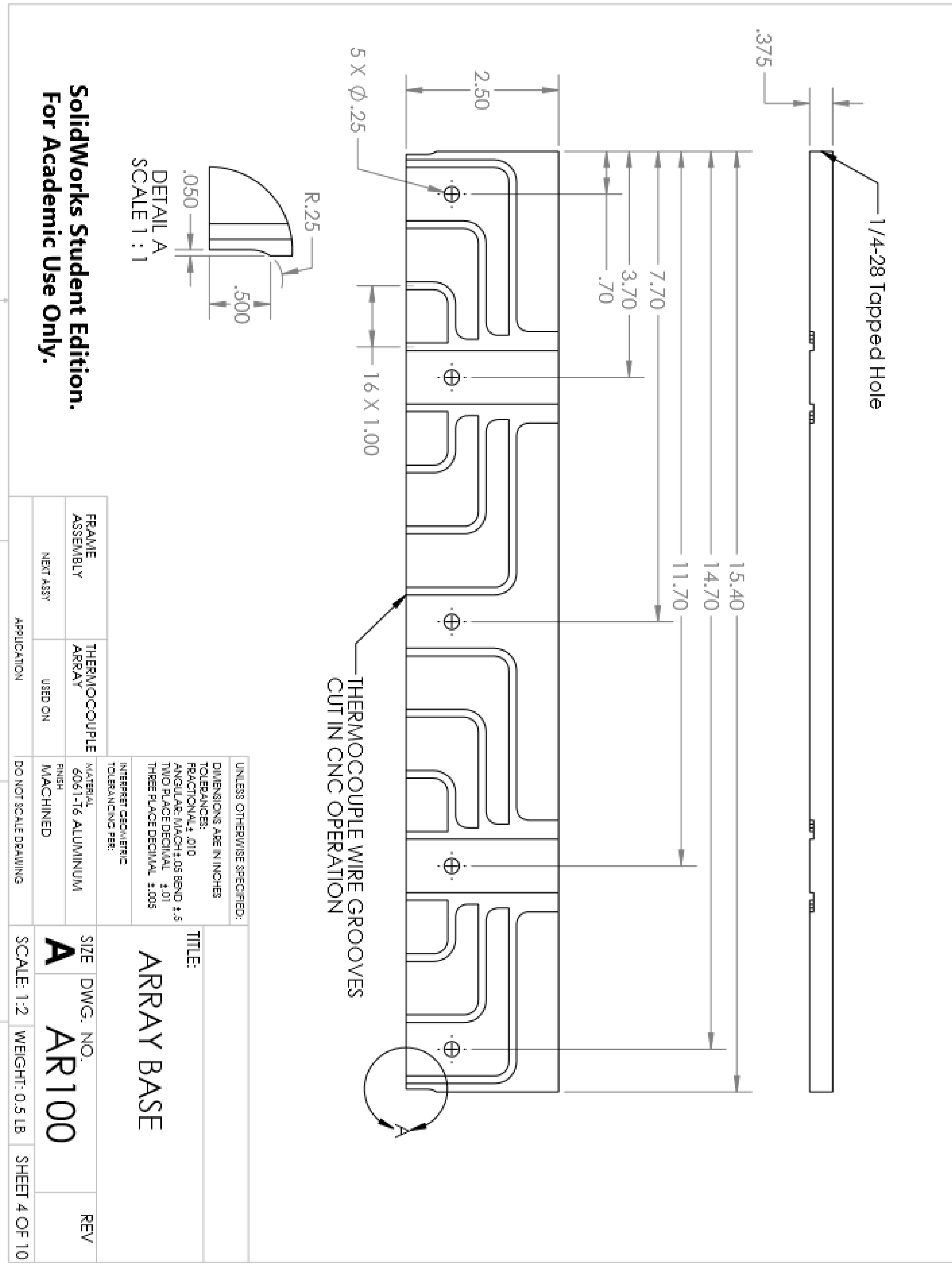
5
4
3
2
1


.375
1/4-28 Tapped Hole
5 X Ø.25
2.50
.70
3.70
7.70
11.70
14.70
15.40
16 X 1.00
THERMOCOUPLE WIRE GROOVES CUT IN CNC OPERATION
R.25
.050
.500
DETAIL A
SCALE 1 : 1
A
SolidWorks Student Edition.
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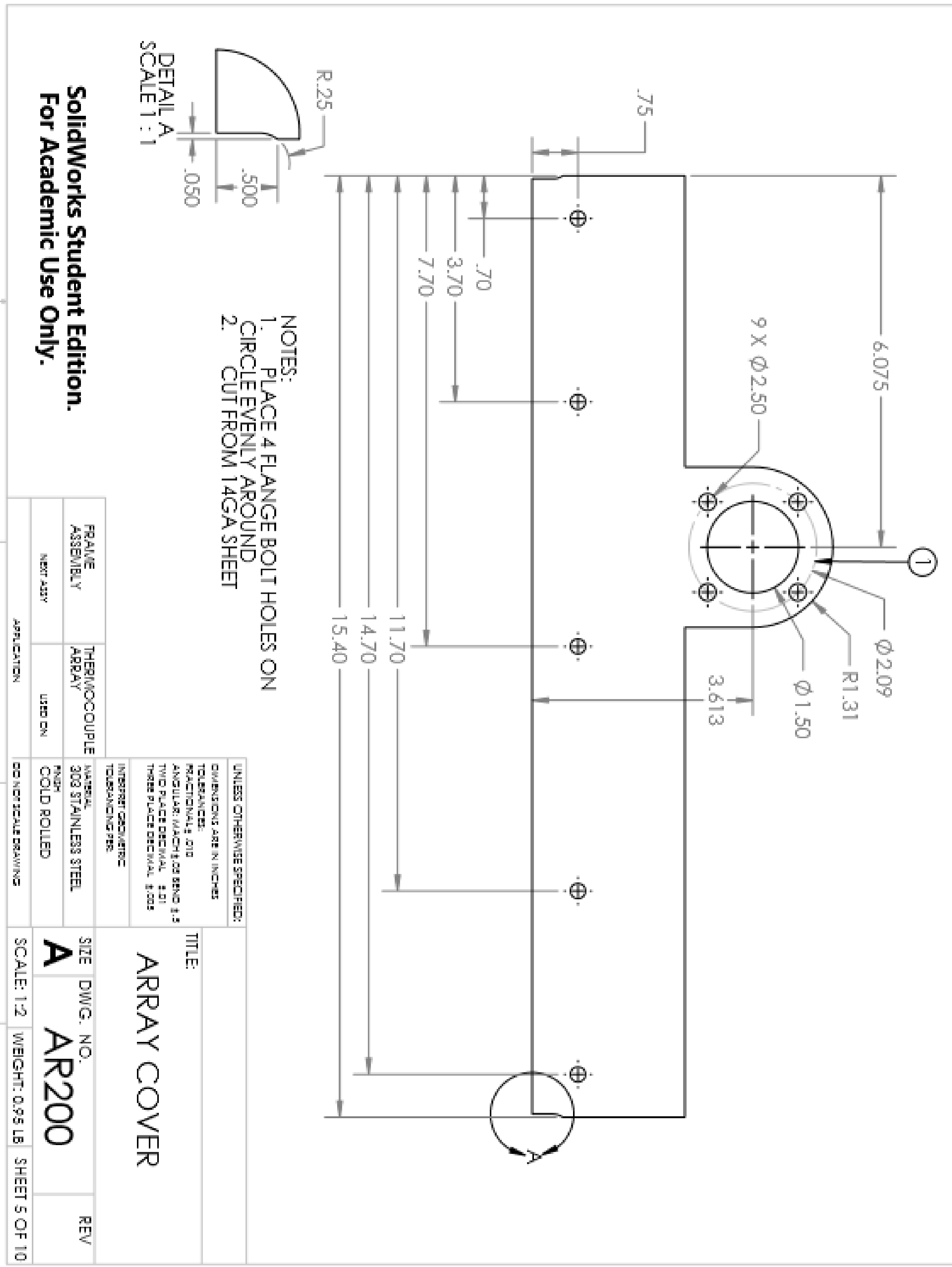
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL± .010
ANGULAR: MACH± .05 BEND ± .5
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6 ALUMINUM
FINISH
MACHINED
DO NOT SCALE DRAWING
FRAME ASSEMBLY
THERMOCOUPLE ARRAY
NEXT ASSY
USED ON
APPLICATION
TITLE:
ARRAY BASE
SIZE
A
DWG. NO.
AR100
REV
SCALE: 1:2
WEIGHT: 0.5 LB
SHEET 4 OF 10
5
4
3
2
1


.75
R.25
DETAIL A
SCALE 1 : 1
.500
.050
.70
3.70
7.70
11.70
14.70
15.40
6.075
9 X ⌀2.50
⌀2.09
R1.31
⌀1.50
3.613
A
NOTES:
1. PLACE 4 FLANGE BOLT HOLES ON CIRCLE EVENLY AROUND
2. CUT FROM 14GA SHEET
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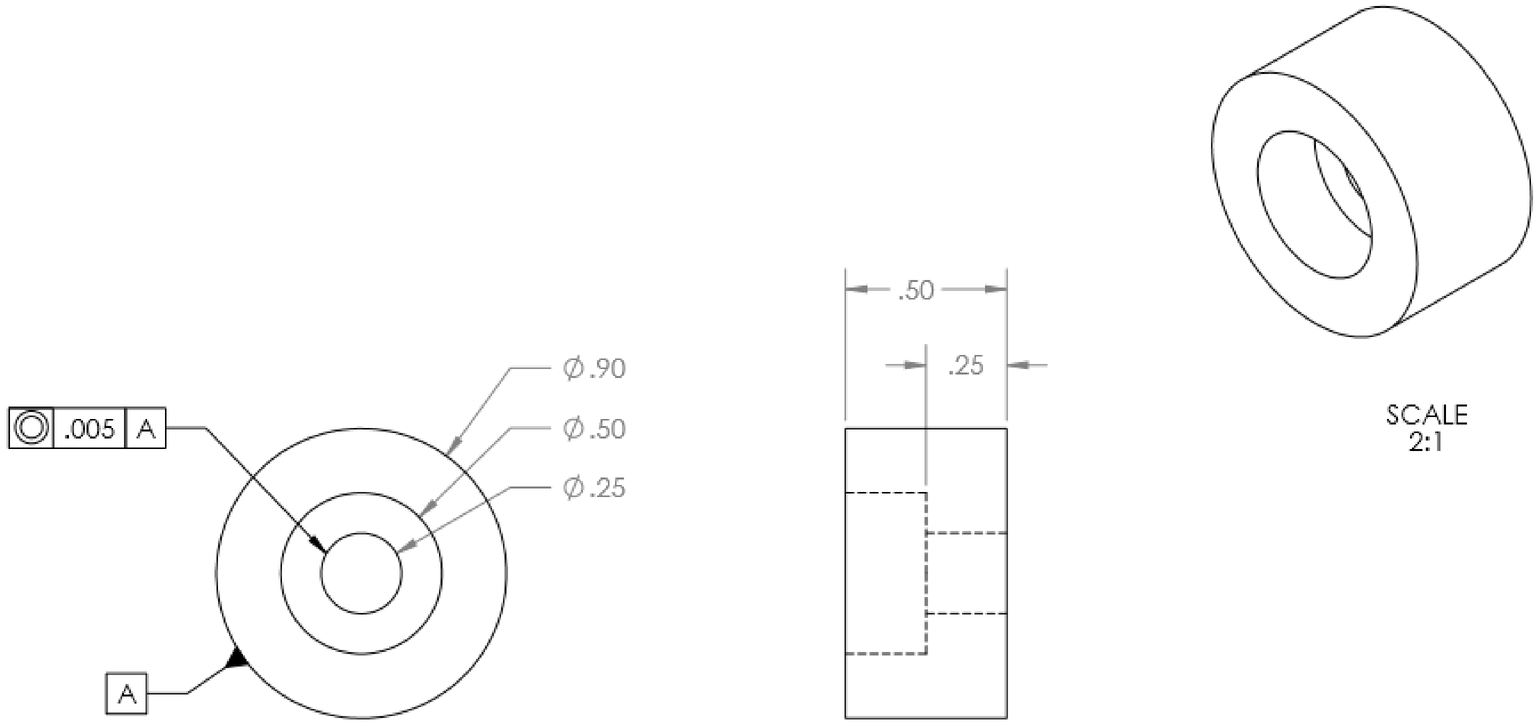
UNLESS OTHERWISE SPECIFIED:
MATERIAL
303 STAINLESS STEEL
FINISH
COLD ROLLED
DO NOT SCALE DRAWING
FRAME ASSEMBLY
THERMOCOUPLE ARRAY
NEXT ASSY
USED ON
APPLICATION
TITLE:
ARRAY COVER
SIZE
A
DWG. NO.
AR200
REV
SCALE: 1:2
WEIGHT: 0.95 LB
SHEET 5 OF 10



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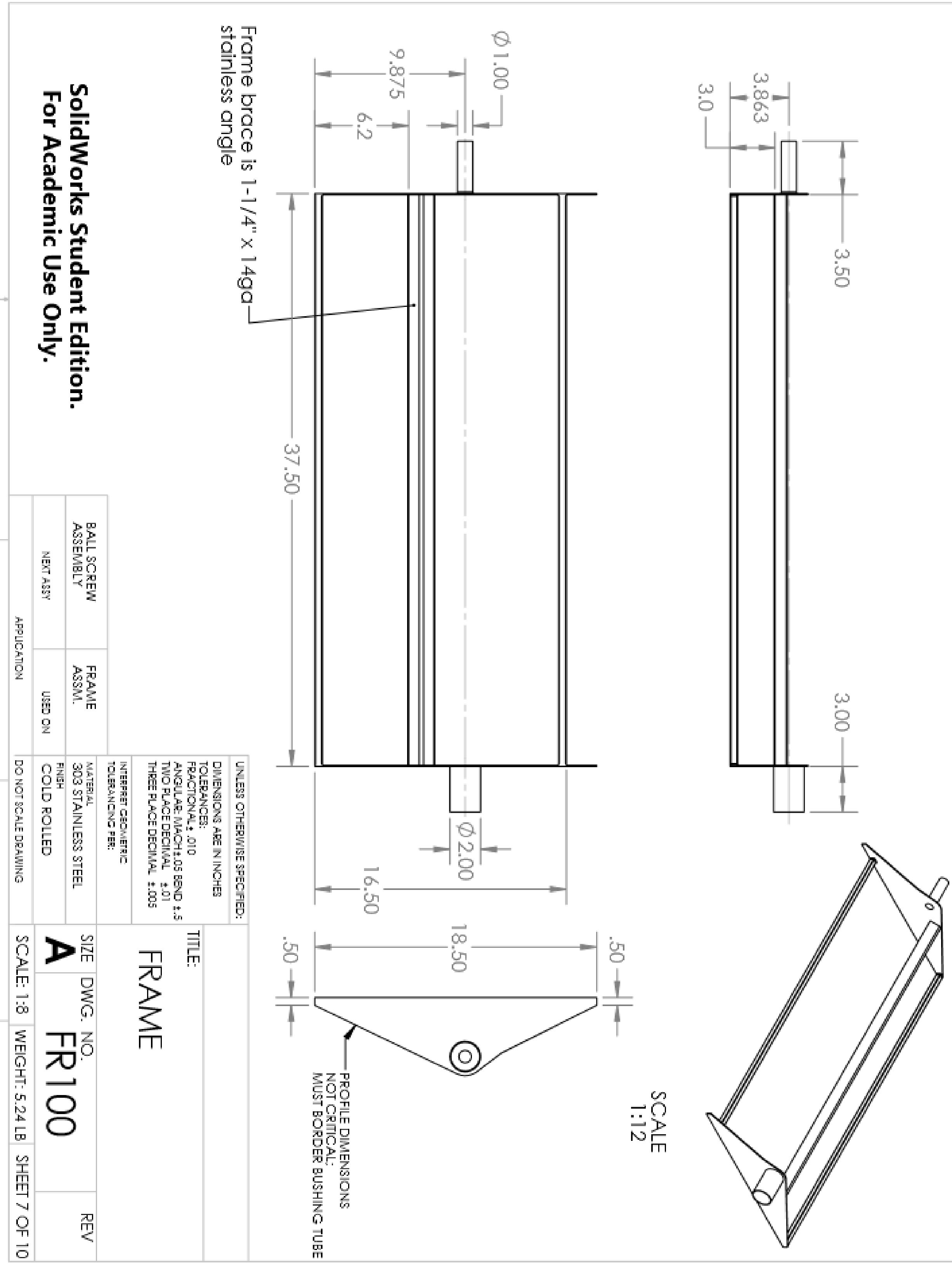
		UNLESS OTHERWISE SPECIFIED:		
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± .010 ANGULAR: MACH±.05 BEND ±.5 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005	TITLE: ARRAY WHEEL	
		INTERPRET GEOMETRIC TOLERANCING PER:		
FRAME ASSEMBLY	THERMOCOUPLE ARRAY	MATERIAL 304 STAINLESS BAR	SIZE A	DWG. NO. AR300 — REV
NEXT ASSY	USED ON	FINISH MACHINED		
APPLICATION		DO NOT SCALE DRAWING	SCALE: 4:1	WEIGHT: 0.02 LB — SHEET 6 OF 10

5 4 3 2 1


Ø1.00
9.875
6.2
3.863
3.0
3.50
3.00
37.50
Ø2.00
16.50
18.50
.50
.50
SCALE 1:12
Frame brace is 1-1/4" x 14ga stainless angle
PROFILE DIMENSIONS NOT CRITICAL: MUST BORDER BUSHING TUBE
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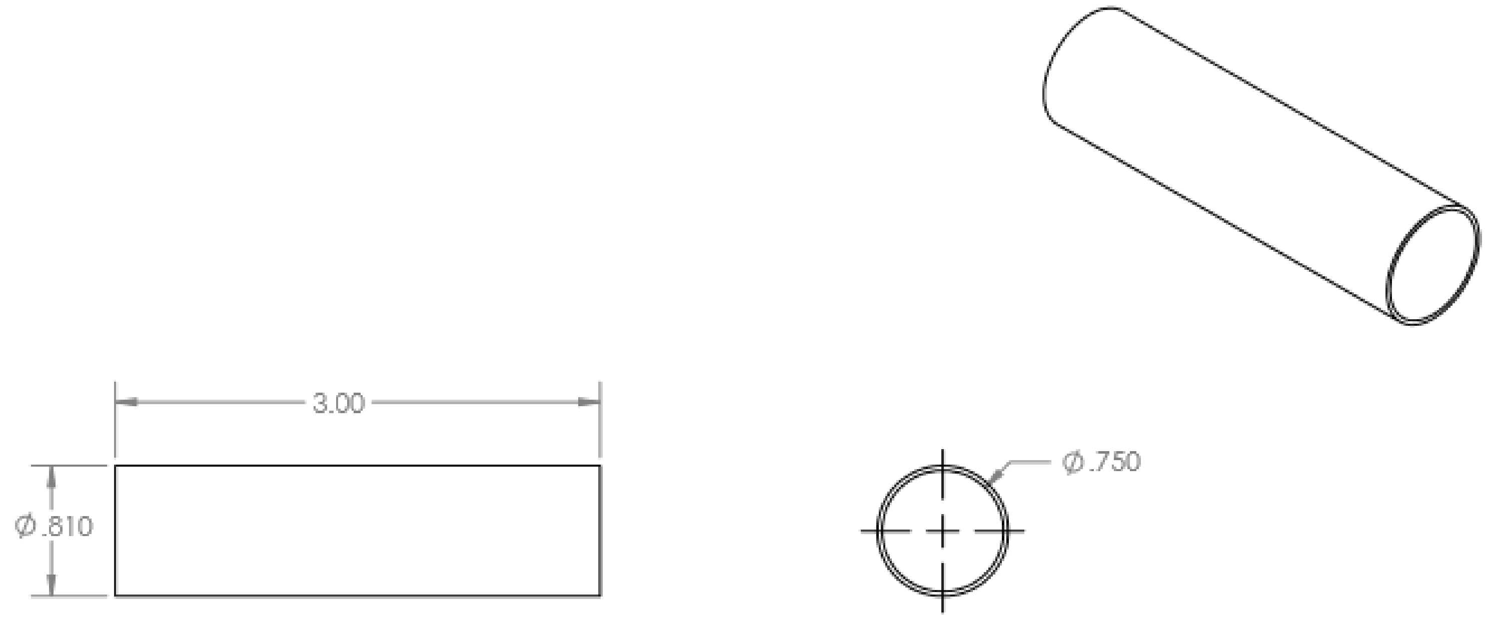
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±.010
ANGULAR: MACH ±.05 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
303 STAINLESS STEEL
FINISH
COLD ROLLED
DO NOT SCALE DRAWING
BALL SCREW ASSEMBLY
NEXT ASSY
FRAME ASSM.
USED ON
APPLICATION
TITLE:
FRAME
SIZE
A
DWG. NO.
FR100
REV
SCALE: 1:8
WEIGHT: 5.24 LB
SHEET 7 OF 10
1
2
3
4
5



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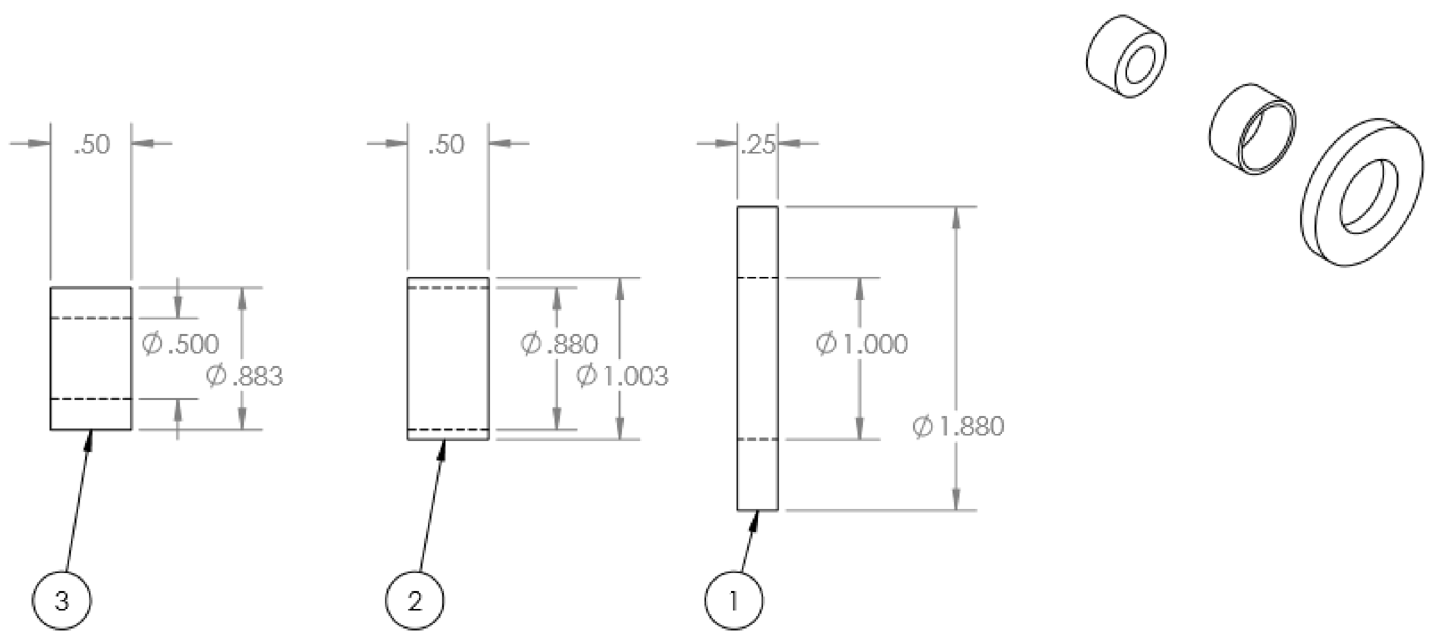
BALL SCREW ASSM.	FRAME ASSEMBLY	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .010 ANGULAR: MACH ±.05 BEND ±.5 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005 INTERPRET GEOMETRIC TOLERANCING PER:	TITLE: KNOB END BUSHING
NEXT ASSY	USED ON	MATERIAL BRASS	SIZE A — DWG. NO. FR200 — REV
APPLICATION		FINISH MACHINED — DO NOT SCALE DRAWING	SCALE: 1:1 — WEIGHT: 0.07 LB — SHEET 8 OF 10

5 4 3 2 1



Part	Name	Fit	Material
1	Bushing Spacer	.003 Interferance	303 Stainless Bar
2	Bushing Support	.003 Interferance	303 Stainless Tube
3	Bushing	.003 Interferance	Brass

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .010
ANGULAR: MACH ± .05 BEND ± .5
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL VARIOUS

FINISH VARIOUS

DO NOT SCALE DRAWING

BALL SCREW ASSM.	FRAME ASSM.
NEXT ASSY	USED ON
APPLICATION	

TITLE: FREE END BUSHING

SIZE A | DWG. NO. FR300 | REV

SCALE: 1:1 | WEIGHT: 0.23 LB | SHEET 9 OF 10

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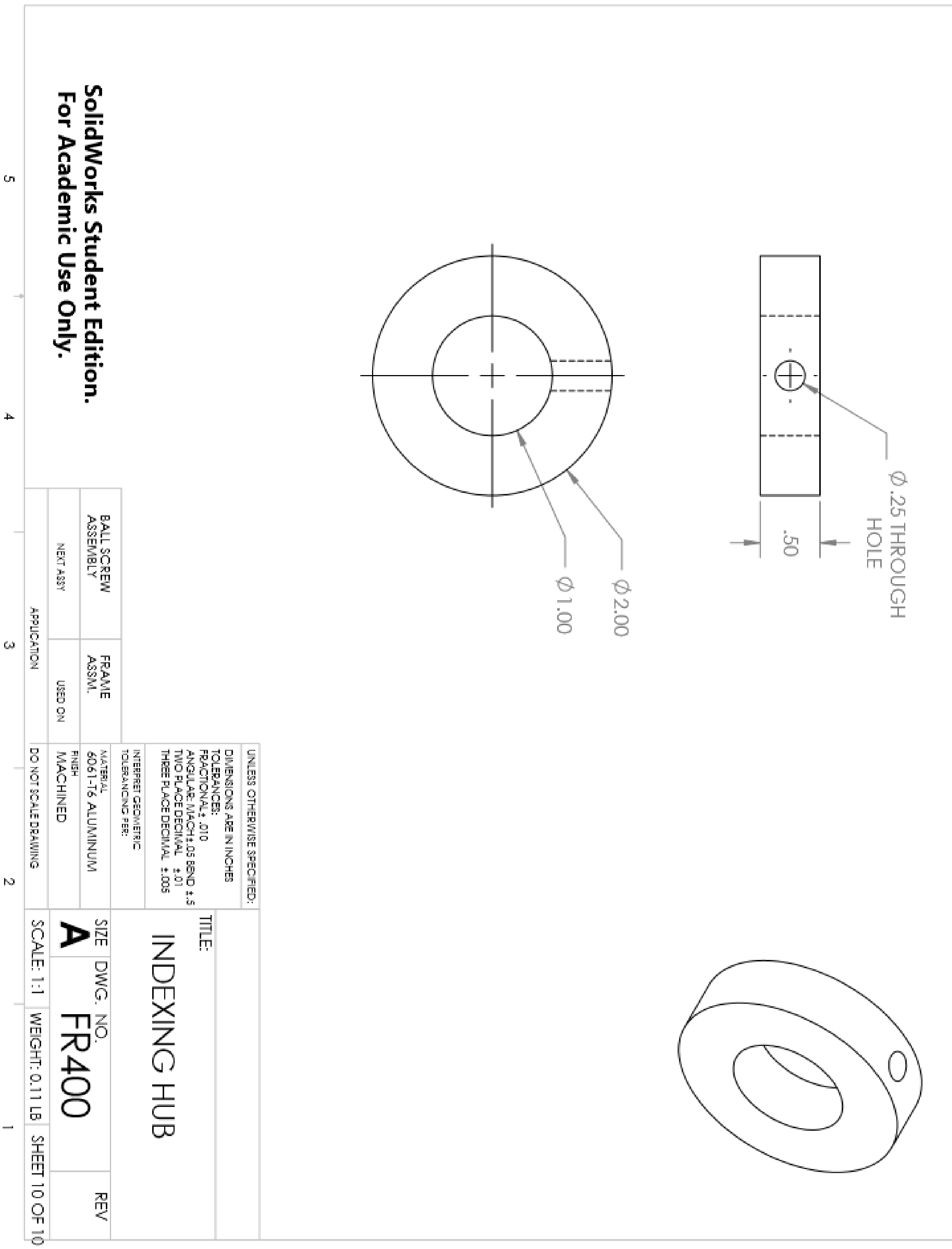
5 4 3 2 1



Ø .25 THROUGH HOLE
.50
Ø 2.00
Ø 1.00
SolidWorks Student Edition.
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BALL SCREW ASSEMBLY
FRAME ASSM.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .010
ANGULAR: MACH ±.05 BEND ±.5
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6 ALUMINUM
FINISH
MACHINED
DO NOT SCALE DRAWING
TITLE:
INDEXING HUB
SIZE
A
DWG. NO.
FR400
REV
SCALE: 1:1
WEIGHT: 0.11 LB
SHEET 10 OF 10
5
4
3
2
1

FRAME RAILS				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	CUT STOCK TO LENGTH & DEBURR	CHOP SAW	TAPE MEASURE, BELT SANDER/BENCH GRINDER	0.25
20	MACHINE TO EXACT LENGTH	VERTICAL MILL	MILLING VICE, PARALLELS, 1/2 2-FLUTE HSS END MILL	0.5
30	PART INSPECTION	FLAT BENCH	TAPE MEASURE	0.1
NOTES: Make sure that each frame rail is exactly the same length			TOTAL TIME:	0.85

Figure E1: Frame rail build sheet.

FRAME END				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	PRINT TEMPLATE	HP PLOTTER	LARGE PRINTER IN LAB	0.25
20	TRIM TEMPLATE	FLAT BENCH	KNIFE, RAZOR	0.1
30	CUT PART	HANGAR, OPTICAL PLASMA	MASKING TAPE, TAPE MEASURE, PLIERS	2
40	DEBURR PARTS	BELT SANDER, BENCH GRINDER, BENCH WIRE WHEEL	VICE, PADDLE WHEEL ANGLE GRINDER	1
50	TRANSFER HOLE LOCATIONS	BONDERSON 108	TAPE MEASURE, CENTER PUNCH, SHARPIE	1
60	DRILL HOLE(S)	MUSTANG 60', DRILL PRESS	MACHINING VICE, WOOD BACKING, 1/8" HSS TWIST DRILL BIT, 7/8" HSS TWIST DRILL BIT	0.5
70	BORE LARGE HOLE	BUILDING 41, VERTICAL MILL	BORING INSERT, DIAL CALIPERS	1.5
80	DEBURR PARTS	BELT SANDER, BENCH GRINDER, BENCH WIRE WHEEL	NONE	0.3
90	PART INSPECTION	FLAT BENCH	TAPE MEASURE, DIAL CALIPERS	0.25
NOTES: Try to get bottoms as straight as possible. Make sure centers of extension tube holes on each side line up with each other.			TOTAL TIME:	6.9

Figure E2: Frame end build sheet.

FRAME ASSEMBLY				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	WELD FRAME ENDS	TIG WELDER	FIXTURING EQUIPMENT, WELDING HELMET, WELDING GLOVES, STAINLESS FILLER ROD	1.5
20	CLEAN WELDS	BENCH	VICE, ANGLE GRINDER WITH PADDLE SANDING WHEEL	0.5
30	PRESS FIT BUSHINGS TO BUSHING TUBES	ARBOR PRESS	FLAT BLOCKS, SHIMS	0.5
40	WELD BUSHING TUBES TO FRAME	TIG WELDER	FIXTURING EQUIPMENT, WELDING HELMET, WELDING GLOVES, STAINLESS FILLER ROD	1.5
50	PRESS FIT INDEXING HUB	ARBOR PRESS	FLAT BLOCKS, SHIMS	0.25
60	WELD LINEAR SUPPORT	TIG WELDER	FIXTURING EQUIPMENT, WELDING HELMET, WELDING GLOVES, STAINLESS FILLER ROD	0.5
NOTES: When welding busing tubes, use lead screw to make sure they are in line and square			TOTAL TIME:	4.75

Figure E3: Frame assembly build sheet.

THERMOCOUPLE ARRAY ASSEMBLY				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	FIT THERMOCOUPLE WIRES TO ARRAY	BENCH	QUICK GRIPS, STRAIGHT ANLGE IRON FOR BACKING, MASKING TAPE	1
20	FASTEN ARRAY COVERS TO ARRAY	BENCH	CRESCENT WRENCH, PHILLIPS DRIVER, IMPACT DRIVER	0.5
30	FASTEN BALL NUT FLANGE TO ARRAY COVERS	BENCH	CRESCENT WRENCH, PHILLIPS DRIVER, IMPACT DRIVER	0.5
40	FASTEN ARRAY WHEELS TO SIDES	BENCH	PHILLIPS DRIVER	0.1
NOTES: Wire exposure from bottom of array is .050". Clearance from grill surface is .250" to array, .200" to wire tips.			TOTAL TIME:	2.1

Figure E4: Thermocouple array assembly build sheet.

THERMOCOUPLE ARRAY				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	CUT STOCK	VERTICAL BAND SAW	TAPE MEASURE	0.1
20	MILL OPERATION, FINAL LENGTH	MANUAL MILL	DIAL CALIPERS, TAPE MEASURES, 1/2" 2-FLUTE HSS END MILL	0.5
30	CNC OPERATION, CUT WIRE GROOVES, DRILL HOLES	HAAS VF2 CNC MILL	MILLING VICE, 1-5/8" PARRALLELS, 1/8" 2-FLUTE HSS END MILL, 1/4" HSS TWIST DRILL	1
40	DRILL WHEEL MOUNTING HOLES	MANUAL MILL	DIAL CALIPERS, DRILL BIT FOR 1/4"-20 TAPPED HOLE	0.75
50	TAP WHEEL MOUNTING HOLES	BENCH VICE	1/4"-20 TAP, TAP MAGIC CUTTING FLUID	0.5
60	DEBURR AND INSPECT	BENCH	DEBURRING TOOL	0.25
NOTES: Set G55 home location to back left of stock/vice. Use drilled holes to transfer to array covers later.			TOTAL TIME:	3.1

Figure E5: Thermocouple array build sheet.

BALL NUT FLANGE				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	MILL OPERATION, CUT CLEARANCE FOR ARRAY, FACE TO MATCH ARRAY THICKNESS	MANUAL MILL	1/2" 4-FLUTE CARBIDE END MILL, MILLING VICE, DIAL CALIPERS	2
20	DEBURR AND INSPECT	BENCH	DIAL CALIPERS, FILE, DEBURRING TOOL	0.5
NOTES: Flange needs .200" removed from circular edge for proper clearance. Remove from side opposite of set screw.			TOTAL TIME:	2.5

Figure E6: Ball nut flange build sheet.

THERMOCOUPLE ARRAY COVERS				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	PRINT TEMPLATE	HP PLOTTER	LARGE PRINTER IN LAB	0.25
20	TRIM TEMPLATE	FLAT BENCH	KNIFE, RAZOR	0.1
30	CUT PART	HANGAR, OPTICAL PLASMA	MASKING TAPE, TAPE MEASURE, PLIERS	2
40	DEBURR PARTS	BELT SANDER, BENCH GRINDER, BENCH WIRE WHEEL	VICE, PADDLE WHEEL ANGLE GRINDER	1
50	TRANSFER HOLE LOCATIONS	FLAT BENCH	CENTER PUNCH, TAPE MEASURE, DIAL CALIPERS, SHARPIE	1
60	DRILL HOLES	MUSTANG 60', DRILL PRESS	MACHINING VICE, 1/4" HSS TWIST DRILL BIT	2
70	BORE LARGE HOLES	DRILL PRESS	1-3/8" WHOLE SAW, VICE, CUTTING FLUID	2
80	PART INSPECTION AND DEBURR	METROLOGY LAB	DEBURRING TOOL, DIAL CALIPERS, FILE	1
NOTES: Use the array to transfer hole locations by aligning bottom edges. Use ball nut flange to transfer flange holes. Clamp pieces together and drill simultaneously for proper alignment.			TOTAL TIME:	9.35

Figure E7: Thermocouple array cover build sheet.

THERMOCOUPLE ARRAY WHEELS				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	BORE INSIDE DIAMETER, TURN OUTSIDE DIAMETER, FACE, PART OFF, ALL ON STOCK PIECE	MANUAL LATHE	DIAL CALIPERS, BORING TOOL OR 51/4" HSS TWIST DRILL BIT, CARBIDE INSERT, PARTING INSERT	3
20	INSPECT PART AND DEBURR	FLAT BENCH	DIAL CALIPERS, DEBURRING TOOL	0.5
~~30~~	~~PRESS IN BEARINGS~~	~~ARBOR PRESS~~	~~FLAT SURFACE~~	~~0.25~~
NOTES: Matching diameter on each wheel is critical to proper array height from front to back of apparatus. Step 30 is crossed out after design modification.			TOTAL TIME:	3.75

Figure E8: Thermocouple array wheel build sheet.

LEAD SCREW				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	CUT STOCK TO LENGTH	CHOP SAW, OR HORIZONTAL BAND SAW	TAPE MEASURE	0.5
20	LATHE OPERATION, LENGTH, LOCATINGS SHOULDER, SNAP RING GROOVE	MANUAL LATHE	DIAL CALIPERS, TAPE MEASURE	3
25	MILL OPERATION, SLOT FOR SET SCREW	MANUAL MIL	3/32" 2 FLUTE HSS END MILL	0.5
30	INSPECT AND DEBURR	FLAT BENCH	EMORY CLOTH, DIAL CALIPERS, WIRE WHEEL	0.5
NOTES: Ensure there are no burrs on the threads so there will be no issues with ball nut installation.			TOTAL TIME:	4.5

Figure E9: Lead screw build sheet.

BRASS BUSHINGS				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	CUT STOCK TO LENGTH	VERTICAL BAND SAW	TAPE MEASURE	0.5
20	LATHE OPERATON, BORE INSIDE DIAMETER, TURN OUTSIDE DIAMETER, FACE, PART OFF	MANUAL LATHE	DIAL CALIPERS	3
30	DEBURR AND INSPECT	LATHE, FLAT BENCH	FILE, DIAL CALIPERS	0.5
40	PRESS FIT	ARBOR PRESS	NONE	0.5
50	INSPECT	FLAT BENCH	DIAL CALIPERS	0.5
NOTES: Bushing length is not critical.			TOTAL TIME:	5

Figure E10: Brass bushing build sheet.

INDEXING HUB				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	LATHE OPERATION, FACE, TURN, BORE, PART OFF	MAUAL LATHE	DIAL CALIPERS, 15/16" HSS TWIST DRILL, 1" REAMER, CARBIDE CUTTING INSERT, PARTING TOOL	1
20	DRILL SPRING & DETENT HOLE	DRILL PRESS	1/4" HSS TWIST DRILL	0.25
30	INSPECT AND DEBUR	FLAT BENCH	DIAL CALIPERS, DEBURING TOOL, FILE	0.25
40	PRESS FIT TO FRAME	ARBOR PRESS	FLAT BLOCKS/SHIIMS	0.25
NOTES: Point spring and detent hole directly upwards with respect to frame when pressing on.			TOTAL TIME:	1.75

Figure E11: Indexing hub build sheet.

INDEXING KNOB				
OP #	OPERATION	CELL/TOOL	TOOLING	TIME ALLOTED [HR]
10	LATHE OPERATION, TURN, FACE, TURN HUB CLEARANCE, CHAMFER EDGE	MANUAL LATHE	CARBIDE CUTTING INSERT, 1/2" HSS TWIST DRILL, DIAL CALIPERS	1.5
20	DRILL SET SCREW HOLE	DRILL PRESS	1/4" HSS TWIST DRILL, DRILL FOR 1/8" NC TAPPED HOLE	0.5
30	TAP SET SCREW HOLE	VICE	1/8" NC TAP, TAP MAGIC CUTTING FLUID	0.25
40	MILL OPERATION, CUT DETENT GROOVE	MICRO MILL	1/4" 2-FLUTE HSS END MILL	0.5
50	DRILL HOLE FOR SAFETY HANDLE	DRILL PRESS	5/16" HSS TWIST DRILL, MACHINE VICE	0.25
60	CUT STOCK FOR SAFETY HANDLE (USE CHIPPING HAMMER)	BENCH WITH VICE	TAPE MEASURE, HACK SAW	0.1
70	DEBURR HANDLE, REMOVE PAINT, RESIZE	BELT SANDER	DIAL CALIPERS	0.25
80	TAP HOLE	BENCH WITH VICE	3/8"-16 BOTTOMING TAP, TAP HANDLE, TAP MAGIC CUTTING FLUID, VICE, RAG	0.5
90	CUT THREADS IN HANDLE	BENCH WITH VICE	3/8"-16 DIE CUTTER, DIE HANDLE, TAP MAGIC CUTTING FLUID, VICE	0.5
100	DEBUR, CLEAN, AND INSPECT	BENCH WITH VICE	FILE, BELT SANDER, DEBURRING TOOL, SIMPLE GREEN, PAPER TOWELS	0.25
110	ASSEMBLE KNOB	BENCH	NONE	0.1
NOTES: Safety handle placement is not critical, just needs to be towards outer edge. Must assemble apparatus to determine detent groove location; mark with respect to hub.			TOTAL TIME:	4.7

Figure E12: Indexing knob build sheet.

Appendix F (Testing Apparatus Stress Analysis)

```
    {Constants}
g = 32.174                                  {EU Gravitational Constant}
E_st = 30*10^6                              {Elastic Modulus of Carbon Steel}
    {Conversion Factors}
lbm2slug = 1/32.174                         {conversion lbm to slug}
inch2feet = 1/12                            {Conversion inches to feet}
feet2inch = 12                              {Conversion feet to inches}
    {Mass of Rail Components}
V_r = L_r*((b_ro*h_ro) - (b_ri*h_ri))       {volume of single rail}
m_r = V_r*(rho_ss)*(lbm2slug)               {mass of single rail}
rho_ps = 0.282                              {density of plain steel}
rho_ss = 0.29                               {density of stainless steel}
b_ro = 0.5                                  {rail outer width}
h_ro = 0.5                                  {rail outer height}
b_ri = b_ro - 2*t_r                         {rail inner width}
h_ri = h_ro - 2*t_r                         {rail inner height}
t_r = 0.065                                 {rail tubing wall thickness}
L_r = 37.5                                  {rail length}
W_r = m_r*g                                 {rail weight}

    {Mass of Array Component}
V_a = 2*b_a*h_a*L_a                         {Volume of Array Member}
rho_Al = 0.098                              {Density of Aluminum}
m_a = V_a*rho_Al*lbm2slug                   {Mass of Array Member}
b_a = 3/8                                   {Array member base width (one side)}
h_a = 2.5                                   {Array member height}
L_a = 17.5                                  {Array member length}
W_a = m_a*g                                 {Array weight}
    {Force and Stress Analysis of Rails}
R_A+R_B-(1/2)*W_a = 0                       {Sum of Forces on single rail}
(L_r-2[in])*R_B-((L_r-2[in])/2)*(1/2)*W_a = 0   {Sum of Moment about Left rail support}
sigma_r_max = M_r_max*y_r/I_r               {Maximum Stress in rail}
M_r_max = ((L_r-2[in])/2)*(1/2)*W_a         {Max moment applied to rail by array member}
```

y_r = (1/2)*h_ro {Max stess location on rail cross section}

I_r = (1/12)*(b_ro*h_ro^3 - b_ri*h_ri^3) {Rail moment of Inertia}

y_max = -((1/2)*W_a*((L_r-2[in])/2)^3)/(48*E_st*I_r) {Maximum Rail deflection}

$g = 32.174$

$E_{st} = 30 \cdot 10^6$

$lbm2slug = \frac{1}{32.174}$

$inch2feet = \frac{1}{12}$

$feet2inch = 12$

$V_r = L_r \cdot [b_{ro} \cdot h_{ro} - b_{ri} \cdot h_{ri}]$

$m_r = V_r \cdot \rho_{ss} \cdot lbm2slug$

$\rho_{ps} = 0.282$

$\rho_{ss} = 0.29$

$b_{ro} = 0.5$

$h_{ro} = 0.5$

$b_{ri} = b_{ro} - 2 \cdot t_r$

$h_{ri} = h_{ro} - 2 \cdot t_r$

$t_r = 0.065$

$L_r = 37.5$

$W_r = m_r \cdot g$

$V_a = 2 \cdot b_a \cdot h_a \cdot L_a$

$\rho_{Al} = 0.098$

$m_a = V_a \cdot \rho_{Al} \cdot lbm2slug$

$b_a = 3 / 8$

$h_a = 2.5$

$L_a = 17.5$

$W_a = m_a \cdot g$

$R_A + R_B - 1 / 2 \cdot W_a = 0$

$$\left[L_r - 2 \ [in]\right] \cdot R_B - \left[\frac{L_r - 2 \ [in]}{2}\right] \cdot 1 / 2 \cdot W_a = 0$$

$$\sigma_{r,max} = M_{r,max} \cdot \frac{y_r}{I_r}$$

$$M_{r,max} = \left[\frac{L_r - 2 \ [in]}{2}\right] \cdot 1 / 2 \cdot W_a$$

$$y_r = 1 / 2 \cdot h_{ro}$$

$$I_r = \frac{1}{12} \cdot \left[b_{ro} \cdot h_{ro}^{\ 3} - b_{ri} \cdot h_{ri}^{\ 3}\right]$$

$$y_{max} = \frac{-1 / 2 \cdot W_a \cdot \left[\frac{L_r - 2 \ [in]}{2}\right]^3}{48 \cdot E_{st} \cdot I_r}$$

SOLUTION

Unit Settings: SI C kPa kJ mass deg

b_a = 0.375 [in]
b_{ro} = 0.5 [in]
feet2inch = 12 [in/ft]
h_a = 2.5 [in]
h_{ro} = 0.5 [in]
I_r = 0.003647 [in^4]
L_a = 17.5 [in]
m_a = 0.09994 [slug]
$M_{r,max}$ = 28.54 [lbf*in]
ρ_{ps} = 0.282 [lbm/in^3]
R_A = 0.8039 [lbf]
$\sigma_{r,max}$ = 1957 [lbf/in^2]
V_a = 32.81 [in^3]
W_a = 3.216 [lbf]
y_{max} = -0.001712 [in]

b_{ri} = 0.37 [in]
E_{st} = 3.000E+07 [lbf/in^2]
g = 32.17 [ft/s^2]
h_{ri} = 0.37 [in]
inch2feet = 0.08333 [ft/in]
lbm2slug = 0.03108 [slug/lbm]
L_r = 37.5 [in]
m_r = 0.03823 [slug]
ρ_{Al} = 0.098 [lbm/in^3]
ρ_{ss} = 0.29 [lbm/in^3]
R_B = 0.8039 [lbf]
t_r = 0.065 [in]
V_r = 4.241 [in^3]
W_r = 1.23 [lbf]
y_r = 0.25 [in]

No unit problems were detected.

Appendix G (Materials and Cost)

Table G1: *Testing apparatus budget and materials.*

Material	Quantity	Units	Unit price	Total Price [$]	Source	Part #
1/2x1/2x.065 wall Square Tubing	80	[in]	$0.88	$70.40	Melo Machine	SSTTSS-002-008
14 Ga. Stainless Steel Sheet	864	[in^2]	$0.09	$78.62	Melo Machine	PLA14SS
3/8x2-1/2 6061 Aluminum Bar	60	[in]	$0.35	$21.00	http://www.metalsdepot.com	F5182
Thermocouple wire	500	[ft]	$0.89	$443.00	Omega Engineering	HH-N-20-SLE-500
thermocouple plug (male)	5	each	$2.45	$12.25	http://www.omega.com	SMPW-CC-N-F
thermocouple plug (female)	5	each	$2.95	$14.75	http://www.omega.com	SMPW-CC-N-M
lead screw (3/4x1/2) Ball Screw, 3/4" Diameter, 1/2" Lead, 4' Length	4	[ft]	$33.27	$133.08	McMaster-Carr	5966k22
1" OD Brass Round Stock for bushings	4	[in]	$0.00	$0.00	Melo Machine	n/a
ball nut with flange (matches lead screw dimensions)	1	each	$265.56	$265.56	McMaster-Carr	5966k79
Express Sleeve 1'' to 1-1/2'' Length: 12	1	[12]	$115.99	$115.99	http://www.jegs.com	893-14036
Express Sleeve 1" to 1-1/2" Length: 3	1	[3]	$33.99	$33.99	http://www.jegs.com	893-14035
DAQ software	1	each	$99.00	$99.00	http://www.mccdaq.com	mmc daq cd (download name)
1" OD X .065" wall X .870" ID 304 Stainless Round Tube	1	each	$5.40	$5.40	https://www.metalsdepot.com	T4R1065
2" OD X .065" wall X 1.870" ID 304 Stainless Round Tube	1	each	$9.88	$9.88	https://www.metalsdepot.com	T4R2065
3 inch Dia. 6061-T6 Aluminum Round	1	each	$18.72	$18.72	https://www.metalsdepot.com	R33
Bearings Ultra-Precision Mini Stainless Steel Ball Bearing - ABEC-7, Double Shielded for 1/4" Shaft Diameter, 5/8" OD	2	each	$8.60	$17.20	http://www.mcmaster.com	3759T58
Hardware (add on)	1	Approx	-$303.49	-$303.49	n/a	n/a
Machine Screw, round head, SS 1/4" -20x1-1/14"	1	pair	$1.18	$1.18	Home Depot	887480145014
Machine Screw, round head, SS 1/4" -20x1"	4	pair	$1.18	$4.72	Home Depot	887480144918
Hex Nut, SS, 1/4" -20	2	bag 4	$1.18	$2.36	Home Depot	887480000511
Washer, Split Lock, SS, 1/4"	2	bag 6	$1.18	$2.36	Home Depot	887480004113
AmeriGas Propane Tank	1	each	$48.22	$48.22	Home Depot	0000-600-419

Master Lock	1	Pair	$13.38	$13.38	Rite Aid	55815
Brass fittings, chipping hammer, thread tape, spring, ball, pressure gauges, whole saw, wire	1	misc.	$127.78	$127.78	Miners ACE Hardware	916320
Brass fittings, tubing, returned gauges	1	misc.	$53.71	$53.71	Miners ACE Hardware	926835
Brass fittings, tubing	1	misc.	$35.34	$35.34	Home Depot	1052 57 56713
DAQ Repair	1	misc.	$120.34	$120.34	Omega Engineering	n/a
Misc Tax/Shipping	1	Approx	$61.23	$61.23	n/a	n/a
Omega order 11/13 shipping	1	n/a	$10.00	$10.00	n/a	n/a
Omega order 11/13 tax	1	n/a	$38.40	$38.40	n/a	n/a
Jegg order 11/13 shipping	1	n/a	$0.00	$0.00	n/a	n/a
Jegg order 11/13 tax	1	n/a	$0.00	$0.00	n/a	n/a
Home Depot 11/20/15 Tax	1	n/a	$4.71	$4.71	n/a	n/a
McMaster first order #4030013	1	n/a	$26.83	$26.83	n/a	n/a
Melo Machine Inbound Freight	1	n/a	$28.44	$28.44	n/a	n/a
Metals Depot Shipping	1	n/a	$22.47	$22.47	n/a	n/a
DAQ software tax	1	n/a	$7.92	$7.92	n/a	n/a

Total Budget:	$1,644.74
Provided by Sponsor:	$2,000.00
Total Spent:	$1,887.00
Remaining funds:	$113.00
Remaining Budget:	-$242.26

Table G2: *Phase two materials and spending.*

Material	QTY	Units	Price	Total [$]	Source	Date	Card #	Receipt Total	Acct Balance
Propane Bottle (new)	1	each	55.99	55.99	Conserve Fuel	4/29/2016	2835		
Propane Bottle (exchange)	1	each	21.99	21.99	Conserve Fuel	4/29/2016	2835		
Tax	1		6.24	6.24	Conserve Fuel	4/29/2016	2835	84.22	1915.78
Nexgrill Grill Comb Brush	1	each	4.97	4.97	Home Depot	5/3/2016	2850		
1/4" ID x 20' Vinyl Tube	1	each	6.24	6.24	Home Depot	5/3/2016	2850		
Expanded Steel	2	each	19.97	39.94	Home Depot	5/3/2016	2850		
Tax	1		4.08	4.08	Home Depot	5/3/2016	2850	55.23	1860.55
SFY Soap Pads	1	each	2.49	2.49	Vons	5/6/2016	2850		
Weiman wipes	1	each	5.29	5.29	Vons	5/6/2016	2850		
Easy Off BBQ Spray	2	each	5.49	10.98	Vons	5/6/2016	2850		
BBQ Gloves	1	each	9.99	9.99	Vons	5/6/2016	2850		
Sandwich Buns	6	bag	1.49	8.94	Vons	5/6/2016	2850		
White Sliced Bread	2	bag	1.49	2.98	Vons	5/6/2016	2850		
Tri Tip Roast	1	lb	17.41	17.41	Vons	5/6/2016	2850		
Tri Tip Roast	1	lb	17.48	17.48	Vons	5/6/2016	2850		
Tri Tip Roast	1	lb	17.48	17.48	Vons	5/6/2016	2850		
Tri Tip Roast	1	lb	18.66	18.66	Vons	5/6/2016	2850		
Tri Tip Roast	1	lb	18.24	18.24	Vons	5/6/2016	2850		
Tri Tip Roast	1	lb	17.89	17.89	Vons	5/6/2016	2850		
Tax	1		2.3	2.30	Vons	5/6/2016	2850	150.13	1710.42
Jockos mix	1	each	8.99	8.99	Vons	4/29/2016	2850		
Grill Brush	1	each	5.99	5.99	Vons	4/29/2016	2850		
Sandwich Buns	3	bag	1.49	4.47	Vons	4/29/2016	2850		
Tri Tip Roast	1	lb	17.31	17.31	Vons	4/29/2016	2850		
Tri Tip Roast	1	lb	17.31	17.31	Vons	4/29/2016	2850		
Tri Tip Roast	1	lb	17.19	17.19	Vons	4/29/2016	2850		
Tri Tip Roast	1	lb	17.19	17.19	Vons	4/29/2016	2850		
Tri Tip Roast	1	lb	23.18	23.18	Vons	4/29/2016	2850		
Tri Tip Roast	1	lb	17.19	17.19	Vons	4/29/2016	2850		
Bags	2	each	0.10	0.20	Vons	4/29/2016	2850		

Tax	1		0.48	0.48	Vons	4/29/2016	2850	129.50	1580.92
FS Hot dog Buns	2	bag	2.49	4.98	Smart and Final	5/27/2016	2850		
Rainbow Giant H/D Buns	6	bag	4.99	29.94	Smart and Final	5/27/2016	2850		
O/C Lg Hot Dog Bun	5	bag	3.59	17.95	Smart and Final	5/27/2016	2850		
Seeded Bun	1	bag	3.29	3.29	Smart and Final	5/27/2016	2850		
Gardenburger Patty	1	bag	13.99	13.99	Smart and Final	5/27/2016	2850		
Brawny Towels	1	pack	6.99	6.99	Smart and Final	5/27/2016	2850		
FS Mld slcd cheddar	1	pack	5.59	5.59	Smart and Final	5/27/2016	2850		
FS third steam pan	8	each	0.79	6.32	Smart and Final	5/27/2016	2850		
Heinz Picinic Pack	3	pack	5.49	16.47	Smart and Final	5/27/2016	2850		
SH 9in Paper Plate	1	pack	2.99	2.99	Smart and Final	5/27/2016	2850		
FS 9in Paper Plate	1	pack	5.99	5.99	Smart and Final	5/27/2016	2850		
Hoffy Bigdog Frank	1	pack of 200	175.8	175.8	Smart and Final	5/27/2016	2850		
arctic ice	2	bag	4.49	8.98	Smart and Final	5/27/2016	2850		
Tax	1		2.5	2.5	Smart and Final	5/27/2016	2850	301.78	1279.14
Heinz Ket 20 oz	2	each	2.95	5.9	Campus Market	5/27/2016	2835		
French 80z mustard	2	each	2.18	4.36	Campus Market	5/27/2016	2835		
heinz sweet relish	1	each	3.49	3.49	Campus Market	5/27/2016	2835	13.75	1265.39
Hose barb 1/4x1/4"mpt lf	1	each	3.99	3.99	Miners Ace Hardware	5/18/2016	2835		
Hose barb 3/8hx1/4fpt lf	1	each	4.59	4.59	Miners Ace Hardware	5/18/2016	2835		
coupling 1/4"fpt brs ll	1	each	4.99	4.99	Miners Ace Hardware	5/18/2016	2835		
male cnnctr 3/8x1/4brs	1	each	2.99	2.99	Miners Ace Hardware	5/18/2016	2835		
~~Hose propane 1/4xmptx3/8~~	~~1~~	~~each~~	~~32.99~~	~~32.99~~	~~Miners Ace Hardware~~	5/18/2016	2835	RETURN	
Cal Poly Discount	1	each	-4.96	-4.96	Miners Ace Hardware	5/18/2016	2835		

Tax	1		3.57	3.57	Miners Ace Hardware	5/18/2016	2835	48.16	
Propane Hose return	1	each	-35.63	-35.63	Miners Ace Hardware	5/25/2016	2835	12.53	1252.86
SFY Coast	5	each	1.49	7.45	Vons	5/13/2016	2850		
white bread	6	bag	0.99	5.94	Vons	5/13/2016	2850		
wheat bread	1	bag	0.99	0.99	Vons	5/13/2016	2850		
Tri Tip Roast	1	lb	23.46	23.46	Vons	5/13/2016	2850		
Tri Tip Roast	1	lb	22.74	22.74	Vons	5/13/2016	2850		
Tri Tip Roast	1	lb	21.04	21.04	Vons	5/13/2016	2850		
Tri Tip Roast	1	lb	19.6	19.6	Vons	5/13/2016	2850		
Tri Tip Roast	1	lb	23.19	23.19	Vons	5/13/2016	2850		
Tri Tip Roast	1	lb	20.95	20.95	Vons	5/13/2016	2850	145.36	1107.50
Perm Mounting sqs 1x1	1	pack	2.99	2.99	Beverly's	5/18/2016	2835		
Project Board	1	each	5.99	5.99	Beverly's	5/18/2016	2835		
Tax	1		0.72	0.72	Beverly's	5/18/2016	2835	9.70	1097.80
~~unvrsl parts 10ft ng hose~~	~~2~~	~~each~~	~~39.97~~	~~79.94~~	~~Home Depot~~	~~5/19/2016~~	~~2835~~	RETURN	
ss clamp 1/4"x5/8"	2	each	0.83	1.66	Home Depot	5/19/2016	2835		
3/8x3/8 brass coupling flare	2	each	3.36	6.72	Home Depot	5/19/2016	2835		
3/8x3/8 brass adapter barb	2	each	3.74	7.48	Home Depot	5/19/2016	2835		
bag	1	each	0.10	0.10	Home Depot	5/19/2016	2835		
Tax	1		7.66	7.66	Home Depot	5/19/2016	2835	103.56	
Return Hoses	2	each	-39.97	-79.94	Home Depot	5/26/2016	2835		
Return Tax	1		-6.39	-6.39	Home Depot	5/26/2016	2835	17.23	1080.57
Flare adptr3/8x3/8brs	1	each	3.99	3.99	Miners Ace Hardware	5/26/2016	2835		
male connctr 3/8x3/8brs	1	each	3.99	3.99	Miners Ace Hardware	5/26/2016	2835		
hose air 3/8" id	25	ft	1.39	34.75	Miners Ace Hardware	5/26/2016	2835		
Tax	1		3.42	3.42	Miners Ace Hardware	5/26/2016	2835	46.15	1034.42

Propane Exchange	1	each	21.99	21.99	Conserve Fuel	5/26/2016	2850		
Tax	1		1.76	1.76	Conserve Fuel	5/26/2016	2850	23.75	1010.67
thermometer	2	each	13.99	27.98	Vons	4/22/2016	2850		
Tri Tip Roast	1	lb	26.84	26.84	Vons	4/22/2016	2850		
Tri Tip Roast	1	lb	27.67	27.67	Vons	4/22/2016	2850		
Tri Tip Roast	1	lb	29.59	29.59	Vons	4/22/2016	2850		
Tax	1		2.24	2.24	Vons	4/22/2016	2850	114.32	896.35
Tube sq stl 72x1/2x1/16	2	each	11.22	22.44	Home Depot	4/13/2016	2850/ 0686		
2'x5'x1/2" 18ga gavl hardwre cloth	1	each	6.94	6.94	Home Depot	4/13/2016	2850/ 0686		
diable 4-1/2" 60g stl demon conical	1	each	7.97	7.97	Home Depot	4/13/2016	2850/ 0686		
Avanti pro 4-1/2 x1/16/7/8	10	each	1.89	18.90	Home Depot	4/13/2016	2850/ 0686		
Tax	1		4.50	4.50	Home Depot	4/13/2016	2850/ 0686	26.83	869.52
500gb ext hard drive	1	each	49.99	49.99	Amazon	5/20/2016	2835		
Ship/hand	1	each	3.99	3.99	Amazon	5/20/2016	2835		
Tax	1		4.05	4.05	Amazon	5/20/2016	2835	58.03	811.49

Appendix H (Safety Instructions)

SAFETY INSTRUCTIONS

READ CAREFULLY BEFORE ASSEMBLY AND OPERATION OF YOUR GRILL

CHOOSING THE LOCATION OF YOUR GRILL…

DO NOT use gas grills in garages, porches, breezeways, sheds or other enclosed areas. Grills are intended to be used **OUTDOORS ONLY,** with at least **21 inches/54 cm** clearance from the back and side of any combustible surface. The grill should not be placed under or on top of any surface that will burn. Do not obstruct the flow of combustion and ventilation air around the grill housing.

PROTECT CHILDREN: Keep children away from grill during use and until grill has cooled after you are finished. Do not allow children to operate the grill.

FOR YOUR SAFETY…

DO NOT store or use gasoline or other flammable vapors and liquids in the vicinity of this or any other appliance.

DO NOT store empty or full spare gas cylinders and/or chemicals under or near this or any other appliance.

Keep the fuel hose and electrical cord away from hot surfaces. Protect the fuel hose from dripping grease. Avoid unnecessary twisting of the hose. Prior to each use, visually inspect the hose for cuts, cracks, excessive wear or other damage and replace if necessary.

NEVER test for gas leaks with a lighted match or open flame.

NEVER light grill with lid closed or before checking to ensure burner tubes are fully seated over gas valve orifices.

NEVER lean over cooking surface while lighting grill. Use barbecue tools with wood handles and good quality insulated oven mitts when operating grill.

IF YOU SMELL GAS…

1. **Shutoff gas to the appliance at it's source.**
2. **Extinguish any open flame.**
3. **Open grill lid to release any accumulation of fumes.**
4. **If gas odor persists, immediately contact your gas supplier.**

CHECKING FOR GAS LEAKS…

NEVER TEST FOR GAS LEAKS WHILE THE GRILL IS LIT! Prior to the first use and at the beginning of each new season (or, if using Propane, whenever gas cylinder is changed), it is a must that you check for gas leaks. Follow these steps:

1. Make a soap solution by mixing one-part liquid detergent and one-part water.
2. Turn off heat control valve(s), and then turn on gas at source.
3. Apply the soap solution to all gas connections: bubbles will appear in the soap solution if connections are not properly sealed. Turn off gas at source and tighten or repair as necessary.
4. If any connections required being tightened or repaired, repeat steps 1 through 3.
5. If you have a gas leak you cannot repair, turn off gas at the source, disconnect fuel line from the grill and immediately call your grill dealer and gas supplier for professional assistance.

Appendix I (Testing Instructions)

ReliaBull Heat Technology: Test Procedure 1

REQUIRED MATERIALS:

- Bull Outdoor Products Grillhead: Brahma
- Brazing Bull Test Apparatus
- Laptop computer with MCC DAQ software
- Standard 120V power supply
- Fuel (Natural Gas or Propane) ****READ SAFETY INSTRUCTIONS****
- Personal Protective Equipment
  - Good quality, well insulated gloves or oven mitts.

PREPARATION:

Before beginning test, please carefully read and follow SAFETY INSTRUCTIONS.

PROCEDURE:

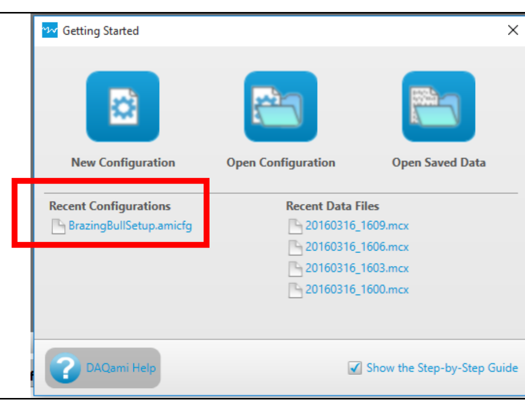
1. Insert Brazing Bull Test Apparatus into grill head with indexing knob on right hand side
   a. Align as necessary
   b. Route thermocouples to DAQ box outside of grill head through exhaust vent
2. Position thermocouple array to Location 1 at left side of grill
3. Position ambient temperature thermocouple adequate distance from grill head
4. Initiate MCC DAQ software
5. Record Fuel type
6. Open valve at gas supply
7. Light all burners and set to “High” setting (excluding infrared burner at back of grill)
8. Close BBQ grill head lid
   a. Before closing lid, verify all burners are lit
9. Monitor thermocouple readings and temperature gauge on lid
10. Once Temperature has leveled out for approximately 2 minutes, begin recording data with MCC DAQ software
    a. Record a minimum of 150 temperatures at current location
11. Start/Record time
12. Record temperature from gauge on lid
13. Record pressures
    a. Line pressure,
    b. Exhaust pressure
    c. Air inlet pressure
    d. Ambient pressure
14. Record array position (over grate or between grates)
    a. Y/N
15. Pause MCC DAQ data recording
16. Advance thermocouple array by turning indexing knob 2 full rotations
17. Repeat Steps 11-16 until thermocouple array reaches final location at right hand side of grill
18. Stop MCC DAQ software
19. Turn all burner knobs to off position
20. Close valve at gas supply
21. Export data to excel spreadsheet

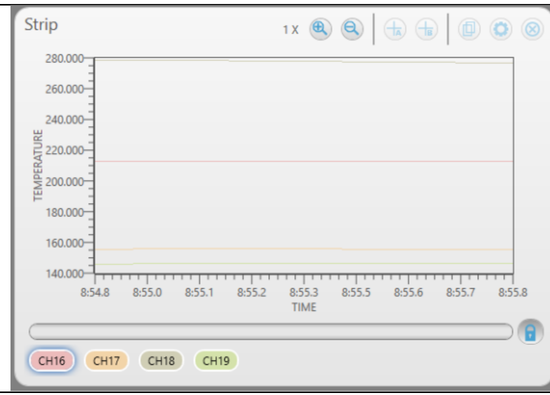
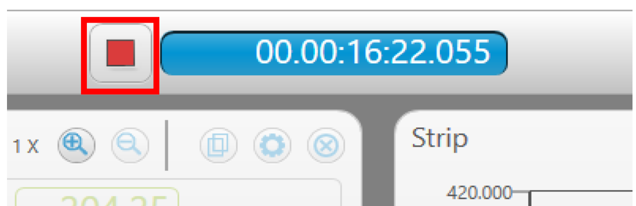
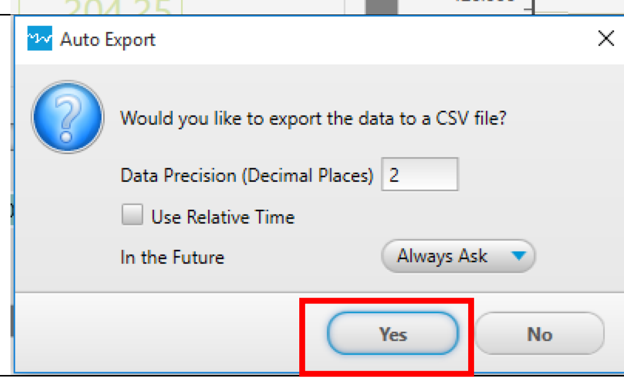
Step by Step Guide for Brazing Bull Testing Method

Materials Required:

- Brazing Bull Test Apparatus
- Data Acquisition (DAQ) box
    - USB-2416 w/ AI-EXP32
- Laptop Computer
    - w/ DAQami software
- Well insulated leather gloves
- U-tube manometer
- Insulated cup with ice water

<table>
<tr><th colspan="2">Step 1</th></tr>
<tr><td>a) Warm up DAQ box by plugging in power supply (30 minutes).
a. This warm up period is necessary to produce reliable temperature readings.</td><td>This step allows the temperature of the connection ports to equalize with the temperature of the thermocouples.</td></tr>
<tr><th colspan="2">Step 2</th></tr>
<tr><td>a) Connect all thermocouples

NOTE: The addition of thermocouples will result in a slower sampling rate, be sure that each locations records at least 151 readings</td><td>Ch(0) to ch(15)→thermocouples A through P
Ch(16)→Right Rear Fixed Thermocouple (RR)
Ch(17)→Right Front Fixed Thermocouple (RF)
Ch(18)→Left Rear Fixed Thermocouple (LR)
Ch(19)→Left Front Fixed Thermocouple (LF)
Ch(20)→Ambient Thermocouple (AMB)
Ch(21)→Exhaust Thermocouple (EXH)
Ch(22)→Ice Bath Thermocouple (ICE)
Ch(23)→Analog Gauge Thermocouple (ATP)</td></tr>
<tr><th colspan="2">Step 3</th></tr>
<tr><td>a) Connect DAQ to Laptop with USB cable
b) Open DAQami software
c) Open Brazing Bull Setup Configuration</td><td>
</td></tr>
</table>

<table>
<tr><th colspan="2">Step 4</th></tr>
<tr><td rowspan="2">a) Begin recording data by pressing play button located at the top center of the DAQami window.
b) Monitor fixed thermocouple readings in strip window and continue preheat until readings show constant temperatures (Constant readings can be recognized by a horizontal line in the strip window).
c) Upon completion of preheat (approximately 45-60 minutes), press stop and choose “yes” to save csv file when prompted to do so.</td><td>
</td></tr>
<tr><td>
</td></tr>
<tr><th colspan="2">Step 5</th></tr>
<tr><td rowspan="2">a) Position thermocouple array in desired location for beginning of test.
b) Press play and record data for approximately two minutes and twenty seconds.
c) Press stop and choose “yes” to save csv file when prompted to do so.</td><td>
</td></tr>
<tr><td>
</td></tr>
</table>

<table>
<tr><th colspan="2">Step 6</th></tr>
<tr><td>a) Rotate indexing knob 2 complete rotations.
    a. At every complete rotation a click will be felt indicating an advancement of 0.500±0.004 inches.</td><td>If the desired direction of thermocouple array advancement is left to right, turn knob clockwise (shown below). If the desired direction is right to left, turn knob counter-clockwise.
</td></tr>
<tr><th colspan="2">Step 7</th></tr>
<tr><td>a) Repeat Step 5 and 6 until sufficient data is recorded from all desired array locations.</td><td>The number of locations may vary depending upon the area of the grill being tested. For example, if one were to test the area over a single burner, there would be less indexing locations for that particular test run than if one were testing the entire grill surface.</td></tr>
<tr><th colspan="2">Step 8</th></tr>
<tr><td>a) Move all files from DAQami folder to a new folder designated for completed test run.</td><td>The DAQami software exports csv files to the DAQami folder, for organizational purposes, a new folder should be created after the completion of each test and all csv files should be moved to the new folder corresponding to that test.</td></tr>
</table>

Appendix J (Propane Test Results)

Test Run-1_Propane

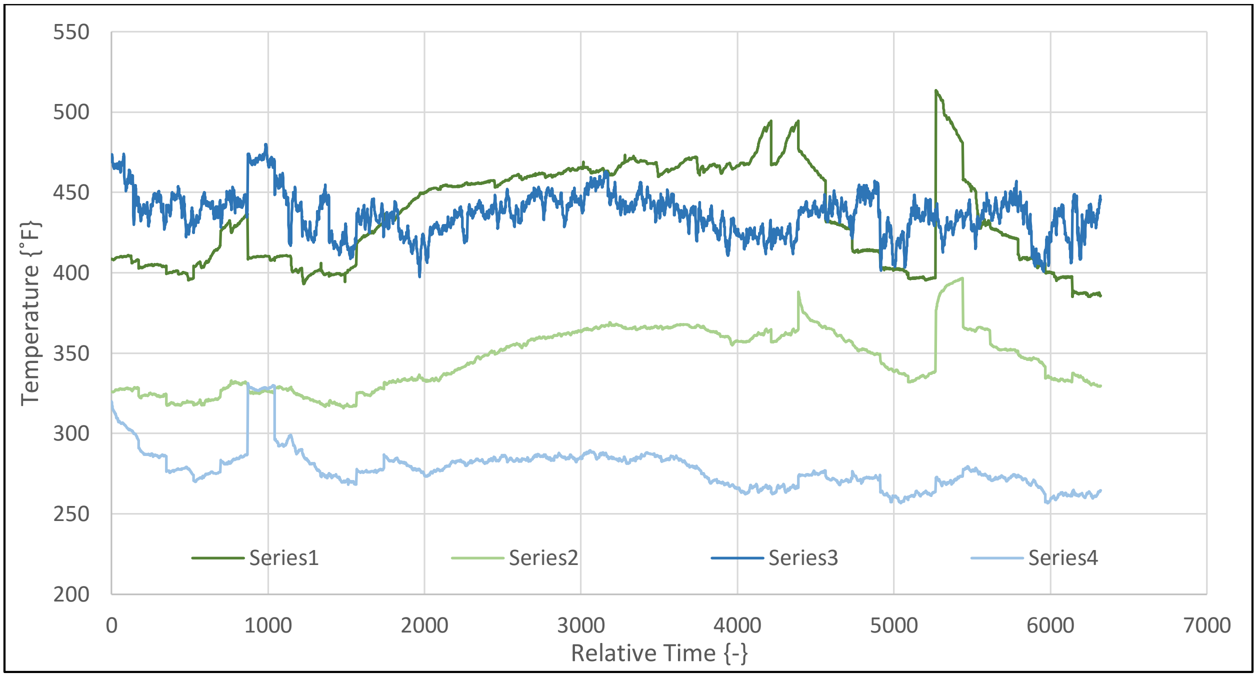


Figure J1: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-1.*

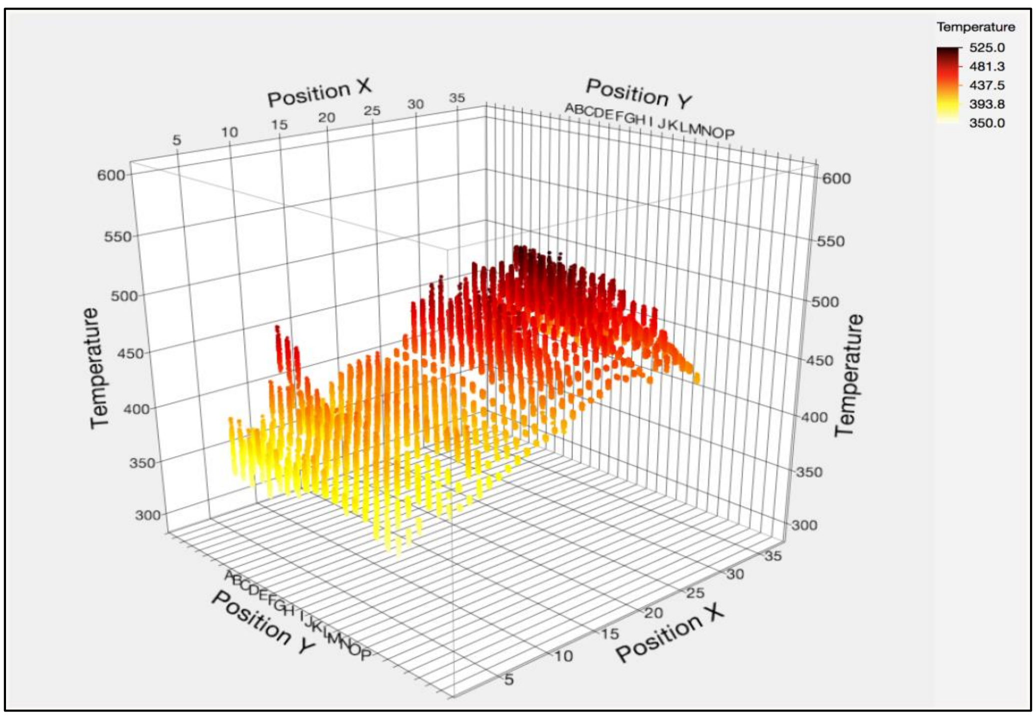


Figure J2: *3D Scatterplot of Test Run-1.*

394	391	393	400	423	466	427	403	398	404	411	425	430	429	426	426	430	437	443	465	465	459	455	459	467	475	489	484	450	457	474	496	494	454	438	426
393	390	391	402	422	463	423	404	400	402	411	424	432	431	427	426	429	437	446	470	470	457	454	458	466	472	487	485	450	457	471	490	490	450	442	428
387	388	390	402	422	459	421	398	404	405	415	426	433	431	424	426	428	433	451	476	475	459	455	458	468	473	488	492	458	459	470	488	491	448	442	427
406	400	398	405	415	442	419	408	407	408	417	422	426	427	425	427	430	436	448	464	465	458	456	459	468	474	483	492	470	459	472	482	485	463	452	440
382	382	387	404	415	431	412	407	414	410	422	421	423	424	420	422	425	435	452	476	471	455	449	454	468	471	483	507	481	461	471	480	488	450	441	427
398	394	396	407	412	427	415	412	420	413	421	419	421	423	423	425	428	434	449	466	467	457	451	455	467	472	480	503	489	462	473	478	485	465	454	440
387	386	399	410	408	420	412	415	426	419	424	416	417	419	418	420	423	432	451	468	473	458	447	452	465	467	480	507	499	461	472	477	491	460	444	432
393	392	405	412	408	420	412	416	423	423	425	415	417	417	416	418	423	433	450	459	470	460	448	453	464	466	479	498	497	459	472	476	491	467	447	435
399	394	405	412	408	419	411	413	415	419	423	413	415	414	414	416	422	431	445	452	464	459	449	453	461	464	477	486	490	455	469	473	489	468	448	436
402	392	400	411	408	417	410	408	408	412	422	411	412	410	410	414	420	428	439	448	459	461	450	450	458	461	474	481	485	452	466	470	486	464	446	436
399	391	396	406	410	415	407	404	401	404	418	410	410	408	408	413	418	424	433	442	454	457	449	448	455	457	470	475	475	449	463	464	480	454	442	433
395	387	393	401	410	411	402	397	395	398	414	408	407	408	408	413	417	421	429	436	447	451	445	445	451	455	463	466	465	445	458	460	474	448	439	430
395	389	393	406	408	407	399	394	392	397	419	410	406	408	409	413	417	421	428	433	440	443	442	443	450	458	465	461	457	442	456	458	471	449	440	430
398	392	389	398	403	402	396	391	389	393	414	409	403	406	408	412	416	419	425	429	434	436	439	441	448	454	460	455	451	440	453	454	467	450	441	431
393	382	376	383	388	395	389	385	384	387	403	400	398	402	405	409	413	416	421	423	428	431	433	437	445	447	447	448	443	435	448	446	453	444	435	424
382	372	366	370	376	389	384	380	377	381	386	389	392	396	401	404	408	410	414	416	422	427	429	432	439	442	438	441	437	430	443	442	442	435	427	416

Figure J3: *Grid of average temperatures with color mapping for visual representation of Test Run-1.*

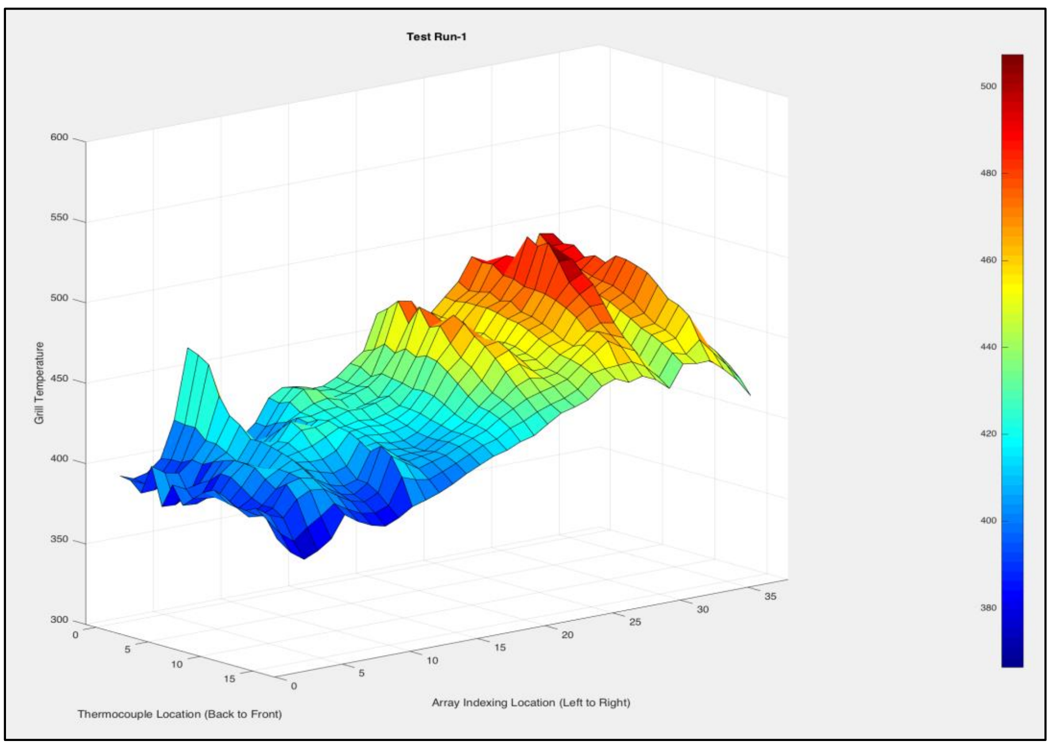


Figure J4: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-1.*

Test Run-2_Propane

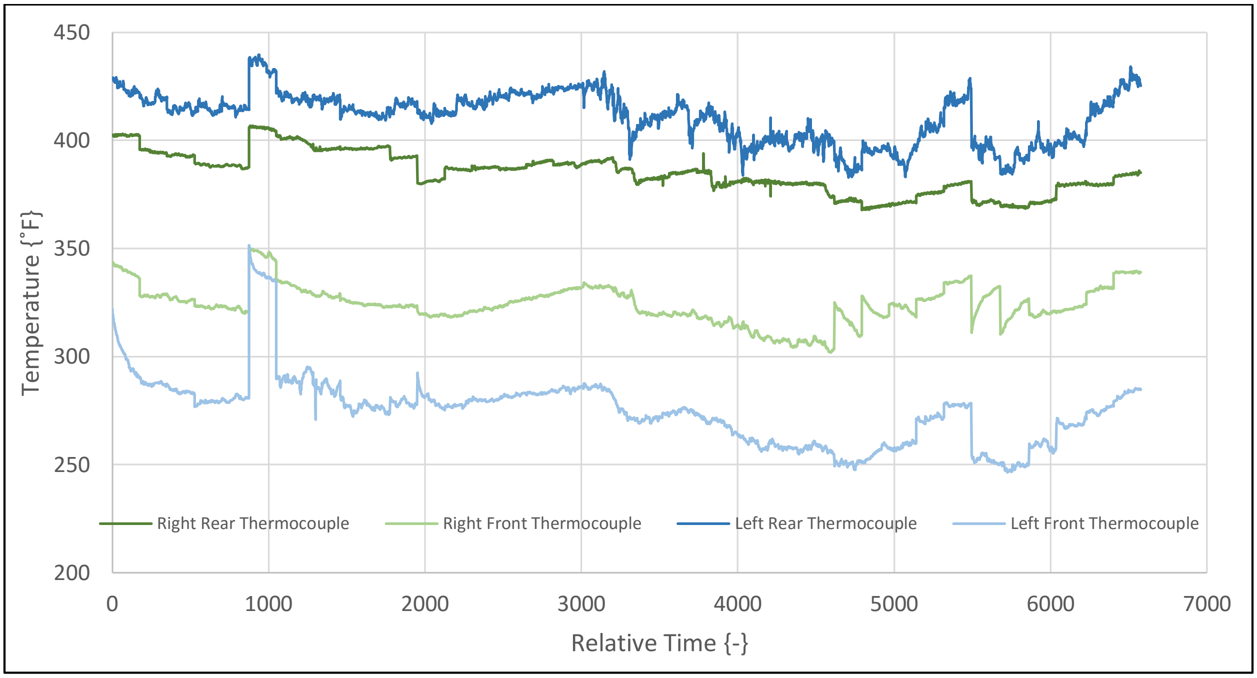


Figure J5: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-2.*

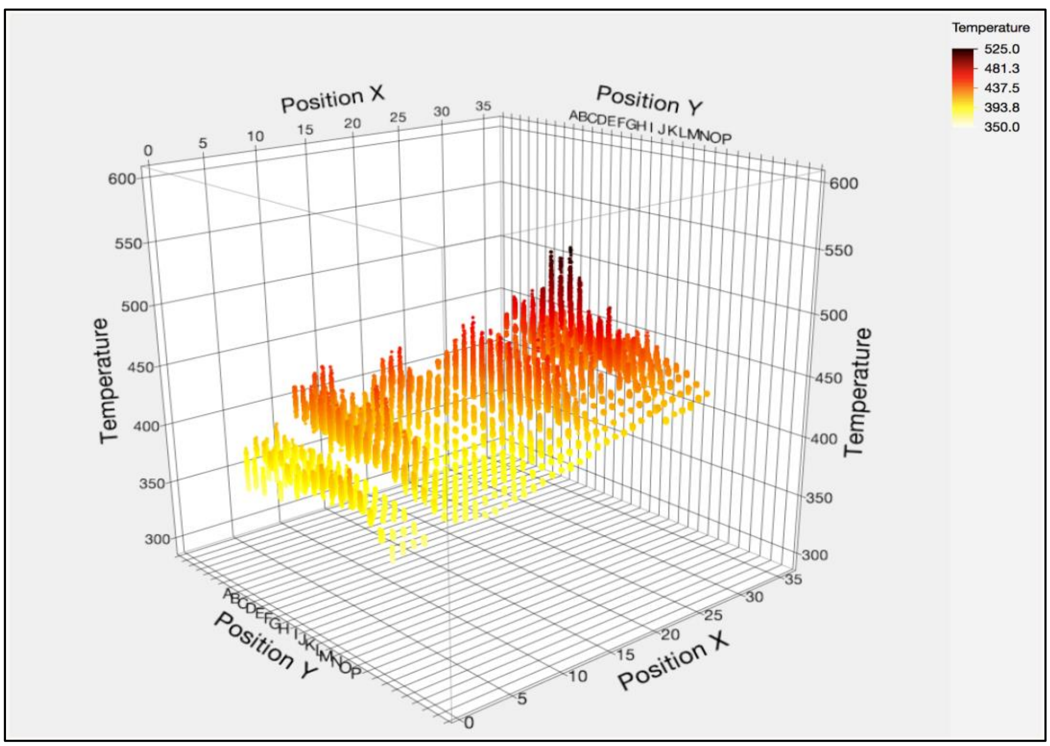


Figure J6: *3D Scatterplot of Test Run-2.*

384	399	387	397	393	430	421	431	417	412	404	409	415	424	430	428	424	421	419	422	431	430	432	431	432	437	438	432	451	461	446	432	426	438	441	446
383	399	386	398	393	430	422	432	416	411	403	409	417	427	431	429	423	419	418	421	432	430	434	429	429	435	437	428	447	457	444	433	427	436	436	443
381	395	383	394	391	429	424	429	413	416	402	410	419	432	434	431	425	419	418	424	438	435	437	428	430	436	436	432	450	461	444	436	429	437	436	442
401	401	393	400	397	430	419	414	409	412	404	407	410	419	420	422	421	419	418	424	434	433	430	428	430	436	436	435	456	462	437	434	432	439	440	444
381	389	382	391	389	420	415	409	413	414	404	404	404	414	414	418	418	416	414	425	441	436	425	420	426	433	433	438	478	490	439	427	428	434	434	437
398	396	393	398	396	424	415	408	419	412	404	403	403	408	410	413	415	415	414	423	438	436	425	423	427	432	433	439	472	489	442	430	431	438	440	442
390	393	392	394	393	415	413	408	429	413	402	400	399	403	405	403	410	412	410	421	439	440	421	420	423	429	431	438	477	496	448	430	431	435	437	435
397	397	396	395	394	416	413	410	424	411	401	399	398	402	403	404	408	411	409	418	433	438	421	419	422	429	432	438	472	481	444	433	435	437	440	437
402	399	397	394	392	415	411	407	415	406	399	397	397	399	400	401	404	407	406	412	426	435	423	417	420	427	431	436	462	463	441	433	436	436	439	438
406	399	395	391	390	413	408	406	412	402	395	394	394	395	395	397	400	403	402	407	421	439	428	416	418	425	429	435	461	458	444	434	437	434	437	437
404	395	391	387	387	413	404	405	412	398	391	390	390	392	391	390	397	400	398	402	418	439	434	415	416	423	427	433	461	462	442	436	438	431	434	434
404	392	388	385	385	410	397	402	403	392	388	387	387	390	390	390	394	397	396	398	410	431	432	416	414	419	423	428	447	451	433	431	433	427	429	430
409	392	387	385	384	408	394	397	394	388	386	386	386	388	389	390	394	396	396	398	405	417	421	414	412	417	420	422	430	433	424	424	426	425	427	428
405	390	385	384	383	408	393	393	390	386	384	384	385	387	388	390	393	395	396	397	401	406	411	410	410	415	418	419	423	426	417	419	420	421	424	426
396	379	378	377	376	401	388	388	386	381	379	381	382	383	383	386	389	392	393	394	396	400	405	405	406	409	414	415	417	420	409	412	413	416	418	420
386	370	371	371	370	397	384	381	379	377	374	375	377	380	380	383	386	388	390	390	392	395	399	401	403	404	407	409	413	415	402	406	407	409	413	415

Figure J7: *Grid of average temperatures with color mapping for visual representation of Test Run-2.*

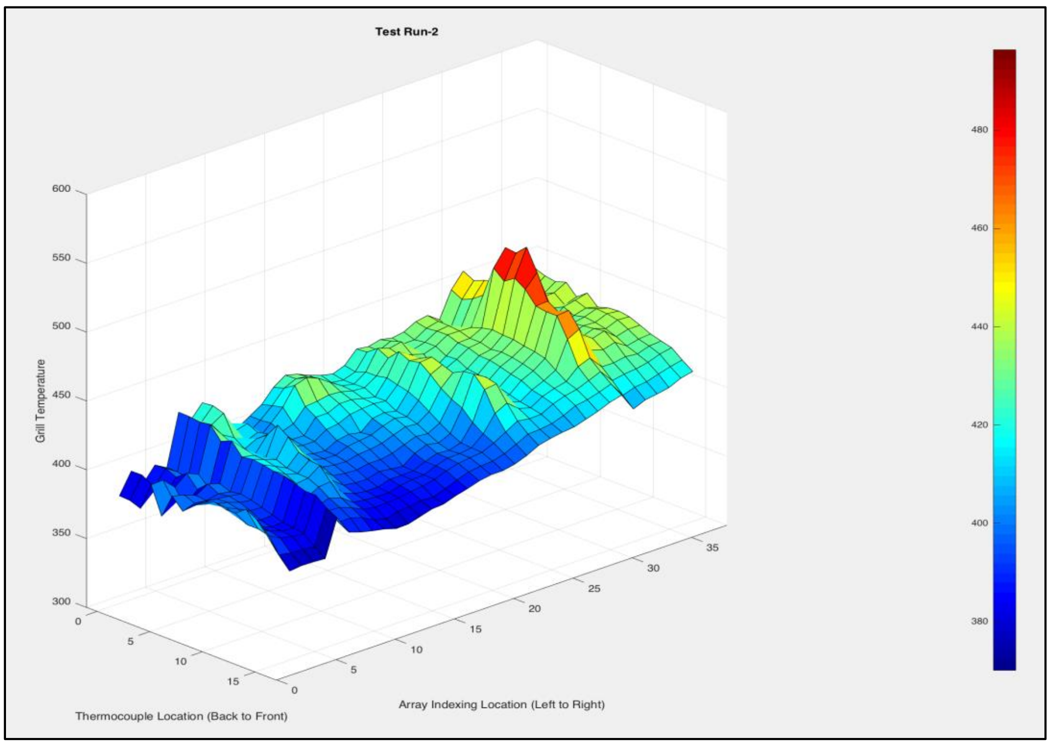


Figure J8: 3D mesh plot of average temperature grid produced using MATLAB for Test Run-2.

Test Run-3_Propane

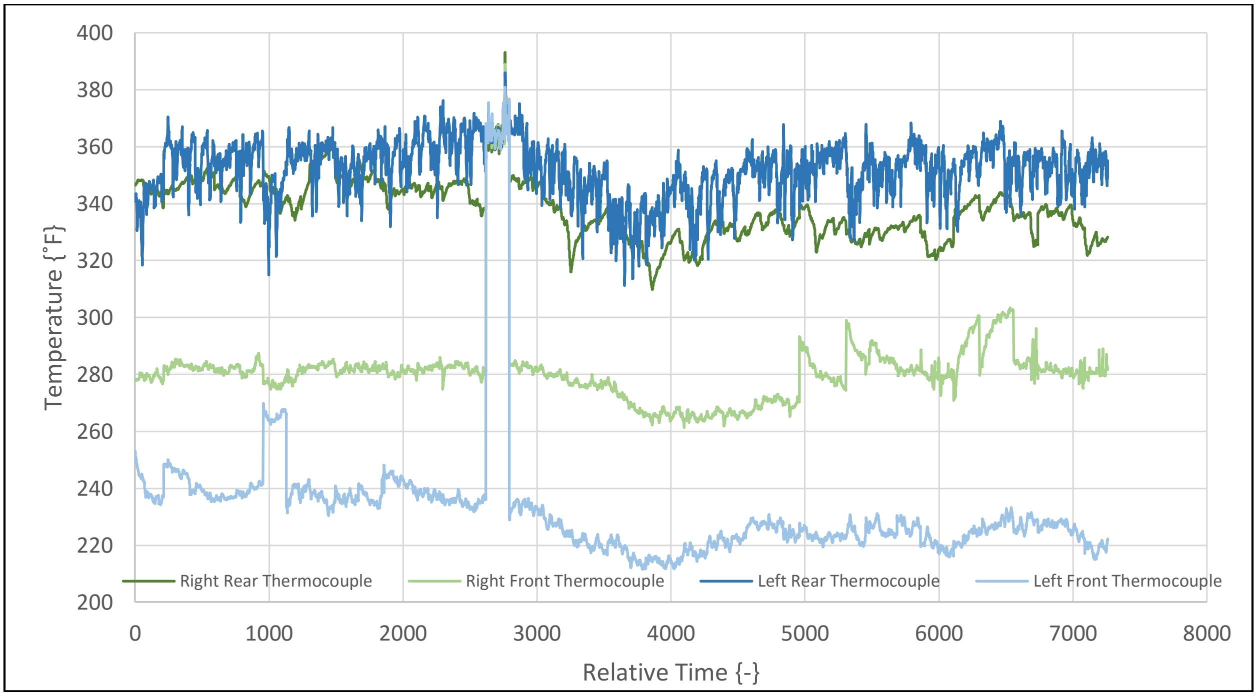


Figure J9: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-3.*

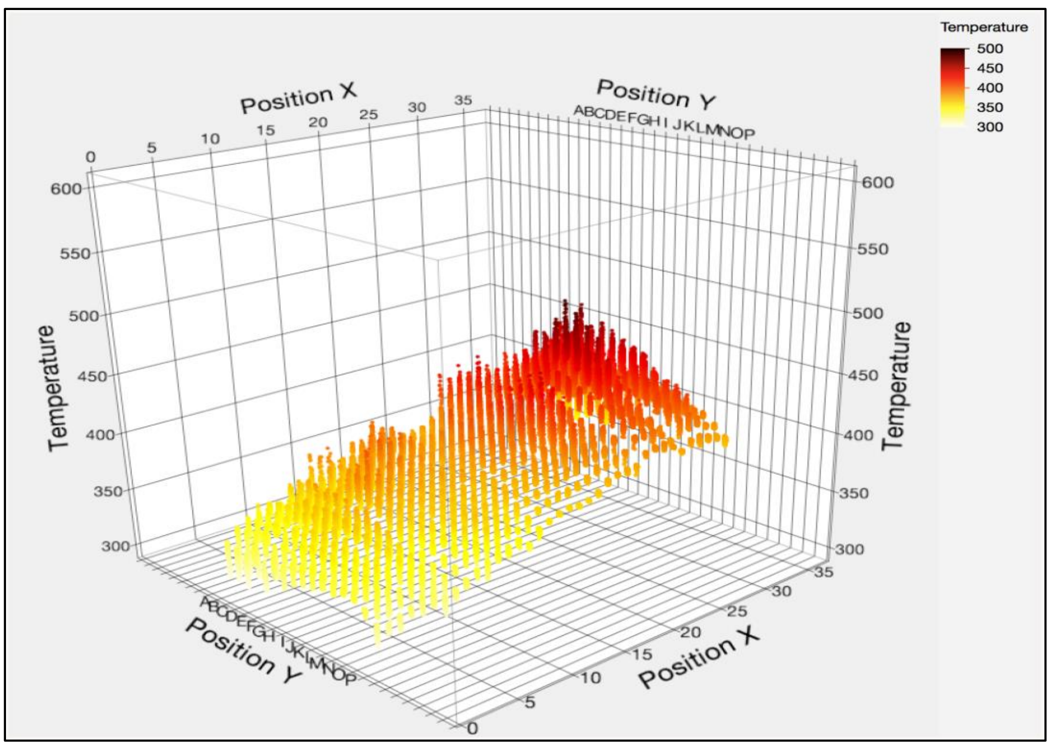


Figure J10: *3D Scatterplot of Test Run-3.*

321	326	341	345	351	347	357	355	356	350	362	367	371	371	343	381	375	375	374	376	379	385	390	398	400	404	401	396	402	398	403	406	402	397	376	370
319	324	339	346	353	348	360	354	359	355	365	367	371	374	362	382	373	374	374	374	377	386	393	398	400	402	401	399	404	401	406	411	409	399	374	371
316	324	340	345	356	350	363	358	362	362	368	369	375	378	361	382	374	374	375	377	382	392	397	399	402	406	409	409	410	405	410	421	417	401	377	375
333	339	349	352	361	355	358	357	362	363	369	372	376	377	353	381	378	379	382	383	386	393	396	399	404	409	416	418	417	408	409	421	422	410	394	390
317	326	342	348	362	355	360	364	369	369	376	380	378	374	364	379	375	380	388	386	389	398	394	398	407	413	425	433	431	413	413	431	437	410	382	377
331	337	349	354	364	356	356	370	371	370	371	376	374	373	372	378	377	383	389	387	390	397	394	400	404	412	424	438	440	419	410	423	434	417	398	393
327	337	350	353	365	357	357	381	380	375	383	374	370	368	358	368	376	383	392	390	396	398	394	397	400	412	428	452	456	423	409	422	439	422	394	387
334	344	354	357	365	360	356	380	376	375	373	372	370	369	373	374	377	383	392	393	403	399	399	396	397	409	425	452	455	424	408	419	438	427	400	392
338	346	353	357	365	362	355	371	370	371	371	369	368	368	379	373	376	381	389	392	405	402	401	394	396	404	420	447	447	422	406	417	434	428	402	395
339	346	350	353	363	363	352	366	364	367	368	366	366	366	378	370	374	379	386	389	402	408	404	393	395	401	415	439	439	421	406	418	432	426	401	395
339	344	347	348	360	362	349	359	360	362	365	363	363	365	380	368	372	375	380	386	396	408	403	389	394	399	411	426	428	416	402	418	424	416	396	392
338	340	344	346	357	359	345	351	353	356	361	360	362	364	379	367	370	372	375	381	388	400	398	388	391	396	407	414	415	408	396	413	414	406	394	389
339	340	343	349	356	355	341	345	348	352	359	361	362	364	377	366	370	372	375	381	384	389	392	387	389	397	407	409	406	402	392	407	408	405	394	390
339	339	339	343	351	348	336	339	343	348	355	358	358	360	374	363	367	370	372	376	379	381	384	385	386	393	402	403	400	396	388	401	405	401	393	389
332	331	330	332	341	340	329	333	339	345	349	352	352	355	369	357	363	366	368	369	371	374	379	381	382	386	395	395	394	390	382	392	393	390	385	382
319	320	320	326	329	328	323	327	332	338	339	345	345	350	368	353	358	360	363	361	362	366	373	376	377	377	385	387	387	383	376	383	381	380	378	372

Figure J11: *Grid of average temperatures with color mapping for visual representation of Test Run-3.*

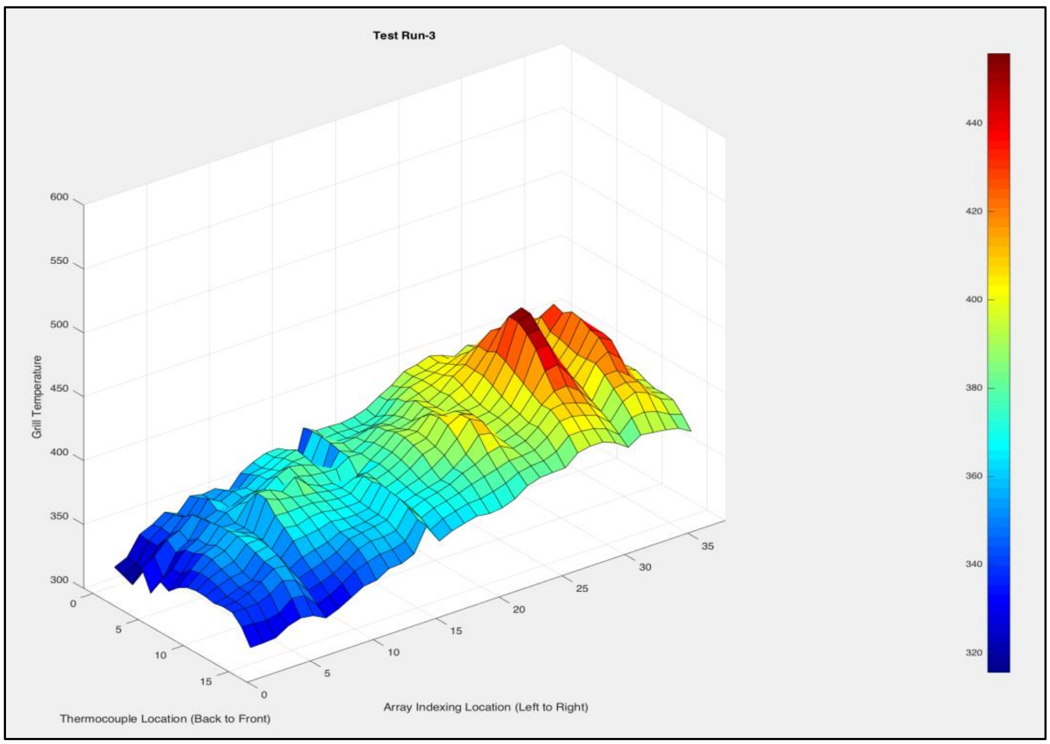


Figure J12: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-3.*

Test Run-4_Propane

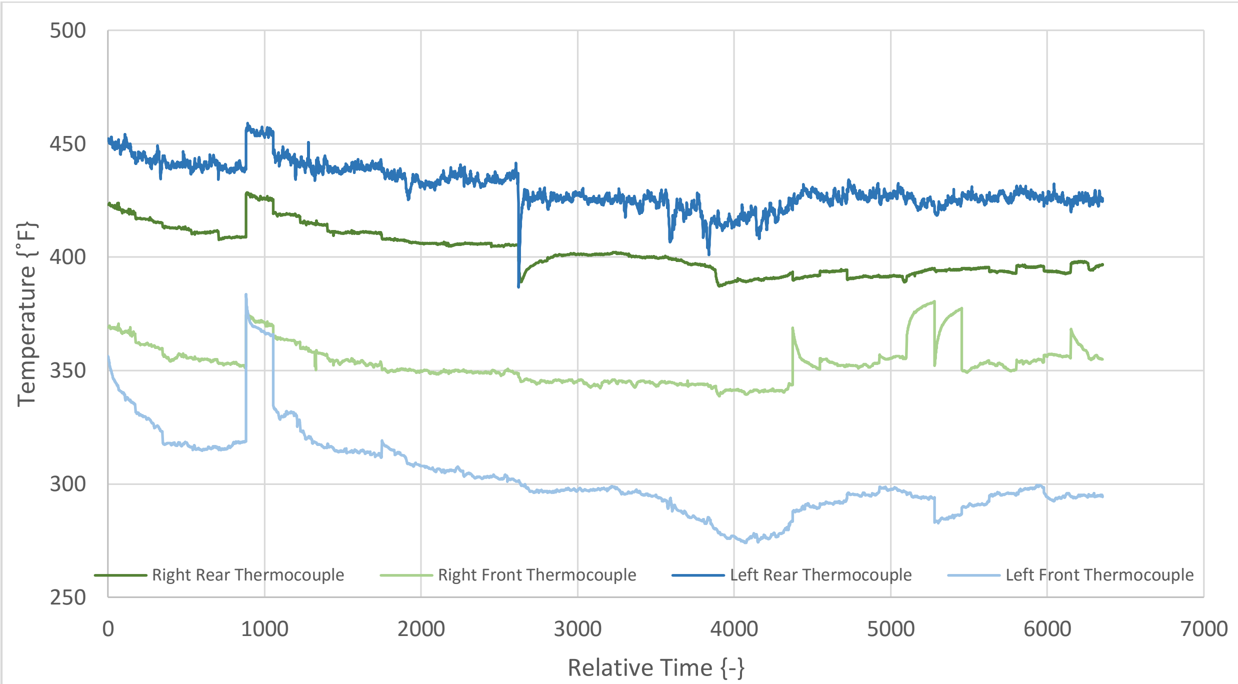


Figure J13: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-4.*

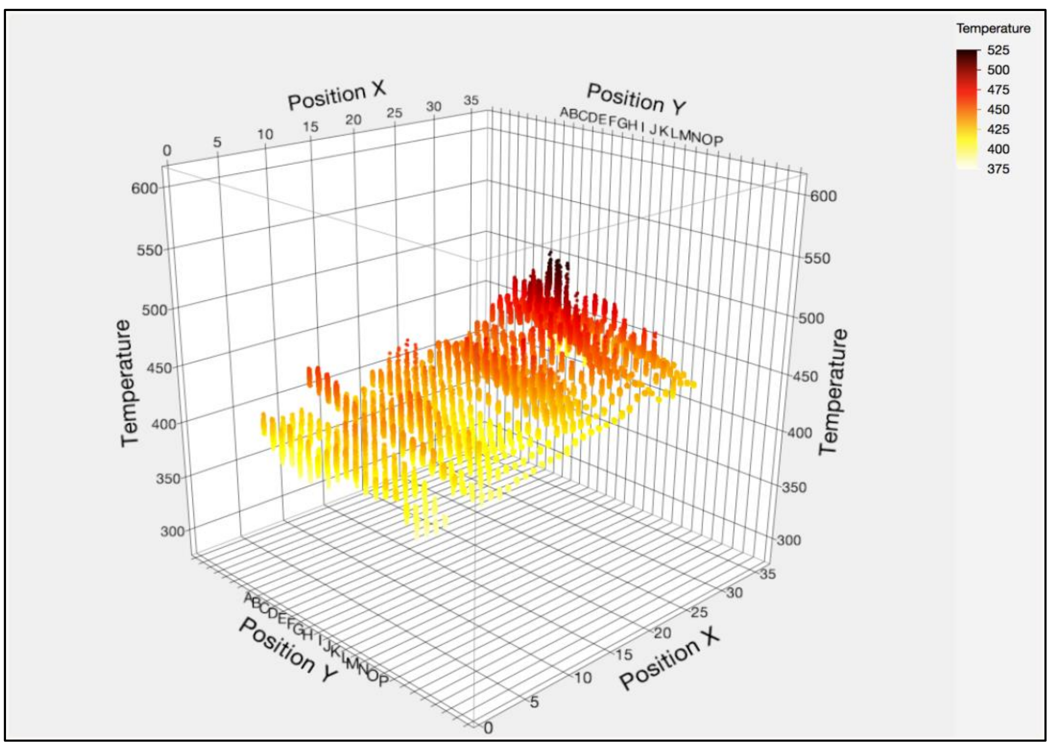


Figure J14: *3D Scatterplot of Test Run-4.*

424	416	417	417	417	452	445	431	426	419	418	426	434	429	430	429	429	430	431	438	446	445	439	440	439	450	449	458	466	469	476	458	448	454	438	438
420	410	412	415	418	454	445	429	424	419	417	425	437	429	432	430	429	428	430	439	445	442	437	439	438	448	446	457	465	467	478	463	450	451	434	435
411	403	409	412	416	452	443	429	422	421	415	422	439	428	431	432	427	427	431	444	447	441	437	439	440	447	445	461	463	466	485	473	451	451	433	431
426	416	416	418	420	449	438	427	423	425	419	420	434	426	428	429	427	427	433	443	444	439	438	440	441	448	449	465	462	461	464	463	453	455	443	440
406	394	405	413	413	435	429	424	424	427	416	414	433	423	424	424	424	425	438	450	445	435	433	437	439	447	449	487	474	467	462	465	451	450	430	424
419	406	413	419	418	440	429	427	425	429	420	417	425	423	423	422	423	426	439	449	443	437	435	438	440	449	454	490	483	469	450	456	456	455	442	436
411	401	417	428	419	433	426	428	429	436	425	417	423	420	417	416	419	427	445	454	444	433	432	435	438	450	462	510	494	465	445	456	466	452	433	428
418	412	426	435	423	437	426	430	435	442	435	420	423	419	414	413	418	430	447	448	443	432	433	436	440	451	469	504	485	459	442	455	476	454	435	432
424	418	426	432	421	437	424	425	436	439	430	417	421	415	409	409	415	429	445	442	442	429	432	433	437	448	467	482	467	453	438	452	475	452	436	434
425	417	420	428	418	436	421	419	430	433	426	414	417	411	405	404	411	425	442	441	444	431	430	429	433	444	468	467	456	448	435	448	470	449	435	434
423	412	415	422	413	435	419	414	423	425	422	411	414	409	405	405	410	420	434	438	443	438	429	427	430	440	463	456	451	446	433	443	462	445	434	434
419	408	412	416	411	434	419	409	415	417	417	408	412	410	407	407	410	416	428	432	438	440	427	424	428	438	452	449	447	442	431	440	453	440	435	433
420	410	414	416	410	433	418	409	410	416	422	409	411	410	410	410	412	416	429	427	431	432	425	424	429	443	450	444	444	440	429	439	455	440	435	433
423	412	410	411	405	432	417	409	407	412	420	408	409	409	410	411	411	415	427	426	424	424	423	423	427	435	441	440	440	437	427	438	448	437	435	432
417	404	398	398	395	424	411	405	401	403	407	402	404	404	405	407	408	411	419	420	417	417	418	419	421	429	433	436	435	432	424	432	437	433	428	426
409	398	391	387	389	419	408	400	397	395	393	395	398	399	401	403	404	404	406	410	412	414	415	415	416	419	421	429	430	427	419	423	423	427	424	420

Figure J15: *Grid of average temperatures with color mapping for visual representation of Test Run-4.*

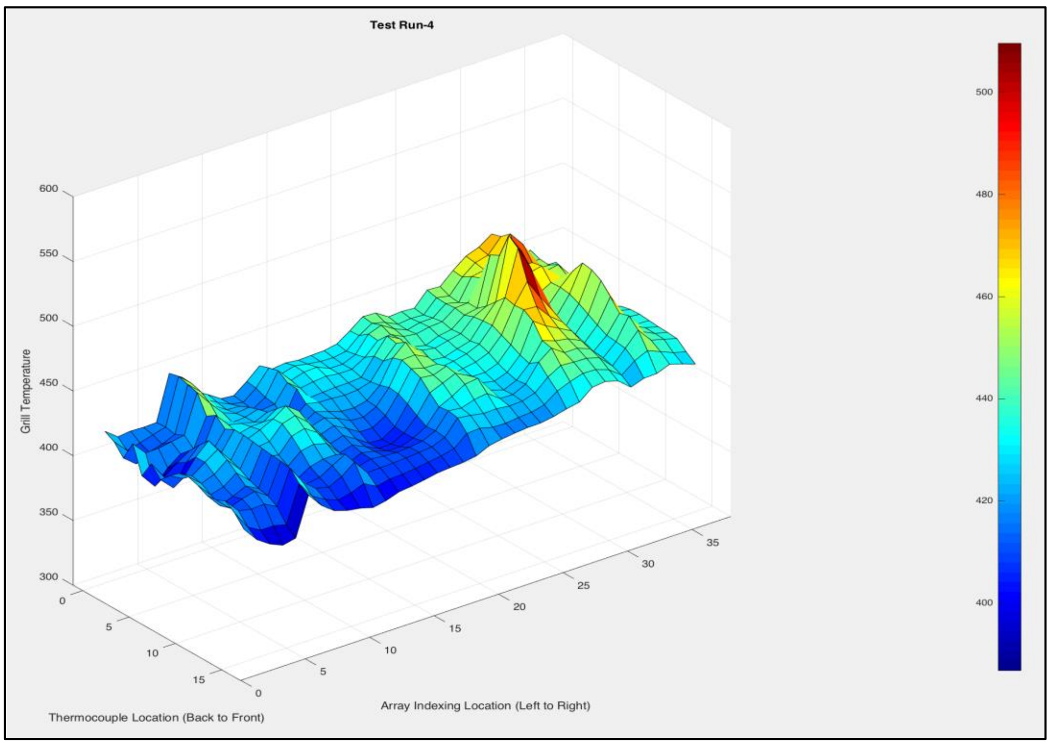


Figure J16: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-4.*

Test Run-5_Propane

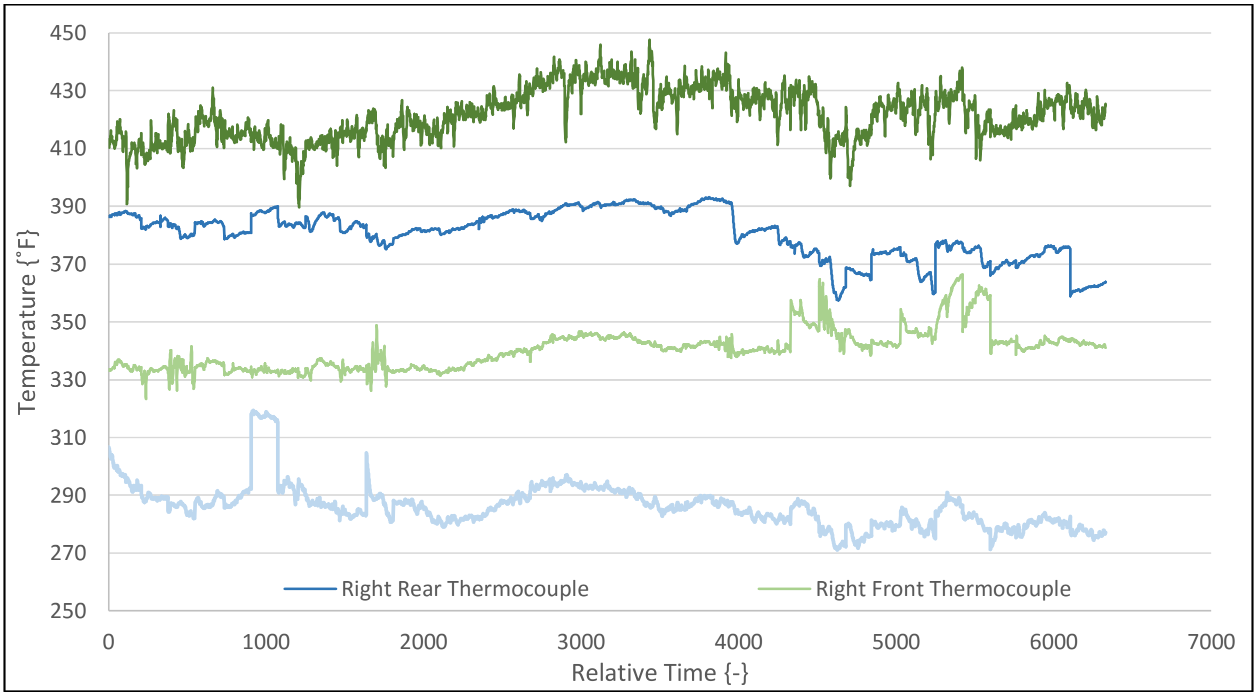


Figure J17: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-5.*

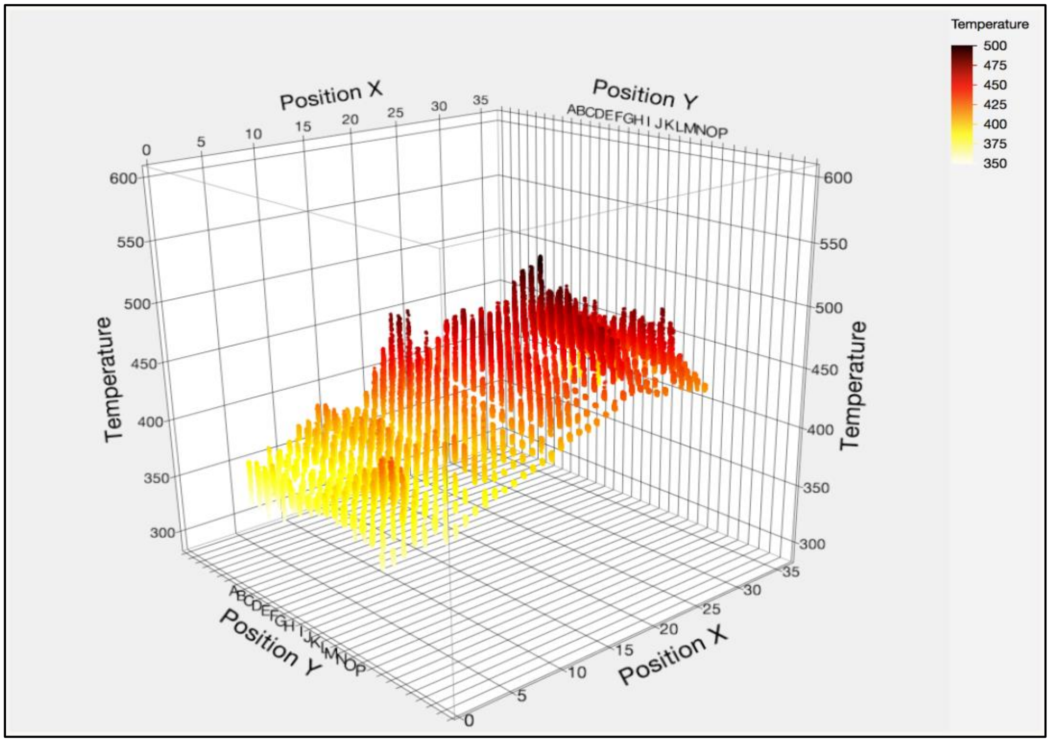


Figure J18: *3D Scatterplot of Test Run-5.*

376	370	377	384	390	400	399	412	404	394	398	404	413	425	436	439	429	430	432	433	442	455	453	451	449	459	446	446	458	465	480	449	445	441	434	413
376	370	375	384	391	397	396	412	402	397	398	404	416	427	442	441	427	429	431	432	446	460	453	450	447	456	445	445	459	462	482	451	446	441	432	412
374	368	375	383	391	393	393	411	403	399	400	405	418	430	448	442	427	430	432	437	454	468	455	452	446	459	450	449	462	459	495	455	448	442	435	413
385	379	384	388	393	396	390	399	399	397	399	401	411	417	431	430	425	427	430	437	448	458	449	450	447	457	453	453	460	452	466	456	451	447	442	428
372	366	375	381	387	385	384	402	402	399	401	398	410	418	432	435	423	426	436	445	458	464	445	445	443	456	455	461	474	452	469	457	449	441	432	409
380	373	382	385	390	389	387	397	401	399	399	398	404	410	418	423	421	423	433	444	452	456	442	443	444	454	456	462	471	450	459	456	452	446	440	426
375	371	380	382	384	382	386	397	405	400	397	397	401	406	413	419	417	421	432	449	455	452	438	439	441	451	456	465	474	451	457	453	449	440	432	414
379	378	384	385	386	386	388	397	405	398	397	397	401	404	409	415	415	420	430	444	447	444	437	439	440	451	455	462	467	451	453	454	449	442	435	420
382	382	386	386	386	386	386	395	401	396	397	397	400	402	405	409	412	419	428	441	441	438	435	438	438	449	453	458	460	450	449	452	449	442	435	423
384	383	387	390	390	386	385	392	400	398	403	397	399	400	401	404	409	417	429	440	440	433	434	434	437	447	455	457	457	451	446	451	455	446	435	424
385	383	390	396	395	387	386	390	399	400	411	400	398	398	400	401	407	416	427	438	440	429	434	432	436	448	461	458	453	448	444	455	457	452	432	423
382	378	391	400	396	388	383	386	393	396	408	401	397	397	399	401	405	413	422	433	436	427	433	430	434	446	460	451	447	443	440	456	452	450	429	423
382	377	396	407	396	390	382	381	386	393	414	403	396	397	400	402	406	413	425	430	429	425	429	429	435	448	462	445	441	438	437	451	453	451	430	425
381	378	402	406	393	389	378	377	382	389	408	400	394	395	398	401	404	411	426	426	423	421	424	427	434	448	458	441	437	434	433	446	454	447	431	425
376	372	397	396	382	384	373	372	378	383	398	395	391	393	396	399	402	407	418	418	417	417	419	423	428	442	446	437	432	428	427	439	443	433	425	420
363	364	376	377	371	377	366	367	373	376	383	384	385	387	391	394	397	400	405	409	411	412	414	418	421	429	431	430	426	422	422	429	426	420	420	413

Figure J19: *Grid of average temperatures with color mapping for visual representation of Test Run-5.*

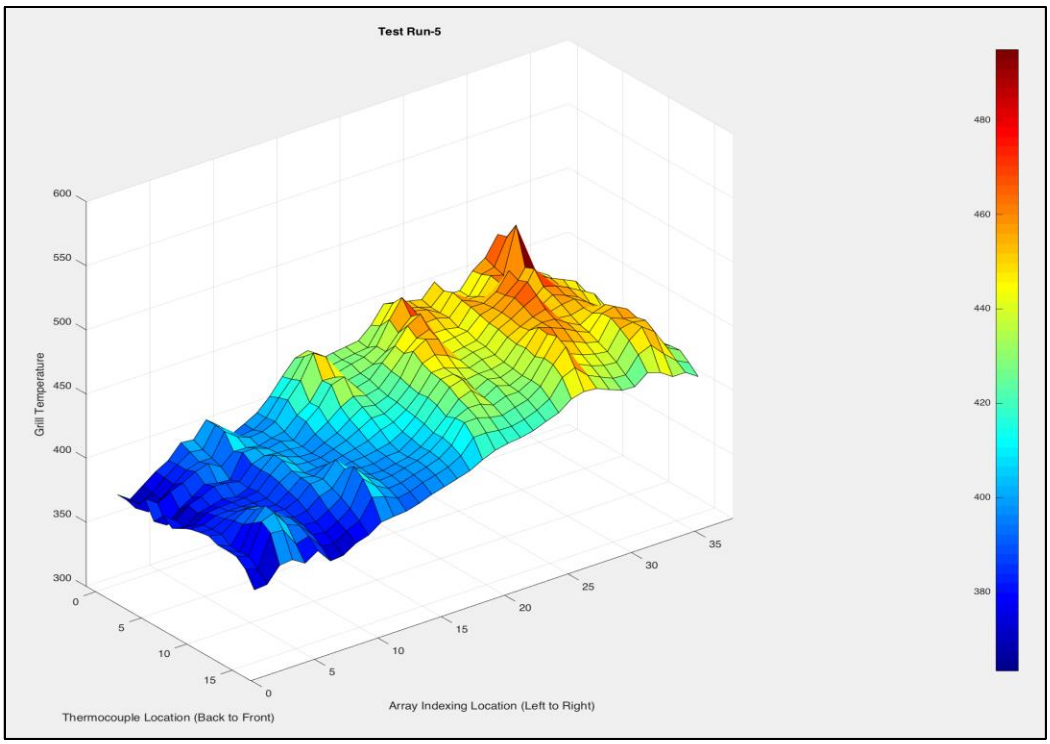


Figure J20: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-5.*

Test Run-6_Propane

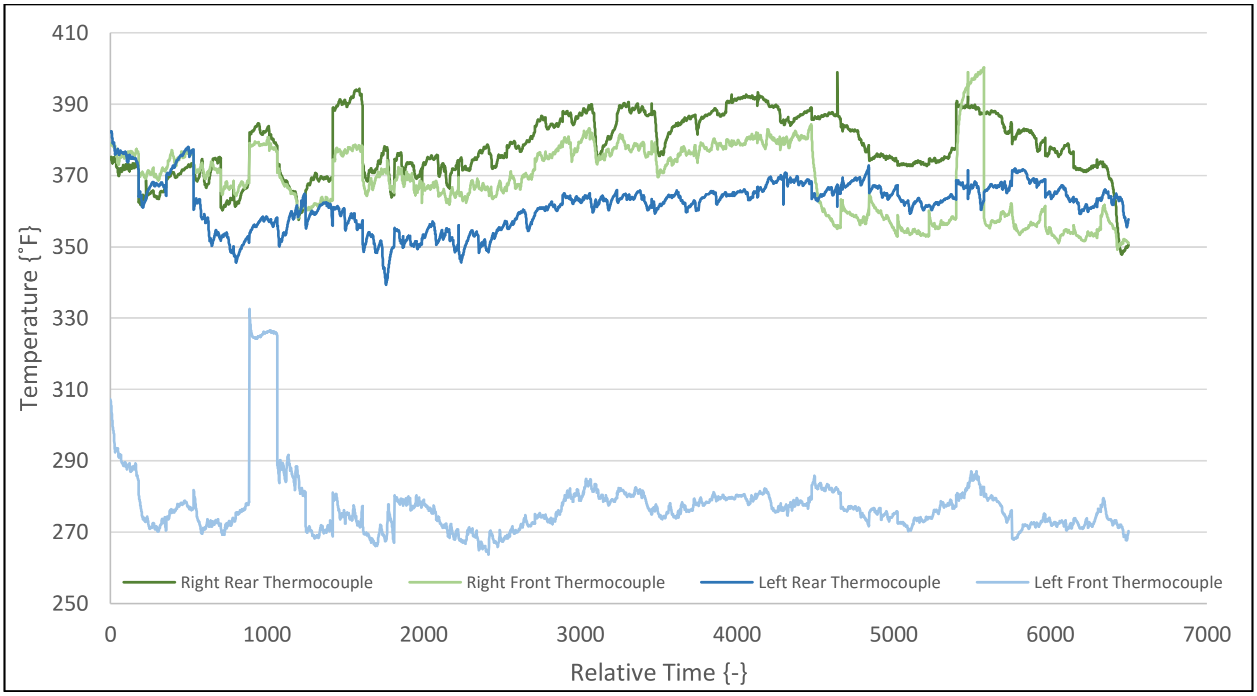


Figure J21: *Steady state temperature plot using temperature data from fixed thermocouples for Test Run-6.*

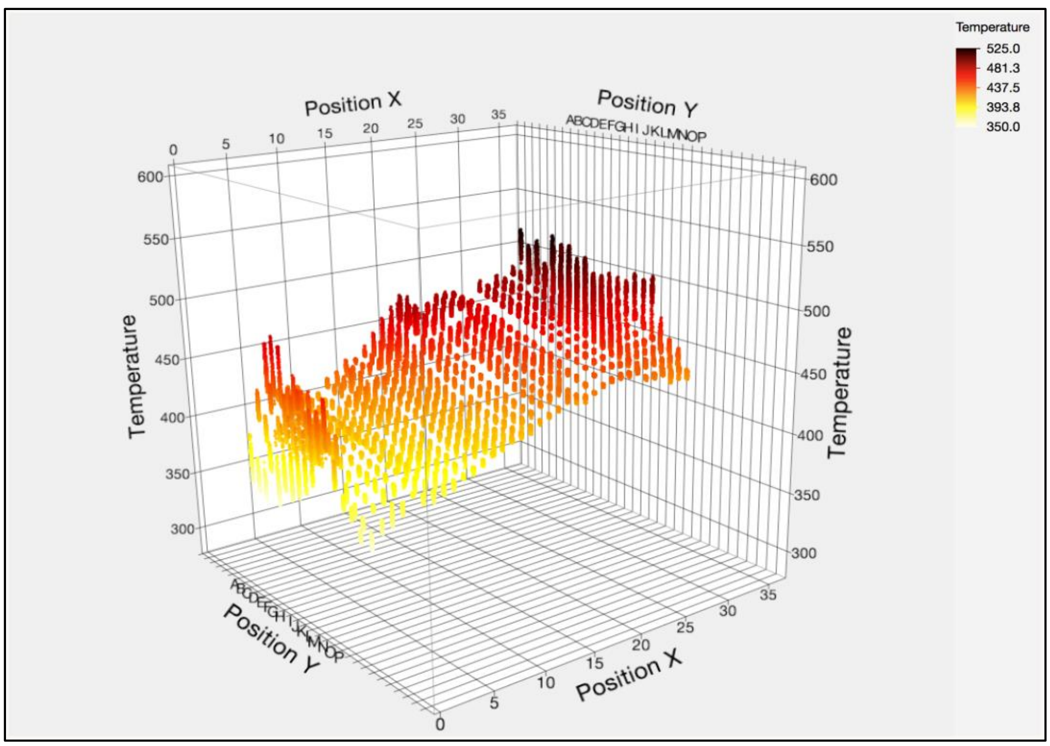


Figure J22: *3D Scatterplot of Test Run-6.*

379	422	451	429	430	429	413	420	429	432	440	444	449	452	461	465	482	470	471	476	482	484	484	476	474	484	483	486	486	493	518	492	491	488	503	458
368	407	450	424	426	425	409	418	427	430	436	441	445	447	457	461	479	466	468	474	481	481	479	469	471	481	481	484	485	490	507	485	485	486	504	467
362	435	446	423	425	425	410	419	427	431	433	443	443	444	451	457	476	465	467	471	478	480	478	467	470	480	480	484	484	490	513	486	488	487	503	461
389	411	430	421	422	422	409	414	422	425	427	433	434	436	440	444	455	453	456	459	463	467	468	463	466	476	477	480	479	483	493	482	483	482	491	468
370	421	442	422	420	421	406	416	423	425	427	435	433	432	436	439	453	449	452	458	462	467	468	458	463	474	474	477	476	480	514	491	492	483	498	464
384	424	435	420	419	419	407	413	418	421	423	428	428	428	431	434	443	443	447	452	457	461	463	456	461	472	473	476	474	478	499	488	489	480	488	470
386	433	436	420	417	417	406	413	417	419	421	427	426	424	426	428	437	439	443	449	455	460	460	451	458	468	470	472	471	477	503	497	497	480	486	474
390	422	423	417	416	415	407	411	415	417	418	424	424	423	424	426	433	437	442	449	452	457	457	451	457	466	469	470	471	478	487	488	485	476	479	477
398	418	416	414	413	413	406	409	412	414	415	420	421	420	420	423	429	434	438	445	447	452	453	448	454	463	466	468	468	475	476	476	473	471	474	478
416	423	412	410	410	411	406	406	408	410	411	416	417	416	415	420	425	430	434	440	443	448	450	446	451	459	462	464	465	470	468	467	465	466	470	482
431	422	405	405	407	408	405	403	405	407	409	414	414	415	412	417	422	428	431	438	440	444	448	447	449	455	458	460	462	467	461	460	460	461	467	481
443	417	397	399	403	404	402	399	402	404	406	410	411	412	408	414	418	424	428	434	436	441	443	444	444	451	453	455	460	463	454	454	454	456	461	481
404	388	389	396	400	402	401	396	399	402	403	408	409	409	402	410	416	421	426	431	434	438	435	432	440	448	451	452	457	460	449	448	449	451	453	451
386	378	386	393	398	400	399	394	396	398	400	405	407	409	404	409	415	419	424	429	433	436	432	425	438	445	448	450	451	452	441	444	446	446	446	445
382	371	381	387	392	395	392	389	390	392	397	401	404	407	404	409	413	418	423	427	431	435	430	424	435	441	444	445	445	446	438	439	439	436	437	437
367	360	370	376	380	388	384	384	386	388	391	394	398	403	405	411	412	415	418	421	425	431	432	428	431	435	438	439	439	440	432	432	432	428	431	426

Figure J23: *Grid of average temperatures with color mapping for visual representation of Test Run-6.*

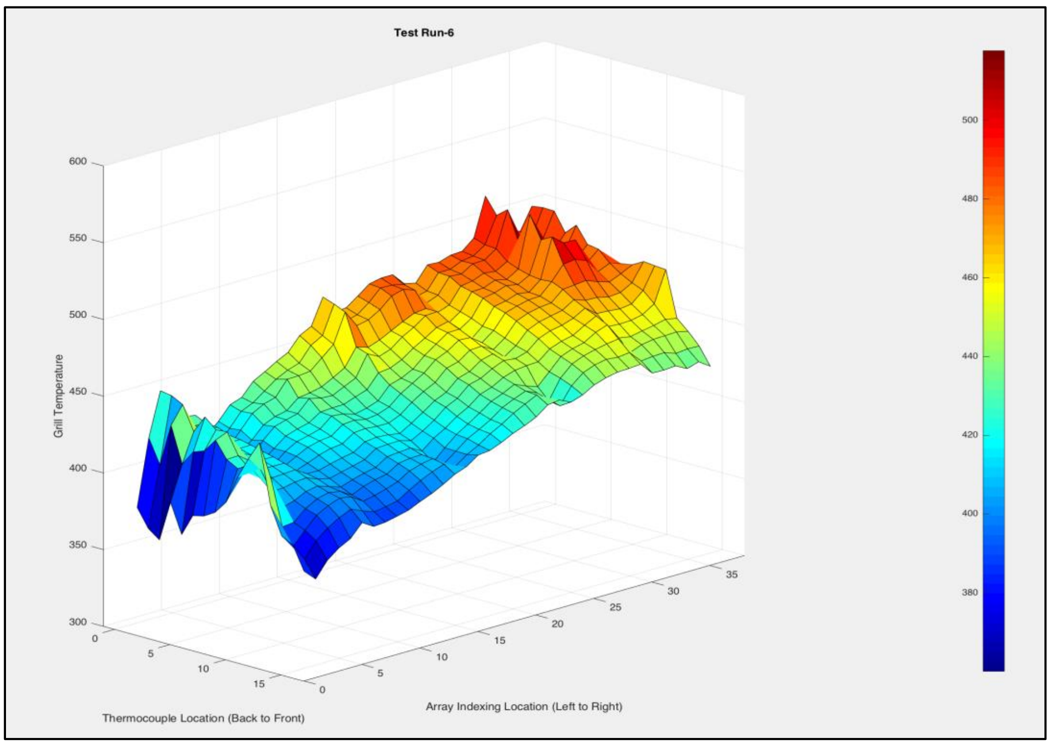


Figure J24: *3D mesh plot of average temperature grid produced using MATLAB for Test Run-6.*

Appendix K (DVPR)

Senior Project DVP&R Format

Report Date: TBD | Sponsor: Bull Outdoor Products, Inc. | Component/Assembly: Brahma Grill Heads (N.G. & Propane) | REPORTING ENGINEER(S): Monty Dodge & Sam Melo

TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibilit	Test Stage	SAMPLES Quantity	SAMPLES Type	TIMING Start date	TIMING Finish date	TEST RESULTS Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	Leak Test-NG	Check all Natural Gas Supply Lines for any leaks	Zero Leaks	Monty & Sam	PV	1	C	2/18/2016	2/18/2016				
2	Test 1--NG	Burner Position-High | Measure Entire Temperature Grid | Above Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/18/2016	2/18/2016				
3	Test 2--NG	Burner Position-Low | Measure Entire Temperature Grid | Above Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/18/2016	2/18/2016				
4	Test 3--NG	Burner Position-High | Measure Entire Temperature Grid | Between Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/18/2016	2/18/2016				
5	Test 4--NG	Burner Position-Low | Measure Entire Temperature Grid | Between Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/18/2016	2/18/2016				
6	Test 5--NG	Ramp Test | Begin Recording Temperatures With Burener Valves Off And Record Until Steady State is Reached	Reach Steady State Conditions	Monty & Sam	PV	2	C	2/18/2016	2/18/2016				
7	Leak Test--Pro	Check all Natural Gas Supply Lines for any leaks	Zero Leaks	Monty & Sam	PV	1	C	2/19/2016	2/19/2016				
8	Test 1--Pro	Burner Position-High | Measure Entire Temperature Grid | Above Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/19/2016	2/19/2016				
9	Test 2--Pro	Burner Position-Low | Measure Entire Temperature Grid | Above Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/19/2016	2/19/2016				
10	Test 3--Pro	Burner Position-High | Measure Entire Temperature Grid | Between Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/19/2016	2/19/2016				
11	Test 4--Pro	Burner Position-Low | Measure Entire Temperature Grid | Between Grill Grates	Temperature Distribution @ All Locations	Monty & Sam	PV	1	C	2/19/2016	2/19/2016				
12	Test 5--Pro	Ramp Test | Begin Recording Temperatures With Burener Valves Off And Record Until Steady State is Reached	Reach Steady State Conditions	Monty & Sam	PV	1	C	2/19/2016	2/19/2016				

Senior Project DVP&R Format

Report Date: TBD | Sponsor: Bull Outdoor Products, Inc. | Component/Assembly: Brahma Grill Heads (N.G. & Propa | REPORTING ENGINEER(S): Monty Dodge & Sam Melo

TEST PLAN							TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibilit	TIMING: Start date	TIMING: Finish date	TEST RESULTS: Test Result	TEST RESULTS: Quantity Pass	TEST RESULTS: Quantity Fail	NOTES
1	Leak Test-NG	Check all Natural Gas Supply Lines for any leaks	Zero Leaks	Monty & Sam	2/18/2016	2/18/2016	Passed	10	0	No failed tests, only retest supply connection with each performance test
2	Test 1--NG	Burner Position-High | Measure Entire Temperature Grid |Measured Left to Right	Temperature Distribution @ All Locations	Monty & Sam	2/21/2016	2/21/2016	Not Acceptable	0	1	Not Preheated long enough
3	Test 2--NG	Burner Position-Low | Measure Entire Temperature Grid |Measured Left to Right	Temperature Distribution @ All Locations	Monty & Sam	3/10/2016	3/10/2016	Not Acceptable	0	1	Appears to show low temperatures @ left side. Suspect Pressure drop in Manifold
4	Test 3--NG	Burner Position-Low | Measure Entire Temperature Grid |Measured Right to Left	Temperature Distribution @ All Locations	Monty & Sam	3/16/2016	3/16/2016	Not Acceptable	0	1	Appears to show low temperatures @ right side. Suspect Pressure drop in Manifold
5	Test 4--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured Left to Right	Temperature Distribution @ All Locations	Monty & Sam	4/1/2016	4/1/2016	Not Acceptable	0	1	Improved appearance of low temperature, still shows suspicious trend at left side (start of test). Suspect a bias due to radiation from thermocouple array.
6	Test 5--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternatin sequence at ends	Temperature Distribution @ All Locations	Monty & Sam	4/6/2016	4/6/2016	Acceptable	1	0	Believe to have found valid testing method. Results show larger temperature variation and higher average temperature above flame tamers. We will now use this as our reference to determine improvement of uniformity. Standard deviation of average temperatures is 22°F.
7	Test 6--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | Flame tamers w/o holes	Temperature Distribution @ All Locations	Monty & Sam	4/7/2016	4/7/2016	Acceptable	1	0	Data shows that the areas of higher distributions and higher average temperatures have shifted to locatios between flame tamers. Overall standard deviation of avergae temperatures is 19°F.
8	Test 7--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | 1/3 of holes on flame tamers covered from rear.	Temperature Distribution @ All Locations	Monty & Sam	4/8/2016	4/8/2016	Acceptable	1	0	Overall standard deviation of avergae temperatures is 19°F.
9	Test 8--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | 1/2 of holes on flame tamers covered from rear.	Temperature Distribution @ All Locations	Monty & Sam	4/13/2016	4/13/2016	Acceptable	1	0	Overall standard deviation of avergae temperatures is 18°F.
10	Test 9--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | 2/3 of holes on flame tamers covered from rear.	Temperature Distribution @ All Locations	Monty & Sam	4/14/2016	4/14/2016	Acceptable	1	0	Overall standard deviation of avergae temperatures is 16°F.
11	Test 10--NG	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | flame tamers w/o holes & w/ holes in between upside down.	Temperature Distribution @ All Locations	Monty & Sam	4/7/2016	4/7/2016	Acceptable	1	0	High overall standard deviation of mean temperatures likely due to insufficient preheat.

12	Leak Test--Propane	Check all Propane Supply Lines for any leaks	Zero Leaks	Monty & Sam	4/21/2016	4/21/2016	Passed	6	0	No failed tests, only retest supply connection with each performance test
13	Test 1--Propane	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternatin sequence at ends	Temperature Distribution @ All Locations	Monty & Sam	4/21/2016	4/21/2016	Acceptable	1	0	High Contrast in Temperature with left side of grill having much lower temperatures. Suspect pressure drop in maifold
14	Test 2--Propane	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | Flame tamers w/o holes	Temperature Distribution @ All Locations	Monty & Sam	4/22/2016	4/22/2016	Acceptable	1	0	High Contrast in Temperature with left side of grill having much lower temperatures. Suspect pressure drop in maifold
15	Test 3--Propane	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | 1/3 of holes on flame tamers covered from rear.	Temperature Distribution @ All Locations	Monty & Sam	4/27/2016	4/27/2016	Acceptable	1	0	High Contrast in Temperature with left side of grill having much lower temperatures. Suspect pressure drop in maifold
16	Test 4--Propane	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | 1/2 of holes on flame tamers covered from rear.	Temperature Distribution @ All Locations	Monty & Sam	4/29/2016	4/29/2016	Acceptable	1	0	High Contrast in Temperature with left side of grill having much lower temperatures. Suspect pressure drop in maifold
17	Test 5--Propane	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | 2/3 of holes on flame tamers covered from rear.	Reach Steady State Conditions	Monty & Sam	4/30/2016	4/30/2016	Acceptable	1	0	High Contrast in Temperature with left side of grill having much lower temperatures. Suspect pressure drop in maifold
18	Test 6--Propane	Burner Position-Low | Measure Entire Temperature Grid | Preheat w/ array at location 6.5 | Measured with alternating sequence at ends | flame tamers w/o holes & w/ holes in between upside down.	Reach Steady State Conditions	Monty & Sam	5/6/2016	5/6/2016	Acceptable	1	0	High Contrast in Temperature with left side of grill having much lower temperatures. Suspect pressure drop in maifold
19	Bench Test-Manifold Pressure	Verify Pressure at each burner orifice with all valves open	Record Pressure Values	Monty & Sam	5/10/2016	5/10/2016	Acceptable	1	0	Verified pressure drop in manifold to be a 33 percent decrease from right to left