Radome Test Fixture

Final Proposal

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1 BACKGROUND

1.1 Introduction

This project entails the design of test fixture for supersonic missile radomes. A radome is an aerodynamic dome installed on the tip of an aircraft to protect radar equipment. Radomes need to withstand extremely high stress caused by thermal and pressure loads during supersonic flight. Currently our client, Chuck Vallance, is a retired Raytheon employee. Mr. Vallance is volunteering his time to help our group design a test fixture for missile radomes. Missile radome testing is required to produce safe, effective missiles in addition to reducing the time and cost of generating new missile designs.

Testing Equipment for radomes is usually fabricated or even manufactured on site for high-speed flight components. Designing and testing missiles is expensive. The US currently spends $236.7 billion per year on updating major weapons systems [1]. These programs are funded through US tax dollars. The team is working with Chuck to create a test fixture, which expedites the flight component testing process. If the team can streamline the process of producing missiles, tax dollars are free to fund other programs.

It is important for the team to develop a reliable test fixture to test radomes for their ability to withstand these forces and temperatures. The US Military uses missiles to preform tactical strikes to neutralize threats to national security. If a radome cannot operate as intended, it would cause an issue of national security. Faulty radomes could jeopardize the outcome of tactical strikes, leading to unintended casualties or collateral damage, in addition to mission failure.

1.2 Project Description

The team started this project with a focus on flight component testing. The goal is to design a test fixture that can support evaluation of radomes by subjecting them to high force and high temperature conditions. The following text is the original project description provided by our sponsor, Chuck Vallance.

> "Outer mold line flight components, such as missile and aircraft radomes and wing leading edges often operate in extremely harsh environments. Small practical radomes can be 6 inches in diameter and 18 inches in length. A large radome can be 4 feet in diameter and 8 feet long. Wing leading edges can vary as dramatically. Successful design efforts for these hardware components include testing to validate the design. Common environments to which the hardware is subjected include internal and external pressures, high heat fluxes, and pressure induced flight loads. Specialized test rigs to perform the testing are standard. The output of this project will be a set of design specifications for a test fixture which can be deployed in standard laboratories (may be outside) and capable of testing a wide variety of radomes and leading edge shapes and sizes as well as producing a wide variety of test environments (pressures, loads, fluxes). Some fabrication and testing of scaled models of the test fixture will benefit this project to prove it is viable but is not required." [2]

The description has been altered for this project by only considering missiles and placing a focus on radomes. Wing-leading edges may be considered later in this project.

1.3 Original System

This project involved the design of a completely new radome test fixture. There was no original system when this project began.

2 REQUIREMENTS

In order to determine the requirements for this project, the team examined the project description and held meetings with Chuck Vallance. Chuck supplied the team with key customer requirements necessary to complete the project in its entirety. The team then translated the customer requirements to engineering requirements by quantifying each parameter. These requirements were placed into a House of Quality to outline correlations and importance. The following subsections discuss in detail the customer requirements, engineering requirements, and their relationships in the house of quality.

2.1 Customer Requirements (CRs)

Chuck was able to provide valuable insight about the project. He explained what was required of the test fixture. The team weighted each CR based on chucks recommendations. These requirements and their respective weights are listed in the bulleted outline below.

- Must be durable
  - The test fixture needs to be long lasting and be able to survive transport.
  - Weight: 10%
- Operate under high force
  - Test fixture must supply and withstand high force loads.
  - Weight: 10%
- Operate under high temperature
  - Test fixture must supply and withstand high temperatures.
  - Weight: 10%
- Supports radome
  - Test fixture must be able to support the weight and geometry of a range of radomes.
  - Weight: 15%
- Must fit in a standard load test area
  - Raytheon has standard load test areas that are as large as 10 feet by 10 feet. The test fixture footprint is constrained by this area.
  - Weight: 15%
- Must mount to a plate on the ground
  - Mounting plates are included in Raytheon's standard load test areas. These plates have holes for peg supports. The test fixture must be compatible with the plate.
  - Weight: 5%
- Operates safely
  - Test fixture must be safe to operate for all employees involved.
  - Weight: %15
- Reasonable set-up time
  - Test Fixture must be able to set up quickly providing for prompt operation.
  - Weight: 5%

- Provide instructions
  - Instructions must be provided so that device is operated the same way every time.
  - Weight: 5%
- Radome and fixture must be compatible
  - The apparatus that attaches the radome to the fixture must be compatible with a range of radome geometries.
  - Weight: 10%

The team based the CR weights on relevance. For example, if the test fixture does not fit in a standard load test area, then the test fixture is useless. This CR was given a higher weight for this reason. In contrast, the team's ability to provide instructions does not affect the overall function of the test fixture.

2.2 Engineering Requirements (ERs)

The team created ERs to quantify Mr. Vallance's requirements. ERs are helpful because they provide values and tolerances that the final device must comply to. Because much of the details of missiles and the conditions that they operate are classified, the ERs in this section are estimates. The twelve ERs are listed below.

The first ER is that the fixture must have a factor of safety of four. Having a factor of safety of four is the target value. The factor of safety must be greater than four but less than six. If the factor of safety is above six, the fixture will be over engineered and thus be difficult to maneuver or assemble.

Another ER is that the fixture must withstand 2.25 kips. This value is based on the amount of force that a missile radome will encounter on a mission. Because the radome is subjected to this force, the fixture must also withstand the same force. The tolerance for this ER requires that the fixture withstand at least 2.25 kips.

Missile radomes must operate under high temperatures. The test fixture must withstand at least 300 degrees Fahrenheit in order to provide accurate radome testing. If the test fixture cannot support this heat, the components of the fixture may deform.

The fixture must have at least four supports at the base. This ER is targeted toward allowing the fixture to mount to the plate on the ground. Any less supports may cause failure and will affect the factor of safety.

The fixture must also not have a footprint larger than 10 feet by 10 feet. The ER is meant to ensure that the fixture will fit inside a standard test area. The team does not know how large these test areas are, but based on knowledge of the size of radomes, this seems like a reasonable assumption.

The fixture cannot be taller than ten feet. This ER contributes to assembly time and transport. This also accounts for any roof or covering over a given test area.

The team decided to allow the fixture to have a five-minute time delay of operation. This ER is to help increase the safety of the fixture. The tolerance of this ER is plus or minus two since a delay is necessary but should only be long enough for operators to clear the area.

The set-up time for the test fixture must not exceed one hour. The goal is to have the set-up time be as low as possible. This equipment is generally heavy and may require forklifts or cranes to assemble. Because of this, one hour may not be enough time. This is why the set-up time is allowed to be between one and three hours.

The text fixture should come with one set of physical instructions. This ER will contribute to increasing safety and decreasing set-up time. At the most, there should be two copies of instructions supplied. This is because more than two would be redundant. Two copies allow for one primary set and one backup set.

The test fixture must allow for at least two exit routes. This ER will allow for a quick evacuation should something go wrong. This ER should be easy to accommodate because testing will take place outside.

The last two ERs are that the apparatus that will attach to the radome can adjust to a maximum of six-foot diameter and have at least two fasteners per foot. The size of the apparatus is important because radomes can be a range of sizes and the apparatus must be compatible. Having two fasteners per foot will allow for durability and stability of the radome during testing.

It is important to note that cost is not a factor in this design. Chuck Vallance is not interested in cost and has told the team that the test fixture can be as expensive as necessary as long as all CRs are met.

In order to determine if all ERs are met, the team developed a testing procedure that contains individual tests for each ER. These procedures are outlined in the following subsection.

2.3 Testing Procedures (TPs)

Testing procedures allow for sound research and project progression. Since the team's project is analytical, it would not involve an actual building of the design as the design would be complex and costly to manufacture. However, to prove that the team has met the ERs, testing procedures were created. A few of these procedures will require detailed finite element analysis (FEA) using computer software. The team have found software that can be used to simulate the subsystems specifically for the team design. The different testing procedures for each ER can be found in the following subsections.

2.3.1 TP #1: FEA for Factor of Safety

FEA for factor of safety can be conducted in SolidWorks. SolidWorks is a three-dimensional modeling computer software that can be used to model designs like the test fixture for this project. SolidWorks is also capable of FEA and can simulate realistic testing to estimate things like a factor of safety. The user inputs a force, material, and a part to get an output of factor of safety. This will be used for the ER that requires the factor of safety to be four. This testing procedure allows the team to conduct realistic analytical research on how the fixture will behave.

2.3.2 TP #2: FEA for Reaction Force

Similar to the previous subsection, SolidWorks will also be used to simulate force on the test fixture. The same inputs that were required for the factor of safety calculation are required for the FEA reaction to force as well. This SolidWorks analysis will be able to determine if and where the specimen will fail.

2.3.3 TP #3: FEA for Thermal Loads

FEA for thermal loads will be conducted using the computer software, ANSYS. ANSYS is a simulation software for engineers to perform FEA on specific parts of interest. ANSYS has different applications for simulating thermal and strength reactions for different engineering structures. ANSYS is available for the team to use through Northern Arizona University's engineering department. To evaluate thermal loads, ANSYS allows for the construction of a feature while considering material composition and specific geometry. It then can take an input of radiative heat flux from, in this case, a quartz lamp and output temperatures of the feature. It will also determine if failure will occur at these temperature points. This testing procedure will be used to validate the ER that requires the test fixture to withstand 300 degrees Fahrenheit.

2.3.4 TP #4: Analyze Quantity

Analyzing quantities refers to counting features to ensure that certain ERs are met. This applies to the ER that requires that the test fixture has at least four supports on the base. The team can easily add as many supports to the base as necessary. Two other ERs that can be met by analyzing the quantity are the requirements to have two sets of physical instructions and to have two exit routes. All three of these ERs can be confirmed to be met by counting the features in question.

2.3.5 TP #5: Tape Measure

Since this test fixture is designed from scratch, the team has a lot of freedom with dimensioning. This makes certain ERs measurable with a basic tape measure. The tape measure can come from any hardware store. The tape measure will be used to verify ERs that are dimension specific. These ERs include: the footprint of the test fixture cannot be larger than 10 feet by 10 feet, the test fixture cannot be taller than 10 feet, and the radome apparatus must be adjustable to six feet in diameter. The footprint and the height will just be measured one time after construction is complete because the area and height will not change. To determine if the radome apparatus is adjustable to a six-foot diameter, the team will use the tape measure while the apparatus is being adjusted and record success or failure when the diameter reaches a maximum.

2.3.6 TP #6: Stopwatch

A generic stopwatch will be used to validate two ERs. It is important that the set-up time for the test fixture be under one hour. This will be measured using a stopwatch and the time will be recorded. If the time measured is more than one hour, the team will reassess the components of the fixture and attempt to reduce the set-up time until it is within one hour. The fixture should also have a delay time of five minutes before operating. This ER will also be evaluated using a stopwatch. This time delay will most likely be programed into the sensors that will begin the testing process. Therefore, this ER will be simple to meet.

These TPs, ERs, and CRs are directly related. This relationship is shown in the House of Quality that can be found in the section below.

2.4 House of Quality (HoQ)

The HoQ is used for developing relationships between the CRs and the ERs. The HoQ uses these relationships and the weights of the CRs to generate an absolute technical importance (ATI) and a relative technical importance (RTI). Correlations were ranked a one, three, or nine. Nine represents a very strong relationship, three represents an average relationship, and one represents a weak relationship. Unmarked correlations mean that the CR and ER in question are unrelated. The HoQ can be seen in **Error! Reference source not found.** below. **Error! Reference source not found.** includes each ERs ATI, RTI,

Table 1: House of Quality

Customer Requirement	Weight	Engineering Requirement	Must have a factor of safety of 4	Must withstand 2.25 kips	Must withstand 300 degrees	Must have at least 4 supports on the base	Must have a footprint no larger than 10ft x 10ft	Must not be taller than 10ft	Has a delay time of 5 min	Setup time must not exceed 1 hr	Must have 1 set of physical instructions	Must allow for 2 exit routes in case of an emergency	Apparatus must adjust to be 6ft in diameter	Apparatus must have 2 fasteners per ft diameter
1. Must be durable	10%		9	9	9	9							1	3
2. Operate under high force	10%		3	9	3	3								3
3. Operate under high temperature	10%		1	3	9									
4. Can support a radome	15%						9	3					9	3
5. Must fit in a standard load test area	15%						9	9					1	
6. Must mount to a plate on the floor	5%					9	3							
7. Operates safely	15%		1	3	3	9		1	9	3	3	9		
8. Reasonable setup time	5%					3	1	3		9	9			
9. Provide instructions	5%									9	9	3		
10. Radome and fixture must be compatible	10%			1	3	1	3	3	1	1			9	9
Absolute Technical Importance (ATI)			1.45	2.65	2.85	3.25	3.2	2.4	1.45	1.45	1.35	1.5	2.5	1.95
Relative Technical Importance (RTI)			9	4	3	1	2	6	9	9	10	8	5	7
Target ER values			4	2.25 kips	300 F	4	10ft	10ft	5min	1hr	1	2	6	2/ft
Tolerances of Ers			+-2	+-1	+-50	+2	-4	-4	+- 2	+-2	+1	+-1	+2	+2
Testing Procedure (TP#)			1	2	3	4	5	5	6	6	4	4	5	4

target values, and tolerances.

The team used the RTI values to determine the most relevant ER. Having at least four supports on the base was identified to be number one according to the RTI. Because of this, the team will place a high importance on meeting this ER. It is reasonable that having enough supports would be an important thing to consider. The base supports affect the durability, safety, and functionality of the test fixture. Without enough base supports, the test fixture would not be able to operate properly. Other top-ranking ERs include having a footprint of ten feet by ten feet, withstanding the determined amount of heat and force, and having an apparatus that is compatible to any given radome. These top-ranking ERs are of highest importance because they directly relate to several of the CRs.

3 EXISTING DESIGNS

The team conducted research on existing designs based on the project description. This section outlines research strategies and includes existing designs that resemble a radome test fixture. This section also explains the team's Black Box and Functional Model. Additionally, this section explores existing designs for each sub-function of the radome test fixture. This research was used to help generate concepts in Section 4.

3.1 Design Research

Each team member conducted research on existing test fixture designs to benchmark existing test fixtures. Team members searched for patents and academic articles to learn about how flight components are tested. The team generated the requirements form client interviews and the project description, because there is not an original system. There were problems retrieving current information on radome testing due to the classified nature of this project. Several designs were found including a radome stress test fixture, an aircraft heat/stress testing facility, and an engine testing apparatus. These designs were selected because they contain aspects of this project's goal. They include heating and stress systems. This research was helpful in giving the team ideas on how to move forward with the project. After a team meeting, it was decided that existing designs needed to be researched that focused on aircrafts and flight. Appropriate system level designs are outlined and explained in Section 3.2.

3.2 System Level

The team found several articles about supersonic flight testing facilities from NASA's website. One article discussed flight-testing for entire aircrafts at supersonic speeds. Team members also explored NASA's testing system for engines to explore how moving components could be integrated into the testing procedure. A patent was found that focused on a radome stress testing apparatus to gain insight into stress test setups for flight components.

3.2.1 Existing Design #1: Radome test systems and methods

This patent, figure shown below, displays the full system and method for testing aircraft radomes [3]. The radome is placed onto a fitting where it is secured to the structure. Then two force-providing devices are placed into position on the inside and outside of the radome. These devices are headed with a swivel joint to mold the head to the shape of the radome. This design really helps with generating a force and moment in specific locations. The methods of attachment can also be examined to apply it to our design. The following (Figure 1) is a picture of the radome stress testing device [3].

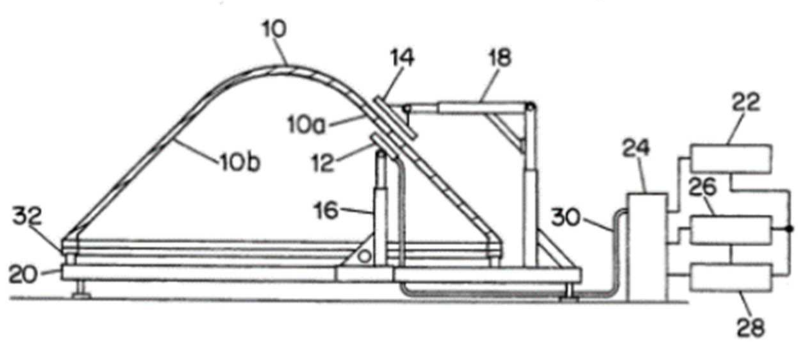


Figure 1: Stress Testing Device [3]

3.2.2 Existing Design #2: Flight Research Facility

NASA's flight research facility contains various systems of quartz lamps, cable pulleys to test various aircraft thermal and mechanical loading conditions [4]. The team's test fixture will need a system to produce similar heat and force, while testing structures with differing size and geometry. The testing apparatus for the flight components also contains equipment to read strain and temperature gauges installed in flight components, such as the X-15 aircraft [4]. From discussions with Chuck, the team's device must also include a temperature sensor for calculating the heat flux into the flight components. The testing facility also fabricates fixtures to arrange heating to the contour of various aircrafts [4]. The team's design should focus less on the fabrication of fixtures to reduce the time to set up the team's test fixture. Below is a picture of a combined heat and loading setup (Figure 2) at NASA's flight research facility [4].

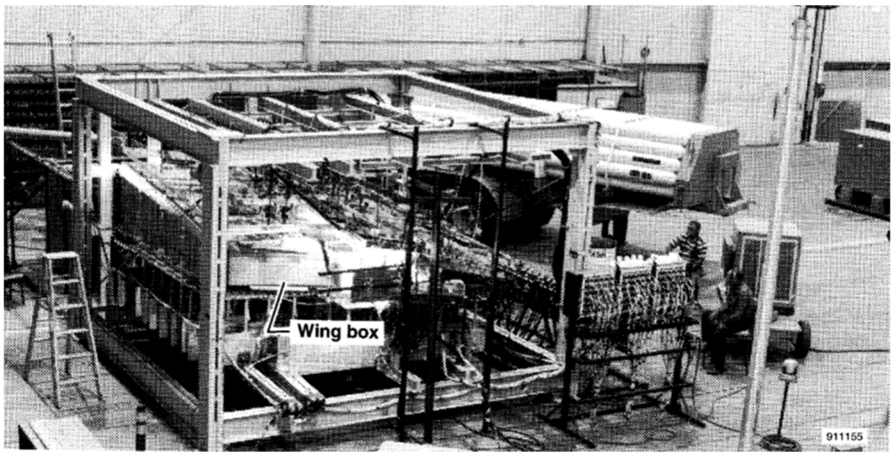


Figure 2: Combined Loading Setup [4]

3.2.3 Existing Design #3: Propulsion Flight-Test Fixture

NASA had developed a propulsion flight-test fixture to test flight data on engines [5]. This fixture allows for testing engines in early stages [5]. However, it is used in flight as opposed to a wind tunnel or rigs built in a test area on the ground [5]. The device works by being mounted to the engine and to another plane or missile [5]. This test fixture relates to the project requirements because it tests a flight component for force and temperature [5]. Figure 3 below shows an aircraft with this device attached underneath the plane.

Figure 3: Propulsion Flight-Test Device [5]

This device is different from the project description in that the force and temperature are applied through actual flight conditions. The team must apply force and temperature artificially through other methods. From a detailed examination of this device, the team was able to learn more the possibility of using moving parts in the radome test fixture design. Simulating flight more realistically may be a reasonable design component.

3.3 Functional Decomposition

The team created a functional decomposition to outline the critical sub-functions of a test fixture. Generating a functional decomposition allowed the team to focus on the abstract functions performed by a test fixture. In the subsequent sections, the team discusses the production of the Black Box Model and Functional Diagram. The team also discusses how a functional decomposition contributed to this project and outlines three main subsystems in the test fixture design. Finally, the team cites concrete examples for each subsystem level component from research of existing designs.

3.3.1 Black Box Model

First, the team created a Black Box Model of a test fixture. The Black Box Model contains the critical material, energy, and signal inputs and outputs for a test fixture. The inputs and outputs for the system are categorized by flow type: Material, Energy, or Signal. Using knowledge form existing Fixture design and interviews with Chuck, the team generated a black box model (Figure 4).

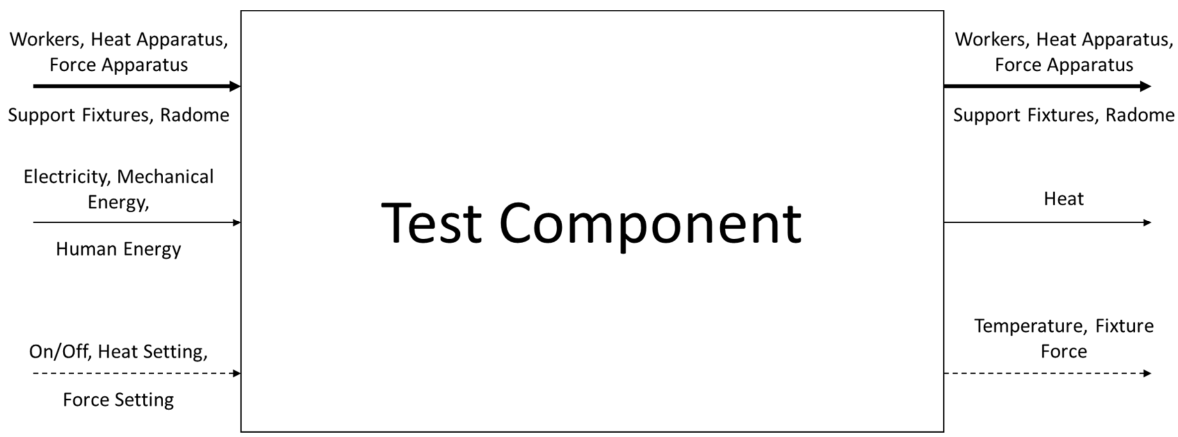


Figure 4: Black Box Model

The Material inputs for the Black Box model are the Force Apparatus, Heat Apparatus, Support Fixture, Equipment, Workers, and the Radome. Each material flows in and out of the black box model. Definitions for the material flows are listed below. Arrows to the right denote flows into the system, while arrows to the right represent floes out of the system. Double arrows represent flows that go in and out of the system.

- ⇔ The Force Apparatus includes the any component of the system used to generate mechanical energy.
- ⇔ The Heat Apparatus accounts for any materials used to directly heat the system (e.g. quartz lamps)
- ⇔ The Support Fixture is composed of any structural components used to hold the Radome, Heat Apparatus, and Force Apparatus in place.
- ⇔ Equipment includes any tools or machinery used to assemble the test fixture.

- ⇔ Workers include any personnel included in the assembly of the Radome.
- ⇔ The Radome includes the Radome, pre-fitted with a metal base to attach to the test fixture.

Electricity, Human Energy, and Mechanical Energy are the energy inputs for the Black Box Model. The system energy output is excess heat generated by the heating Apparatus. Each energy flow is described below.

- ⇨ Electricity accounts for any electricity consumed by the test fixture. Both Kilowatt-hours and peak rates will be relevant to this project.
- ⇨ Mechanical Energy includes the mechanical energy provided by equipment
- ⇨ Human Energy describes any physical effort by workers to assemble the test fixture
- ⇦ Heat describes the excess heat generated by the test fixture, which dissipated into the surroundings.

The Signal inputs for the Radome Test Fixture include Heat Setting, Force Setting, and an On/Off signal. The output signals for the radome include Temperature and Fixture Force.

- ⇨ The test fixture will have a Heat Setting input, which will adjust the heat generated by the test fixture
- ⇨ The test fixture also contains a Force Setting, which dictates the amount of force applied by the test fixture.
- ⇨ The test fixture will have an On/Off switch to begin or terminate operation.
- ⇦ The Temperature of the Radome will be monitored to calculate the heat flux.
- ⇦ The Fixture Force will be monitored to determine the strength of each Radome.

Creating a Black Box model helped the team visualize which flows are important for the system to function. The Black Box model displays the requirements to set up the test fixture as well as the data extracted from the system.

3.3.2 Functional Model

Using the input flows from the Black Box Model, the team generated a Functional Model. The function in the Black Box Model is divided into sub-functions in the Functional Model. The Functional Model displays how flows are used to perform sub-functions within the test fixture (Figure 5).

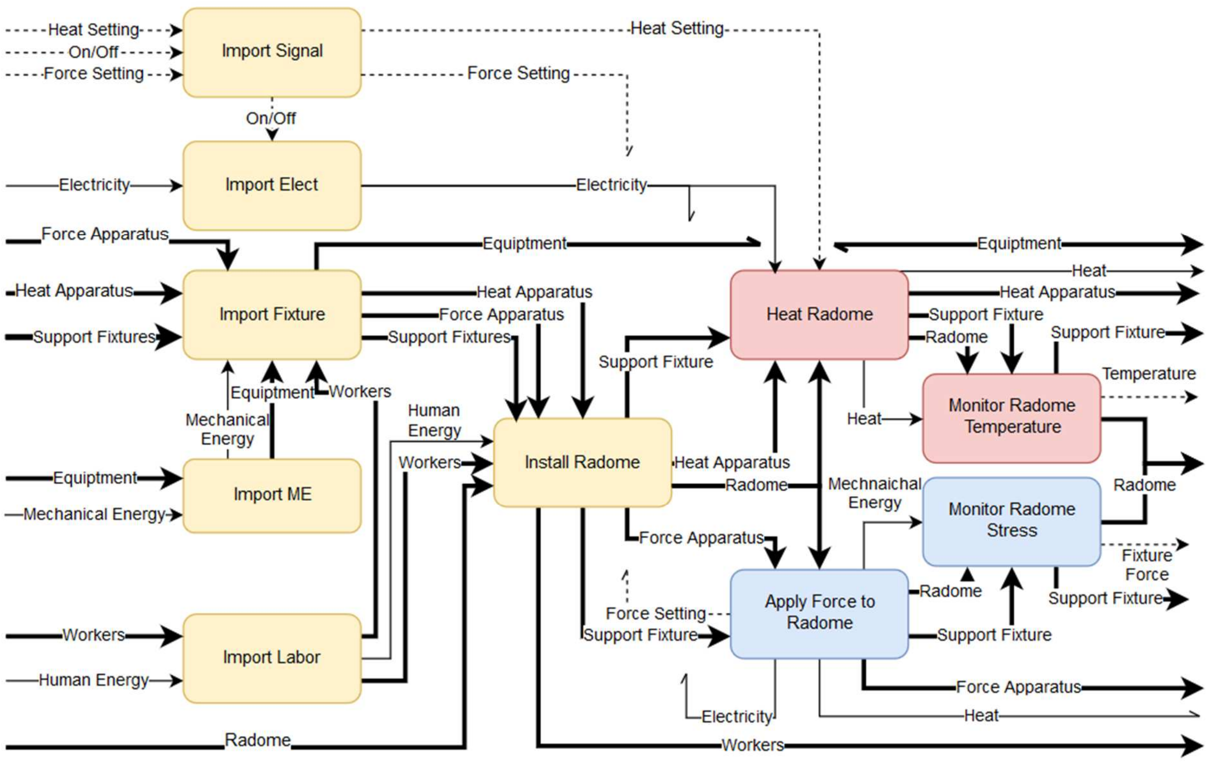


Figure 5: Functional Model

The Radome Test Fixture has nine sub-functions. Each sub-function contributes to the performance of particular subsystem. Each sub-function in the Functional Model is color coded with an associated subsystem. The three subsystems in our design are Setup Test (1), Heat Radome (2), and Stress Test Radome (3). Setup Test (yellow) includes all signals into the system, acquiring electricity, importing labor, setting up the test fixture, and installing the radome. Next, Heat Radome (red) consists of heating the Radome and monitoring the temperature from the radome to calculate heat. Lastly, Stress Test Radome (blue) includes applying force to the radome and collecting force data to calculate stresses in the radome.

3.4 Subsystem Level

After creating the Functional Model, the team searched for subsystems of existing test fixtures that related to the subsystems in the functional diagram. Team members researched how test fixtures setup tests, heat components and test samples for stress. Analyses of various subsystem level designs are outlined below.

3.4.1 Subsystem #1: Setup Test

The Setup Test subsystem involves setting up the test fixture and installing the radome. This subsystem integrates labor, machinery, and the assembly of the of the physical components of the test fixture. The Import Fixture sub-function and Install Radome sub-function from Figure 5 closely relate to the setup time and stability of the test fixture. Below the team examines existing designs and methods for setting up systems.

3.4.1.1 Existing Design #1: Radome test system and methods

This patent contains an attachment method that can be used to secure the radome to our structural device

[3]. Most of current designs have the radome held on its side; however, this design is unique by placing the radome facing upwards. We could utilize this design if we so choose to, however it is not necessary.

3.4.1.2 Existing Design #2: Skates for moving heavy objects

This design is for transporting heavy objects or machines over the testing area [6]. In Figure 6, the design involves skates that can withstand and transport heavy loads, which is needed in our design [6]. These skates can be used when moving the fixture or can be permanently attached to the design. As our design is considered heavy, it is important to consider the way of transporting it. Below () is an image of the skates [6].

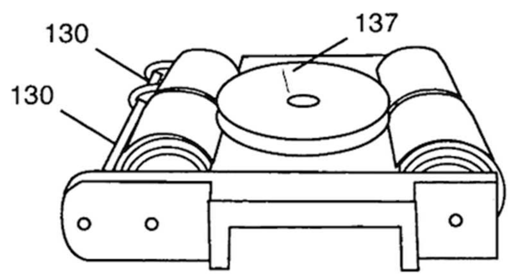


Figure 6: Heavy Object Skates [6]

3.4.1.3 Existing Design #3: Portable Lifter

This design has a combination of lifting and moving heavy objects [7]. The design consists of two main parts, each of the parts has two wheels and a mechanical lifter, both parts get assembled together around the object that is needed to be moved [7]. This patent is different than the above as it can lift objects for different heights and transport them at the same time [7]. When transporting our test fixture, this design can be used to lift the fixture and transport it from a place to another and then dissemble the lifter from the fixture to keep our device fixed in the required spot.

3.4.2 Subsystem #2: Heat Radome

One of the most important customer needs is provide a heat flux to the testing area to generate heat dependent stress testing. The Heat Radome Sub-function involves producing adequate heat flux to the radome and testing the temperature of the radome to calculate heat flux. Electricity and Heat are the most important flows in this sub-function. Heat testing a radome requires an ample amount of heat and electricity, so the heating rate and heating efficiency are important factors for test fixture design. Below are a few existing sub systems for producing heat.

3.4.2.1 Existing Design #1: Quartz Lamps

The team explored how quartz lamps are used to generate heat flux in flight components. Quartz lamps include a tungsten filament in a quartz bulb, which generate infrared radiation [4]. The bulbs are fitted with reflectors to direct light. These reflectors range from stainless steel sheets to ceramics, which are only efficient for high heat applications [4]. Choosing quartz lamps to heat the team's test fixture would require the customer to change reflectors for different tests. Figure 7 shows the heating apparatus for NASA's YF-12 Airplane [4].

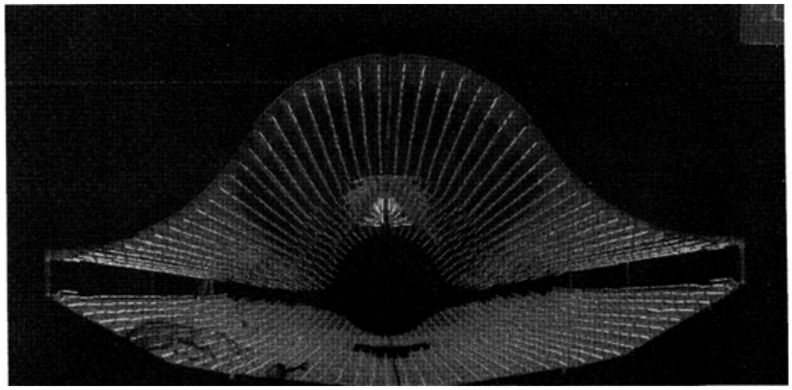


Figure 7:YF-12 Airplane Heating [4]

Quartz lamps also have a relatively long life and increase in efficiency with higher power supplied [4]. Using quartz lamps for the test fixture would allow the team to generate high heat fluxes efficiently.

3.4.2.2 Existing Design #2: Laser Heating Material Specimens

The team examined less traditional methods of heating flight components. Ultra-High Temperature Ceramics (UHTCs) like Hafnium dioxide are tested for use in hypersonic flight using laser heating [8]. The team could use lasers in our design to test radomes for higher heat fluxes or to generate a large amount of heat in a single area. Lasers capable of generating heat fluxes of 100 MW/m^2 are used to test UHTC specimens [8]. For comparison, NASA's test apparatus of the YF-12 Airplane at Mach 3 speeds could produce a maximum heat flux of 18MW for a 5000 ft^2 area [4]. Below (Figure 8) is a picture of the laser test specimen setup [8].

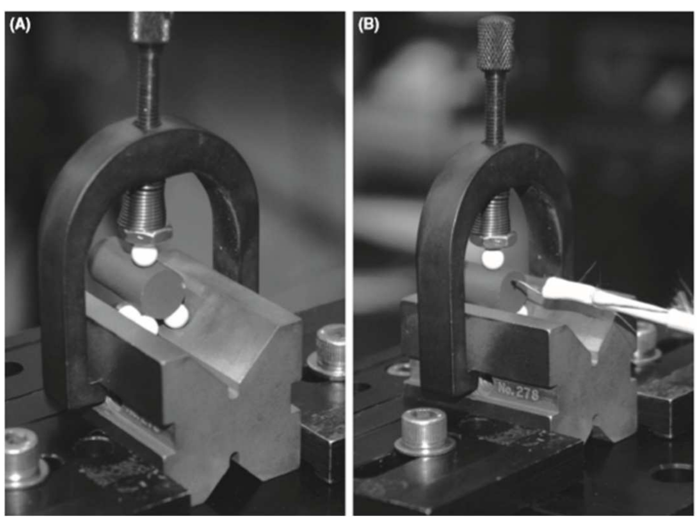


Figure 8: Laser Test Setup [8]

3.4.2.3 Existing Design #3: Radomes heated by hot gases

The idea of this design is to heat up radomes using hot-burned gases [9]. The radome is placed into a chamber; the tip of the radome will be facing a nozzle, which is similar to the jet aircrafts nozzles [9]. The nozzle produces huge amounts of heat on the radome and hence the thermal properties of the radome can be assigned. This idea would be useful to produce heat energy for our design, as long as the nozzle provides enough heat to the radome.

3.4.3 Subsystem #3: Stress Test Radome

Producing a force on the radome is critical to radome testing. From the team's interviews with Chuck, the device needs to produce a force normal to the axis of the radome to generate a moment within the radome. The Functional Model displays the relation between force production and mechanical energy (Force) and the support structure. The team researched how other subsystems exerted force on components and collected stress/strain data. Below are a few existing designs for stress testing or force production.

3.4.3.1 Existing Design #1: Hydraulics

This is a laboratory that has different setups to test radomes and different small flight components [10]. The lab is found in National Chang-Shan Institute of Science and Technology (NCSIST), one of the setups is for testing the strength of a radome using hydraulic device [10]. The radome is tested while it is attached on the side to a fixed wall, and then a strap goes around the radome and connects to the hydraulics as showing in Figure 10 below [10].

Figure 9: Radome Hydraulic Pull Setup [10]

The hydraulics will apply force to the radome pulling it downward to test the strength of the radome and how much it can withstand. This is one of the practical ways to produce force on radomes.

3.4.3.2 Existing Design #2: Radome test system and methods

This patent, the same as Section 3.4.1.1, has a unique way of producing a force and moment on the radomes structure [3]. Most designs have only a single force producer to generate the moment on the radome; however, this design has two force producers. One is placed on the outside, while the other is placed on the inside, offset from the other one to generate point moments. This could be used to utilize very accurate analysis of stress testing on our design.

3.4.3.3 Existing Design #3: Water Jet

Smith's design includes a water jet to test the wear and erosion of radomes due to rain in adverse weather conditions [11]. The water jet design is capable of delivering a small jet of water at a speed of 5000 feet per second [11]. The team could use smith's research to generate a system where fluid applies force on the radome. Appling force with a fluid would alleviate the need to insulate the force apparatus from heating devices. The water jet subsystem is displayed in Figure 11 below [11].

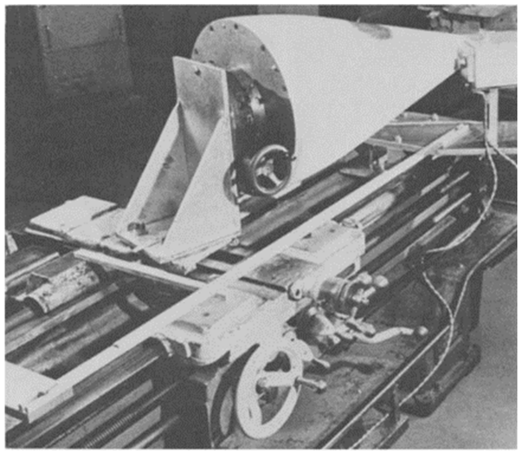


Figure 10: Water Jet

4 DESIGNS CONSIDERED

In the first stage of concept generation, each member focused on a specific sub-function and came up with about six ideas. The team then met to discuss how to put each sub-function together. We decided to utilize a morphological matrix (morph matrix). A morph matrix is a tool where all sub-functions are listed and can be combined to create complete designs. The morph matrix for the radome test fixture project can be found in Table 2 below.

Table 2: Morphological Matrix

Sub-Functions	Generated Ideas				
Hold Radome	Bolted to the fixture	Radome is rooted in the ground	Springs	Screw radome in like a lightbulb	Screw radome in (lightbulb)
Produce Heat	Nichrome Coils	Quartz Lamp	Wind from fans	Thermite (lit on fire)	Insulator
Apply Force	Cables (pull on radome)	Electro-magnetism	Dropping it into water from high distance	Wind from fans	Pressurized Container
Hold Force	Adhesive	Welding	To the ground	To the fixture	Springs
Hold Heat	Free Standing	Suspended from fixture	Magnetic field	Ceramic shell	Adhesive
Move Apparatus	Wheels	Nanobots	Zero friction	Forklift	Crane

The team developed ten different designs from the morph matrix. Four of the ten designs are detailed in following sections. The remainder of the sketches can be found in Appendix A. All designs are classified as force/heat.

4.1 Design #1: Electromagnetism/Quartz Lamp

For this design, the force provider will be utilizing a force generated by electromagnetism. The power required to operate the devices will depend on the material selected. The principle behind its force is having an armature connecting two rails form a circuit, and then sending a current through it will generate a force, as shown in the lower image below. These rails and armature will be connected to a circular ring allowing it to rotate around the radome freely. The ring will then be connected to the base platform for stability. Then we will have a quartz heat lamps evenly spaced around the radome testing area, shown Figure 12 below.

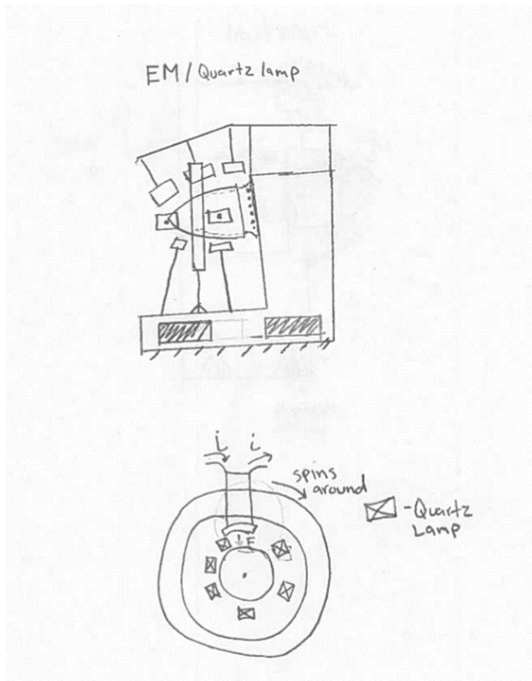


Figure 11: Electromagnetism and Quartz Lamp Design

The lamps will be attached to rods that will have a single degree of freedom. This will allow us to adjust the heat flux as needed. The radome will then be connected to the device through a series of circular bolts. The bolts will be mounted to the main design frame. The base of the frame will have forklift slots either cut in or built around the bottom to allow the device to be moved easily.

Pros: One-piece design, Simple Setup, Mobile, Precise Force generation, Adjustable heat flux

Cons: Requires a lot of Electrical Power, could be unsafe to operate if not properly insulated, might be too heavy for a forklift to move.

4.2 Design #2: Hydraulics/Coils

The Hydraulic/Coil design integrates nichrome coils and hydraulic ram. This device also utilizes smart materials to reduce setup time. The Hydraulics/Coils device uses a hydraulic ram to produce a moment on the radome base while the nichrome coils heat the radome (Figure 12).

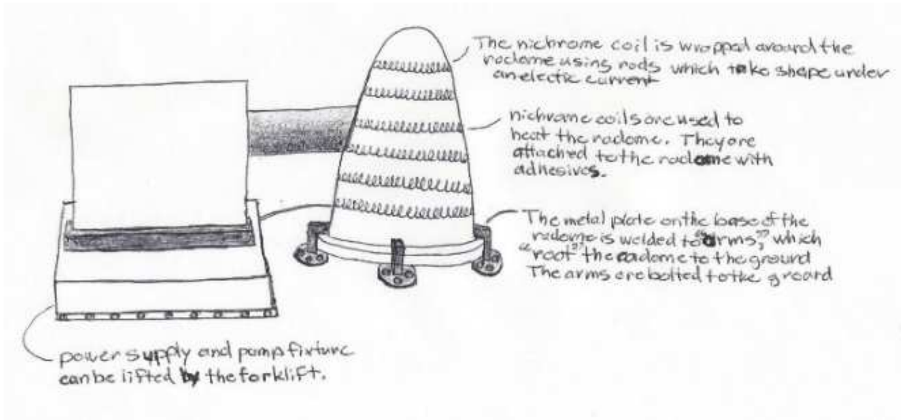


Figure 12: Hydraulics/Nichrome Design

The coils are wrapped around a rod that takes the shape of the radome when a weak electric current is applied. The rod is removed, and the coils are glued in place. This device holds the radome to the ground using elbow brackets, which are welded to the radome base and bolted to the floor. The power supply for the nichrome coils is grouped with the force apparatus, which is lifted in by a forklift and bolted to the floor.

Pros: Mobile, quick setup

Cons: does not test bolts in radome base, damages nichrome coils, low heat flux

4.3 Design #3: Wind/Thermite

The Wind/Thermite Design takes may elements form bio inspired designs. This setup emulates how the roots of a tree resist wind loads by anchoring to the ground. The wind thermite design uses wind to exert a force on the radome and thermite to apply a thermal load (Figure 13).

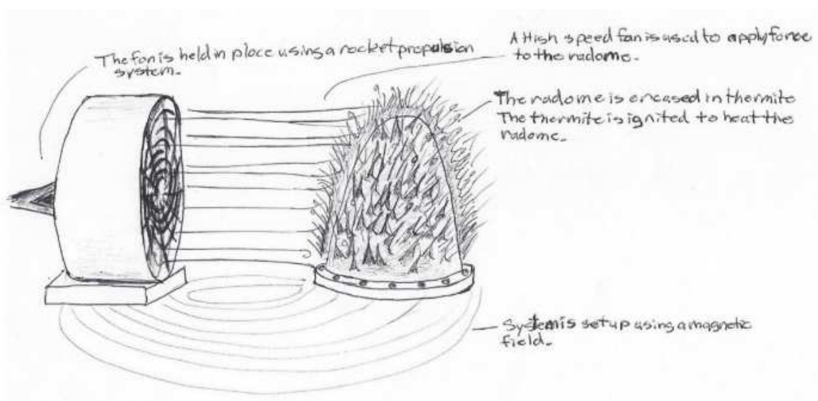


Figure 13: Wind /Thermite Design

The base of the radome is bolted directly to the floor. The fan is moved into place using a strong magnetic field. Heat is applied to the radome by igniting a thermite coat applied to the radome. After the thermite starts to burn, a fan blows air on the radome. Rockets are installed on the fan to hold it in place while it operates.

Pros: Rigid radome base, high heat flux, Cons: low force, unsafe (molten iron particulate), damages facility

4.4 Design #4: Drop/Insulator

The Drop/Insulator design heats the radome in an insulated case. This design tests radomes by dropping them and using the impact force to test radome stress (Figure 14).

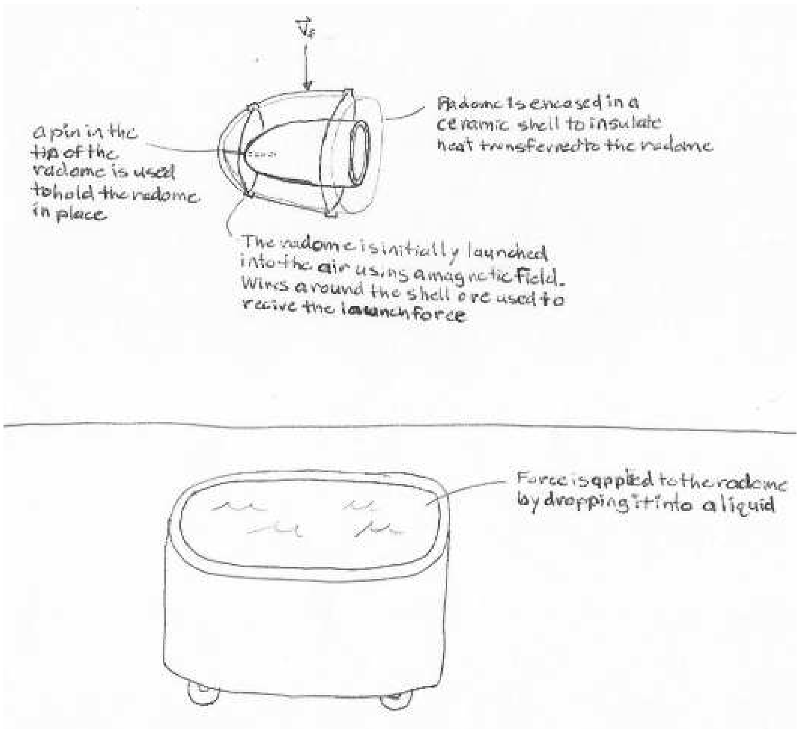


Figure 14: Drop/Insulator Design

The radome is attached to the case by a pin through the tip of the radome. To begin testing, the case is launched into the air using a magnetic rail. Wires are installed around the glass insulator to transmit force from the rail to the insulating shell. Force is applied to the system when the radome is dropped into a pool of water. The temperature and strain data from the radome are recorded in a black box located inside the radome.

Pros: quick setup

Cons: varies with weather, dangerous, destroys insulator, dissimilar force distribution, uniform radome heating (no temperature gradient).

5 DESIGN SELECTED – First Semester

The following section will examine the thought process behind our final design selection. A Pugh Chart and Decision matrix are provided as visuals. The final portion of the section contains the final design selection and its relation to the engineering requirements of other designs.

5.1 Rational for Design Selection

The team input their ten designs into a Pugh Chart. The design that implemented cables to drive the force and nichrome coils to drive the heat was considered the datum. The team chose this datum randomly. The remaining nine designs were compared to the datum by examining safety, force efficiency, thermal efficiency, base supports, appropriate dimensions, delay time, set up time, and radome compatibility. A sample of The Pugh Chart for the radome test fixture is shown in Table 3 below.

Table 3: Pugh Chart Sample

	EM/Quartz	Pressure/Coils	Hydraulics/thermite
Safety	-	+	-
Force efficiency	S	-	S
Thermal Efficiency	+	S	-
4 base supports	S	S	S
10x10 footprint	S	S	S
10ft tall	S	S	S
5 minute delay	+	S	-
hour set up	+	-	-
instructions	S	S	S
6ft diameter apparatus	S	S	S
2 fasteners per ft on apparatus	S	S	S
Total	3	-1	-4

The Pugh Chart was helpful in eliminating unreasonable ideas. The team took the top five designs from the Pugh Chart and included them in a Decision Matrix. The team used the same engineering requirements in the decision matrix as the Pugh Chart. All of the designs considered allowed for freedom as far as providing instructions, having four supports, and being compatible with the radome. For this reason, the team gave the fourth ER and the last three ERs a zero-weight percentage. A sample of the decision matrix for the radome test fixture is shown in Table 4 below.

Table 4: Decision Matrix Sample

	Weight	EM/Quartz		Pressure/Coils	
Safety	20%	4	0.8	5	1
Force efficiency	20%	5	1	1	0.2
Thermal Efficiency	20%	5	1	4	0.8
4 base supports	0%	5	0	5	0
10x10 footprint	15%	5	0.75	5	0.75
10ft tall	10%	5	0.5	5	0.5
5 minute delay	5%	4	0.2	4	0.2
hour set up	10%	4	0.4	3	0.3
instructions	0%	5	0	5	0
6ft diameter apparatus	0%	5	0	5	0
2 fasteners per ft on apparatus	0%	5	0	5	0
Total	100%		4.65		3.75

From the Decision Matrix, the Considered Design #1 that used electromagnetism and quartz lamps ranked the highest. This design tied with the cable and coils design, but the latter is similar to current industry techniques. The team has chosen to discard this idea for the sake of creativity and innovation. The electromagnetism design was superior to the other designs for the following reasons. First, the force that the electromagnetism can provide is far more accurate and stronger than any other types of force producers currently on the market. It is only limited to how much power you can supply to the device rather than limited technology. Secondly, the heat flux and temperature engineering requirement need an accurate mapping that the other designs do not provide. Like the other designs, the dimensions of the structure can vary depending on selected radomes for testing. Thirdly, the setup time of this design is far superior due to the setup only requiring the installation of the radome. This contrasts other designs since they require more than this. Finally, the design is adjustable. Unlike other designs, it can easily be fitted to varying radome designs. The only drawback of the design is the amount of electrical current present during operation. We will need to install many safety features to prevent users from being injured.

Full versions of The Pugh Chart and the Decision Matrix can be found in Appendix B.

5.2 Design Description

The following section describes each component of the design. Descriptions include a discussion of geometry, material choice and relevant analytical findings. Drawings of each component are also shown in Appendix B.

5.2.1 Base Plate

The base plate is currently the base object that all the components are attached to. It is a 10 X 10 square foot made of solid steel. Currently, it has holes on the sides to bolt the structure into the floor as well as holes for the crane hooks shown in Appendix B Figure 1. The biggest issue that needs to be accounted for is the bending that will be created when moving the fully build structure as there is a lot of weight in the center and it is being from the corners. Currently there is no calculations for the dimensions, but SolidWorks simulations will be implemented to make sure the design holds within a factor of safety of 4. The sheer created by the solid rods that the force ring stand will slide on will also be calculated. Finally, the implementation of simulations for the bolts connecting the radome stand to the base will be conducted.

5.2.2 Armature

The armature is used to connect the rail to generate a force for the radomes to be tested. Shown in Appendix B Figure B2 is a rectangular prism with half circles extruded cut out of them. The circles are present to act as a path for the armature to move. The main issues that will need to be tested is the amount of current running through the armature and the bending created by the cable that is attached to our radome. Simulations in ANSYS and SolidWorks will be run to confirm the design.

5.2.3 Quartz Heat Lamp

This heat lamp will be a standard quartz heat lamp bought from an online company. Depending on which model is purchased, will change the number required and positions of all the heat lamps to create a sufficient heat flux profile. Once we have an exact model selected, tests in ANSYS will be run. A model of a standard heat lamp is showing in Appendix B Figure B3.

5.2.4 Crane loop

The crane loops, as shown in appendix B Figure B4, are large eye ring bolts that will be attached to the base plate at the 4 corners. The main functionality of these are to provide a place to attach cables to transport the design. As such, simulations will need to be run for the shear stress of the loop and threading. Additional stress testing will be evaluated for bending of the loops. The tests will be performed in SolidWorks.

5.2.5 Radome Stand

The radome stand acts as the housing unit for the radome being tested as well as the quartz heat lamps. As showing in Appendix B Figure B5, The stand takes the shape of a curved hollow steel tube. The radome will be attached to the base plate at the bottom via bolts. On the upper opening section, the radome will also be attached via another circular threaded hole pattern. Finally, there are 4 rods sticking out of the top section of the stand, these act as the stands for the quartz lamps. The main issues that need to be tested are, the bending in the curved tube caused by the testing of the radome. The next issues are the sheer and tension stress caused in both the bolts for attaching the radome and base plate. The final issue is the heat produced by the lamps. We will run simulations in ANSYS to confirm the design will not melt.

5.2.6 Force Ring Mount

The force ring mount acts as a moveable stand sitting on 4 rails acting as the guides for travel. As shown in Appendix B Figure B6, the part has a hollow section where the radome will be positioned. The main functionality of this part is to position the force subsystem to be perpendicular to the radome's ogive. The main test that need to be run are at the bottom 4 holes. There will be tremendous compression stresses at the bottom area. SolidWorks simulations will be run to confirm the dimensions.

5.2.7 Force Ring Moveable

The force ring moveable part will be sitting on the circular spot of the force ring mount. The main functionality of this design is to provide 360 degrees of freedom for providing forces. As shown in Appendix B Figure B7, there are two holes on the top of the ring. These holes are for the housing of the rails that are connected by the armature. The main testing that will need to be done is to keep the rails from pushing themselves apart. So, simulations in SolidWorks will need to be run to confirm the hole dimensions.

5.2.8 Rails

The rails' main purposes are to hold the armature and generate a magnetic field via current running through them. The main tests that will need to be conducted is the bending moment created by an off centered force and the current running through the rails. Large currents will be travelling through the rails. Thus, to prevent them from melting after a single test, simulations will be run in ANSYS to calculate the viability of the part. Drawings of the rails can be found in Appendix B Figure B8.

6 PROPOSED DESIGN – First Semester

The following section outlines the proposal for implementing the test fixture. This chapter includes a discussion of how the test fixture will be implemented along with a list of resources and an implementation timeline.

6.1 Design Implementation

The test fixture will be implemented using 3D modeling and FEA. The team plans to evaluate the final design with computational methods to test the device efficacy. The generation and evaluation materials will include personal computers, Solid works, and ANSYS. The estimated the cost of this fixture using pricing form vendors and estimate any machining and manufacturing costs. An exploded view of the team's design is shown below (Figure 15).

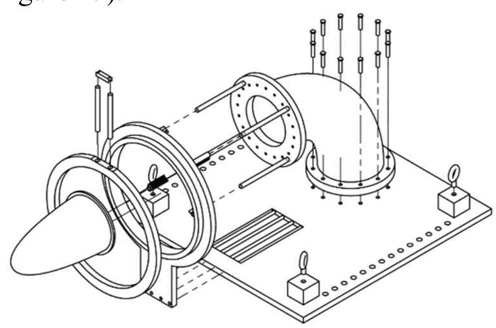
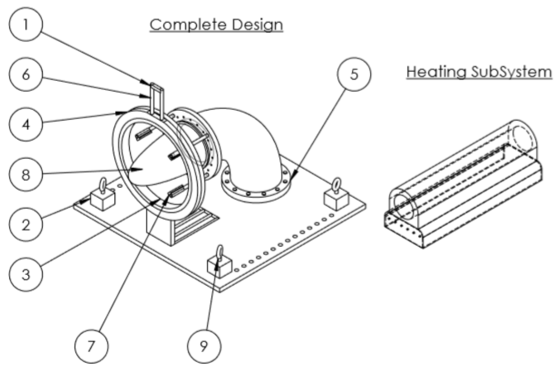


Figure 15: Test Fixture (Exploded View)

This assembly includes the test fixture and all components necessary to affix the radome and generate a moment on the radome. The force strap is not shown on this drawing. It will attach to the actuator (part 1) and apply force to the radome.

6.1.1 Material Selection

The team selected material from vendors to create this test fixture. The Components of the design are outlined below in the assembly view (Figure 16).



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Armeture	Device Used to Pull Cable	1
2	Base Plate	Frame of the Device	1
3	Force Ring Mount	Mount for the force subsystem	1
4	Moveable Force Ring	Adjustable Ring for force subsystem	1
5	Radome Stand	Radome Attachment Method	1
6	Rail	Simple rails used for force subsystem	2
7	Reflector	Reflector for heat subsystem	4
8	Lamp	Heat Source	24
9	Crane Loop	Loops for moving the device	4
10	Bolt		12
11	Radome		1

Figure 16: Assembly View

The team decided to fabricate the Armature, Base plate, Circular rings, and Elbow tube from steel plate. These products will be purchased from Metals Depot. Likewise, the crane loops and rails will be manufactured on site from W1 Drill Rod. This material will also be purchased form Metals Depot. The team will also need to purchase reflective stainless-steel sheets to use for radome covers. These will be purchased form OnlineMetals.com. The projected cost for fabricated arts is multiplied by a manufacturing cost factor of 1.5 times the material cost. All material costs are summarized in the bill of materials. Additionally, all materials are purchased at their base thickness /diameter to minimize machining costs and unwanted material treatment. Finally, the quartz lamps and bolts will be purchased directly. The quartz lams will be supplied by Grainger Inc. and the bolts will be purchased from Bolt Depot.

6.2 Fall Schedule

In the Fall semester, the team will conduct various analyses to enhance the implementation of the test fixture. The Gantt chart (Appendix D) schedules of the implementation and development process for the test fixture. First, the team members will conduct individual post mortem analyses over the summer. The final post mortem reports will be turned in on the 27th of August. The team members will then prepare for a hardware with Dr. Oman on September 24th. Because this project is analytical, the hardware review may include results form analyses and algorithms to evaluate the test fixture. Next, the team will conduct a follow up hardware review on October 17th. This review any include a software and possibly a scale (or scaled subsystem) model of the device. Additionally, a second set of analytical analyses will be performed in October. The team plans to set factor of safety, current required, and design dimensions with the final set of analyses. Lastly, a final CAD package will be created by early December.

7 References

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8 APPENDIX A: Designs Considered

8.1 Cable/Coil Design

The radome will be attached to a device similar to the male end of a light socket. The radome will then be screwed in. Coils will then be placed in the proximity of the radome to generate heat. A cable will be wrapped around the radome at a user-selected position. The cable is then attacked to a puller and crank system to generate a force. The base of the system will have deployable wheels to be used during transport. This design is shown in Figure A1 below.

Pros: Easy setup, Mobile

Cons: The cable aspect cannot be used due to customer's preference, coils have low heat, light socket design is not practical for larger radomes.

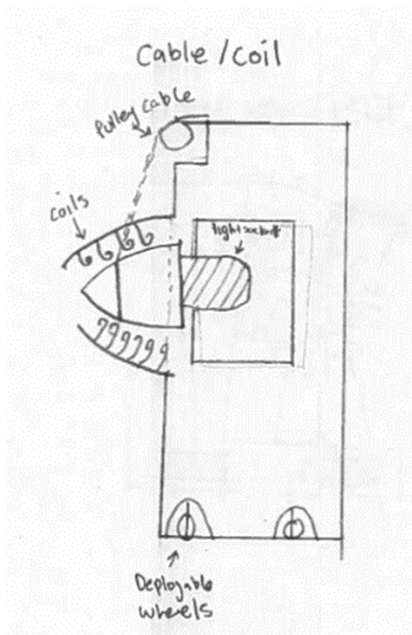

Figure A1: Cable/Coil Design

8.2 Pressurized/Coil Design

This design would have the radome housed in something similar to an oven. The oven walls will be covered in nichrome coils to generate heat. The container will then be pressurized to produce stress. The radome will be fitted to a series of spring to allow for bending freedom. The springs will then be mounted to the devices base structure. Rockets will then be attached to the bottom of the structure to provide the ability to transport this system. This design is not to be taken seriously, as the pressure container cannot generate a precise force. In addition, the rockets are not practical. This design is shown in Figure A2 below.

Pros: Rockets

Cons: No direct force, Coils have a heat limit, Rockets are impractical for movement.

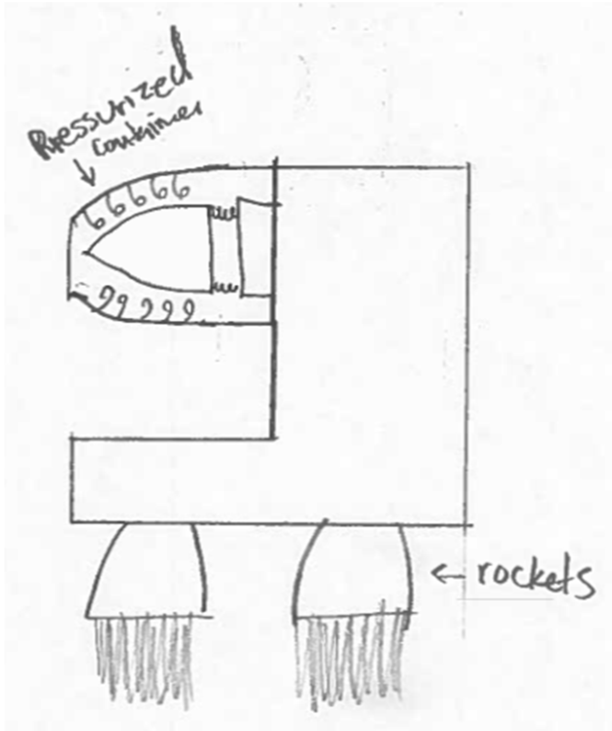

Figure A2: Pressurized/Coil Design

8.3 Drop/Insulator Design

This design produces heat by, which is retained by an insulated box. The radome is located inside the insulating box. The inside walls of the box would be made of reflective surfaces to trap the heat produce by a lamp. The radome is attached to the device support structure using springs. A door opens, allowing the radome to fall, producing force on the radome. The fixture can be moved by a rocket propulsion system. This design is shown in Figure A3 below.

Pros: The design has an insulator to separate the explosion from the surrounding, rockets for moving

Cons: The lamp may not produce enough heat, dropping the radome is not efficient

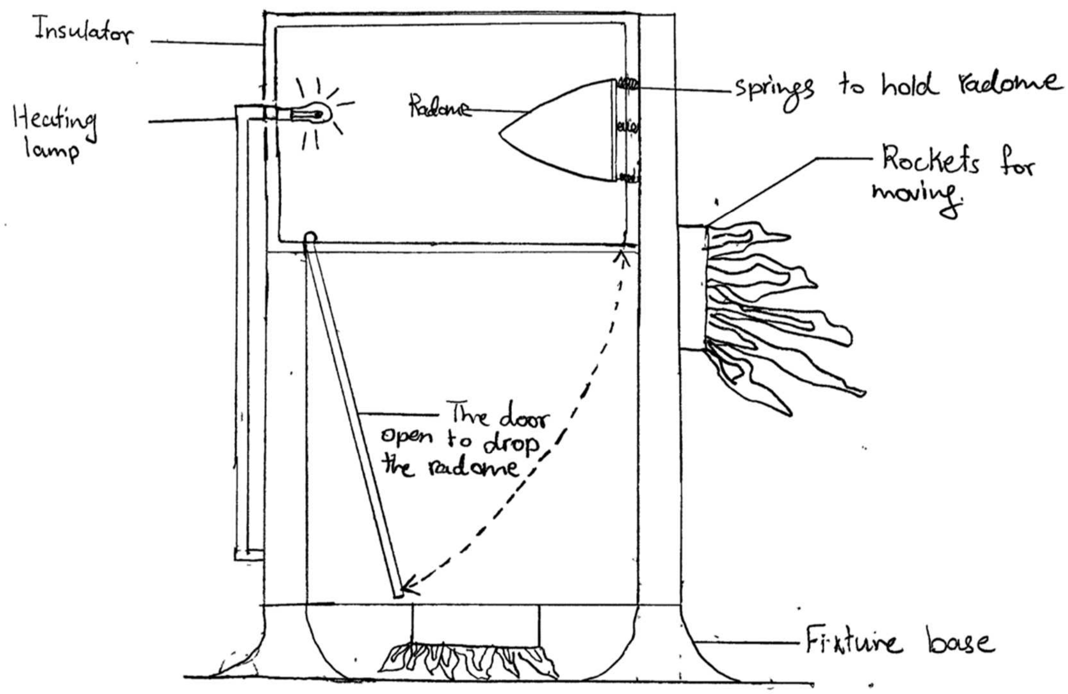

Figure A3: Drop/Insulator Design

8.4 Drop/Thermite Design

In this design, the thermite is used to produce heat and will be attached to the radome with adhesive. The radome will be attached to the fixture using a pin that goes through the radome and its base. There is a magnet to hold the radome and release it. The design has a box that contains the radome while it is burned, the box has a door that opens to let the radome drop down and produce force on it. The design requires a crane to transport and keep the fixture in place. This design is shown in Figure A4 below.

Pros: Light and easy to transport, fast radome installment

Cons: The thermite might not be efficient to produce enough heat, dropping the radome could not be accurate for force produce

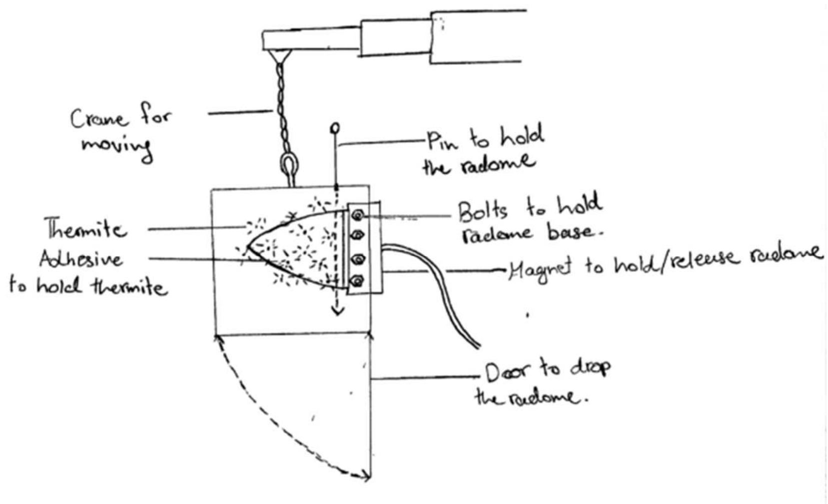

Figure A4: Drop/Thermite Design

8.5 Hydraulics/Thermite Design

This design features hydraulic rams to enact the force on the radome. The use of hydraulics would be able to provide enough force, but they may be difficult to assemble within an hour because of their complexity. Thermite would be used to apply heat to the radome. Thermite would be difficult to regulate and very unsafe which is why this is not a good option for the test fixture. The radome is attached to the fixture by spring loading this would allow for adjustability. The team is unsure if the springs would be able to withstand the high load conditions. The entire fixture would be able to slide into the test area via frictionless supports. This may be an unreasonable way to transport the device. This design is shown in Figure A5 below.

Pros: Provides plenty of force, adjustable

Cons: long assembly time, unsafe, difficult to regulate, springs may not be able to support high loads

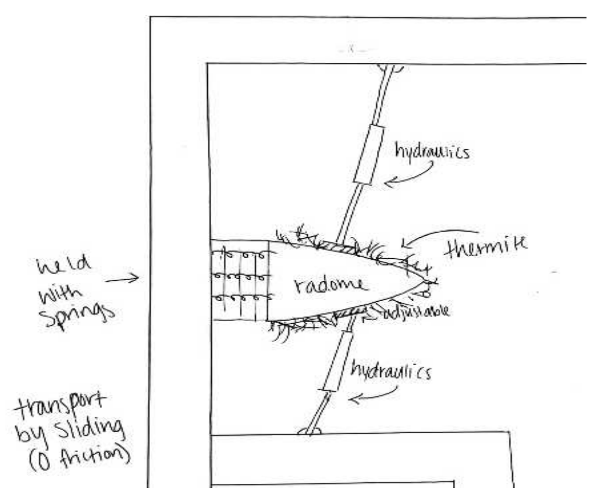

Figure A5: Hydraulics/Thermite Design

8.6 Wind/Insulator Design

This design would use an insulator to amplify the heat from a quartz lamp. Strong industrial fans would be used to supply the force. The radome is attached to the fixture with pins that pierce the radome itself. The use of these pins is not a good idea because they would damage the radome and affect its resistance to the high loads. The insulator would allow for better thermal efficiency because less lamps would be needed. However, the insulator would be heavy and might be difficult to set up and transport. The fans will most likely not supply enough force on the radome. This device would be transported and assembled with the use of a forklift. Forklifts are widely available easy to use, which is why they are a good option for transportation. This design is shown in Figure A6 below.

Pros: high thermal efficiency, uses common components, easy to transport

Cons: damage to radome, hard to assemble, fans do not supply enough power

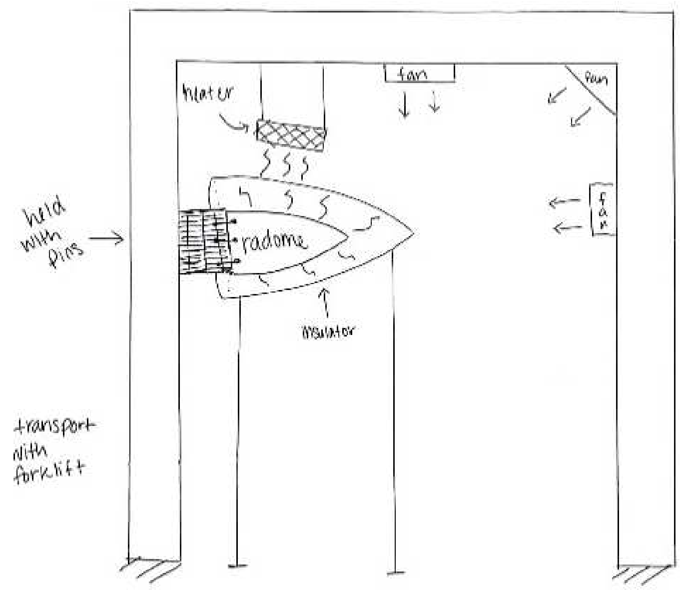

Figure A6: Wind/Insulator Design

9 APPENDIX B: Design Selected

Table B1: Pugh Chart

	EM/Quartz	Pressure/Coils	Hydraulics/thermite	Drop/Insulator 1	hydraulics/coils	wind/thermite	drop/thermite	drop/insulator 2	wind/insulator	cable/coils
Safety	-	+	-	-	S	-	-	-	S	D
Force efficiency	S	-	S	+	S	-	+	+	-	A
Thermal Efficiency	+	S	-	-	S	-	-	-	-	T
4 base supports	S	S	S	S	+	-	S	S	S	U
10x10 footprint	S	S	S	S	S	-	S	S	S	M
10ft tall	S	S	S	-	S	S	-	S	S	
5 minute delay	+	S	-	+	S	-	-	+	S	
hour set up	+	-	-	S	-	+	S	-	-	
instructions	S	S	S	S	S	S	S	S	S	
6ft diameter apparatus	S	S	S	S	S	S	S	S	S	
2 fasteners per ft on apparatu	S	S	S	S	S	S	S	S	S	
Total	3	-1	-4	-1	0	-5	-3	-1	-3	

	Weight	EM/Quartz		Pressure/Coils		Drop/Insulator 1		hydraulics/coils		wind/insulator		cable/coils	
Safety	20%	4	0.8	5	1	1	0.2	4	0.8	5	1	5	1
Force efficiency	20%	5	1	1	0.2	2	0.4	5	1	1	0.2	5	1
Thermal Efficiency	20%	5	1	4	0.8	1	0.2	4	0.8	2	0.4	4	0.8
4 base supports	0%	5	0	5	0	1	0	5	0	5	0	5	0
10x10 footprint	15%	5	0.75	5	0.75	2	0.3	5	0.75	5	0.75	5	0.75
10ft tall	10%	5	0.5	5	0.5	1	0.1	5	0.5	5	0.5	5	0.5
5 minute delay	5%	4	0.2	4	0.2	5	0.25	4	0.2	3	0.15	4	0.2
hour set up	10%	4	0.4	3	0.3	3	0.3	4	0.4	3	0.3	4	0.4
instructions	0%	5	0	5	0	5	0	5	0	5	0	5	0
6ft diameter apparatus	0%	5	0	5	0	5	0	5	0	5	0	5	0
2 fasteners per ft on apparatu	0%	5	0	5	0	5	0	5	0	5	0	5	0
Total	100%		4.65		3.75		1.75		4.45		3.3		4.65

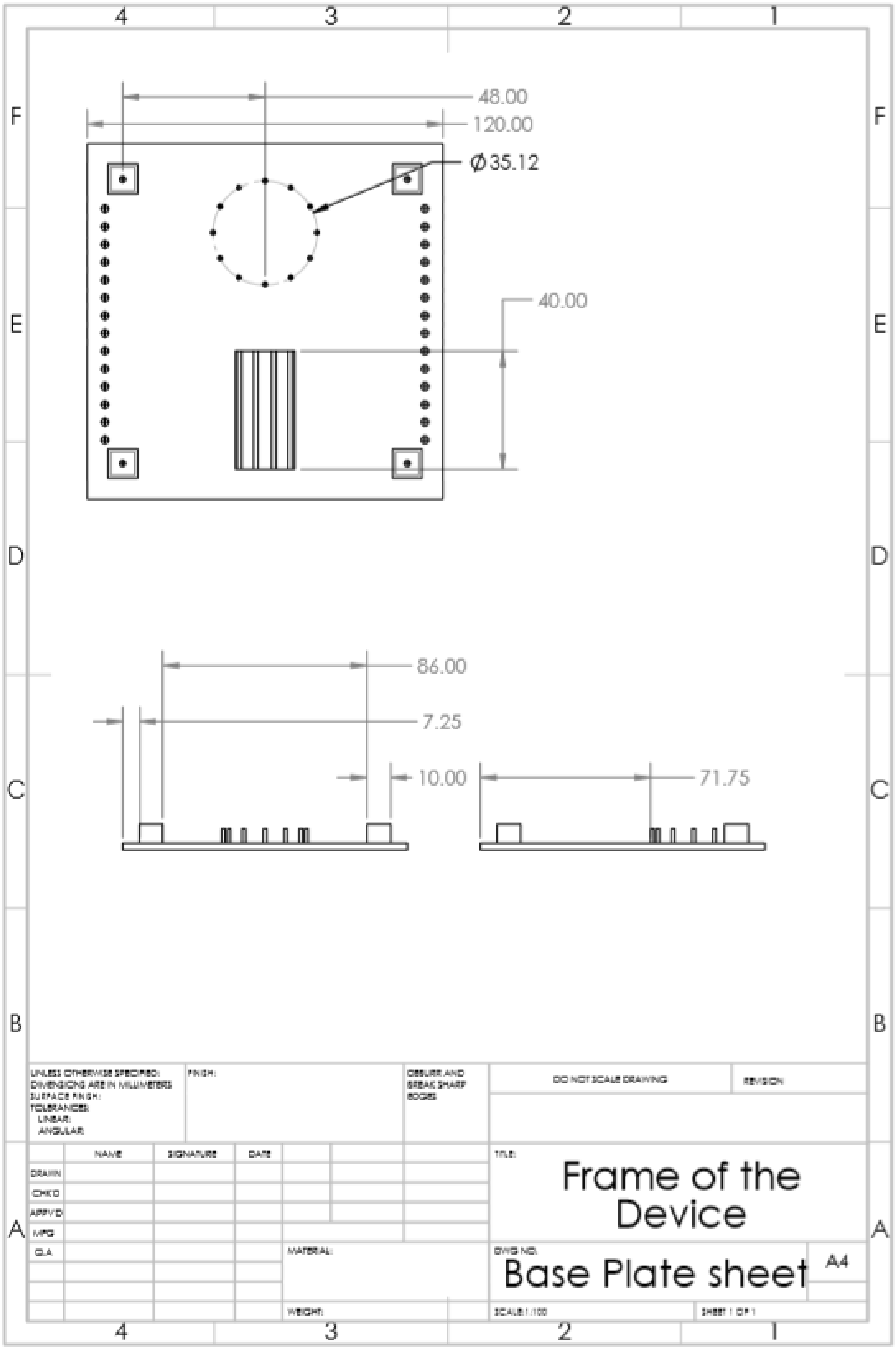

Figure B1: Base Plate Steel

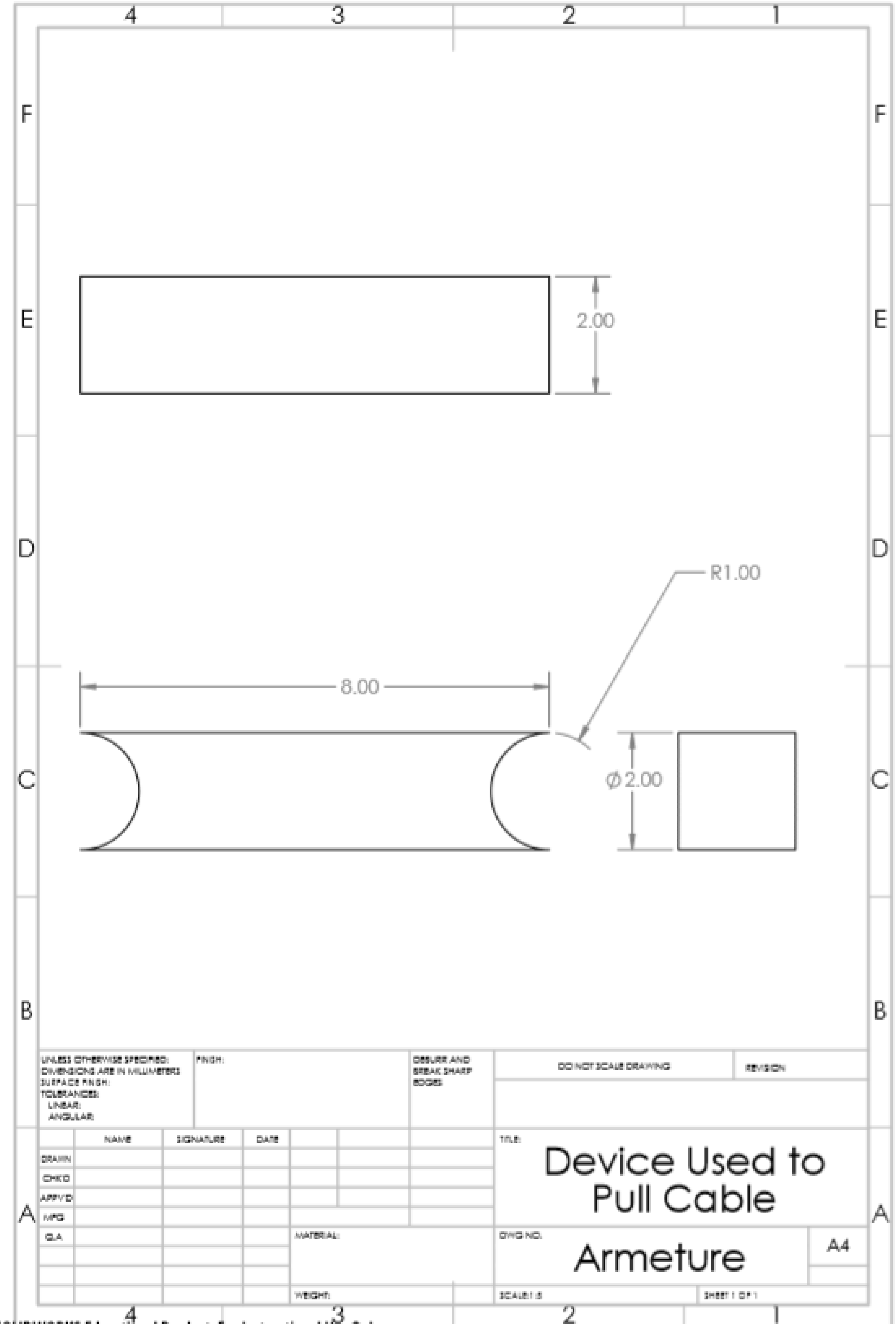

Figure B2: Armature

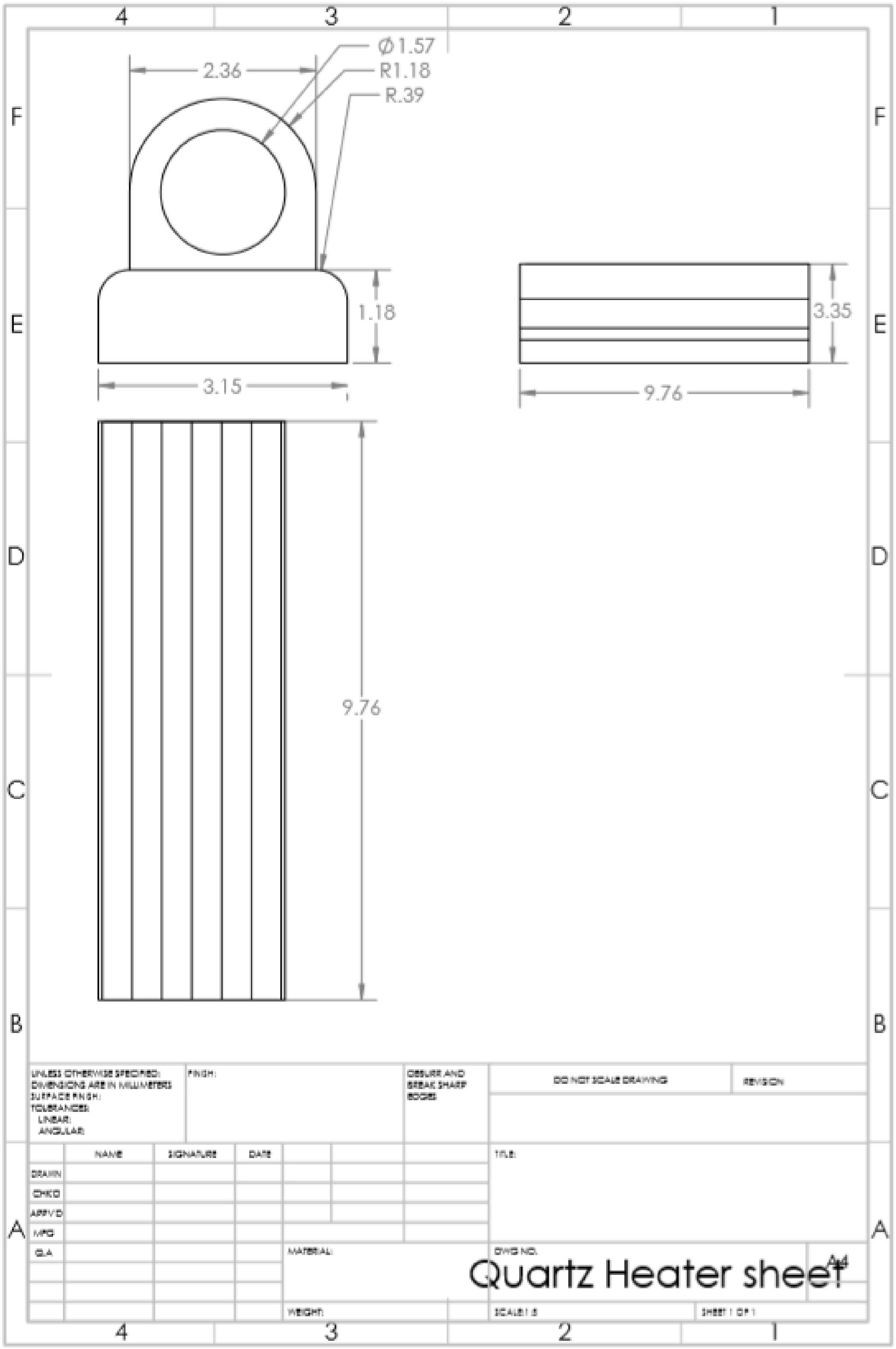

Figure B3: Quartz Heater Sheet

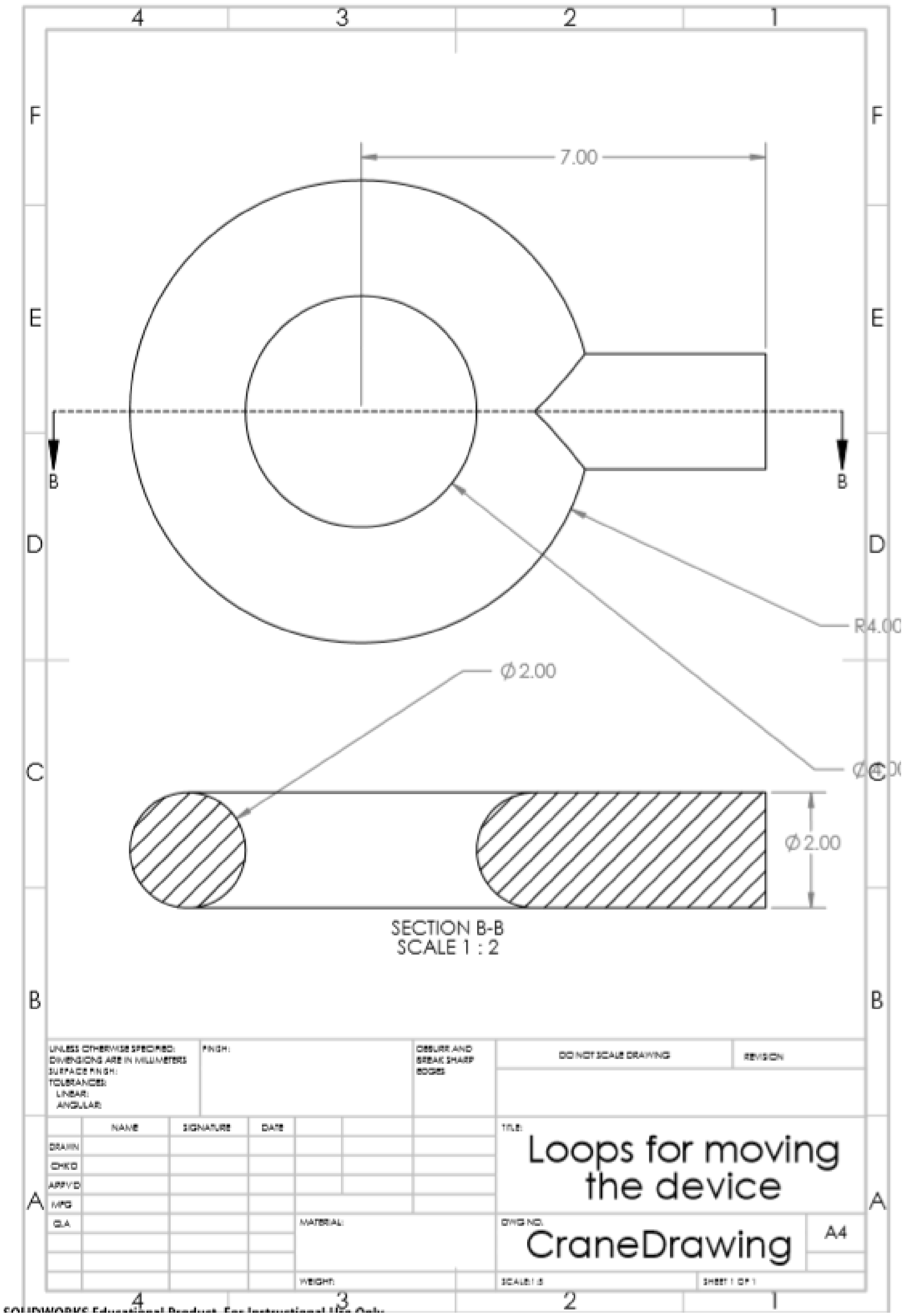

Figure B4: Crane Loop

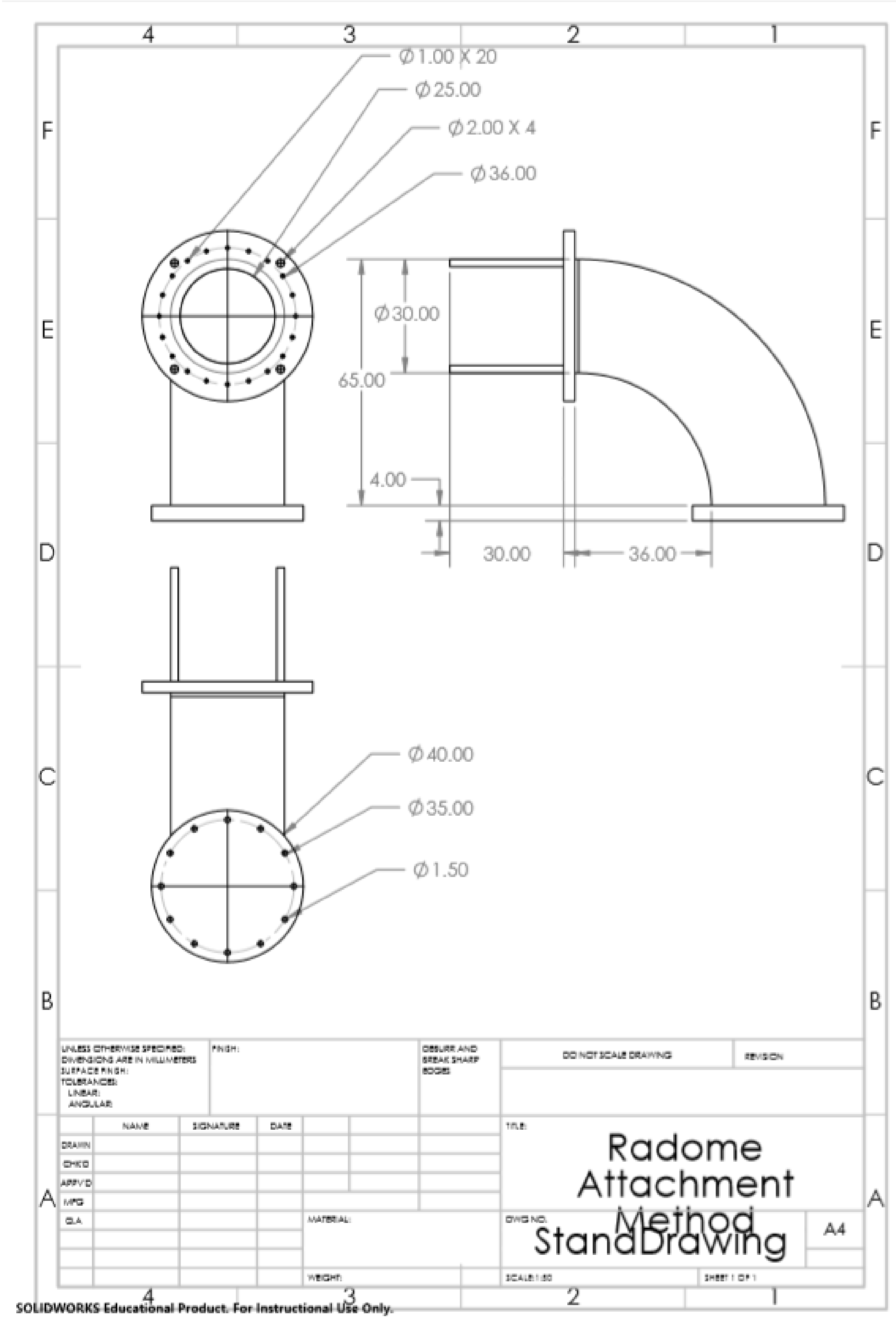

Figure B5: Radome Attachment

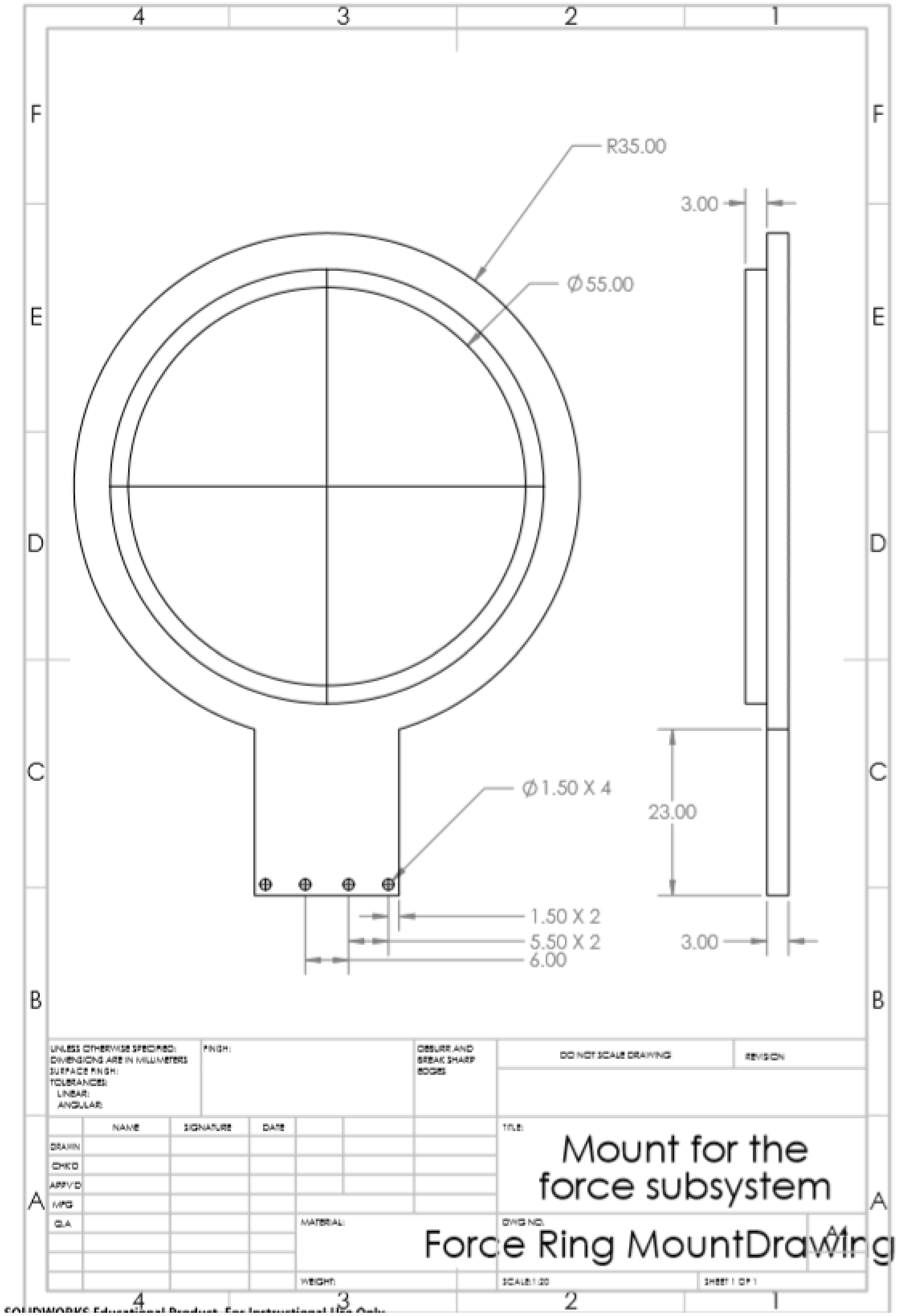

Figure B6: Force Ring Mount

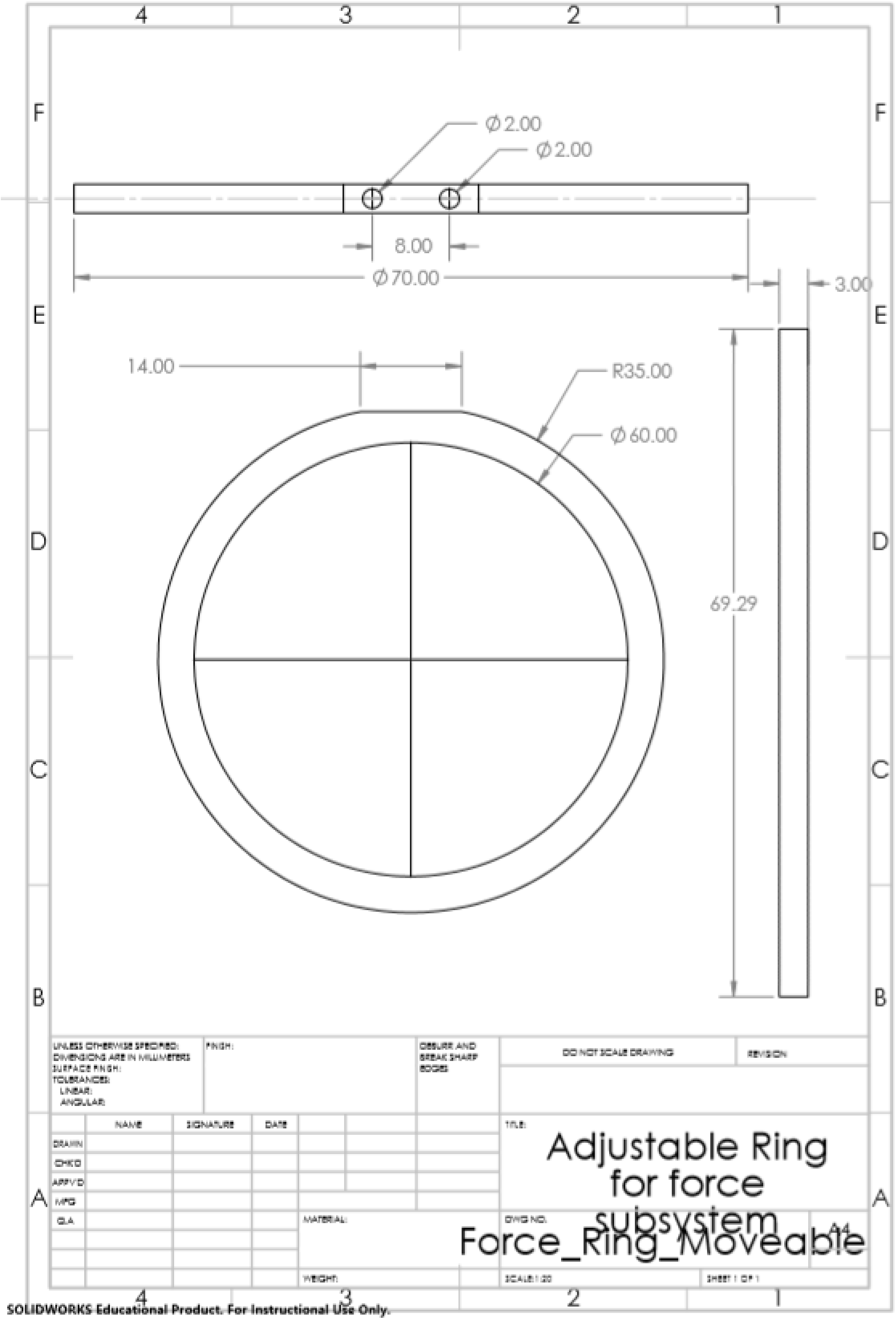

Figure B7: Force Ring Movable

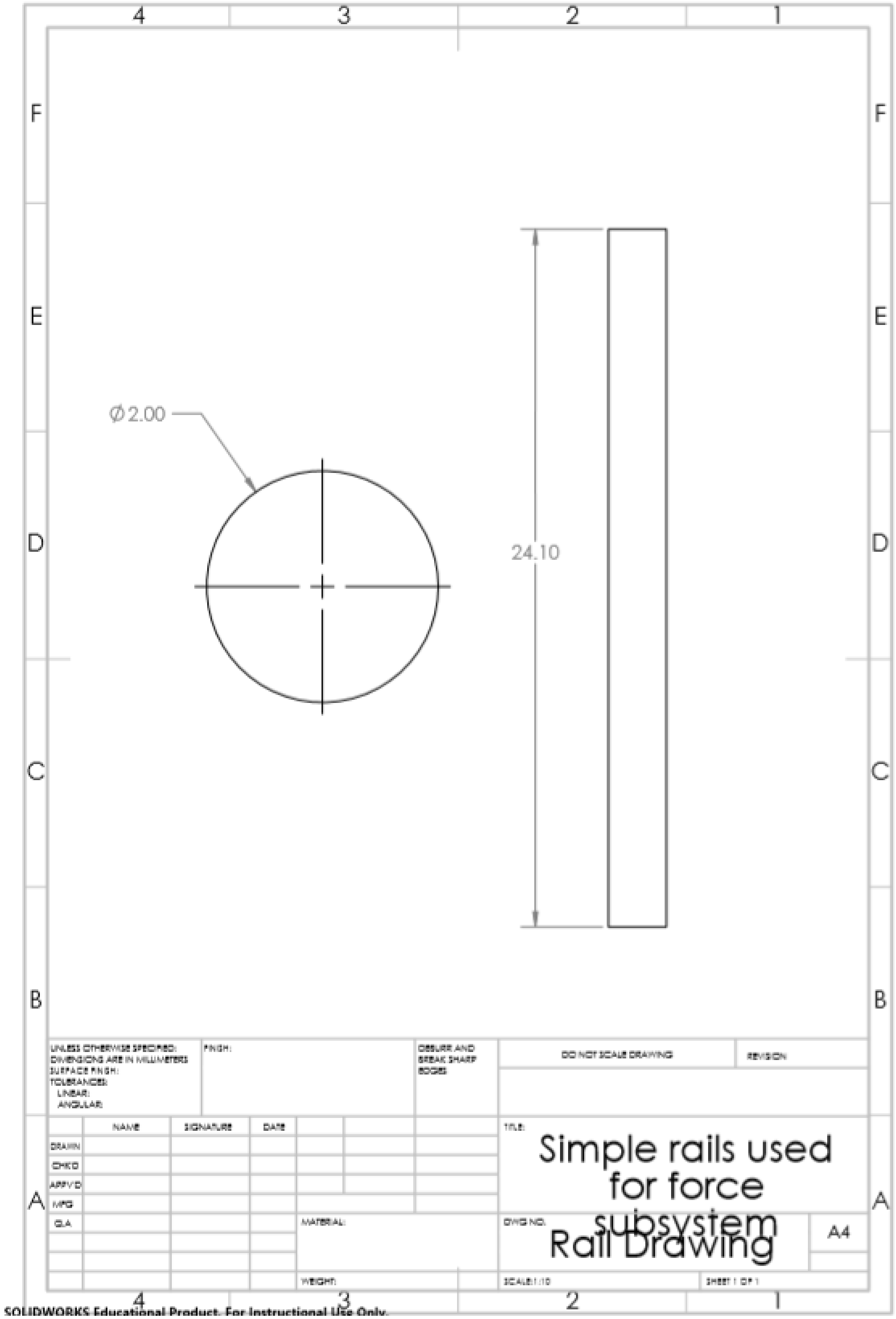

Figure B8: Rails

10 APPENDIX C: Proposed Design

Table C1: Bill of Materials

Bill of Materials								
Test Fixture for Flight Components								
Part #	**Part Name**	**Qty**	**Description**	**Functions**	**Material**	**Dimensions**	**Cost**	**Site Number**
1	Armature	1	Short bar	Device Used to Pull Cable	Steel Plate	2"x2"x8"	$95.15	1
2	Base Plate	1	Flat Plate	Frame of the Device	Steel Plate	10'x10'x3"	$22,409.00	1
3	Force Ring Mount	1	Circular Ring	Mount for the force subsystem	Steel Plate	70"OD, 60"IDx3"	$2,023.03	1
4	Moveable Force Ring	1	Circular Ring	Adjustable Ring for force subsystem	Steel Plate	70"OD, 55"IDx3"	$2,917.84	1
5	Radome Stand	1	Elbow Tube	Radome Attachment Method	Steel Plate	25"Dx50" R@90°	$1,065.34	1
6	Rail	2	Bar	Simple rails used for force subsystem	W1 Drill Rod	2"x12"	$201.92	2
7	Reflector	4	Casing	Reflector for heat subsystem	STAINLESS #8 Sheet 304 Annealed	3.35"x3.15"x9.75"	$14.25	2
8	Lamp	24	Cylinder	Heat Source	Quartz, Tungsten	9.75"x1/2"D	$1,632.00	3
9	Crane Loop	4	Eyehook	Loops for moving the device	W1 Drill Rod	4"ID, 8"OD	$378.28	4
10	Bolt	12	Fastener	Secures Armature to Base Plate	Steel Plate	1-1/2"Dx7"	$421.08	5
Total Cost Estimate:							$31,157.89	

Table C2: Bill of Materials Cost Estimate Links

Site Number	Link to Cost estimate
1	https://www.metalsdepot.com/steel-products/steel-plate
2	https://www.metalsdepot.com/tool-steel-products/w1-drill-rod?gclid=EAIaIQobChMIkq-Q4PPZ2gIVCLbACh2zCQmhEAQYBCABEgIUcfD_BwE
3	https://www.onlinemetals.com/merchant.cfm?pid=22607&step=4&id=735&CAWELAID=120293320000008809&CATARGETID=120293320000067740&cadevice=c&gclid=EAIaIQobChMI6emYtLrZ2gIVS77ACh2EAAH4EAQYBSABEgK53PD_BwE
4	https://www.grainger.com/product/1UMN3?cm_mmc=PPC:+Google+PLA&s_kwcid=AL!2966!3!50916822357!!!g!78146078534!&ef_id=WhzVVwAAAGNhpUZi:20180427024642:s
5	https://www.boltdepot.com/Hex_bolts_Grade_8_steel_plain_finish_1-1_2-6.aspx

11 APPENDIX D: Gantt Chart

Table D1: Gantt Chart

Name	Begin d...	End date
Rewrite Proposal	8/20/18	8/27/18
Individual Post Mortem	8/22/18	8/29/18
Hardware Review 1	9/7/18	9/24/18
Hardware Review 2	9/25/18	10/15/18
Draft Midpoint Report	8/30/18	10/10/18
Midpoint Report	10/10/18	10/10/18
Draft Analytical Analyses	10/5/18	10/24/18
Draft Final Poster	10/25/18	11/26/18
Draft Final Report	10/25/18	12/5/18
Final Report	12/5/18	12/5/18