# Radial Expansion Tester

# Final Proposal

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# DISCLAIMER

# EXECUTIVE SUMMARY

This report contains the information regarding the final design for the Radial Expansion Tester Capstone that was requested by Poba Medical. The Radial Expansion Tester is a machine that will be able to test plastic extrusions' ability to become medical balloons in order to save time and money for Poba Medical by streamlining their testing process. For This project, the team needs to create a machine that can apply up to 150 lbs of axial force, test unexpanded extrusions ranging from .2-.625”, measure expanded diameters of up to 2.5”, control the temperature of a 2 inch section of the extrusion up to 250℉, pressurize the extrusions up to 300 psi, and output measurements relating to diameter measurement and temperature.

This report will start by listing the customer needs, and then translating them into engineering requirements. The team will then present a black box model and functional model in order to break down the project into smaller parts, as well as begin visualization of the design. A functional model is then created, in order to show how each of the customer and engineering requirements relate to each other. The team has also presented any relevant codes and regulations.

The report then shows all testing procedures that are planned for next semester. The team will test each system individually, and then test the whole system at once in order to make sure that nothing interferes with each other. The report then lists all possible potential failures, paying special attention to the ones that would be catastrophic.

The report then goes over the final design. The design chosen was a motor and ball screw system for axial force, a LS-7070M for radial measurement, and a custom made nozzle attached to an air heater for temperature control. The team has been provided with pneumatic clamps and air cylinders to ensure that the extrusion will stay in place while the axial force is being applied. The report then shows how the team selected these designs, and ends with a conclusion. Lengthy calculations have been included in the appendices, and all references have also been included.

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# 1 BACKGROUND

## 1.1 Introduction

Our team has been tasked with designing and building a radial expansion tester, with controlled temperature and axial load, for the extruded plastic tubes used by Poba Medical in the manufacture of their medical balloons. The device must be able to inflate the tubes to bursting, pull the tubes with 150 lbs of force, heat a section of the tubes to 250ºF, and measure the diameter of the tubes as they inflate. Poba Medical is a company that manufactures balloons and catheters for a variety of medical purposes. Currently, to determine whether or not it is possible to manufacture a balloon design with a tube of a specific size and material, Poba needs to actually attempt to make the balloon. This requires new tooling to be purchased and time to be spent making the balloon. Our device will allow Poba to measure the properties of their tube stock and decide in advance if a balloon design is feasible based on their findings. This will save them a significant amount of time and money.

## 1.2 Project Description

The following is the original project description from the project proposal as we received it from Poba Medical:

> To design and build a radial expansion tester for thermoplastic extrusions. The extrusion profile required for testing is a circular cross-sectional tube. The extrusions are made from different thermoplastic materials and are used to form medical balloons through a blow molding process. The machine needs to be capable of measuring the radial expansion of thermoplastic tubes at controlled temperature under a constant axial load.

Design inputs:

- Constant axial force applied during testing with the ability to pull up to 150 lbs
- Test extrusion diameters from .02-.625
- Test expanded extrusion diameter up to 2.5”
- Material temperatures control, including temperatures up to 250F
- Continuous diameter measurements during radial expansion of tubing

Project completion goal:

Once the project is complete Poba wants to use this machine during its incoming extrusion inspections. Poba wants to have the ability to record radial expansion data. This will help Poba improve its extrusion designs.

# 2 REQUIREMENTS

The requirements section will review the customer requirements, the engineering requirements, and a QFD for the Radial Expansion Tester. The Radial Expansion Tester will need to pressurize plastic extrusions, apply up to 150 lbf of axial force, heat a section of the extrusion up to 250℉, measure temperature, radial expansion of the extrusion, and output all of these measurements. The customer requirements were generated through reverse engineering the project description, as well as multiple meetings with engineers at Poba. The engineering requirements were given in the project description, as well as meetings with engineers at Poba. The QFD was created to see how these requirements relate to each other, as well as benchmark other similar devices to get an idea of what does and doesn’t work.

## *2.1 Customer Requirements (CRs)*

Customer requirements are important for a design project because they help define what the design needs to do. While vague, they are an important stepping stone to creating a clear set of expectations for the machine. For the Radial Expansion Tester, the team was given a list of technical requirements. These were then reverse engineered into customer requirements by making them less technical for use in a QFD. Along with this, multiple meetings with the engineers at Poba Medical resulted in extra customer requirements. The customer requirements are as follows:

1. Actuate axial load
2. Pressurize balloons
3. Test unexpanded diameters
4. Test expanded extrusion diameters
5. Continuously measure diameters during expansion
6. Temperature control for extrusion
7. Continuously measure temperature

8. Durable and robust design
9. Reliable design
10. Safe to operate
11. Stay within budget

When the team states that the Radial Expansion Tester must “test” unexpanded and expanded diameters, it means that the radial expansion tester must have the ability to hold unexpanded extrusions with enough force so that the extrusion will not slip when axial force is applied. Temperature control includes being able to heat the extrusion, and a durable and robust design for the team means a design that will be able to be used for up to 2 years. A reliable design means that the design will give reliable numbers, as well as work in a predictable way.

These needs all relate to the successful completion of the Radial Expansion Tester. This is because the purpose of the Radial Expansion Tester is to test how medical balloons created from plastic extrusions react while being pressurized while under the influence of axial force and high temperatures. Therefore, actuating an axial load is necessary as Poba wants to test balloons under the influence of and axial load, controlling the temperature of the extrusion is important because Poba wants to test under the influence of high temperatures, and taking measurements of everything going on is important because it will create quantifiable data about how the balloon is reacting.

The customer needs were grouped into 6 different groups to further organize them and begin breaking the machine into subsystems. The groups decided upon were Pulling, Heating, Diameter Measurement, Pressurization, and General. The pulling group included Actuate axial load, and continuously measure axial load. The heating group included Temperature control for extrusion, and Continuously measure temperature. Diameter Measurement includes Test unexpanded diameters, Test expanded diameters, and continuously measure diameters during expansion. Finally, general includes Durable and robust design, reliable design, safe to operate, and stay within budget.

As stated before, this grouping allows the group to break up the device into multiple different subsystems that can be prototyped individually. This allows the team to focus on one topic at a time and not get overwhelmed. The group also made a Discord with a group for each of these groups in order to easily share any ideas the members may come up with.

## *2.2 Engineering Requirements (ERs)*

Engineering requirements help translate customer requirements into actual technical requirements that the team can aim for. This moves the team closer to the prototyping stage, as it allows them to clearly define goals and specify what the machine needs to do. For the Poba Medical team, a list of technical requirements was given. This made defining the engineering requirements for this project fairly straightforward. However, after a few meetings with engineers at Poba, extra customer requirements were added which had to be translated into engineering requirements. During these meetings the engineers from Poba also specified tolerances for each of these requirements. The requirements are as follows:

1. Apply up to 150 lbf of axial load
2. Control Temperature of Extrusion up to 250℉
3. Hold Extrusions with Enough Force for No slippage
4. Measure Temperature of Extrusion within 1-2℉
5. Pressurize Balloons up to 300psi
6. Change Test diameter from .2-2.5”
7. Measure Test diameter within .005 in
8. Output measurements
9. Costs between $5,000-10,000

Like in the last section, controlling the temperature will involve being able to heat an extrusion up to 250℉, pressurizing the balloons involves pressurizing the inside of the balloon so it can expand, and changing the test diameter gives the team an amount that they need to shoot for for the expansion of the balloon.A Radial Expansion tester that meets all of these requirements would accomplish everything that the client required. This is because the machine would be able to pressurize the balloons, apply an axial load, control the temperature of the extrusion, measure all of the changes that are happening, and output those measurements giving quantifiable data. The measurement constraints were added during meetings with engineers at Poba, and they exist to give the team an idea of how accurate the Radial Expansion Tester must be.

These specific requirements are based on the upper limits of the balloons being created at Poba Medical. The balloons that are defining the engineering requirements are created from hard nylon, and need much more force than other types of balloons that Poba is creating. For instance, applying 150 lbf of axial load is needed for the nylon material, as most balloons will need much less force, especially when the balloons are being heated. Another example of the upper limit relating to the hard nylon is the balloons needing to be heated up to 250℉. This is enough to melt most of the balloons that Poba is creating, but it is only enough to soften the nylon.

The accuracy for the measurements is required due to the accuracy that is needed in the medical device field. Balloons that are being tested with the team's machine will be going into people, and the surgeon using them will want to have a high level of confidence in the balloons. The measurements then need to be output so that engineers can read them and gain knowledge about how the balloons react under certain conditions. The budget relates to how much devices in this field can cost, and it was hinted that if the team is obviously trying and doing good work they could be given slightly more money, as buying a device off the shelf is much more than $10,000.

This list of requirements relates directly to the customer requirements, with each engineering requirement being relevant to at least one customer requirement. An example of this is “Apply up to 150 lbf of axial load” relating to “actuate axial load.” A less obvious example of this is “change diameters from .2-2.5” relating to “test unexpanded diameters,” and “test expanded diameters.” A QFD was created to track all of these relationships, as well as to benchmark similar products and has been included in section 2.3.

## 2.3 Functional Decomposition

Functional decomposition is an important tool in engineering design because it helps engineers begin to visualize their design. This aids prototyping because it allows engineers to better know what they are shooting for, making brainstorming easier. For the Radial Expansion Tester, both a Black Box Model and Functional Decomposition have been created. These are the same as the ones in the Preliminary Report, because while many design choices have changed for the Radial Expansion Tester, no conceptual design choices have been made, making these models entirely valid for the current design.

### 2.3.1 Black Box Model

Black Box Models are extremely helpful in visualizing the overall design. They allow engineers to see all of the inputs and outputs without having to worry about how they were transformed. This helps prepare for creating a functional model, which will clarify the problem even further. The team's black box model has been included below.

*Figure 1: Black Box Model*

### 2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Functional models perform a very similar function to black box models. They are essentially just expanding upon the "black box" of the black box model, allowing engineers to see the "flow" of the design, which makes it easier for engineers to break the design down into many different steps. For instance, in the model below there is a box that states "convert electrical energy into translational energy," which the team accomplished using a ball screw and motor. The team's functional model has been included below.

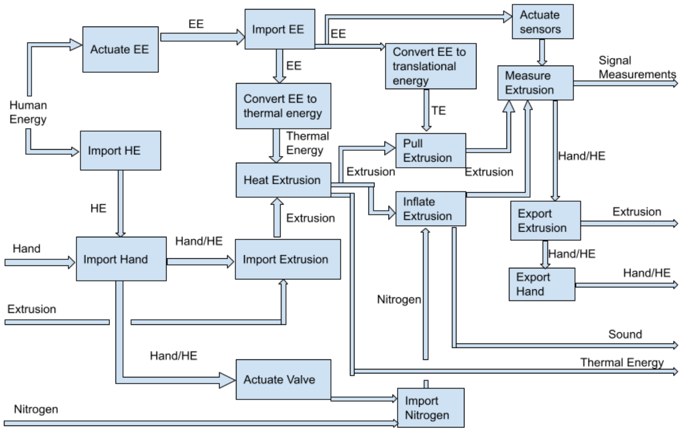


*Figure 2: Functional Decomposition*

## 2.4 House of Quality (HoQ)

To summarize and compare the engineering and customer requirements for this project, a house of quality was created. Because of the size of the appendix, it has been moved to Appendix D. The house of quality for the Radial Expansion Tester was created by taking the engineering requirements, as well as extra requirements given by the engineers at poba, and backtracking to get custom requirements. At first, it seemed that nothing was related, and that because of the backtracking it was close to a 1:1 ratio for comparisons. However, after the team has learned more about the balloon blowing process, they have found out that all of the requirements given to us are interrelated and necessary to blow a proper balloon. The house of quality now reflects this change, and all of the customer and engineering requirements have many more relationships between them.

The house of quality for this report also has the testing procedures included. These are included in the engineering requirements. They are “Axial Load Validation,” “Diameter Measurement Validation,” “Heating System Validation,” and “Full System Operation.” These relate directly to the sections in chapter 3 that have similar names. These engineering requirements act as an end goal for the project. This is because once the system passes “Full System Operation,” it has all 3 systems working, as well as properly outputting data.

Creating the house of quality for this report has helped the team realize how much their understanding of the project has changed, as well as helping the team organize the multitude of engineering requirements. The team can now see this machine as 3 interrelated subsystems, instead of 3 separate subsystems that have no effect on each other. For instance, in order for the balloon to be properly expanded, it must be heated, then pressurized, and then have an axial force applied to it. This requires all subsystems to be working in unison. It has also helped the team see the end goal of getting all subsystems working together and at once.

## 2.5 Standards, Codes, and Regulations

Since the scope of this project covers such a wide range of categories it would be wise to consider all of the different kinds of standards, codes, and regulations which will dictate the design of the project such as material properties, hardware specifications, medical standards, and engineering specifications. Below is a table which organizes all of the relevant standards which will be considered.

Table 1: Standards of Practice as Applied to this Project

| **Standard Number or Code** | **Title of Standard** | **How it applies to Project** |
|---|---|---|
| ASME Y14.5 | Dimensioning and Tolerancing Standard | Establishes rules, definitions, requirements, and recommendations for interpreting GD&T which the team will reference when creating drawings and tolerancing parts. |
| ISO 14644-1 | Cleanroom Standards | Specifies the classification of air cleanliness in terms of airborne particles in cleanrooms. Will dictate which material and products can be used so that the project does not cause unnecessary cleanroom contamination. |
| SAE J429/ ASTM A325 | Bolt Grade Standards | Establishes the material properties of fasteners such as minimum proof strength, minimum tensile yield strength, and hardness. Will be referenced when choosing fasteners for structural purposes. |
| ASTM B221-08 | Standard Specification for Aluminum | Designates the chemical composition and material property requirements for specific types of aluminum. This will be useful when considering which type of aluminum will be used for the various components of the machine. |
| HS Number | Harmonized System Number | 4 or 6 digit code which classifies products being traded around the world for the purposes of tariffs and import taxes. Will determine the cost of shipping |

| | | |
|---|---|---|
| | | for any products purchased outside of the U.S. |
| AMBA 20 | Radial Bearings of Ball, Roller Types. | Establishes the boundary dimensions and tolerances for various geometries of specified bearing types. Sets the standards for bearings which will be implemented within the machine. |
| IEEE 1100 | Recommended Practice for Powering and Grounding Electronic Equipment | Collection of consensus best practices for powering and grounding of electronic equipment used in commercial and industrial applications. Provides a good guide as to how the electrical system of the machine ought to be grounded. |

Naturally, the team will be operating within the above standards set by various organizations. However, some specifications will undoubtedly play a vital role in the engineering design process. The cleanroom specification designated by ISO 14644-1 will be one of the most important specifications to consider as the team's machine will operate within the level 1,000 Poba cleanroom. Understanding the environment and acceptable procedures which give it it's designation will allow the team to make intelligent decisions regarding what acceptable materials and products would be feasible to incorporate within the machine and which ones ought to be avoided. Also of importance would be the fastener standards set by SAE J429 as this establishes the requirements that must be met in order to be classified as a specific "grade" of bolt, a designation which will be considered when selecting fasteners to join various load bearing elements throughout the machine. Since there will inevitably be a number of different parts manufactured by the team, the ASME Y14.5 standard for GD&T will serve as the guide which should be followed when detailing the drawings for all of these components to assure that the desired part be manufactured correctly. Considering all of the applicable standards, codes and regulations will allow the design of the machine to be driven by a set of pre-established successful practices and will ensure that the resulting product conform to all of the required specifications set out by them.

# 3 Testing Procedures (TPs)

In order to confirm that each individual subsystem within the machine is operating in a manner that will meet each associated engineering requirement, a set of testing procedures for each of them is detailed below. Once each of the major subsystems are tested and are deemed successful, they will be incorporated into the final full system testing procedure which will determine if they are all able to effectively work together as desired .

## 3.1 Testing Procedure 1: Axial Load Validation

The axial load subsystem consists of the stepper motor, gear train, ballscrew, and closed-end clamp along with all of the associated mounts and hardware within them. Once this system is fully assembled it will be necessary to confirm that it can pull the plastic extrusions with the required amount of force specified by the engineering requirement, in this case, 150lbs. In order to confirm that it is capable of doing so, the team will affix an axial load gauge, supplied by Poba to the moving side of the extrusion clamp and will run the motor up until the load tester reads 150lbs. While doing so the team will perform a visual inspection of all associated mounts, hardware, and components to look for any signs of deformation or damage which will be recorded into a notebook.

### 3.1.1 Testing Procedure 1: Objective

It is not only necessary to perform this test in order to confirm that the system is capable of meeting the engineering requirement, but to confirm that it is capable of doing so repeatedly in a controlled manner. This requires that all associated components be free of visual damage or deformation and that the machine is still capable of adequately functioning afterward.

### 3.1.2 Testing Procedure 1: Resources Required

All axial load system components must be purchased and all of the associated equipment necessary to run and assemble it must be acquired including the axial load gauge and all fasteners required for assembly.

### 3.1.3 Testing Procedure 1: Schedule

Prior to running this test all necessary mounts must be manufactured, the system must be assembled, and a method of securely mounting the axial load gauge must be established. Since this system includes many separate parts, it will be one which the team will focus on completing first as there naturally exist many potential failure points within it. As such, the mounts for the ball screw as well as the baseplate they will be affixed to will be given priority in the manufacturing schedule starting no later than the first week in January. The test will be performed shortly after all components have been assembled within the month of January and should take less than an hour to complete.

## 3.2 Testing Procedure 2: Heating System Validation

The heating subsystem consists of an assortment of flexible air hoses, fittings, airflow meter, temperature controller, duct heater, thermocouple, and heating nozzle which will be responsible for meeting the engineering requirement of heating a 2” section of extrusion up to 250 °F. In order to validate that the system is operating as expected the team will incorporate the use of a secondary temperature sensor which will be positioned to measure the air expelled from the heating nozzle to confirm that it outputs the correct temperature of air. Once in operation, the team will perform a visual inspection of each component to assure that there is no physical degradation or failures. The test will be performed over a wide range of temperatures and air flow rates to confirm the desired temperature is achieved throughout them and to establish that the system is capable of operating repeatedly without failure or degradation.

### 3.2.1 Testing Procedure 2: Objective

This testing procedure will allow the team to establish that the heating system is capable of meeting its associated engineering requirement and that it can do so in a safe and effective manner.

### 3.2.2 Testing Procedure 2: Resources Required

In order to operate this procedure, all associated equipment must be purchased, manufactured, and assembled including the heating system components as well as the secondary temperature probe.

### 3.2.3 Testing Procedure 2: Schedule

Since this system consists of a large number of off-the-shelf items, very little manufacturing time will be necessary prior to assembly, as such, once assembled the test can be performed within a few hours depending on whether or not the heating nozzle has had sufficient time to cool off between each operating cycle. After the axial load system is assembled and verified, the heating system testing procedure outlined here can be completed immediately on or before the third week in January.

## 3.3 Testing Procedure 3: Diameter Measurement

Since the client has specified the use of an optical micrometer capable of accuracy well beyond the scope of this project, the testing procedure to confirm that it is capable of meeting the engineering requirement of measuring expanded balloons within 0.005” will be fairly straightforward. First, once the machine is mounted and operational, a test gauge of known dimensions will be measured to confirm that it does so to the desired accuracy. Then, extrusion specimens of various diameters up to 2.5” will be measured to confirm that it is capable of measuring the diameters of the transparent material without affecting the accuracy of the measurement.

### 3.3.1 Testing Procedure 3: Objective

This procedure will allow the team to confirm that the device is capable of operating as expected

### 3.3.2 Testing Procedure 3: Resources Required

The optical micrometer and all its associated components must be purchased prior to performing this test. It is most likely that the optical micrometer will include a gauge of known dimensions which can be used to calibrate the machine and confirm operation. However, in the event that this is not provided, Poba is capable of supplying a set of precision ground “gauge pins” which could be used for the same purpose.

### 3.3.3 Testing Procedure 3: Schedule

Since this device is an off-the-shelf product which can be shipped as soon as it is purchased, this testing procedure will likely be one of the first ones performed by the team. It is planned that it will take an afternoon to get the system operational and perform the associated tests. This procedure is scheduled to take place over winter break.

## 3.4 Testing Procedure 4: Full System Operation

All other engineering requirements not specified as being tested by above procedures such as the “ability to hold extrusions without slippage” and “pressurize balloons up to 300 psi” require the full system operation of the machine due to the fact that they are all affected by numerous different characteristics of the machine’s design. As such, these requirements will be tested by operating the machine in the manner in which it was designed. First, the raw extrusion will be loaded into the clamping mechanisms, then pulled taught by the axial load system, then pressurized with nitrogen, then heated by the heating nozzle, then stretched to the desired length by the axial load system, then finally the resulting diameter expansion will be measured by the optical micrometer. Prior to these operations, the extrusion body will be marked with a marker so that the team can verify that no slippage occurs throughout any of the operations. The pressure will be read from the associated pressure gauges and recorded in a notebook to confirm it did achieve the desired level. And once the test has been completed for one extrusion size, it will then be repeated for different sizes to confirm that it can do so adequately.

### 3.4.1 Testing Procedure 4: Objective

By operating the entire system, the team can confirm that it can achieve every engineering requirement sequentially and continually throughout the process without the additional operation of each subsequent subsystem negatively affecting the operation of another. It will be the final test to confirm that each separate system is capable of working harmoniously with each other.

### 3.4.2 Testing Procedure 4: Resources Required

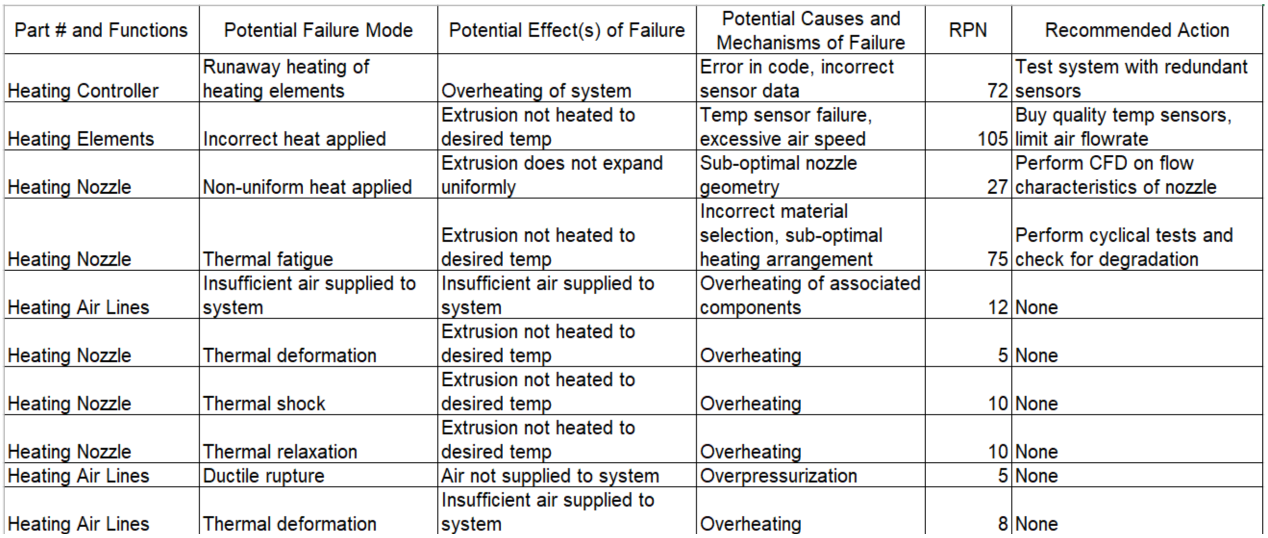
Since this will be the final and full system testing procedure, it requires that the machine be completed prior to performing. As such, all ancillary system components must be bought, manufactured and assembled.

### 3.4.3 Testing Procedure 4: Schedule

This test will be one of the last ones performed on the machine. This means that the scheduled time it will be completed will be dictated by when every separate subsystem is completed. The full system testing procedure will most likely take place over multiple days and in order to account for unforeseen setbacks and design iterations, the team will plan on completing this as early as March of the 2022 spring semester.

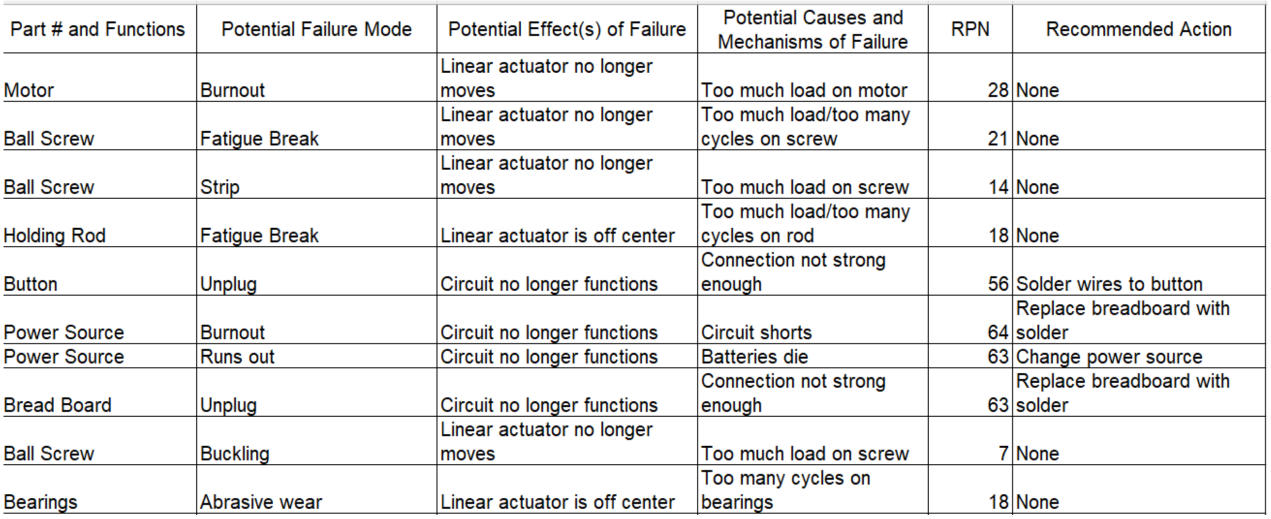
# 4 Risk Analysis and Mitigation

For the purpose of FMEA, the project was divided into four critical subsystems: axial loading, heating, clamping, and pressurizing. Each subsystem was analyzed to determine all possible modes of failure for every component in the respective subsystem. Results were tabulated in an FMEA spreadsheet for each subsystem and RPN values were generated to determine how important it was to address each individual failure mode. In this section, the ten most critical failures (as determined by RPN values) will be addressed. Below are the shortened FMEA tables for each subsystem, full FMEA tables can be found in the appendix.



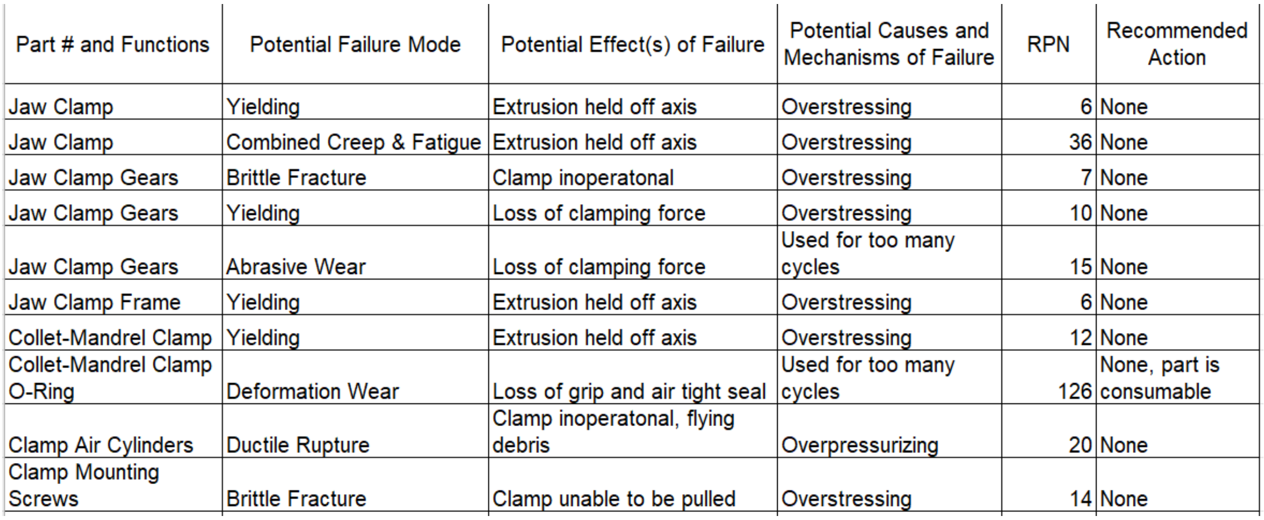
| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| Heating Controller | Runaway heating of heating elements | Overheating of system | Error in code, incorrect sensor data | 72 | Test system with redundant sensors |
| Heating Elements | Incorrect heat applied | Extrusion not heated to desired temp | Temp sensor failure, excessive air speed | 105 | Buy quality temp sensors, limit air flowrate |
| Heating Nozzle | Non-uniform heat applied | Extrusion does not expand uniformly | Sub-optimal nozzle geometry | 27 | Perform CFD on flow characteristics of nozzle |
| Heating Nozzle | Thermal fatigue | Extrusion not heated to desired temp | Incorrect material selection, sub-optimal heating arrangement | 75 | Perform cyclical tests and check for degradation |
| Heating Air Lines | Insufficient air supplied to system | Insufficient air supplied to system | Overheating of associated components | 12 | None |
| Heating Nozzle | Thermal deformation | Extrusion not heated to desired temp | Overheating | 5 | None |
| Heating Nozzle | Thermal shock | Extrusion not heated to desired temp | Overheating | 10 | None |
| Heating Nozzle | Thermal relaxation | Extrusion not heated to desired temp | Overheating | 10 | None |
| Heating Air Lines | Ductile rupture | Air not supplied to system | Overpressurization | 5 | None |
| Heating Air Lines | Thermal deformation | Insufficient air supplied to system | Overheating | 8 | None |

Figure 3: Shortened FMEA for heating subsystem.



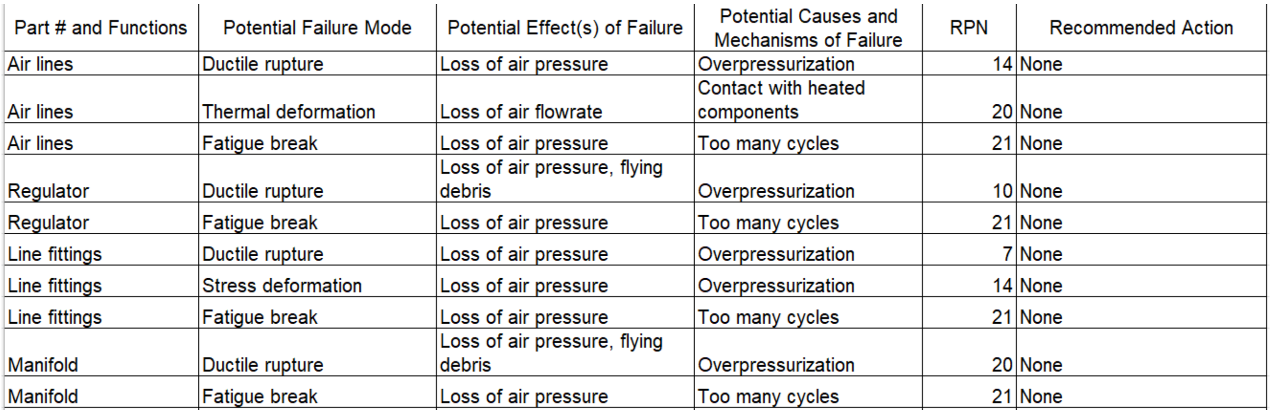
| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| Motor | Burnout | Linear actuator no longer moves | Too much load on motor | 28 | None |
| Ball Screw | Fatigue Break | Linear actuator no longer moves | Too much load/too many cycles on screw | 21 | None |
| Ball Screw | Strip | Linear actuator no longer moves | Too much load on screw | 14 | None |
| Holding Rod | Fatigue Break | Linear actuator is off center | Too much load/too many cycles on rod | 18 | None |
| Button | Unplug | Circuit no longer functions | Connection not strong enough | 56 | Solder wires to button |
| Power Source | Burnout | Circuit no longer functions | Circuit shorts | 64 | Replace breadboard with solder |
| Power Source | Runs out | Circuit no longer functions | Batteries die | 63 | Change power source |
| Bread Board | Unplug | Circuit no longer functions | Connection not strong enough | 63 | Replace breadboard with solder |
| Ball Screw | Buckling | Linear actuator no longer moves | Too much load on screw | 7 | None |
| Bearings | Abrasive wear | Linear actuator is off center | Too many cycles on bearings | 18 | None |

Figure 4: Shortened FMEA for axial loading subsystem.



| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| Jaw Clamp | Yielding | Extrusion held off axis | Overstressing | 6 | None |
| Jaw Clamp | Combined Creep & Fatigue | Extrusion held off axis | Overstressing | 36 | None |
| Jaw Clamp Gears | Brittle Fracture | Clamp inoperatonal | Overstressing | 7 | None |
| Jaw Clamp Gears | Yielding | Loss of clamping force | Overstressing | 10 | None |
| Jaw Clamp Gears | Abrasive Wear | Loss of clamping force | Used for too many cycles | 15 | None |
| Jaw Clamp Frame | Yielding | Extrusion held off axis | Overstressing | 6 | None |
| Collet-Mandrel Clamp | Yielding | Extrusion held off axis | Overstressing | 12 | None |
| Collet-Mandrel Clamp O-Ring | Deformation Wear | Loss of grip and air tight seal | Used for too many cycles | 126 | None, part is consumable |
| Clamp Air Cylinders | Ductile Rupture | Clamp inoperatonal, flying debris | Overpressurizing | 20 | None |
| Clamp Mounting Screws | Brittle Fracture | Clamp unable to be pulled | Overstressing | 14 | None |

Figure 5: Shortened FMEA for clamping subsystem.



| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| Air lines | Ductile rupture | Loss of air pressure | Overpressurization | 14 | None |
| Air lines | Thermal deformation | Loss of air flowrate | Contact with heated components | 20 | None |
| Air lines | Fatigue break | Loss of air pressure | Too many cycles | 21 | None |
| Regulator | Ductile rupture | Loss of air pressure, flying debris | Overpressurization | 10 | None |
| Regulator | Fatigue break | Loss of air pressure | Too many cycles | 21 | None |
| Line fittings | Ductile rupture | Loss of air pressure | Overpressurization | 7 | None |
| Line fittings | Stress deformation | Loss of air pressure | Overpressurization | 14 | None |
| Line fittings | Fatigue break | Loss of air pressure | Too many cycles | 21 | None |
| Manifold | Ductile rupture | Loss of air pressure, flying debris | Overpressurization | 20 | None |
| Manifold | Fatigue break | Loss of air pressure | Too many cycles | 21 | None |

Figure 6: Shortened FMEA for pressurizing subsystem.

## 4.1 Critical Failures

### 4.1.1 Potential Critical Failure 1: O-Ring Deformation Wear

This potential failure involves the O-ring used in the collet-mandrel clamp. The clamp works by squashing the O-ring which causes it to expand inward, squeezing the extrusion running through the center of the O-ring. Each time this is done, there is significant deformation wear on the O-ring, which leads to the O-ring losing grip on the extrusions and losing the ability to seal extrusions when they are pressurized. This failure is frequent and causes the device to lose a primary function. Despite this, the team does not recommend any changes to the system because the O-ring is intended to be a consumable part. The client fully expects to swap these O-rings themselves.

### 4.1.2 Potential Critical Failure 2: Incorrect Heat Applied

This potential failure involves the heating element in the heating subsystem. Heat is applied to the extrusions by blowing air through a heating element and then onto the extrusions. It is possible that the heating element will fail to apply the correct amount of heat. There are two ways this might happen, the temperature sensors sending incorrect information to the heater or the air flowrate being too high/low. The odds of this happening are fairly high, and the consequence is a severe decline in the usefulness of the device, though no primary functions are completely lost. To test for this failure, a separate set of temperature sensors can be used to validate the results of the first set of sensors. Mitigation of this failure is possible by purchasing high quality temperature sensors and limiting the air flowrate to a select range.

### 4.1.3 Potential Critical Failure 3: Heating Nozzle Thermal Fatigue

This potential failure comes from the heating nozzle. The heating nozzle is the device used to direct hot air radially around the extrusion for even heating. Due to the large number of times the nozzle will be heated and cooled, it is possible that it will suffer from thermal fatigue. If this were to happen, the extrusion would likely not be heated to the desired temperature, which is a serious drop in the efficacy of the device. While this failure is not likely to be common, it is relatively difficult to test for and detect. To test for this, the nozzle can be cyclically heated and checked for degradation. The failure can be mitigated by constructing the nozzle from heat resistant materials.

### 4.1.4 Potential Critical Failure 4: Runaway Heating

This potential failure is a failure of the temperature controller. The controller reads data from the sensors and instructs the heating element on what to do based on the data. If the controller receives incorrect data from the sensors, or the controller is not properly coded, it is possible that the controller will make the heating element get far hotter than it is supposed to. This scenario would be a major fire hazard and is therefore quite severe. It is also moderately likely to occur. To prevent this, the system can be tested at all temperature ranges with redundant sensors to validate the results.

### 4.1.5 Potential Critical Failure 5: Power Source Burnout

This potential failure involves the power source used to power the axial loading subsystem and could be caused by a short circuit. The power supply burning out would be a fire hazard and a loss of a primary function of the device. While this failure is likely to occur, it can be easily tested for by simply powering the circuit with a small amount of power. To help mitigate this failure, the current breadboard wiring system could be replaced with a more secure soldered system.

### 4.1.6 Potential Critical Failure 6: Batteries Dying

This failure is very straightforward. When the batteries die, there will be no power to drive the axial loading subsystem, and thus a primary function of the device will be lost. Though this failure would be frequent and fairly severe, it is extremely easy to detect by trying to power the circuit and can be prevented by switching to a different power source, such as a wall outlet.

### 4.1.7 Potential Critical Failure 7: Unplugging in the Breadboard

This failure is also very straightforward. It is common for wires plugged into a breadboard to accidentally become unplugged. In this case, the axial loading subsystem would lose power when that happens. Again, this is a frequent and severe failure that can be easily detected with a quick visual inspection. Replacing the current breadboard system with a more secure soldered system would also fix this failure.

### 4.1.8 Potential Critical Failure 8: Unplugging in the Button

This failure has to do with the wires connecting to the button that actuates the axial loading subsystem coming unplugged. It is likely that this failure would also be very frequent. When this happens, the axial loading subsystem would no longer function. The failure can be detected via visual inspection and can be fixed by soldering the wires to the button.

### 4.1.9 Potential Critical Failure 9: Combined Creep and Fatigue in the Jaw Clamp

This failure involves the jaw clamp that sits at the opposite end of the device from the previously mentioned collet-mandrel clamp. The jaws of the clamp are going to be frequently loaded for extended periods of time, making them possibly subject to combined creep and fatigue. As a result, the jaw clamp would then hold the extrusions off axis, causing them to be heated unevenly. This is a moderately severe failure, but the failure is not very likely to happen and not very hard to detect via cyclical load testing. At this point, the RPN values are getting small enough that the team no longer recommends taking any action to mitigate this failure mode.

### 4.1.10 Potential Critical Failure 10: Motor Burnout

This failure comes from the motor that drives the axial loading subsystem. If the motor tries to drive more load than it is capable of, the motor will burnout, crippling the axial loading subsystem. While severe, this failure is not likely to occur and is easy to detect. It can be tested for simply by running the motor under load. The team does not recommend any action be taken to mitigate this failure.

## 4.2 Risks and Trade-offs Analysis

Some of our recommended actions for mitigating critical failures help mitigate other critical failures, some are completely independent from all the other critical failures, but none seem to interfere with the mitigation of other critical failures. The first, ninth, and tenth critical failures all have no recommended action either because the failure is expected to happen, or the RPN values are too low to justify taking action. Critical failures two and four are somewhat related to each other and would both benefit from testing with additional temperature sensors. On a similar note, critical failures five, seven, and eight can all be mitigated by soldering the wiring system together instead of relying on the loose contacts of the breadboard and button. Lastly, critical failures three and six have mitigation techniques that are completely independent from all the others. The heating nozzle construction and power source for the axial loading system do not interfere with or help the mitigation of any of the other critical failures.

# 5 DESIGN SELECTED – First Semester

This chapter will review the design that has been selected for the radial expansion tester at the end of the Fall 2021 semester. It will start by giving an overview of the design, as well as a few pictures to help visualize the design. It will then explain why we chose our selected designs for each subsystem. Axial load will be supplied by a ball screw and motor system, heating will be accomplished through a made in house air heater, and radial measurement will be accomplished using an LS-7070M. Poba has given the group pneumatic clamps and air cylinders to hold the extrusion in place. It will then review the initial prototype that was created Fall 2021.

## 5.1 Design Description

### 5.1.1 Final Design Selected

The design that the team is moving forward with stands vertically and actuates linear force using a triple stack Nema 34 motor driving a ball screw that will be holding a carriage with a pneumatic clamp attached. There will be a 1:1.5 gear reduction between the lead screw and the motor in order to raise the screw, reducing the output torque required by the motor and raising the screw closer to the baseplate, reducing the moment created by the extrusion. The radial measurement will be accomplished using a LS-7070M digital micrometer. Temperature control will be accomplished using a made in-house air heater, and balloon pressurization will be accomplished using $N_2$ and the procedures already in use by Poba. The balloon will be held in place using pneumatic clamps and air cylinders that were provided by Poba. All data taken will be put onto a small computer that will be bought. A picture of the final assembly has been included below.

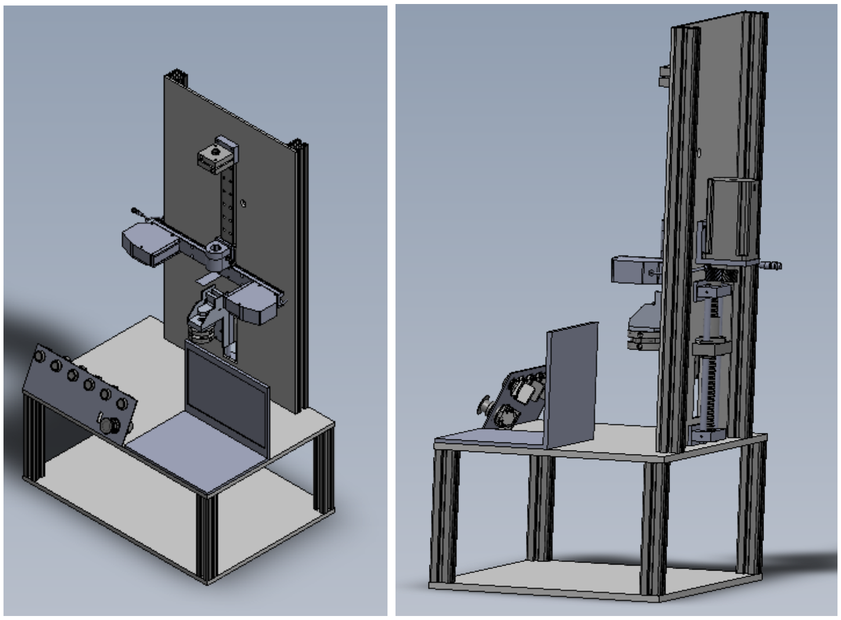


*Figure 7: Isometric and Back View of Radial Expansion Tester*

### 5.1.2 Axial Load Actuation Selection

As stated in the preliminary report, the team decided to go with an electric stepper motor and ball screw due to the fact that it was cheaper, more controllable, and could actuate higher axial forces when compared to other subsystems. Along with this, it is relatively simple and the Engineers from Poba requested it. Next, the team had to decide on a ball screw and motor. In order to find the torque that the motor must supply, the team used the two following equations:

$$T_R = \frac{Fd_m}{2}\left(\frac{l+\pi f d_m}{\pi d_m - fl}\right) \quad (8.2)\ [1]$$

$$T_c = \frac{Ff_c d_c}{2} \quad (8.6)\ [1]$$

Where $T_R$ is the torque required by the motor to raise the screw, and $T_c$ is the torque required by the motor to raise the collar, F is the axial load that is pushing against the motor, $d_m$ is the mean diameter of the screw, l is the lead of the screw, f is the coefficient of friction between the screw and nut, $f_c$ is the coefficient of friction between the screw and the collar, and $d_c$ is the diameter of the collar. $T_R$ and $T_c$ will be added together to find the total torque required by the motor.

After plugging in values from [1] and [28], the team found that the necessary torque is 2.1 N-m, meaning a triple stack Nema 34 motor would work perfectly fine for this application. This motor was chosen because it supplies more than enough torque, as well as it being recommended by the engineers at Poba.

The team then used the calculations in Appendix A to find an appropriate ball screw. The ball screw chosen was a 1 foot long, .655” diameter screw. However, the team needed to move the ball screw above the motor, as there would be too large of a moment on the ball screw due to the force from the extrusion for safe use of the ball screw. This was done by creating a helical gear system with a 1:1.5 reduction. A figure of the subsystem has been included below.

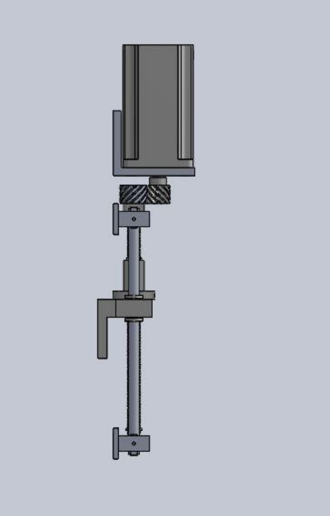


*Figure 8: Axial Load Subsystem*

### 5.1.3 Temperature Control Selection

Based on the information in the last report, the team decided to go with a made in house heater. This heater will use an Omega T-Type Duct Heater, which will blow hot air into a made in house nozzle. The team has decided to go with the AHP-3741 [] model omega heater due to its price and compact design. The heater will be connected through a series of ⅛” NPT fittings, which are what Poba has in house.

In order to get even heating on the extrusion, a proper nozzle must be created and it must be made out of an acceptable material. Vergil created a design in which two brass pieces are assembled to create one sealed piece in which a NPT fitting can be attached. Brass was chosen due to its cost, ease to machine, and low thermal conductivity. There will be channels within the piece so that air can flow through into the chamber containing the extrusion. A figure has been provided below to help visualize the nozzle.

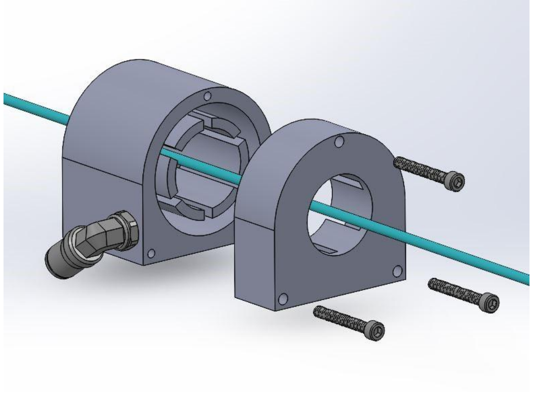


*Figure 9: Isometric View of Nozzle*

To ensure that the flow is uniform,a flow analysis was performed with solidworks. Four different geometries were tested, and it was found that a geometry with a gradual lead angle, and larger radii of the sides closer to the slits worked the best. A figure of the simulation has been included below.

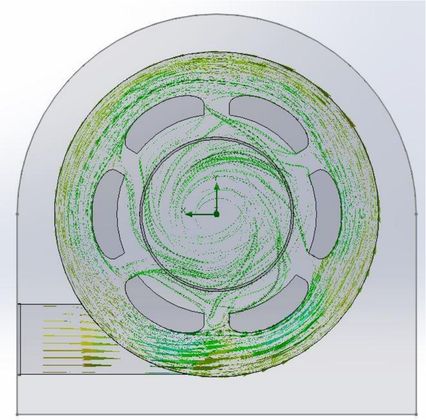


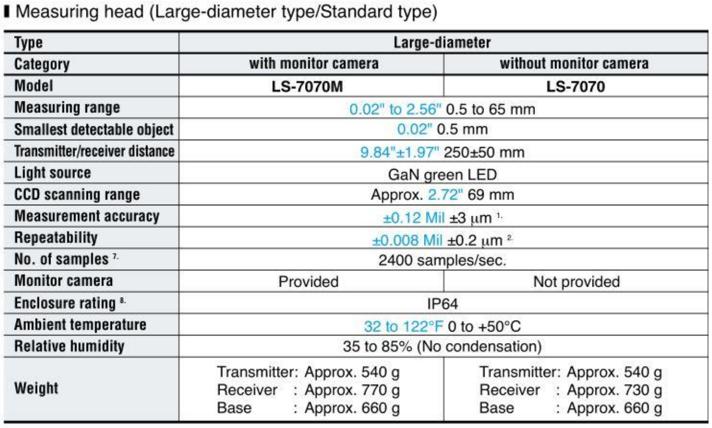
*Figure 10: Final Nozzle Design*

### 5.1.4 Diameter Measurement Selection

The selection of the LS-707M was fairly straightforward compared to the other two subsystems. The team had initially come up with an idea using, and evaluated these concepts based on their. A Pugh chart has been included below.

Poba then had the team come up with two separate bill of materials, one for a system using a camera, and one using a digital micrometer. Poba ultimately decided they wanted to spend the money on the digital micrometer because it would simplify the process so much, and because they could keep it and use it on other systems if they wanted to. Based on the data sheet below, the LS-707M will meet our requirements of measuring between .2-2.5”.

*Table 2: LS-7000 Series Spec Sheet*



Measuring head (Large-diameter type/Standard type)

| **Type** | **Large-diameter** | |
|---|---|---|
| **Category** | **with monitor camera** | **without monitor camera** |
| **Model** | **LS-7070M** | **LS-7070** |
| **Measuring range** | 0.02" to 2.56" 0.5 to 65 mm | |
| **Smallest detectable object** | 0.02" 0.5 mm | |
| **Transmitter/receiver distance** | 9.84"±1.97" 250±50 mm | |
| **Light source** | GaN green LED | |
| **CCD scanning range** | Approx. 2.72" 69 mm | |
| **Measurement accuracy** | ±0.12 Mil ±3 μm [1.] | |
| **Repeatability** | ±0.008 Mil ±0.2 μm [2.] | |
| **No. of samples** [7.] | 2400 samples/sec. | |
| **Monitor camera** | Provided | Not provided |
| **Enclosure rating** [8.] | IP64 | |
| **Ambient temperature** | 32 to 122°F 0 to +50°C | |
| **Relative humidity** | 35 to 85% (No condensation) | |
| **Weight** | Transmitter: Approx. 540 g<br>Receiver : Approx. 770 g<br>Base : Approx. 660 g | Transmitter: Approx. 540 g<br>Receiver : Approx. 730 g<br>Base : Approx. 660 g |

### 5.1.5 Clamp Selection

While the clamps were essentially decided for the team as the Engineers from Poba decided they wanted us to use what they had on hand to reduce costs, the team still made sure that these clamps would work. This was done by performing a shear-moment analysis of the clamp, as well making sure that the clamp will supply enough pressure to hold the balloon in place. These calculations can be found in Appendix B, and it was found that the pneumatic clamps supplied to the team will work.

### 5.1.6 Initial Prototype

For the initial prototype, the team was mainly trying to figure out the spacing of everything. Along with this, the team was trying to show that the lead screw would move, even with a DC motor. This was because parts were not ordered until late november, and will not be arriving until mid winter break. The team created this prototype using a piece of particle board for the baseplate, a breadboard system to drive the motor, a lead screw taken from a 3D-printer, a 3D-printed carriage with support rods taken from a 3D-printer, a 12V DC motor, a guide rail taken from a 3D-printer, and a 3D-printed heater. A picture of this iteration has been provided below.

*Figure 11: First Iteration of Radial Expansion Tester*

For the second iteration, the team purchased a more powerful DC motor, and repositioned the assembly so it was vertical. This was done in order to test if the axial load system would create a significant enough moment to require additional support. Along with this, the team wanted to prove that the axial load system would move with a more powerful motor. The team is also going to apply axial loads to the clamps to see where failure will happen.

Through these prototypes, the team has learned a lot about the importance of iteration, as well as the importance of prototyping early. This is because the first prototype acted as nothing but an industrial model, and didn't meet any of the engineering requirements. Had the team waited until next semester to start prototyping, they would not know that there will be some amount of eccentricity between the lead screw and the motor, and that this would cause additional friction that the motor would need to overcome. Along with this, the team initially made the Radial Expansion Tester so that the motor was acting against gravity, instead of with it. The team also learned how everything will be spaced, and how things will need to be mounted for a vertical assembly.

## 5.2 Implementation Plan

In order to create this design, the team will first order all of the components necessary. This will be done using the BOM in Appendix C. The team hopes to have this done by the end of november, and as of 11/24/2021 some parts have already been ordered. The final cost of the BOM came out to $7,877 not including shipping, which is quite a bit lower than our budget of $10,000. Along with this, the team is not expecting to have manufacturing costs as we have access to the NAU Machine Shop, the Poba facilities, as well as Vergil's expertise.

The parts should get here sometime during winter break. The Engineers at Poba have requested that anyone from the Capstone Team that is in town to come in and begin assembling the Radial Expansion tester. The team plans to start with the skeleton, which is the baseplate and all parts holding the baseplate up, and then attach the digital micrometer. The team will then build the rest of the Radial Expansion Tester around the digital micrometer. A picture of the final assembly and an exploded view of the final assembly have been included below.

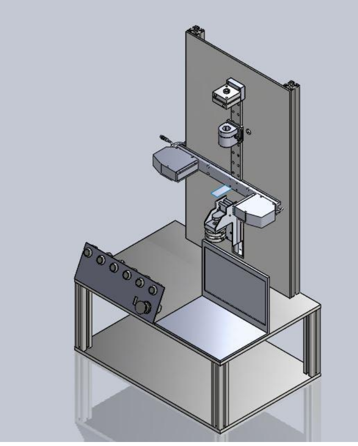


*Figure 12: Isometric View of Final CAD*

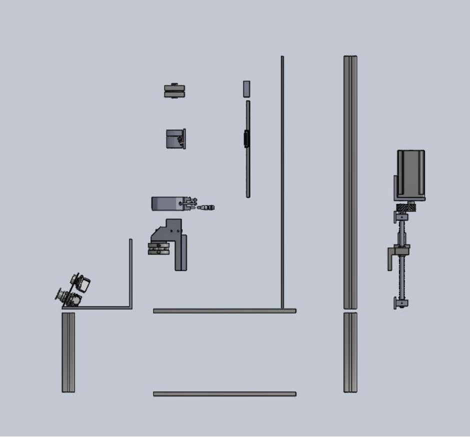


*Figure 13: Exploded View of Final CAD*

In order to better schedule out next semester, the team has created the Gantt Chart in Appendix E. This Gantt Chart lays out all class activities that must be completed, as well as a general outline of how long the assembly is planned to take. The team has decided to keep their schedule of taking a week to work on the class assignments, as it seems to work well for the team. The team also created a rough Gantt chart for the design process, with a day planned to meet to assemble the skeleton with one of the Engineers from Poba over winter break, 1 week for each member to assemble/attach their subsystems to the skeleton. The rest of the semester will be used to make adjustments to the subsystems, work on controllers, and integrate the system into Poba's $N_2$ system.

# 6 CONCLUSIONS

In conclusion, this report contains all of the information necessary to justify moving forward into the next semester with the Radial Expansion Tester. Poba Medical wants a machine that can test extrusions' ability to become medical balloons before they do a full order of a certain type of extrusion. They gave the team a list of technical requirements in order to easily define the scope of the problem, which can be listed as the following:

- Constant axial force applied during testing with the ability to pull up to 150 lbs
- Test extrusion diameters from .02-.625
- Test expanded extrusion diameter up to 2.5”
- Material temperatures control, including temperatures up to 250F
- Continuous diameter measurements during radial expansion of tubing

The team took those requirements and broke them down into customer needs and engineering requirements. The team then created a black box and hypothetical model in order to begin brainstorming on how the machine would actually work, and created a QFD in order to compare the customer needs and engineering requirements, as well as break down the problem even further.

After the team had a solid idea of what their design would look like, they made testing criteria in order to show that they are hitting all of the necessary engineering requirements. They then explored possible ways that the design could fail, focusing especially on critical failures. After this, the team came up with their final design for the fall semester.

The team has decided to go with a ball screw and motor system to create axial force, a LS-7070M to measure the diameter of the extrusion during expansion, a custom nozzle attached to an air heater to heat the extrusion, and pneumatic clamps and air cylinders provided by Poba to hold the extrusion in place. These systems were then analyzed to determine if they would work, and exact products were found that would fit within the technical requirements found in these calculations. These products can be found in the BOM in appendix C.

Overall, the semester went well for the team. Everyone has learned a lot, and both the engineers at Poba and Dr Willy seem to be happy at where we are at. There where a couple of mishaps along the way, in which things didn’t get turned in even though they where done, but it all seemed to work out in the end. However, the team didn’t follow their initial schedule at all, but that was because it was extremely unrealistic, and would not have worked in the real world. The team has made 2 separate prototypes in order to visualize spacing and see where things could fail, and things are starting to get ordered as of late november. Everyone on the team is happy with where we are at at the end of Fall 2021.

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# 8 APPENDICES

## 8.1 Appendix A: Axial Load System Calculations

The axial load system will need to go through three separate checks. The carriage will need to be checked for a shear failure, and the screw will need to be checked for shear and fatigue failure. To start these calculations, the following FBD was created:

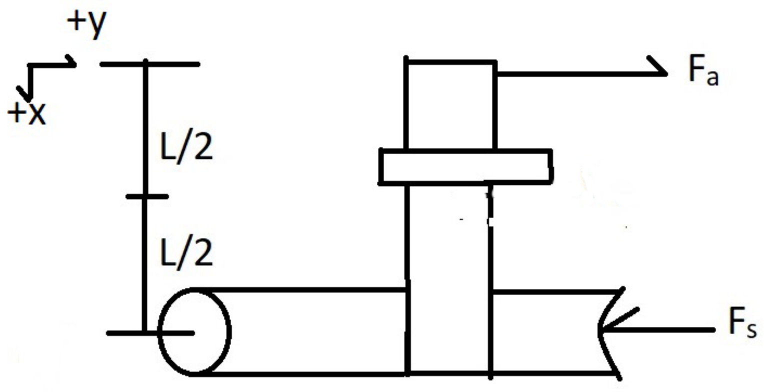


*Figure 14: FBD of Carriage System*

Where $F_a$ is the force produced by the extrusion, and $F_s$ is the force produced by the screw. Through inspection, we can see that $F_a = F_s = 150$ lb. Using this information, the following shear - moment equations can be created.

$$V = 150 < x>^{0} - 150 < x - 4.04 >^{0} - 606 < x - 4.04>^{-1} \qquad ()$$

$$M = 150 < x>^{1} - 150 < x - 4.04>^{0} - 606 < x - 4.04>^{0} \qquad ()$$

Based on these shear-moment equations, the following shear-moment diagrams can be created:

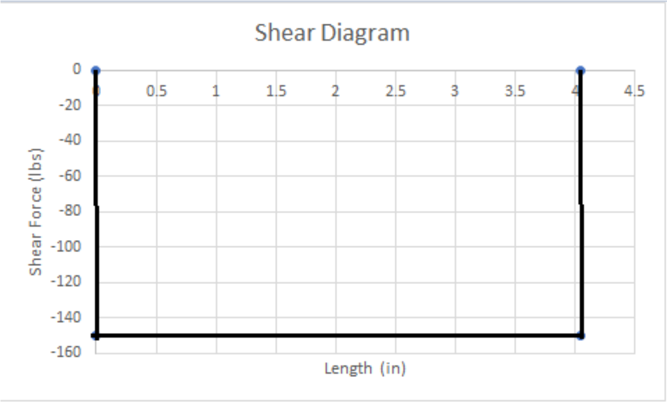


*Figure 15: Shear diagram of Screw-Carriage System*

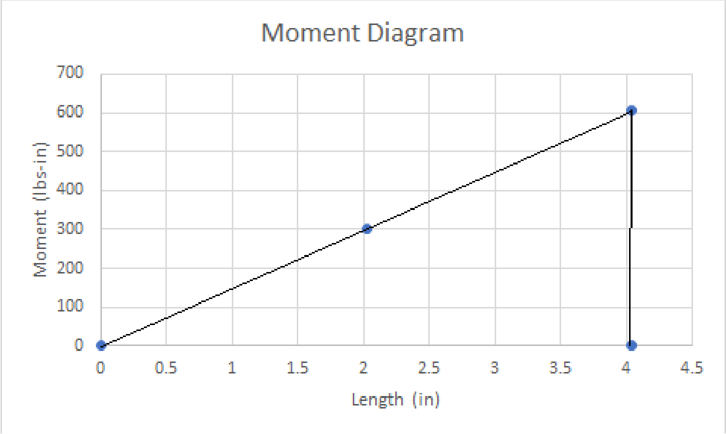


*Figure 16: Moment Diagram of Screw-Carriage System*

From these, we can do a quick yield check on the PLA carriage. The maximum shear stress the carriage will see is 150 lbs, which can easily be handled by the PLA which has a yield strength of 88.4 kpsi. Next, the following FBD can be created from the above shear-moment diagrams:

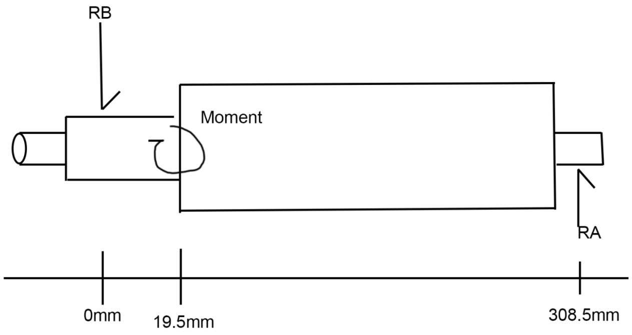


*Figure 17: FBD of screw*

The following shear-moment diagrams can be created from this:

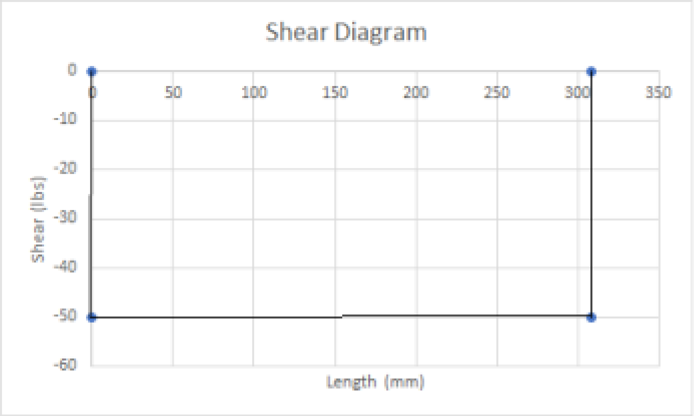


*Figure 18: Shear Diagram of Shaft*

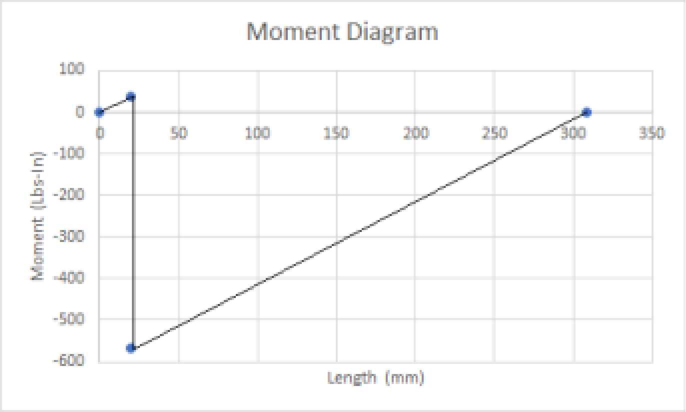


*Figure 19: Moment Diagram of Shaft*

Then, through a standard shaft analysis on excel, it is found that the minimum diameter for a shaft .9 inches away from the baseplate will be 16.5mm, which is .649 inches, meaning that a .655” screw will be more than sufficient.

## 8.2 Appendix B: Clamp Selection Calculations

To start the calculations, you can make a simple FBD of the system, as shown below:

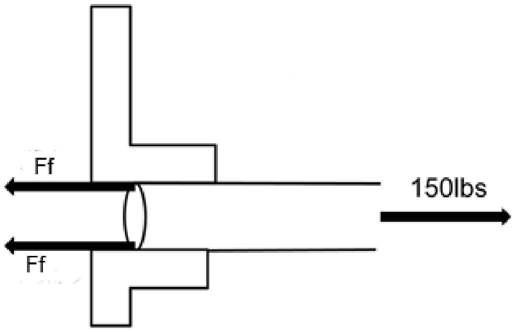


*Figure 20: FBD of Extrusion Being Clamped*

Where $F_f$ is the friction force. It should be noted that there is only one friction force, and it is acting along the area that the extrusion is contacting the clamp. Assuming static equilibrium, you can then apply the following equations to the FBD:

$$P = \frac{F_p}{A_p} \qquad (1)$$

$$0 = 150 - F_f \qquad (2)$$

$$F_f = \mu_s F_N \qquad (3)$$

Where $F_p$ is the force applied by the pneumatic clamp on the extrusion, $A_p$ is the are that the pressure is applied over, $F_f$ is the frictional force between the extrusion and the clamp, $\mu_s$ is the coefficient of static friction, and $F_N$ is the normal force of the extrusion acting on the clamp. Based on Newton's Third Law, we can assume that $F_p$ = $F_n$. The air cylinder can apply up to 200 psi [], so assuming that a 1 inch length of tube is being held, the $F_f$ would be equivalent to 942 lbs, which is much more than is necessary for this machine.

In order to analyze the bending and shear stress that the clamp will see, the following FBD and shear-moment diagram have been created.

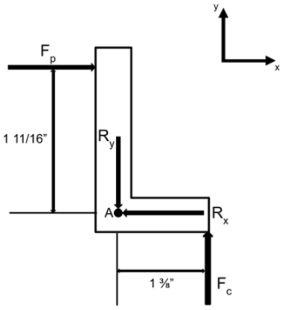


*Figure 21: FBD and Shear-Moment Diagram of Clamp*

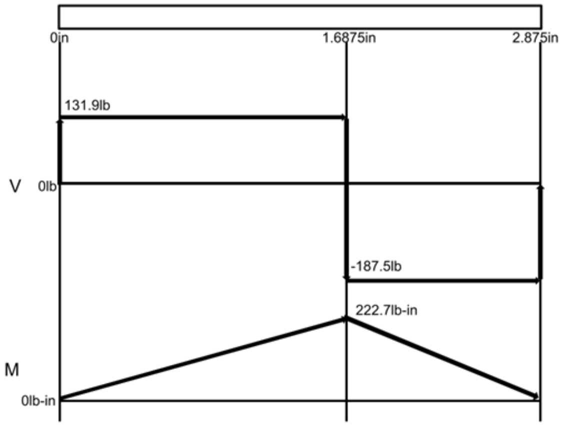


*Figure 22: Shear-Moment Diagram of Clamp*

Based on the previous FBD and Shear-Moment Diagram, maximum bending stress the jaws will need to withstand is 7600 psi. This is well within the acceptable stress of the aluminum being used.

## 8.3 Appendix C: Full BOM

| **Ball Screw Assembly** | # Of Parts | Price Per Part | Total Price | Link |
|---|---|---|---|---|
| Nema 34 Stepper Motor | 1 | 70.00 | 70.00 | https://www.omc-stepperonline.com/nema-34-stepper-motor/s-series-nema-34-stepper-motor-bipolar-1-8deg-12-0-nm-1699-68oz-in-6-0a-86x86x151-5mm-4-wires.html |
| Stepper Motor Bracket | 1 | 6.65 | 6.65 | https://www.omc-stepperonline.com/nema-34-bracket-for-stepper-motor-alloy-steel-bracket-st-m7. |

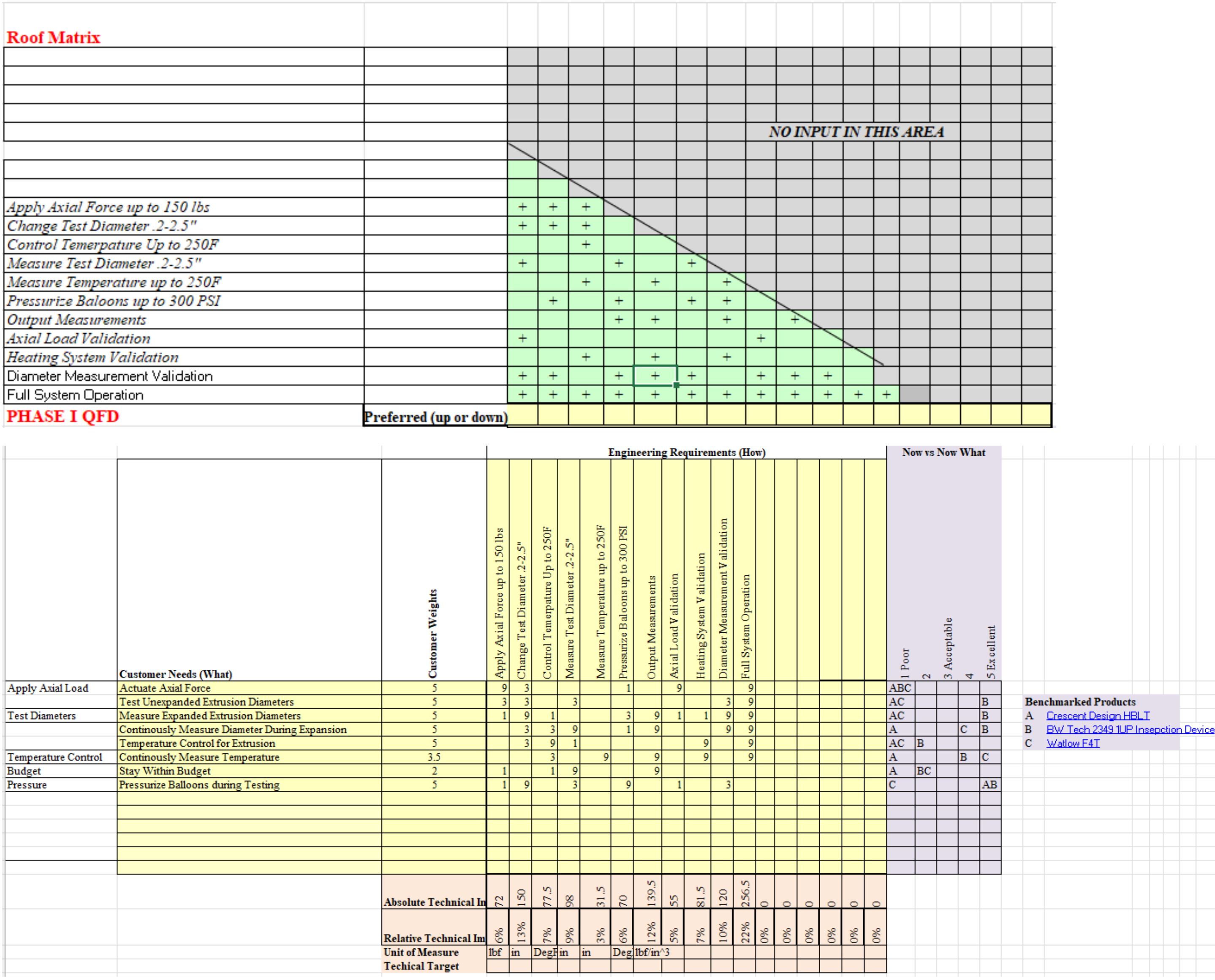
| | | | | |
|---|---|---|---|---|
| | | | | html |
| Stepper Motor Coupler | 1 | 13.49 | 13.49 | https://www.amazon.com/uxcell-Coupling-Diameter-Aluminum-Connector/dp/B06X9X92W5/ref=asc_df_B06X9X92W5/?tag=hyprod-20&linkCode=df0&hvadid=241964173834&hvpos=&hvnetw=g&hvrand=17730990502199139537&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9030289&hvtargid=pla-446569763203&psc=1 |
| Ball Screw, .655" Root Dia, 1 ft Length | 1 | 66.56 | 66.56 | https://www.mcmaster.com/3405N013/ |
| Guide Rails 1/2" OD 1 ft Length | 2 | 9.00 | 18.00 | https://www.mcmaster.com/6061K33/ |
| Linear Bearings 1/2" ID | 2 | 23.80 | 47.60 | https://www.mcmaster.com/60595K73/ |
| Retaining Rings for Linear Bearing | 6 | 0.64 | 3.84 | https://www.mcmaster.com/9968K24/ |
| Ball Bearing 1/2" ID 0.63 OD | 2 | 9.62 | 19.24 | https://www.mcmaster.com/60355K704/ |
| 1 Inch Helical | 1 | 36.57 | 36.57 | https://www.mcmaster.com/helical-gears/metal-gears-and-gear-racks-20-pressure-angle/ |
| 1.5 Inch Helical Gear | 1 | 40.20 | 40.20 | https://www.mcmaster.com/helical-gears/metal-gears-and-gear-racks-20-pressure-angle/ |
| | | | | |
| Total | 322.15 | | | |
| | | | | |
| **General** | # Of Parts | Price Per Part | Total Price | |
| Al Extrusion 45x45 10Ft Length | 2 | 64.40 | 128.80 | https://www.mcmaster.com/6575N25-6575N187/ |
| Al Extrusion hardware | 1 | 20.00 | 20.00 | https://www.amazon.com/CheeMuii-Brackets-Aluminum-Extrusion-Accessories/dp/B098NVHDYM/ref=sr_1_6?dchild=1&keywords=t+slot+hardware&qid=1634150201&s=industrial&sr=1-6 |
| Linear Gude Rail: 42 mm Wide 310mm L | 1 | 244.90 | 244.90 | https://www.mcmaster.com/7917N9-7917N84/ |

| | | | | |
|---|---|---|---|---|
| Carriage for 42mm wide gudie rail | 2 | 105.36 | 210.72 | https://www.mcmaster.com/7917N22/ |
| | | | | |
| Total | 604.42 | | | |
| | | | | |
| **Heating** | # Of Parts | Price Per Part | Total Price | |
| Duct Heater: "AHP-3741" 200W, 57W/in2, 120V, 1/4" NPT | 1 | 98.41 | 98.41 | https://www.omega.com/en-us/industrial-heaters/duct-and-enclosures-heaters/duct-heaters/ahp-series/p/AHP-3741 |
| Thermocouple: "J type" | 1 | 52.08 | 52.08 | https://www.mcmaster.com/6441T671/ |
| Temp Controller: "CND3" 1 Control output, 1/8DIN (RTD **or** Thermocouple) | 1 | 90.54 | 90.54 | https://www.omega.com/en-us/control-monitoring/controllers/pid-controllers/cnd3-series/p/CN08D3-S-AC |
| | | | | |
| Total | 241.03 | | | |
| | | | | |
| **Clamp** | # Of Parts | Price Per Part | Total Price | |
| "Bimba Clamp" | 1 | 166.60 | 166.60 | https://www.bimba.com/en/detail/flat_1_square |
| | | | | |
| Total | 166.60 | | | |
| | | | | |
| **Air Control** | # Of Parts | Price Per Part | Total Price | |
| Brass Quick-Disconnect Male 1/4" NPT | 1 | 1.62 | 1.62 | https://www.mcmaster.com/1077T17/ |
| Brass Quick-Disconnect Female 1/4" NPT *For 1/4" hose ID* | 1 | 8.66 | 8.66 | https://www.mcmaster.com/6534K51/ |
| Air manifold 1/4" NPT in, 1/8" NPT out. 1 in 4 out | 1 | 17.82 | 17.82 | https://www.mcmaster.com/5469K121/ |
| Tube Fitting 1/4" NPT to 1/4" Tube | 8 | 4.06 | 32.48 | https://www.mcmaster.com/51875K52/ |
| Tube Fitting 1/4" NPT to 1/8" Tube | 4 | 3.00 | 12.00 | https://www.mcmaster.com/51875K52/ |
| 1/4" Push-to-connect tube plugs | 6 | 0.93 | 5.58 | https://www.mcmaster.com/5111K504/ |
| 1/4" NPT Plugs | 5 | 1.96 | 9.80 | https://www.mcmaster.com/50925K381/ |
| 1/8" NPT Plugs | 5 | 1.51 | 7.55 | https://www.mcmaster.com/5092 |

|  |  |  |  |  |
|---|---|---|---|---|
|  |  |  |  | 5K231/ |
| Air Flow meter 1/4" NPT Male fittings | 1 | 59.00 | 59.00 | https://www.mcmaster.com/8051K34/ |
| Air flow control valve 1/4" NPT Female fittings | 1 | 46.86 | 46.86 | https://www.mcmaster.com/62005K623/ |
| High temp PFA Tubing 1/4 OD 1/8 ID 5Ft | 1 | 31.60 | 31.60 | https://www.mcmaster.com/52705K32/ |
| High Temp Push-to-connect 1/8" NPT 1/4" Tube --To Heater Nozzel-- | 1 | 7.16 | 7.16 | https://www.mcmaster.com/5523K35/ |
| Push-To-Connect 1/4" Tube to 1/4" NPT Male | 4 | 2.26 | 9.04 | https://www.mcmaster.com/51235K108/ |
| Push-To-Connect 1/8" Tube to 1/4" NPT Male | 4 | 2.78 | 11.12 | https://www.mcmaster.com/51235K102/ |
| Normally Closed Air Solenoid Valve - To Heater- | 1 | 84.49 | 84.49 | https://www.mcmaster.com/4738K137/ |
|  |  |  |  |  |
| Total | 344.78 |  |  |  |
|  |  |  |  |  |
| **Nitrogen Control** | # Of Parts | Price Per Part | Total Price |  |
| Air regulator 1/4" od tube | 1 | 33.78 | 33.78 | https://www.mcmaster.com/41735K11-41735K201/ |
|  |  |  |  |  |
| Total | 33.78 |  |  |  |
|  |  |  |  |  |
| **Raw Stock** | # Of Parts | dim | Total Price |  |
| Brass for heating nozzel | 1 | 3"x3"x5" |  |  |
| Aluminum base plate | 3 | 24"x24"x0.25" |  |  |
| Aluminum for general brackets | 1 | 6"x6"x12" |  |  |
| Teflon Sheet for heat sheilding | 1 | 6"x6"1/8" | 28.67 | https://www.mcmaster.com/8545K15/ |
|  |  |  |  |  |
| **Assorted Electrical** | # Of Parts | Price Per Part | Total Price |  |
| 200W Power Supply | 1 | 18.29 | 18.29 | https://www.omc-stepperonline.com/switching-power-supply/201w-24v-83a-115230v-switching-power-supply-stepper-motor-cnc-router-kits-s-201-24.html?mfp=49-power-w%5B158.4%2C201%5 |

| | | | | |
|---|---|---|---|---|
| | | | | D |
| Arduino board | 2 | 40.00 | 80.00 | https://www.sparkfun.com/products/11061 |
| Stepper motor driver | 1 | 37.40 | 37.40 | https://www.omc-stepperonline.com/digital-stepper-driver-24-72a-18-80vac-or-36-110vdc-for-nema-34-motor-dm860t.html |
| | | | 0.00 | |
| **Optical Micrometer** | # Of Parts | Price Per Part | | |
| Keyence "LS-7000" | 1 | 6000.00 | 6000.00 | |
| | | | | |
| Grand Total Before tax/ shippping | 7877.12 | | | |

## 8.4 Appendix D: HOQ



**Roof Matrix**

NO INPUT IN THIS AREA

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Apply Axial Force up to 150 lbs* | | + | + | + | | | | | | | | | | | | | | |
| *Change Test Diameter .2-2.5"* | | + | + | + | | | | | | | | | | | | | | |
| *Control Temerpature Up to 250F* | | | | + | | | | | | | | | | | | | | |
| *Measure Test Diameter .2-2.5"* | | + | | | + | | + | | | | | | | | | | | |
| *Measure Temperature up to 250F* | | | | + | | + | | + | | | | | | | | | | |
| *Pressurize Baloons up to 300 PSI* | | | + | | + | | + | + | | | | | | | | | | |
| *Output Measurements* | | | | | + | + | | + | | + | | | | | | | | |
| *Axial Load Validation* | | + | | | | | | | + | | | | | | | | | |
| *Heating System Validation* | | | | + | | + | | + | | | | | | | | | | |
| Diameter Measurement Validation | | + | + | | + | + | + | | + | + | + | | | | | | | |
| Full System Operation | | + | + | + | + | + | + | + | + | + | + | + | + | | | | | |
| **PHASE I QFD** | **Preferred (up or down)** | | | | | | | | | | | | | | | | | |

**Engineering Requirements (How)**

**Now vs Now What**

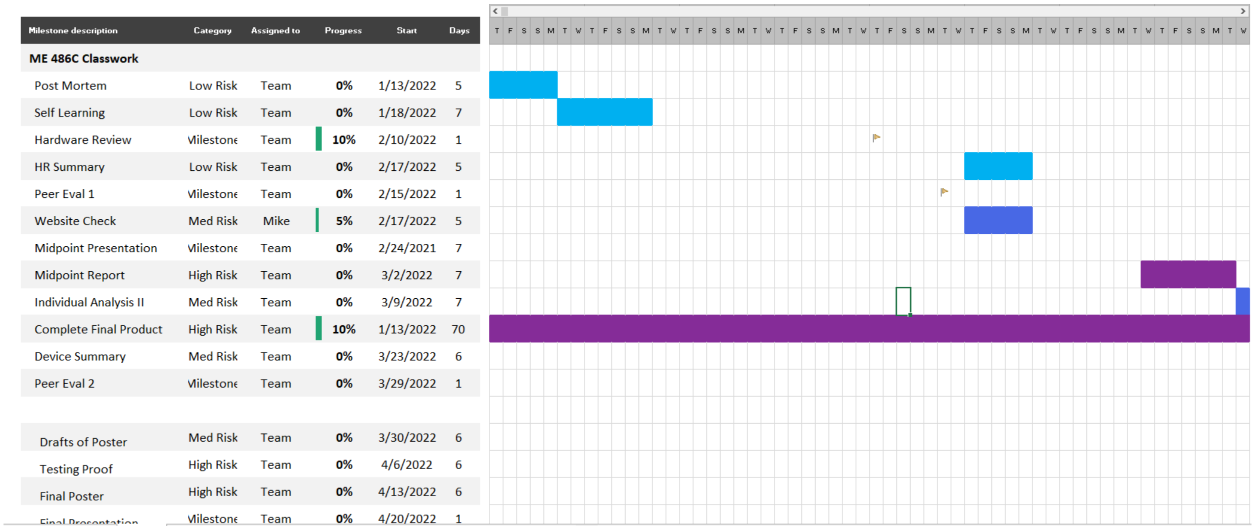
| | **Customer Needs (What)** | **Customer Weights** | Apply Axial Force up to 150 lbs | Change Test Diameter .2-2.5" | Control Temerpature Up to 250F | Measure Test Diameter .2-2.5" | Measure Temperature up to 250F | Pressurize Baloons up to 300 PSI | Output Measurements | Axial Load Validation | Heating System Validation | Diameter Measurement Validation | Full System Operation | | | | | | | 1 Poor | 2 | 3 Acceptable | 4 | 5 Excellent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Apply Axial Load | Actuate Axial Force | 5 | 9 | 3 | | | | 1 | | 9 | | | 9 | | | | | | | ABC | | | | |
| | Test Unexpanded Extrusion Diameters | 5 | 3 | 3 | | 3 | | | | | | 3 | 9 | | | | | | | AC | | | | B |
| Test Diameters | Measure Expanded Extrusion Diameters | 5 | 1 | 9 | 1 | | | 3 | 9 | 1 | 1 | 9 | 9 | | | | | | | AC | | | | B |
| | Continously Measure Diameter During Expansion | 5 | | 3 | 3 | 9 | | 1 | 9 | | | 9 | 9 | | | | | | | A | | | C | B |
| | Temperature Control for Extrusion | 5 | | 3 | 9 | 1 | | | | | 9 | | 9 | | | | | | | AC | B | | | |
| Temperature Control | Continously Measure Temperature | 3.5 | | | 3 | | 9 | | 9 | | 9 | | 9 | | | | | | | A | | | B | C |
| Budget | Stay Within Budget | 2 | 1 | | 1 | 9 | | | 9 | | | | | | | | | | | A | BC | | | |
| Pressure | Pressurize Balloons during Testing | 5 | 1 | 9 | | 3 | | 9 | | 1 | | 3 | | | | | | | | C | | | | AB |
| | **Absolute Technical Im** | | 72 | 150 | 77.5 | 98 | 31.5 | 70 | 139.5 | 55 | 81.5 | 120 | 256.5 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | |
| | **Relative Technical Im** | | 6% | 13% | 7% | 9% | 3% | 6% | 12% | 5% | 7% | 10% | 22% | 0% | 0% | 0% | 0% | 0% | 0% | | | | | |
| | **Unit of Measure** | | lbf | in | DegF | in | in | Deg | lbf/in^3 | | | | | | | | | | | | | | | |
| | **Techical Target** | | | | | | | | | | | | | | | | | | | | | | | |

**Benchmarked Products**

| | |
|---|---|
| A | Crescent Design HBLT |
| B | BW Tech 2349 1UP Insepction Device |
| C | Watlow F4T |

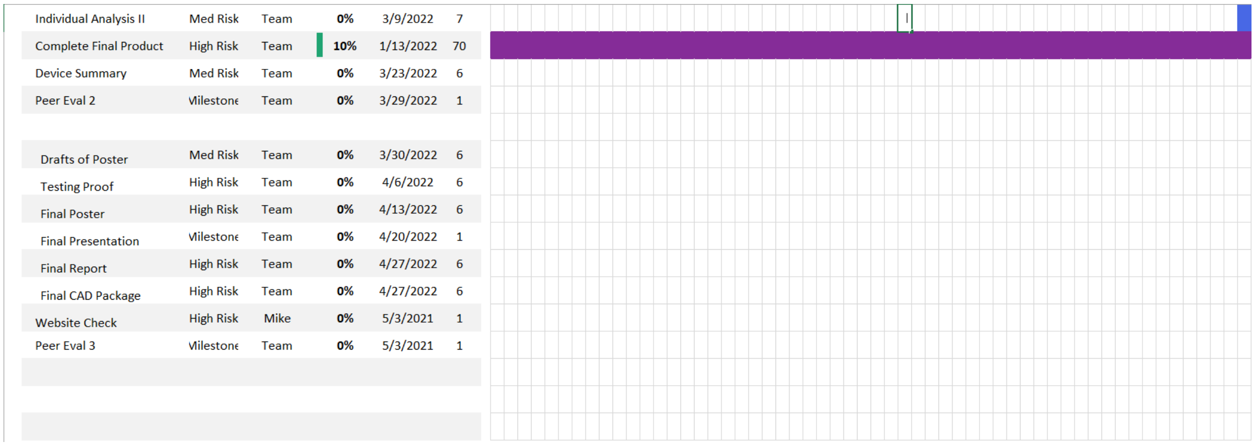
Figure 23: HOQ

## 8.5 Appendix E: 486 Gantt Chart



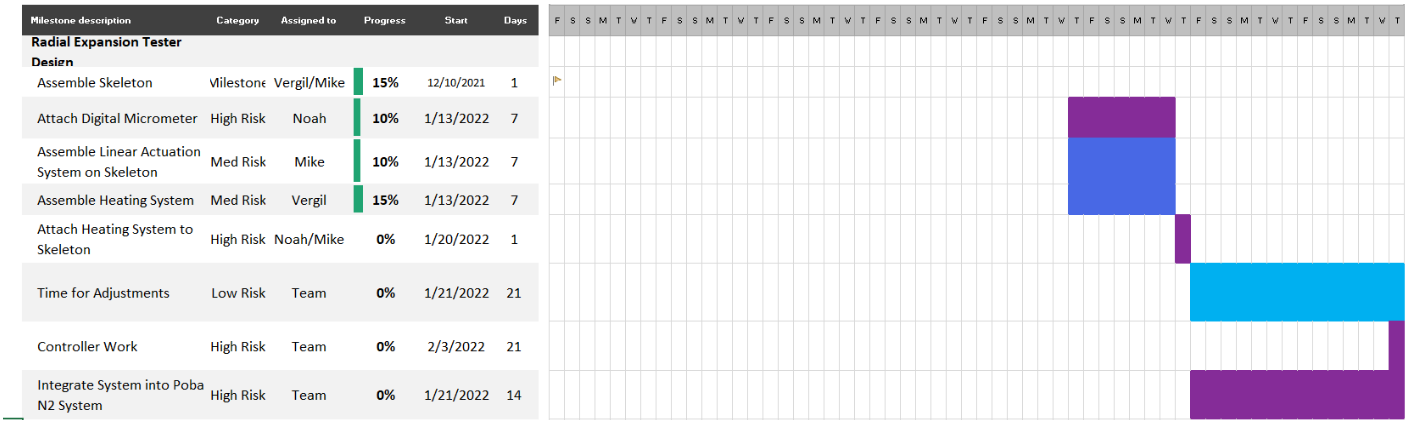
| Milestone description | Category | Assigned to | Progress | Start | Days |
|---|---|---|---|---|---|
| **ME 486C Classwork** | | | | | |
| Post Mortem | Low Risk | Team | 0% | 1/13/2022 | 5 |
| Self Learning | Low Risk | Team | 0% | 1/18/2022 | 7 |
| Hardware Review | Milestone | Team | 10% | 2/10/2022 | 1 |
| HR Summary | Low Risk | Team | 0% | 2/17/2022 | 5 |
| Peer Eval 1 | Milestone | Team | 0% | 2/15/2022 | 1 |
| Website Check | Med Risk | Mike | 5% | 2/17/2022 | 5 |
| Midpoint Presentation | Milestone | Team | 0% | 2/24/2021 | 7 |
| Midpoint Report | High Risk | Team | 0% | 3/2/2022 | 7 |
| Individual Analysis II | Med Risk | Team | 0% | 3/9/2022 | 7 |
| Complete Final Product | High Risk | Team | 10% | 1/13/2022 | 70 |
| Device Summary | Med Risk | Team | 0% | 3/23/2022 | 6 |
| Peer Eval 2 | Milestone | Team | 0% | 3/29/2022 | 1 |
| | | | | | |
| Drafts of Poster | Med Risk | Team | 0% | 3/30/2022 | 6 |
| Testing Proof | High Risk | Team | 0% | 4/6/2022 | 6 |
| Final Poster | High Risk | Team | 0% | 4/13/2022 | 6 |
| Final Presentation | Milestone | Team | 0% | 4/20/2022 | 1 |

*Figure 24: Top Half of Classwork Portion of Gantt Chart*



| Milestone description | Category | Assigned to | Progress | Start | Days |
|---|---|---|---|---|---|
| Individual Analysis II | Med Risk | Team | 0% | 3/9/2022 | 7 |
| Complete Final Product | High Risk | Team | 10% | 1/13/2022 | 70 |
| Device Summary | Med Risk | Team | 0% | 3/23/2022 | 6 |
| Peer Eval 2 | Milestone | Team | 0% | 3/29/2022 | 1 |
| | | | | | |
| Drafts of Poster | Med Risk | Team | 0% | 3/30/2022 | 6 |
| Testing Proof | High Risk | Team | 0% | 4/6/2022 | 6 |
| Final Poster | High Risk | Team | 0% | 4/13/2022 | 6 |
| Final Presentation | Milestone | Team | 0% | 4/20/2022 | 1 |
| Final Report | High Risk | Team | 0% | 4/27/2022 | 6 |
| Final CAD Package | High Risk | Team | 0% | 4/27/2022 | 6 |
| Website Check | High Risk | Mike | 0% | 5/3/2021 | 1 |
| Peer Eval 3 | Milestone | Team | 0% | 5/3/2021 | 1 |

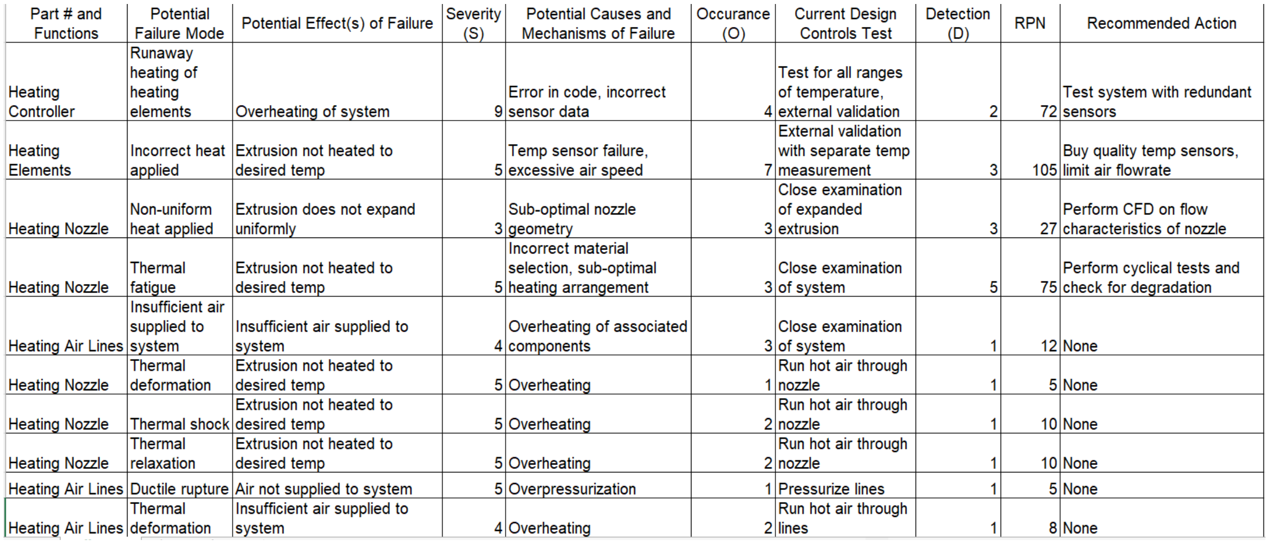
*Figure 25: Bottom Half of Classwork Portion of Gantt Chart*



| Milestone description | Category | Assigned to | Progress | Start | Days |
|---|---|---|---|---|---|
| **Radial Expansion Tester Design** | | | | | |
| Assemble Skeleton | Milestone | Vergil/Mike | 15% | 12/10/2021 | 1 |
| Attach Digital Micrometer | High Risk | Noah | 10% | 1/13/2022 | 7 |
| Assemble Linear Actuation System on Skeleton | Med Risk | Mike | 10% | 1/13/2022 | 7 |
| Assemble Heating System | Med Risk | Vergil | 15% | 1/13/2022 | 7 |
| Attach Heating System to Skeleton | High Risk | Noah/Mike | 0% | 1/20/2022 | 1 |
| Time for Adjustments | Low Risk | Team | 0% | 1/21/2022 | 21 |
| Controller Work | High Risk | Team | 0% | 2/3/2022 | 21 |
| Integrate System into Poba N2 System | High Risk | Team | 0% | 1/21/2022 | 14 |

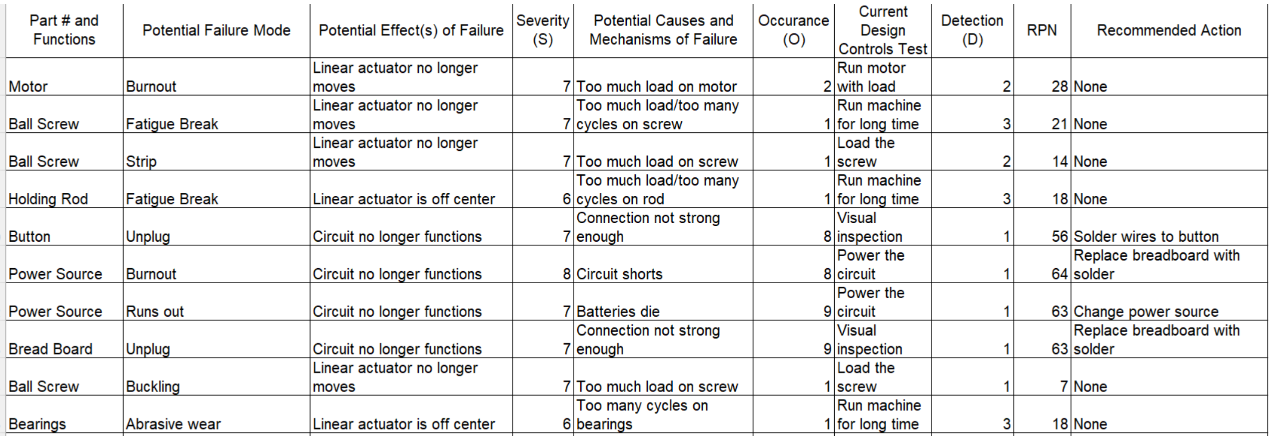
*Figure 26: Design Gantt Chart*

## 8.6 Appendix F: Full FMEA Charts



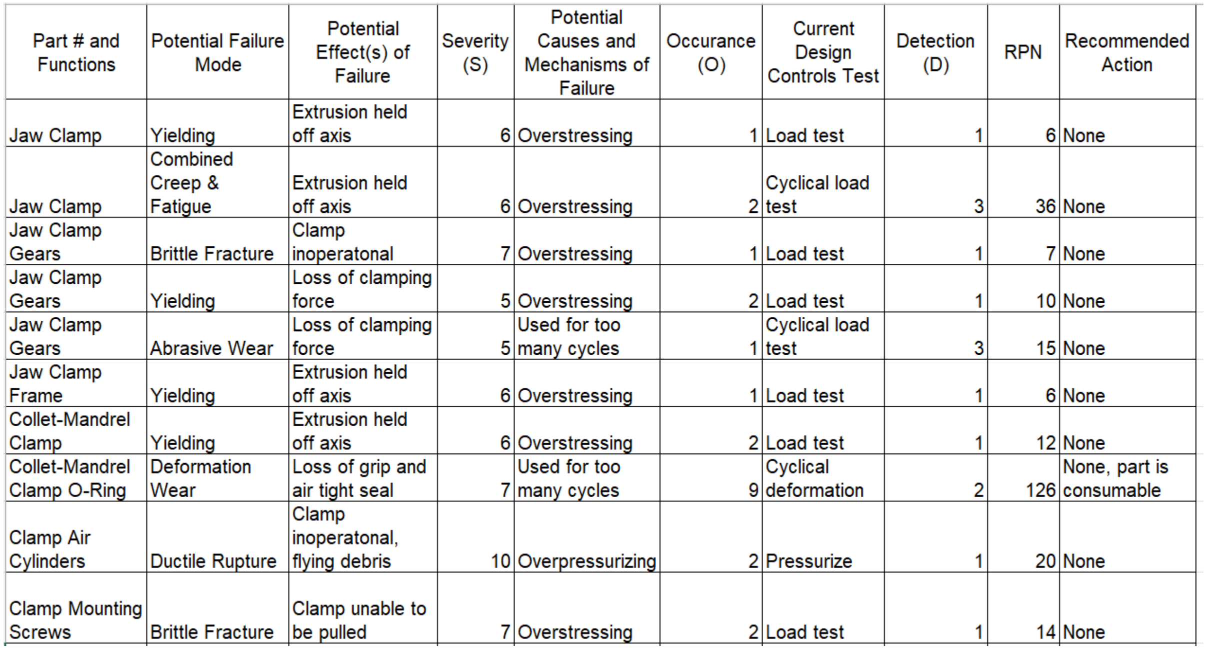
| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action |
|---|---|---|---|---|---|---|---|---|---|
| Heating Controller | Runaway heating of heating elements | Overheating of system | 9 | Error in code, incorrect sensor data | 4 | Test for all ranges of temperature, external validation | 2 | 72 | Test system with redundant sensors |
| Heating Elements | Incorrect heat applied | Extrusion not heated to desired temp | 5 | Temp sensor failure, excessive air speed | 7 | External validation with separate temp measurement | 3 | 105 | Buy quality temp sensors, limit air flowrate |
| Heating Nozzle | Non-uniform heat applied | Extrusion does not expand uniformly | 3 | Sub-optimal nozzle geometry | 3 | Close examination of expanded extrusion | 3 | 27 | Perform CFD on flow characteristics of nozzle |
| Heating Nozzle | Thermal fatigue | Extrusion not heated to desired temp | 5 | Incorrect material selection, sub-optimal heating arrangement | 3 | Close examination of system | 5 | 75 | Perform cyclical tests and check for degradation |
| Heating Air Lines | Insufficient air supplied to system | Insufficient air supplied to system | 4 | Overheating of associated components | 3 | Close examination of system | 1 | 12 | None |
| Heating Nozzle | Thermal deformation | Extrusion not heated to desired temp | 5 | Overheating | 1 | Run hot air through nozzle | 1 | 5 | None |
| Heating Nozzle | Thermal shock | Extrusion not heated to desired temp | 5 | Overheating | 2 | Run hot air through nozzle | 1 | 10 | None |
| Heating Nozzle | Thermal relaxation | Extrusion not heated to desired temp | 5 | Overheating | 2 | Run hot air through nozzle | 1 | 10 | None |
| Heating Air Lines | Ductile rupture | Air not supplied to system | 5 | Overpressurization | 1 | Pressurize lines | 1 | 5 | None |
| Heating Air Lines | Thermal deformation | Insufficient air supplied to system | 4 | Overheating | 2 | Run hot air through lines | 1 | 8 | None |

Figure 27: Full FMEA for the heating subsystem.



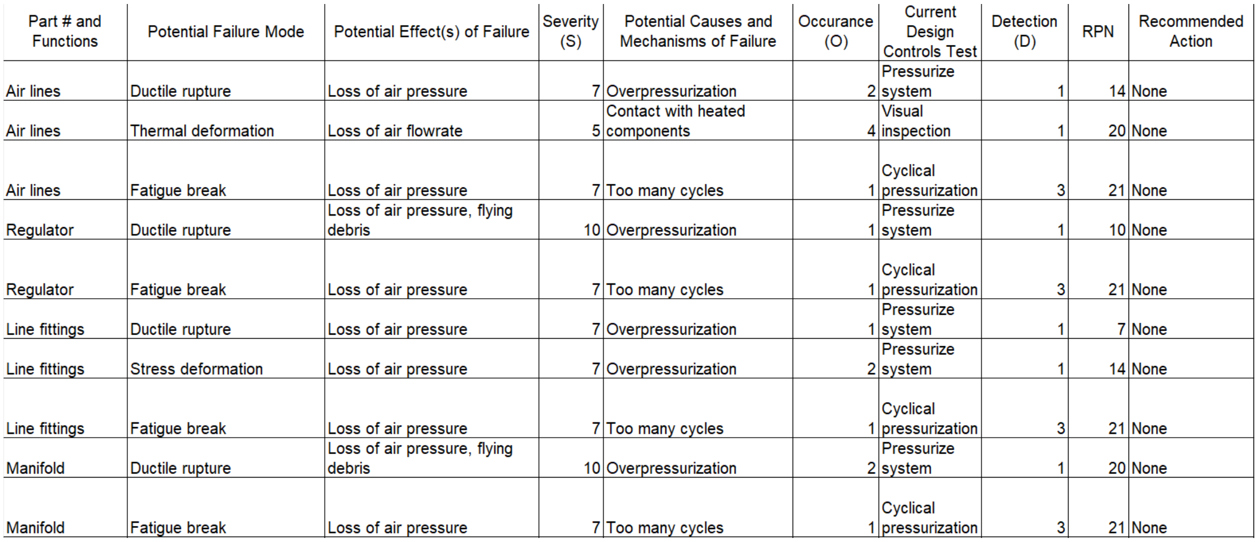
| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action |
|---|---|---|---|---|---|---|---|---|---|
| Motor | Burnout | Linear actuator no longer moves | 7 | Too much load on motor | 2 | Run motor with load | 2 | 28 | None |
| Ball Screw | Fatigue Break | Linear actuator no longer moves | 7 | Too much load/too many cycles on screw | 1 | Run machine for long time | 3 | 21 | None |
| Ball Screw | Strip | Linear actuator no longer moves | 7 | Too much load on screw | 1 | Load the screw | 2 | 14 | None |
| Holding Rod | Fatigue Break | Linear actuator is off center | 6 | Too much load/too many cycles on rod | 1 | Run machine for long time | 3 | 18 | None |
| Button | Unplug | Circuit no longer functions | 7 | Connection not strong enough | 8 | Visual inspection | 1 | 56 | Solder wires to button |
| Power Source | Burnout | Circuit no longer functions | 8 | Circuit shorts | 8 | Power the circuit | 1 | 64 | Replace breadboard with solder |
| Power Source | Runs out | Circuit no longer functions | 7 | Batteries die | 9 | Power the circuit | 1 | 63 | Change power source |
| Bread Board | Unplug | Circuit no longer functions | 7 | Connection not strong enough | 9 | Visual inspection | 1 | 63 | Replace breadboard with solder |
| Ball Screw | Buckling | Linear actuator no longer moves | 7 | Too much load on screw | 1 | Load the screw | 1 | 7 | None |
| Bearings | Abrasive wear | Linear actuator is off center | 6 | Too many cycles on bearings | 1 | Run machine for long time | 3 | 18 | None |

Figure 28: Full FMEA for the axial loading subsystem.



| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action |
|---|---|---|---|---|---|---|---|---|---|
| Jaw Clamp | Yielding | Extrusion held off axis | 6 | Overstressing | 1 | Load test | 1 | 6 | None |
| Jaw Clamp | Combined Creep & Fatigue | Extrusion held off axis | 6 | Overstressing | 2 | Cyclical load test | 3 | 36 | None |
| Jaw Clamp Gears | Brittle Fracture | Clamp inoperatonal | 7 | Overstressing | 1 | Load test | 1 | 7 | None |
| Jaw Clamp Gears | Yielding | Loss of clamping force | 5 | Overstressing | 2 | Load test | 1 | 10 | None |
| Jaw Clamp Gears | Abrasive Wear | Loss of clamping force | 5 | Used for too many cycles | 1 | Cyclical load test | 3 | 15 | None |
| Jaw Clamp Frame | Yielding | Extrusion held off axis | 6 | Overstressing | 1 | Load test | 1 | 6 | None |
| Collet-Mandrel Clamp | Yielding | Extrusion held off axis | 6 | Overstressing | 2 | Load test | 1 | 12 | None |
| Collet-Mandrel Clamp O-Ring | Deformation Wear | Loss of grip and air tight seal | 7 | Used for too many cycles | 9 | Cyclical deformation | 2 | 126 | None, part is consumable |
| Clamp Air Cylinders | Ductile Rupture | Clamp inoperatonal, flying debris | 10 | Overpressurizing | 2 | Pressurize | 1 | 20 | None |
| Clamp Mounting Screws | Brittle Fracture | Clamp unable to be pulled | 7 | Overstressing | 2 | Load test | 1 | 14 | None |

Figure 29: Full FMEA for the clamping subsystem.



| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action |
|---|---|---|---|---|---|---|---|---|---|
| Air lines | Ductile rupture | Loss of air pressure | 7 | Overpressurization | 2 | Pressurize system | 1 | 14 | None |
| Air lines | Thermal deformation | Loss of air flowrate | 5 | Contact with heated components | 4 | Visual inspection | 1 | 20 | None |
| Air lines | Fatigue break | Loss of air pressure | 7 | Too many cycles | 1 | Cyclical pressurization | 3 | 21 | None |
| Regulator | Ductile rupture | Loss of air pressure, flying debris | 10 | Overpressurization | 1 | Pressurize system | 1 | 10 | None |
| Regulator | Fatigue break | Loss of air pressure | 7 | Too many cycles | 1 | Cyclical pressurization | 3 | 21 | None |
| Line fittings | Ductile rupture | Loss of air pressure | 7 | Overpressurization | 1 | Pressurize system | 1 | 7 | None |
| Line fittings | Stress deformation | Loss of air pressure | 7 | Overpressurization | 2 | Pressurize system | 1 | 14 | None |
| Line fittings | Fatigue break | Loss of air pressure | 7 | Too many cycles | 1 | Cyclical pressurization | 3 | 21 | None |
| Manifold | Ductile rupture | Loss of air pressure, flying debris | 10 | Overpressurization | 2 | Pressurize system | 1 | 20 | None |
| Manifold | Fatigue break | Loss of air pressure | 7 | Too many cycles | 1 | Cyclical pressurization | 3 | 21 | None |

Figure 30: Full FMEA for the pressurizing subsystem.