# Sprue Bar Casting Process Improvement

Final Design Report

ENG 4860: Engineering Design

| | |
|---|---|
| Sponsor Company: | Matrix Industries Inc. |
| Team Name: | Red and Blue |
| Team Number: | 20 |

**Group Members**


Muhammed Anwar ______________________

Charles Buenafe ______________________

Yan Pan Chung ______________________

Justin Paulic ______________________


**Date Submitted:**

December 4th, 2019

**Submitted to:**

Dr. Paul E. Labossiere, P. Eng.

Dr. Qingjin Peng, P. Eng

Peter Hnatishin, General Manager – Matrix Industries Inc, Project Champion

# Executive Summary

The objective of this project is to improve the current wax sprue bar production rate at Matrix Industries from five sprue bars per hour to a minimum of 50 sprue bars per hour. The project team has designed a robot system that has the capacity to produce 146 sprue bars per hour. This system consists of a FANUC R-2000iC/125L robot, a SCHUNK PZN-plus 160-2-AS-SD gripper, and a sprue bar rack designed by the team to allow the robot to produce seven sprue bars of any type simultaneously. The deliverables of the project include a Bill of Materials and a Computer-Aided Design model of the robot system.

The cost of the robot, operator training for the robot, and the gripper is [redacted], resulting in a payback period of approximately [redacted]. Although this is outside of the initial project cost constraint, the system may also be implemented into Matrix Industries' ceramic coating process, decreasing the payback period dramatically.

Apart from the initial cost constraint, the robot system meets or exceeds all other project constraints. At 9 ft x 5 ft, the workplace area of this wax sprue bar process is within the 9 ft x 7 ft constraint. The sprue hardening time of the robot system is two minutes, which is less than the constraint of 15 minutes. Finally, the robot system is capable of producing wax sprues that meet the quality standards of Matrix Industries.

Although the FANUC robot and the SCHUNK gripper were selected by the team, the overall system is compatible with any robot or gripper that meet the client's requirements. However, if Matrix Industries decides to implement a robot system, it is recommended that the proper cost analysis, safeguarding techniques, infrastructure capabilities, and commissioning methods are researched before implementation.

# Table of Contents

# List of Figures

# List of Tables

# 1 Introduction

Matrix Industries is a manufacturing company that specializes in producing metal castings, which includes sand casting, investment casting and heat treating for equipment manufacturers. Matrix Industries focuses on low volume production runs, minimal tooling investment, and short lead-time. The company website [1] also states that they offer production castings and prototype castings as well as repair, replacement, and service part castings in a wide variety of metals. Products range from 28 grams to 454 kilograms in orders ranging from one to 50,000 parts.

Currently, Matrix Industries produces approximately five sprue bars per hour, and has one operator assigned for making sprue bars as well as attaching wax patterns onto the sprue bar. The productivity of the operator decreases due to working on two different jobs and having to leave their work center to perform a job in the next work centre. Given this, the team has been tasked to generate a design concept to increase the wax sprue bar production from five to 50 pieces per hour by 4$^{th}$ December 2019.

This document communicates the process that was followed to investigate the problem, analyze the problem, generate possible solutions, and develop a solution that the client and the project team deemed to be most suitable for Matrix Industries' process.

## 1.1 Focused Process Flowchart

Matrix industries currently uses a simplistic and linear approach to sprue bar production. The entire process of producing a wax sprue bar and forming a wax tree is presented in Figure 1.

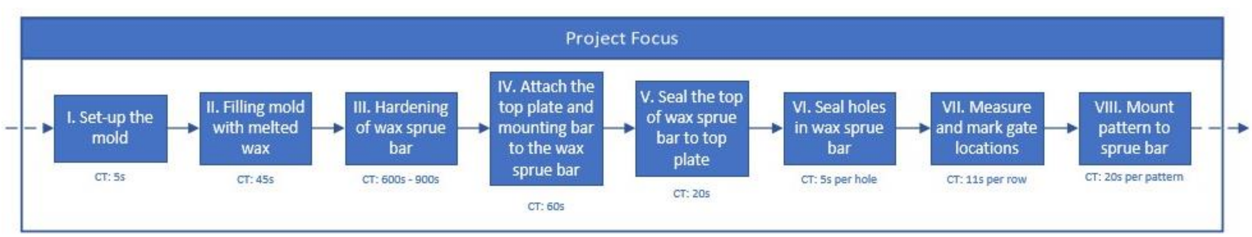



Figure 1: Flowchart of the wax sprue bar production process with cycle times (CT).

Operators at Matrix Industries follow these steps to form a wax tree:

I. Setting up the mold: The mold of the sprue bar is set up under a tank of melted wax. A metal bar is placed inside the mold. This metal bar serves multiple purposes; it reduces the amount of wax used per sprue bar and the hardening time of the sprue bar. The metal bar placed inside the mold also serves as an attachment point for the top plate and mounting bar.

II. The mold is then filled with melted wax.

III. The mold is put aside to allow the wax to harden. This part of the process is not water cooled.

IV. The sprue bar is removed from the mold. A top plate and a mounting bar are attached to the sprue bar. The top plate forms the opening of the ceramic mold later in the process. The mounting bar is used to easily handle the sprue bar and the wax patterns mounted on the sprue bar. Figure 2 shows the sprue bar connected to a top plate and a mounting bar.

Figure 2: A wax sprue bar with the top plate and mounting bar attached.

V. Using a soldering iron, the wax at the top of the sprue bar is partially melted. This procedure seals the top of the sprue bar to the top plate, ensuring that the opening of the ceramic mold is adequate for pouring molten metal into the ceramic mold, which will be done later in the process.

VI. Using the soldering iron, pieces of wax are melted to fill up any holes and defects present on the sprue bar.

VII. Operators then measure and mark the location of each pattern to be placed onto the sprue bar.

VIII. The patterns are placed onto the sprue bar by partially melting the gates and placing them onto the marked locations. Figure 3 shows a wax tree that is formed when the patterns are placed onto the sprue bar.

Figure 3: A wax tree formed out of a sprue bar, several wax patterns, a top plate, and a mounting bar.

The goal of this project is to reduce this process cycle time, ultimately increasing the volume of sprue bars produced.

## 1.2 Client's Needs

The client's needs were determined through multiple methods. First, the team viewed the investment casting process at Matrix Industries and documented the wax sprue bar forming process. Then, the client discussed their thoughts and expectations for this project with the team. Lastly, the team constructed the need statements and prioritized each need with approval from the client. Table I shows a categorized and prioritized list of the client's needs.

TABLE I
LIST OF CLIENT'S NEEDS

| No. | Category | Need | Priority |
|---|---|---|---|
| 1 | Quality | Increase output of sprue bar production | 5 |
| 2 | Process | Sprue is easily removable from product | 5 |
| 3 | Safety | Process is safe for operators | 5 |
| 4 | Safety | Process is ergonomic | 4 |
| 5 | Quality | Minimize ceramic debris entry into mold | 4 |
| 6 | Quality | Minimize gap between sprue bar and top plate | 4 |
| 7 | Quality | Process produces minimal defects | 4 |
| 8 | Process | Process is cost efficient | 4 |
| 9 | Process | Easy to install/integrate into current overall process | 4 |
| 10 | Process | Process is intuitive | 4 |
| 11 | Process | Operator can easily identify product mounting locations | 3 |
| 12 | Process | Process is easily accessible | 3 |

## 1.3 Engineering Metrics

Based on the client's needs, engineering metrics were created. These metrics were used to quantify the performance of the current process and are ranked on their importance according to the client. Additionally, these metrics aid in the creation of a new design and will help compare any new design concepts against the current process and against each other. The metrics are listed in Table II.

TABLE II
ENGINEERING METRICS

| Metrics # | Need # | Metric | Imp | Current Value | Target Value | Acceptable Range | Units |
|---|---|---|---|---|---|---|---|
| 1 | 1 | Sprue bars produced per hour | 5 | 5 | 50 | 40+ | bars/h |
| 2 | 2,7 | Number of cuts from chop saw required to remove product | 5 | 1 | 1 | 1-2 | cuts/bar |
| 3 | 2,7 | Average time per cut from chop saw | 5 | 40 | 40 | 40-45 | s/cut |
| 4 | 3,4 | Frequency of injuries sustained due to process | 5 | 0 | 0 | 0 | injuries/yr |
| 5 | 3,4 | Severity of injuries sustained due to process | 5 | 0 | 0 | 0 | time off |
| 6 | 4 | Operators' comfort levels during process | 4 | 4 | 4 | 3-4 | [1-5] Scale |
| 7 | 5 | Volume of ceramic contaminants | 4 | 5 | 0 | 0-2.5 | $mm^3$ |
| 8 | 5,7 | Number of ceramic contaminants in mold | 4 | 2 | 0 | 0-1 | # |
| 9 | 6 | Distance between top plate a sprue bar | 4 | 2-5 | 0 | 0-2.5 | mm |
| 10 | 8 | Cost of sprue bar production | 4 | 4 | 4 | 4-5 | $/sprue |
| 11 | 9 | Shut down time during implementation | 4 | N/A | 8 | 6-10 | h |
| 12 | 9 | Cost of implementation | 4 | 5,000 | 20,000 | <20,000 | $ |
| 13 | 9,10 | Time to train operators to use process | 4 | 5 | 5 | 5-6 | h |
| 14 | 9,10 | Time for operators to develop skills using process | 4 | 1 | 1 | 1-1.2 | week |
| 15 | 10 | Operators' initial ease of use | 4 | 4 | 4 | 3-4 | [1-5] Scale |
| 16 | 11 | Time to mark gate locations | 3 | 11 | 0 | 0-5.5 | s/row |
| 17 | 11 | Time to mount product on sprue bar | 3 | 20 | 20 | 20-25 | s/product |
| 18 | 12 | Time to repair | 3 | N/A | 0 | 0-0.5 | h |
| 19 | 12 | Time taken for regular maintenance | 3 | N/A | 0 | 0-0.5 | h |
| 20 | 12 | Set up/take down time | 3 | 20 | 20 | 20-25 | min/day |

## 1.4 Constraints and Limitations

The time, cost, scope, and final product form the basis of the project constraints and limitations. The following constraints and limitations were established by Matrix Industries.

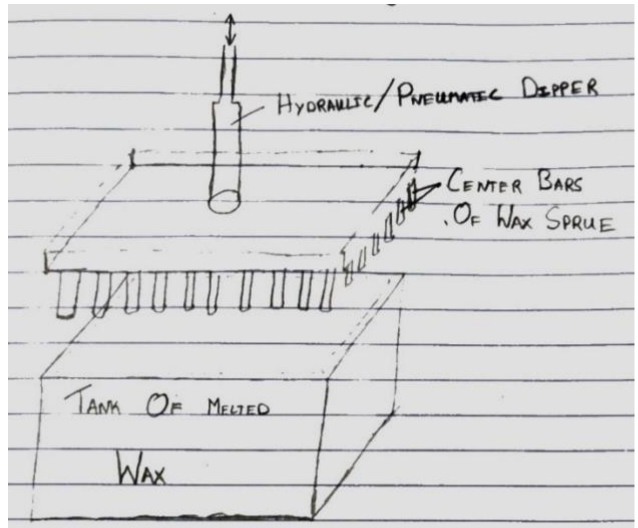
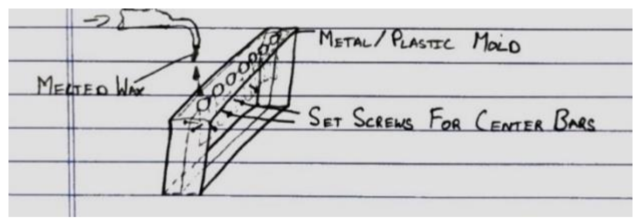
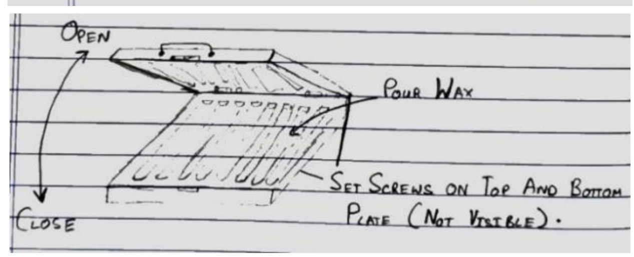
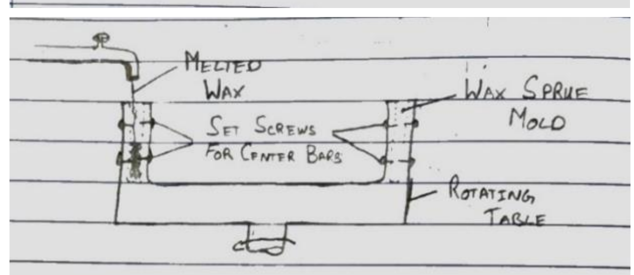
- The footprint of the wax sprue bar workplace area is limited to 2.75 m x 2.13 m (9 ft x 7 ft).
- The project must be finished by 4$^{th}$ December 2019.
- The time for sprue hardening must be no longer than 15 minutes.
- Before assembling, the final product must be capable of getting through the back door which is 3.66 m x 3.66 m (12 ft x 12 ft).
- The final design must require no more than one operator to make the wax sprue bar and mount the patterns onto the sprue bar.
- The final design must be able to produce the seven highest volume sprue bar types. CAD models and volumes of these sprue bar types are in Appendix A.
- The drawings of the final design must be convertible into STEP file format.
- The tent for mounting and sealing the sprue bar must remain in place.

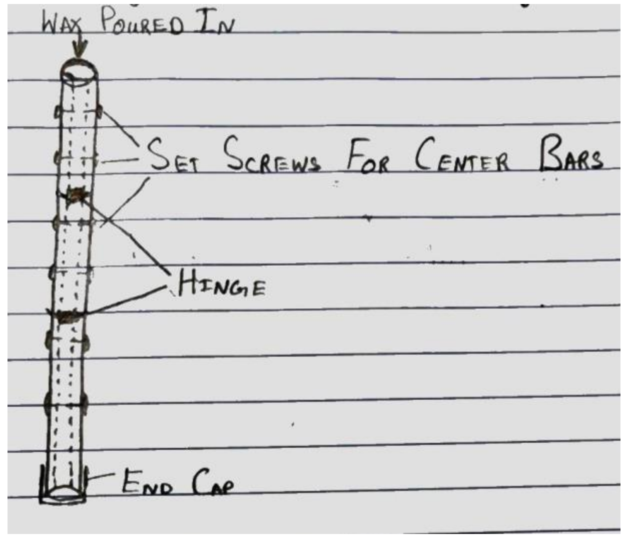
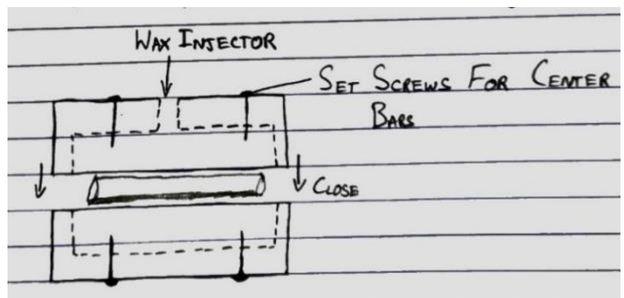
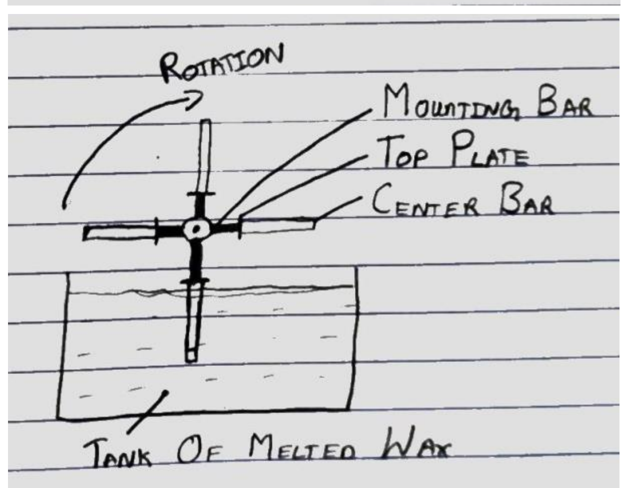
# 2 Methodology

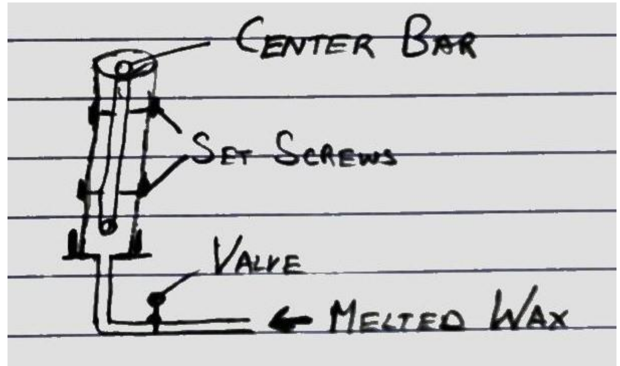
The team utilized several techniques to generate and conceptualize ideas. An individual brainstorming session preceded a brainstorming session with the client. During this client meeting, all ideas were exchanged between the team members and the clients. These ideas were then discussed to ensure the function of each concept was understood. Initially, 18 concepts were generated.

A preliminary screening procedure followed this session where 12 of the 18 initial concepts were immediately removed or combined based on similarity to other concepts, non-feasibility, and infrastructure limitations. Table III shows a sketch of the eight remaining concepts and a brief description of the underlying idea.

TABLE III
IDEAS GENERATED

| # | Name and Underlying Idea | Sketch |
|---|---|---|
| 1 | **Robotic Arm**<br>Tank of melted wax with a robotic system to repeatedly dip center bars into wax until sprue forms. |  |
| 2 | **MultiMold**<br>A single large mold consisting of multiple mold cavities. |  |
| 3 | **Waffles**<br>Wax is poured into the mold cavity. The top of the mold is closed to form the sprue bar, similar to a waffle maker. |  |
| 4 | **Rotary Table**<br>A rotating table with several molds on the outer edge. |  |

| # | Name and Underlying Idea | Sketch |
|---|---|---|
| 5 | **Large Sprue Bar**<br>One long sprue bar, which is cut into multiple sprue bars once cooled. |  |
| 6 | **Injection Molding**<br>Injection mold the sprue bars, along with the patterns. Then attach the patterns onto the sprue bar. |  |
| 7 | **Ferris Wheel**<br>A tank of melted wax, with a Ferris wheel or railing system, which repeatedly dips the center bar into the tank to form sprue bars. |  |

| # | Name and Underlying Idea | Sketch |
|---|---|---|
| 8 | **Beer Mold**<br>The mold is automatically filled from the bottom once a metal bar is detected inside the mold. Similar to the way stadiums fill up beer glasses. |  |

## 2.1 Concept Selection

Once the top eight concepts were generated, the team began a screening process to reduce the number of overall concepts and identify the top concepts to be analyzed using a screening matrix. The selection criteria used to score the concepts were derived from the client's needs and engineering metrics developed earlier in the project. The relationship between each criterion and the applicable client needs and engineering metrics is detailed in Table IV.

TABLE IV
SELECTION CRITERIA RELATIONSHIPS

| Selection Criteria | Client Need | Engineering Metric |
|---|---|---|
| Productivity | 1. Increase output of sprue bar production | 1. Sprue bars produced per hour |
| | 8. Process is cost efficient | 10. Cost of sprue bar production |
| Intuitiveness | 10. Process is intuitive | 13. Time to train operators to use process |
| | | 14. Time for operators to develop skills using process |
| | | 15. Operator's initial ease of use |
| Cost of Integration | 8. Process is cost efficient | 10. Cost of sprue bar production |
| | | 12. Cost of implementation |
| | 9. Easy to install/integrate into current overall process | 11. Shut down time during implementation |
| | | 13. Time to train operators to use process |
| | | 14. Time for operators to develop skills using process |
| | | 15. Operator's initial ease of use |

| Selection Criteria | Client Need | Engineering Metric |
|---|---|---|
| Ease of Handling | 12. Process is easily accessible | 4. Frequency of injuries sustained due to process |
| | | 20. Set up/take down time |
| Locator Metering | 11. Operator can easily identify product mounting locations | 16. Time to mark gate locations |
| | | 17. Time to mount product on sprue bar |
| Safety | 3. Process is safe for operators | 4. Frequency of injuries sustained due to process |
| | | 5. Severity of injuries sustained due to process |
| Ergonomics | 4. Process is ergonomic | 4. Frequency of injuries sustained due to process |
| | | 5. Severity of injuries sustained due to process |
| | | 6. Operators comfort level during process |
| Reliability | 12. Process is easily accessible | 18. Time to repair |
| | | 19. Time taken for regular maintenance |
| | | 20. Set up/take down time |
| Quality | 2. Sprue is easily removable from product | 2. Number of cuts from chop saw to remove product |
| | | 3. Average time per cut from chop saw |
| | 5. Minimize ceramic debris entry into mold | 7. Volume of ceramic contaminants |
| | | 8. Number of ceramic contaminants in mold |
| | 6. Minimize gap between sprue bar and top plate | 9. Distance between top plate and sprue bar |
| | 7. Process produces minimal defects | 2. Number of cuts from chop saw to remove product |
| | | 3. Average time per cut from chop saw |
| | | 8. Number of ceramic contaminants in mold |

Each criterion has corresponding client needs that it relates to and each client need has engineering metrics in place to measure its performance. Some client needs apply to multiple selection criteria and therefore some engineering metrics also apply to multiple selection criteria. The use of the selection criteria allows for a general comparison between concepts while still considering the client's needs in the process.

After the selection criteria were determined, each of the top eight concepts were compared to the current process in a screening matrix shown in Table V. The screening matrix scores each concept based on the number of criteria that are predicted to be better or worse than the current process. The highest ranked concepts in the screening matrix will be further analyzed.

TABLE V
CONCEPT SCREENING MATRIX

| | A | B | C | D | E | F | G | H | REF. |
|---|---|---|---|---|---|---|---|---|---|
| Selection Criteria | Robotic Arm | MultiMold | Waffles | Rotary Table | Large Sprue Bar | Injection Molding | Ferris Wheel | Beer Molding | Current Process |
| Productivity | + | + | + | + | + | + | + | + | 0 |
| Intuitiveness | + | 0 | - | - | - | 0 | 0 | - | 0 |
| Cost of Integration | - | 0 | - | - | - | 0 | - | - | 0 |
| Ease of Handling | + | - | 0 | - | - | + | + | 0 | 0 |
| Locator Marking | 0 | + | + | + | + | + | 0 | + | 0 |
| Safety | + | 0 | 0 | 0 | - | + | + | + | 0 |
| Ergonomics | + | 0 | 0 | + | 0 | + | + | 0 | 0 |
| Reliability | - | 0 | 0 | 0 | - | + | - | - | 0 |
| Quality | 0 | + | + | 0 | - | + | 0 | 0 | 0 |
| PLUSES | 5 | 3 | 3 | 3 | 2 | 7 | 4 | 3 | |
| SAMES | 2 | 5 | 4 | 3 | 1 | 2 | 3 | 3 | |
| MINUSES | 2 | 1 | 2 | 3 | 6 | 0 | 2 | 3 | |
| NET | 3 | 2 | 1 | 0 | -4 | 7 | 2 | 0 | |
| RANK | 2 | 3 | 5 | 6 | 8 | 1 | 3 | 6 | |
| CONTINUE? | YES | YES | NO | NO | NO | YES | YES | NO | |

The Injection Molding, Robotic Arm, MultiMold, and Ferris Wheel concepts scored the highest when compared to the current process and were chosen for further analysis. These top four concepts were then further developed and analyzed to determine the overall best design.

- **Robotic Arm** - This design involves using a robotic arm to dip multiple sprues in a tank of wax. The arm then lifts and rotates the sprues to allow for even curing of the wax on each sprue. Different types of sprues may be mounted at once. This concept fully automates the wax dipping process, while the operator will need to load and unload the sprues on to the mounting rack. This eliminates further operator engagement, which will allow the operator to assist in other steps of the casting process, further increasing process production. An Early Visual Representation (EVR) of the Robotic Arm concept is illustrated in Figure 4.

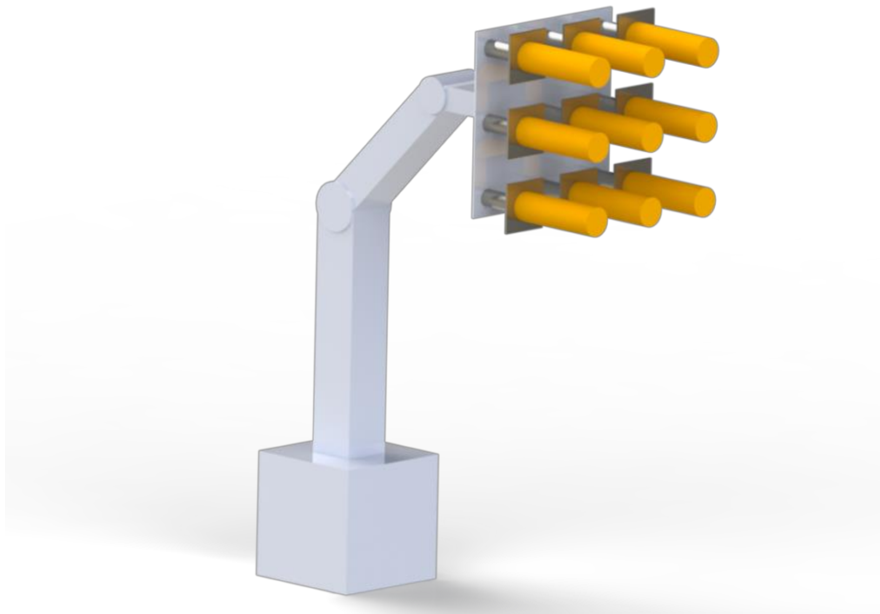


Figure 4: EVR of the Robotic Arm concept.

- **MultiMold** – This design involves using a single mold to form multiple sprues at one time. Wax is poured into each cavity of the mold, allowed to cure, and then the mold is taken apart to retrieve the sprues. Each mold contains the same type of sprue, therefore numerous molds would be necessary for this concept. However, the MultiMold takes advantage of the operator's familiarity of wax pouring, which is used in the current process. In addition, since the mold can dictate the outer shape of the wax sprue, this concept allows for the integration of locator markings on the wax sprue to aid in the mounting of the wax patterns. An EVR of the MultiMold concept is illustrated in Figure 5.

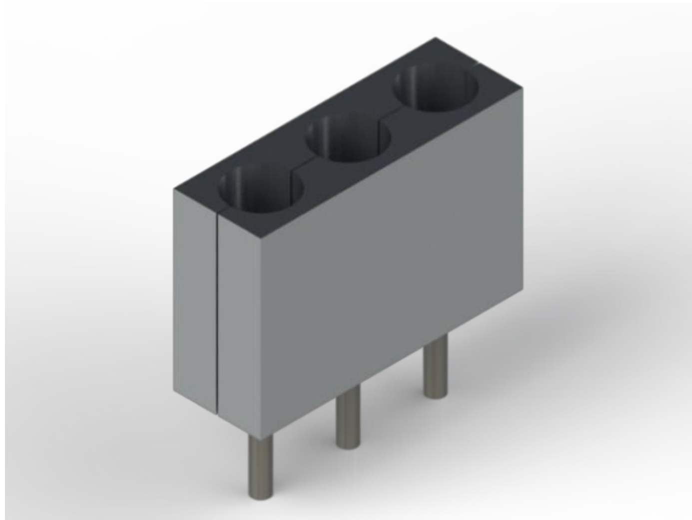


Figure 5: EVR of the MultiMold concept.

- **Injection Molding** – This design injects wax into an aluminum mold, which is allowed to cure and form the sprue bars in the process. The molds are then taken apart to retrieve the sprue. This concept takes advantage of Matrix Industries' injection molding process that is currently being used to form the wax patterns. Similar to the MultiMold concept, the Injection Molding process also allows for the integration of locator markings to aid with the mounting of the wax patterns. An EVR of the Injection Molding concept is illustrated in Figure 6.

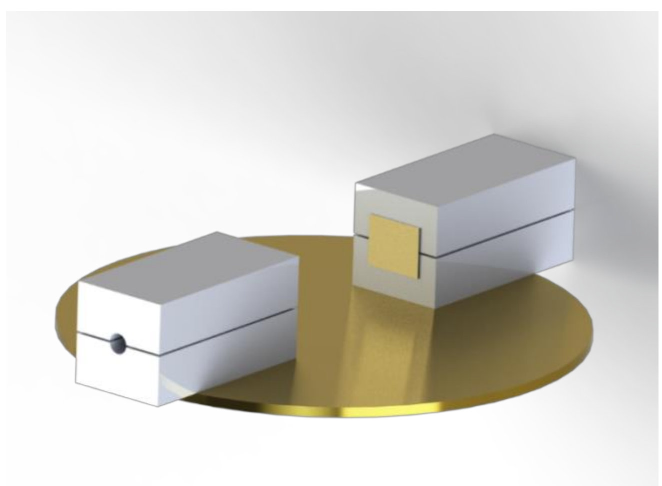


Figure 6: EVR of the Injection Molding concept.

- **Ferris Wheel** – This design is a combination of two similar design concepts, involving the use of a wax tank and a rotating mechanism. The sprues are mounted to the outside of the mechanism, which rotates and dips the sprues into the wax to form the wax sprue bars. Additionally, the wax sprue bars rotate individually to allow for even curing of the wax. An EVR of the Ferris Wheel concept is illustrated in Figure 7.

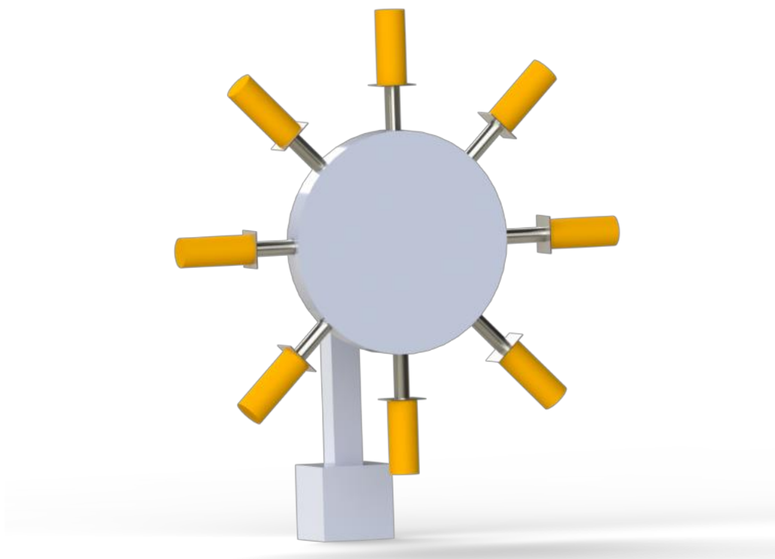


Figure 7: EVR of the Ferris Wheel concept.

After further development of each concept, a weighted decision matrix (WDM) was used to determine the most desirable concept to design. Before proceeding with the WDM, the importance of each selection criteria was assigned using the criteria weighting matrix (CWM) shown in Table VI. The CWM compares selection criteria to one another based on the priority of the client's needs related to the selection criteria.

TABLE VI
CONCEPT CRITERIA WEIGHTING MATRIX

| | Selection Criteria | A Productivity | B Intuitiveness | C Cost of Integration | D Ease of Handling | E Locator Marking | F Safety | G Ergonomics | H Reliability | I Quality |
|---|---|---|---|---|---|---|---|---|---|---|
| A | Productivity | A | A | A | A | A | F | A | A | A |
| B | Intuitiveness | | B | C | B | E | F | B | B | I |
| C | Cost of Integration | | | C | D | C | F | G | C | I |
| D | Ease of Handling | | | | D | D | F | D | H | D |
| E | Locator Marking | | | | | E | F | G | H | I |
| F | Safety | | | | | | F | F | F | F |
| G | Ergonomics | | | | | | | G | G | I |
| H | Reliability | | | | | | | | H | I |
| I | Quality | | | | | | | | | I |
| | Total Hits | 8 | 4 | 4 | 5 | 2 | 9 | 4 | 3 | 6 |
| | Weighting | 0.18 | 0.09 | 0.09 | 0.11 | 0.04 | 0.20 | 0.09 | 0.07 | 0.13 |

The most important selection criteria as determined by the CWM were safety and productivity; however, each criterion was considered during concept selection based on their weighting. Since the biggest concern in any operation is worker safety, it follows that safety was the highest weighted criteria in the CWM. Productivity was the second highest weighted criteria due to the client's main need for increasing the number of sprue bars per hour.

Before a WDM could be used to determine the most desirable concept, each concept had to be rated based on each of the selection criteria. This was done using a concept rating matrix (CRM). The CRM uses a pairwise comparison of each of the four concepts regarding each of the selection criteria. A concept's rating for a given criterion is calculated by summing the number of wins it has against the other concepts. The CRM is shown in Table VII.

TABLE VII
CONCEPT RATING MATRIX

| Selection Criteria | A vs B | A vs C | A vs D | B vs C | B vs D | C vs D | Robotic Arm A | MultiMold B | Injection Molding C | Ferris Wheel D |
|---|---|---|---|---|---|---|---|---|---|---|
| Productivity | A | A | A | C | D | D | 3 | 0 | 1 | 2 |
| Intuitiveness | B | C | A | B | B | C | 1 | 3 | 2 | 0 |
| Cost of Integration | B | C | D | B | B | C | 0 | 3 | 2 | 1 |
| Ease of Handling | A | A | A | C | D | D | 3 | 0 | 1 | 2 |
| Locator Marking | B | C | A | C | B | C | 1 | 2 | 3 | 0 |
| Safety | A | A | A | C | B | D | 3 | 1 | 1 | 1 |
| Ergonomics | A | A | A | C | D | D | 3 | 0 | 1 | 2 |
| Quality | B | C | A | C | B | C | 1 | 2 | 3 | 0 |
| Reliability | B | C | A | B | B | C | 1 | 3 | 2 | 0 |

Each concept's rating for each criterion is shown in grey in Table VII. These ratings and the weights of each selection criteria were then used in the WDM to rank the remaining four concepts based on their adherence to the criteria. The WDM in Table VIII shows the correlation between ratings and weights that was used to select the most desirable concept.

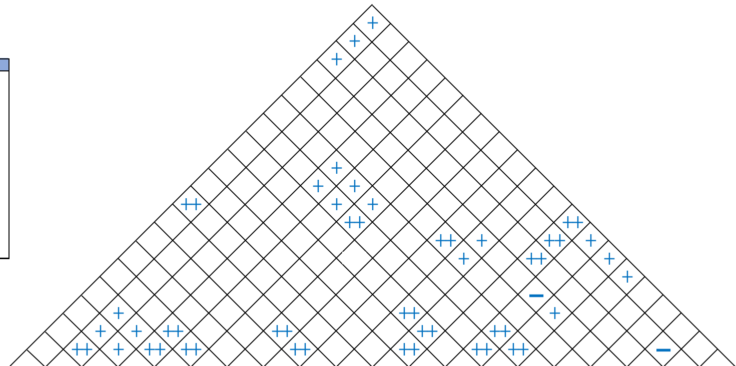
TABLE VIII
CONCEPT WEIGHTED DECISION MATRIX

| **Selection Criteria** | **Weight %** | **Robotic Arm** | | **MultiMold** | | **Injection Molding** | | **Ferris Wheel** | |
|---|---|---|---|---|---|---|---|---|---|
| | | Rating | Weight Score | Rating | Weight Score | Rating | Weight Score | Rating | Weight Score |
| Productivity | 0.18 | 3 | 0.53 | 0 | 0.00 | 1 | 0.18 | 2 | 0.36 |
| Intuitiveness | 0.09 | 1 | 0.09 | 3 | 0.27 | 2 | 0.18 | 0 | 0.00 |
| Cost of Integration | 0.09 | 0 | 0.00 | 3 | 0.27 | 2 | 0.18 | 1 | 0.09 |
| Ease of Handling | 0.11 | 3 | 0.33 | 0 | 0.00 | 1 | 0.11 | 2 | 0.22 |
| Locator Marking | 0.04 | 1 | 0.04 | 2 | 0.09 | 3 | 0.13 | 0 | 0.00 |
| Safety | 0.20 | 3 | 0.60 | 1 | 0.20 | 1 | 0.20 | 1 | 0.20 |
| Ergonomics | 0.09 | 3 | 0.27 | 0 | 0.00 | 1 | 0.09 | 2 | 0.18 |
| Reliability | 0.07 | 1 | 0.07 | 3 | 0.20 | 2 | 0.13 | 0 | 0.00 |
| Quality | 0.13 | 1 | 0.13 | 2 | 0.27 | 3 | 0.40 | 0 | 0.00 |
| Total Score | | 2.07 | | 1.29 | | 1.60 | | 1.04 | |
| Rank | | 1 | | 3 | | 2 | | 4 | |
| Continue? | | YES | | NO | | NO | | NO | |

The WDM determined the Robotic Arm concept is the most favorable concept to continue into detailed design. In the Productivity and Safety criteria, the Robotic Arm was rated better than any other concept, which was a critical contributor to the Robotic Arm achieving the highest total score. Due to the Robotic Arm's automation features that would eliminate employees from having to manually transport material, it also scored high in the Ease of Handling and Ergonomics criteria.

Although the WDM provides a strong analysis for concept selection, a Quality Function Deployment was used to ensure the concept meets client specifications. This was done by performing a competitive analysis between the four remaining concepts as well as the current process within a House of Quality. Figure 8 displays the House of Quality and the competitive analysis.

| Legend | | |
|---|---|---|
| Θ | Strong Relationship | 9 |
| O | Moderate Relationship | 3 |
| ▲ | Weak Relationship | 1 |
| ++ | Strong Positive Correlation | |
| + | Positive Correlation | |
| — | Negative Correlation | |
| ▼ | Strong Negative Correlation | |
| ▼ | Objective Is To Minimize | |
| ▲ | Objective Is To Maximize | |
| x | Objective Is To Hit Target | |



| Row # | Max Relationship Value in Row | Relative Weight [%] | Weight / Importance [1-5] | Column # / Demanded Quality ("Customer Requirements/Need Statements" or "Whats") \ Quality Characteristics (a.k.a. "Functional Requirements/Engineering Metrics" or "Hows") | 1 Sprue bars produced per hour | 2 Number of cuts from the chop saw required to remove product | 3 Average time per cut from chop shaw | 4 Frequency of injuries sustained due to process | 5 Severity of injuries sustained due to process | 6 Operators comfort levels during process | 7 Volume of ceramic contaminants | 8 Number of ceramic contaminants in mold | 9 Distance between top plate and sprue bar | 10 Cost of sprue bar production | 11 Shut down time during implementation | 12 Cost of implementation | 13 Time to train operators to use process | 14 Time for operators to develop skills using process | 15 Operators initial ease of use | 16 Time to mark gate locations | 17 Time to mount product on sprue bar | 18 Time to repair | 19 Time taken for regular maintenance | 20 Set up/take down time | Current Process | Robotic Arm | MultiMold | Injection Molding | Ferris Wheel |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Direction of Improvement: Minimize (□), Maximize (□), or Target (x) | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | | | | | |
| 1 | 9 | 10.2 | 5.0 | Increase output of sprue bar production | Θ | | | | | □ | | | | O | | | | □ | | O | | □ | □ | O | 0 | 5 | 2 | 2 | 4 |
| 2 | 9 | 10.2 | 5.0 | Sprue is easily removable from product | □ | Θ | Θ | | | | | | | | | | | | | | | | | | 4 | 3 | 4 | 5 | 3 |
| 3 | 9 | 10.2 | 5.0 | Process is safe for operators | | | | Θ | Θ | O | | | | | | | □ | | | | | | | | 4 | 5 | 4 | 4 | 4 |
| 4 | 9 | 8.2 | 4.0 | Process is ergonomic | | | | Θ | Θ | Θ | | | | | | | | | | | | | | | 3 | 5 | 1 | 3 | 4 |
| 5 | 9 | 8.2 | 4.0 | Minimize ceramic debris entry into mold | | | | | | | Θ | Θ | O | | | | | | | | | | | | 2 | 3 | 4 | 5 | 3 |
| 6 | 9 | 8.2 | 4.0 | Minimize gap between sprue bar and top plate | □ | | | | | | O | O | Θ | □ | | | | | | | O | | | | 2 | 1 | 4 | 5 | 0 |
| 7 | 9 | 8.2 | 4.0 | Process produces minimal defects | | Θ | Θ | | | | Θ | Θ | | □ | | | | | | □ | □ | | | | 2 | 4 | 3 | 5 | 3 |
| 8 | 9 | 8.2 | 4.0 | Process is cost efficient | O | | | | | | | | | Θ | □ | □ | | | | □ | □ | O | O | O | 3 | 4 | 3 | 0 | 3 |
| 9 | 9 | 8.2 | 4.0 | Easy to install/integrate into current overall process | | | | | | | | | | | Θ | Θ | O | O | O | | | | | | 5 | 1 | 3 | 4 | 2 |
| 10 | 9 | 8.2 | 4.0 | Process is intuitive | □ | | | | | | | | | | | | Θ | Θ | Θ | □ | | □ | □ | □ | 3 | 4 | 4 | 4 | 3 |
| 11 | 9 | 6.1 | 3.0 | Operator can easily identify product mounting locations | O | | | | | | | | | | | | O | O | O | Θ | Θ | | | | 0 | 0 | 4 | 5 | 0 |
| 12 | 9 | 6.1 | 3.0 | Process is easily accessible | | | | | | | | | | | | | | | | | | Θ | Θ | Θ | 5 | 3 | 3 | 3 | 3 |
| | | | | Target or Limit Value | 50 [bars/h] | 1 [cuts/column] | 40 [s/cut] | 0 [injuries/year] | 0 [time off] | 4 [1-5] | 0 [mm3] | 0 | 0 [mm] | 4 [$/sprue] | 8 [h] | 20,000 [$] | 5 [h] | 1 [week] | 4 [1-5] | 0 [s/row] | 20 [s/product] | 0 [h] | 0 [h] | 20 [min/day] | | | | | |
| | | | | Difficulty (0=Easy, 10=Extremely Difficult) | 10 | 3 | 3 | 2 | 2 | 5 | 8 | 8 | 9 | 5 | 5 | 5 | 6 | 6 | 6 | 8 | 4 | 6 | 6 | 6 | | | | | |
| | | | | Max Relationship Value in Column | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | | | | | |
| | | | | Weight / Importance | 161.2 | 165.3 | 165.3 | 165.3 | 165.3 | 114.3 | 171.4 | 171.4 | 98.0 | 120.4 | 81.6 | 81.6 | 126.5 | 126.5 | 116.3 | 110.2 | 95.9 | 98.0 | 98.0 | 118.4 | | | | | |
| | | | | Relative Weight | 6.3 | 6.5 | 6.5 | 6.5 | 6.5 | 4.5 | 6.7 | 6.7 | 3.8 | 4.7 | 3.2 | 3.2 | 5.0 | 5.0 | 4.6 | 4.3 | 3.8 | 3.8 | 3.8 | 4.6 | | | | | |

Competitive Analysis (0=Worst, 5=Best)

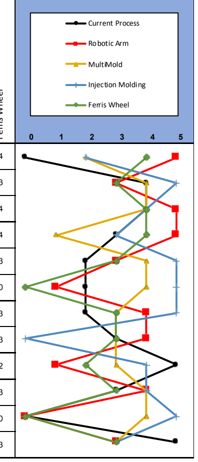



Figure 8: House of Quality with a competitive analysis feature that compares each concept regarding each client need. Highly rated concepts for a given quality have their symbol marked on the right side of the competitive analysis chart. The overall performance of each concept can then easily be contrasted between other concepts.

In the competitive analysis, the Robotic Arm and the Injection Molding concepts are consistently rated the highest regarding client needs compared to the other designs. While Injection Molding rates highest in the quality criterion, the Robotic Arm rates highest in the productivity and safety criteria. Since the productivity and safety criteria have been determined to be the most critical criteria in selecting a concept to develop, the House of Quality's competitive analysis verifies that the Robotic Arm is the favorable concept to continue to a detailed design.

After a rigorous concept selection process, which included analyzing each concept, comparing each concept to one another, and consulting with the client for preferences and specifications, the Robotic Arm was determined to be the most favorable concept. The Robotic Arm design produced the best ratings in productivity, ease of handling, ergonomics, and, most importantly, safety. This indicates that the Robotic Arm design can produce the highest amount of wax sprue bars while making the process easier and safer for operators. In addition, the client emphasized the benefit of automating the dipping and curing steps of the process with the Robotic Arm for the purpose of increasing the availability of the operator to perform other value-added tasks. The EVR of the robotic arm concept is illustrated in Figure 9.

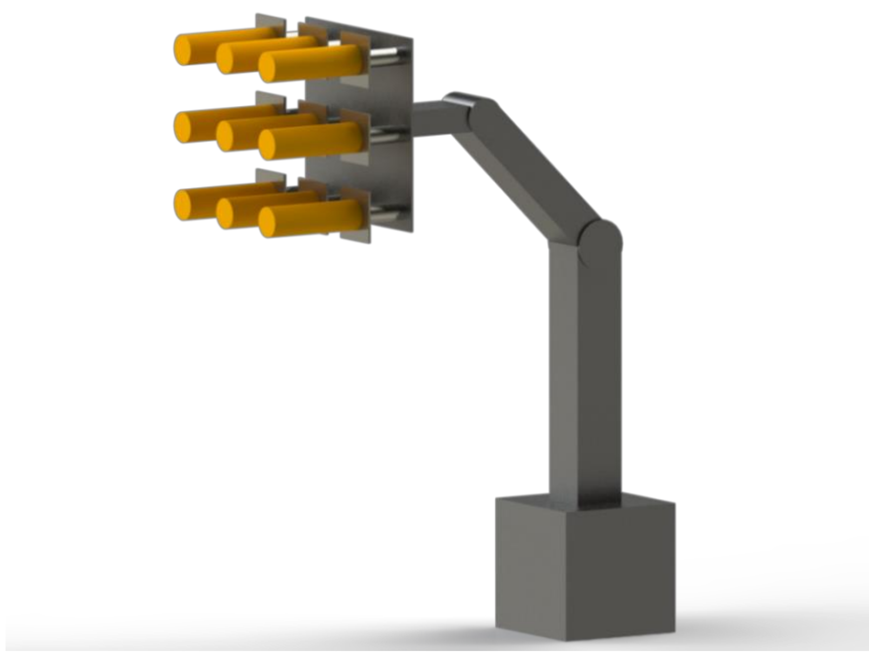


Figure 9: EVR of the Robotic Arm concept.

The Robotic Arm produces sprue bars by dipping the center bars, up to the top plate, into a tank filled with melted wax. This process occurs multiple times until the proper wax thickness of the sprue is achieved.

# 3 Scope Change

Once the team had chosen to pursue the robotic arm concept, communication with the client was critical before proceeding further with the project. The robotic arm concept introduced changes to the problem scope that needed to be reviewed and discussed by both the project team and client. First, the robotic arm concept would include either designing or procuring a robotic arm as well as designing an entire robotic system to perform the task of producing wax sprue bars. In addition, the cost associated with designing a robotic system to improve the current wax sprue bar process would exceed the initial cost constraint of $20,000 set by the client. Lastly, integrating the robotic system into an additional process at Matrix Industries would be necessary to justify the increased cost and complexity associated with a robotic system.

After discussing these scope changes with the client, the team was given permission to continue the project with the constraints of designing or procuring a cost-efficient robot, which will be justified through a cost benefit analysis regarding wax sprue bar production. In addition, the client suggested that incorporating the robotic system into their existing ceramic molding process would increase cost-efficiency. Thus, the ceramic process was taken into consideration in designing of the robotic system. However, an in-depth investigation of this process was not done as it was still deemed out of scope of the project.

# 4 Testing and Data Collection

Before beginning to further develop the selected design, data was collected to find the parameters and constraints that the robotic arm would need to adhere to. Data was also collected on the average weight of a sprue bar assembly, time required for wax on the center bar to solidify, and dimensions of the wax tanks, ceramic tanks, and rainbow sander. This data is detailed in Table IX. This data was collected to be eventually used in designing the required fixtures of the robotic system.

TABLE IX
DATA COLLECTED DURING TESTING

| | | |
|---|---|---|
| **Curing time of wax on center bar [s]** | | 25 |
| **Mass of sprue bar assembly (including wax) [kg]** | | 3.62 |
| **Wax Tank [m]** | Diameter | 0.914 (3 ft) |
| | Height | 0.914 (3 ft) |
| **Ceramic Tank #1 [m]** | Diameter | 0.914 (3 ft) |
| | Height | 0.914 (3 ft) |
| **Ceramic Tank #2 [m]** | Diameter | 0.914 (3 ft) |
| | Height | 0.914 (3 ft) |
| **Liquidized Sand Bed [m]** | Diameter | 0.712 (2.3 ft) |
| | Height | 0.914 (3 ft) |
| **Rainbow Sander [m]** | Length | 1.213(4 ft) |
| | Width | 1.016 (3.33 ft) |
| | Height | 1.213 (4 ft) |

Additionally, several experiments were conducted to justify the dipping method as a legitimate strategy for sprue bar production. During experimentation, the team had several key takeaways:

- If the sprue bars stay perpendicular to the ground throughout the process, gravity pulls the wax to the bottom of the sprue bar, causing a phenomenon known as an "elephant's foot", where the top of the sprue bar is significantly thinner than the bottom of the sprue bar. Figure 10 shows a section of a sprue bar, after it was dipped into a wax tank and kept perpendicular to the ground for the entire process.

Figure 10: A section cut from a sprue bar dipped into a wax tank 5 times and held perpendicular to the ground throughout the process.

- Sprue bars dipped in the melted wax tank for a longer period of time tend to be thicker than sprue bars dipped for a short period of time.

- The proper sprue bar thickness is achieved after being dipped six times at a duration of five seconds per dip.
- “Elephant’s foot” can be reduced if the sprue bar is concentrically rotated while oriented parallel to the ground.
- If a sprue bar begins rotating after the sprue bar has been oriented parallel to the ground, the melted wax coalesces into beads, as shown in Figure 11.

Figure 11: Sprue bar dipped in the wax tank, oriented parallel to the ground, and then rotated, forming beads while solidifying.

- The beads can be eliminated if the sprue bar begins rotating prior to being lifted from the wax tank and tilted.
- The wax hardens sufficiently enough for the next dip after being removed from the wax for approximately 20 seconds.

Detailed information of testing methods and data collection can be found in Appendix B.

The collected data served as a foundation for the target process flow. The Robotic Arm concept process must be compatible with Matrix Industries’ existing infrastructure and perform the following functions:

1. Grasp multiple sprue bar assemblies hanging on a shelf.
2. Lift and handle the sprues from the shelf.
3. Repeatedly dip the sprues into a wax tank until the proper sprue bar thickness is achieved.

4. Tilt and rotate the sprue bars.
5. Hang the sprues on a separate shelf.

These functions were considered when designing the wax sprue and ceramic mold forming processes.

# 5 Robot Procurement

The procurement phase began by consulting with Dr. Subramaniam Balakrishnan, a professor at the University of Manitoba who specializes in robotics. Dr. Balakrishnan recommended procuring a robot over designing a robotic system since an off-the shelf robotic system has many advantages [2]:

- **Tested design:** Off-the-shelf robotic systems have been tested not only by the manufacturer, but also in the field, by the manufacturer's customers. This reduces the overall cost of the project, as field-testing designs is not a cheap endeavour.
- **Flexibility:** Off-the-shelf robotic systems are much more flexible, as they are produced for a wider market. A custom designed robot would only be capable of some very specific tasks and will be obsolete if the process is significantly changed.
- **Maintenance support:** Manufacturers of off-the-shelf robotic arms can provide support for maintenance of products and troubleshoot any issues that might arise. This reduces the overall downtime, as there is a high probability that the manufacturers have seen similar issues with other customers.
- **Economies-of-scale:** As robotic arm manufactures make a large number of robotic systems, they can manufacture robotic systems at a much cheaper price than making custom parts for a unique process. This means that overall price of off-the-shelf robotic systems is close to the same as designing and manufacturing a custom manipulator.
- **Safety:** Off-the-shelf options come with some tried and tested pre-built safety attachments, which can heavily reduce or eliminate injury to persons or damage to property. Whereas, a custom designed option may not include these attachments.

For these reasons, the client and the team agreed to procure a robot as opposed to designing a unique system.

## 5.1 Robot Requirements

Before selecting a robot, a deeper investigation into the requirements of the robot had to be performed. The requirement categories necessary to determine the robotic system specifications were listed by Dr. Balakrishnan.

- **Payload**

  The mass and size dimensions of the object or objects being handled.

- **Gripper**

  The function and requirements necessary for the robot to handle the object or objects. Essentially the "hand" of the robot used to grab the object.

- **Reach**

  The maximum extension of the robot determined by the work envelope.

- **Proximity of Tasks**

  The distance between tasks that the robot will perform.

- **Degrees of Freedom**

  The maneuverability or motion capabilities of the robot.

- **Speed**

  The speed that the robot must move the object.

- **Worker Replacement**

  The number of workers that the robot will relieve of their duties. This can also be represented by the amount of time relieved workers would have been working.

- **Volume of Work**

  The amount of time the robot will be working per day or the number of jobs the robot will complete per day.

- **Environment**

  The environmental qualities that the robot will be working in. This includes the temperature of the location and the type and quantity of particulates the robot may come into contact with.

Once the specification for each requirement category was established, a suitable robotic system could be procured. The client specified the requirements listed in Table X

TABLE X
ROBOT REQUIREMENTS DESIRED BY CLIENT

| Requirement Category | Client Requirements |
|---|---|
| Payload [kg] | 100 – 300 |
| Gripper | Must grab multiple mounting bars. |
| Reach [m] | 2.5 – 3 |
| Proximity of Tasks [m] | 5 |
| Degrees of Freedom | 6 |
| Speed | Minimal (not specific, but high speed not required) |
| Worker Replacement | 3 workers, 8-hour shifts (24 hours per day) |
| Volume of Work [hrs/day] | 8 |
| Ambient Conditions | Non-harsh, typically 20-25°C. Robot may come into contact with wax or ceramic slurry/dust. |

Each requirement was investigated further during the process design and procurement phase to narrow the scope of robot selection and ensure the proper robot was chosen. This would also help reduce overall costs of the system.

Finally, Dr. Balakrishnan recommended researching FANUC, Yaskawa Motoman, ABB, and KUKA AG, four of the world's largest robot suppliers, and selecting an appropriate robot from one of these companies. Each of these companies offer a wide range of reliable robots and deal with a variety of customers in different industries. Rather than researching a wide range of companies, focusing on these four companies would be more efficient for our team since they are likely to offer a robot that meets the client's specifications.

In order to conduct a thorough search for the proper robot, multiple robots that fit the requirements were selected from each company. The selected robots were then analyzed with the help of representatives from each respective company to ensure the robots met the client's requirements. Once a single robot from each company was selected, the remaining robots were compared to determine the proper robot for the client.

## 5.2 FANUC

FANUC America Corporation is a leading supplier of robots, CNC systems, and factory automation. FANUC offers robot models with payload capabilities ranging from 0.5 kilograms to 2300 kilograms as stated on their company website [3] FANUC offers five series of robots that meet the payload and reach requirements. Each of the qualifying series are shown in Table XI, along with the range of payloads and reaches of the robots within each series. Robots that are not in the Assembly/Handling category were still considered since modifications to the robot might be possible.

TABLE XI
QUALIFYING ROBOTS FROM FANUC [3]

| Robot Series | Payload Range [kg] | Reach Range [m] | Applications |
|---|---|---|---|
| M-900iA | 150-200 | 3.5 | Machining/Loading |
| M-900iB | 280 | 2.65-3.1 | Machining/Loading |
| R-2000iB | 200-220 | 2.2-2.6 | Assembly/Handling |
| R-2000iC | 100-270 | 2.65-3.5 | Assembly/Handling |
| R-2000iD | 210 | 2.6 | Welding/Cutting |

FANUC was then contacted regarding the series in Table XI, and a representative assisted in finding the most suitable robot for the client's process. FANUC considered the process layout and the client's requirements, and recommended the R-2000iC/125L, which is shown in Figure 12.

[redacted]

Figure 12: The selected robot from FANUC; the R-2000iC/125L. [4]

The exact specifications and the quoted cost of the R-2000iC/125L are displayed in Table XII. The maximum moment refers to the highest moment that the wrist of the robot can withstand. Since the wrist is the constraining component of the robot, the maximum moment that the wrist can handle is the maximum moment that the robot can handle. The maximum moment of the robot is an important specification because, although the robot may have a payload capacity of 125 kg, it may not have enough torque to tilt and rotate the payload. The footprint of the robot is also an important specification because a smaller footprint would allow for open space on the facility floor, which would increase worker and product safety.

TABLE XII
SPECIFICATIONS OF THE SELECTED FANUC ROBOT [4]

| **Product Name** | R-2000iC/125L |
|---|---|
| **Reach [m]** | 3.1 |
| **Payload [kg]** | 125 |
| **Maximum Moment [Nm]** | 710 |
| **Footprint [$m^2$]** | 0.47 |
| **Quoted Cost [USD]** | [redacted] |

Note that FANUC included process specific software add-ins, a 575-volt breaker, a continuous-turn wrist, and an estimated shipping cost in their quote. The price quotation from FANUC is located in Appendix C. The specific costs included in each company's quotes are detailed and analyzed in Section 5.6: Cost Comparison.

## 5.3 Yaskawa Motoman

Yaskawa Motoman is a leading industrial robotics company that provides automation products and solutions for many industry applications. The Motoman product line includes a variety of industrial arm robot models and robotic systems that include robot, process, and safety equipment according to their company website [5]. Motoman offers eight series of robots that qualify for the client's payload and reach requirements. Table XIII lists each of the series, as well as the payload range and reach range of the robots in the corresponding series.

TABLE XIII
QUALIFYING ROBOTS FROM MOTOMAN [5]

| Robot Series | Payload Range [kg] | Reach Range [m] | Applications |
|---|---|---|---|
| EP | 130-200 | 3.5 | Assembly/Handling |
| GP | 120-400 | 3.0-3.5 | Assembly/Handling |
| PH | 130-200 | 3.5 | Assembly/Handling |
| MH | 120-900 | 3.0-4.6 | Assembly/Handling |
| UP | 400 | 3.5 | Assembly/Handling |
| ES | 165-200 | 3.1 | Welding/Cutting |
| SP | 105-185 | 3.0-3.1 | Welding/Cutting |
| MPL | 160-800 | 3.1 | Palletizing |

A Motoman representative was contacted to discuss the series in Table XIII. The GP180 from the GP series of robots was recommended by the representative as the most appropriate robot for the client's process. The GP180 is displayed in Figure 13.

Figure 13: The selected robot from Motoman; the GP180. [5]

The specifications of the GP180 are displayed in Table XIV. Motoman provided the team with a price quote for the GP180, which includes a 575-volt step-up transformer in addition to the robot. The quoted cost is also listed in Table XIV and the price quotation from Motoman is located in Appendix D.

TABLE XIV
SPECIFICATIONS OF THE SELECTED MOTOMAN ROBOT [5]

| | |
|---|---|
| **Product Name** | GP180 |
| **Reach [m]** | 3.4 |
| **Payload [kg]** | 180 |
| **Maximum Moment [Nm]** | 618 |
| **Footprint [$m^2$]** | 0.48 |
| **Quoted Cost [USD]** | $ 44,175.00 |

## 5.4 ABB

ABB is a technology leader that works to write the future of industrial digitalization with utilities, industry, transportation, and infrastructure customers. ABB is also a leading supplier of industrial robots and robot application solutions according to their company website [6]. Of the robots ABB offers, seven fell within the range of the client's requirements. Table XV lists each qualifying robot series and their respective specifications.

TABLE XV
QUALIFYING ROBOTS FROM ABB [6].

| Robot Series | Payload Range [kg] | Reach Range [m] | Applications |
|---|---|---|---|
| IRB 660 | 180-250 | 3.15 | Palletizing |
| IRB 6640 | 130-235 | 2.8-3.2 | Washing and Cleaning |
| IRB 6650S | 90-200 | 3.0-3.9 | Assembly/Handling |
| IRB 6660 | 100-205 | 1.93-3.35 | Machining/Loading |
| IRB 6700 | 150-235 | 2.65-3.2 | Assembly/Handling |
| IRB 6790 | 205-235 | 2.65-2.80 | Washing and Cleaning |
| IRB 7600 | 150-500 | 2.3-3.5 | Heavy Part Handling |

An ABB representative was then contacted regarding the robots in Table XV to select the most suitable robot for the client's process. Based on the process, and the client's requirements, ABB recommended the IRB 6700-150/3.20, which is displayed in Figure 14.

Figure 14: The selected robot from ABB; the IRB 6700-150/3.2. [7]

Table XVI displays the specifications of the IRB 6700-150/3.2, including the quoted cost. The price quotation from ABB is located in Appendix E. ABB did not include any process specific add-ins, a continuous-turn wrist, a 575-volt step-up transformer, or shipping costs in their price quote.

TABLE XVI
SPECIFICATIONS OF THE SELECTED ABB ROBOT [7]

| | |
|---|---|
| **Product Name** | IRB6700-150/3.2 |
| **Reach [m]** | 3.2 |
| **Payload [kg]** | 150 |
| **Maximum Moment [Nm]** | 570 |
| **Footprint [$m^2$]** | 0.72 |
| **Quoted Cost [USD]** | [redacted] |

## 5.5 KUKA AG

KUKA AG is one of the world's leading suppliers of intelligent automation solutions and offer a broad range of industrial robots as stated on their company website [8]. Consistent communication with KUKA AG was not established and thus an in-depth analysis of how their products may work in the client's application was not performed.

## 5.6 Cost Comparison

The price quotations from each of the three companies differed regarding items included in the costs. In order to compare the price of each robot fairly, a cost comparison between each of the core robot components was performed, since each company provided at least the cost of the core robot components. These core robot components include the manipulator, controller, and teach pendant, and in combination are also referred to as the "robot" in this document. FANUC also included the cost of software add-ins, a breaker, and the continuous-turn wrist feature. These additional items are all necessary for the client's process, and thus would have to be purchased regardless of which robot were to be implemented in the process

Each of the necessary items mentioned in the price quotations are briefly described as follows:

- **Manipulator**

  The entire mechanical unit consisting of the arms, elbows, and wrist. It is one of the core robot components. An example of a manipulator is shown in Figure 15.

Figure 15: An ABB manipulator. [9]

- **Controller**

  The computer that controls the motion of the manipulator. It is one of the core robot components. An example of a controller is shown in Figure 16.


Figure 16: A Yaskawa Motoman controller. [10]

- **Teach Pendant Unit (TPU)**

  The handheld device that a person can use to command the manipulator. It is one of the core robot components. An example of a TPU is shown in Figure 17.

Figure 17: An ABB Teach Pendant Unit (TPU). [11]

- **Software Add-Ins**

  The specific motion, safety, and network software features necessary for the material handling processes the client requires.

- **Breaker**

  One of the components required to supply electrical power to the robot.

- **Continuous-Turn Wrist**

  The feature that allows the wrist of the robot to rotate nearly infinitely in order for the wax to harden evenly.

The cost of these items corresponding to each robot is detailed in Table XVII as a price quotation breakdown.

TABLE XVII
BREAKDOWN OF PRICE QUOTATION FROM EACH COMPANY

| | Cost [USD] | | |
|---|---|---|---|
| **Item** | **FANUC** | **Motoman** | **ABB** |
| **Manipulator, Controller, TPU** | [redacted] | $ 44,174.00 | [redacted] |
| **Software Add-ins** | [redacted] | N/A | [redacted] |
| **Breaker** | [redacted] | N/A | [redacted] |
| **Continuous-Turn Wrist** | [redacted] | N/A | [redacted] |
| **Shipping** | [redacted] | N/A | [redacted] |
| **Discount** | [redacted] | N/A | [redacted] |
| **Total** | [redacted] | $ 44,174.00 | [redacted] |

An estimate of the total FANUC robot cost excluding the additional items was calculated to fairly compare prices. This was done by excluding the shipping and discount from the total cost, taking the discount as a percentage, and multiplying the discount by the manipulator, controller, and TPU cost. Table XVIII shows this process.

TABLE XVIII
ADJUSTED COST OF FANUC ROBOT FOR FAIR PRICE COMPARISON

| | |
|---|---|
| **Cost excluding shipping and discount:** | [redacted] |
| **Discount as percentage of above cost:** | [redacted] |
| **Manipulator, Controller, TPU with [redacted] discount:** | [redacted] |

The adjusted cost of the FANUC robot allows for a fair comparison between each of the companies' robots. Note that the cost of each robot is not the complete cost of integrating a robot into the client's process. Additional costs such as those included in the FANUC quote, as well as employee training, electrical integration, commissioning, and more, must also be considered before purchasing a robot.

## 5.7 Selection Criteria

A WDM was used to select the appropriate robot. Six selection criteria were used in the WDM and are defined as follows.

- **Adjusted Cost**

  The cost of the core components of the robot. The cost of the FANUC robot was adjusted to better represent only the core components. Lower adjusted costs are desirable.

- **Horizontal Reach**

  The distance the robot can stretch horizontally. Although this was a qualifying criterion, robots with a greater reach can be used for a greater variety of tasks.

- **Payload Capacity**

  The maximum mass of the parts the robot can safely handle. Although this was a qualifying criterion, robots with a greater payload capacity can be used for a greater variety of tasks and provide a greater factor of safety.

- **Maximum Moment**

  The maximum allowable moment at the wrist of the robotic arm. Robots with a greater maximum moment can tilt and rotate heavier parts, which is necessary in the sprue casting process.

- **Footprint**

  The area of the base of the robot. Robots with smaller footprints allow for more open space in the work area, which increases safety.

- **Customer service**

  The speed and quality of the company representatives' support. Since the robot will need servicing and maintenance throughout its life cycle, it is important the company provides quick and thorough support.

A summary of each selection criterion corresponding to each robot is shown in Table XIX.

TABLE XIX
ROBOT SELECTION CRITERIA DATA

| Selection Criteria | FANUC [4] | Motoman [5] | ABB [7] |
|---|---|---|---|
| **Adjusted Cost [USD]** | [redacted] | 44,175.00 | [redacted] |
| **Horizontal Reach [m]** | 3.1 | 2.7 | 3.2 |
| **Payload Capacity [kg]** | 125 | 180 | 150 |
| **Maximum Moment [Nm]** | 710 | 618 | 570 |
| **Footprint [m$^2$]** | 0.47 | 0.48 | 0.72 |
| **Customer Service** | High | Low | Medium |

## 5.8 Criteria Weighting Matrix

Prior to using a WDM to select the most suitable robot, a CWM was used to determine the importance of each selection criteria. The CWM is shown in Table XX.

TABLE XX
ROBOT CRITERIA WEIGHTING MATRIX

| | Selection Criteria | Adjusted Cost<br>A | Horizontal Reach<br>B | Payload Capacity<br>C | Maximum Moment<br>D | Footprint<br>E | Customer Service<br>F |
|---|---|---|---|---|---|---|---|
| A | Adjusted Cost | A | A | A | A | A | A |
| B | Horizontal Reach | | B | B | D | B | F |
| C | Payload Capacity | | | C | D | C | F |
| D | Maximum Moment | | | | D | D | D |
| E | Footprint | | | | | E | F |
| F | Customer Service | | | | | | F |
| | Total Hits | 6 | 3 | 2 | 5 | 1 | 4 |
| | Weighting | 0.29 | 0.14 | 0.10 | 0.24 | 0.05 | 0.19 |

The most important criterion as determined by the CWM was cost. The second and third most important criteria were maximum moment and customer service, respectively. Since each robot will be able to perform the desired task, it follows that cost would have the greatest influence on the robots' score. The maximum moment and customer service criteria are important properties of the robot once it has been implemented into the facility, thus gathering high weights.

## 5.9 Robot Rating Matrix

After obtaining the weights for each selection criterion, each robot was rated corresponding to the criteria in a robot rating matrix (RRM). The RRM is detailed in Table XXI.

TABLE XXI
ROBOT RATING MATRIX

| Selection Criteria | A vs B | A vs C | B vs C | FANUC A | Motoman B | ABB C |
|---|---|---|---|---|---|---|
| Adjusted Cost | B | X | B | 0 | 2 | 0 |
| Horizontal Reach | A | C | C | 1 | 0 | 2 |
| Payload Capacity | B | C | B | 0 | 2 | 1 |
| Maximum Moment | A | A | B | 2 | 1 | 0 |
| Footprint | X | A | B | 1 | 1 | 0 |
| Customer Service | A | A | C | 2 | 0 | 1 |

Total criteria ratings of each robot are shown in grey in Table XXI. The 'X' in the RRM indicates that the two candidates tied since they have similar characteristics in terms of that criteria.

## 5.10 Weighted Decision Matrix

The ratings form the RRM and the criteria weights from the CWM were used in the robot WDM to determine the most desirable robot. The robot WDM is displayed in Table XXII.

TABLE XXII
ROBOT WEIGHTED DECISION MATRIX

| Selection Criteria | Weight % | FANUC | | Motoman | | ABB | |
|---|---|---|---|---|---|---|---|
| | | Rating | Weight Score | Rating | Weight Score | Rating | Weight Score |
| Adjusted Cost | 0.29 | 0 | 0.00 | 2 | 0.57 | 0 | 0.00 |
| Horizontal Reach | 0.14 | 1 | 0.14 | 0 | 0.00 | 2 | 0.29 |
| Payload Capacity | 0.10 | 0 | 0.00 | 2 | 0.19 | 1 | 0.10 |
| Maximum Moment | 0.24 | 2 | 0.48 | 1 | 0.24 | 0 | 0.00 |
| Footprint | 0.05 | 1 | 0.05 | 1 | 0.05 | 0 | 0.00 |
| Customer Service | 0.19 | 2 | 0.38 | 0 | 0.00 | 1 | 0.19 |
| Total Score | | 1.05 | | 1.05 | | 0.58 | |
| Rank | | 1 | | 1 | | 3 | |
| Continue? | | YES | | YES | | NO | |

The WDM determined that the R-2000icC/125L from FANUC and the GP180 from Motoman tied as the most favorable robots. In terms of cost and payload capacity, the Motoman robot was rated better than any other candidate. Conversely, in terms of maximum allowable moment and quality of customer service, the FANUC robot achieved the highest score.

The Motoman and FANUC robot are both suitable for this project. However, the team decided to proceed with the FANUC R-2000iC/125L for the final design, shown in Figure 18. FANUC provided specific procurement specifications for the given project and the FANUC robot has a higher maximum moment, which is desirable for this project. Although the cost of the Motoman robot is lower, total integration costs are less transparent compared to the FANUC robot, which may cause discrepancies if the client were to purchase the Motoman robot.

[redacted]

Figure 18: The FANUC R-2000iC/125L was selected for the final project design. [4]

TABLE XXIIITable XXIII summarizes the specifications of the selected FANUC R-2000iC/125L robot.

TABLE XXIII
SPECIFICATIONS OF THE SELECTED ROBOT

| | |
|---|---|
| **Company Name** | FANUC |
| **Product Name** | R-2000iC/125L |
| **Cost [USD]** | [redacted] |
| **Horizontal Reach [m]** | 3.1 |
| **Payload Capacity [kg]** | 125 |
| **Maximum Moment [Nm]** | 710 |
| **Footprint [m$^2$]** | 0.47 |

# 6 Sprue Bar Rack Design

In order to satisfy the client's highest prioritized need of increasing the production rate of wax sprue bars, the robot would need to dip multiple sprue bars simultaneously. In order for the robot to do this, it would either have to handle multiple individual sprue bars or handle one rack that holds multiple sprue bars. Since designing a gripper to handle multiple individual sprue bars would be too difficult and infeasible given the scope of the project, a method to mount multiple sprue bars on one rack that the robot grasp was designed.

## 6.1 Purpose

The current process at Matrix Industries limits the number of sprue bars that can be produced concurrently to one, as only one mold is available. This design must cause a dramatic increase in sprue bar production by allowing for simultaneous production of multiple wax sprues.

This component must fulfill three main functions:

- It must hold multiple center bar, top plate, and mounting bar assemblies in place and must have compatibility with different kinds of sprue bars at the same time, to allow flexibility. This ensures an increase in the production of wax sprue bars.
- It must be grasped by a conventional gripper and allow for grasping, lifting, tilting, and rotating. This ensures multiple bars can be dipped into the wax tank and cool with a smooth coat of wax by tilting and rotating the rack.

- It must be capable of hanging on the current shelves available at Matrix industries. This fulfills the commitment to the client for a process that is integrated into their current process infrastructure.

## 6.2 Design Methodology

The initial sprue bar rack design implemented into the Robotic Arm concept, displayed in Figure 19, served as the base rack design. This concept was improved to develop a final sprue bar rack design.

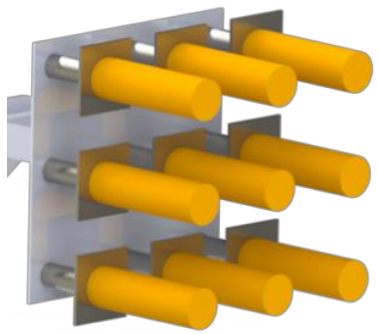


Figure 19: Initial sprue bar rack design from the Robotic Arm concept.

Since the square shape of the rack was an inefficient use of space when being dipped into a circular tank, the team began to develop a circular rack. Next, a method of securing each sprue bar assembly to the rack was developed. The sprue bar assemblies must not rotate or translate in any direction and must be easily removeable from the rack. Due to these constraints, the only viable design was to incorporate sprue slots in the rack, where the mounting bar of the sprue bar assembly could be inserted and latched in. Figure 20 shows the sprue bar slots in the rack. Six sprue slots were arbitrarily placed around the rack. Initially, the diameter of the rack was set at 3 feet, which is the same diameter as the wax tank. With six sprue slots arbitrarily chosen, it allowed for any combination of sprue bar types to fit on the rack.

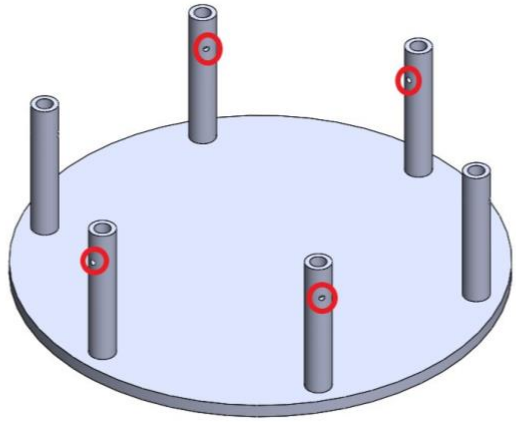


Figure 20: Sprue slots in the sprue bar rack used to secure the sprue bar assemblies. A fastener must be used with the holes in the slots to secure the assemblies.

Finally, the method of hanging the rack on existing shelves was designed in tandem with the robot grasping method; Figure 21 shows a model of the existing shelf at matrix.

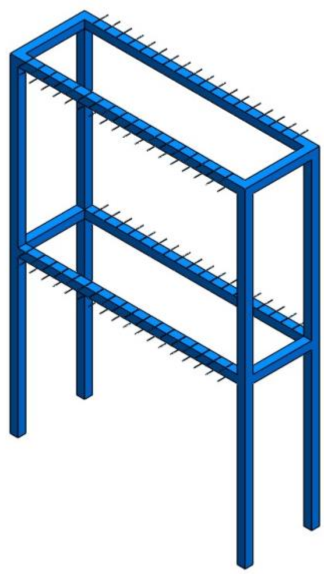


Figure 21: Existing shelf at Matrix Industries.

To allow the robot to grasp the rack without the need of an expensive vision system upgrade, a center bar for the rack was designed to fit between the hooks in the shelves, as opposed to on individual hooks. The center bar would also serve as the grasping point of the robot. A T-shaped center bar, shown hanging on the shelf in Figure 22, was determined to be the simplest and most reasonable design. The two spokes parallel to the ground are 76.2 mm (3 in) long starting from the central bar to the end and a diameter of 25.4 mm (1 in). This ensures at least one contact point on either side of the rack.

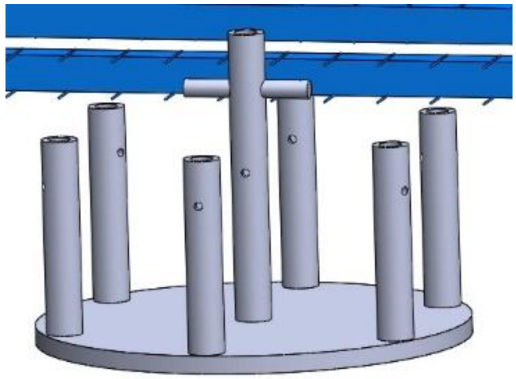


Figure 22: Center bar design of the sprue bar rack, shown hanging on a shelf.

With the initial components of the sprue bar rack defined, a further detailed design was conducted to finalize the rack.

## 6.3 Rack Detailed Design

Once the initial shape and concept of the rack had been determined, specific dimensions and features were determined. First, the method of fastening the sprue bar assembly to the holes in the sprue slots was determined. After examining a number of different fasteners such as bolts and screws, it was determined that quick release pins would provide the simplest means of properly securing the sprue assembly.

A quick release pin is a simple pin with a spring-loaded ball installed at the end of the pin. This ball prevents the pin from falling out and releasing the fastened components. Figure 23 shows an example of a quick release pin. A quick release pin is easily removable if a force parallel to the pin is applied; it forces the ball down releasing the pin. The pin will retain the sprue bars in place while the robot manipulates the rack, since there are no significant parallel external forces.

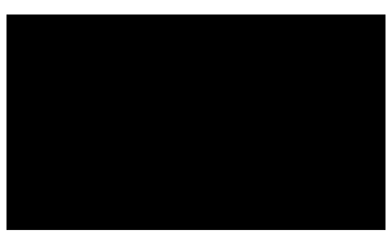


Figure 23: Quick release pin, used to retain the mounting bars in place. [12]

A center bar, top plate and mounting bar assembly is held in place by sliding the mounting bar through the sprue slot in the rack. Once the assembly is in place, a quick release pin is pushed through the holes in the sprue bar slot shown in Figure 24. This holds the assemblies firmly in place and prevents them from rotating within the rack.

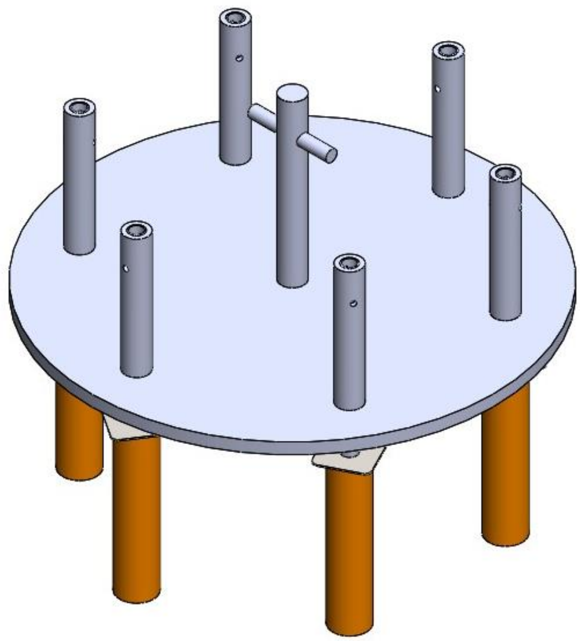


Figure 24: Initial sprue bar rack design with six sprue bars attached.

## 6.4 Design Process

Aluminium 6061-T6 was chosen as the material for the rack. It is commonly used to manufacture weight sensitive structures such as bicycle frames, aircraft structures, and aircraft fittings [13].Thus, aluminum 6061-T6 would be ideal for this rack due to its low price, low weight, and strength. Assigning a material to the rack allowed the team to perform a fundamental element analysis (FEA) to ensure feasibility, as the preliminary rack mass was 53.94 kg plus an additional six 3.62 kg sprue bar assemblies for a total mass of 76.66 kg.

## 6.5 Stress Analysis

There were two important stress inducing scenarios to be analyzed for the preliminary rack design:

a) when the loaded sprue bar rack is lifted up from the tank and horizontally oriented by the gripper
b) when the gripper is applying force at the top of the central bar and lifting the loaded rack

For both scenarios, the team conducted a numerical yielding failure study using SolidWorks software and an analytical crack growth study to investigate the structural stability of the rack. Additionally, the maximum moment applied to the wrist of the robot by the loaded rack was investigated for Scenario A.

Since the initial dimensions of the preliminary design were arbitrarily and safely chosen, conducting a stress analysis would hopefully identify features to be streamlined. Moreover, the structure was enhanced by maximizing the sprue bar load capacity and decreasing the weight of the structure.

## 6.6 Test Scenario A: Rack Held Horizontally by the Gripper

In order to analyze the loaded sprue bar rack when it is held horizontally by the gripper, an FEA was performed with the fixture point set as the grasping point of the gripper. Gravity was set as the external force applied to the structure. Figure 25 shows the boundary conditions on SolidWorks.

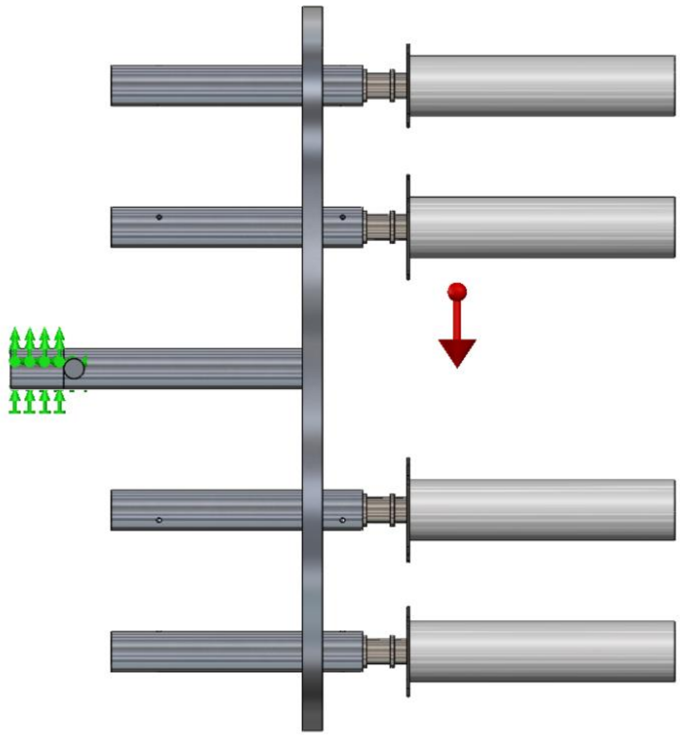


Figure 25: Stress analysis boundary conditions for the tilted orientation of the sprue bar rack.

The green arrows in Figure 25 indicate the fixture point of the robot on the rack. The red arrow indicates the direction of gravitational force as it is the only external force on the structure.

### 6.6.1Yielding

The yielding stress of aluminum 6061-T6 is 275 MPa [13]. A safety factor of two was chosen to account for product safety. Since workers will not be near the robot during operation, a greater safety factor is not necessary. Thus, the allowable working stress of the rack becomes 137.5 MPa. An FEA was conducted to check whether the rack would fail while loaded with wax sprue bars in terms of von Mises yielding criteria. Figure 26 shows the results of the yielding study.

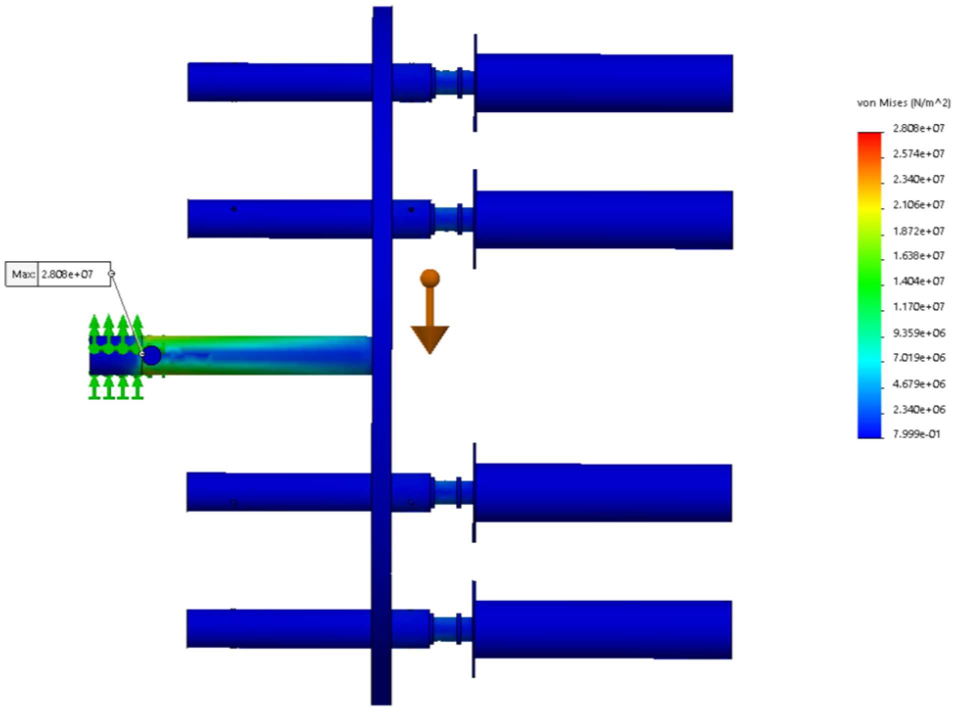



Figure 26: Von Mises stress concentrations of the sprue bar rack in the horizontal position.

As shown in Figure 26, the von Mises stress had a maximum value of 28.08 MPa at the location closest to the gripper. However, the von Mises stress did not exceed the allowable working stress of 137.5 MPa, thus the rack is safe in terms of yielding for Scenario A.

### 6.6.2 Fracture

A crack growth analysis was conducted by assuming a 6.35 mm (¼ in) long crack at the location where the yielding stress is highest on the rack. An initial crack length of 6.35 mm was chosen as it would be reasonably detectable by the human eye before catastrophic failure. Linear elastic fracture mechanics and Equation (1) were used to determine whether the crack would be stable in mode I fracture.

$$K_I = \sigma\beta\sqrt{\pi a} < K_{Ic} \quad (1)$$

In this equation, $K_I$ is the critical value of mode I fracture while the $K_{IC}$ is the fracture toughness of the material, which is 29 MPa for 6061-T6 [13]. If the $K_I$ of the structure is less than the fracture toughness of the material, the structure will have a stable crack growth, which is preferred for a safe design. β is the stress intensity factor, which depends on where the crack occurs and how the load is applied. Since the central bar is cylindrical, the team used a β value of 1.52 for a cylinder with a radial crack under axial tension which was taken from [14]. Finally, *a* is the assumed crack length of 6.35 mm. An FEA was performed to determine the maximum stress at the critical crack location, which is circled in Figure 27.

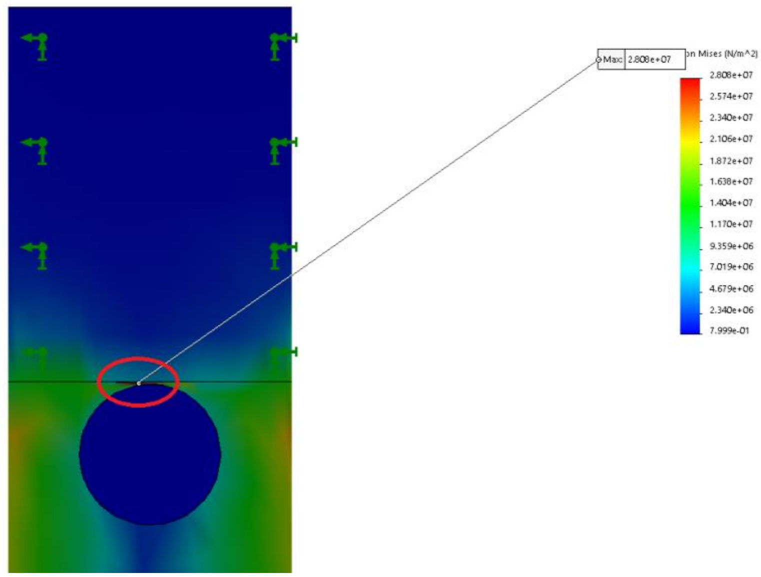



Figure 27: Crack position in the fracture calculations.

The resulting stress at the crack location is 28.08 MPa as shown in Figure 27. $K_I$ at the crack location is calculated using Equation (1) as follows.

$$K_I = 28.08 \times 1.52\sqrt{\pi \times 0.00635} = 6.03\ Mpa < K_{Ic}$$

The $K_I$ value with a crack length of 6.35 mm is still stable since it is less than the $K_{IC}$ value of 29 MPa, indicating that the rack design is safe in terms of fracturing in Scenario A.

## 6.7 Test Scenario B: Gripper Grasping the Central bar

In order to ensure the central bar was strong enough to endure the force of the gripper, an FEA was performed with the fixture set as the edge of the round plate. Gravitational forces were induced on the structure, as well as the force applied by the gripper. Grippers capable of handling 75 kg workpieces typically have an approximate closing force of 15,000 N according to the

SCHUNK company website [15].Thus, the force applied by the gripper was set to 15,000 N. Figure 28 shows the arranged boundary conditions on SolidWorks.

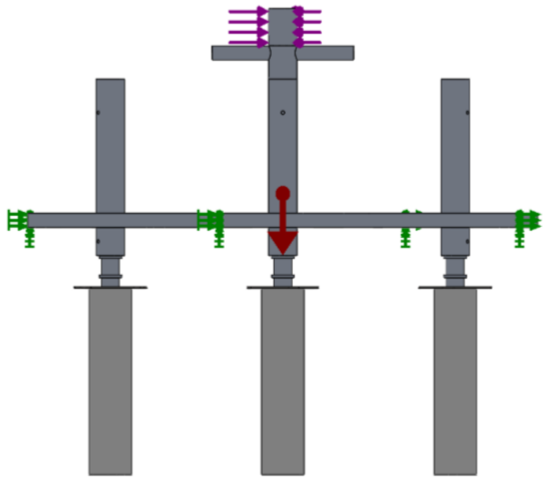


Figure 28: Boundary conditions of the grasping force analysis.

## 6.7.1Yielding

The von Mises stress from the FEA is 1.64 MPa at the gasping point of the central bar, which is much lower than the maximum allowable working stress of 137.5 MPa. Figure 29 illustrates the von Mises stress concentrations in the rack induced by the gripper.

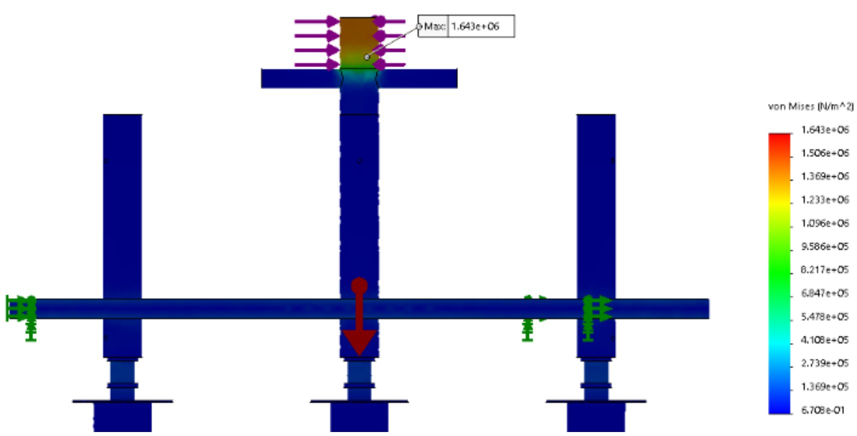



Figure 29: Von Mises Stress results of the grasping force analysis.

## 6.7.2 Fracture

Similar to the FEA performed in Scenario A, the 6.35 mm crack was assumed to occur at the location of maximum stress as calculated in the yielding analysis. The location of maximum stress, and thus the location of fracture analysis, is illustrated in Figure 30.

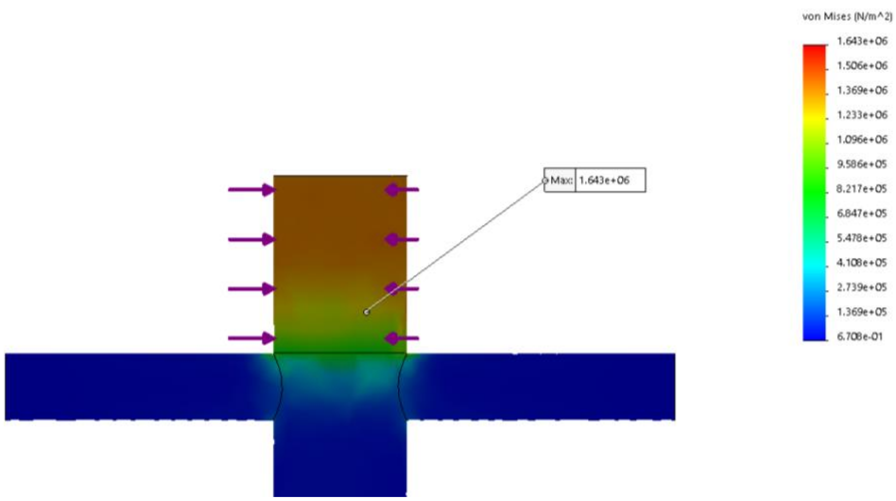



Figure 30: Crack position with the grasping force applied.

Using Equation (1) , the $K_I$ value was calculated with a stress of 1.64 MPa, assuming a mode I fracture, as follows.

$$K_I = 1.64 \times 1.52\sqrt{\pi \times 0.00635} = 0.36MPa \ll K_{Ic}$$

Since the value of $K_I$ is much smaller than the 6061-T6 fracture toughness of 29 MPa, the crack growth is stable in Scenario B.

## 6.8 Moment

The geometry and mass of the loaded rack induces a moment on the wrist of the robot when being tilted and rotated. Thus, it is critical that the induced moment is less than the maximum moment capability of the robot, which is 710 Nm. The team calculated the moment on the wrist of the robot when the rack is in the horizontal position analytically and numerically using SolidWorks.

The moment on the wrist, $M_{wrist}$, is obtained by multiplying the weight of the loaded rack by the distance between the wrist and the center of mass of the loaded rack. Equation (2) was used to calculate the moment on the wrist.

$$M_{wrist} = mg \times d \tag{2}$$

In this equation, *mg* is the weight of the loaded sprue rack and *d* is the distance from the grasping point where the gripper is holding the central bar to the center of mass for the loaded rack, which was obtained from the SolidWorks model. Although the distance from the center of mass to the grasping point of the central bar does not represent the exact moment value, it was used as a preliminary calculation. Figure 31 shows the *d* measurement from SolidWorks.

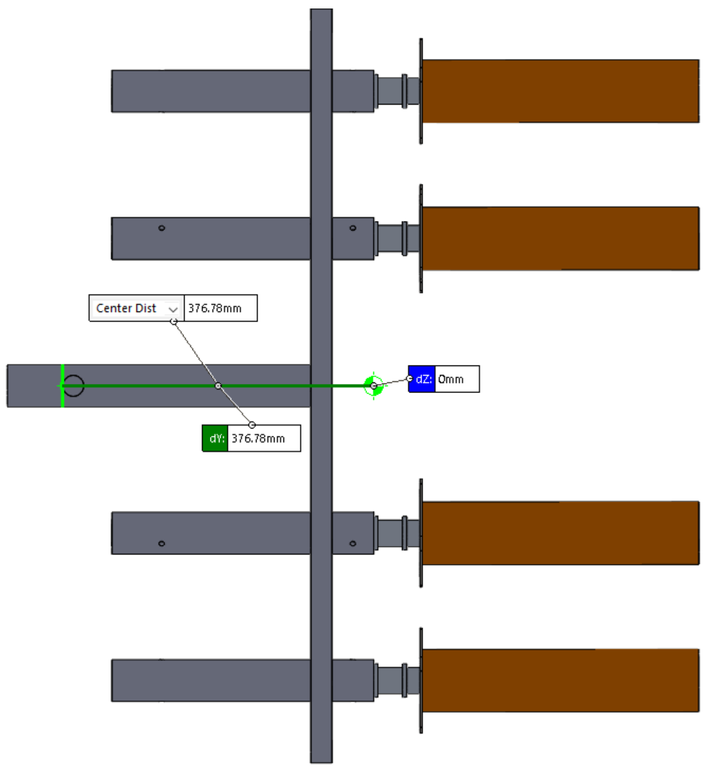



Figure 31: The distance used to calculate the wrist moment.

This distance was calculated as 377 mm and the mass of the loaded rack was calculated as 75.66 kg.

Equation (2) was used to calculate the approximate moment at the wrist as follows.

$$M_{wrist} = 75.66 \times 9.81 \times 0.377 = 279.64\ Nm$$

Since the moment induced on the robot by the loaded rack is less than the 710 Nm, which is the maximum moment of the robot, this design is compatible with the robot.

## 6.9 Summary of Preliminary Rack Design

Each of the stress, moment, and mass calculations pertaining to the two scenarios are summarized in Table XXIV. These values are also compared to the property constraints of the material and robot.

TABLE XXIV
SUMMARIZED RESULT OF PRELIMINARY RACK DESIGN

| Scenario | Yielding [MPa] | | Fracture [MPa] | | Moment [Nm] | | Total Mass [kg] | |
|---|---|---|---|---|---|---|---|---|
| | FEA | Criteria | FEA | Criteria | Model | Criteria | Model | Criteria |
| A | 28.08 | 137.5 | 6.03 | 29 | 279.64 | 710 | 75.656 | 125 |
| B | 1.643 | 137.5 | 0.36 | 29 | N/A | N/A | | |

As shown in Table XXIV, all of the calculated values are far below the constraint values, suggesting that the current design is not close to failing and is overdeveloped. Thus, the design could be enhanced to reduce the overall weight of the loaded rack while increasing the number of possible sprues secured to the rack. This was done by conducting two separate design enhancements.

## 6.10 Stage 1 Enhancement

First, the team decided to enhance the design by increasing the sprue bar capacity of the rack and reducing the thickness of the aluminum to reduce the mass. This was done by creating an additional sprue slot within the central bar of the rack and using 4.76 mm (3/16 in) aluminum 6061-T6, which is an industry standard aluminum thickness [13]. Moreover, some unnecessary components, including the top and bottom portions of the six sprue slots, were removed to reduce weight. Figure 32 illustrates the features of the stage 1 enhanced rack design.

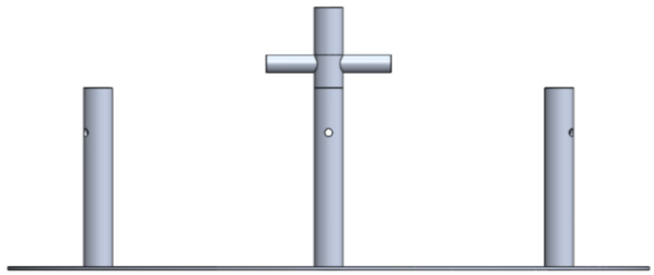


Figure 32: Side view of the stage 1 enhanced sprue bar rack design.

After modifying the design, an FEA was conducted to ensure the design would not fail by yielding, fracture, or moment. Since the analysis procedure was similar to the preliminary design, the resulting images of the FEA are located in Appendix F. It was noticed that the center of mass shifted from 377 mm to 480 mm due to the additional sprue bar at the center of the rack. This measurement, shown on the SolidWorks model, is provided in Appendix F. Table XXV shows the summarized results of the yielding, fracture, and moment analyses, as well as the mass of the rack.

TABLE XXV
SUMMARIZED RESULT OF STAGE 2 RACK DESIGN

| Scenario | Yielding [MPa] | | Fracture [MPa] | | Moment [Nm] | | Total Mass [kg] | |
|---|---|---|---|---|---|---|---|---|
| | FEA | Criteria | FEA | Criteria | Model | Criteria | Model | Criteria |
| A | 70.21 | 137.5 | 15.07 | 29 | 175.52 | 710 | 37.26 | 125 |
| B | 5.138 | 137.5 | 1.10 | 29 | N/A | N/A | | |

As shown in the Table XXV, the calculated yielding, fracture, moment, and mass values met the criteria values after the structure was modified. Thus, the design could be enhanced to further reduce the mass of the rack.

## 6.11 Stage 2 Enhancement

The second design enhancement involved reducing the diameter of the plate from 914 mm (3 ft) to 610 mm (2 ft) in order to reduce mass. This diameter also allowed for all sprue types to fit into the rack. After performing an FEA regarding Scenario A on the enhanced loaded rack design weighing approximately 32 kg, the team found that the connection between the plate and the central bar had high stress concentrations. This location is shown in Figure 33 regarding Scenario A.

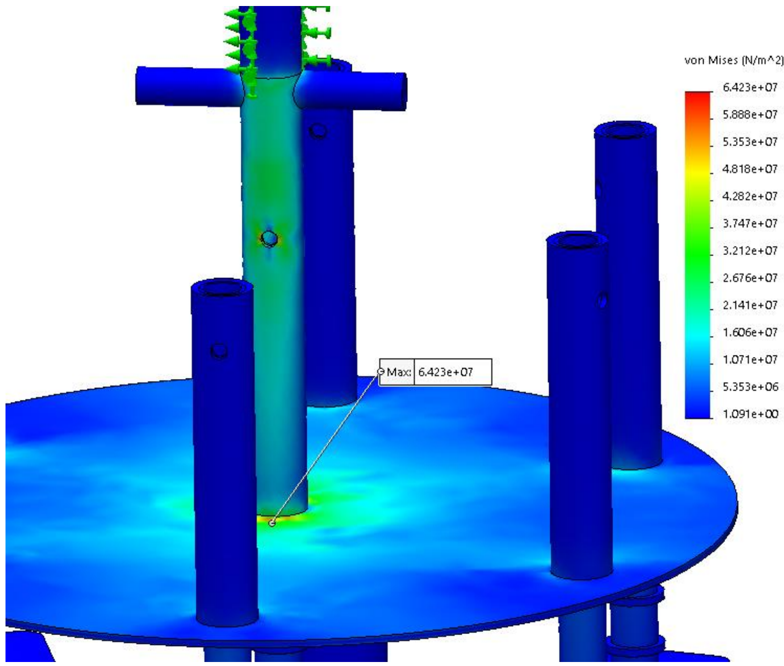


Figure 33: Location of high stress concentrations after decreasing the plate diameter.

Thus, the team decided to add a fillet to the connection between the central bar and plate to reduce the stress concentration as well as the six other sprue slots. The results of an FEA regarding Scenario A are shown in Figure 34.

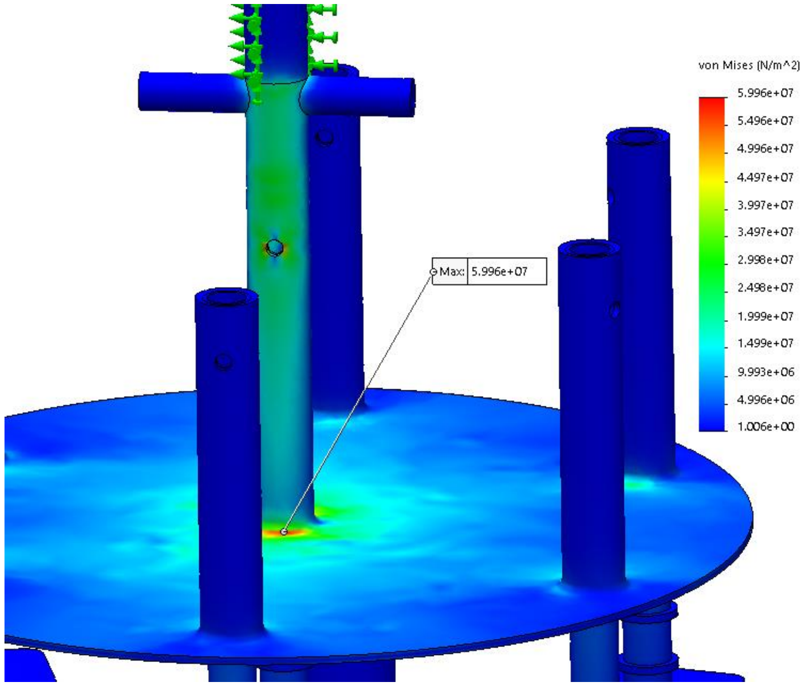



Figure 34: Improved FEA results after adding fillets at the connections.

After the fillets were implemented into the design at the connection of the central bar and the six other sprue slots, the stress decreased from 64.23 MPa to 59.96 MPa. Therefore, the fillets were included in the design to reduce the possibility of failure at the connection. An FEA was conducted to ensure structural stability regarding yielding, fracture, and the moment. Since the analysis procedure was similar to the preliminary design, the resulting images of the FEA are located in Appendix G. The distance of the center of mass shifted once more from 480 mm to 509 mm. This measurement, shown on the SolidWorks model, is provided in Appendix G. Table XXVI shows the summarized results of the yielding, fracture, and moment analyses, as well as the mass of the stage 2 rack design.

TABLE XXVI
SUMMARIZED RESULTS OF STAGE 2 RACK DESIGN

| Scenario | Yielding [MPa] | | Fracture [MPa] | | Moment [Nm] | | Total Mass [kg] | |
|---|---|---|---|---|---|---|---|---|
| | FEA | Criteria | FEA | Criteria | Model | Criteria | Model | Criteria |
| A | 59.96 | 137.5 | 12.87 | 29 | 160.08 | 710 | 32.06 | 125 |
| B | 3.128 | 137.5 | 0.68 | 29 | N/A | N/A | | |

Although the mass of the design was reduced, each of the yielding, fracture, and moment values of the design were also reduced. This suggests that adding fillets on each sprue bar slot and reducing the plate diameter drastically reduced the stresses induced in the rack. The diameter of the plate could not be reduced further due to size constraints of the sprues being mounted to the rack. Since each of the stress results regarding the second-stage rack design are under the necessary criteria, it was chosen as the final sprue bar rack design.

However, since each of the stress analyses were conducted with SolidWorks' default mesh size, a mesh convergence test was performed to ensure the values calculated from the FEA were accurate.

### 6.11.1 Convergence Test

A series of SolidWorks simulations were performed on the rack for each loading scenario, while increasing the number of finite elements for each simulation until the results of the simulation began to converge. The convergence test results for Scenario A and Scenario B are plotted in Figure 35 and Figure 36, respectively.

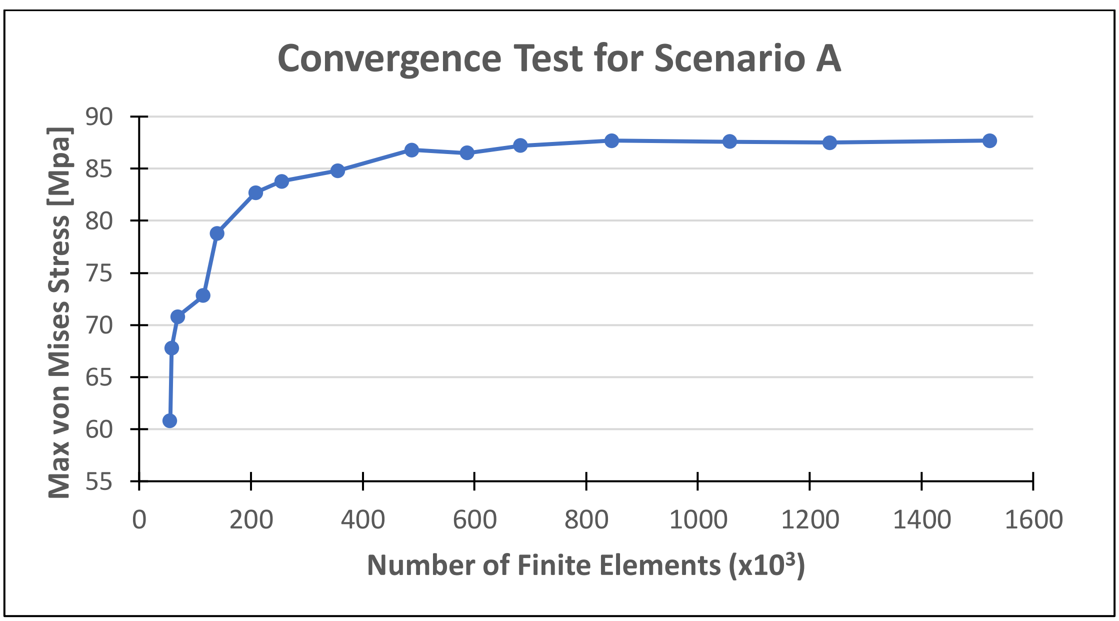



Figure 35: Convergence test results for Scenario A.

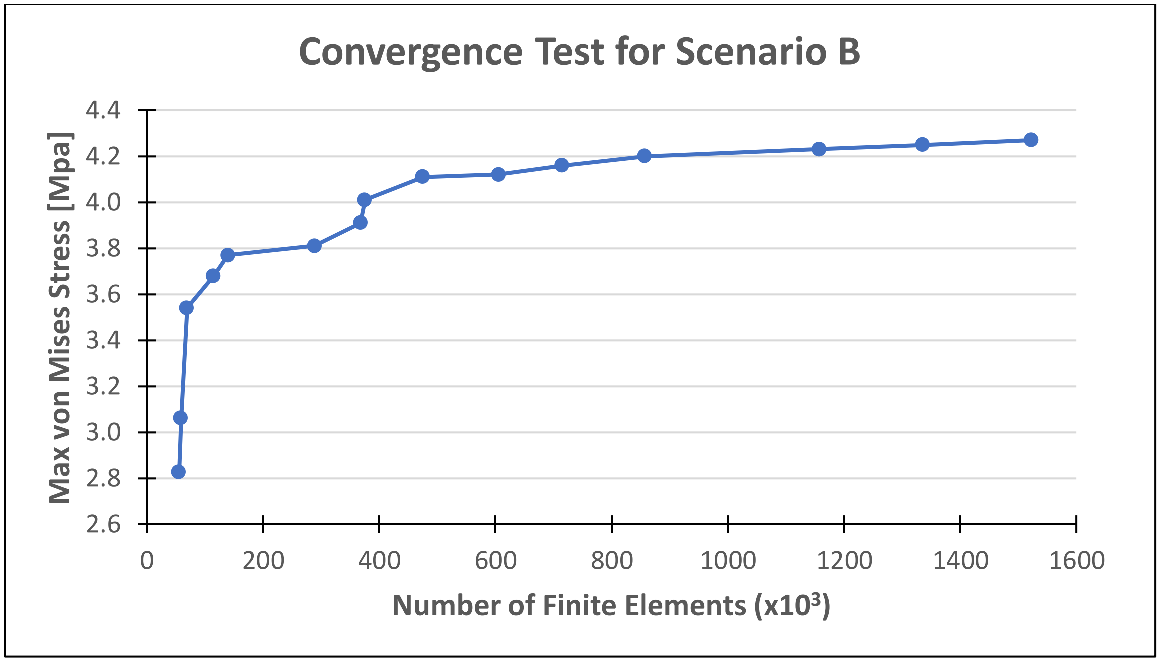



Figure 36: Convergence test results for Scenario B.

As shown in each plot, the maximum von Mises stresses for each scenario trended towards a certain value as the number of finite elements were increased. For Scenario A, the von Mises stress trended towards 87.5 MPa as the number of finite elements increased past 800,000. For Scenario B, the von Mises stress trended towards 4.20 MPa as the number of finite elements increased past 800,000. These results indicate that performing FEA with element numbers above 800,000 would provide reliable results. Therefore, the mesh sizes used in the final rack design stress simulations were set to include 1,057,925 and 1,098,214 finite elements for Scenario A and Scenario B, respectively. Figure 37 shows the mesh configuration of the final rack design established on SolidWorks for Scenario A.

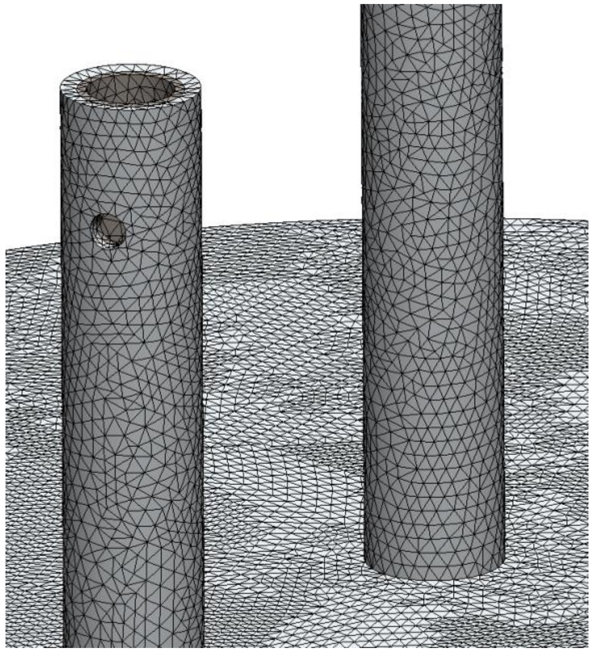


Figure 37: The final rack design with a mesh size of 1,057,925 finite elements for Scenario A.

Table XXVII shows the stress analysis results for the final rack design with finer mesh sizes. The resulting simulation configurations for the two scenarios are provided in Appendix H.

TABLE XXVII
SUMMARIZED RESULTS OF FINAL RACK DESIGN

| Scenario | Number of Finite Elements | Yielding [MPa] | | Fracture [MPa] | | Moment [Nm] | | Total Mass [kg] | |
|---|---|---|---|---|---|---|---|---|---|
| | | FEA | Criteria | FEA | Criteria | Model | Criteria | Model | Criteria |
| A | 1,057,925 | 87.7 | 137.5 | 18.83 | 29 | 160.08 | 710 | 32.06 | 125 |
| B | 1,098,214 | 4.27 | 137.5 | 0.93 | 29 | N/A | N/A | | |

As the results of the yielding and fracture analyses were within the criteria while the mesh sizes in the simulation decreased, the rack design is reliable under Scenario A and Scenario B loading circumstances.

## 6.12 Final Sprue Bar Rack Design

The final sprue bar rack design after two enhancement stages is shown in Figure 38 with the quick release pins inserted into the sprue slot holes. This design has a mass of 6.72 kg and has a capacity of seven sprue bar assemblies.

Figure 38: Render of the final sprue bar rack design.

Table XXVIII lists important dimensional characteristics of the rack. A drawing featuring detailed dimensional measurements is located in Appendix I.

TABLE XXVIII
FINAL RACK DESIGN SPECIFICATIONS

| Specification | Value |
|---|---|
| **Sprue Capacity** | 7 |
| **Sprue Slot Height [mm]** | 228 |
| **Inner Diameter of Slot [mm]** | 32 |
| **Diameter of Round Plate [mm]** | 610 |
| **Fillet Radius [mm]** | 10 |
| **Central Bar Height [mm]** | 368 |
| **Grasping Point Length [mm]** | 67 |
| **Grasping Point Diameter [mm]** | 41 |
| **T-bar Width [mm]** | 178 |
| **T-bar Diameter [mm]** | 26 |
| **Thickness [mm]** | 5 |
| **Material** | 6061-T6 Aluminum |
| **Mass [kg]** | 6.72 |
| **Loaded Mass [kg]** | 32.06 |

Casting the sprue bar rack out of aluminum is the ideal manufacturing process. However, the rack can also be welded out of aluminum tubes and an aluminum plate. Manufacturing of the rack is ultimately Matrix Industries' decision, and thus is not detailed by the team.

The quick release pins used to secure the sprue bar assemblies are the Ring-Grip Quick-Release Pins from McMaster Carr [12] shown in Figure 39. With a useable length of 51 mm (2 in) and a diameter of 11 mm (7/16 in), the pins fit perfectly into the holes of the existing mounting bars; therefore, no additional machining is required.

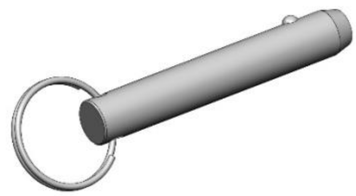


Figure 39: The McMaster Carr Ring-Grip Quick-Release Pin used to fasten sprue bar assemblies to the rack. [12]

Dimensional features, material characteristics, and the cost of each pin are listed in Table XXIX.

TABLE XXIX
RING-GRIP QUICK-RELEASE PIN SPECIFICATIONS [12]

| Specification | Value |
|---|---|
| **Useable Length [in]** | 2 |
| **Diameter [in]** | 7/16 |
| **Material** | Zinc-Plated 1144 Carbon Steel |
| **Diameter with Extended Ball [in]** | 1/2 |
| **Breaking Strength [lbs]** | 13,200 |
| **Cost per Pin [USD]** | [redacted] |

The rack was designed to ensure compatibility with the differing sizes and shapes of each sprue bar type. Type C sprues are the widest sprues at Matrix Industries. Figure 40 shows seven Type C sprue bar assemblies successfully secured to the rack. Configurations of each sprue bar type secured to the rack are located in Appendix J.

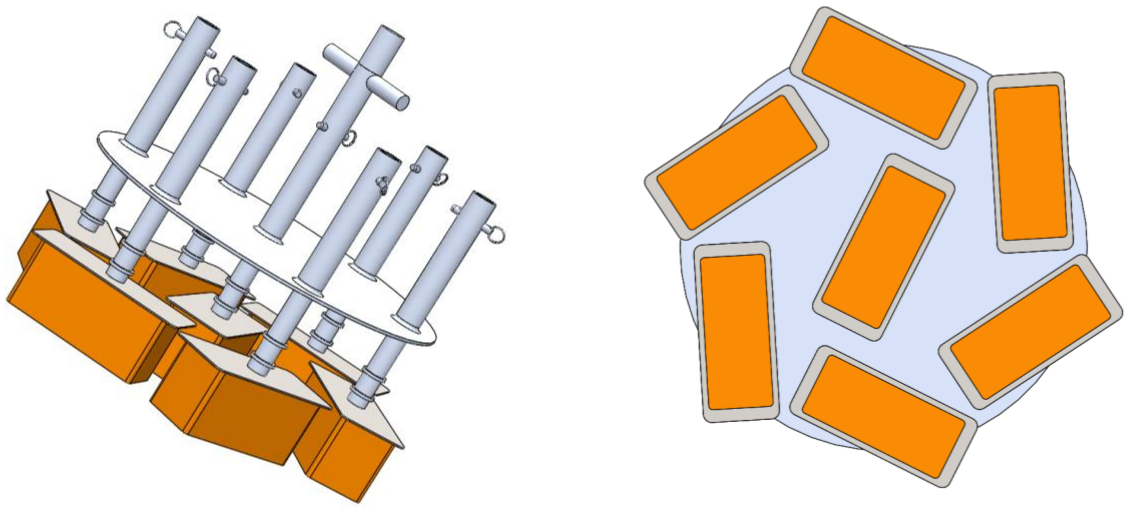


Figure 40: Final sprue rack design with seven Type C sprue bars secured.

Additionally, the rack was designed to produce different sprue types simultaneously. Figure 41 shows the rack securing one of each of the seven highest volume sprue types.

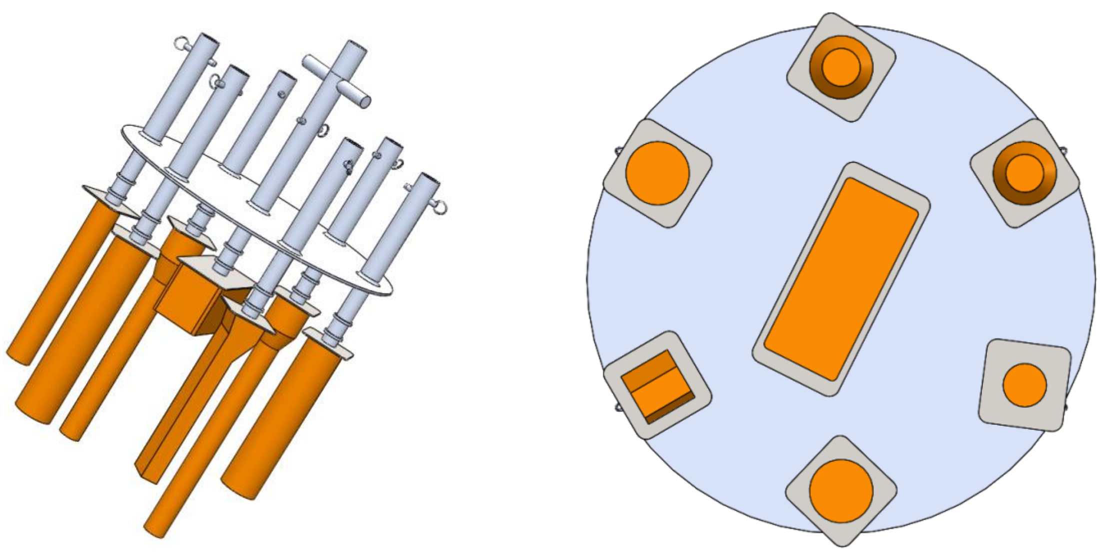


Figure 41: Final sprue rack design with all seven high-volume sprue bar types secured.

# 7 Gripper Procurement

The gripper necessary for the client's process must be able to securely grasp, lift, tilt, and rotate the rack with the attached sprue bars. Since the developed system and sprue bar rack are unique, the ideal gripper for this process would have to be specifically engineered for this process. However, designing a unique gripper for the process would be infeasible due to time constraints and lack of expertise. Thus, different types of grippers were investigated to procure a solution capable of handling the loaded sprue rack.

Prior to gripper selection, the gripper requirements needed to be specified. Grasping in Robotics [16] defines a list of relevant factors necessary to know for gripper selection. The relevant factors and the process requirements are described as follows:

- **Usage**

  Defined as the job or situation that the gripper is being selected for. The usage of the selected gripper requires a cylindrical handle to be grasped, lifted, tilted, and rotated.

- **Ambient Conditions**

  Defined as the temperature, humidity, and degree of pollution in the work area. The ambient conditions of the selected gripper will involve mild temperatures and mild humidity. However, the gripper may come into contact with dust from the ceramic slurry.

- **Workpiece**

  Defined as the type, weight, material, diameter, and location of the center of mass of the workpiece. The selected gripper must handle a 32.06 kg, 41 mm diameter, cylindrical workpiece with the center of mass located 509 mm away from the gripper top edge.

- **Gripper Type**

  Defined as the grasping method of the gripper (either parallel, angular, or centric), as well as the grasping mechanism of the gripper (either electric, hydraulic, or pneumatic). The exact gripper type necessary for the client's process was investigated further to ensure the proper gripper was selected.

- **Jaws**

  Defined as the fit of the jaw (either form fit or force fit), stroke of the jaw, mass of the jaw, and material of the jaw at the contact point. The jaw of the selected gripper must force fit a 41 mm diameter cylinder with a strong jaw material.

- **Forces**

  Defined as the acceleration and process forces on the gripper. The selected gripper must handle a 32.06 kg part that produces a 160 Nm moment at the grasping point.

Since all of the relevant factors in the client's process were defined previously, with exception to the gripper type, further research was conducted to determine a suitable gripper type.

Grasping in Robotics [16] states that pneumatic grippers are compact, easily commissioned, attractively priced, and have high gripping forces, whereas electronic grippers allow for control over the position, stroke, closing speed, and force of the gripper. Since all of the pneumatic gripper attributes are relevant to the client's process, and none of the electronic gripper attributes are, a pneumatic gripper is most suitable.

The grasping method of the gripper is categorized into three types; parallel, angular, or centric. Within each category, there are different finger arrangements. The different arrangements are listed from Grasping in Robotics [16].

- Two finger parallel gripper
- Three finger centric gripper
- Two finger angular gripper
- Three finger angular gripper
- Two finger radial gripper
- Four finger concentric gripper
- Special long stroke grippers

Since the workpiece is cylindrical and does not need precise picking, a three finger centric gripper has the most suitable finger arrangement.

Table XXX lists each of the relevant factor requirements necessary for proper selection of the gripper. Thus, the selected gripper must comply to each and every one of the requirements listed.

TABLE XXX
RELEVANT FACTOR REQUIREMENTS FOR GRIPPER SELECTION

| | |
|---|---|
| **Ambient Conditions** | Dust |
| **Closing Force [N]** | 15,010 |
| **Workpiece Weight [kg]** | 32 |
| **Workpiece Shape** | Cylinder |
| **Workpiece Diameter [mm]** | 41 |
| **Maximum Moment [Nm]** | 160 |
| **Driving Mechanism** | Pneumatic |
| **Finger Arrangement** | Three Finger Centric |

Through investigation, it was determined that SCHUNK was the standalone company for selecting a gripper. By searching SCHUNK's selection of grippers from their website [15], the most suitable gripper was determined to be the SCHUNK PZN-plus 160-2-AS-SD based on the requirements in Table XXX. The gripper, without fingers attached, is displayed in Figure 42, with its specifications listed in Table XXXI.

Figure 42: The selected SCHUNK gripper; the PZN-plus 160-2-AS-SD. [17]

TABLE XXXI
SPECIFICATIONS OF THE SELECTED SCHUNK GRIPPER [17]

| | |
|---|---|
| **Product Name** | PZN-plus 160-2-AS-SD |
| **Finger Arrangement** | Three finger centric |
| **Grasping Mechanism** | Pneumatic |
| **Version** | Dust-tight version |
| **Stroke per Jaw [mm]** | 8 |
| **Weight [kg]** | 8.9 |
| **Recommended Workpiece Weight [kg]** | 55 |
| **Moment Mx Maximum [Nm]** | 170 |
| **Moment My Maximum [Nm]** | 180 |

The maximum moments detailed in Table XXXI are defined by the directions shown in Figure 43. Since the moment in the z-direction ($M_z$) and the force in the downward z-direction ($F_z$) are minimal, the corresponding specifications were excluded from Table XXXI.

[redacted]

Figure 43: Notation of the moments and force acting on the gripper. [17]

Finally, the team designed preliminary fingers for the gripper that would allow the robot to grasp and manipulate the rack throughout the sprue bar forming process. Figure 44 shows three basic preliminary fingers attached to the gripper. They are designed such that the diameter of the central bar will be grasped sufficiently with the 8 mm stroke of the gripper. Each finger has a height of 64 mm 2.5 (in), which allows it to pick up the rack from above the handles.

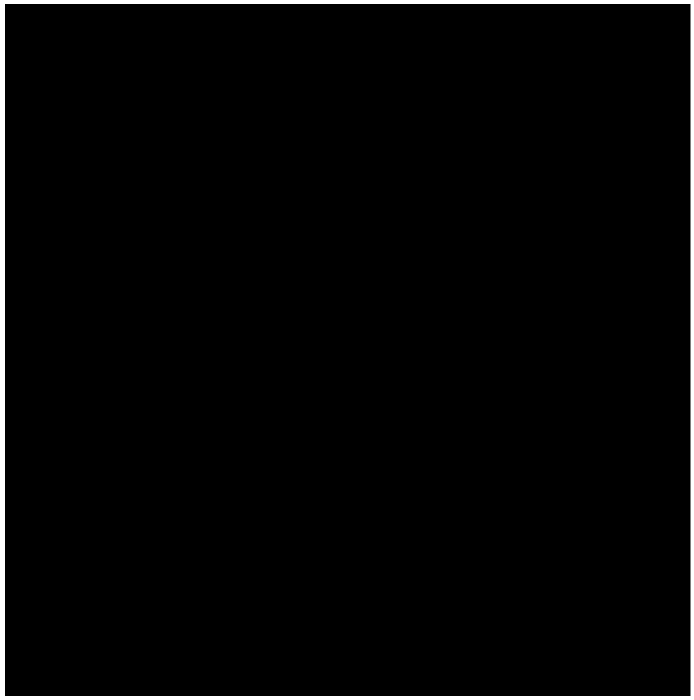


Figure 44: Gripper with three custom designed fingers attached grabbing the rack central bar.

Stress and failure calculations were not performed on the gripper fingers. It is recommended that Matrix Industries either designs ideal fingers or outsources the design of ideal fingers should they choose to implement this system into their design.

# 8 Work Center Layout and Process Flow

A preliminary work center layout and a preliminary process flow were designed for the sprue bar forming process and the ceramic mold coating process. Although an in-depth analysis of the ceramic process is out of the scope of this project, Matrix Industries requested that the robot system be compatible with the ceramic process. The work center was designed for an efficient use of space and the process flow was designed to minimize sprue bar production time. The layout does not feature exact positions of each process component, as an exact layout should be conducted by Matrix Industries to ensure the process can be implemented into the existing infrastructure and plant layout.

## 8.1 Work Center layout

To maximize the operational space of the robot, the robot was located in the center of the fixed components, such as the tanks, shelves, and rainfall sander. The fixed components were arranged in a circular formation along the outer edge of the robot's reach, as shown in Figure 45. This reduces the risk of collisions with other equipment and allows the work center to include both the wax sprue bar process and the ceramic mold process. The wax tank is located on the opposite end of the ceramic tanks, allowing for multiple shelves to be located in between the tanks. These shelves hold the initial sprue bar racks, the wax sprue Work-In-Progress (WIP), the ceramic WIP, and the completed molds. The wax sprue bar process has a total work area of 2.75 m x 1.52 m (9 ft x 5 ft), which is within the 2.75 m x 2.13 m (9 ft x 7 ft) constraint.

.

Figure 45: Recommended layout of the robot work center.

## 8.2 Wax Sprue Production Process Flow

Once the preliminary work center layout had been established, the wax testing and data collection results were used to generate a recommended process flow for producing wax sprue bars. Figure 46 shows the recommended process flow chart for consistent wax sprue bars.

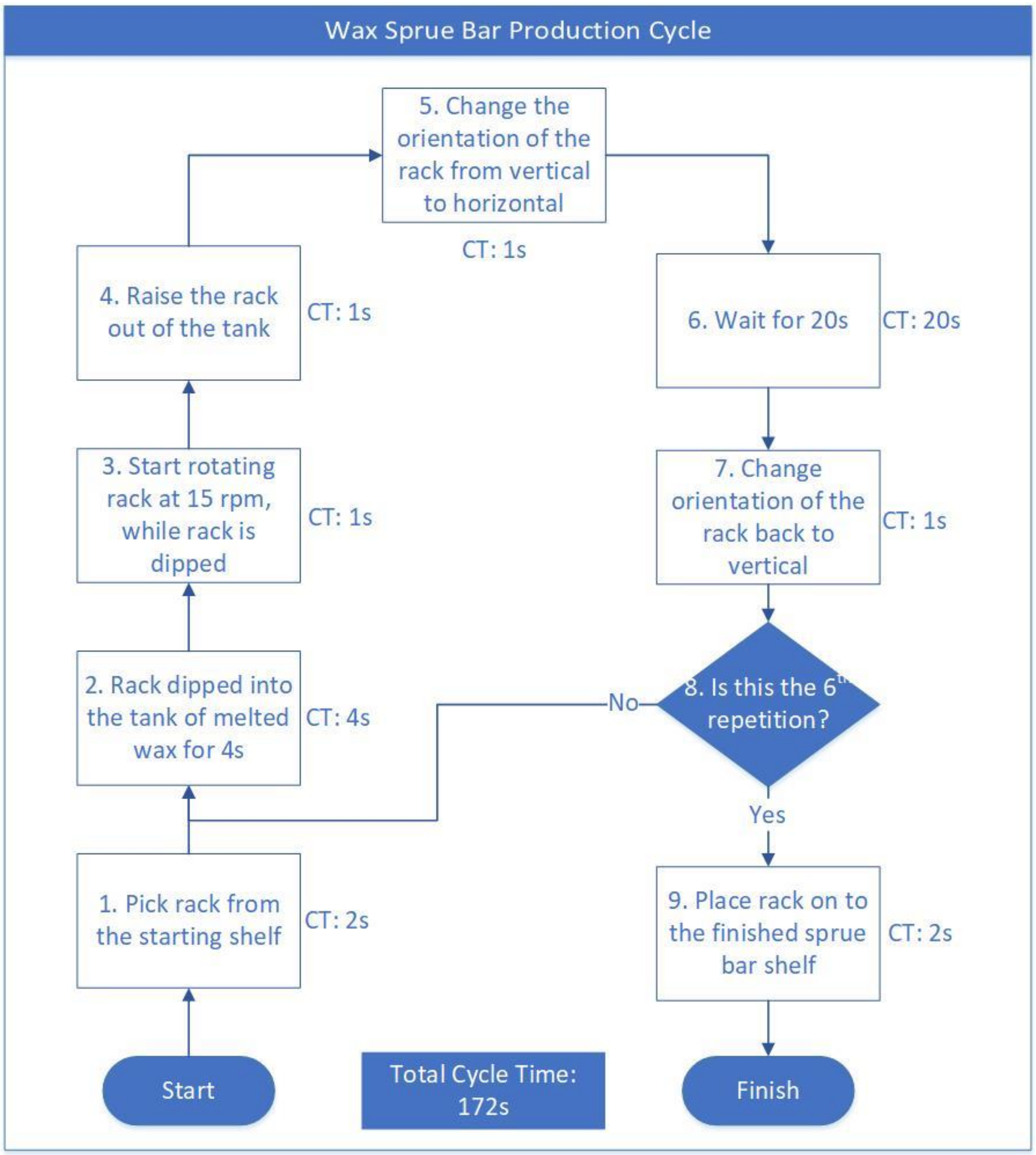



Figure 46: Recommended process flow for the production of wax sprue bars.

Each step of the wax sprue production process flow is briefly detailed as follows:

1. The robot grasps the rack from the top of the central bar and lifts the rack off the shelf. This step is displayed in Figure 47.

Figure 47: Robot lifting a rack of sprue bars from a shelf.

2. The robot dips the sprue bars into the wax tank for four seconds, as shown in Figure 48.

Figure 48: Robot dipping a rack of sprue bars into a wax tank.

3. The robot begins rotating the sprue bar rack while it is still in the tank.
4. The robot raises the rack out of the tank while rotating the rack.

5. The robot tilts the rack until it is parallel to the ground while rotating the rack. Figure 49 shows the robot holding the rack in the horizontal position.

Figure 49: Robot holding the rack in the horizontal orientation. The robot also concentrically rotates the rack while in this position.

6. The robot maintains the rack in the horizontal and rotates the rack for 20 seconds while the wax hardens.
7. The robot tilts the rack back to the vertical orientation.
8. The robot repeats the dipping and rotating steps, steps 2 through 7, five times for a total of six dips.
9. The robot places the rack onto the wax curing shelf, as shown in Figure 50.
10. The robot begins the cycle again with a new sprue bar rack.

Figure 50: Robot hanging a rack on the wax curing shelf.

Ideally, ten sprue bar racks are necessary to maintain efficient cycle repetitions where the robot is functional and conducting value added work. Note that this number of racks in not shown in the previous figures to allow for a better view of the process. This allows for a starting shelf of four racks, and as the four racks are completed, another shelf of four racks can be replaced, while two racks are on the WIP shelf.

The total cycle time for this process is 172 seconds, which produces seven sprue bars every cycle. This means the total sprue bar capacity of this work center is approximately 146 sprue bars per hour.

## 8.3 Ceramic Coating Process Flow

A preliminary ceramic coating process flow was generated to ensure compatibility with the robot system. The entire work area, including the wax sprue production process and the ceramic coating process, forms a circle with a diameter of 6.7 m (22 ft). Figure 51 shows the recommended process flow chart for the ceramic molds.

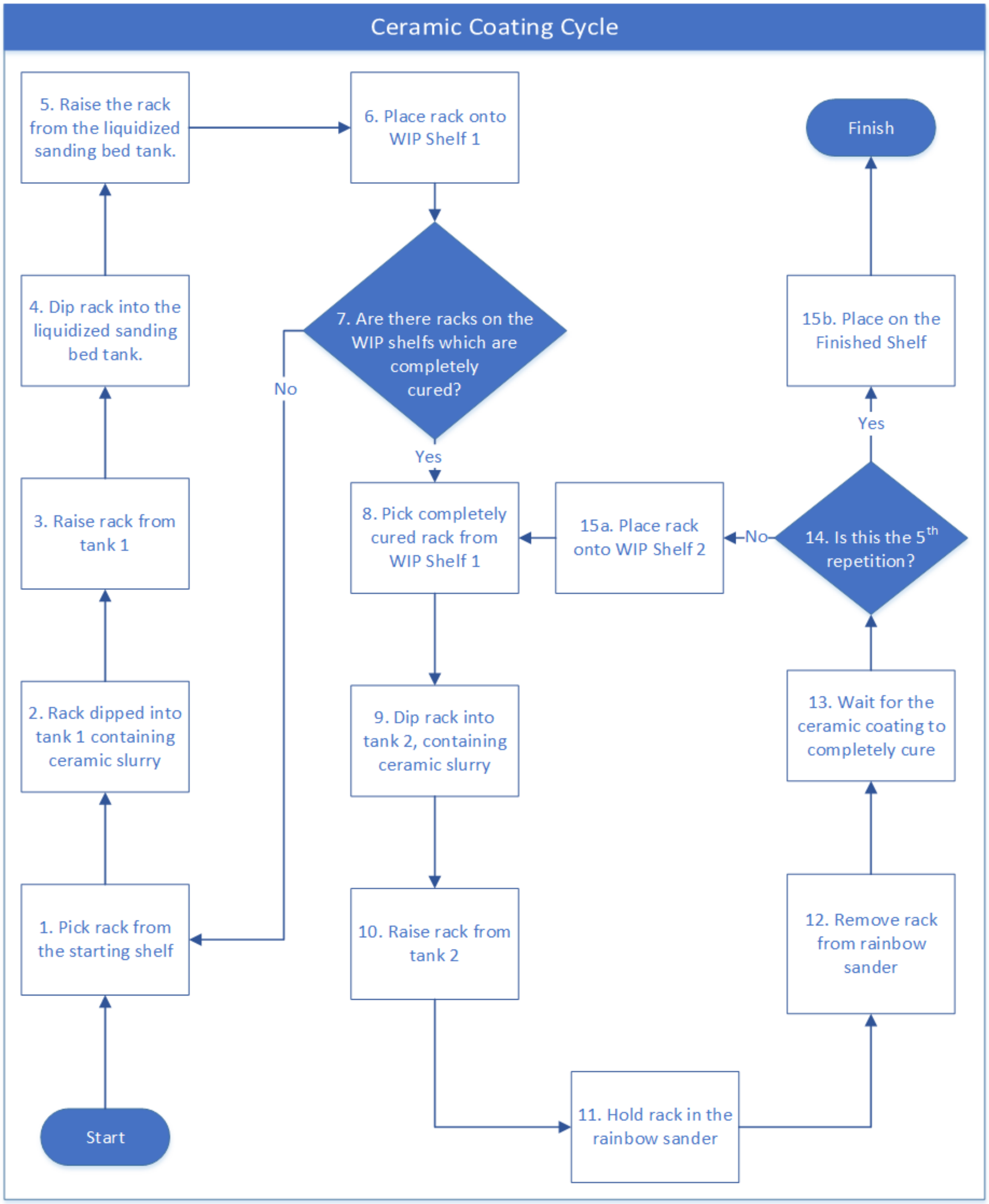



Figure 51: Recommended process flow for the ceramic coating process.

1. The robot grasps the rack from the top of the central bar and lifts the rack off the shelf.
2. The robot dips the wax trees into the first ceramic tank, as shown in Figure 52.

[redacted]

Figure 52: Robot dipping a rack into ceramic tank 1.

3. The robot raises the rack out of the tank.
4. The robot dips the rack into the liquidized sanding bed, coating the ceramic in sand. This step is displayed in Figure 53.

[redacted]

Figure 53: Robot dipping a rack into the liquidized sanding bed.

5. The robot raises the rack out of the tank.
6. The robot places the rack onto WIP shelf 2.

7. The robot repeats steps 1 through 6 if no ceramic coatings have cured on WIP shelf 2. If any ceramic coatings have cured on WIP shelf #2, the robot proceeds to step 8.
8. The robot lifts a cured rack from WIP shelf 2.
9. The robot dips the rack into the ceramic tank 2, as shown in Figure 54.

Figure 54: Robot dipping a rack into ceramic tank 2.

10. The robot raises the rack out of ceramic tank 2.
11. The robot holds the rack in the rainfall sander, as shown in Figure 55.

Figure 55: Robot holding a rack in the rainfall sander.

12. The robot removes the rack from rainfall sander and hangs it on WIP shelf 2.
13. The robot waits for the ceramic coating to completely cure.
14. The robot repeats steps 8 through 13 four additional times until the wax tree has been completely coated in ceramic.
15. The robot places the rack on the finished shelf.

This process is flow is a preliminary recommendation. An ideal process flow and cycle times should be determined by Matrix Industries prior to implementation of the system.

# 9 Process Additions

During the analysis of the top four concepts, the robotic arm concept scored low in the locator marking and quality criteria. Due to this, the project team came up with two process additions to combat these.

## 9.1 Locator Design

The locator design provides the function of creating marks on the wax sprue bar with the purpose of helping process operators identify the mounting locations of the wax patterns. In addition, the client suggested using 6.35 mm (1/4 in) spacing of the locator teeth. The team produced a preliminary locator design concept to accomplish this task, which is shown in the Figure 56.

Figure 56: Preliminary locator design concept.

The locator has a length of 457 mm (18 in), width of 51 mm (2 in), and thickness of 6.35 mm (1/4 in), with teeth spacing of 6.35 mm (1/4 in). The length of the locator allows it to mark the pattern locations on any of the sprue types Matrix Industries uses. This locator can be produced using any type of steel plate and the simple design allows for straightforward manufacturability, making the locator inexpensive and easy to produce.

## 9.2 New Sprue Bar Design

Another process addition designed by the project team was the integration of a radius to the top of the circular sprue bars. Figure 57 illustrates the integration of a radius to a Type I sprue bar.

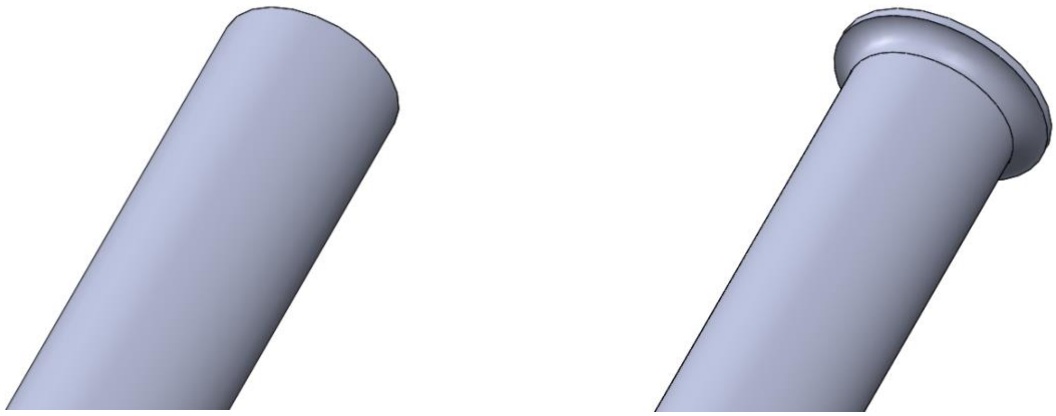


Figure 57: Old Type I sprue bar versus new Type I sprue bar.

The addition of a radius to the top of all the circular sprue bars minimizes the ceramic debris that falls into the ceramic mold. In addition, the structural rigidity of the top of the circular sprue bars would also increase with the addition of a radius. The engineering drawings for all five circular sprue bars with a radius on the top can be seen in Appendix I.

# 10 Cost-Benefit Analysis

A preliminary cost-benefit analysis was performed to determine the potential cost effectiveness of the FANUC robot based on how quickly the robot recovers the cost of its initial investment. According to Dr. Balakrishnan, a cost-effective robot would, ideally, have a payback period of approximately 15 months or less. Given that the average worker hourly wage in the process is [redacted] CAD, the payback period of the robot, based on the procurement cost of the robot, operator training, gripper, and shipping, totalling [redacted] CAD, is calculated to be [redacted]. This is reasonable as it only accounts for the wax sprue bar production process. This system is also capable of automating the ceramic mold production process, which would drastically reduce the payback period of the robot. However, investigation into the ceramic mold production process is out of the scope of the project.

The analysis of the payback period was calculated using the data found in Table XXXII. The robot cost, shipping cost, and training cost were provided in USD in the FANUC price quotation. These prices excluded taxes, and since the FANUC distributor is located in Ontario, the Ontario sales tax and current USD to CAD conversion rate as of November 22, 2019 were used in the calculation. Since the robot would relieve three wax process workers of one eight-hour shift per day, the hours relieved per day is 24.

TABLE XXXII
VALUES USED IN PAYBACK PERIOD CALCULATION

| | |
|---|---|
| **Robot Cost [USD]** | [redacted] |
| **Training Cost [USD]** | [redacted] |
| **Shipping Cost [USD]** | [redacted] |
| **Gripper Cost [USD]** | [redacted] |
| **Ontario Sales Tax** | 13% |
| **Current Conversion Rate (USD to CAD)** | 1.33 |
| **Hourly Wage [CAD]** | [redacted] |
| **Hours Relieved per Day** | 24 |
| **Work Days per Month** | 20 |

The values in Table XXXII were used in Equation (3) to determine the payback period.

$$Payback\ Period = \frac{(Robot\ Cost + Training\ Cost + Gripper\ Cost) \times Tax \times Conversion\ Rate}{Worker\ Wage \times Hours\ per\ Day \times\ Days\ per\ Month} \quad (3)$$

It is important to note that the costs used to calculate the payback period are not exhaustive. Additional costs including power consumption, commissioning, electrical integration, process programming, purchase of the gripper and sprue bar racks, and possibly many others, should be included in the cost-benefit analysis prior to purchase. Conversely, relieving employees of their sprue casting process duties would allow them to contribute elsewhere in the casting process and could increase production value. Thus, it is recommended that an intensive cost-benefit analysis is performed by Matrix Industries prior to purchase.

# 11 Recommendations

Before implementation of a robotic sprue casting system, a number of additional factors must be considered by Matrix Industries to ensure economic feasibility and proper process performance. These factors include, but are not limited to, safeguards, commissioning, electrical integration, pneumatic and hydraulic integration, employee training, operator training, software programming, and the possible risks.

Safeguarding is required for any robot in a manufacturing plant, and consists of a safety fence, safety gate with interlocking devices, safety plug and socket, and other protection devices [18].

The safety fence is required to:

- prevent access to the safeguarded space, except through openings equipped with interlocking or presence sensing devices,
- withstand foreseeable operational and environmental forces,
- be fixed in place and only removable with the use of tools,
- cause minimum obstruction to the view of the workspace,
- be located sufficient distance from the workspace of the robot.

The safety gate and plug are required to:

- prevent the robot system from operation until the guard is closed,
- not restart automatic operation upon closure of the guard,
- remain locked and closed until risk of injury from any hazard is negated.

Other protection devices can be implemented into the design of the safeguarding system depending on the client's desires. Such protection devices include presence sensing devices that would cease operation of the robot if an object enters the safeguarded area. It is recommended that Matrix Industries investigates the most suitable safeguarding measures for their process and can refer to ISO 10218 for proper safety standards.

Commissioning of the robot by a governing safety authority must take place prior to initialization of the system. It is recommended that Matrix Industries understands the cost of commissioning and researches the proper commissioning process prior to purchase of the robot.

Matrix Industries must also ensure the proper electrical, pneumatic, and hydraulic infrastructure is present in their facility prior to implementation of the robot. Otherwise, the proper infrastructure must be implemented.

The cost of employee training regarding use of the robot is included in the FANUC quote. However, either a specified FANUC robot operator should be hired or contracted to monitor proper operation of the robot, or a current Matrix Industries employee should be trained in the operation and programming of the robot. This is important as process problems are inevitable, such as loss of power to the robot or unexpected cancellation of the process and can result in robot and product damage if not rebooted correctly.

It is essential that Matrix Industries performs an in-depth risk assessment to mitigate any risks they may face based on their implementation plans.

Overall, it is recommended that Matrix Industries investigates the solutions suggested in this document and works with the proper third parties to ensure their needs are met. This includes working with the robot manufacturer of their choice to procure the ideal robot and working with a gripper manufacturer to design the ideal gripper for their system.

# 12 Conclusion

The project team was tasked with designing a preliminary system to increase the output of Matrix Industries' sprue bar casting process from five sprue bars per hour to 50 sprue bars per hour. The team designed an automated system capable of producing up to 146 sprue bars per hour by repeatedly dipping seven sprue bars simultaneously into a wax tank until the proper wax thickness is achieved. This system consists of a procured robot, a procured gripper, and a designed sprue bar rack. A Bill of Materials is located in Appendix K.

After researching four different robot manufacturers and dealing with representatives from three of them, the FANUC R-2000iC/125L was determined to be the ideal robot for this system. This robot has a reach of 3.1 meters and is capable of handling parts up to 125 kilograms.

The team designed a sprue bar rack capable of securing seven sprue bars simultaneously, which allows the robot to produce seven sprues concurrently. This rack can be integrated into all of Matrix Industries current infrastructure and can secure any combination of sprue bar types. Ideally, ten racks would be implemented into the wax sprue production system but would have to be manufactured. An accurate manufacturing price was not established.

A gripper, which allows the robot to handle the racks, was selected. The SCHUNK PZN-plus 160-2-AD-SD is a three finger concentric gripper with a recommended workpiece weight of 55 kilograms.

The robot system consisting of the robot, operator training, gripper, and rack, displayed in Figure 58, costs [redacted] CAD and has a payback period of [redacted]. However, if Matrix Industries also incorporates this system into the ceramic coating process, the payback period will decrease significantly. Although this cost is outside the initial project cost constraint, the client agreed that designing an expensive, yet cost-efficient, robot system is acceptable.

[redacted]

Figure 58: Final robot system designed to produce wax sprues.

Aside from the initial cost constraint, this design meets or exceeds all project constraints. At 9 ft x 5 ft, the workplace area is within the 9 ft x 7 ft constraint. The sprue hardening time of the robot system is two minutes, which is under the 15 minutes constraint. The sprue bar rack allows the system to produce all of Matrix Industries' sprue types and is able to produce any combination of sprue types simultaneously. Finally, the robot system meets all other quality constraints that were initially established.

Before Matrix Industries considers implementing this design, or a similar design, into the current process, it is recommended that Matrix Industries considers numerous factors including, but not limited to, additional implementation costs, safeguarding methods, and robot maintenance. Although the project team has recommended the FANUC robot and the SCHUNK gripper, the rest of the system is capable of working with any type of robot and gripper that meet the client's requirement. Overall, it is the decision of Matrix Industries to use this system, or any part of this system, to improve the current sprue bar production process.

# 13 References


[1] "Matrix Industries - Metal Casting in Winnipeg." [Online]. Available: http://www.matrixmetalcasting.com/. [Accessed: 24-Oct-2019].

[2] S. Balakrishnan, Oct-2019.

[3] "Industrial Robot Finder Tool | FANUC America." [Online]. Available: https://www.fanucamerica.com/products/robots/robot-finder-tool. [Accessed: 10-Nov-2019].

[4] "Industry Leading R-2000 Series Robots | FANUC America." [Online]. Available: https://www.fanucamerica.com/products/robots/series/r-2000. [Accessed: 10-Nov-2019].

[5] "GP180 | Motoman Industrial Robots - Yaskawa Motoman Robotics." [Online]. Available: https://www.motoman.com:443/en-us/products/robots/industrial/assembly/gp-series/gp180. [Accessed: 10-Nov-2019].

[6] "Our businesses - ABB Group." [Online]. Available: https://new.abb.com/about/our-businesses. [Accessed: 10-Nov-2019].

[7] "IRB 6700 - Industrial Robots From ABB Robotics." [Online]. Available: https://new.abb.com/products/robotics/industrial-robots/irb-6700. [Accessed: 10-Nov-2019].

[8] "Robot systems," *KUKA AG*. [Online]. Available: https://www.kuka.com/en-ca/products/robotics-systems. [Accessed: 10-Nov-2019].

[9] "IRB 120 - Industrial Robots (Robotics) - Industrial Robots From ABB Robotics." [Online]. Available: https://new.abb.com/products/robotics/industrial-robots/irb-120. [Accessed: 23-Nov-2019].

[10] "DX200 - Yaskawa Motoman Robotics." [Online]. Available: https://www.motoman.com:443/en-us/products/controllers/dx200. [Accessed: 23-Nov-2019].

[11] "ABB Teach Pendant." [Online]. Available: https://new.abb.com/products/3HAC028357-001/teach-pendant. [Accessed: 23-Nov-2019].

[12] “McMaster-Carr.” [Online]. Available: https://www.mcmaster.com/. [Accessed: 25-Nov-2019].

[13] “MetalsDepot® - 3003, 5052, 6061 Aluminum Sheet.” [Online]. Available: https://www.metalsdepot.com/aluminum-products/aluminum-sheet. [Accessed: 24-Nov-2019].

[14] R. G. Budynas and J. K. Nisbett, *Shigley’s Mechanical Engineering Design*, 10th ed. McGraw-Hill Education, 2015.

[15] “SCHUNK Grippers.” [Online]. Available: https://schunk.com/de_en/gripping-systems/category/gripping-systems/schunk-grippers/. [Accessed: 25-Nov-2019].

[16] G. Carbone, Ed., *Mechanisms and Machine Science: Grasping in Robotics*, vol. 10. Springer-Verag London, 2013.

[17] “PZN-plus 160-2-AS-SD.” [Online]. Available: https://schunk.com/de_en/gripping-systems/series/pzn-plus/. [Accessed: 25-Nov-2019].

[18] “FANUC Safety Manual.pdf.” [Online]. Available: https://www.fanucamerica.com/cmsmedia/robots/safety/. [Accessed: 30-Nov-2019].

# Appendix A – Sprue Bar Types

## Table of Contents



## List of Figures



The drawings of six of seven sprue bar types are provided in Figures A1 through A6. The dimensions for sprue Type I were not available in order to generate CAD drawings. the production volumes of all seven sprue bar types at Matrix Industries are tabulated in Table AI.

TABLE AI
PRODUCTION VOLUMES OF ALL SEVEN SPRUE BAR TYPES IN MATRIX INDUSTRIES

| Sprue Bar Type | Production Volume |
|---|---|
| **A** | 160 per year |
| **C** | 500 per year |
| **F** | 500 per year |
| **G** | 170 per year |
| **H** | 950 per year |
| **I** | 1500 per year |
| **M** | 900 per year |

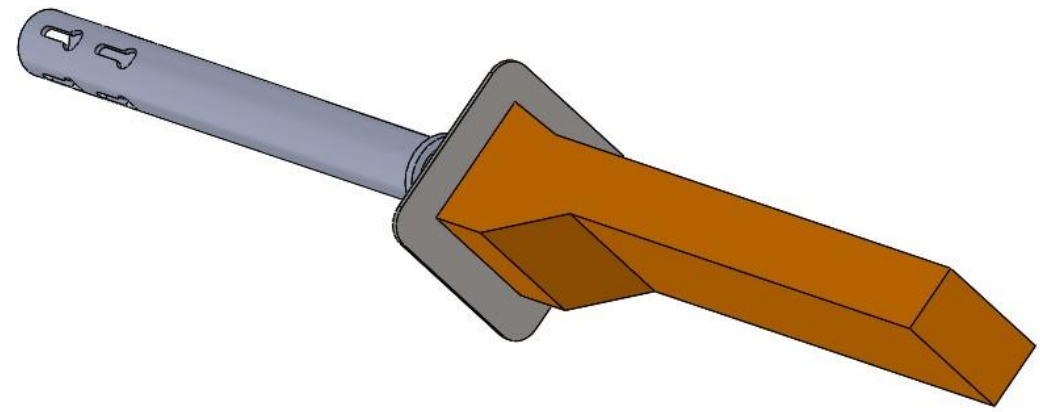


Figure A1: Type A Sprue Bar.

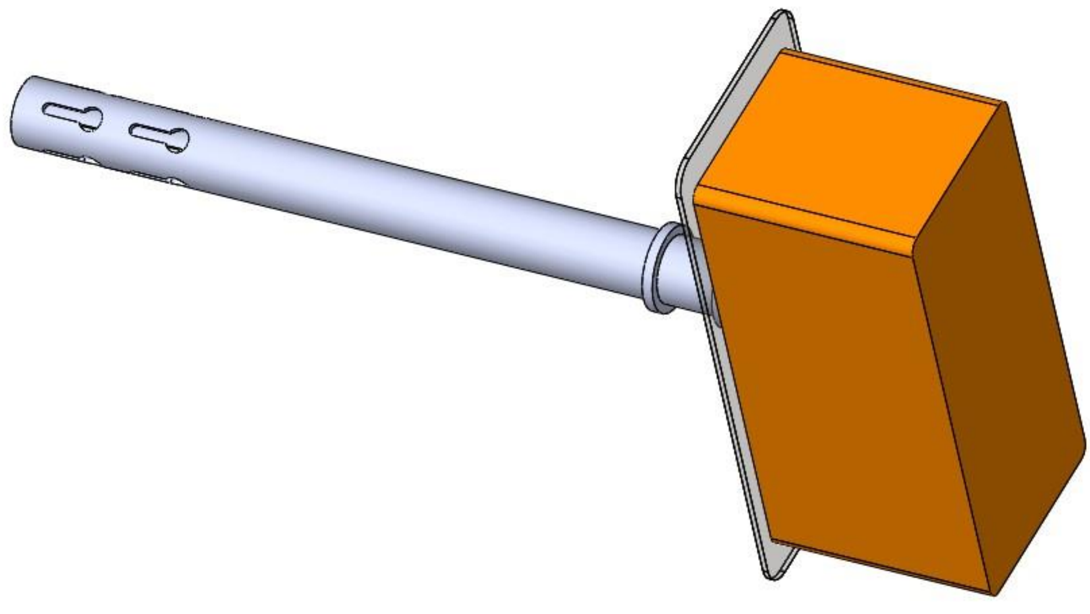


Figure A2: Type C Sprue Bar.

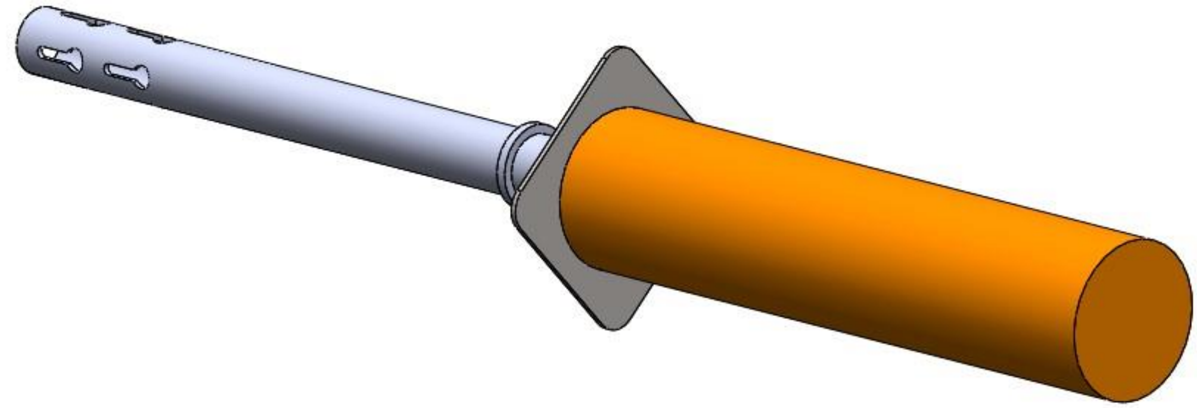


Figure A3: Type F Sprue Bar.

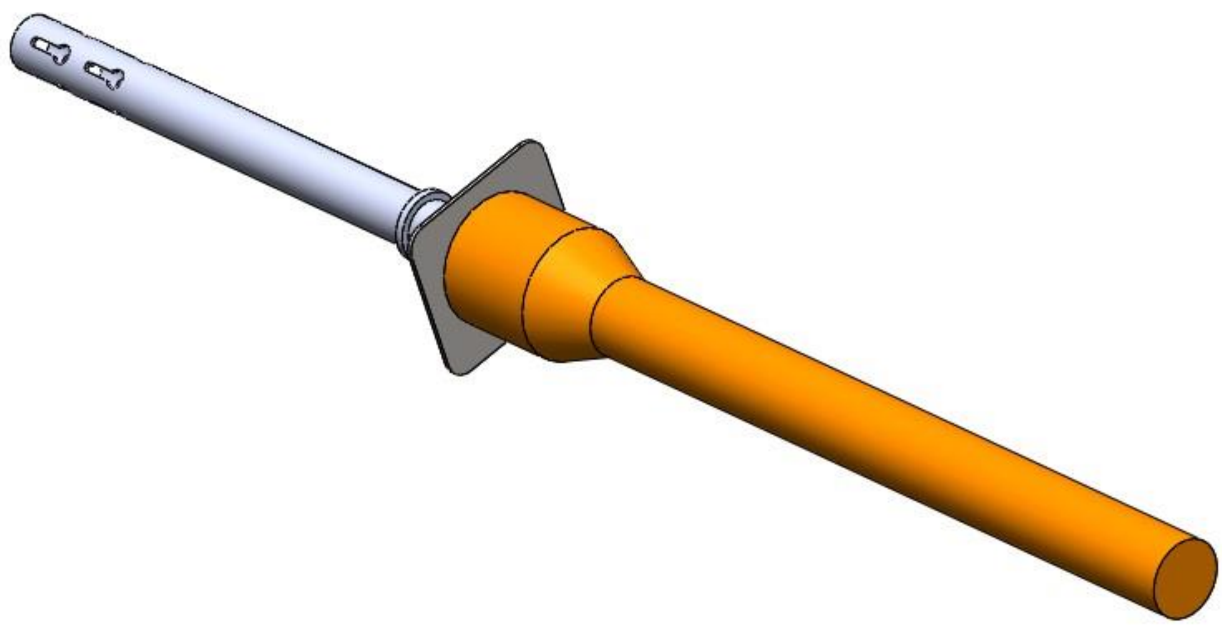


Figure A4: Type G Sprue Bar.

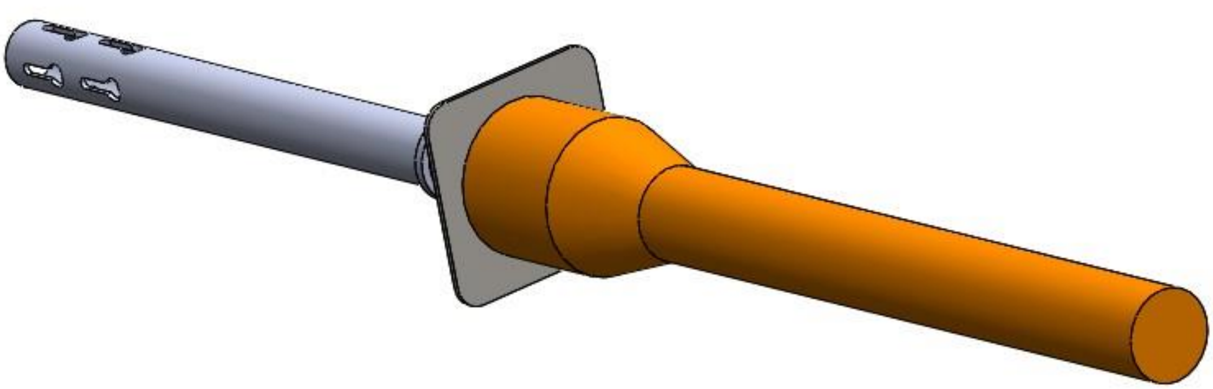


Figure A5: Type H sprue Bar.

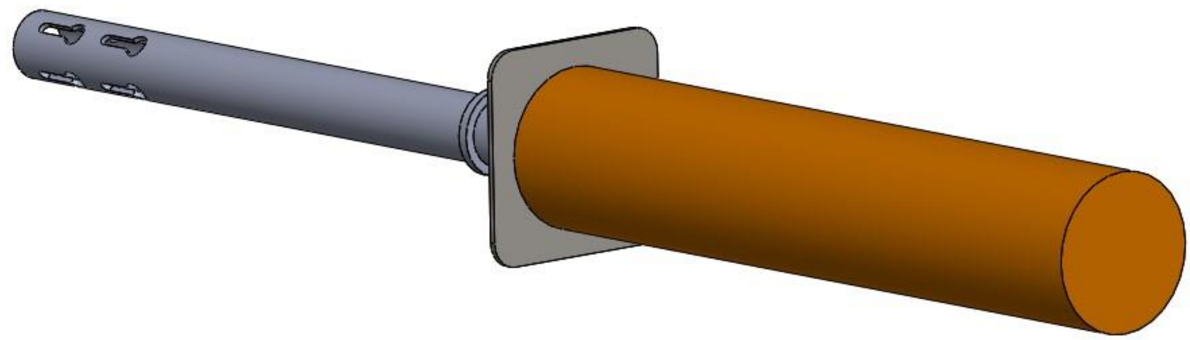


Figure A6: Type M Sprue Bar.

# Appendix B – Data Collection Tests

## Table of Contents



## List of Figures



## List of Tables

Appendix B provides the strategy implemented by the team and the data collected to test the performance of the wax sprue dipping process.

## Test Strategy

A data collection strategy was used to collect data since the Robotic Arm dips the sprue bars into a wax tank and relies on lifting and rotating the sprue bar for even curing, a series of tests were conducted to help determine the following:

- Thickness of wax coating after each dip
- Curing time for wax after each dip in the wax tank
- Best motion for sprue bars after dipping for the smoothest finish
- Total cycle time for sprue bar forming process

The thickness of the wax coating was measured to ensure it satisfies the standard wax coating thickness of 0.3 in or 7.62 mm from the current wax sprue bar process. To measure the thickness of the wax coating after each test trial, a length of wax coating was cut from the sprue bar as displayed in Figure B1.

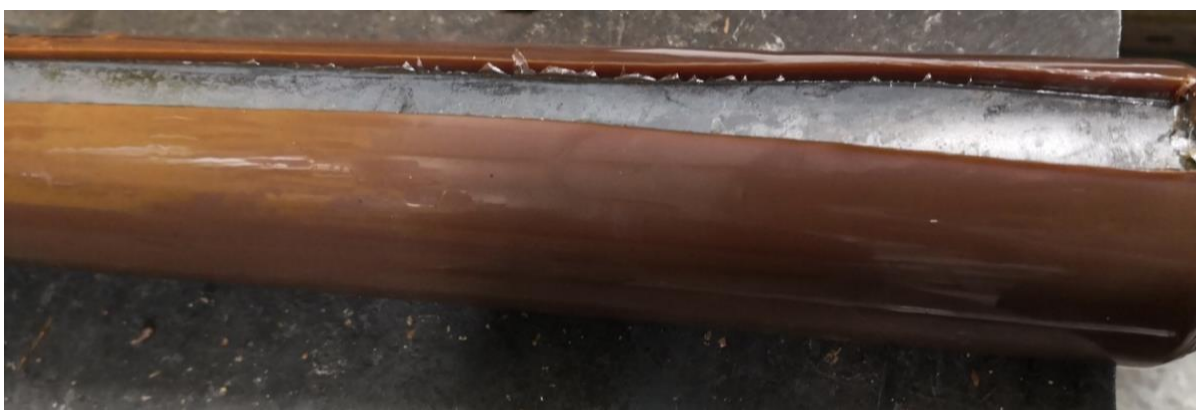


Figure B1: Wax coating section cut.

A Vernier caliper was used to take measurements at the top, middle, and bottom of the wax coating section. All these tests were conducted manually by the project team at the Matrix Industries facility. A type F sprue bar assembly was used for all experiments as control, which is shown in Figure B2.

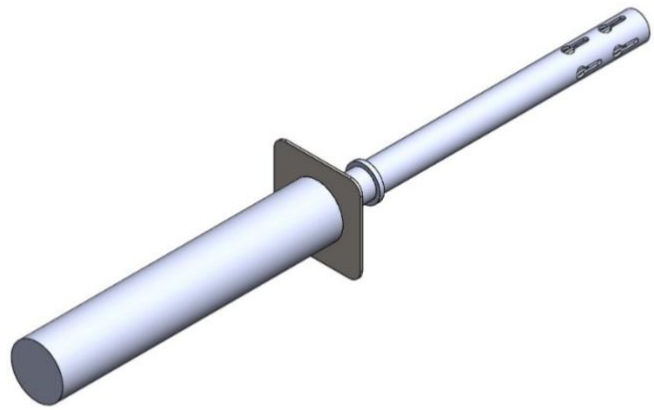


Figure B2: Type F sprue bar assembly, used for all experiments as control.

## Test 1

The steps for Test #1 were as follows:

1. Assemble the type F sprue bar assembly.
2. Dip the center bar into the tank of melted wax and remove it.
3. Allow the wax to completely cure before dipping it into the tank a second time.
4. Measure the thickness of wax coating after each test.
5. Repeat each step until a thickness of approximately 7.62mm (the average thickness of the current sprue bars) is achieved.

For this test, the same sprue bar was dipped until a thickness of 7.62 mm is achieved. This test helps determine the curing time for wax on the center bar, as well as the difference in thickness of the wax when the assembly remains in a vertical position. The results for Test #1 are shown in Table BI.

TABLE BI
TEST #1: WAX COATING THICKNESS RESULTS

| Section of Wax Coating | Thickness of Wax [mm] | | | | |
|---|---|---|---|---|---|
| | Dip #1 | Dip #2 | Dip #3 | Dip #4 | Dip #5 |
| Top | 1.56 | 3.04 | 3.03 | 4.11 | 4.54 |
| Middle | 2.61 | 4.04 | 5.09 | 5.56 | 6.34 |
| Bottom | 3 | 4.68 | 5.38 | 7.57 | 7.07* |

*An accurate measurement of the bottom of the strip was not possible due to elongation of the removed section; measurement was taken as close as possible from the bottom.

From the results of Test #1, the wax coating thickness at the bottom of the sprue grew much faster than the top and middle with each subsequent dip. This phenomenon is called "elephant's foot" and was the result of keeping the sprue bar completely vertical as the wax cured. The "elephant's foot" was expected in this test but must be avoided for the final wax sprue bar product. More importantly, the results from Test #1 showed the wax coating growth trend and curing time.

## Test 2

The steps for Test #2 are as follows:

1. Assemble type F sprue bar assembly.
2. Dip the assembly into the tank of melted wax three times consecutively for one second each.
3. Measure the thickness of wax on the sprue bar.
4. Repeat each step with a dip duration of five seconds and again with a duration of ten seconds.

For this test, different sprue bars of type F were used for each trial and were dipped thrice. The orientation of the sprue bar was kept vertical, similar to Test #1, which allows Test #1 results to be used as a control. Test #2 allows for a better understanding of the relationship between the wax coating thickness and the amount of time the sprue bar stays dipped in the tank. The results for Test #2 are shown in Table BII.

TABLE BII
TEST #2: WAX COATING THICKNESS RESULTS FOR MULTIPLE DIP TIMES

| Section of Wax Coating | Thickness of Wax [mm] | | |
|---|---|---|---|
| | Dip #1 (1 sec) | Dip #2 (5 sec) | Dip #3 (10 sec) |
| Top | 1.89 | 2.2 | 2.48 |
| Middle | 2.59 | 3.52 | 3.26 |
| Bottom | 3.86 | 3.84 | 4.03 |

The results of Test #2 indicate that the longer dipping times increased the wax coating thickness for the top and bottom of the sprue bar, but the middle saw a decrease in wax coating thickness between Dip #1 (five seconds) and Dip #1 (ten seconds). This is an outlier, which is proven in later tests.

## Test 3 and 4

The steps for Tests #3 and #4 are as follows:

1. Assemble sprue bar assembly.
2. Dip the assembly into the tank of melted wax for five seconds (Test #3) or 10 seconds (Test #4).
3. Remove from the tank and allow to cure.
4. Measure the thickness of the wax.
5. Repeat each step until a thickness of approximately 7.62 mm or greater is achieved.

For both of these tests, the same sprue bar was dipped until a wax thickness of 7.62 mm or greater was achieved and measurements were taken after each dip. This test builds on the knowledge of the relationship between the wax coating thickness and the amount of time the sprue bar stays dipped in the tank. Test #3 focused on a five second dip in the tank, while Test #4 focused on a ten second dip in the tank. The results for Test #3 and Test #4 are displayed in Table BIII and BIV, respectively.

TABLE BIII
TEST #3: WAX COATING THICKNESS RESULTS (5 SEC DIP)

| Section of Wax Coating | Thickness of Wax [mm] | | | |
|---|---|---|---|---|
| | Dip #1 | Dip #2 | Dip #3 | Dip #4 |
| Top | 1.63 | 2.33 | 3.19 | 5.05 |
| Middle | 2.24 | 3.64 | 4.9 | 6.6 |
| Bottom | 2.5 | 3.97 | 6.68 | 8.03 |

TABLE BIV
TEST #4: WAX COATING THICKNESS RESULTS (10 SEC DIP)

| Section of Wax Coating | Thickness of Wax [mm] | | | |
|---|---|---|---|---|
| | Dip #1 | Dip #2 | Dip #3 | Dip #4 |
| Top | 1.97 | 3.29 | 4.73 | 6.92 |
| Middle | 2.47 | 3.97 | 5.66 | 8.4 |
| Bottom | 2.81 | 4.88 | 6.8 | 9.99 |

The results of Test #3 and Test #4 show that the ten second dip test produced a thicker wax coating in fewer dips when compared to the five second dip test. These results dismiss the results of Test #2 of a decrease in the middle section between the five and ten second dip as an anomaly in the data.

## Test 5

The steps for Test #5 are as follows:

1. Assemble type F sprue bar assembly.
2. Dip the assembly into the tank for one second.
3. Remove the assembly from the tank, keeping it perpendicular to the ground.
4. Change the orientation of the assembly to be parallel to the ground and rotate the bar at about 10 RPM until the wax cures.
5. Once the wax has cured, check the quality of the wax finish.
6. Repeat each step with a rotation speed of approximately 15 RPM and again with a rotation speed of approximately 20 RPM.

For this test, different sprue bars were used for each trial and the finish of the wax was inspected after each trial. This test helped to establish if it is possible to reduce or eliminate “elephant’s foot” by changing the sprue bar’s orientation and rotating the sprue bar. It also establishes the approximate speed of rotation for the best results. The results for Trials #1 (10 RPM) and #2 (15 RPM) are shown in Figure B3 and Figure B4, respectively.

Figure B3: Wax sprue bar coating finish on a horizontally oriented sprue bar (Test #5: Trial #1 - 10 RPM).

Figure B4: Wax sprue bar coating finish (Test #5: Trial #2 - 15 RPM).

The results of this test were unexpected, as the wax would coalesce into beads during the changing of orientation. The experiment was abandoned after Trial #2, as the desired results could not be achieved; instead a new experiment was established.

## Test 6

The steps for Test #6 are as follows:

1. Assemble type F sprue bar assembly.
2. Dip the assembly into the tank for one second
3. Begin rotating the bar at approximately 10 RPM while the assembly is dipped in the tank.

4. Remove the bar from the tank.
5. Once removed from the tank, change the orientation to horizontal and continue the rotation of the bar at approximately 10 RPM until the wax cures.
6. Once the wax has solidified, check the quality of the wax finish.
7. Repeat each step with a rotation speed of approximately 15 RPM and again with a rotation speed of approximately 20 RPM.

For this test, different sprue bars were used for each trial and the finish of the wax was inspected after each trial. Similar to Test #5, this test helps establish if it is possible to reduce or eliminate "elephant's foot" by changing the sprue bar's orientation and rotating the assembly. It also establishes the approximate speed of rotation for the best results. The result of Trial 1 of this test is shown in Figure B5.

Figure B5: Wax sprue bar coating finish (Test #6: Trial #1 - 10 RPM)

The other trials are not shown as the results were consistent throughout each trial. This test determined that rotating the sprue bar assembly during the entire dipping and removing process prevented the formation of wax beads. Additionally, this test resulted in a consistent thickness of wax coating on the sprue bar.

Once the method of eliminating the "elephant's foot" phenomenon was verified, another experiment was conducted to ensure that the wax coating remained consistent and wax thickness of approximately 7.62 mm is achieved, after five dips. For this experiment, the time between dips was selected to be 20 seconds.

## Test 7

The steps for Test #7 are as follows:

1. Assemble type F sprue bar assembly.
2. Dip the center bar into the tank of melted wax.
3. Start rotating the bar while it is in the tank.
4. Remove the bar vertically, from the tank.
5. Rotate the bar to a horizontal orientation, while rotating at approximately 15 RPM.
6. Wait 20 seconds, while rotating the sprue bar, before dipping the center bar into the tank a second time.
7. Repeat six times.
8. Measure the thickness of the wax both vertically and horizontally, at the end of the test.

For this test, sprue bar was dipped five times and measurements were taken at the end of all 6 dips. This test helps to verify that this cycle will consistently produce sprue bars with consistent wax thickness. A "T" section was removed from the sprue bar after the test, red outline in Figure B6, to test both vertical and horizontal thickness.

Figure B6: "T" section removed from the sprue bar for testing purposes.

Four measurements were taken horizontally at 0°, 90°, 180° and 270°. Three vertical measurements were taken top, middle, and bottom. The results of Test #7 are shown in Table BV.

TABLE BV
TEST 7: CYCLE VERIFICATION RESULTS

| **Section of Wax Coating** | **Thickness of Wax [mm]** | | | | |
|---|---|---|---|---|---|
| | | **0°** | **90°** | **180°** | **270°** |
| Top | 7.17 | 7.48 | 7.54 | 7.69 | 7.42 |
| Middle | 7.56 | | | | |
| Bottom | 7.65 | | | | |

These results show that over the course of an entire cycle, the thickness of the wax coating was within ±0.5mm. Slight "elephant's foot" is still evident in the results of the vertical measurements; however, this is well within acceptable range.

# Appendix C – FANUC Price Quotation

Appendix C includes the price quotation of the R-2000iC/125L robot provided by FANUC.

[redacted]

[redacted]

# Appendix D – Yaskawa Motoman Price Quotation

Appendix D includes the price quotation of the GP180 robot provided by Yaskawa Motoman.

**Wayne Spooner**
to me

Hey Norman,

Managed to squeeze a few minute here....so here is the price for the GP180

Yaskawa GP180 with YRC1000 Controller
5 M Manipulator Cable
Teach Pendant with 8 M Cable
575 V Step Up Transformer
Price.......................$44,175 USD

Hope this helps have a nice weekend

**From:** yanpan chung
**Sent:** November 8, 2019 5:06 PM
**To:** Wayne Spooner
**Subject:** Re: Robot Inquiry

Hi Wayne,

...

# Appendix E - ABB Price Quotation

Appendix E includes the price quotation of the IRB 6700-150/3.2 and IRB 6650S-90/3.9 robots provided by ABB Robotics Canada.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

# Appendix F - FEA Simulation Results of Stage 1 Rack Design

## List of Figures



The stage 1 enhanced rack design ran the same FEA simulations for both scenario A and scenario B. Appendix F provides the simulated results for the stage 1 enhanced rack design, as well as the distance for the center of mass, which are used to determine the wrist moment.

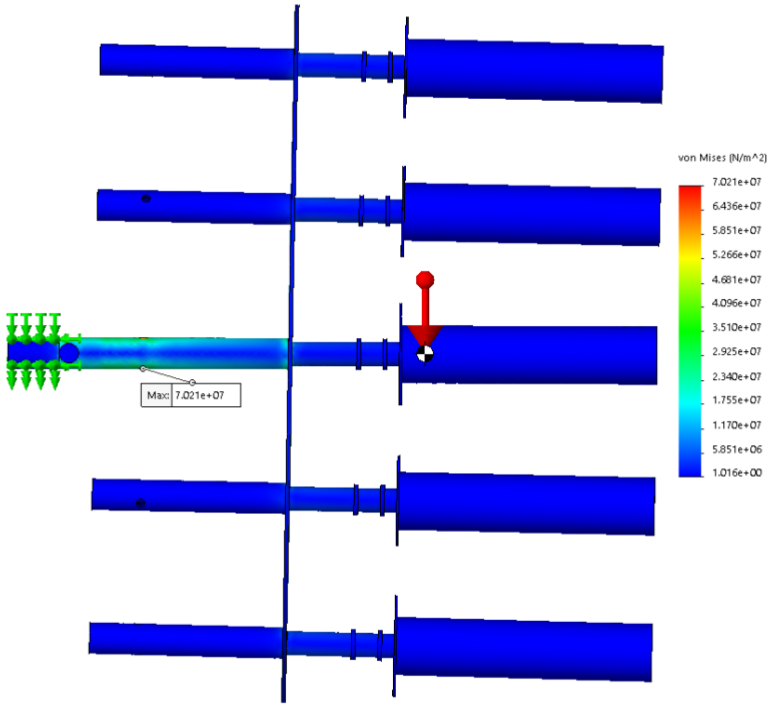



Figure F1: von Mises Results of Stage-1 Rack Design for Scenario A.

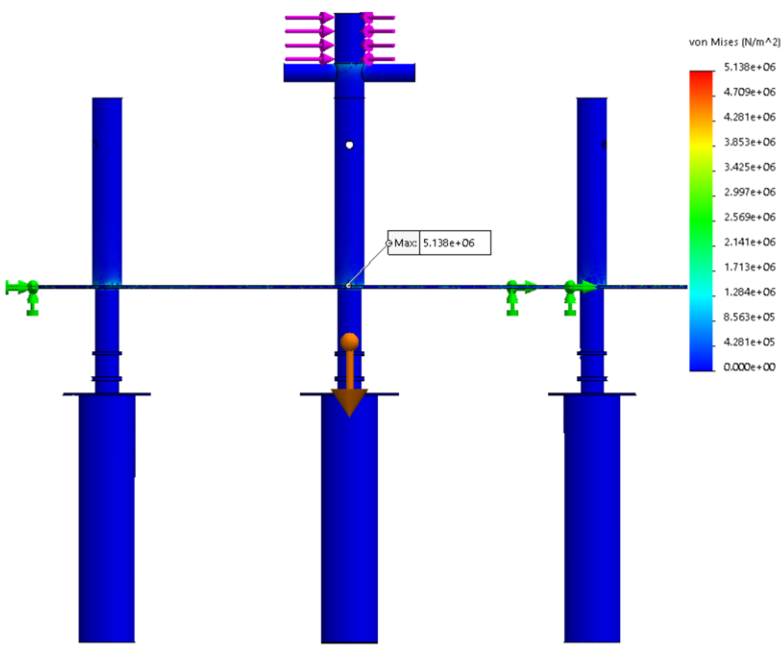



Figure F2: von Mises Results of Stage-1 Rack Design for Scenario B.

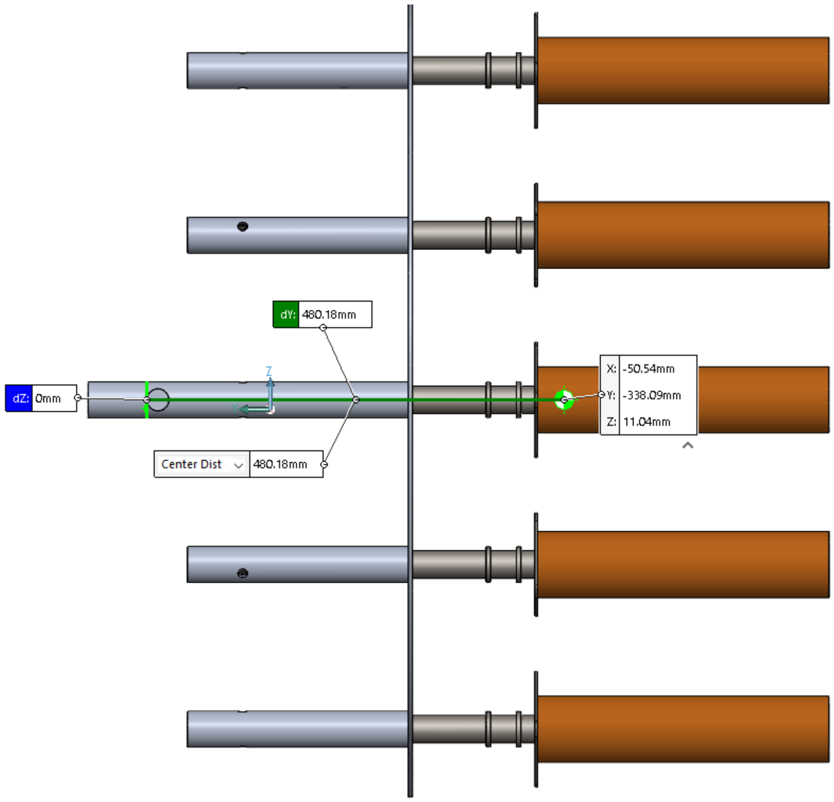



Figure F3: Measurement of Distance to Calculate the Wrist of Moment (Distance for Center of Mass).

# Appendix G - FEA Simulation Results of Stage 2 Rack Design

## List of Figures



The stage 2 enhanced rack design ran the same FEA simulations for both scenario A and scenario B. Appendix G provides the simulated results for the stage 2 enhanced rack designs as well as the distance for the center of mass, which are used to determine the wrist moment.

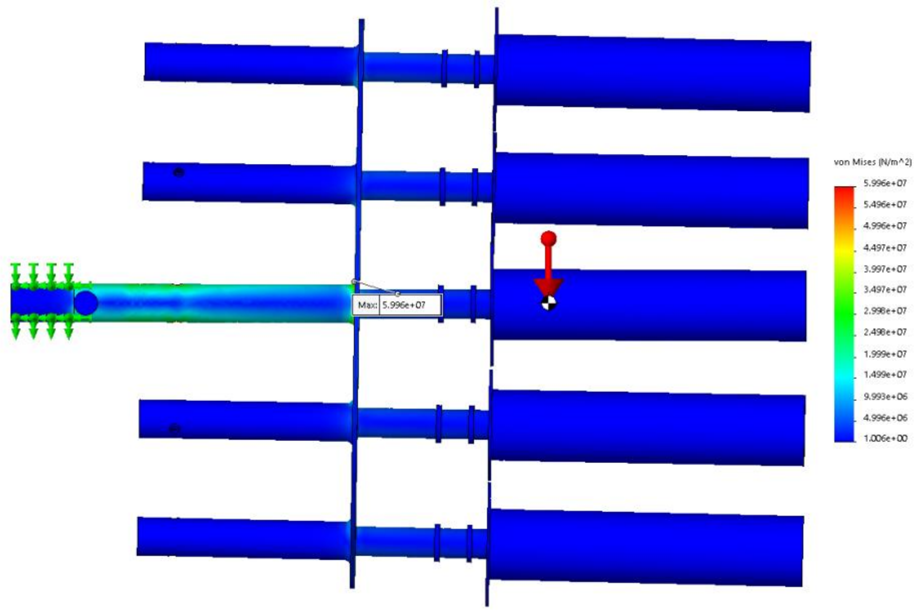



Figure G1: von Mises Results of Stage-2 Rack Design for Scenario A.

.

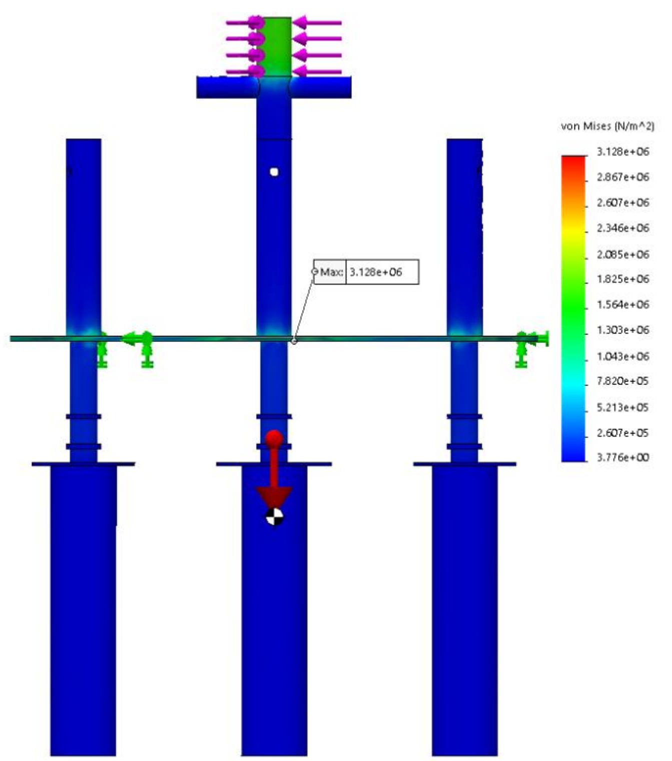



Figure G2: von Mises Results of Stage-2 Rack Design for Scenario B.

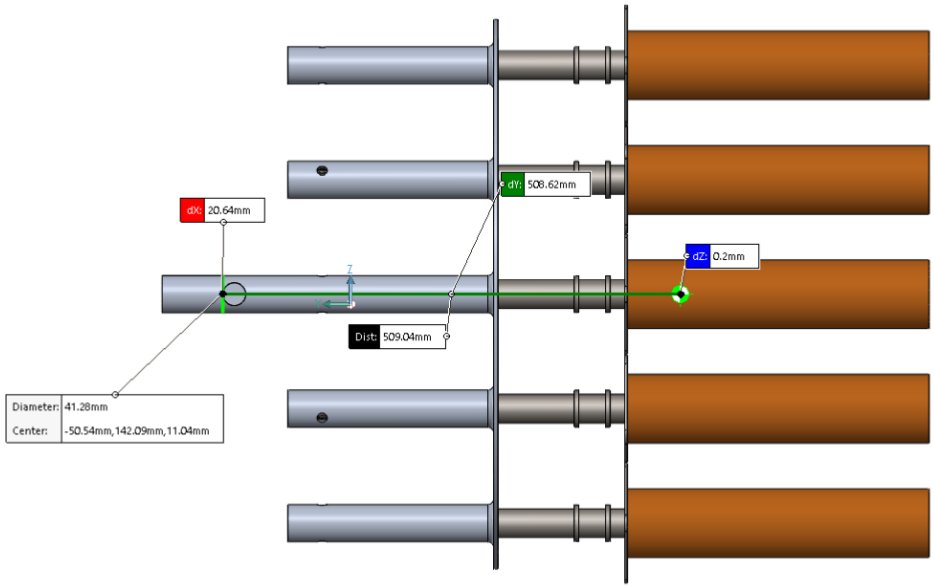



Figure G3: Measurement of Distance to Calculate the Wrist of Moment (Distance for Center of Mass).

# Appendix H - FEA Simulation Results for Final Rack Design with Finer Elements

## List of Figures



Appendix H includes the FEA simulations performed on the final rack design. The size of the meshed elements for the final rack design are established to be finer than stage 2 enhancement such that it provides a more reliable result for the FEA simulation. Scenario A is set to have 1,057,925 finite elements and scenario B is set to have 1,098,214 finite elements.

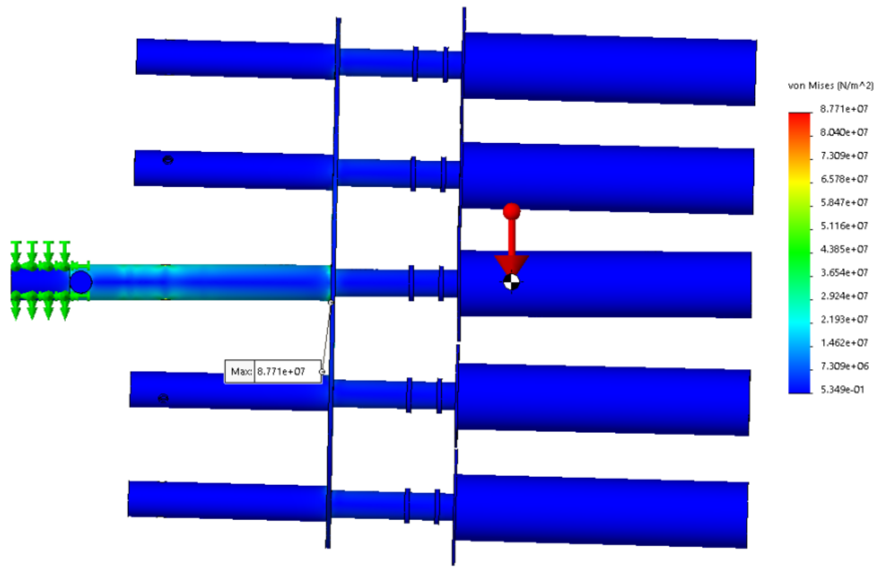



Figure H1: von Mises Stress for final rack design with 1,057,925 finite elements on Scenario A

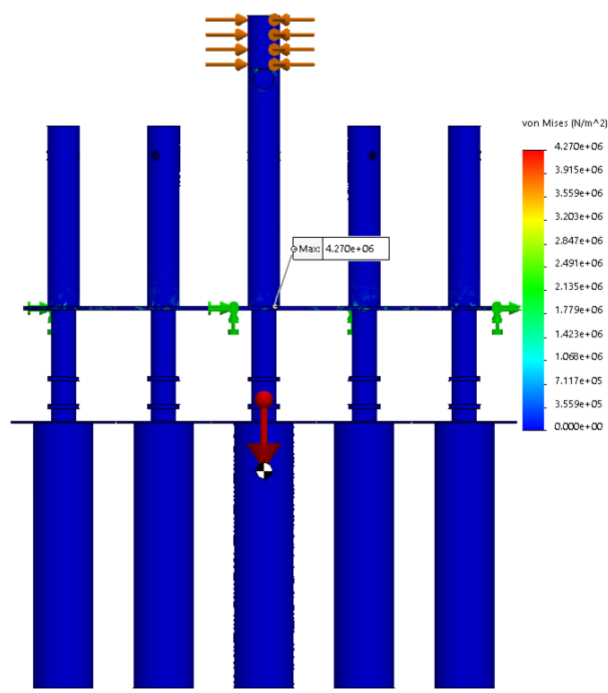
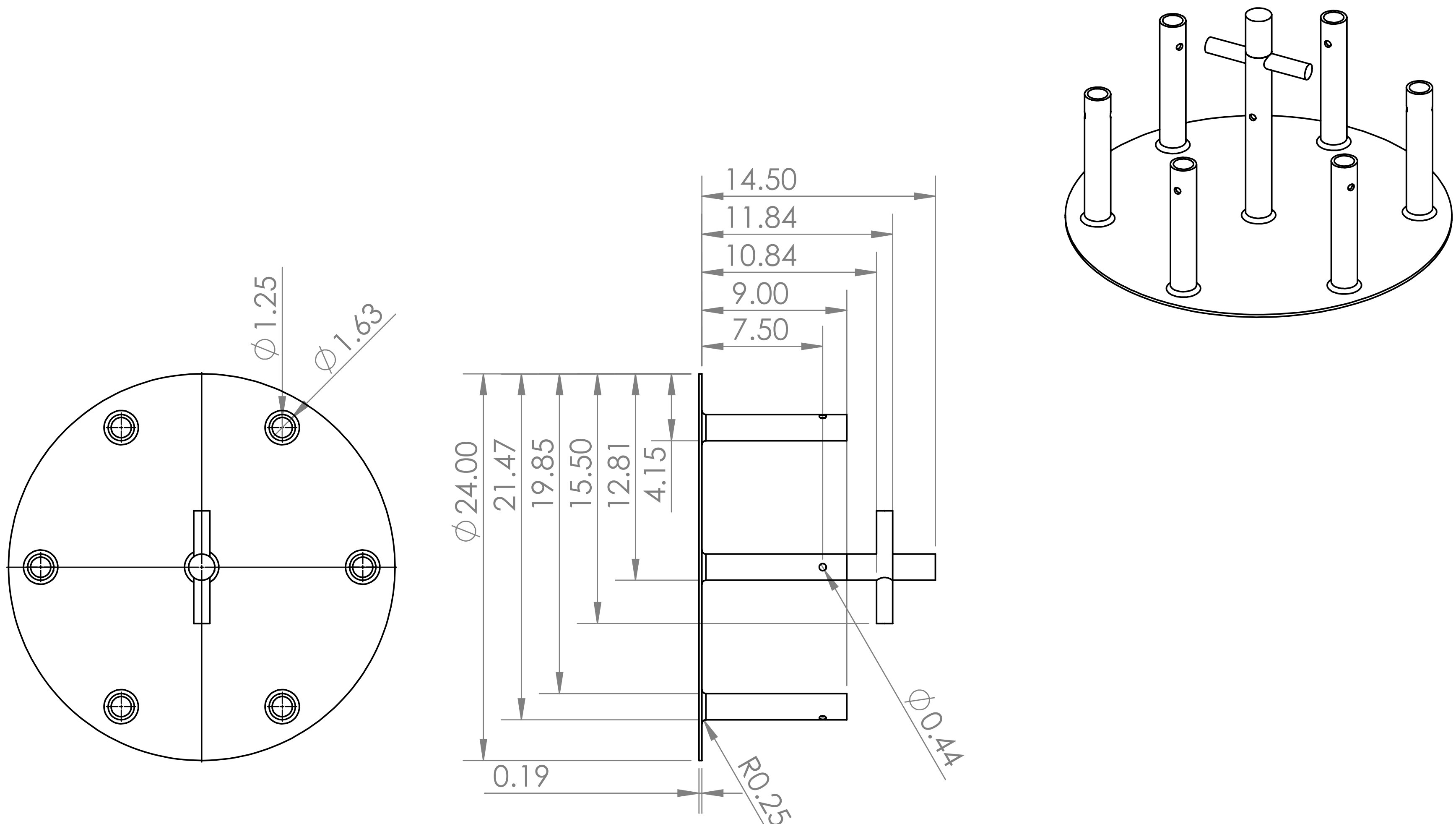



Figure H2: von Mises Stress for final rack design with 1,098,214 finite elements on Scenario B

# Appendix I - Engineering Drawings

Appendix I includes the engineering drawings of each component of the system, which consists of the robot, gripper, rack, and modified sprue bars.

[redacted]




**PROPRIETARY AND CONFIDENTIAL**

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

| | |
|---|---|
| NEXT ASSY | USED ON |
| APPLICATION | |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

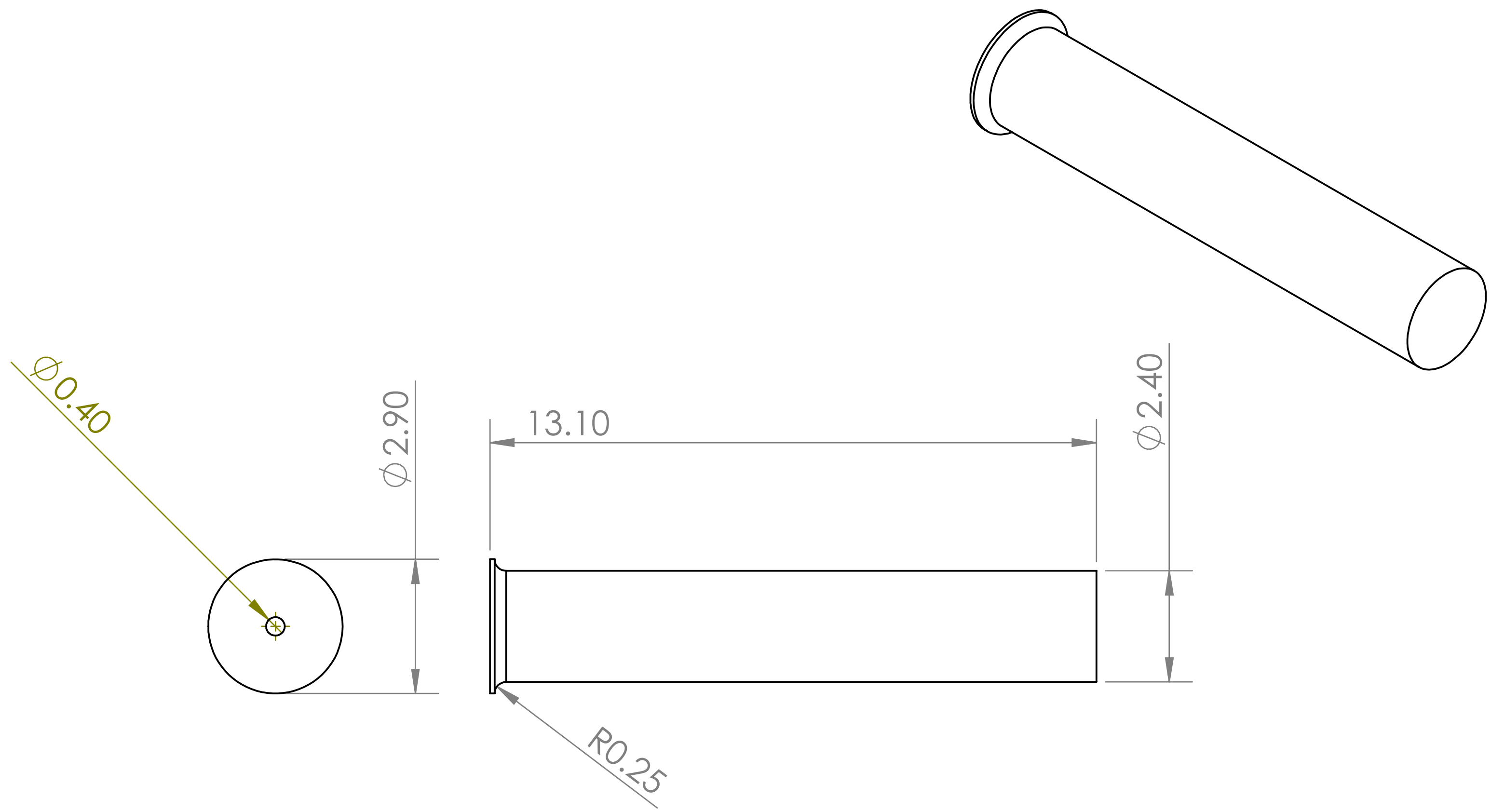
TITLE:
# SPRUE BAR RACK

| SIZE | DWG. NO. | REV |
|---|---|---|
| A | | V3 |

SCALE: 1:10 WEIGHT: SHEET 1 OF 1

[redacted]

[redacted]




| | | UNLESS OTHERWISE SPECIFIED: | | NAME | DATE |
|---|---|---|---|---|---|
| | | DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>FRACTIONAL ±<br>ANGULAR: MACH ± BEND ±<br>TWO PLACE DECIMAL ±<br>THREE PLACE DECIMAL ± | DRAWN | | |
| | | | CHECKED | | |
| | | | ENG APPR. | | |
| | | | MFG APPR. | | |
| | | INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | | |
| | | MATERIAL | COMMENTS: | | |
| NEXT ASSY | USED ON | FINISH | | | |
| APPLICATION | | DO NOT SCALE DRAWING | | | |

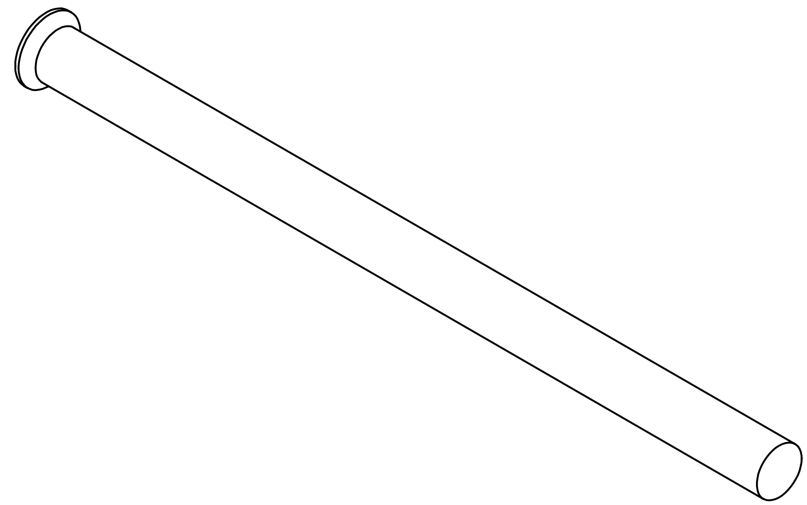
**PROPRIETARY AND CONFIDENTIAL**

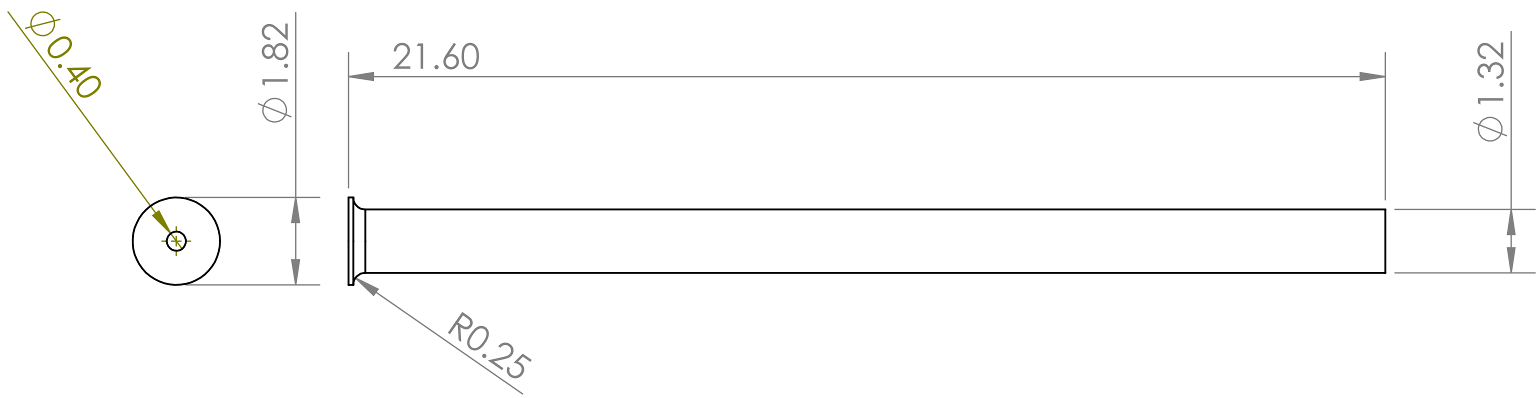
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

TITLE:

# TYPE F NEW

| SIZE | DWG. NO. | REV |
|---|---|---|
| A | | V1 |
| SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1 |






| | | UNLESS OTHERWISE SPECIFIED: | | NAME | DATE |
|---|---|---|---|---|---|
| | | DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>FRACTIONAL ±<br>ANGULAR: MACH ± BEND ±<br>TWO PLACE DECIMAL ±<br>THREE PLACE DECIMAL ± | DRAWN | | |
| | | | CHECKED | | |
| | | | ENG APPR. | | |
| | | | MFG APPR. | | |
| | | INTERPRET GEOMETRIC<br>TOLERANCING PER: | Q.A. | | |
| | | MATERIAL | COMMENTS: | | |
| NEXT ASSY | USED ON | FINISH | | | |
| APPLICATION | | DO NOT SCALE DRAWING | | | |

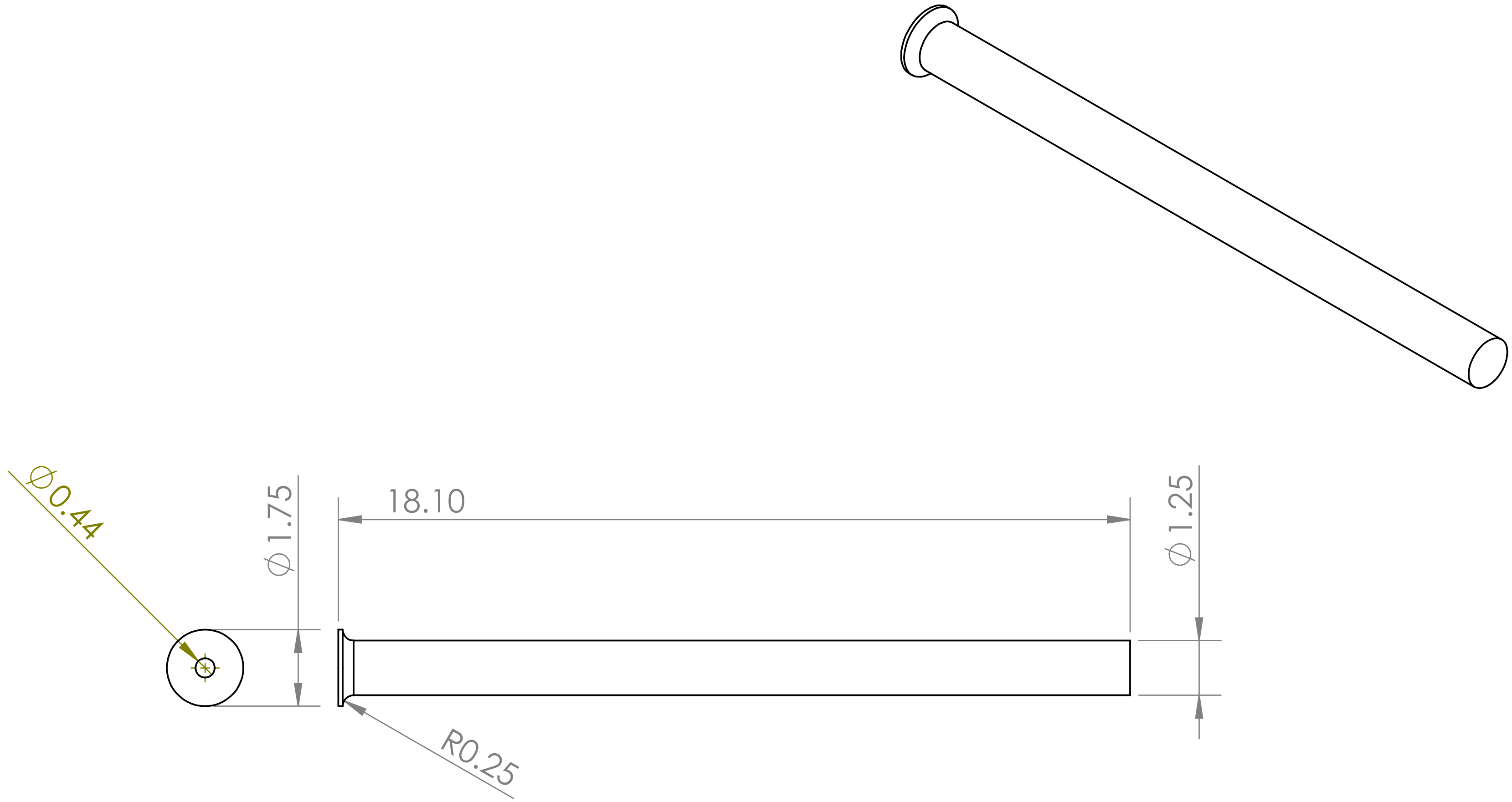
**PROPRIETARY AND CONFIDENTIAL**



TITLE:

# Type G New

| SIZE | DWG. NO. | REV |
|---|---|---|
| **A** | | V1 |
| SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1 |




**PROPRIETARY AND CONFIDENTIAL**



| | |
|---|---|
| NEXT ASSY | USED ON |
| APPLICATION | |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

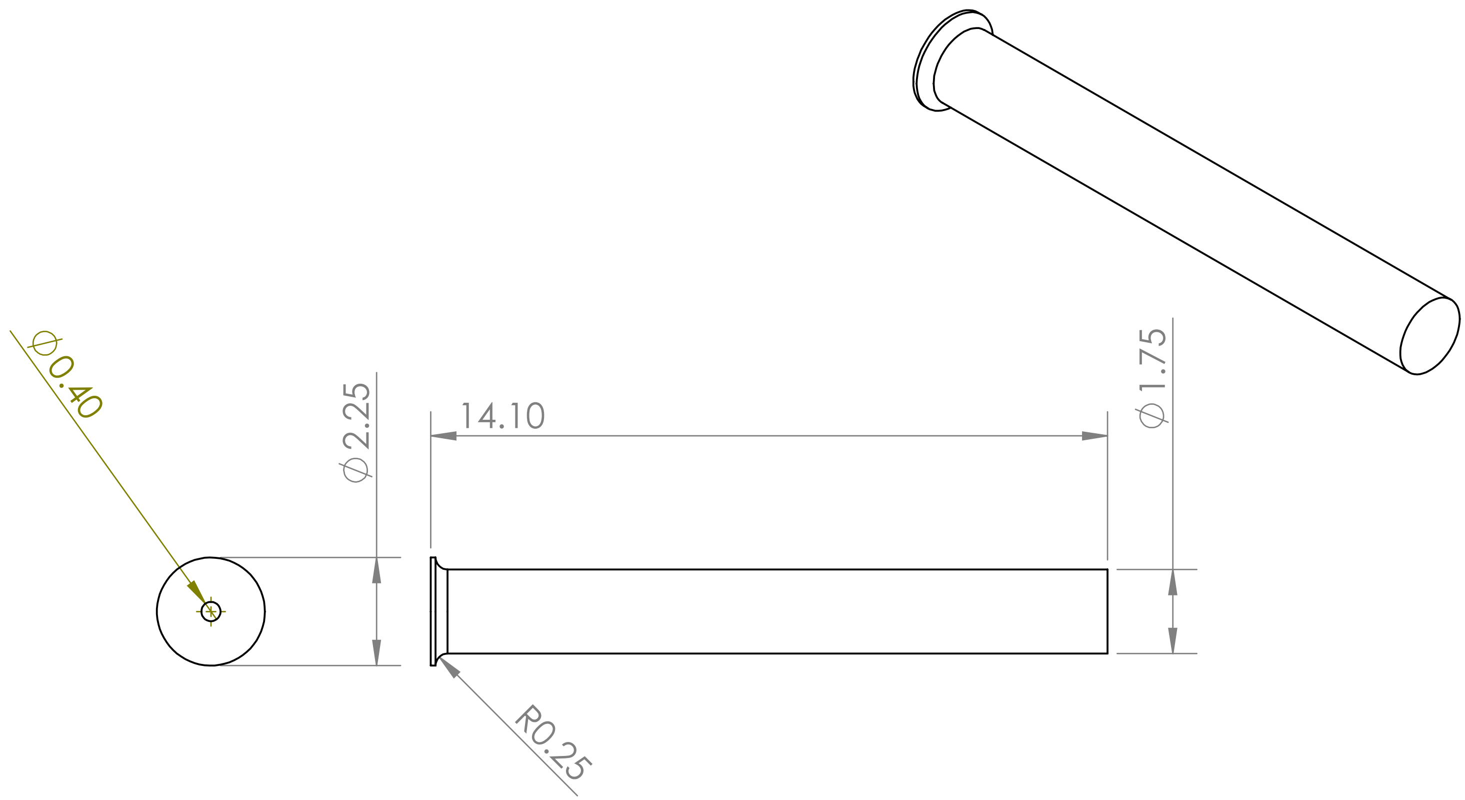
| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

TITLE: TYPE H NEW

SIZE: A | DWG. NO. | REV: V1

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1




**PROPRIETARY AND CONFIDENTIAL**

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

| NEXT ASSY | USED ON |
|---|---|
| APPLICATION | |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

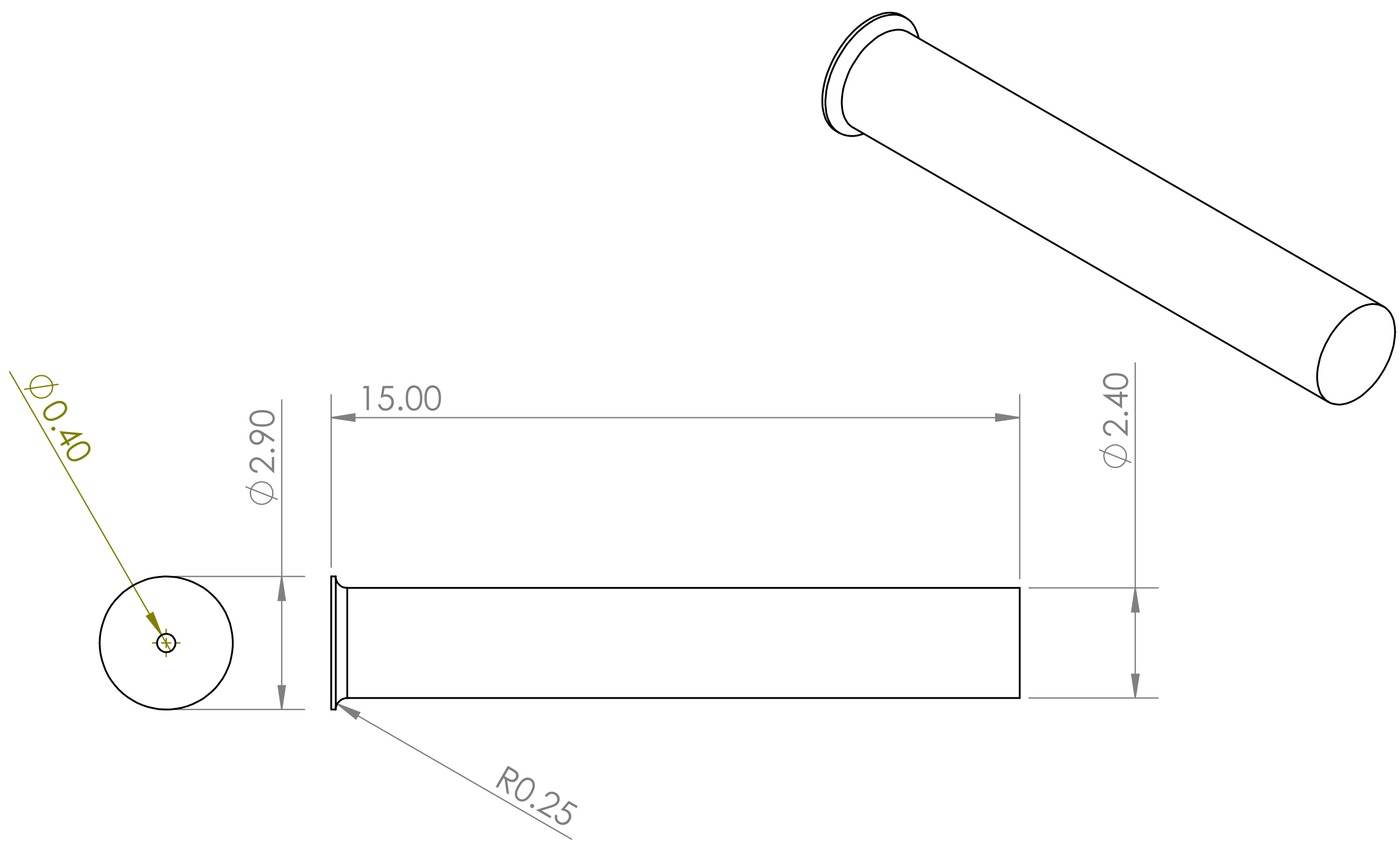
COMMENTS:

TITLE:

# TYPE I NEW

| SIZE | DWG. NO. | REV |
|---|---|---|
| A | | V1 |

SCALE: 1:4 WEIGHT: SHEET 1 OF 1




PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

| NEXT ASSY | USED ON |
|---|---|
| APPLICATION | |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

TITLE:

# TYPE M NEW

| SIZE | DWG. NO. | REV |
|---|---|---|
| A | | V1 |

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

# Appendix J – Loaded Rack Assemblies

## List of Figures



Appendix J includes images of the different sprue types secured to the rack. These SolidWorks models were used to ensure the compatibility of the rack with each sprue type.

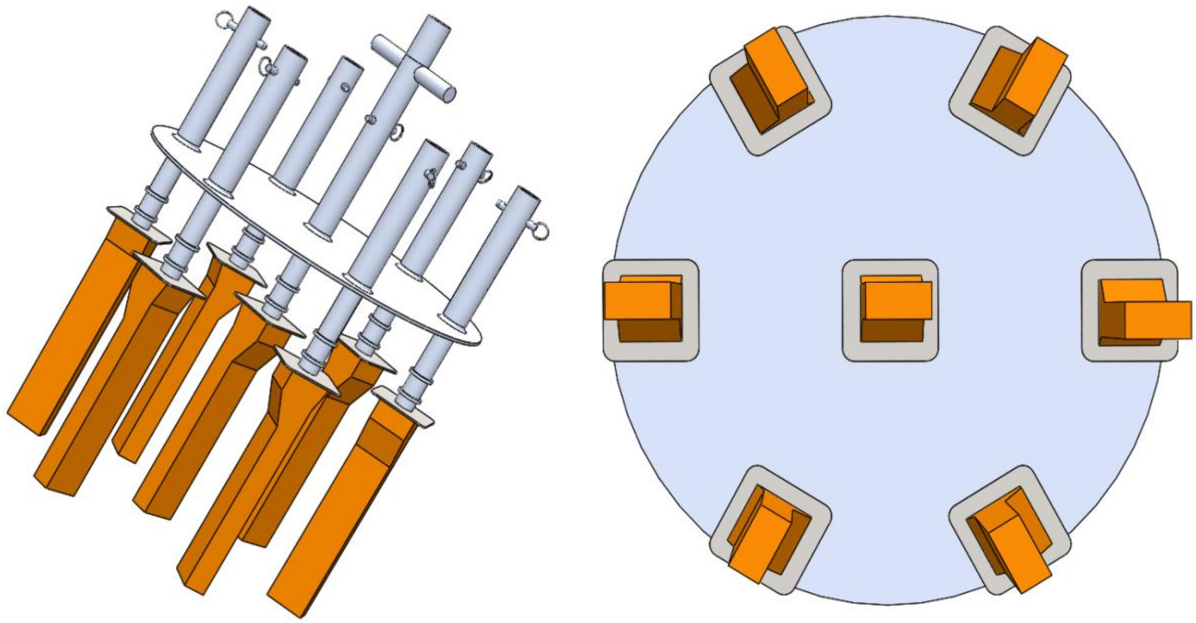


Figure J1: Rack loaded with Type A sprue bars.

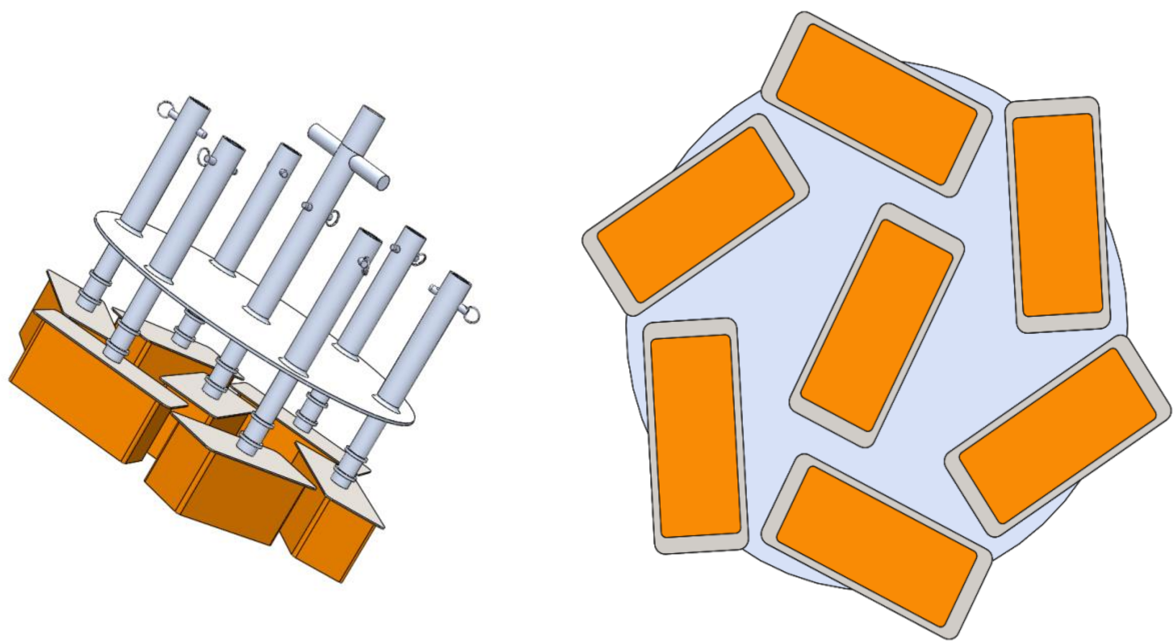


Figure J2: Rack loaded with Type C sprue bars.

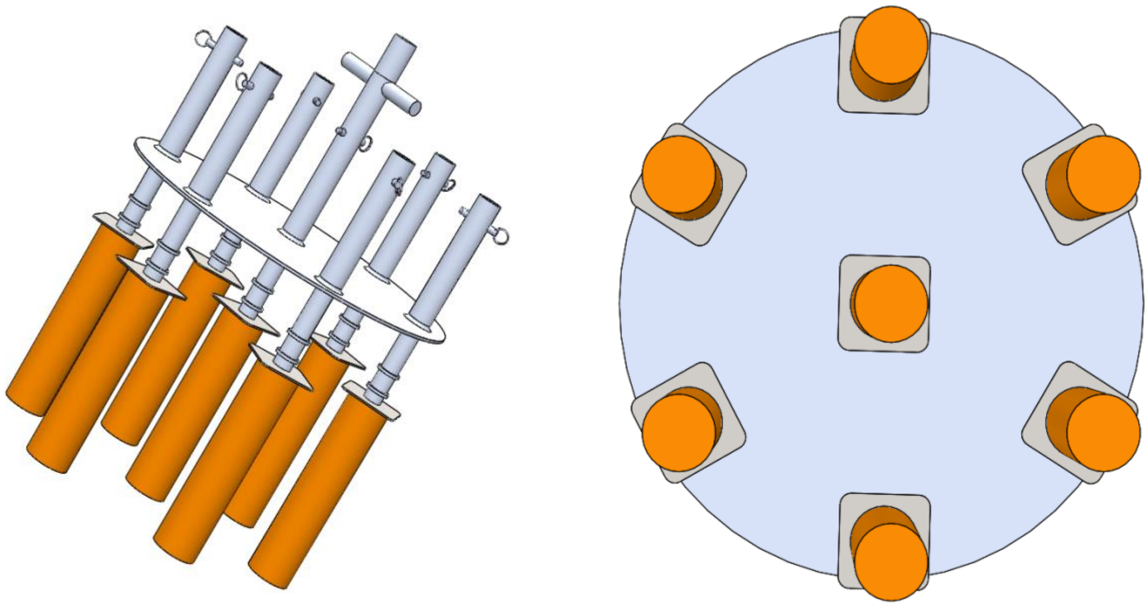


Figure J3: Rack loaded with Type F sprue bars.

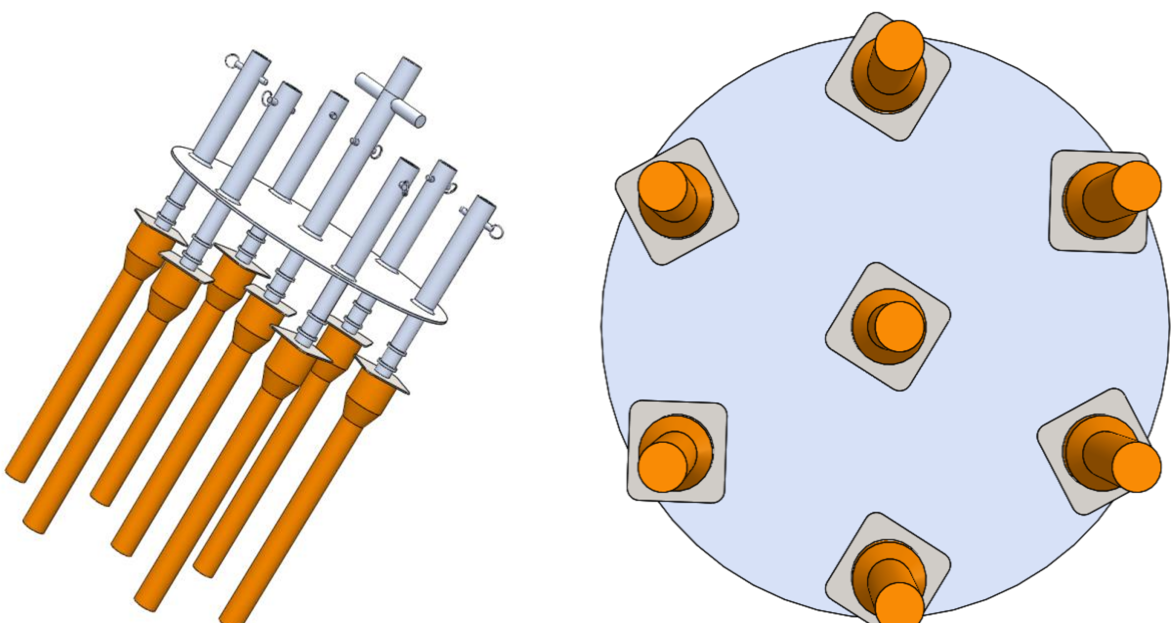


Figure J4: Rack loaded with Type G sprue bars.

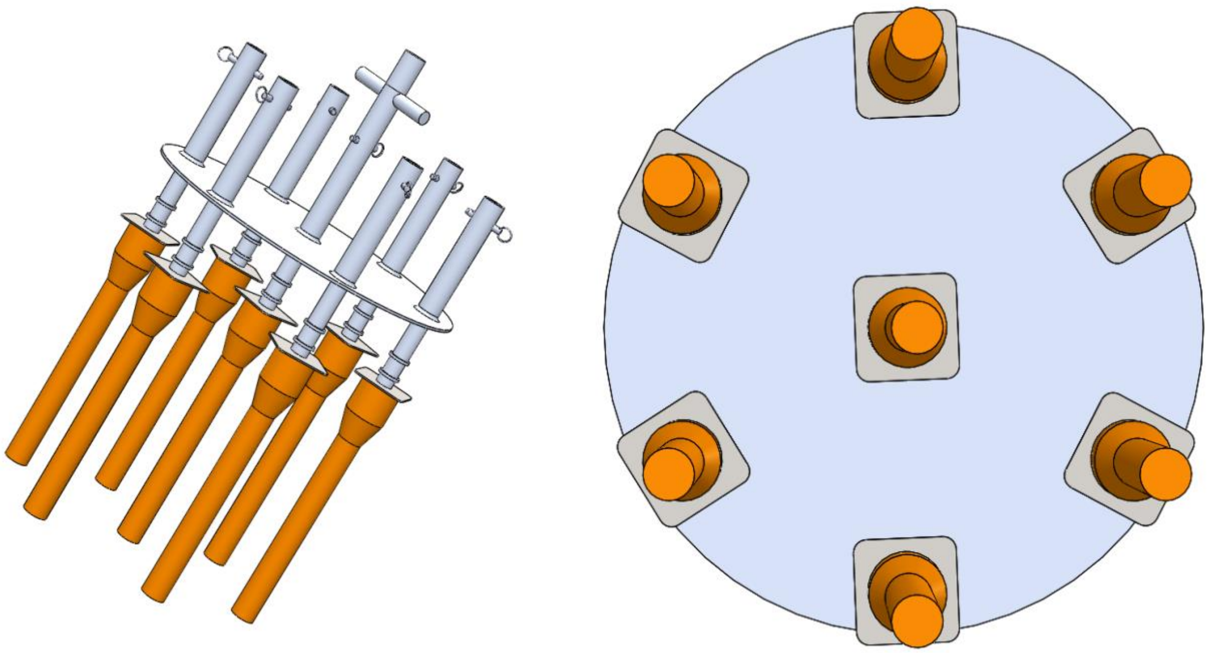


Figure J5: Rack loaded with Type H sprue bars.

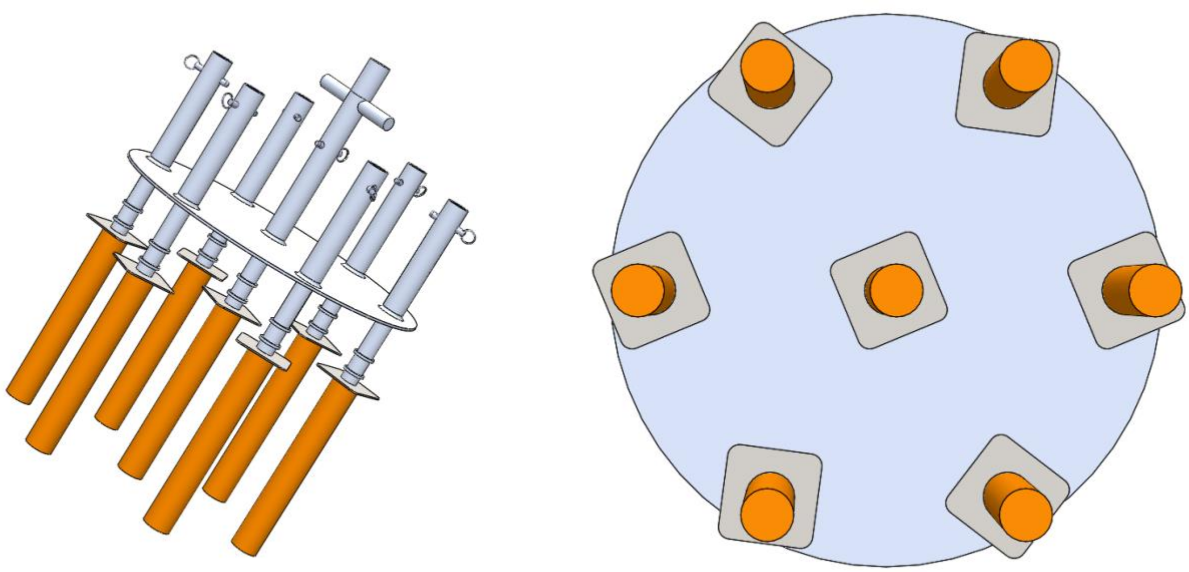


Figure J6: Rack loaded with Type I sprue bars.

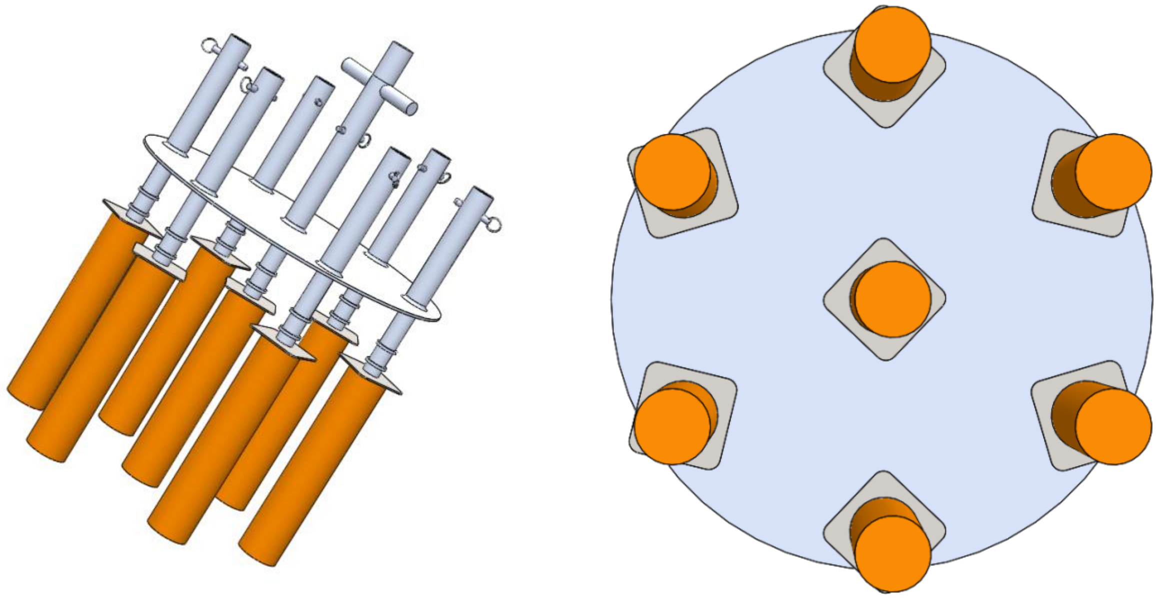


Figure J7: Rack loaded with Type M sprue bars.

# Appendix K - Bill of Materials

Appendix K provides the Bill of Materials displaying the costs and quantities of the robot, quick-release pins, and gripper.

| ITEM NAME | PURPOSE | QUANTITY | UNIT COST [CAD] | SUPPLIER | SHIPPING [CAD] | TOTAL COST [CAD] | MAKE | BUY | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| R-2000iC/125L | Robotic Arm | 1 | [redacted] | FANUC | [redacted] | [redacted] | ☐ | ☑ | USD to CAD exchange @1.33 |
| Zinc-Plated Steel Ring-Grip Quick-Release Pin<br>7/16" Diameter, 2" Usable Length | Fastening mechanism for the mounting bar onto the rack | 70 | [redacted] [redacted] | McMaster | TBD | [redacted] [redacted] | ☐ | ☑ | USD to CAD exchange @1.33 |
| PZN-plus 160-2-AS-SD | Gripping mechanism for the rack | 1 | [redacted] | SCHUNK | TBD | [redacted] [redacted] | ☐ | ☑ | USD to CAD exchange @1.33 |
| | | | | | SUBTOTAL | [redacted] | ☐ | ☐ | |