MECH 4860 – Engineering Design

Final Design Report

Design of an Automated Pork Loin Reorientation System

Prepared For:

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Executive Summary

Team 7 was tasked to design an automated pork loin reorientation system for HyLife Foods LP as the final project for the MECH 4860 Capstone course. HyLife's hog processing plant in Neepawa, MB currently encounters issues on the north loin processing line. Loins are processed every 6 seconds and the existing system does not deliver the loins in the correct orientation; workers are required to manually spin each of the 10kg loins 180 degrees. Manual re-orientation adds 1.8 seconds of non-value-added time per loin and induces repetitive strain to the workers' bodies which is a potential health risk.

The team approached the project in three phases: project definition, concept development, and final design. First, the project was clearly defined by identifying the problem, constraints and limitations, client needs, pertinent metrics, and project scope. Next, the team generated 21 design concepts. The 21 concepts were narrowed down to 4 by weighted decision matrices. Then, a single winning concept was selected both internally as a team and externally with the client. Finally, the agreed-upon concept was further developed into a complete design. For each component of the design, three areas were analyzed: integration with the existing system, structural integrity, and cost. All three phases required their own site visit, critical analysis and communication with the client.

This report details the final design, which consists of a support structure, sliding table, safety guards, modified lower conveyor, and two pneumatically actuated paddles that rotate and move the loin on the sliding table. The system is designed with approved

materials and satisfies the FDA 2017, FS119, and AMI standards for food safe production. After a loin falls onto the table, the first pneumatically actuated paddle rotates the loin 90 degrees, followed by an additional 90 degrees with the second paddle. This action turns the loin 180 degrees and pushes the loin backwards off the table onto the lower conveyor underneath the table. The loin is then delivered to the operators further along the lower conveyor in the desired orientation.

The pneumatic paddles are controlled by a programmable logic controller (PLC), the logic for which is provided in the report. The manual bypass consists of a sliding table that moves backwards, out of the way of the loin as it drops off the decline conveyor. The loin passes through the space vacated by the retracted table, thus landing directly on the lower conveyor and is delivered to the operators in its initial orientation. To operate the bypass, the operator needs to only lift the bypass handle and pull the table back, at which point the handle folds down out of the way when fully retracted. The bypass feature minimizes the risk of halting the loin delivery process in the event of system failure. Overall, the final design costs $36981.23 (USD), which is well within the budget of $200,000 (CAD). The cost is broken down in terms of raw materials, purchased components and machining.

The target specifications which were established at the onset of the project are mostly met, apart from a few that are dependent on testing. The following specifications require the physical system to be built for their evaluation:

- Noise level
- Startup/stop time

- Uptime and reliability
- Variation in loin discharge angle
- Endurance and lifespan of components
- Time without ingress from high pressure washing
- Operational cost
- Disassembly and cleaning time

For implementation, the team recommends calibration of the air pressure to the cylinders, and commissioning of the PLC system. Regulated air pressure would result in less force acting on the paddles but may result in a more controlled motion and longer component life. The PLC flowchart has been presented within this report, but further testing and debugging of the logic would be required upon installation for reliability.

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1 Introduction

This report summarizes the final design project completed by team 7 for the Engineering Design capstone course at the University of Manitoba. The team was selected to collaborate with HyLife Foods LP to design a loin reorientation and delivery system for the company's hog processing plant in Neepawa, Manitoba. The project was defined with information from HyLife and expectations as stated for the Engineering Design course. After defining the project, concepts were generated, evaluated, and the best concept selected to satisfy the project outcomes. Lastly, the final design and project deliverables were created based on the winning concept. These various aspects are detailed in the sub-sections that follow.

1.1 Client Background

HyLife Foods LP was founded in 1994 by four men and has since grown to be Canada's largest hog production and processing company. HyLife Foods LP employs 2,000 people, and are recognized worldwide with locations in Canada, USA, Japan, China, Mexico, and Barbados. The facility involved in the project is in Neepawa, MB which recently received a 98,500 sq. ft. expansion, resulting in an increased operational capacity.

1.2 Project Background & Problem

At the processing plant, the loin goes from the loin-puller to the weigh station at the start of the de-boning loin line. The loin puller is a metal bar used to separate the loin from the belly. This process begins with the cut of meat arriving at the loin puller containing the loin, sirloin, and belly. The loin and sirloin arrive at the loin puller partially separated from the belly as a result of a prior sawing operation. At the loin puller, the loin and sirloin are completely separated from the belly and drop down a chute onto a declining conveyor. The separation process and chute are shown in Figure 1.

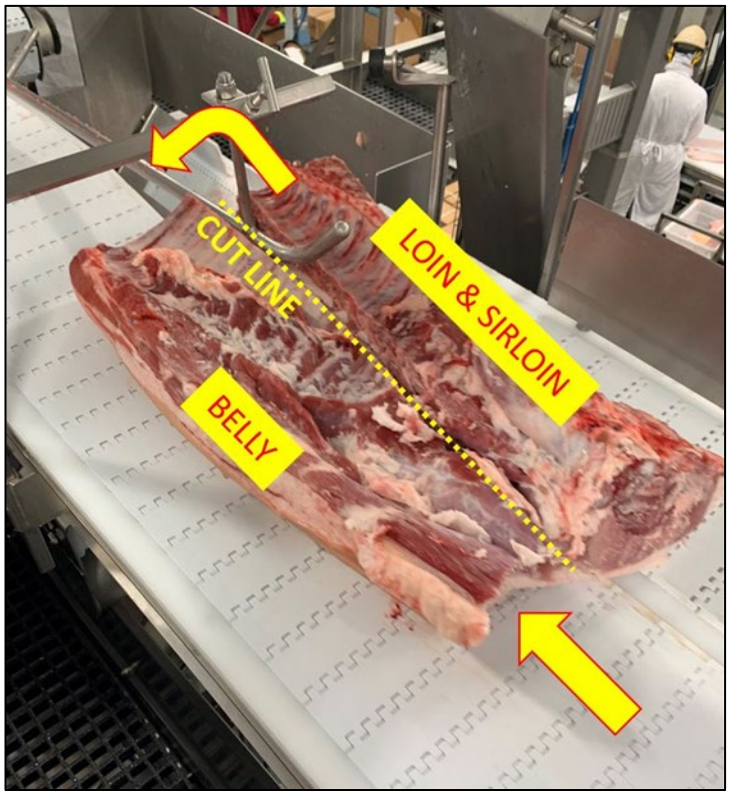


Figure 1: Separation between the belly and the loin and sirloin [1]

After travelling down the decline conveyor, the loin and sirloin fall onto the lower conveyor where the loin and sirloin travel towards the workers. A side view of the decline conveyor, loin chute, lower conveyor, and the path taken by the loin is shown in Figure 2.

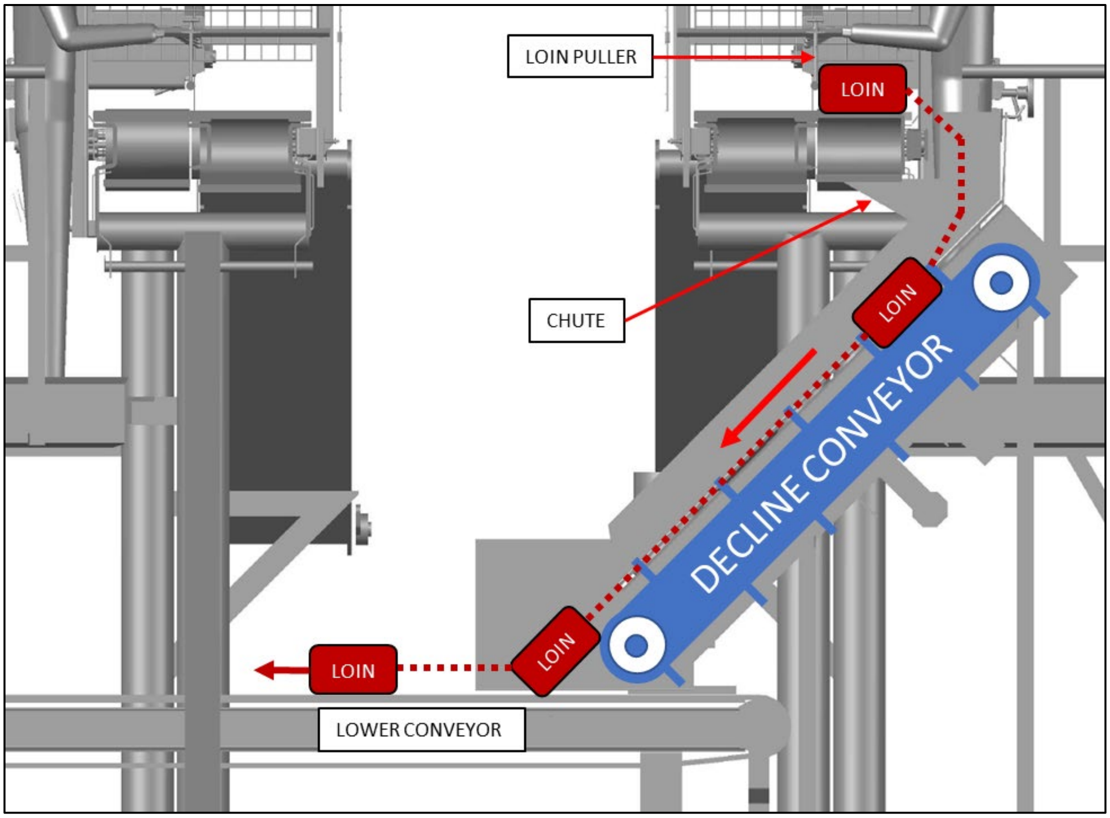


Figure 2: Loin path in the existing system

Once on the lower conveyor, the loin and sirloin travel down the loin line, where the sirloin is removed, followed by the deboning of the rest of the loin. In the current process, the two halves of the pig travel down two separate loin lines. The left half of the hog travels towards the operators in the correct orientation, but the right half of the hog is in the wrong orientation. The correct orientation is defined as having the ham side of the loin, denoted as side "B" in Figure 3, towards the operator, and the shoulder side, denoted as side "A", away from the operator.

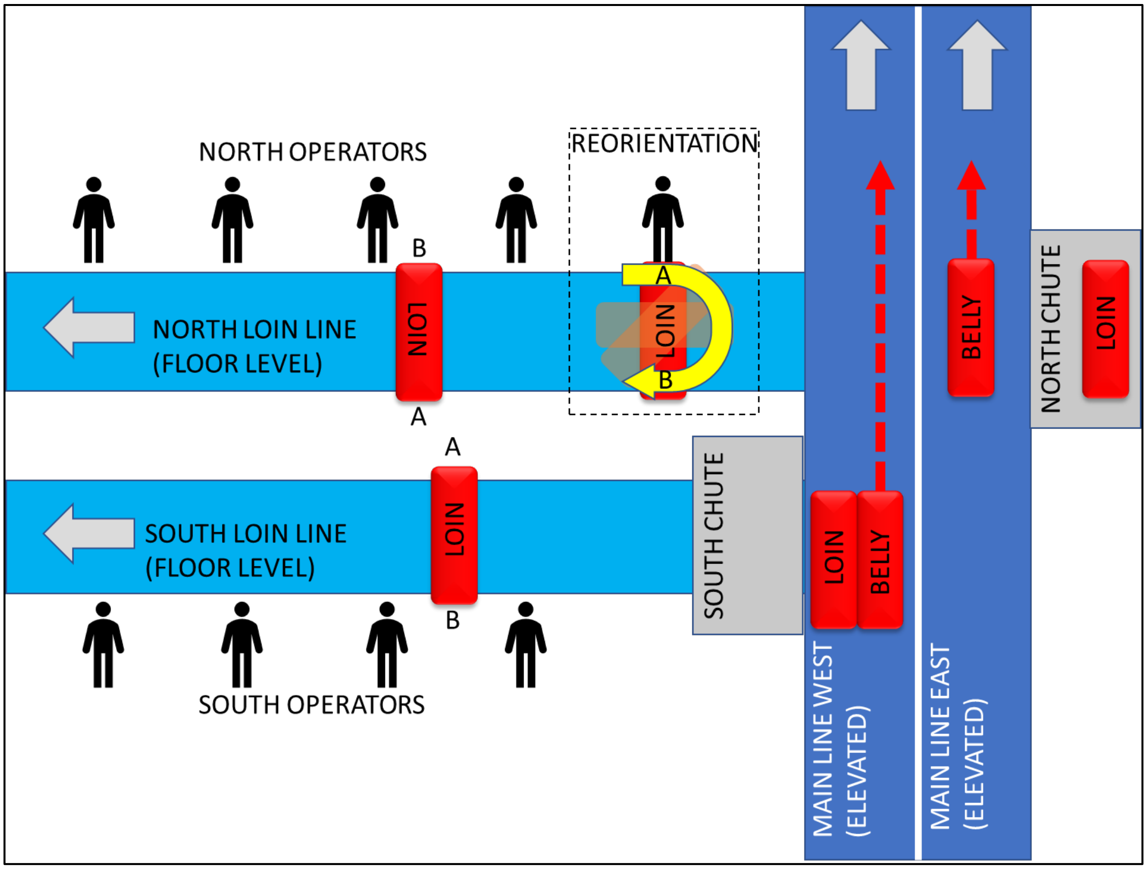


Figure 3: Required re-orientation of the loin along north loin line

To reorient the loin for the operators on the north line, the current process involves manual reorientation of the loin by an operator. The process of manually reorienting the loin results in poor ergonomics and 1.8 seconds of non-value-added time (NVAT). Poor ergonomics are defined as having to reach over a moving conveyor, and the repetitive motion and strain associated with moving the heavy loin.

The problem to be overcome with this project is the poor ergonomics and NVAT. The system designed to overcome this problem is to be fully automated, withstand high pressure and temperature cleaning, and comply with HyLife's sanitation standards.

1.3 Project Objectives and Project Deliverables

The following objectives must be met for the project to be successful.

- Develop a design to reorient loins on the north conveyor without human assistance (fully automated).
- Comply with specifications and standards regarding safe food production and handling.
- Develop a cost estimate for the implementation of the proposed design.

In the project description, HyLife indicated several deliverables that were required at the end of the project. The deliverables were as follows:

- CAD model.
- Bill of materials.
- Preliminary engineering drawings.
- Functional description of the design's operation.

1.4 Customer Needs

A system was developed for organizing the customer needs by utilizing a tiered hierarchy, which features several levels of customer need importance. The highest level needs are referred to as "parent" needs while the lower level, more specific needs were called "child" needs. TABLE I displays the priority level which was assigned to each of the needs as well as the identification number of the need and parent needs in bold text. Parent 3, 7, and 9 do not have child needs since these could not be further broken down into more specific needs. Further, the table is sorted from the highest to lowest priority of parent needs.

TABLE I: LIST OF NEEDS

Description	Priority	Parent ID
Code compliant	5	1
The design complies with HyLife's sanitation standards		1.1
The design does not require tools for cleaning		1.1.1
The design withstands high temperature cleaning		1.1.2
The design withstands high pressure cleaning		1.1.3
The design withstands cleaning chemicals		1.1.4
The design is safe for workers with their existing PPE	5	3
Design integrates with existing process	5	4
Operates with the house air pressure and electrical capacities if required		4.1
The design accommodates future modification and improvement		4.2
The design communicates with existing control systems (PLC, SCADA, DCS) if needed	5	4.3
The design utilizes components standard to HyLife's existing jigs and fixturing	5	4.4
The design delivers the loins in the correct orientation to the weigh station	5	5
Design accepts variable cycle times		5.1
Handle loins at the speed the input line currently supplies them		5.1.1
The design eliminates non-value added time		5.2
Has plenty of power to move loins		5.3
The loin quality is maintained	5	9
The design operates normally after prolonged use	4	8
The design is not prone to failure requiring process stoppage		8.1
The design withstands repeated impact from the loins		8.2
The design has minimal complexity	3	2
The design requires minimal disassembly for cleaning		2.1
The design requires minimal disassembly for service		2.2
The design is easy to manufacture		2.3
The design is easily operated by workers		2.4
The design accepts variations in loin delivery orientation from the loin puller conveyor	3	6
The design accommodates various loin sizes		6.1
The design accommodates various loin weights		6.2
The design is economical	2	7

1.5 Project Metrics

Project metrics were established by the team to evaluate the satisfaction of the client needs (e.g. cost, safety requirements, etc). As seen in TABLE II next, needs have been linked to each metric. The metric(s) which correspond to a need can be reviewed to determine quantitative values the design must reach or exceed to satisfy that need. For example, the need to be compliant with cleaning standards has specific values in the metrics table which must be met. The cleaning standard need can be cross-referenced in the metrics list where the precise temperatures that the design must withstand are listed.

TABLE II: LIST OF METRICS

Metric #	Needs #s	Metric	Imp	Value	Units
1	6	Loin dimensions	3	28-30	in (min, max)
2	6	Weight of loin	3	10	kg (max)
3	1,3	Cleaning water temperature	5	180	deg F
4	2	Time to clean/disassemble	3	15	min
5	1,3	Noise level	5	85	dB
6	6,9	Force from the loin	5	981	N
7	8	Endurance (rotary, impact, abrasion)	4	450K	Cycles
8	8	Time without ingress from HP washing	4	180	s
9	1,8	Chemical resistance	5	Pass	Pass/fail
10	7	Cost	2	200K	CAD (max)
11	4,7	Range of permissible cycle times	5	3-6	s
12	5,6,7	Full automation	5	Pass	Pass/fail
13	1,3,4	E-Stop/Safety guards/lockout capability	5	Pass	Pass/fail
14	1,2,4,7	Startup/Stop time	5	60	s (max)
15	1,2,4,7	Manufacturability	5	Pass	Pass/fail
16	4	Digital input/output communication	5	Pass	Pass/fail
17	2,4,7,8	BOM/spare parts	5	Pass	Pass/fail
18	2,4	CAD model in Inventor	5	Pass	Pass/fail
19	4,7,8	Uptime/reliability	5	100	%
20	5,6	Variation in discharge angle	5	20	deg
21	2,3,4,8	Tools required for service	5	Pass	Pass/fail
22	1,2,3	No tools required for cleaning	5	Pass	Pass/fail
23	1,3,7,8,9	Customer satisfaction	5	100%	Grade received
24	7,8	Operational cost	4	2000	CAD/year
25	1	Meets design codes	5	Pass	Pass/fail

1.6 Constraints and Limitations

Various limitations and constraints were part of the project and are summarized as follows:

- The design must be able to move a 10kg loin.
- The design must accommodate loins up to 30” long.
- The design must process a loin every 6 seconds.
- The travel budget of $400 must not be exceeded.
- The total budget for the design is not to exceed $200,000.
- The loin puller and weigh scale must remain unmodified.
- The design must comply with applicable codes and standards.
- The communication between with the team and client must be limited to one update per week.
- The project must be completed by the end of the Engineering Design course.

1.7 Project Scope

The following dictates the scope of the project:

- Modification and/or replacement of any existing piece of equipment that interacts with the loin between the loin puller and weigh station.
- Production of CAD models accurately depicting the proposed design.
- Bill of materials required for construction and operation of the design.
- Design adherence to all food safety and handling standards and specifications which apply.

The following items were deemed to be outside the scope of this project, as specified by the client:

- Loin orientation received from the loin puller.
- Design/modification of the loin puller and weigh station
- Designing outside the footprint of the existing system

- Creation of software, code, or other low-level computer programming.
- Alterations or repairs to the existing loin orientation device.

1.8 Design Expectations

For the final design to be deemed a success, the design must correctly reorient the loin while being code compliant, simple, reliable, easy to maintain, integrate into the existing process, and be within the budget.

1.9 Code Requirements

There are certain codes and standards that the team must abide by since the final design is to be implemented in a pork processing plant. The first of three documents supplied by HyLife Foods is the *2014 Sanitary Equipment Design Principles* from the AMI (American Meat Institute) Foundation [2]. The main design guidelines from the document are summarized as follows:

1. Ability to clean surfaces to a microbiological level.
2. Must use compatible materials.
3. All areas must be easily accessible for inspection, maintenance, and cleaning.
4. All surfaces must avoid product and liquid collection.
5. All hollow areas must be hermetically sealed.
6. No cracks, lap seams, inside threads, bolt nuts, gaps, and pits.
7. Must be cleaned and sanitized in a timely manner.
8. Maintenance enclosures must avoid accumulating residue.
9. Must have hygienic compatibility with all other plant systems.

10. Must have a validated cleaning and sanitizing protocol.

The next document pertaining to codes and standards was the *FS119 Sanitary Design and Consumption of Food Equipment* document [3]. The main design guidelines from the document are summarized as follows:

1. Surfaces must be impervious, free from any cracks or crevasses, non-porous, non-absorbent, and durable.
2. Material 316SS and 304SS can be used.
3. Material 303SS should not be used.
4. Material aluminum can be used, but its poor corrosive resistance must be considered.
5. No square corners allowed. All corners must be rounded.

The next document pertaining to codes and standards is the *2017 FDA Food Code* document [4]. The main codes from the document are summarized as follows:

- Surfaces that contact food must:
    a. Be non-porous and smooth.
    b. Be free from any imperfections such as cracks and open seams.
    c. Have no sharp angles where buildup could occur.
    d. Have all welds ground smooth.
- For cleaning and inspection, the system must be disassembled using no tools or limited hand tools that are commonly available to maintenance workers.
- Cannot use "V" type threads.

- Non-food contact surfaces must be easily cleaned.
- All covers or lids should overlap and slope for drainage
- If the design requires the use of bearings or lubricants the design must be constructed so that no lubricant can come into contact with the food.
- If the equipment cannot be moved it must be designed so that:
    a. There is enough space to clean around equipment
    b. A space of at least 1mm is between the walls, ceiling, and other equipment
    c. Be on legs of at least 15cm so that it can be cleaned below equipment. This can vary so for further details see the FDA document [4]

2 Concept Selection Process

The concept selection process consisted of the generation of a total of 21 initial concepts that were sketched and categorized into 4 tiers which represent the concepts' potential to be in the final selection. Once the highest-ranking concepts were established, an in-depth analysis of the top concepts was conducted to arrive at a final concept. The final 4 concepts were compared internally and with the client. In addition to discussing the internal selection of a final design, the feedback received from the client has also been summarized and provided in Appendix A. It should be noted that this final design report presents only the final 4 concepts in detail.

2.1 Initial Concept Categorization

The development of a method for sorting through the twenty-one initial concepts was reliant on a plan to prioritize designs which show promise. The team decided to form a four-tier ranking system to organize the concepts. The four-tier setup is shown in Figure 4.

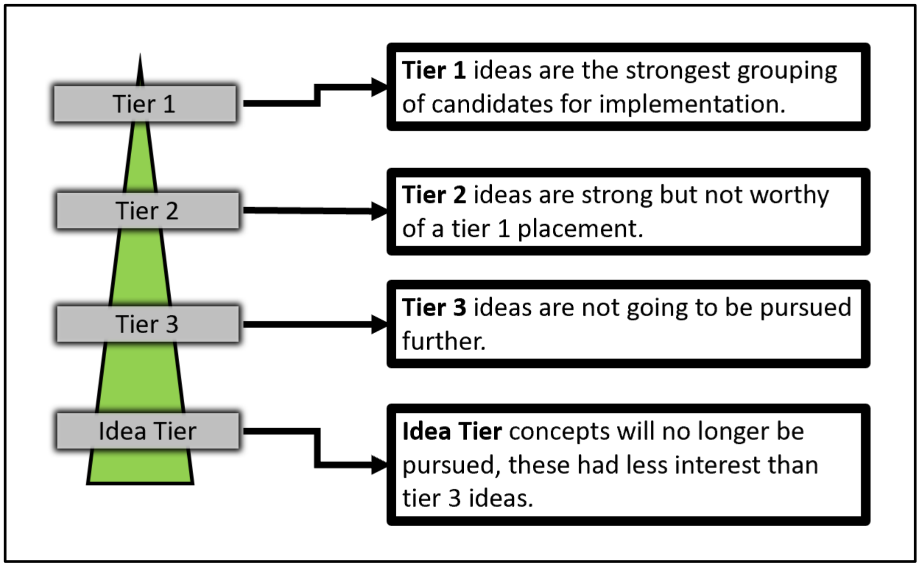


Figure 4: Breakdown of tiers used in concept categorization

The idea tier consists of the concepts that were incomplete but still provided an idea for loin reorientation. Tier 3 contains the concepts that were deemed infeasible, even though they provide a solution on how to re-orient the loin. Tier 2 holds the concepts that provide solutions to the problem and are feasible, but were deemed unreliable. Lastly, Tier 1 consists of the best and most promising concepts that provide a feasible, complete and reliable method of re-orienting the loin. The initial concept sketches for Tier 1 are discussed in the body of this report. The remaining sketches for concepts which fall into Tier 2 have been included in Appendix B. Concepts from Tier 3 and the Idea Tier have been excluded from the report due to their lack of contribution to the final design.

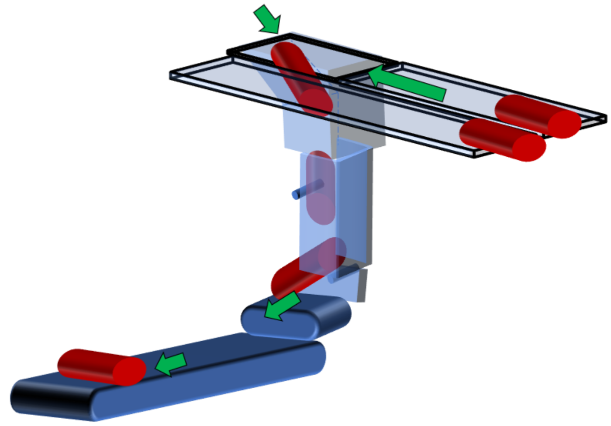
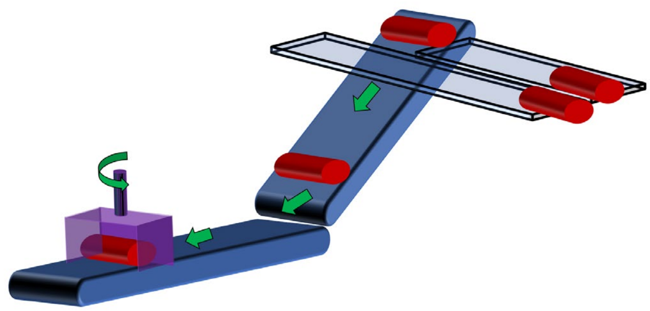
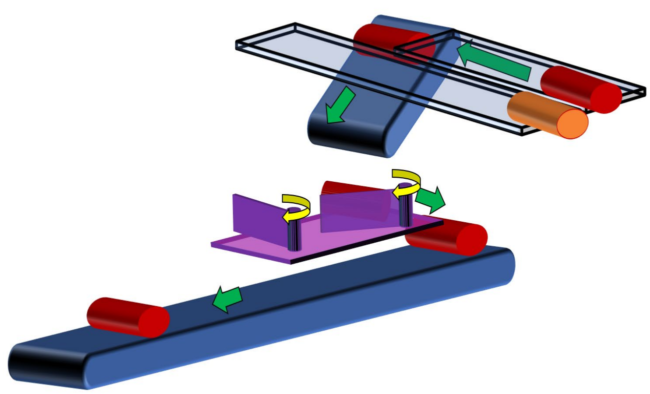
2.2 Summary of Final Concepts

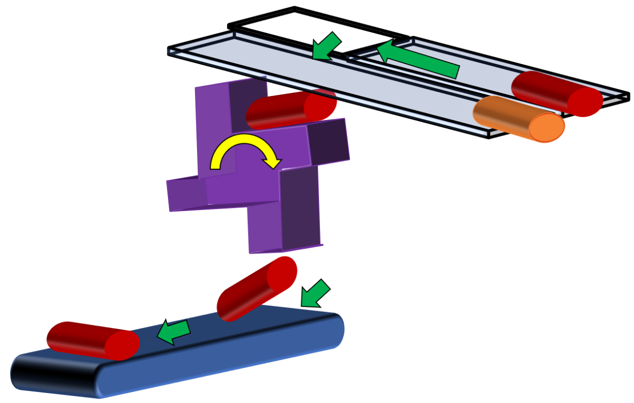
The Tier 1 concepts chosen to advance in the selection process are displayed visually and compared against each other in the next subsection. Tier 1 consists of four concepts, each having their own strengths and weaknesses, and are summarized by utilizing weighted decision matrices. Weighted decision matrices were completed by the team individually, client individually, and collectively as a group-client combination.

2.2.1 Sketches - Tier 1 Concepts

Sketches of the top four concepts which were selected to populate Tier 1 are presented in TABLE III. Each concept is introduced using the Triple F method which shows a figure of the concept, the feature of the concept, and an explanation of the function. The main features are depicted in purple, and the loin path is denoted in green arrows.

TABLE III: FEATURE, FUNCTION, AND FIGURE OF TOP 4 CONCEPTS

Name: Loin Chute **Feature:** Chute, secondary conveyor and ram **Function:** The loin falls down the chute onto a secondary conveyor which brings the loin into position. Then, a ram transfers the loin onto the main conveyor.	
Name: Bite & Turn **Feature:** Clamping and turning motion **Function:** The bite and turn method traps the loin when it arrives at the device. After trapping the loin, it is turned 180 degrees then released. The conveyor takes the loin away after release.	
Name: Pinball Paddles **Feature:** Two perpendicular paddles on a stationary platform **Function:** The loin falls down the slide onto a stationary table, wherein the first paddle rotates 90 degrees, followed by the perpendicular paddle rotating an additional 90 degrees to push the loin backwards off the platform onto a moving conveyor.	

Name: Loinbine **Feature:** Rotating wheel with slots for the loin **Function:** The loin drops into the holder on the rotating wheel. Then as the wheel rotates clockwise the loin falls from the holder where it would travel down a slide to reach the lower conveyor. The wheel/then reorients the loin.	

2.2.2 Fundamental Operation - Tier 1 Concepts

As stated previously, it was decided that only four concepts would be placed in Tier 1. The Tier 1 concepts represent the most capability in addressing the client needs, while maintaining a high degree of realism in terms of manufacturability and cost. The Tier 1 concepts are listed in TABLE IV:

TABLE IV: TIER 1 CONCEPTS

Concept Number	Concept Name
14	Bite & Turn
15	Pinball Paddles
16	The Loinbine
20	Loin Chute

Concept 14, the *Bite & Turn*, was a definitive concept in terms of its simplistic design, integration with the existing process, and working principle. The simplicity in design is attributed to a structure that is welded together with minimal fasteners, one pneumatic cylinder, one motor, and a front restraint bar to capture the loin. The integration with the existing process is straightforward in that the supporting structure for the *Bite & Turn* can bolt onto the existing conveyor and requires no further modification of the surrounding structures. Lastly, the operating principle is simple in that the loin is captured and self aligns within the hood (due to the continuously moving conveyor pushing the loin towards the hood). The front restraint bar is lowered with the pneumatic cylinder, the whole assembly rotates 180 degrees, followed by the raising of the restraint bar, release of the loin, and prompt return to the home position to accept the next loin.

Concept 15, *Pinball Paddles*, was delegated to Tier 1 for its simplicity, ease of cleaning, and potential for being very reliable. The simplicity of the *Pinball Paddles* concept is attributed to the use of a sheet metal slide, either motors or pneumatic cylinders, two 90-degree rotations with the paddles and a small backwards drop onto an underlying conveyor. As a result of only having the two paddles, a sheet metal slide, and a sheet metal table, concept 15 would be easy to clean, which is a crucial need for HyLife. Finally, the reliability of the *Pinball Paddles* concept comes from the passive process of the loin sliding down into place against the first paddle. This is followed by a 90-degree rotation of the first paddle and then again by the second paddle, pushing the loin backwards onto the conveyor under the table.

Concept 16, the *Loinbine*, was selected as a Tier 1 concept for its rapid processing capability (i.e. ability to handle variable cycle times), simple working principle, and unique approach to solving two separate problems: the lowering of the loin to the conveyor and rotating the loin 180 degrees. The *Loinbine* is a positive rotation mechanism, wherein the loin falls onto one of the holders and the assembly consequently indexes in one direction until the loin falls onto the slide and conveyor below. Thus, it is both simple and capable of handling fast cycle times. By taking the loin as it falls into the holder and rotating until the loin falls face down, the loin is both lowered onto the conveyor below and rotated 180 degrees; the integration of both lowering and rotation into a single step simplifies the overall process and increases reliability.

Concept 20, the *Loin Chute*, was conceptualized as a simplified version of the *Loinbine*, considering ideas from concepts 18, 19, and 21. The *Loin Chute* was determined to be a Tier 1 concept on the merit that it further simplified the *Loinbine* concept. Through the use of only the chute and the elimination of the indexing holder assembly, the repeatability of the system could be potentially higher, as once the system is calibrated, each loin would fall by gravity down the chute in the appropriate orientation. At the bottom of the chute, the loin would fall onto a continuously rotating conveyor, which would drag the bottom end of the loin over the remaining 90 degrees and be consequently pushed onto a perpendicular conveyor. The simplicity of the *Loin Chute* is complemented by easy cleaning, as the chute can be quickly washed and the cleaning of a small conveyor is standard affair for HyLife. Thus, the *Loin Chute* was determined to be a Tier 1 concept for its simplification of an existing Tier 1 concept, easy cleaning, and high repeatability after post-installation tuning.

2.3 Analysis of Top Concepts

With the concepts categorized and described in detail, the most promising Tier 1 concepts were then further analyzed. A weighted decision matrix was completed for all Tier 1 and Tier 2 concepts to arrive at the final 4 top concepts to present to HyLife. The completed weighted decision matrix for the final 8 concepts can be accessed in Appendix B. However, only the final scoring for the top 4 concepts will be included in the body of the report to focus efforts on comparison of concepts which progressed to the final selection stage.

2.3.1 Developing Criteria Weighting

In order to compare the concepts, it was important to first develop the weighting criteria. It was decided that the selection criteria would consist of reliability, cost, complexity, safety, ease of integration, commissioning time, and cleaning/maintenance. The criteria and corresponding weights can be seen in TABLE V.

TABLE V: DECISION MATRIX CRITERIA WEIGHTING

Selection Criteria		A	B	C	D	E	F	G
Reliability	A		A	A	D	A	F	A
Cost	B			C	D	E	F	G
Complexity	C				D	E	F	C
Safety	D					D	D	D
Ease of Integration	E						F	G
Commisioning Time	F							G
Cleaning/Maintenance	G							
TOTAL HITS		5	1	3	7	3	5	4
WEIGHT		0.18	0.04	0.11	0.25	0.11	0.18	0.14

The selection criteria were compared, and a winner for each was selected. The number of individual "hits" or wins were summed to form the total number of hits for each. With the total number of hits known, the corresponding weight was calculated. With the weighting of each criteria known, the team could move onto the decision matrix.

2.3.2 Weighted Decision Matrix

Using the weighting criteria from TABLE V, the top concepts were compared against each other. There was a total of 8 final concepts that the team compared against each other, however only the final four Tier 1 concept results from the weighted decision matrix will be presented here. The complete weighted decision matrix with all 8 of the Tier 1 and Tier 2 concepts can be accessed in Appendix B, as mentioned in the preceding section, Section 2.3.1. For each of the concepts a rating was assigned from 1 to 5, depending on how well the concept met the selection criteria. A "1" would indicate that the concept poorly met the criteria, and a "5" meant that the concept did well in that area. After the criteria was rated for each concept, the total score for each concept was found. The weighted decision matrix can be seen in TABLE VI.

TABLE VI: WEIGHTED DECISION MATRIX

		Concept							
		14 Bite & Turn		15 Pinball Paddles		16 The Loinbine		20 Loin Chute	
Selection Criteria	**Weight**	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Reliability	0.18	4	0.71	4	0.71	4	0.71	5	0.89
Cost	0.04	5	0.18	3	0.11	4	0.14	4	0.14
Complexity	0.11	4	0.43	3	0.32	4	0.43	4	0.43
Safety	0.25	4	1.00	5	1.25	4	1.00	5	1.25
Ease of Integration	0.11	5	0.54	3	0.32	4	0.43	4	0.43
Commisioning Time	0.18	3	0.54	3	0.54	4	0.71	4	0.71
Cleaning/Maintenance	0.14	5	0.71	5	0.71	4	0.57	4	0.57
TOTAL SCORE		4.11		3.96		4.00		4.43	
RANK		2		4		3		1	

The results only show the scores for the top ranking 4 concepts. The exact ranking of the final 4 concepts which the weighted decision matrix yielded should not be looked at too deeply in terms of a final concept selection. At the point that these concepts were ranked, there was no CAD models created or fine details established. Further development of each concept was conducted before final internal and external concept selection.

With ratings of 4.43/5, 4.11/5, 4.00/5, and 3.96/5 the respective concepts 20, 14, 16, and 15 (i.e. *Loin Chute, Bite & Turn, Loinbine, Pinball Paddles*) would move on to the final concept development phase. As stated in the preceding section, the scores that each of these concepts received should not be read into too deeply. Further analysis will be conducted on each to develop a better understanding of which concepts will be best suited for implementation.

2.4 Further Development of Final 4 Concepts

Before presenting the top 4 concepts to HyLife, each design was modelled in CAD software and placed into the existing CAD model of the HyLife gantry in preparation for the client review. Each design's operation is explained in detail in this section utilizing renders from the CAD models as visuals. This concept development stage helped the team get an idea of how each of the concepts would be packaged into the design space.

2.4.1 Top Concept 1

Top Concept 1, *Pinball Paddles-TC1*, features a three-step process to move the loin from the upper conveyor down to the lower conveyor, while reorienting the loin 180 degrees as required by HyLife. It uses a stainless steel sheet metal slide, two pneumatic cylinders with proximity sensors pre-installed, two stainless steel paddles (secured to welded shafts on the table with retaining rings), a secondary conveyor (which may be exchanged for an extended lower conveyor) and one additional proximity sensor for detecting a loin and starting the process. *Pinball Paddles-TC1* is isolated and labelled in Figure 5.

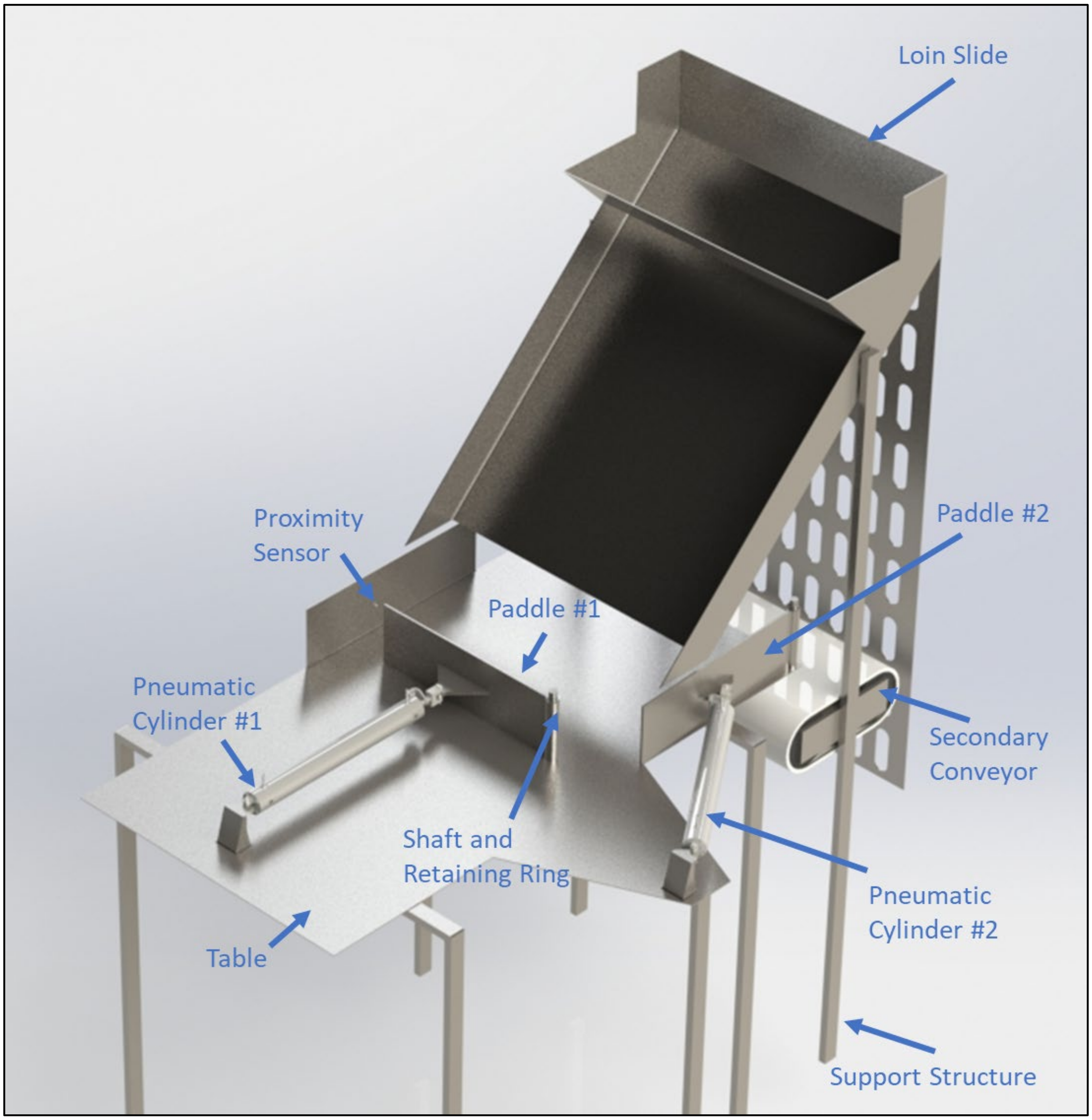


Figure 5: Pinball Paddles-TC1 - isolated overview diagram

Figure 5 shows that *Pinball Paddles-TC1* is straightforward in terms of manufacturing. The first step in its function is to bring the loin down the stainless steel slide until it lands on the table and butts up against paddle #1. At this point, a proximity sensor (labelled in the Figure 5) detects the loin and triggers the first pneumatic cylinder to actuate 90 degrees, as indicated next in Figure 6.

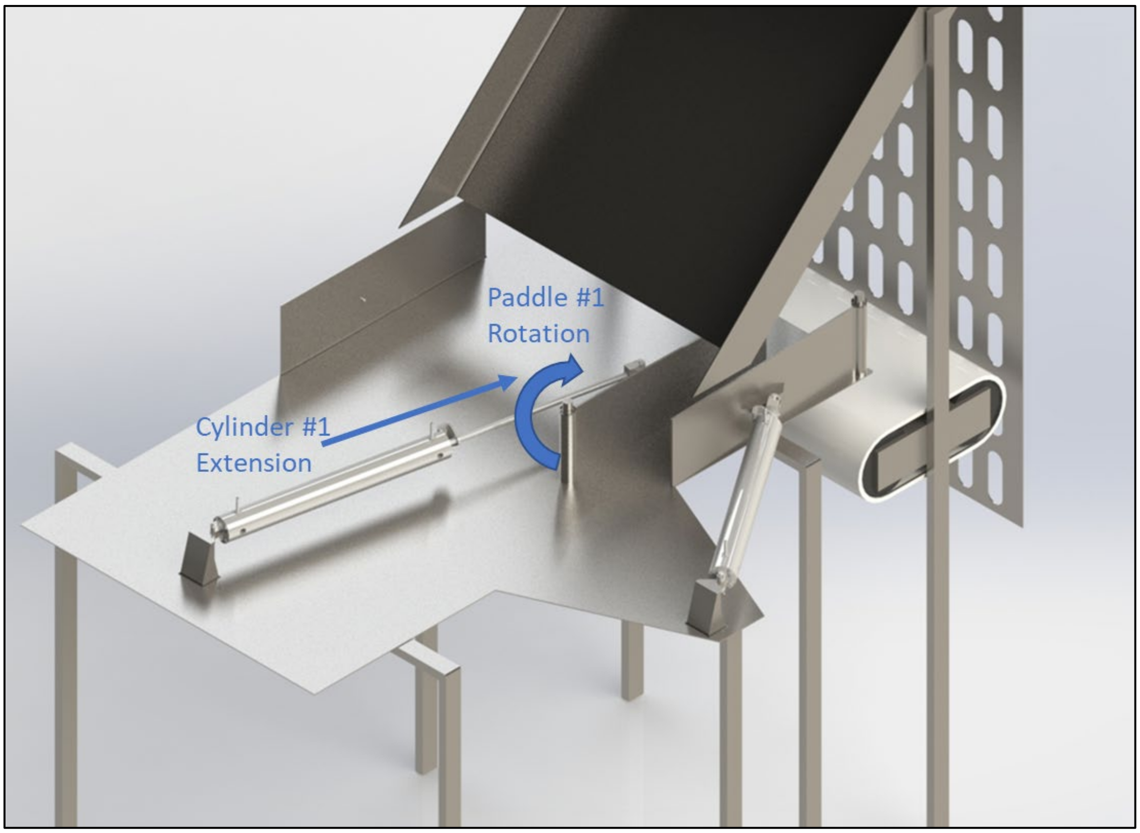


Figure 6: Pinball Paddles-TC1 - paddle 1 operation

It should be concluded from Figure 6 that the fully extended position of the first paddle will, in effect, push the loin up against the second paddle. At this point, the first paddle retracts to its original home position and the second paddle rotates 90 degrees by means of the second pneumatic cylinder, as indicated in Figure 7.

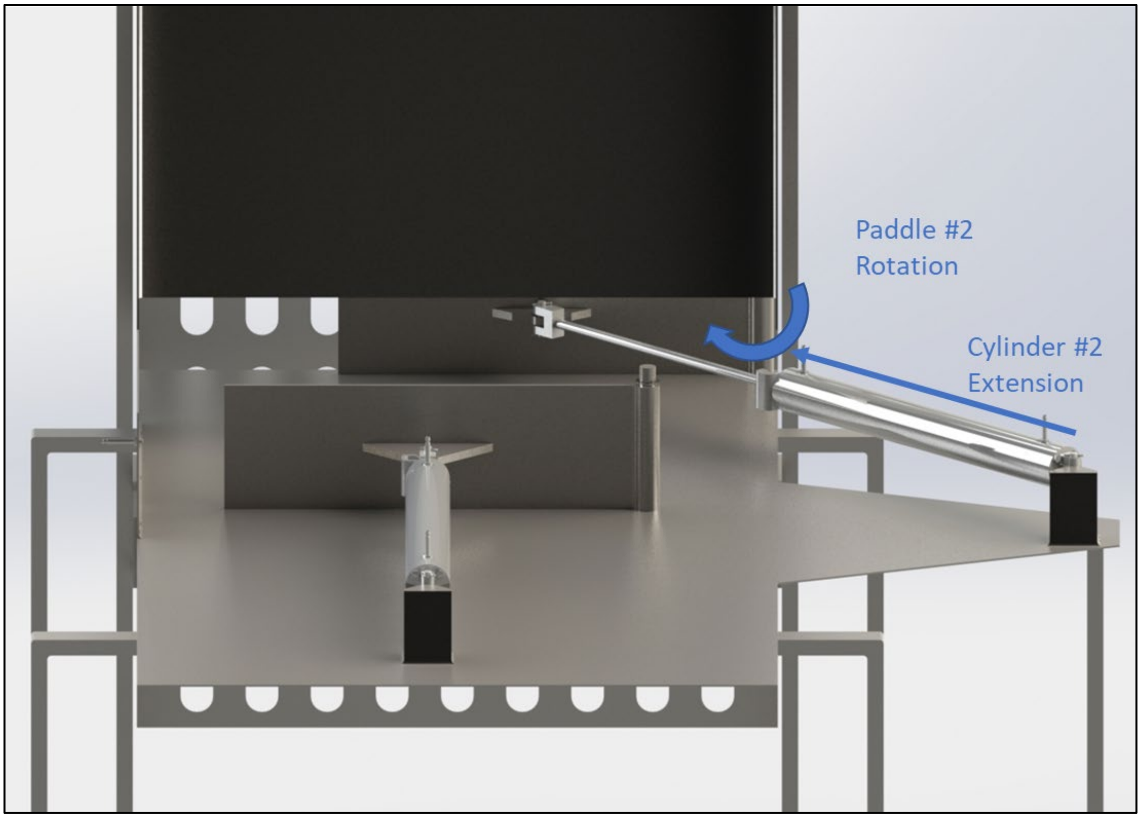


Figure 7: Pinball Paddles-TC1 - paddle 2 operation

Figure 7 shows the end of the second paddle stroke, where the loin is pushed backwards off of the sheet metal table and onto an underlying conveyor. On the conveyor, the loin is finally carried to the operators on the processing line. The underlying conveyor and concept integration with the existing equipment is shown in Figure 8.

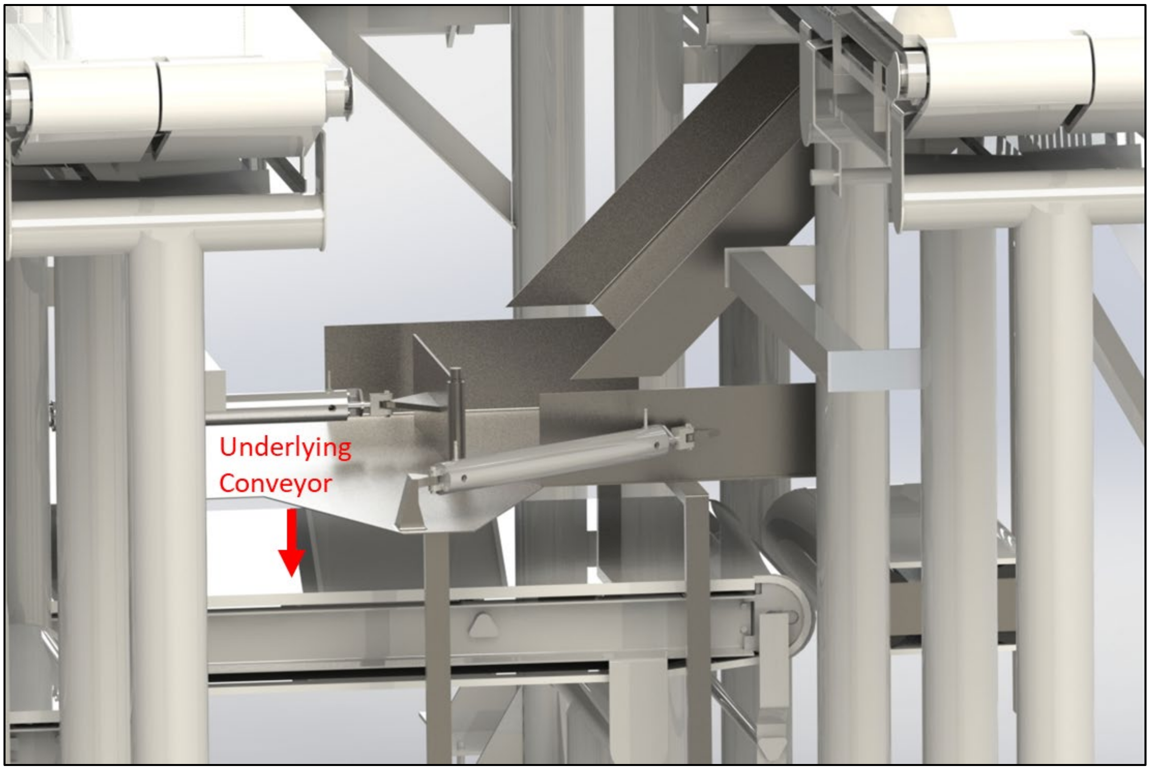


Figure 8: Pinball Paddles-TC1 - underlying conveyor and process integration

Figure 8 shows the integration with the existing process and equipment. An isometric view shows minimal change from the existing setup at HyLife and is presented in Figure 9.

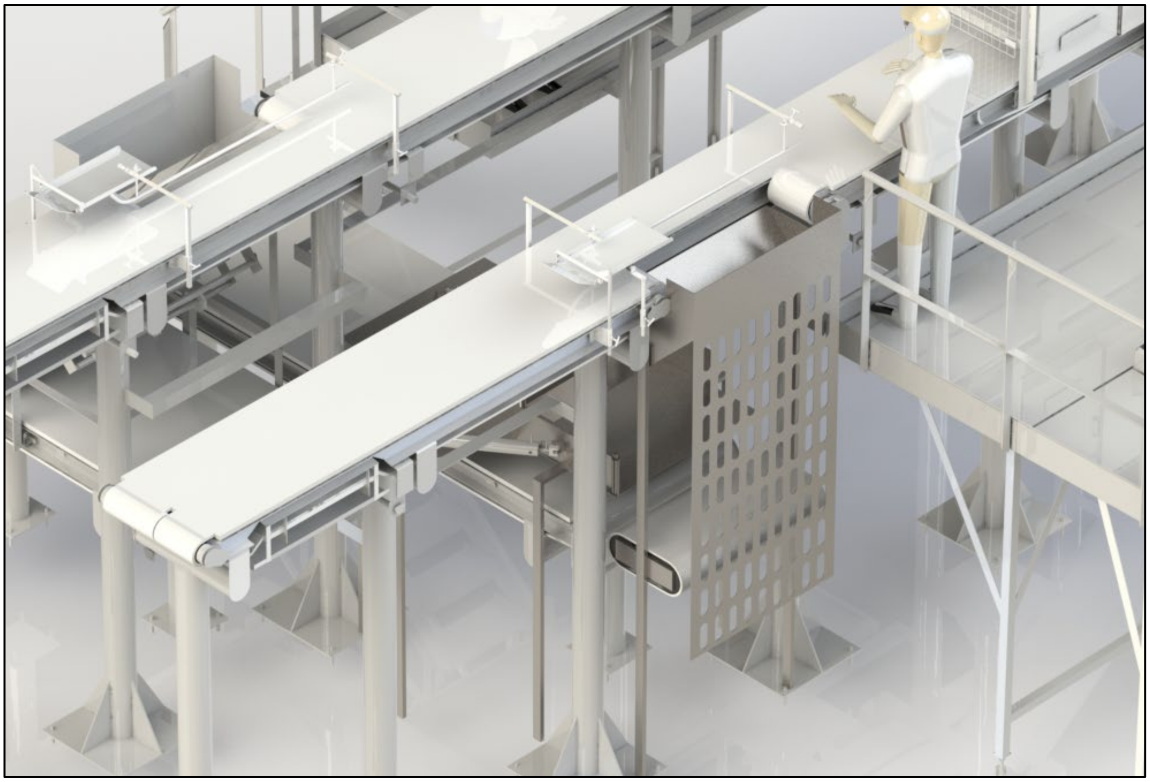


Figure 9: Pinball Paddles-TC1 - isometric view

Overall, *Pinball Paddles-TC1* provides a system that integrates with HyLife's existing process. Its design simplicity would also afford HyLife ease of cleaning and rapid servicing when necessary. By utilizing pneumatic cylinders, passive loin movement, and mechanical manipulations of the loin, *Pinball Paddles-TC1* ranked highly during the final design selection.

2.4.2 Top Concept 2

Top Concept 2, *Bite and Turn-TC2*, features a simple approach to reorienting the loin. Without modification to the upper and lower conveyor, *Bite and Turn-TC2* accepts and turns the loin. The *Bite and Turn-TC2* features a hood made from stainless steel sheet metal which has been bent and welded. The entire design rotates under the power of a rotary actuator and the restraint is operated by a pneumatic cylinder. Figure 10 depicts the concept with components labelled.

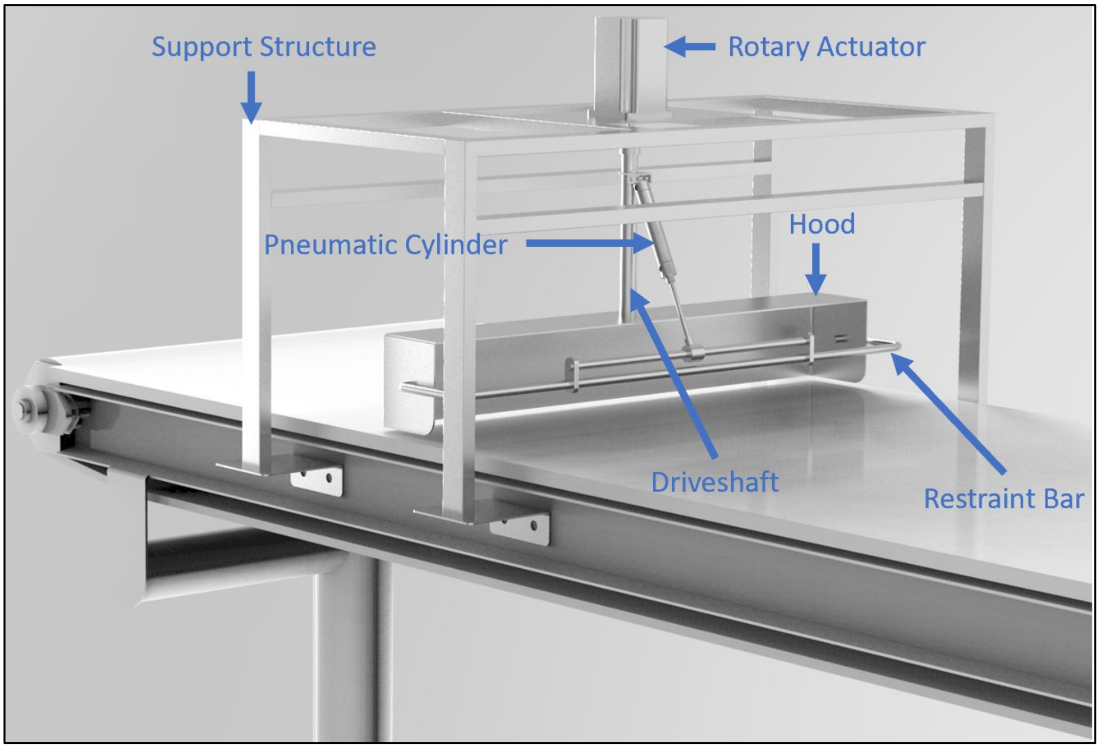


Figure 10: Bite and Turn-TC2 overview diagram

The *Bite and Turn-TC2* operates by accepting the loin in its “as received” orientation (i.e. orientation from the upstream process) when the restraint bar is open. The loin is directed into the hood as the conveyor pushes the loin towards the reorientation system. Once the loin enters the hood, the loin self-aligns and the restraint bar lowers to ensure the loin does not exit the system before being reoriented. The rotary actuator then turns the entire hood and loin 180 degrees. Once the 180 degree turn is complete, the restraint bar is lifted, and the conveyor proceeds to take the loin away. An optical sensor will be placed just before the loin is accepted into the hood to alert the system to immediately close the restraint bar and begin the rotation process. Figure 11 shows the restraint bar in both the open and closed positions.

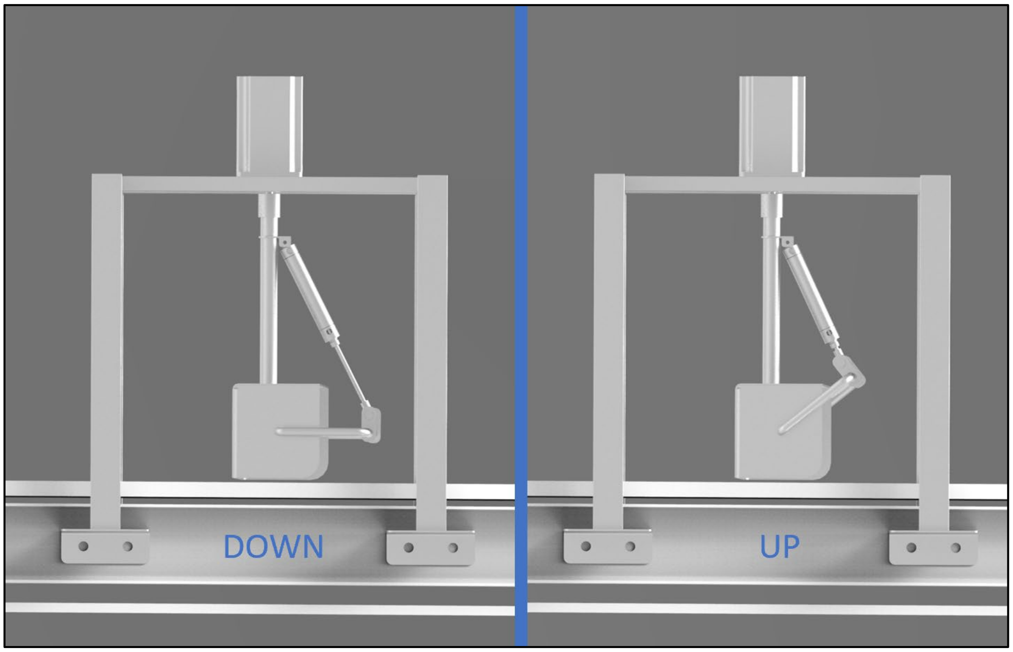


Figure 11: Bite and Turn-TC2 restraint operation

Figure 11 shows that the mechanical operation of the *Bite and Turn-TC2* restraint, while the following Figure 12 features what the *Bite and Turn-TC2* system will look like when rotating the loin midway through rotation.

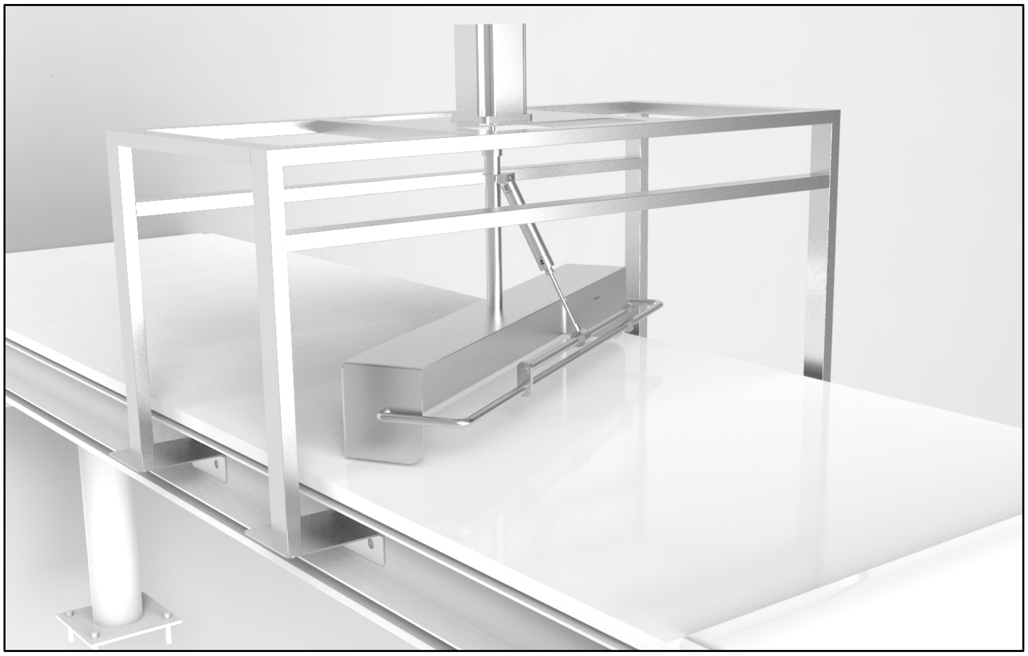


Figure 12: Bite and Turn-TC2 – mid-rotation

HyLife has an existing system for loin reorientation that has remained unused. The design was implemented at the same time as the loin line was developed but did not complete the loin reorientation process correctly. Since the existing system did not complete the reorientation process reliably, it has occupied space and remained idle. Given that the *Bite and Turn-TC2* system features a similar mounting location and integrates well into the overall system, it would integrate and maximizes the use of the existing space by replacing the legacy system. Figure 13 demonstrates how the *Bite and Turn-TC2* system integrates into the overall system.

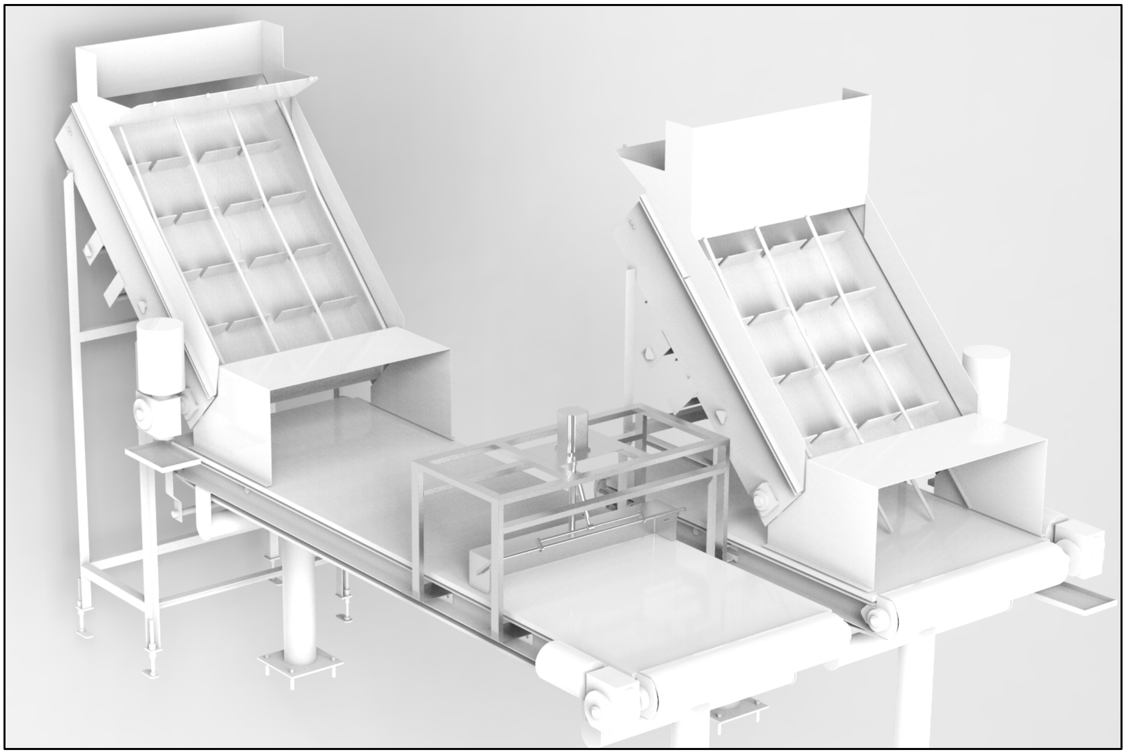


Figure 13: Bite and Turn-TC2 system integration

Overall, the *Bite and Turn-TC2* features a small footprint and is not invasive, in that it does not require extensive modifications to the surrounding equipment.

2.4.3 Top Concept 3

Top Concept 3 is the *Loinbine*, denoted *Loinbine-TC3*. The *Loinbine* originally consisted of a chute that would guide the loin down to a wheel. The wheel consisted of 4 different holders spaced evenly around the wheel. The loin would fall into one of the holders before the wheel rotated. The wheel would rotate, and the loin would fall out onto a slide. The slide in question would guide the loin down to the bottom conveyor. After further discussion it was decided that the *Loinbine-TC3* could be simplified by reducing the number of holders on the wheel from 4 down to only 1. Initially it was also thought that a motor would be used to rotate the loin holder, but it was decided that a pneumatic cylinder would be used instead to rotate the holder. The refined *Loinbine-TC3* concept can be seen in Figure 14.

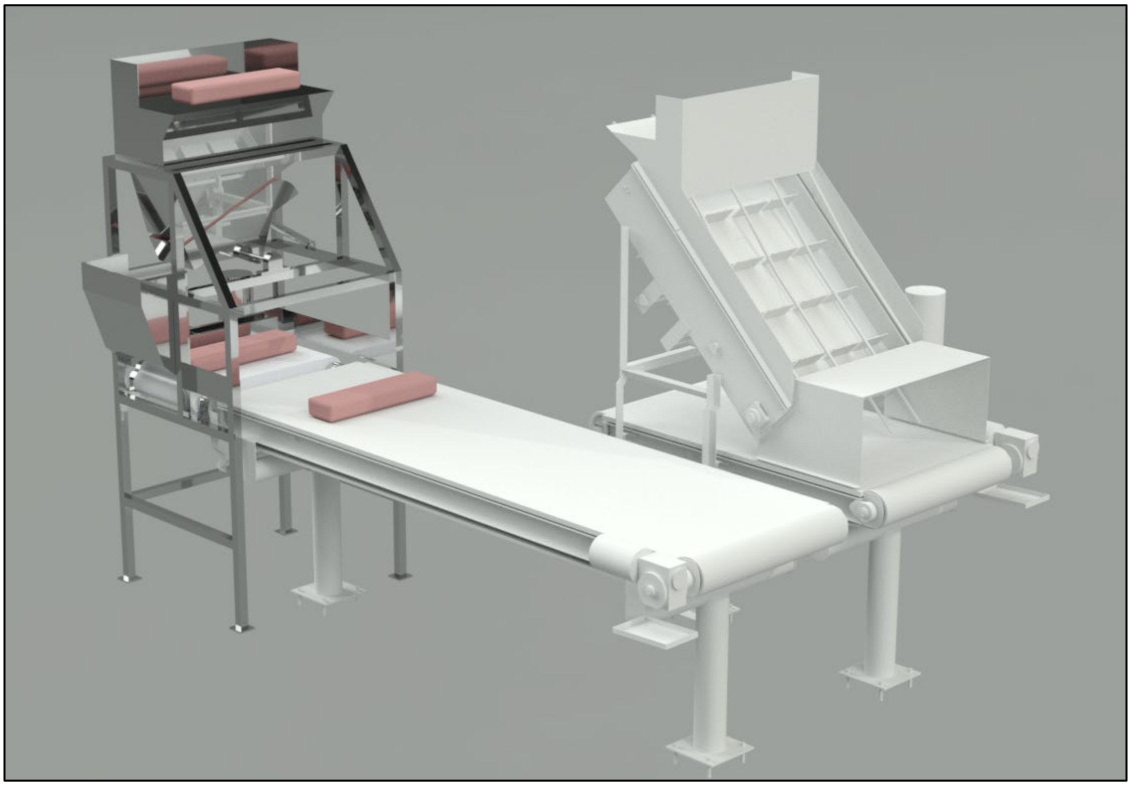


Figure 14: Loinbine-TC3 overview - view 1

Another aspect of the *Loinbine-TC3* design is that a linear ram would be needed to transfer the loin onto the main conveyor. The ram can be seen in Figure 15, adjacent to the cylindrical conveyor motor.

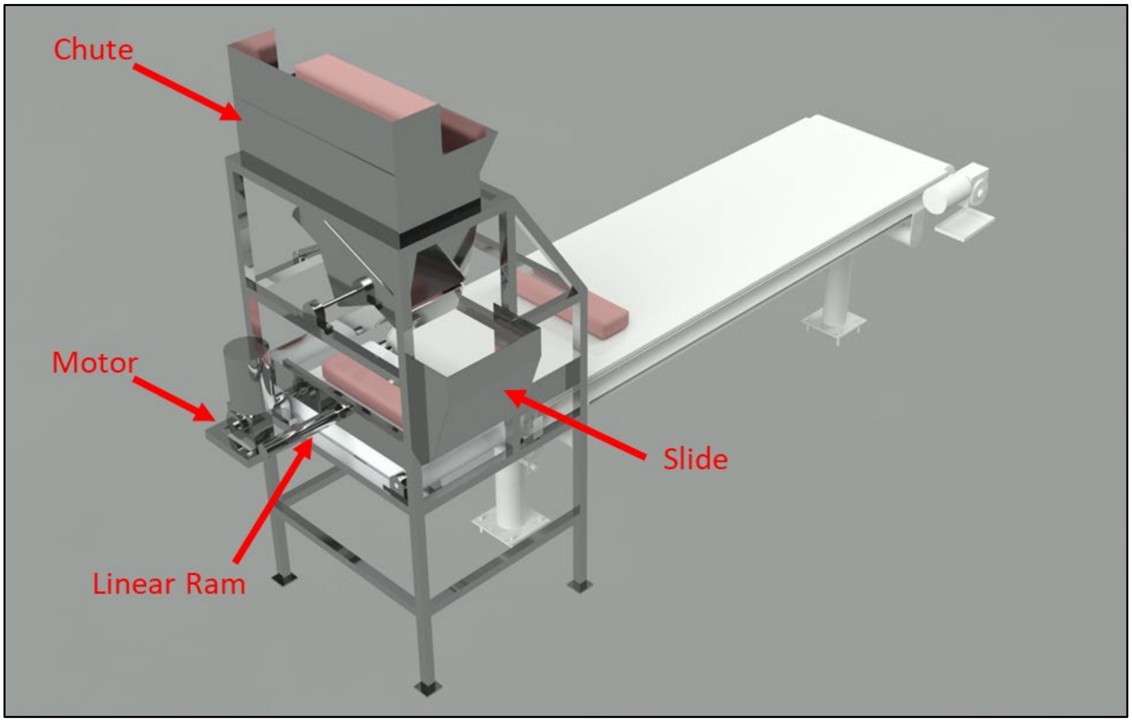


Figure 15: Loinbine-TC3 overview - view 2

Another important aspect is how well the design integrates into the existing process. The design was well packaged and can be seen integrated into the existing process Figure 16.

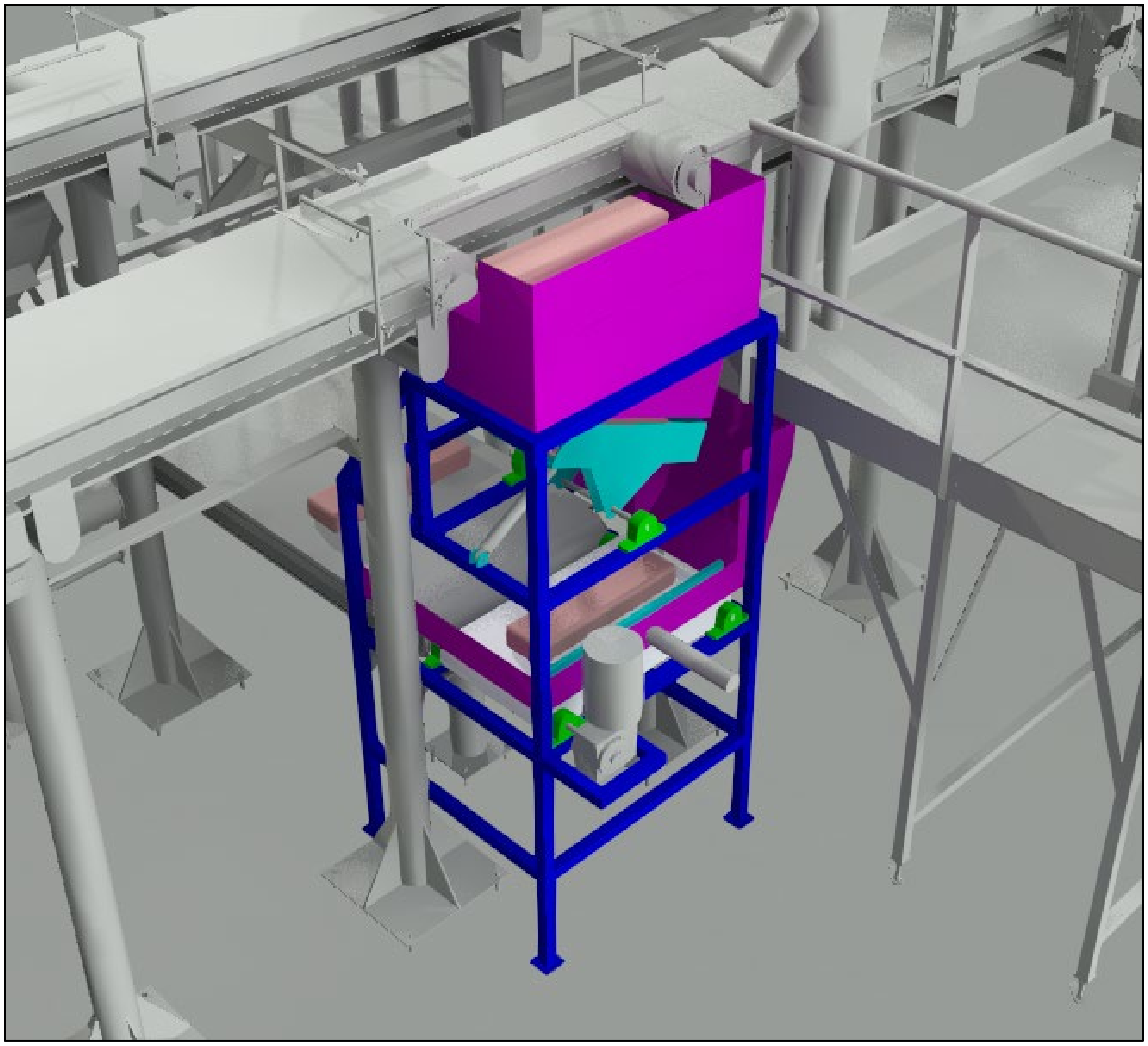


Figure 16: Loinbine-TC3 process integration

The *Loinbine-TC3* would reorient the loin in 5 steps that will be outlined next. The first step involves the loin falling off the upper conveyor into the chute, as shown in Figure 17.

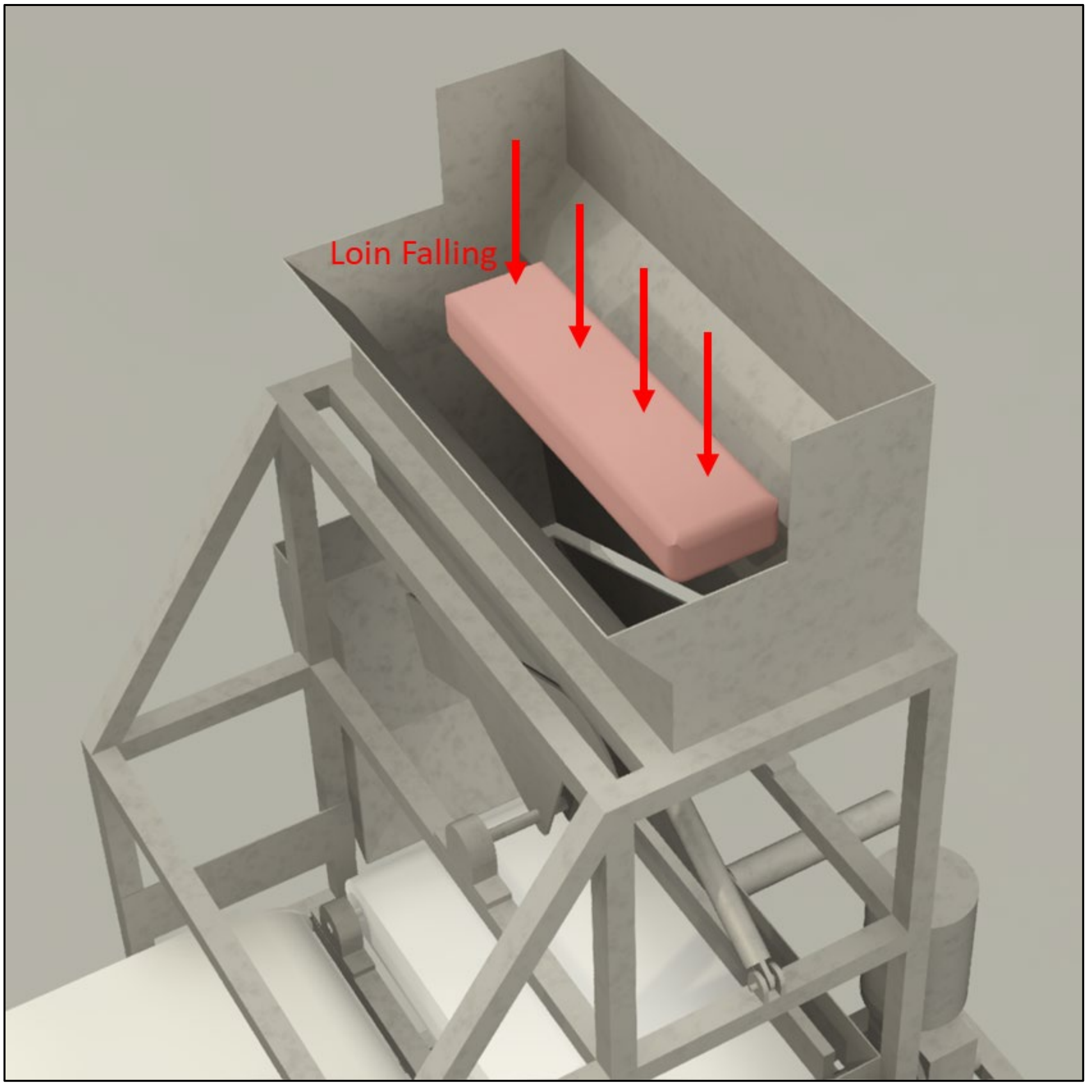


Figure 17: Loinbine-TC3 step 1 – loin falling down into the chute from the upper gantry

After the loin falls into and travels down the chute, it would end up in a holder/cradle as shown in Figure 18.

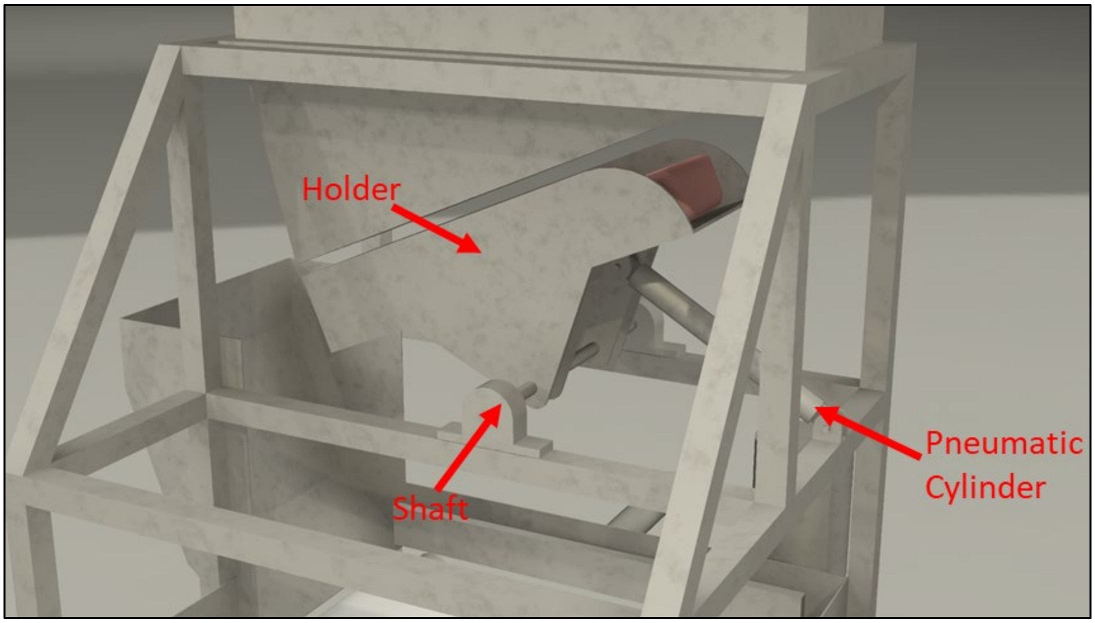


Figure 18: Loinbine-TC3 step 2 – loin is in holder

The holder would then be rotated using a pneumatic cylinder and shaft. As the holder rotates, the loin would fall out of the holder, as demonstrated in Figure 19.

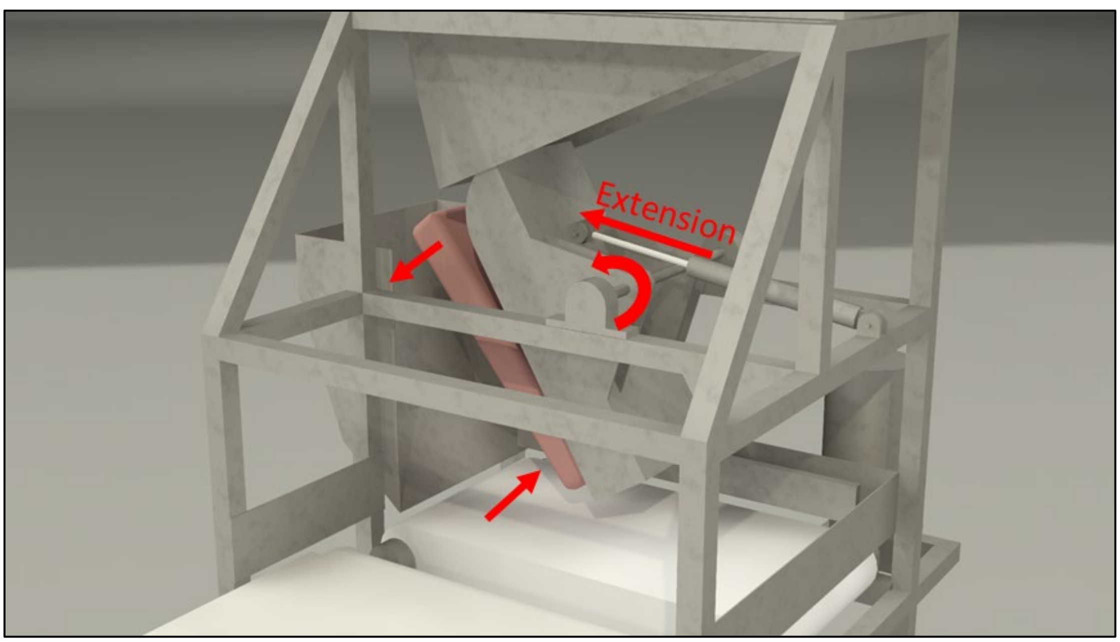


Figure 19: Loinbine-TC3 step 3 – holder rotates, and the loin falls out

After the loin falls out of the holder, a slide/guard would guide the loin downward onto a continuously running conveyor below. Upon contacting the conveyor, the loin would be pulled over into a horizontal position. The loin can be seen in its final position in Figure 20.

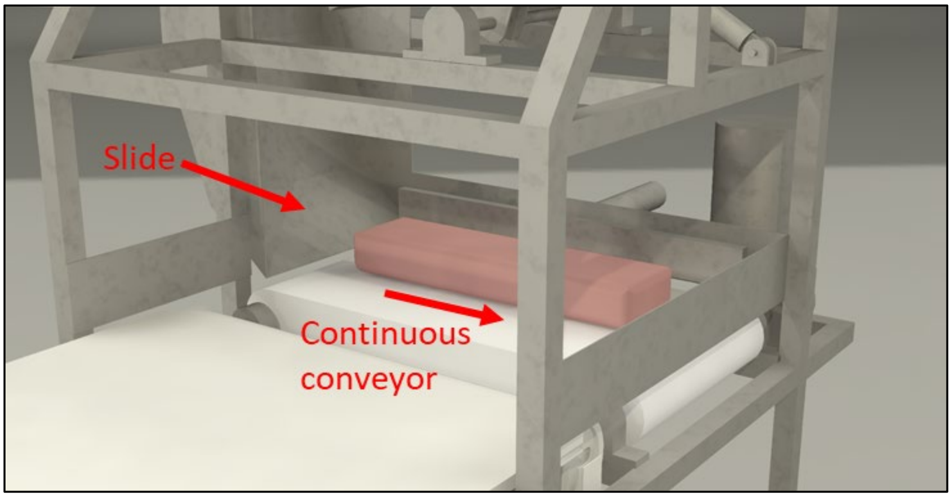


Figure 20: Loinbine-TC3 step 4

With the loin in position, the linear ram would then push the loin onto the lower conveyor as is shown in Figure 21.

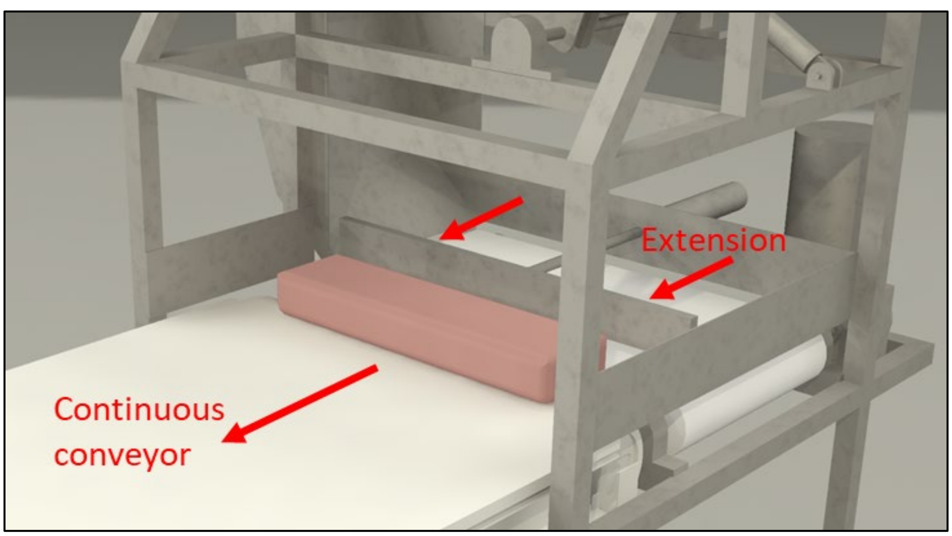


Figure 21: Loinbine-TC3 step 5

The loin would then continue down the main conveyor in the correct orientation to the operators.

2.4.4 Top Concept 4

Top Concept 4 was the *Loin Chute,* denoted *Loin Chute-TC4*. This concept is similar to the *Loinbine-TC3* in that it features a chute, secondary conveyor, and a pneumatic-actuated linear ram. This concept requires the removal of the existing decline conveyor and brings the loin from the upper conveyor to the loin line. Figure 22 shows the components of the *Loin Chute-TC4*.

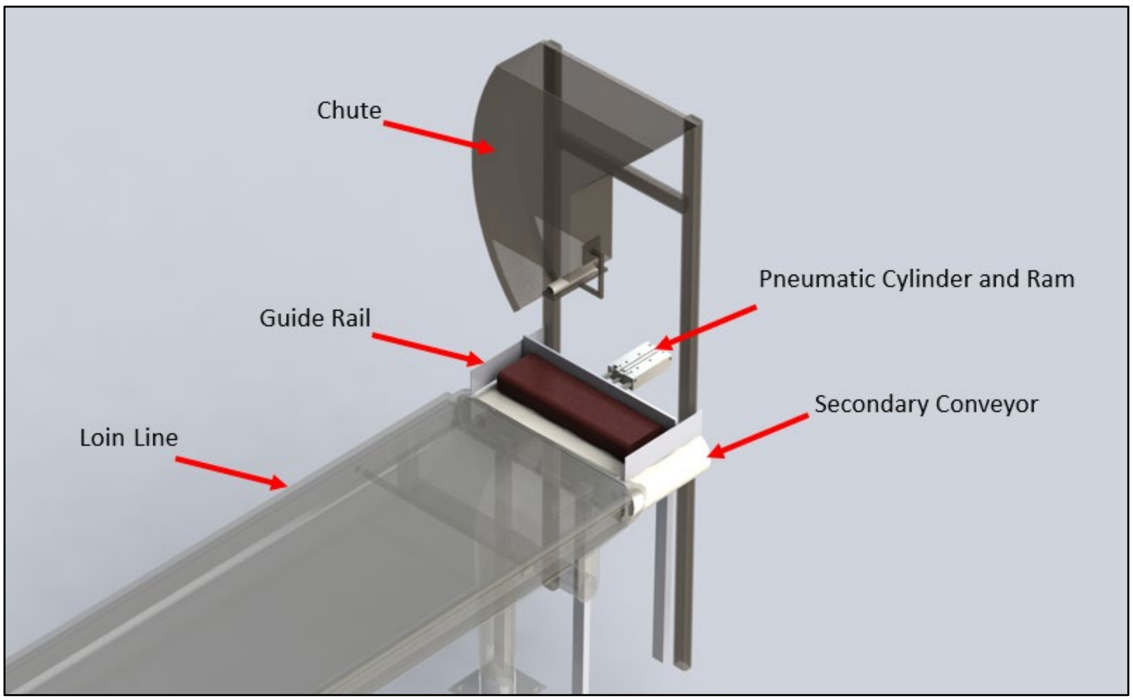


Figure 22: Loin Chute-TC4 overview

The main feature of the *Loin Chute-TC4* is its chute component; the chute geometry is customized to the characteristics of the falling loin, as the loin will be guided down from the main line to a secondary conveyor in a vertical orientation. Figure 23 shows the progression of the loin as it falls and is re-oriented. First, the loin slides down the top part of the chute. Then, the loin falls off and contacts a roller. Next, the loin keeps falling as it is guided by the curved wall of the chute. As the bottom end of the loin makes contact with the secondary conveyor, it gets pulled over by the conveyor until it falls flat and is stopped by the guide rail. Lastly, the pneumatic-actuated linear ram pushes the loin from the secondary conveyor onto the loin line.

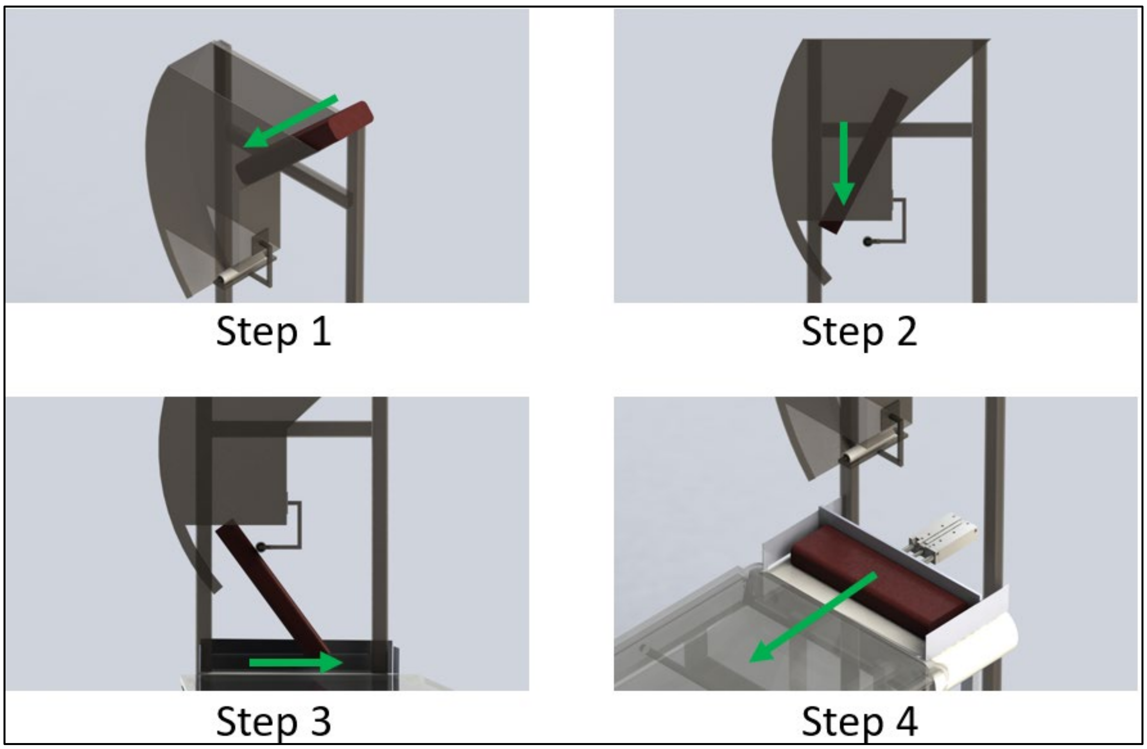


Figure 23: Progression of the loin down the Loin Chute-TC4 in 4 steps with the motion directions denoted by green arrows

The integration of the *Loin Chute-TC4* with the existing system at HyLife is expected to be more challenging compared to the other top concepts due to the chute's complex geometry. The curved part of the chute may interfere with the upper conveyor, depending on its final dimensions. This curved part of the chute also makes it difficult to mount the chute. Figure 24 shows an isometric view of the concept with the existing system.

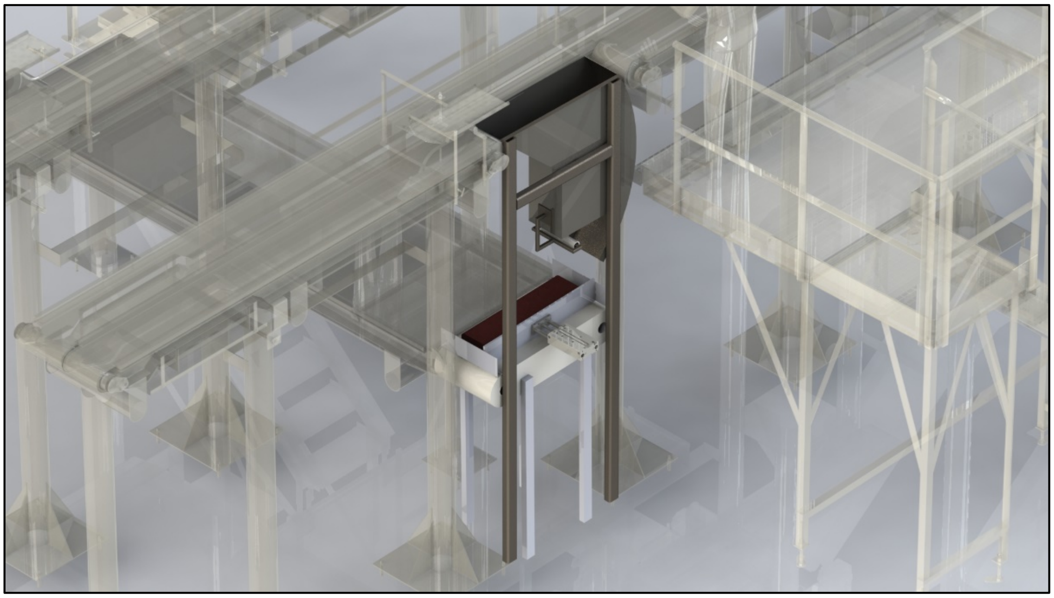


Figure 24: Loin Chute-TC4 process integration

Figure 24 shows that the *Loin Chute-TC4* integrates into the existing system assuming that the space occupied by the chute does not exceed the design space.

2.5 HyLife Concept Review

The following section summarizes the feedback received from the client during the video conference in which the team presented the top four concepts. All client recommendations, questions and concerns were recorded and summarized in the following section.

2.5.1 Top Concept 1 Feedback

In the review of *Pinball Paddles-TC1*, HyLife indicated an interest in its novel approach. While HyLife showed interest, there were various points of improvement suggested if it were chosen moving forward.

The first discussion point was with respect to the use of cotter pins. Particularly, HyLife said that the use of cotter pins is discouraged, as they require small holes in a shaft that are hard to clean. An alternative to cotter pins is the use of retaining rings, which were featured in the mounting of the paddles to the shafts. The retaining rings are a good approach to holding components in place, as external grooves are easy to clean. However, the conceptual retaining rings shown on the paddle shafts would be difficult to remove. If *Pinball Paddles-TC1* is used moving forward, or other concepts require retaining rings, HyLife would assist in the selection of retaining rings that are standard to their facility and easy for maintenance staff to remove.

An additional discussion point was with respect to how the loin slide in *Pinball Paddles-TC1* could introduce variability as a result of the loin sliding freely. HyLife indicated that if *Pinball Paddles-TC1* is selected moving forward, they would prefer that the existing cleated conveyor system be used to bring the loins down to the table with the paddles.

Lastly, HyLife confirmed the suspicion that the secondary small conveyor in *Pinball Paddles-TC1* would be unnecessary, as the existing loin line conveyor can be modularly extended.

2.5.2 Top Concept 2 Feedback

In the review of the *Bite and Turn-TC2*, various recommendations were made. The first recommendation that was made referred to the capability of the design to move out of the way in the event that the loin reorientation system is not working. If a problem occurs that renders the design inoperable, the system must be able to move out of the way. When the design moves out of the way, the loin can freely bypass the system and move towards the operators without being reoriented. Some ideas on how to achieve this were discussed. This would be accounted for if selected moving forward.

Another recommendation that was brought up was a method of guarding the conveyors from the bare metal edges of the hood. The hood component of the design, which is best seen in Figure 12, operates in the close proximity to the conveyor. The implementation of an ultra high molecular weight (UHMW) plastic guard on the bottom of the hood was suggested to act as a runner and protect the conveyor from any damage due to contact.

Additional feedback was with respect to improving operational efficiency. HyLife suggest that there be a back-to-back (two-sided) hood to accept loins on each side. Having a back-to-back hood would require a second restraint bar and would cut the amount of rotation required to accept loins by 50% as a result of a single 180-degree turn per loin, as opposed to two for the single hood design. The main concern with turning the loin in the same direction is that air lines feeding the linear actuator would become wound around the driveshaft. Solving the winding issue would require the team specify a pneumatic connection capable of swiveling and will be considered in future low-level design if the *Bite and Turn-TC2* is chosen moving forward.

2.5.3 Top Concept 3 Feedback

The first comment was that a dead plate (i.e. stationary metal or plastic plate) could be used to transfer the loin over the gap between the new conveyor (which is perpendicular to the loin line) and the actual lower conveyor itself. By doing this there would be no gap between conveyors where the loin could get stuck. By adding a dead plate to the lower conveyor, the design and overall function of the *Loinbine-TC3* would be simplified. The second comment was that any additional conveyors could be installed at an elevated position relative to the lower conveyor to allow reliable transfer between conveyors. The third comment from HyLife was related to the frequency of loin arrival. It was suggested that the design be modified to allow the loins to go through the system during emergency situations. During these emergency situations the frequency of arrival would be higher than usual. HyLife was concerned that this increased frequency may create some jamming issues. Also, if the loin were to get jammed it may be difficult to remove the loin quickly. The final comment was that there may be insufficient clearance between the extended loin holder and the lower conveyor.

2.5.4 Top Concept 4 Feedback

The client noted that this concept would handle variable cycle times and loin orientations effectively. Secondly, the client identified a potential issue regarding the vertical drop that the loin experiences as it exits the chute and lands on the secondary conveyor. The potential of broken bones would be a concern with this concept if the loin experiences a large enough impact. Lastly, through this concept, the team was able to clarify that the client prefers to have the rib side down and the fat side up at the end of the orientation process, as fat removal is the first operation performed on the loin after the loin puller. The *Loin Chute-TC4* achieves this orientation objective in a reliable manner.

2.6 Final Concept Selection

Following the external concept review meeting, a weighted decision matrix was supplied to HyLife. The weighted decision matrix included criteria to evaluate the top concepts as discussed and finalized during the concept review meeting. Out of the 4 top concepts that were presented to HyLife, only *Pinball Paddles-TC1* and *Bite and Turn-TC2* were evaluated by the client due to concerns with *Loinbine-TC3* and the *Loin Chute-TC4*. HyLife's concerns with the *Loinbine-TC3* and the *Loin Chute-TC4* came from the fact that they were prone to jamming and their vertical loin orientation method was not expected to be as effective as horizontal methods. After supplying a weighted decision matrix to HyLife, *Pinball Paddles-TC1* was selected as the preferred concept. TABLE VII features the scores that HyLife assigned to *Pinball Paddles-TC1* and *Bite and Turn-TC2*. Despite the close scores, the client was more confident with *Pinball Paddles-TC1* mainly because of its ease of implementation.

TABLE VII: FINAL CONCEPT EVALUATION SCORE

Concept	Score
Top Concept 1	35/50
Top Concept 2	33.5/50

With a preferred concept selected by HyLife, the final design began based on *Pinball Paddles-TC1*. The evaluations HyLife returned are available in Appendix A. Several members of the client's team were involved in the process of scoring *Pinball Paddles-TC1* and *Bite and Turn-TC2*, therefore the team was satisfied with the final concept selection and proceeded forward to the detailed design phase. Note that one evaluation sheet was used per concept, and a collective score was given by all evaluators.

3 Detailed Design

This section provides a low-level explanation on how each component of the final design was further developed from its initial concept. Each of the following sub-sections include an isolated view and description of a major component of the final design. Furthermore, each subsection provides analysis (stress, fatigue, and cost) to justify the low-level design decisions that were made for each component. Finally, this section is concluded with a summary of all the decisions for a more convenient overview.

3.1 Decline Conveyor

The decline conveyor received minor changes in comparison to the lower conveyor which will be completely altered in the event this design is implemented. The decline conveyor requires minor updates in order to incorporate the eastern extension of the lower conveyor. The extent of the modifications to the decline conveyor include the relocation of cross-members present on the structural support system, this will be discussed in detail in the following sections. Originally, the Pinball Paddles concept was intended to utilize a stainless steel slide which transported the loin from the main upper conveyor to the lower conveyor. However, the slide did not end up being part of the final design. The reasoning for the removal of the slide from the initial concept will be discussed in the following section.

3.1.1 Initial Concept

The initial Pinball Paddles concept featured a stainless steel slide which allowed loins to travel from the upper conveyor onto the lower conveyor. Figure 25 features the original loin slide.

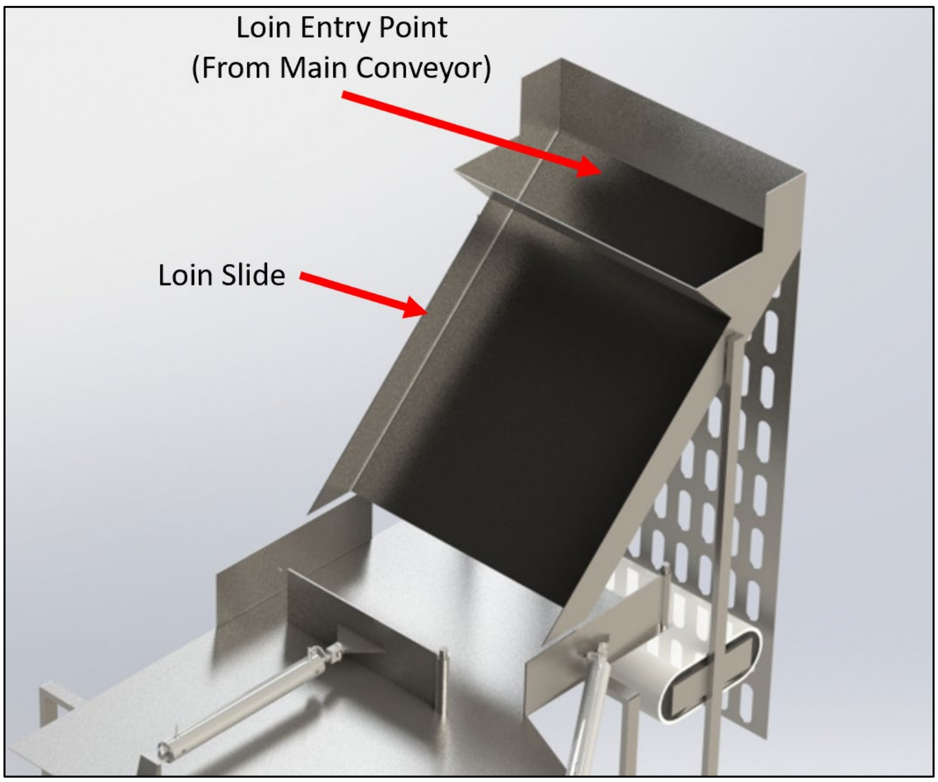


Figure 25: Initial decline slide concept

The declined slide design requires that the loins have a low coefficient of friction when the stainless steel slide. Before committing to the declined design, it was known that physical testing would need to be done to determine whether expecting the loin to slide perfectly was reasonable.

3.1.2 Concept Modifications

As mentioned in the preceding section, the team set out to perform some physical testing to gain an understanding for how loins slide along stainless steel surfaces. Discussion with HyLife before manually manipulating some loins hinted that the conclusion that loins will slide as intended on the stainless steel slide could be flawed. Soon after, the team got a chance to push/pull loins along a stainless steel sheet near the loin line. The friction between the loin and stainless steel was far greater than expected; the friction was assumed to cause loins to be halted or tumble if implemented. It was concluded that the initial slide concept must be modified. The team concluded that utilizing the existing decline conveyor was the best option. The existing decline conveyor can be seen in Figure 26.

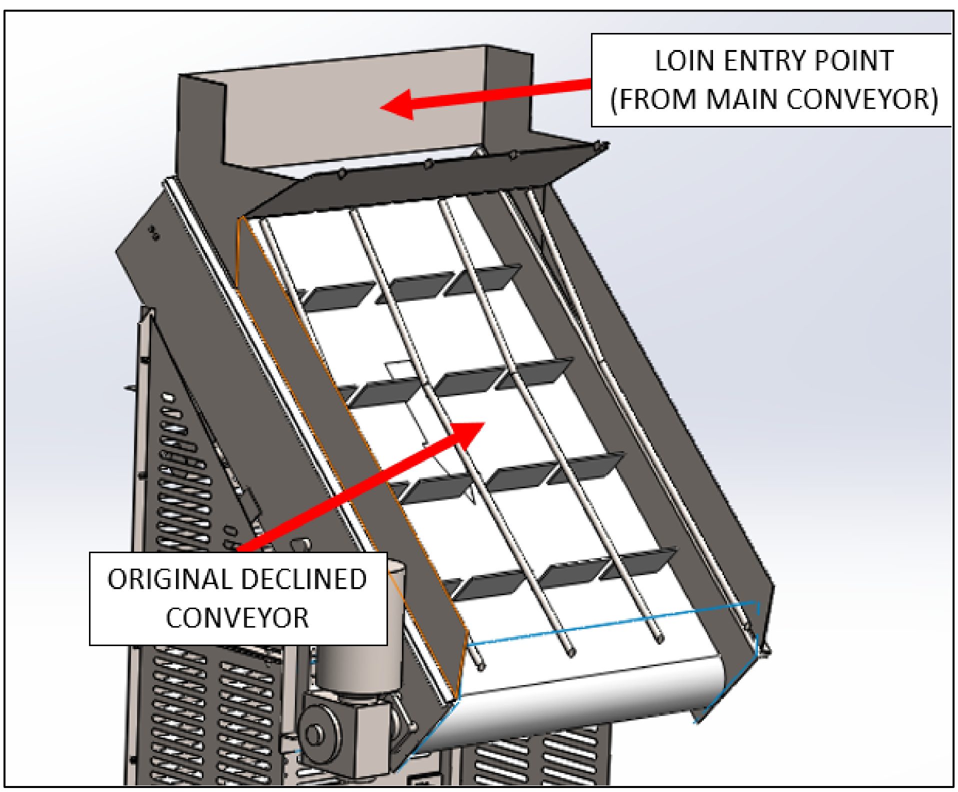


Figure 26: Existing declined conveyor

Utilizing the existing decline conveyor will require some modification to the lower conveyor in order to create enough clearance to incorporate the paddle table between the two. However, the decision to move forward with the existing decline conveyor will still require some modifications to the decline itself to accommodate the eastward expansion of the lower conveyor. The eastward expansion is essential to the operation of the design since the paddle table is intended to rotate loins on the table top before dropping them off the east (rear) end of the table onto the lower conveyor, in the correct orientation. The support structure design section, next, covers the extent of the modifications to the decline conveyor support structure.

3.1.3 Design – Support Structure

Modifications to the decline conveyor structure are required for the implementation of the Pinball Paddles design. The table directs the loin, after reorientation, off the rear end of the table onto the lower conveyor. In order to create enough clearance for the lower conveyor to travel beneath the decline conveyor, a support member requires relocation.

HyLife has assured the team that the minor relocation of the cross-member is not something that will compromise the structural integrity of the decline conveyor support structure. Therefore, a detailed stress analysis was not completed.

3.2 Lower Conveyor

The lower conveyor is the only conveyor receiving alterations. The lower conveyor will need to be dropped from it’s original position by 24”. The drop is required for creating enough clearance between the decline conveyor, paddle table, and lower conveyor itself. There are limitations to how close the lower conveyor can be to the ground since it is a food contact surface. The closest the sag on the bottom of the conveyor can be is 18” from the ground, at any point [3]. The details behind conveyor code compliance will be touched upon within the code compliance section later. The series of sub-headings to follow will cover the initial concepts, final conveyor dimensions and specific design details involved in the lower conveyor setup.

3.2.1 Initial Concept

The original Pinball Paddle concept was intended to keep the existing lower conveyor in place and utilize a slide which allows loins to travel from the upper conveyor to the lower conveyor without the use of the decline conveyor which is currently installed. This initial concept required no change to the lower conveyor because the slide which replaced the decline conveyor was intended to be shorter than the decline conveyor, therefore allowing enough room for the paddle table to be installed. It was determined that the slide would not allow loins to smoothly transition to the lower conveyor due to the high friction.

At this point, modification of the lower conveyor was considered. Dropping the lower conveyor would allow the original decline conveyor to be utilized, allowing for sufficient clearance for installing the paddle table. Therefore, the final concept selected was the relocated lower conveyor approach utilizing the original decline conveyor.

3.2.2 Concept Modifications

Once the team had settled on the idea of utilizing a relocated lower conveyor, it needed to be determined how the lowered portion of the conveyor would angle back up to the existing height. The loin line consists of a series of conveyors, meaning that the team would only have to modify the section which was going to interface with the loin reorientation design. Figure 27 displays the length of the design space which can be worked within to receive the loin from the paddle table, transport the loin underneath the paddle table, then regain the 24” drop via an inclined conveyor to meet up with the second segment of the lower conveyor again. Figure 27 displays the existing first segment of the lower conveyor. Since the existing conveyor receives the loin from the decline conveyor directly, the lower conveyor does not need to extend further east toward the eastern design space limit. However, the new conveyor will need to extend towards the eastern design space limit to accommodate the paddle table pushing the loin behind the declined conveyor.

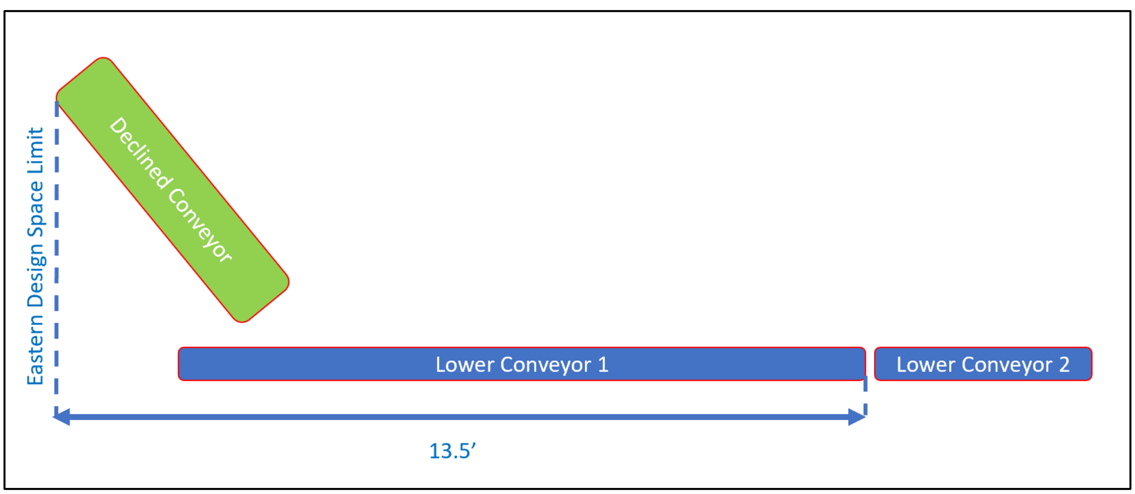


Figure 27: Lower conveyor design space

There were two options to create the desired incline to re-connect to the second segment of the lower conveyor: single segment inclined conveyor or dual segment inclined conveyor. The single segment design utilizes a one-piece conveyor design which transfers from a flat orientation to an angled orientation seamlessly, as seen in Figure 28. The single segment design does not require additional motors or paddles on the conveyor to transfer the loin from the table to the second segment of the existing lower conveyor.

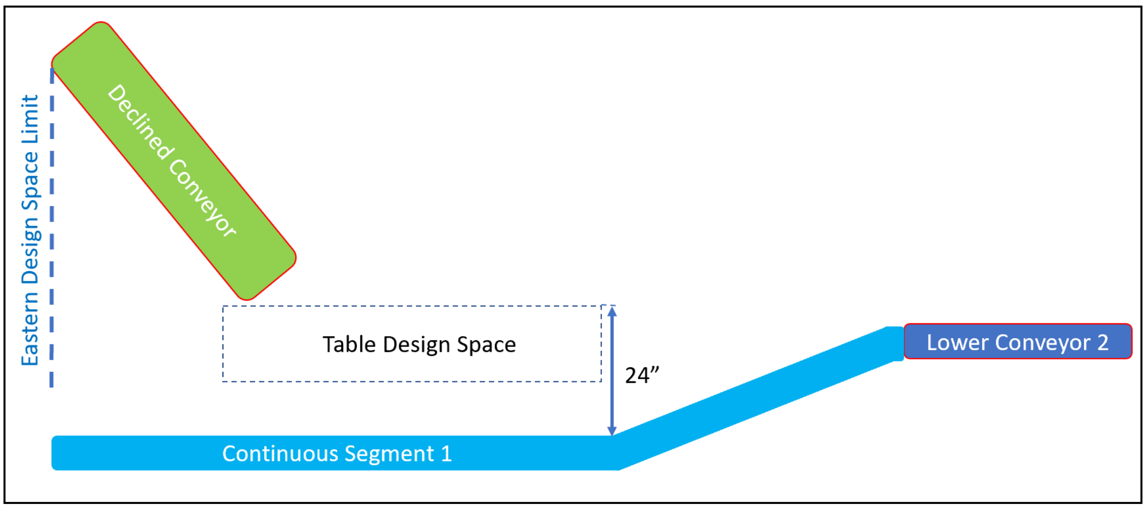


Figure 28: Single segment lower conveyor

The dual segment inclined conveyor design features two individual conveyors which would be used to regain the 24” of drop. The first conveyor is completely flat while the second is a paddled, steeply inclined, conveyor which gives the vertical transport required. This concept allows for steeper angles of incline, requires a “waterfall” effect to transfer the loin from the flat segment 1 to the paddle segment 2, as well as from the paddle segment 2 onto the lower conveyor 2. The dual segment design is featured in Figure 29.

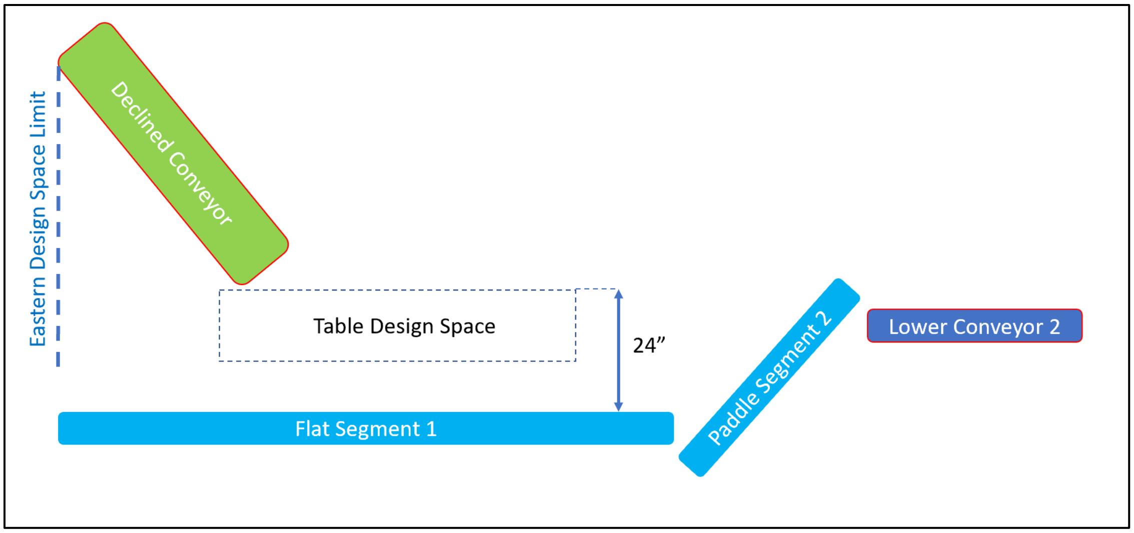


Figure 29: Dual segment lower conveyor

After speaking with the client and discussion of the two high-level concepts, the team decided that the single segment lower conveyor was the preferred concept for this application. The dual segment design would require another motor compared to the single segment design as well as require the “waterfall” effect to transfer the loin twice. The paddled conveyor would also be closer to the ground since it would have to start at a lower level than the first flat segment. This would encroach on the minimum 18” floor distance required to comply with code. Calculations were done to ensure that enough angle could be achieved with the single piece conveyor to meet the existing second lower conveyor segment within the design space. The calculations are available in Appendix C.

3.2.3 Conveyor Geometry

The conveyor geometry is the most critical portion of the overall conveyor design, as it dictates whether the new design can properly align with the conveyor that follows. Discussion with HyLife resulted in the recommendation that the maximum allowable angle is 15°, but 5° to 10° is recommended. The team knew that with the 24” drop, the use of 10° or lower angles would be difficult. To visualize what each of the angles would look like in the application, models were created. Figure 30 displays what a 10° conveyor incline would look like. In order to reach of the second segment of the lower conveyor at the correct height, the incline would have to start too far east and would not allow enough clearance between the bottom of the paddle table and the top of the lower conveyor. Specifically, only 3" of clearance would be achieved beneath the table and the top of the lower conveyor. It is desired to have 12" between the bottom of the table and top of the lower conveyor to avoid jamming in the event of abnormal loin sizes or multiple loins arriving stacked on one another.

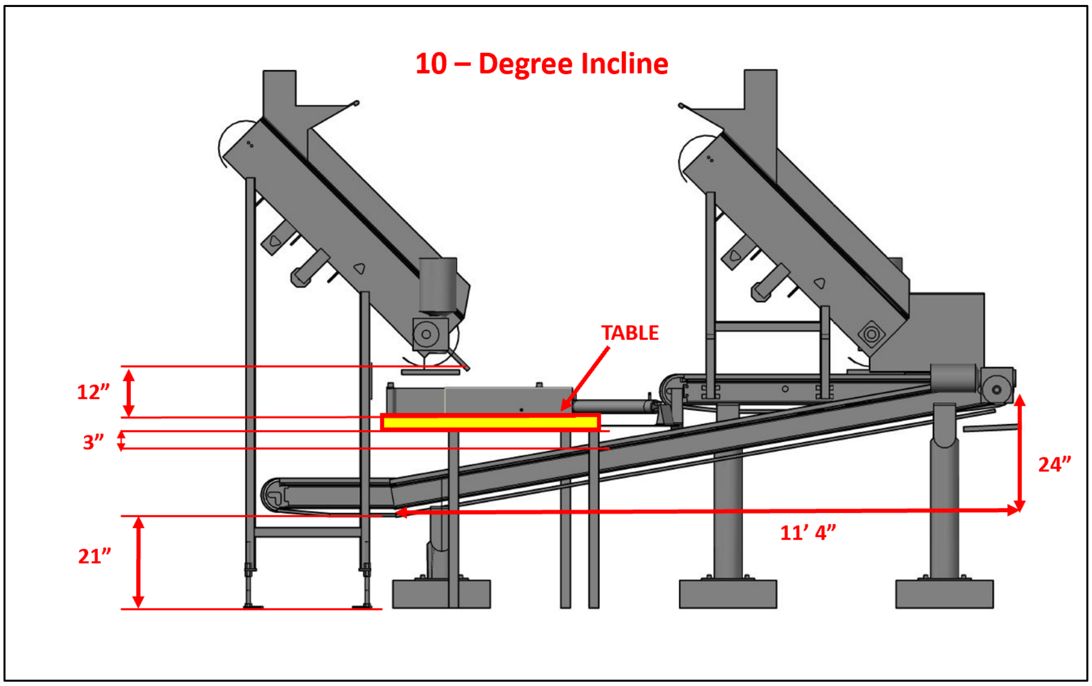


Figure 30: 10° Incline - lower conveyor

At this point, the team decided the only acceptable conveyor angle was the maximum allowable 15°. Figure 31 features the 15° incline conveyor, clearly showing there is much more clearance between the table and the top of the lower conveyor. The team also decided to use a textured top conveyor, since the angle was steeper than the originally recommended 10° angle from HyLife. The textured conveyor will be further discussed in the conveyor belt design section.

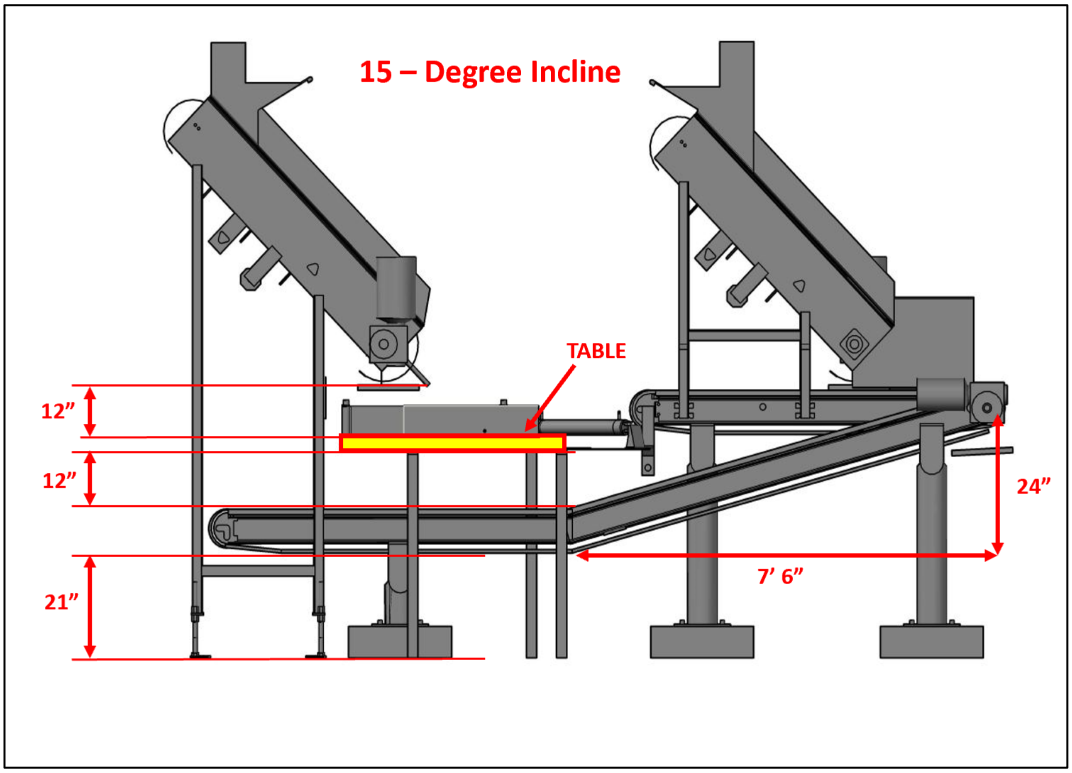


Figure 31: 15° Incline - lower conveyor

Conveyor geometry was also altered laterally, meaning the width of the conveyor was narrowed by 2” overall. The conveyor width change was implemented in order to increase the clearance between the conveyor edges and declined conveyor support structure when the bypass is engaged. In order to accommodate the one-piece inclined conveyor design, the team implemented hold-downs which prevent the conveyor belt from lifting at the transition point from flat to inclined. The hold-down design discussed in more detail Section 3.2.7. Although the hold-downs are not a direct feature of the conveyor geometry, they are required as a result of the geometry. The team’s decision to move forward with a one-piece angled conveyor design introduced the requirement for hold-downs to be implemented.

3.2.4 Design – Support Structure

The lower conveyor support structure design has been limited to a high-level approach. The team's design will outline only the critical conveyor dimensions and recommendations for creating a support structure that integrates with the existing support structure configuration. The locations of the podium-style support legs used on the existing lower conveyor support structure can be utilized once again. The easternmost lower conveyor support podium will require a change in height since the new design will be a total of 24" lower than the existing conveyor support. In addition to a change in podium height, the podium lateral geometry will also require some alterations from the existing geometry. As mentioned in the preceding section, the lower conveyor is intended to be narrowed by 2". The narrower conveyor will require updates to the podium support structures in order to properly mount the lower conveyor. The general podium support geometries can be seen in Figure 32.

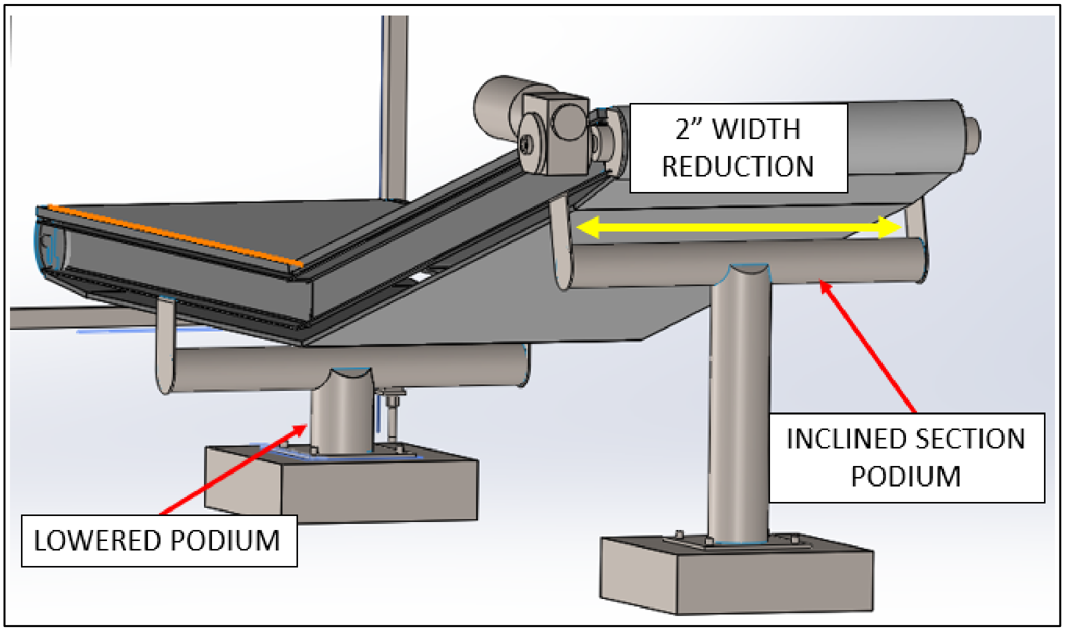


Figure 32: lower conveyor podium specifics

The overall conveyor geometry required is shown in Figure 33. The conveyor length, width, height, and incline angle have been specified. Whether the lower conveyor will require further support locations and/or modified support locations due to the eastern expansion of the conveyor is intended to done so at the discretion of the contractor who designs and builds the conveyor system.

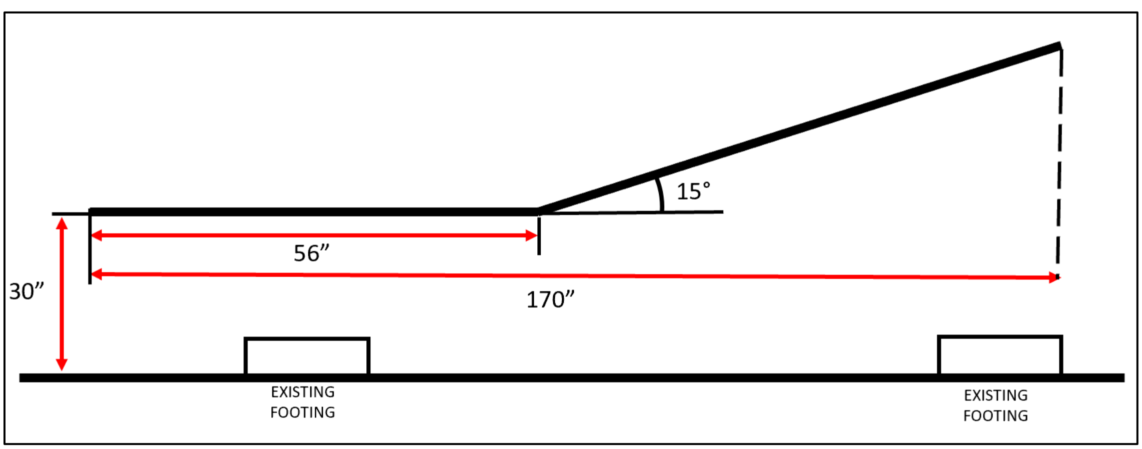


Figure 33: Overall conveyor dimensions

3.2.5 Design – Conveyor Belt

Given that the single-segment lower conveyor will be utilizing an angle of 15°, a textured top belt was selected for added grip. There were concerns with whether the 15° conveyor was too steep to use with a standard smooth top conveyor belt. Currently, the belting used by HyLife on the loin line is sourced from Intralox [5]. Three different textured belt styles were looked into for the team's application. All belting which was considered is from Intralox and falls under their 800 series of belts which is identical to the belts used on the rest of the lower conveyor line. Figure 34 features all three of the Intralox belts taken into consideration before finally selecting a single texture style.

[redacted]

Figure 34: Intralox belt textures [5]

The belt texture selection was determined by HyLife. The Mini Rib was eliminated due to the fact that is was a less aggressive pattern than the Cone Top and Nub Top variations. The Mini Rib was deemed to have a greater chance of loin slippage on the incline than other competing textures. The Nub Top and Cone Top textures were similar to each other. The biggest advantage of the Cone Top belting was the fact that HyLife already had some in their parts inventory and the team was able to look at the belt to determine its overall effectiveness in gripping the loin on an incline. Both the team and client agreed that the Cone Top would be the best choice, especially given the finer gripping studs and slightly sharper points as compared to the Nub Top belt. Thus, the design proceeded with the Cone Top belt.

3.2.6 Conveyor Drive Section

Conveyor drive component selection was based primarily on the components from the existing lower conveyor. If the proposed incline conveyor is implemented, the design would be contracted out by HyLife, and thus the discussion of conveyor drive components is brief.

The particular motor selected to power the one-piece inclined conveyor is a 1 HP Keltech unit. More specifically, the Keltech Model SSM0145CT is the motor of choice for the application [6]. To complement the Keltech 1 HP motor, as used in many other plant locations, a Keltech 90-degree gearbox was selected to provide power transmission to the conveyor drive shaft and ultimately the drive sprockets. The drive sprockets selected for the application were selected to match the pitch of the cone top belting. The sprockets selected are Angled EZ Clean series sprockets corresponding to the series 800 belts. The angled EZ clean sprocket series is specifically designed for easy cleaning since the off-axis design allows the conveyor cleaning sprayers to hit all locations on the belting. Figure 35 displays an example of an angled EZ clean conveyor.

Figure 35: Angled EZ clean sprocket [5]

The sprockets and drive components listed throughout this section are only recommendations to the consultant whom takes on the task of designing the new lower conveyor. The team has not included the low-level design of the conveyor as part of the low-level design process. The specification sheets have been provided for the sprockets and cone top belt in Appendix D.

3.2.7 Conveyor Hold-Down Design

The 15-degree incline of the new conveyor geometry causes the conveyor belt to lift at the point of intersection between the horizontal and inclined conveyor segments. To minimize the conveyor belt lifting, a conveyor belt hold-down device was designed. The device is constructed from UHMW polyethylene, uses 316L stainless steel hardware, and attaches to the sides of the conveyor. The design for the hold-down device is based on a similar hold-down device on another inclined conveyor at the HyLife facility. The existing hold-down device and the one designed for the new conveyor design is shown in Figure 36.

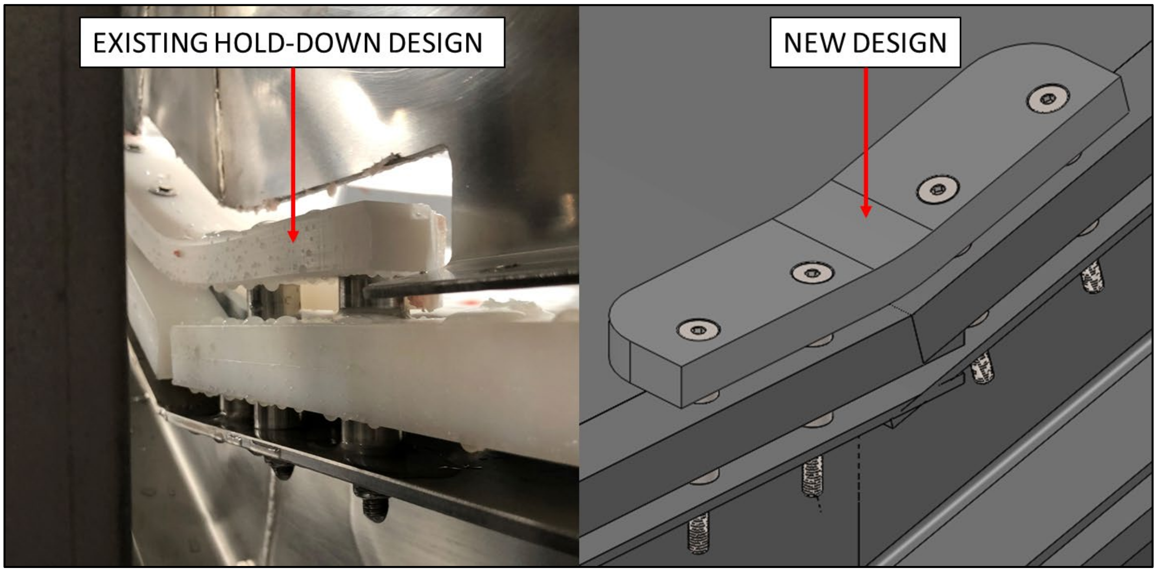


Figure 36: Comparison of the new conveyor hold-down to the existing conveyor hold-down [1]

Figure 36 shows that the hold down device mounts on the side of the conveyor and is bolted down using a series of M8x100 screws, M10 standoffs, and M8 locknuts. The M10 spacers provide more stability versus the M8 spacers due to their larger outer diameter. This stability is important when the conveyor lifts and applies a load to the bottom of the hold-down device, and there is the added benefit that these spacers are used elsewhere in the paddle table design. A side view identifying the various components is shown in Figure 37 next.

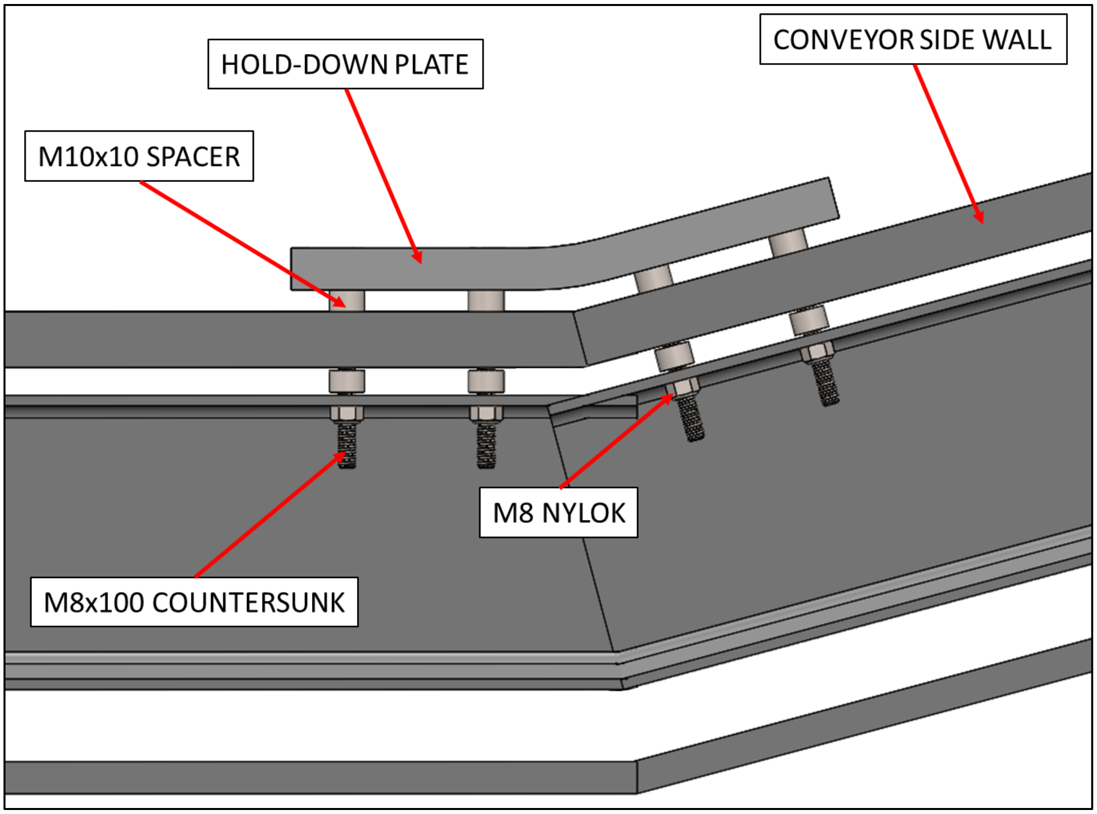


Figure 37: Side-view of conveyor hold-downs with mounting hardware shown

Since the conveyor geometry will be finalized by the company contracted to build it (e.g. Frontmatec) the hold-down device presented is a preliminary design. Further, two hold-down devices will be required since both sides of the conveyor need to be held down. The estimated cost per hold-down device is $164.26 based on the amount of HDPE, machining, and various bolts, nuts, and spacers from McMaster-Carr. Lastly, a technical drawing of the hold-down device is provided in Appendix E.

3.3 Paddle Table and Support Structure

The entire manipulation of the loin is completed on the paddle table. The paddle table is comprised of 2 carefully mounted paddle assemblies, a tube sub-structure attached to a stainless steel top plate, a tube base structure, two pneumatic cylinders, 4 reed switches, and one infrared proximity sensor. The tube sub-structure and tube base structure interface via a food-safe linear-motion bearing. The linear-motion bearing was incorporated into the design to facilitate a bypass in the event that the system is jammed or inoperable. The sliding action and specific details regarding the bypass method will be described in detail within the bypass method detailed design section.

3.3.1 Initial Concept

The initial paddle table concept provided the basis for the final design in terms of the loin falling onto the table in front of the first paddle, and its consequent manipulation by both paddles until it falls onto the lower conveyor. This was shown previously in Figure 5 and was referred to as *Pinball Paddles-TC1*. The original design did not incorporate a bypass function, as this need was not yet established until the later concept review with HyLife. Additionally, the design had a frame composed of 2” square tubing for aesthetic purposes, but no triangulation or structural practices were applied. Lastly, the concept used the existing lower conveyor and had a relatively long table to support the first paddle cylinder, resulting in low table-conveyor clearance, and a large footprint. The details of the new features are discussed in the following section.

3.3.2 Concept Modifications

As mentioned previously, many changes were made to facilitate the functionality of the paddle table in the final design. The first and most straightforward modification between the initial *Pinball Paddles-TC1* concept and the final table design was the change from a rigidly mounted table to the new base frame and movable subframe with a table on top. Unlike the conceptual frame, which was mounted solely to the floor, the final base frame is bolted into the side of the lower conveyor and the concrete floor to provide location and rigidity, while the table and its underlying sub-structure are connected to the base frame with the prior mentioned food-safe linear-motion bearing. An additional change to the table was the mounting positions of the pneumatic cylinders and paddles, which were originally mounted to the top sheet metal and are now mounted to the base frame. This modification increased the rigidity of the paddle and piston mounting locations under loading and now allow for the table to be moved independently of the other components. By virtue of the table moving by itself, the cylinders, base frame, and other ancillary components are no longer “food contact” surfaces and thus require less significant cleaning. Further, the independent movement of the table ensures that tubes and wiring for the cylinders and sensors can be kept out of the way and free from snagging or cable strain.

An additional modification was the implementation of a proper bushing between the paddles and their mounting pins. The original paddle concept had no bearing or bushing, with the paddles mounted on the pins with retaining rings. As was requested by HyLife, this design was changed to utilize a dry Delrin bearing between the pin and paddle, as well as made tool-less, with only gravity holding the paddle down on the pin and the attachment to the pneumatic cylinders via a clevis and cotter pins. This is reflected in the detailed design subsection for the paddles and pins.

Lastly, the eyelet on each paddle for the pneumatic cylinders was modified to facilitate an appropriate range of motion based on the final position of the paddle mount, cylinder mount, and length of cylinder stroke.

3.3.3 Design – Support Structure

During the concept development stages, it was originally thought that the decline conveyor would be replaced with a slide-like structure. By replacing the decline conveyor with a slide, it was thought that the lower conveyor would remain unaltered. After further discussion with HyLife it was decided that the decline conveyor would be kept in its existing location. By keeping the decline conveyor in it's existing location the only way to achieve the necessary 24" of clearance was to lower the lower conveyor. By moving the lower conveyor downwards, a 15 degree incline was needed to allow the west end of the conveyor to remain at its existing location. It was important to keep the west end of the conveyor at the same position so that the loin would easily transition forward onto the weigh scale. This section will first provide an overview of the initial support structure design. Then the modifications to the table will be discussed including paddle placement, leg placement, and tube selection.

3.3.3.1 Initial Concept

As previously mentioned, the initial concept consisted of many features that were later deemed unnecessary. Such features included the loin slide and secondary conveyor. It should also be noted that the table had a large footprint, and that the support structure legs were only placeholders. The additional features listed above can be seen in Figure 38:

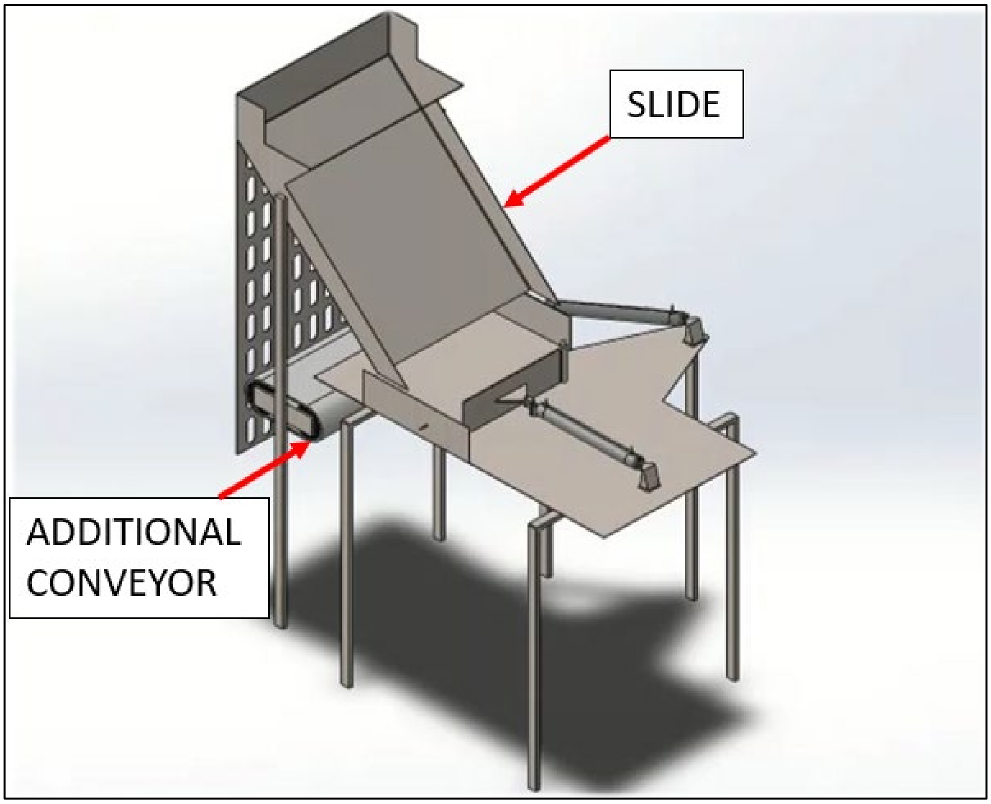


Figure 38: Initial paddle table structure with slide and additional conveyor labelled

It was important to reduce the surface area in the final design because more surface area would increase cleaning times. Moving forward, the support structure would need to be properly designed with enough reinforcements and mounting points to ensure the final support structure would perform as desired.

3.3.3.2 Modifications

To design the support structure, it was important to first understand the design space and make note of any concrete footings, cable trays, other support structures, and both the upper and lower conveyors. The design space can be seen next in Figure 39.

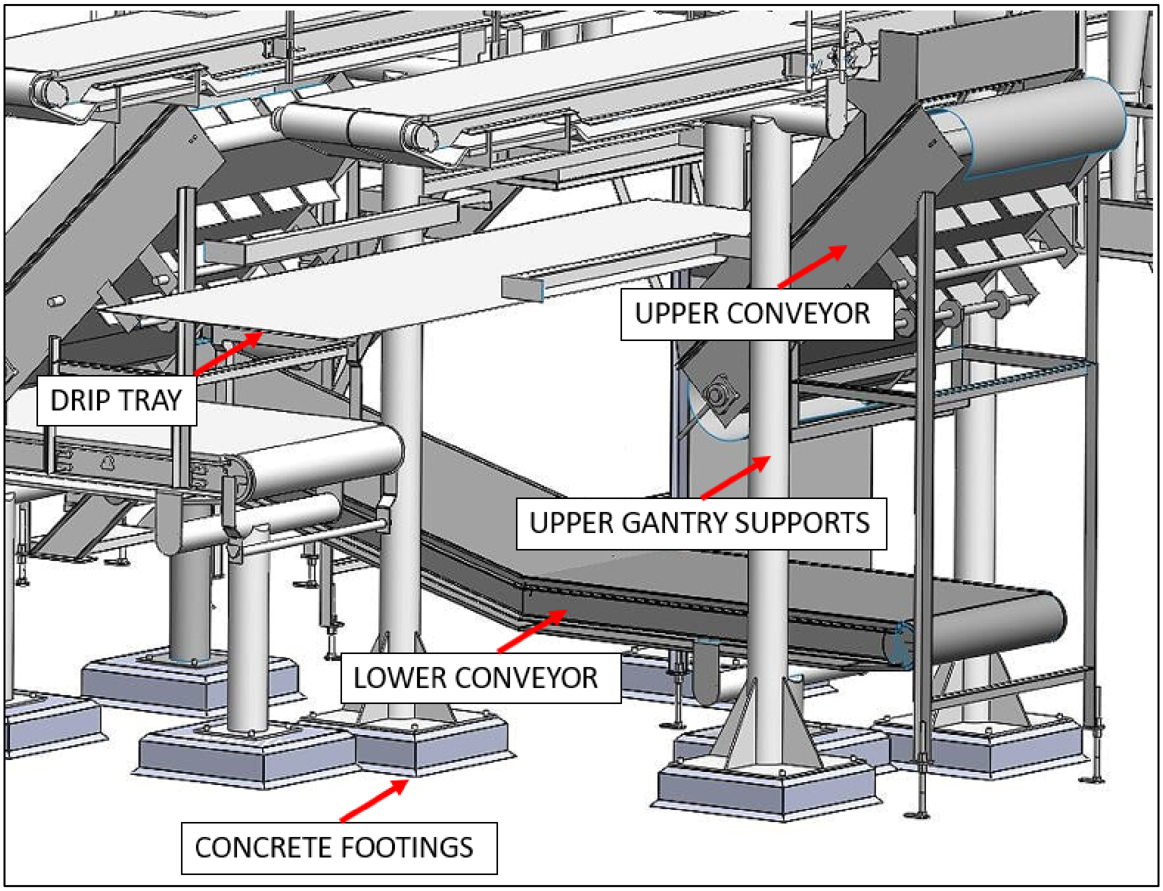


Figure 39: Existing design space with all obstructions and existing equipment labelled

Given the design space, the support structure was to be designed such that the concrete footing pads, upper decline conveyor, and lower incline conveyor remain unmodified.

When determining the height of the table it was important to have a minimum clearance of 12” between the top of the lower conveyor and the underside of the table at all times. It was also important to have 12” of clearance between the top of the table and the underside of the decline conveyor. To achieve this clearance the top of the lower conveyor was located at a height of 29.5” which allowed for 12” of clearance above the lower conveyor, the table thickness, and then an additional 12” of clearance below the decline conveyor above.

With the table height determined, the next task was to determine the table dimensions and layout. The table would need to straddle the lower incline conveyor and maintain 12” of clearance above the lower conveyor belt at all times. The main components to be supported by the table were the two cylinders, two paddles, an area to reorient the loin, and mounting locations for the cylinders and paddles. In order to mount the cylinders and paddles the following geometry in Figure 40 was determined.

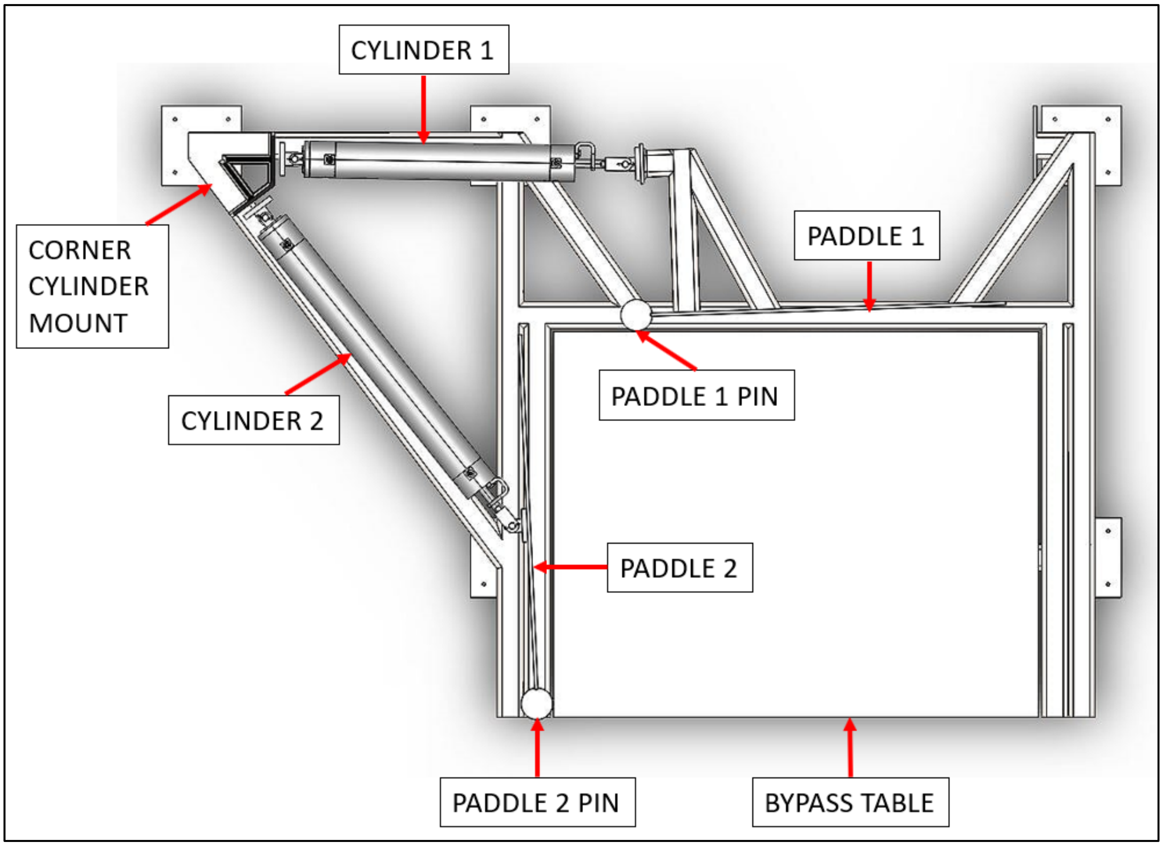


Figure 40: Paddle table geometry with all components shown and labelled

The placement of the tube structure is dependant on the mounting locations of the paddles, paddle pins, cylinder corner bracket, and sliding table area. When determining the placement of paddle 1, the size of the loins and the location where the loins drop were analyzed. After visiting the HyLife pork processing plant in Neepawa, MB it was observed that the loins fell from the upper decline conveyor almost directly downwards, with a few loins landing at a slight angle. To account for this variation in loin drop the front face of paddle 1 was located 17.5” away the decline conveyor. When determining the placement of paddle 2 it was important to give sufficient clearance for paddle 2 to fully rotate the loin 90 degrees. The paddles also needed to be mounted such that the loin would fall off the paddle table directly onto the center of the lower conveyor. The final paddle placement can be seen in Figure 41.

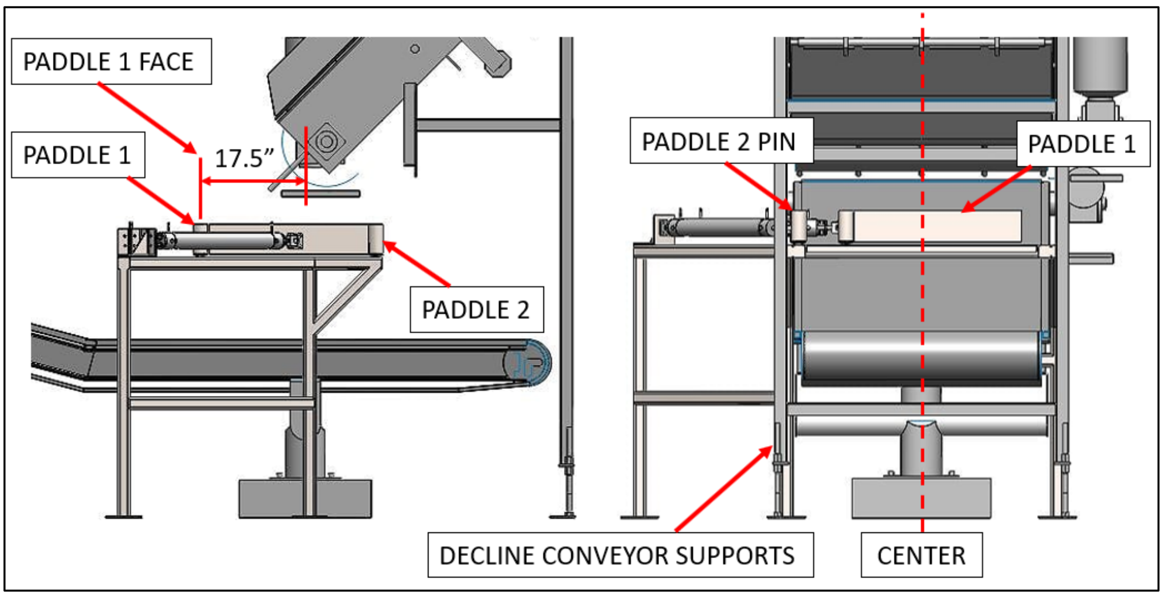


Figure 41: Final paddle placement diagram

Figure 41 shows that pin 2 was offset from the decline conveyor supports. With the paddle placement determined, the support structure needed to be designed so that the paddle mounting pins could be attached. The 2” square tubing layout was as shown in Figure 42.

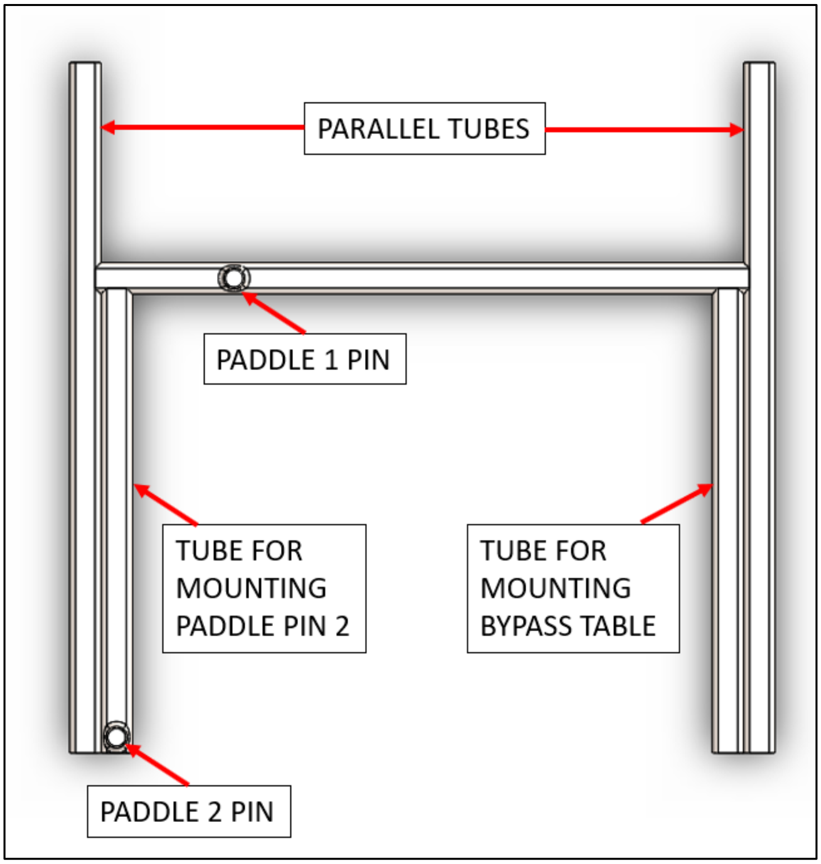


Figure 42: 2" Square tubing layout – top view

Figure 42 shows 2 tube sets that were placed parallel to each other, with another tube mounted perpendicular in-between them. The perpendicular tube allowed for pin 1 and paddle 1 to be located in the correct position. To mount paddle 2 with the mounting pin offset from the support structure of decline conveyor, as shown in Figure 41, another 2" tube was placed alongside the first set of parallel tubes. The pins used for mounting the paddles had a diameter of 1-3/8" plus a 5/16" weld bead around each pin. To allow enough room for the pin to be welded to the support structure, 2" square tubing was used. Figure 42 also shows that the tube placement allowed for a bypass table to be installed. The bypass table is discussed in Section 3.3.4, but it should be noted than an additional tube was placed on the support structure across from paddle 2. The added tube allowed for the bypass table to be installed using a slider mechanism.

The next step was to design a structure to mount the corner bracket so that the air cylinders could be mounted. Because of the inclined lower conveyor, the initial table footprint was shortened, and cylinder 1 was rotated to the same side as cylinder 2. In doing so, both cylinders could use the same mounting location. Cylinder placement will be discussed in greater detail in Section 3.3.6. To mount the cylinder mounting bracket the following tube geometry in Figure 43 was implemented.

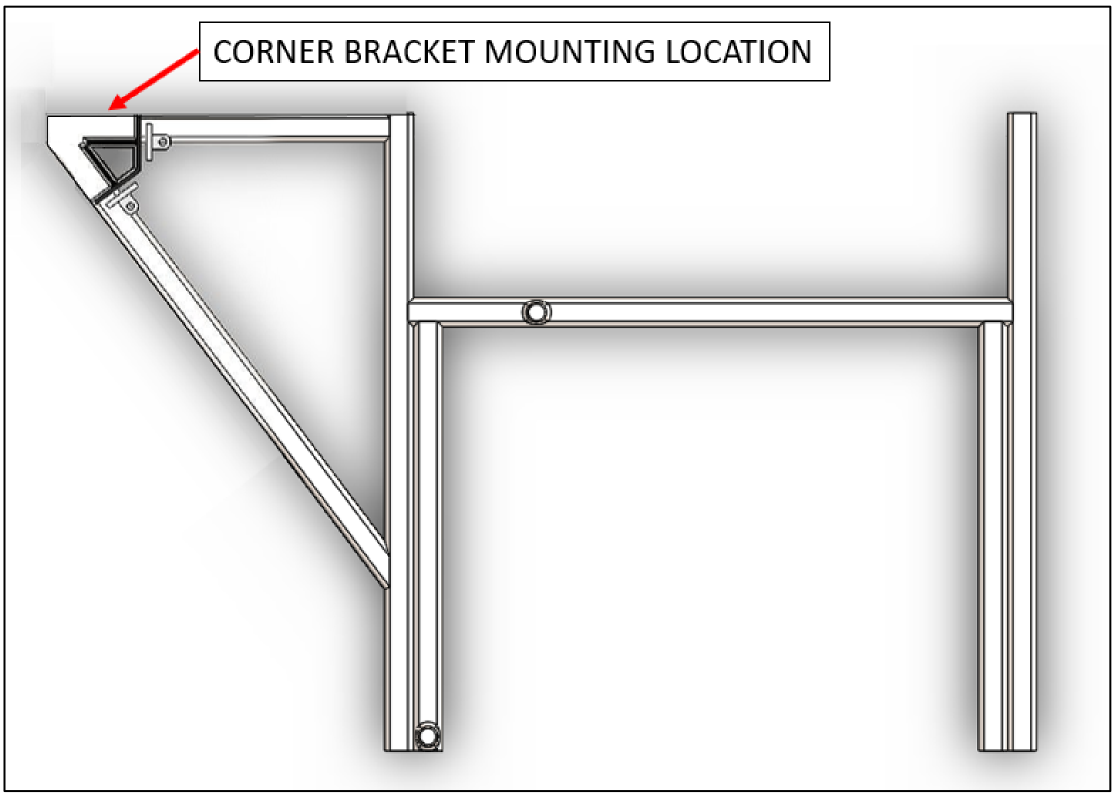


Figure 43: Structural members added in to support the corner cylinder mounting bracket

The cylinder mounting bracket location and tube length were determined based on what was convenient, and the cylinder lengths were determined from there. It should be noted that the corner mounting bracket details are discussed in Section 3.3.6.2.1.

With the overall upper tube layout for the pins, paddles, and cylinder mounting bracket determined, the next task was designing the support legs, and mounting locations. To support the table, 5 legs made from 2” square tubing are used. One leg is placed at each corner of the table, with the fifth leg placed under the corner cylinder mount. The 2” square tubing legs have 6” square footings made of 1/4" 316L stainless steel, welded to the bottom to allow the legs to be bolted to the floor. Due to the existing concrete footings two of the table legs had to be shifted back as shown in Figure 44.

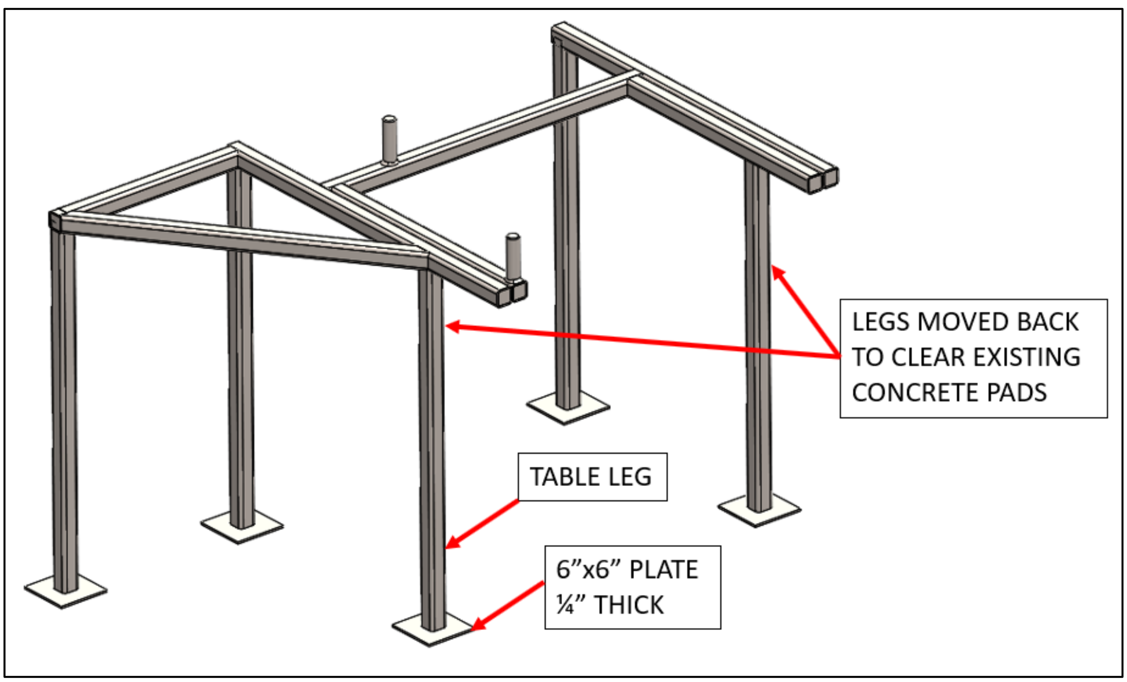


Figure 44: Additional 5 table legs with 6”x6” square 1/4" thick plate footings welded to upper tube structure

It was then decided that some triangulation should be implemented to increase the strength and rigidity of the structure. Triangulation is first placed on both sides of the

2” tube that runs above the conveyor where paddle 1 is located. Triangulation is placed at a 45-degree angle down to the support legs to strengthen the overhanging tubing because the support legs closest to the decline conveyor can not interfere with the existing concrete footings. The triangulation can be seen in Figure 45:

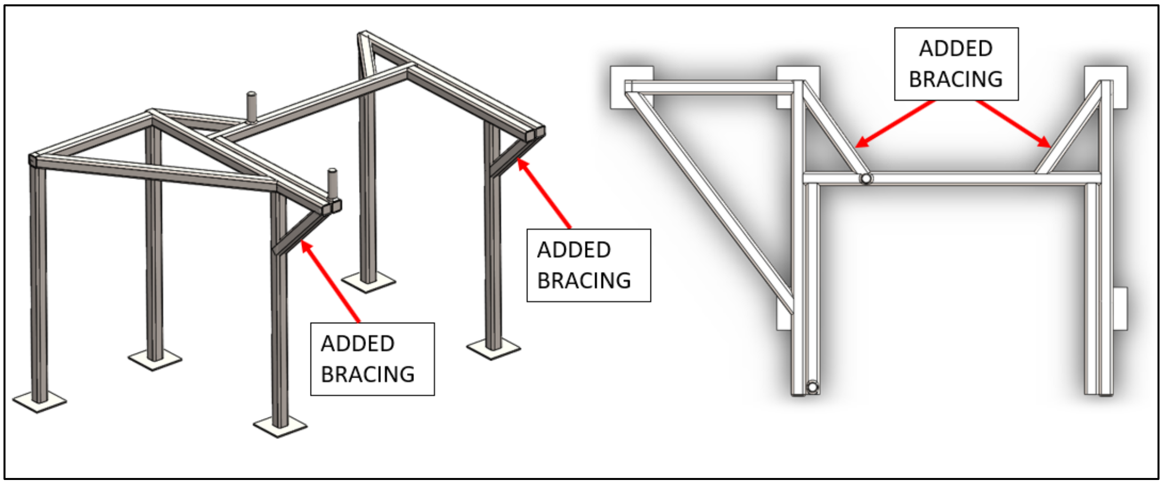


Figure 45: Added triangulation to reinforce support structure

In addition to the triangulation seen in Figure 45, more triangulation is implemented to reinforce the fifth table leg which is under the corner mounting bracket. 2” square tubing is also placed between the table legs on either side of the conveyor to increase strength and rigidity. Two mounting locations were also created on the support frame so that it could be bolted to the lower conveyor for increased strength. The additional square tubing reinforcement and mounting points can be seen in Figure 46.

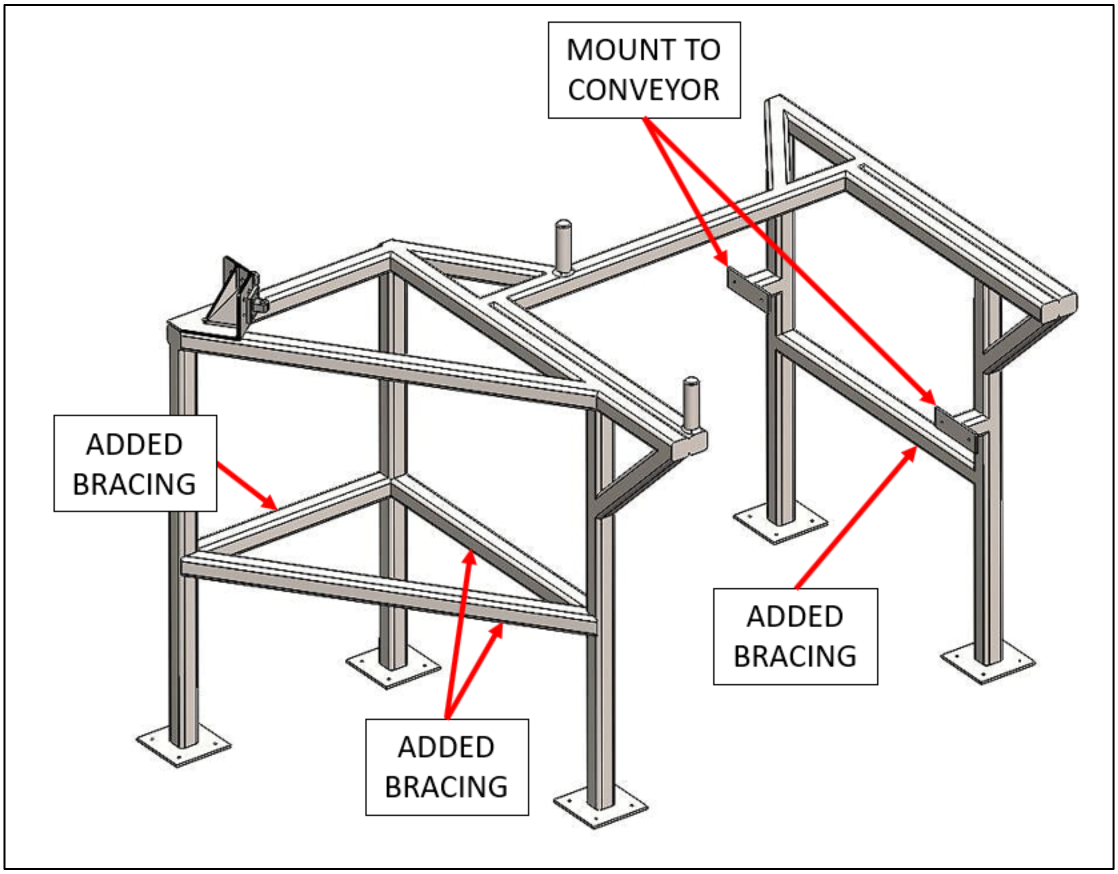


Figure 46: Additional bracing and mounting points where the support structure attaches to the conveyor

With the additional reinforcements and mounting points added to the support structure, the support structure is complete. The finished design provides a compact packaging of the paddle mounting pins, paddles, cylinders, and mounting bracket. Figure 47 shows the finished support structure integrated into the design space.

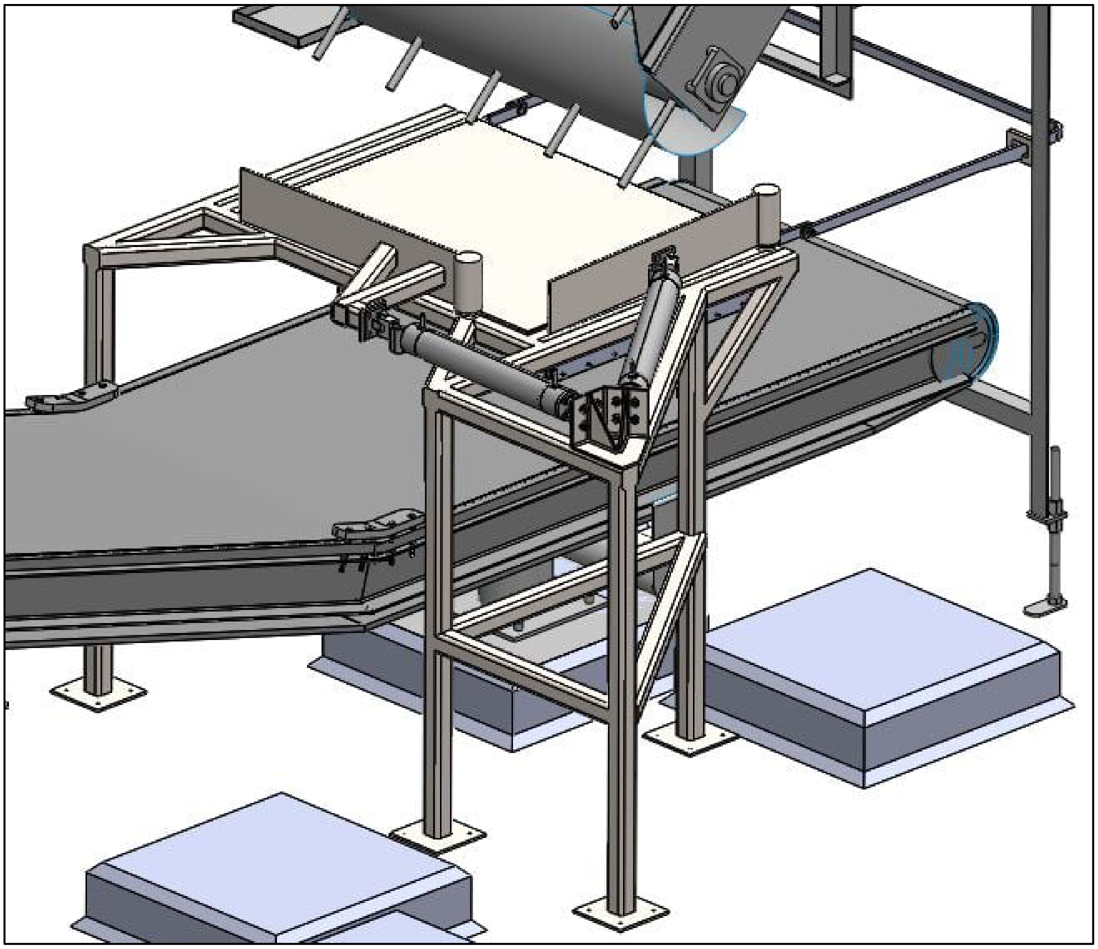


Figure 47: Paddle table support structure integrated into the design space

With the paddle table support structure created, the analysis of the structure could be performed. The analysis consisted of two different loading scenarios. The two scenarios are when the paddles are loaded by the extension of cylinder 1 and 2. The loading scenarios will be investigated and explained in the following sections.

3.3.3.3 Structural Analysis of Square Tubing

As mentioned above, the main support structure is composed entirely of 2” square tubing. The 2” square tubing is made of 316L stainless steel, which has a sidewall thickness of 3/16”, which is approximately 7 gauge. To verify that the 2” tubing was capable of supporting the paddles, cylinders, mounting brackets, and bypass table, a load calculation was performed.

To perform the calculation, a simplified approach was taken to verify the structural integrity of the 2” 7-gauge tubing. The simplification consisted of loading a 2” tube that was modelled as a column with one fixed end and one free end. The steel column was meant to mimic one of the table legs. The loading scenario and cross section of the tubing can be seen next in Figure 48:

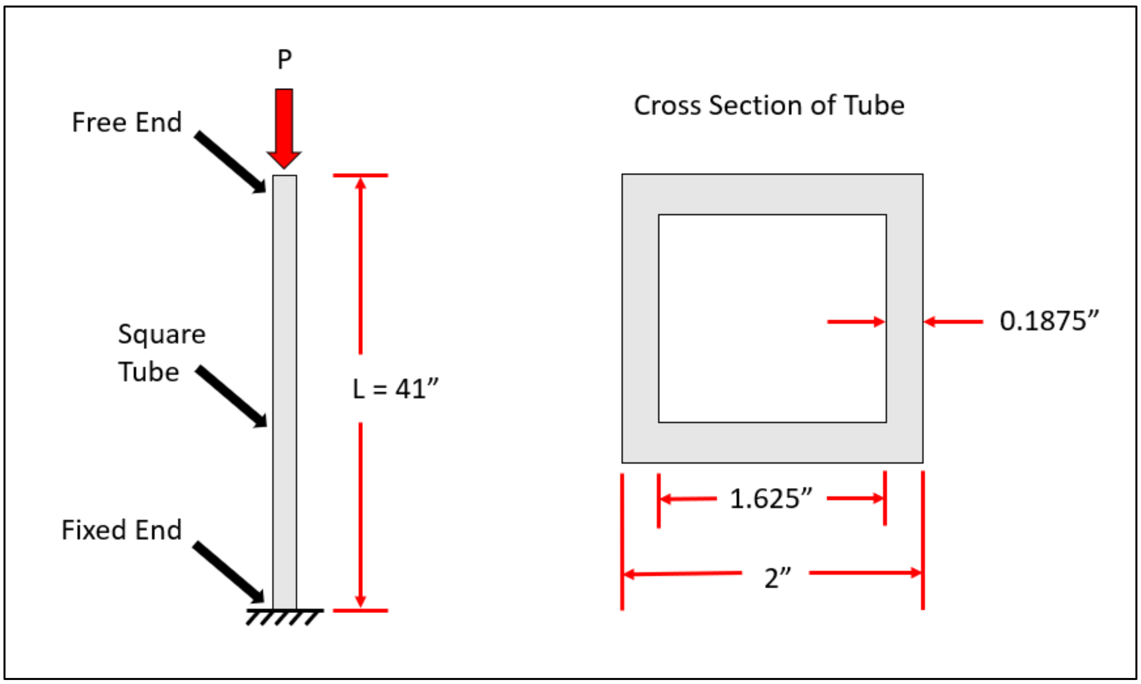


Figure 48: Structural analysis of table leg

Figure 48 shows that the load, P, was applied axially downward on the column from the top. The fixed end mimicked the table leg being fixed to the floor, and the leg length, L, was 41” in length.

When a column experiences a load, it can fail due to compression or due to buckling. For the analysis, the max force, P, that would cause the column to fail due to compression was found. Then similarly, the max load that would cause the column to buckle was calculated. After performing the calculations, it was found that the 2” square tube column with 0.1875” wall thickness would fail due to compression at a load of 33,500 lbs, and similarly, would fail due to buckling at a load of 30,900 lbs. Thus, the tube would fail first due to buckling. But, since the loin weighs 10 kg, or 22 lbs, even with the weight of the structural members, cylinders, paddles, safety guards etc. the load on the table leg would never be close to the 33,900 lbs failure load. There are 5 table legs in total to distribute the load, and cross braces and triangulation would also increase the strength/rigidity of the structure. Thus, in conclusion, the 2” 316L stainless steel square tubing structure with 0.1875” wall thickness will be more than adequate for the anticipated loading scenario. The compression and buckling calculations can be found in Appendix C.

3.3.3.4 Support Structure Numerical Analysis

Finite element analysis was used to assess the support structure when loaded by the extension of paddle 1 and 2 respectively. When either paddle is blocked by a loin or held in place, most or all of the load from each cylinder is transferred to the pins. When the first cylinder pushes on the arm of paddle 1, it transfers the full load to the pin in the direction of the cylinder extension. When the second cylinder pushes on paddle 2, only a portion of the load is transferred to the pin due to the cylinder loading angle.

With a supply of 100psi air, each of the two cylinders can exert up to 490.9lbf. The 100psi air supply represents the maximum pressure available in the plant and thus was used as a worst-case loading scenario. The forces for each loading scenario consist of a force onto the paddle mounting pin, and a force onto the cylinder corner mounting bracket. The forces are outlined next in Figure 49.

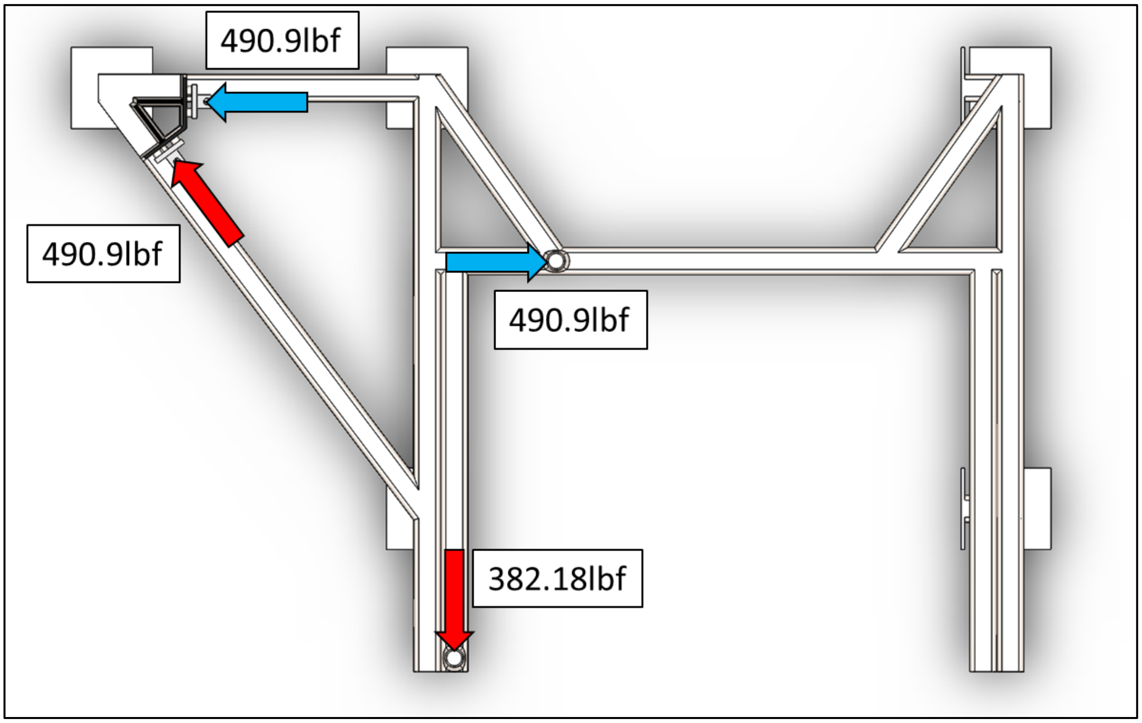


Figure 49: Top view of paddle table structure with forces for paddle 1 loading (blue) and paddle 2 loading (red)

As shown in Figure 49, the blue arrows indicate loading scenario 1, for which there is 490.9lbf applied to the bracket and the pin. The 490.9lbf on the pin is due to the cylinder being parallel to the first paddle, and the assumption that the paddle is held in place. For loading scenario 2 there is a force of 490.9lbf on the cylinder mounting bracket, but only 382.18lbf applied to the pin due to the direction of cylinder extension with respect to the paddle.

In the simulation of both loading scenarios, a mesh convergence study was run and common settings were used in the simulation setup. These settings are shown next in Table VIII.

TABLE VIII: SUPPORT STRUCTURE FEA SETTINGS [7]

Software	Solidworks 2020
Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Automatic transition	Off
Mesh auto loops	Off
Jacobian points	4
Max element size	0.5in
Min element size	0.01in
Material type	316L Stainless steel (Solidworks profile)
Elastic modulus	193GPa
Poisson's Ratio	0.3
Tensile strength	550MPa
Yield strength	137.9MPa
Component contacts	Global contact (bonded)
Solver	Direct sparse solver
Adaptive mesh refinement	h-adaptive, 5 loops, 99% target accuracy
Thermal effects	Disabled

Additionally, common boundary conditions were used. The bottom of the support structure feet and the sides were considered fixed geometry, as shown alongside the force vectors in Figure 50 next.

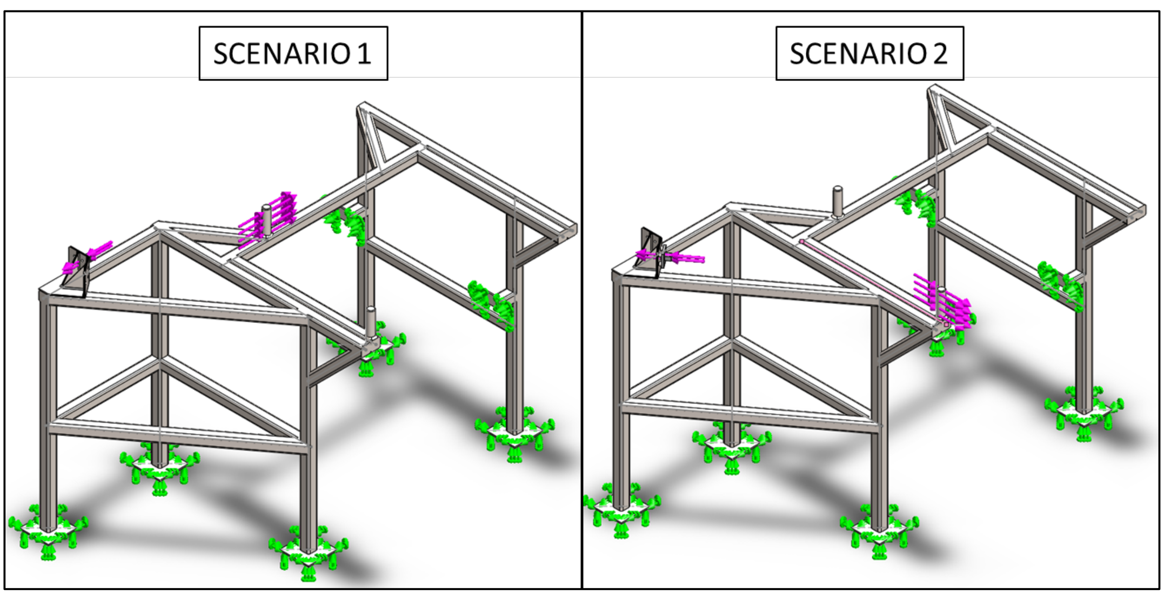


Figure 50: Force vectors (purple) and fixed boundaries (green) for paddle 1 (left) and paddle 2 loading (right)

3.3.3.4.1 Loading Scenario 1 – Paddle 1 Extension

As described prior, the first scenario involved loading the corner cylinder mount and the first paddle pin with 490.9lbf in opposite directions. It was determined from preliminary finite element analysis that most of the structure is below the yield stress. This is shown next in Figure 51.

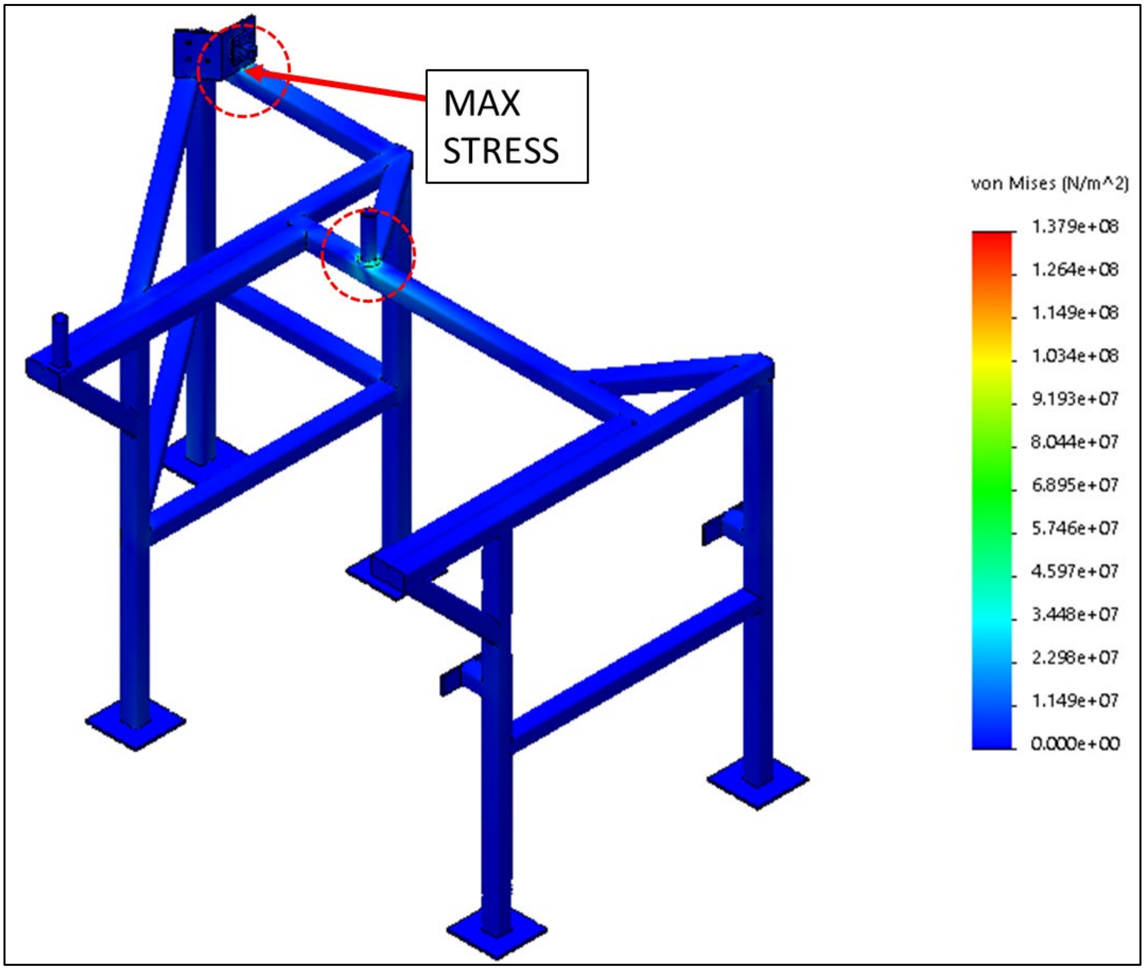


Figure 51: Von Mises stress distribution for table support structure under loading scenario 1. Deformation scale is 1 to 1 and peak stress locations are circled in red.

Figure 51 shows two points of high stress, circled in red. Other locations where components met were also found to have high stress, however the two circled locations experienced the highest stress. A closer view of the two points of interest is shown in Figure 52 next.

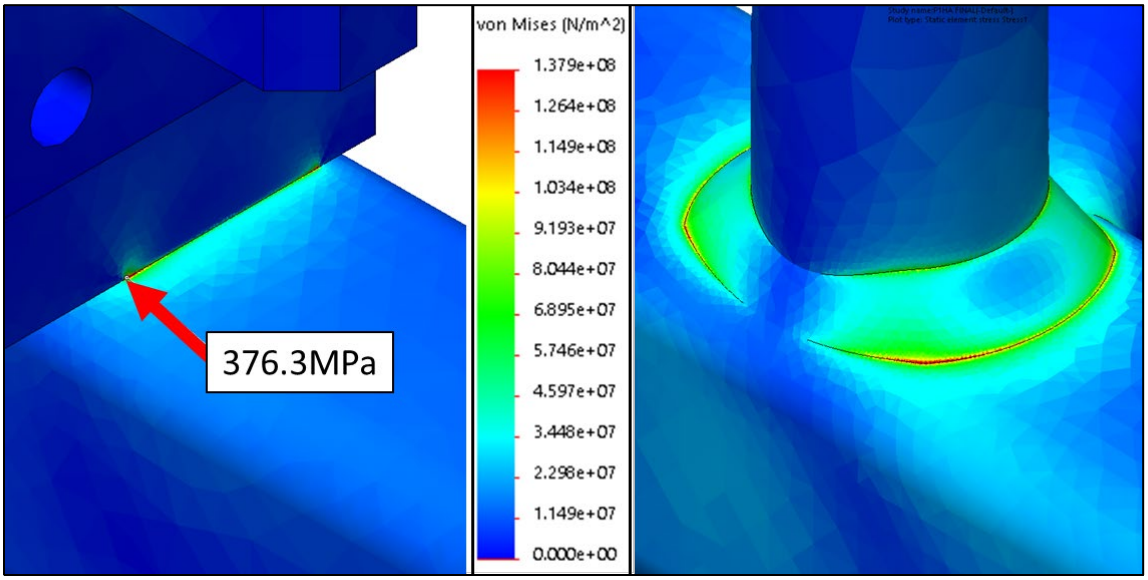


Figure 52: Singularity points from loading scenario 1 on the cylinder corner mounting bracket (left) and paddle pin 1 (right)

From Figure 52, it is seen that the previously circled areas of high stress have a small group of elements with extremely high stress, while the surrounding elements are below yield. The elements of extremely high stress are singularity points as a result a sharp intersection between components and were confirmed to be such by a mesh convergence study. That is, the convergence study showed that as the number of elements increased (i.e. mesh refinement in areas of rapidly changing stress), the stress diverged while the deflection converged. The convergence study has been provided for the reader in Appendix F.

Since the singularity points would be eliminated with welds and the rest of the structure was found to be well below the yield strength of the 316L steel, the support structure should be able to withstand the loading from the first air cylinder. The maximum deflection corresponding to the load of 490.9lbf was found to be 0.5313mm and is shown next in Figure 53.

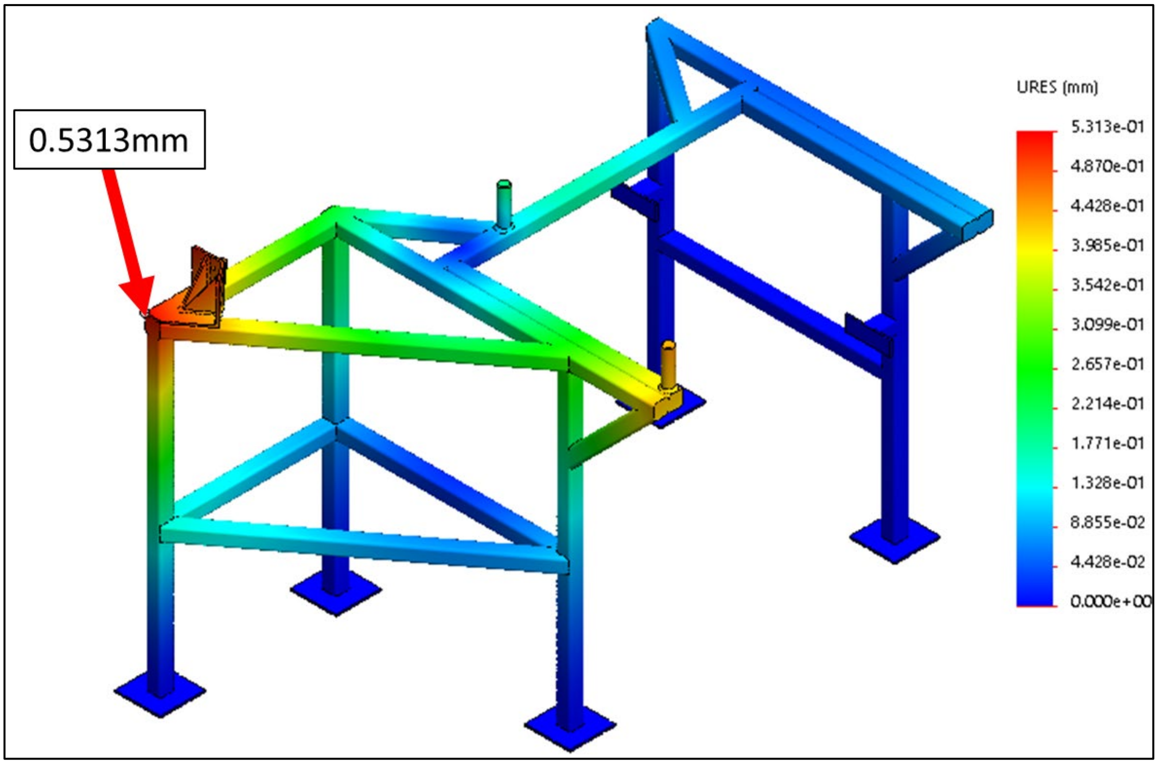


Figure 53: Plot of support structure deflection under loading scenario 2. Peak deflection of 0.5313mm occurs on the corner cylinder bracket. Global deformation scale is 1 to 1.

3.3.3.4.2 Loading Scenario 2 – Paddle 2 Extension

As described prior, the second scenario involved loading the corner cylinder mount with 490.9lbf and the second paddle pin with 382.18lbf. It was determined from preliminary finite element analysis that most of the structure is below the yield stress. This is shown once again in Figure 54 next.

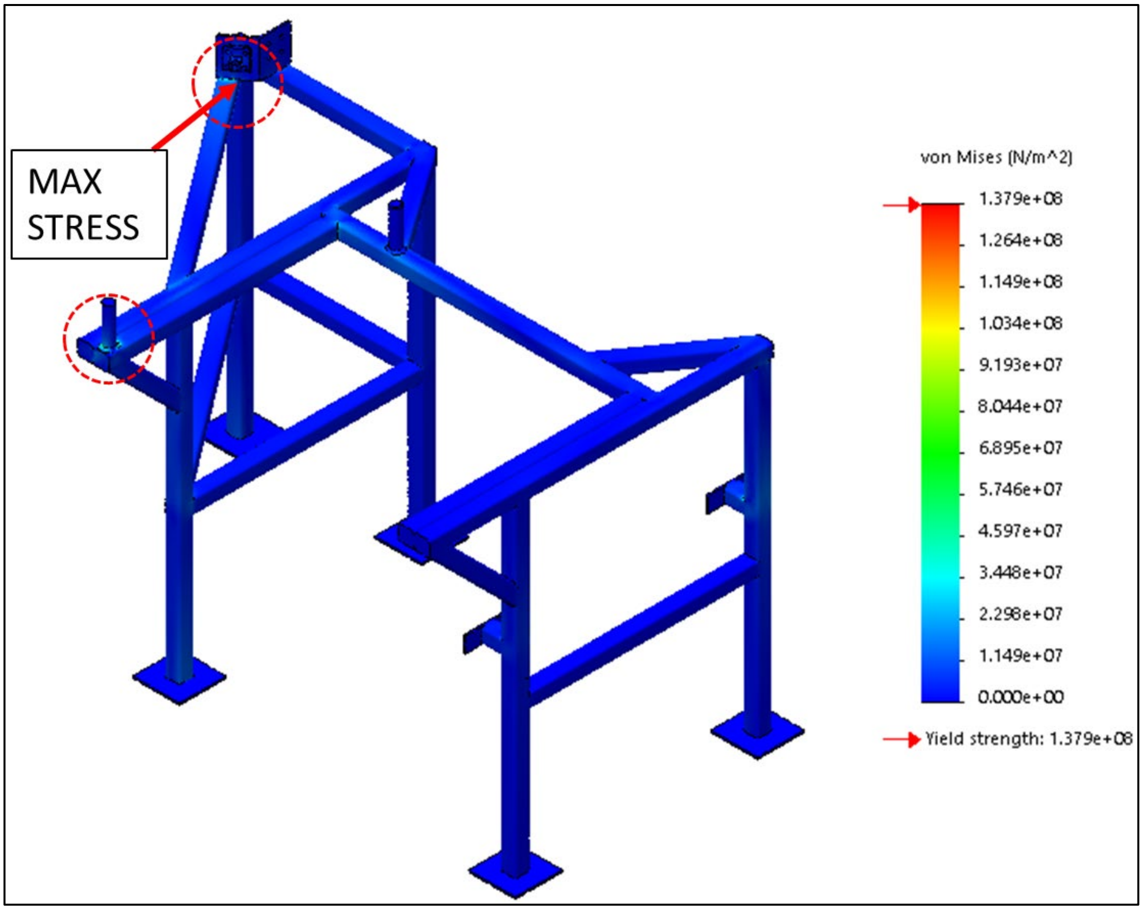


Figure 54: Von Mises stress distribution for table support structure under loading scenario 2. Deformation scale is 1 to 1 and peak stress locations are circled in red.

Figure 54 shows two points of high stress, circled in red. Other locations where components met were again found to have high stress, however the two circled locations experienced the highest stress. Closer views of the two points of interest are shown next in Figure 55.

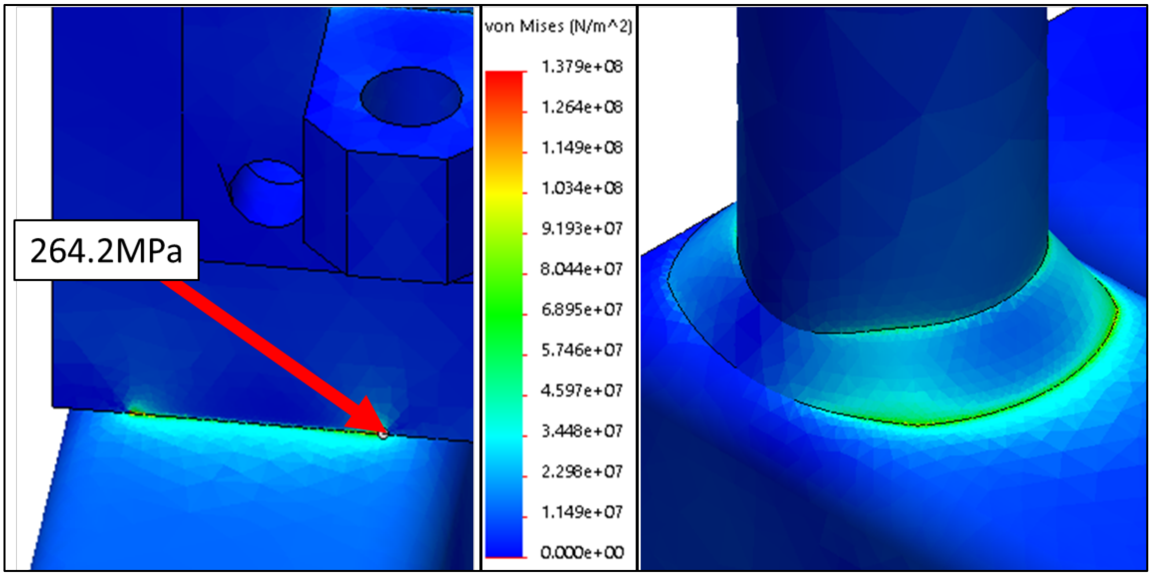


Figure 55: Singularity points from loading scenario 2 on the cylinder corner mounting bracket (left) and paddle pin 2 (right)

From Figure 55, it is seen that the previously circled areas of high stress have singularity points again, which were confirmed again with a mesh convergence study. The convergence study has been provided for the reader in the Appendix F.

Since the singularity points would again be eliminated with welds and the rest of the structure was found to be well below the yield strength of the 316L steel, the support structure should be able to withstand the loading from the second air cylinder. The maximum deflection corresponding to the load was found to be 1.069mm and is shown next in Figure 56.

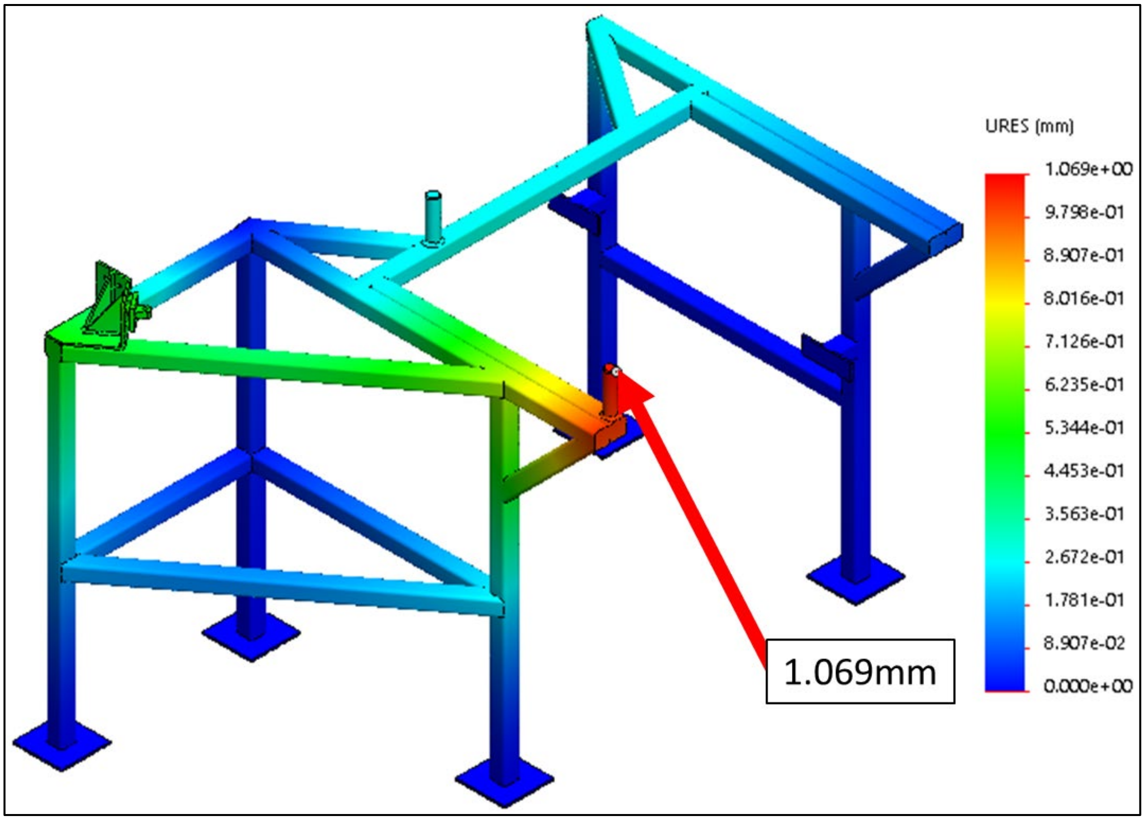


Figure 56: Plot of support structure deflection under loading scenario 2. Peak deflection of 1.069mm occurs on paddle pin 2. Global deformation scale is 1 to 1.

3.3.4 Design – Bypass Table

The bypass method is a way of moving the design out of the way in order to allow loins to transfer from the decline conveyor to the lower conveyor, even when the reorientation device is inoperable. Selection of the bypass method included a concept development process. As mentioned in the support structure concept modifications section, the requirement of a bypass system influenced the design of the support structure which ultimately supports the bypass table and facilitates the mounting of the linear sliding bearing. The bypass table is comprised of a tubular sub-structure and topped by a sheet surface. The sheet surface is where where the loin reorientation process will take place. There is a series of mounting brackets required for the installation of the linear sliding bearing. The mounting brackets secure the linear slides to the bypass table and tubular sub-structure.

3.3.4.1 Concept Development

It has already been determined that the paddles and cylinders will be statically mounted to the support structure rather than dynamically on the bypass table. However, the initial concepts which led up to the final bypass table design will be discussed in the following section. The initial concepts and how they were generated and analyzed will be explained next. Initial concepts for the bypass method were first sorted into a few main categories which allowed the team to weigh the pros and cons of each method from a high-level perspective. Figure 57 shows how bypass methods were sorted with a flow chart.

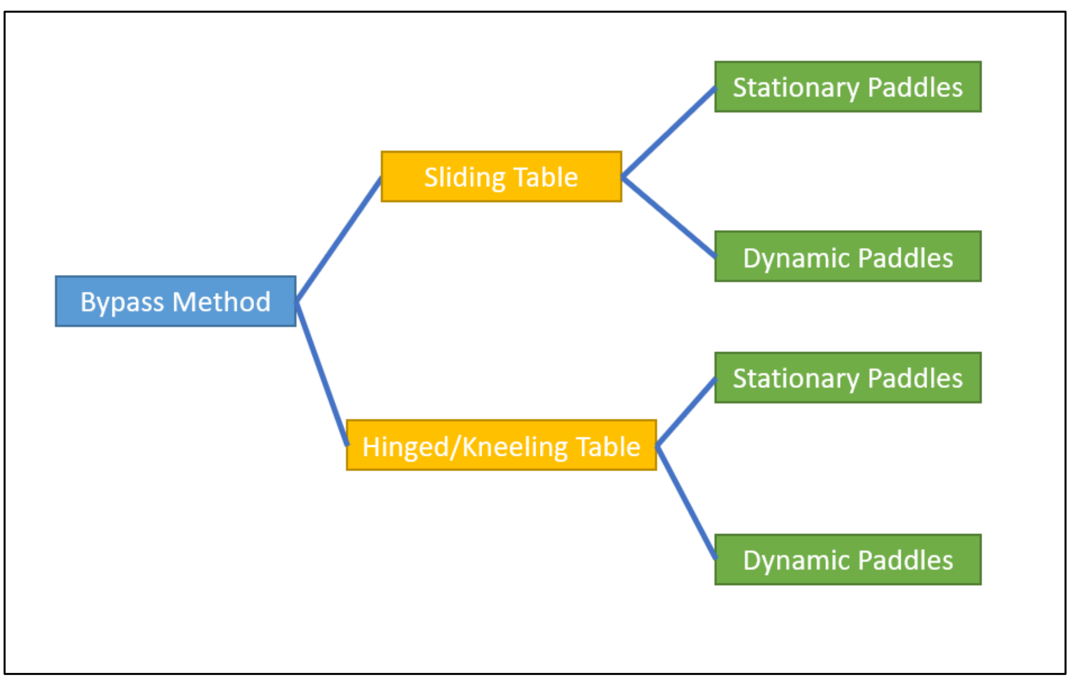


Figure 57: Bypass method high-level flow chart

Figure 57 shows the methodology used for the design of the bypass method. Some of the early concepts had the table (which the loin is reoriented on) be solely supported by cylinders at all four corners. The cylinder supported table would allow the entire table to kneel, essentially creating an extension of the declined conveyor which would ramp down to the lower conveyor. There were also hinged bypass methods which were a trap door style bypass. The hinged bypass would drop down from a cut-a-way in the loin table and once again, ramp down from the declined conveyor, bypassing the reorientation system. Sliding tables were also considered; sliding tables allow the table (with or without the paddles and cylinders still attached) to slide beneath the decline conveyor. When the table slides beneath the decline conveyor, it allows the loins to drop directly onto the loin line from the decline conveyor, bypassing the reorientation process.

Part of each of the sliding and hinged/kneeling table concepts was the decision of whether to allow the cylinders and paddles move with the design or not. In the case of the kneeling table designs, it seemed logical to leave the paddles and cylinders static, remaining in their original mounting location regardless of whether the bypass is active. Since the kneeling and hinged methods turn the table into a ramp, the paddles would get in the way of the loins as they slide down the table toward the conveyor. When considering the sliding table designs, the prospect of doing both static and dynamic paddle and cylinder designs is feasible. The main issues arise with the location of the cylinders when sliding the table, paddles, and cylinders together. The cylinders extend off the sides of the table and interfere with the support structure beneath the declined conveyor. On the other hand, the static paddles and cylinders design would require the design of a more complex mounting frame to mount the paddles and cylinders on an isolated structure.

The team decided to move forward with a bypass method that does not utilize an automated actuation feature. Therefore, the bypass will be fully manual for the purpose of ensuring the bypass method is reliable and easy to clean. The sliding table bypass was chosen due to the fact that for a manually actuated bypass design, the sliding method would allow for a much more user-friendly experience. The kneeling table is a feasible concept but depends on it’s actuation being automated. Therefore, the most practical solution to the bypass method given the decision to progress with manual actuation is the sliding table.

3.3.4.2 Design – Bypass Table Structure

The bypass table structure is comprised of a 316L stainless steel tubular frame topped by a 316L stainless steel sheet top component where the loin reorientation process occurs. The bypass table has been designed to have a 0.25” gap which borders the structural tube from which surrounds it. The entire tube frame members and sheet metal top is welded. In the next section, the linear bearing mounting location will be described. The bypass table is composed of 1” square tubing and can be seen in Figure 58.

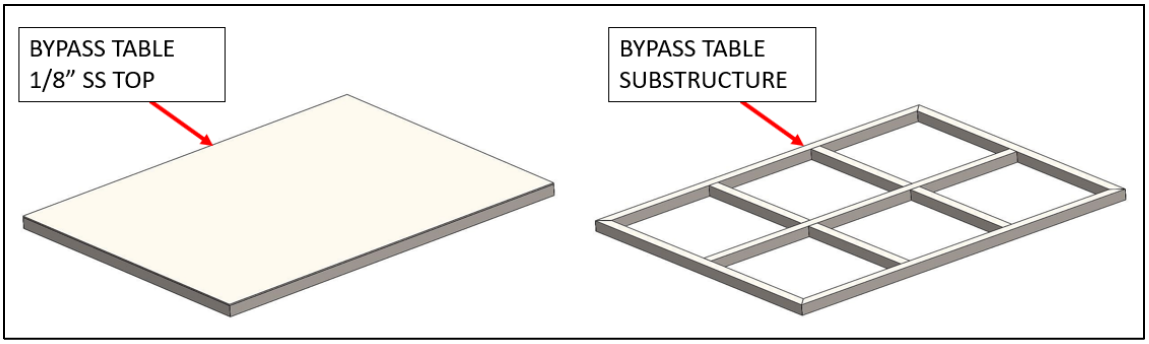


Figure 58: The bypass table 1” square tubing frame and 1/8” thick top

The bypass table structure measures 29”x36.5” and consists for a main 1” square tubing outer frame with 1” square tube cross bracing. The 1” square tubing structure uses 45-degree joints for the outer perimeter members such that the structure is hermitically sealed. The bypass table also features a 1/8” 316L stainless steel top. The table provides enough room for the loin to be reoriented while still being easily integrated into the main support structure.

The 1” 316L stainless steel square tube material selection was based on the desirable corrosion resistance traits that the material possesses in addition to being strong enough for the particular application. A 7-gauge (3/16”) wall thickness was chosen for all tube which make up the bypass table. In order to justify that the material selected for the job is capable of withstanding the forces associated with the handling of the loins, basic hand calculations were performed. The load case which was used to display the strength of the tube for the particular application is featured in Figure 59.

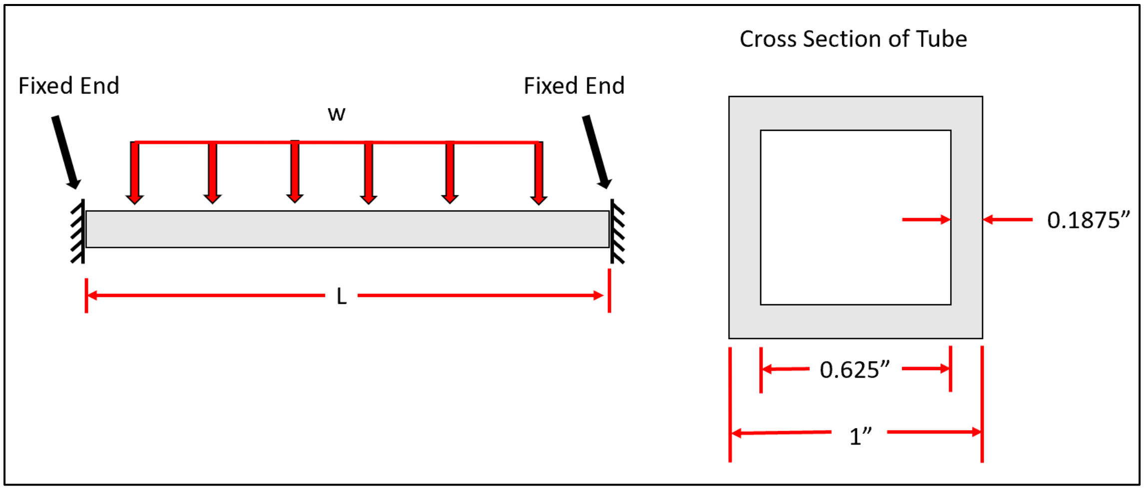


Figure 59: Load scenario diagram for the table support structure for buckling and compression analysis

More specifically, the load case used for justifying the bypass table strength was simplified to consist of only a single 36.5”316L stainless steel 1” square tube with a total distributed load of 100kg applied to it. In reality, tube structure reinforced by the sheet on top of the bypass table will be much stronger. The 100kg load is meant to simulate multiple loins stacked on the table in the event of a system jam in addition to the weight of the structure itself. Bending stress in the beam was calculated for the worst-case scenario, and it was found that the stress in the tube was just under 50 MPa, which is lower than the yield strength of 316L stainless steel.

3.3.4.3 Design – Bypass Linear Bearing Slides and Mounting

The linear bearing slides have been employed to allow the bypass table to slide in and out of bypass mode. The slider which has been selected for the job was sourced from TPA Motion [8], a company with a product offering which contains many custom gear systems, rail systems, linear motion systems and more. TPA Motion offers many products tailored for the food processing industry, the linear bearing slide system selected for this project being one of them. The linear bearing slides are marketed specifically for the food processing industry. TPA states that their slides are built to comply with FDA and USDA food cleanliness standards and be immune to any form of corrosion or failure which may result to the humid environment which most food processing plants host. Figure 60 displays an image of the model series of linear bearing slide which the team has selected for the application of allowing the bypass table to slide on [8].

Figure 60: TPA Motion - washdown linear bearing slide [8]

The linear slide bearings from TPA can be requested to be custom made to the specifications which the customer pleases, however there are some common specifications which can be used to categorize these telescopic linear bearing slides. The linear bearing slides feature a ball cage sliding system, this is the component which allows the slides to smoothly retract and extend as required.

The size of the sliders can be built to have a stroke in the range of 18” to 48”. The overall body size and maximum load capacity is determined by the series of linear slide bearing. The linear slide bearings come in two different series, the 28 series and 43 series. The 43 series is capable of handling loads up to 900 lb per slide [8]. The 28 series is rated for a load of over 350 lb per slide [9]. The dimensions of the body of the slides, both series 28 and 43 are summarized in Figure 61 from the perspective of a cross-section.

Figure 61: Series 28 and 43 dimensions [10]

Looking deeper into the stroke and retracted length of the slides, Figure 62 provides a visual of the slider with dimensions of when the linear bearing is completely extended and contracted. The linear slide bearing can be configured in many different stroke sizes, however for the team’s application, a stroke of 700 mm was selected [9].

Figure 62: Linear slide bearing dimensions [9]

3.3.4.4 Design – Bypass Actuation System

As stated in the preceding section on the concept development process for the bypass feature, the manually actuated sliding bypass was selected. Major components involved in the manual bypass actuation system are labelled and described in Figure 63.

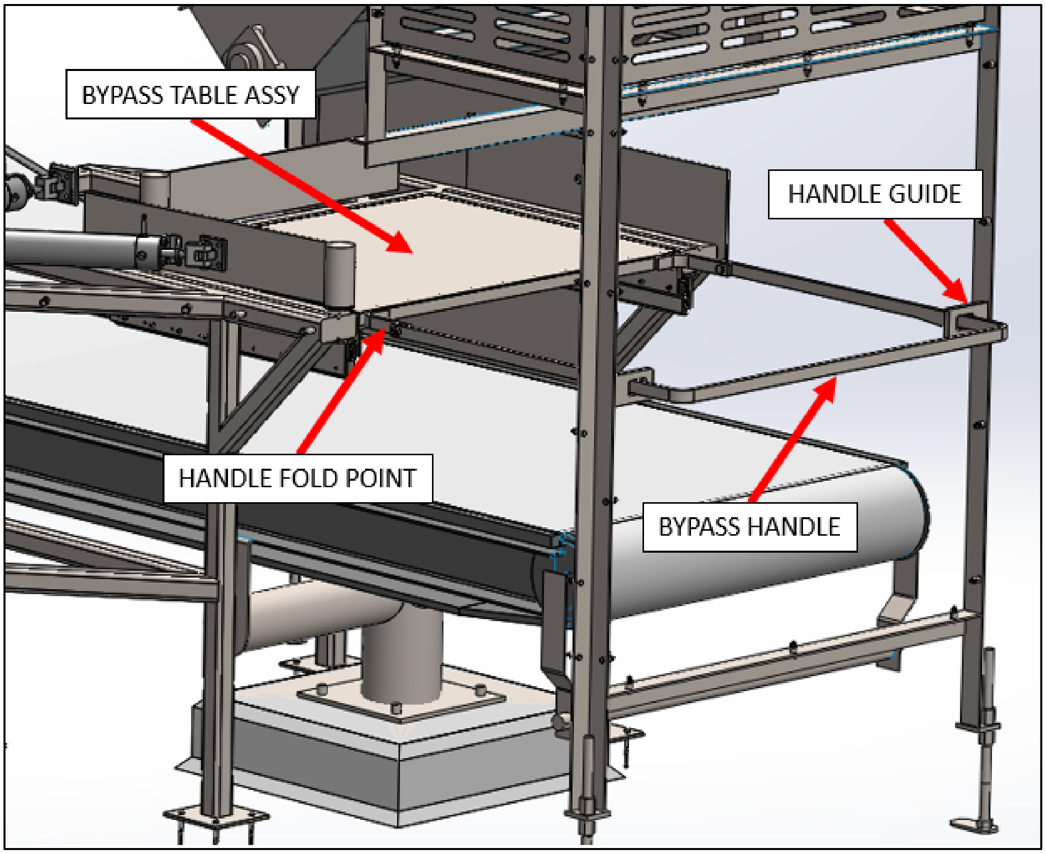


Figure 63: Manual bypass system components

The following section will summarize the design intentions behind each of the major components of the bypass system. The most critical components of the bypass system include the pull handle, guides, and mounts required for installation. The operation of the bypass feature will be briefly discussed in this section before being featured again, in detail, within the final design section specifically for the functional description of the bypass.

The bypass design is mounted directly to the sliding table which loins are rearranged on. Stemming from the table are two slide rails which extend rearward out the back of the support structure for the declined conveyor. The slide rails are interconnected with the handle since both are formed out of the same length of 3/8” thick 316L steel. The slide rails serve multiple purposes for the overall bypass system, the most primary function that the slide rails possess is the solid connection between the bypass table and handle. Having the slide rails protrude from the rear of the declined conveyor sub-structure allows for safe access to the handle from beyond the safety guards. The second purpose of the slide rails is its ability to lock the bypass table in place by while the bypass method is not engaged, and the paddle table is operating as intended. The wedge-shaped stops on the slide rails allow the system to be locked into place when the bypass action is not going to be actuated. Figure 64 shows a detailed visual of the bypass locking face.

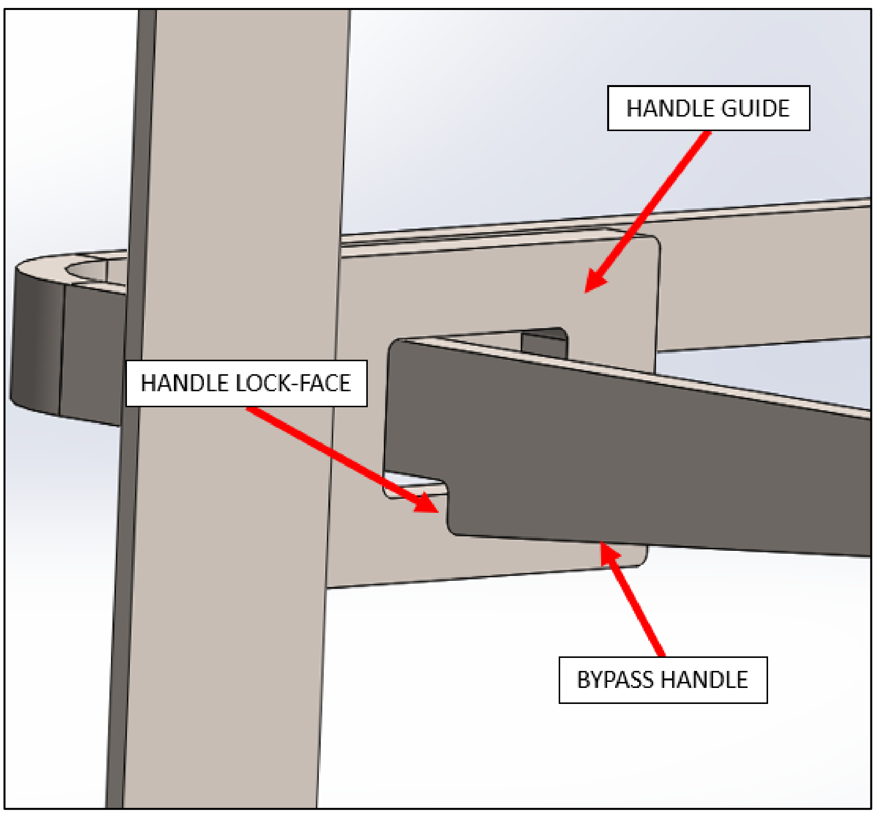


Figure 64: Bypass locking system visual

Designing the bypass locking feature into the slide rail allows the entire system to be bypassed by only one operator. The manually actuated system is desirable for the application since the reliability of the bypass is paramount, as it most often used in situations which are time sensitive. The rearmost decline conveyor support legs have guides which are placed so that as the table is pulled backwards, the slides travel along the guide until the table has reached the extended position. At the point that the table has reached the extended position, the mount which is used to attach the slide rails to the table will protrude from guides. Once the table mount has protruded from the guides on the rear of the declined conveyor structure, the entire sliding handle is able to hinge downward, allowing the pull handle to be tucked out of the way. Figure 65 shows the handle in the bypass position.

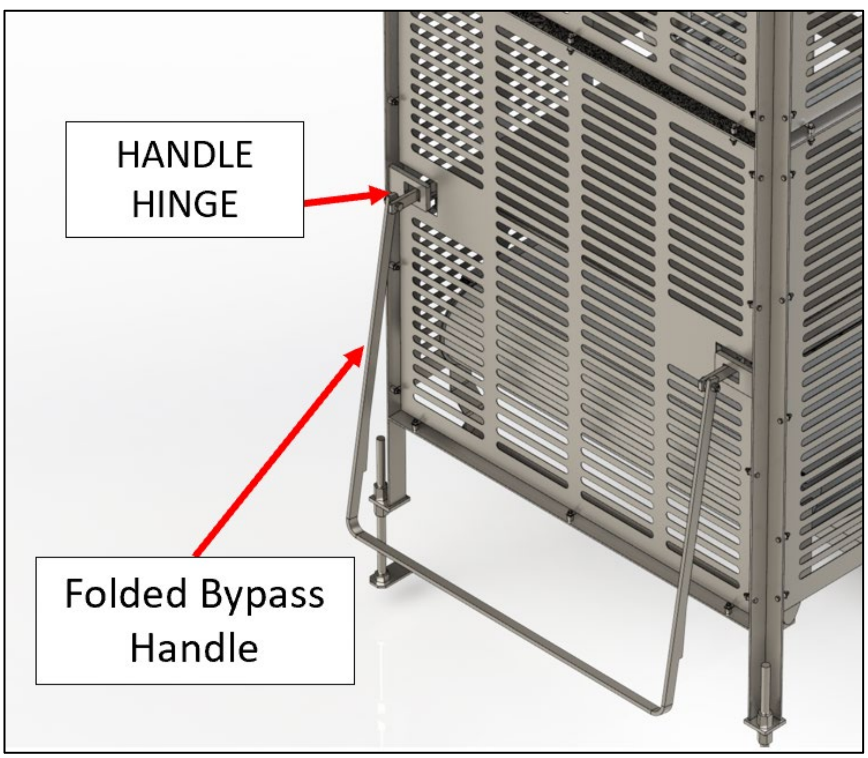


Figure 65: Bypass handle – folded position

As mentioned in the preceding paragraph, the slides have a notch specifically designed for locking the bypass table in the “home” position; the home position is where the bypass is not engaged and the paddles are operating as intended. Given that the bypass table is free to move on the linear bearing slides when the table is not constrained by the locking bypass system, forces exerted on the bypass table must be supported by the bypass locking system. The force which is transmitted through the bypass slide rails will load the rails in compression while the bypass slide guides will experience a combination of shear and bending forces as a result. Analytical calculations have been completed to ensure that the maximum estimated forces that can be exerted on the bypass actuation system can be withstood. Figure 66 shows the loading case which was developed to model the handle slide rails in compression. The critical buckling load in multiple axes was calculated in addition to basic compression failure.

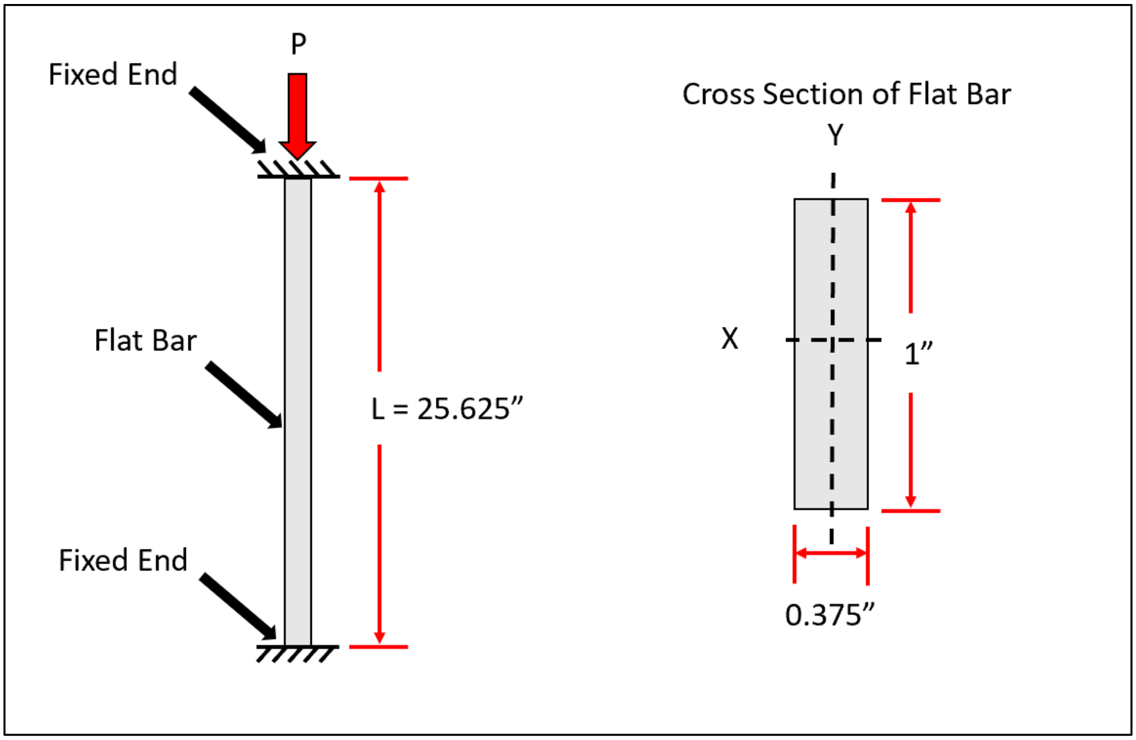


Figure 66: Bypass handle loading case, axes, and cross section

The maximum force which can be transmitted by the cylinders used to reorient the loins is just under 500 lb. Evaluation of the force the cross section can handle in compression before yielding returned a value of 9244 lb. Next, the critical buckling load was calculated for buckling about both X and Y axes (see Figure 66 for handle cross-section orientation). Buckling about the X-axis yielded a critical buckling load of just under 53 000 lb while the critical buckling load about the Y-axis was just under 7400 lb. Therefore, compressive analysis and buckling analyses both yielded values far higher than the maximum expected load on the bypass handle, resulting in a minimum factor of safety of over 14. A full set of the buckling and compression calculations are available in Appendix C.

Analysis was conducted on the handle guide rails once the bypass handle was deemed to be fit to handle the maximum load which it could experience. Since the bypass handle guides are mounted perpendicular to the bypass handle slides, both shear and bending failure modes were considered when analyzing the handle guides. Shear load calculations were conducted by hand on the handle guides, resulting in significantly lower stress levels than the yield strength of 316L stainless-steel. Analysis of the guides in bending proved to be much more complicated than the shear analysis. Figure 67 shows the area of the guide which interfaces with the sliding handle notch.

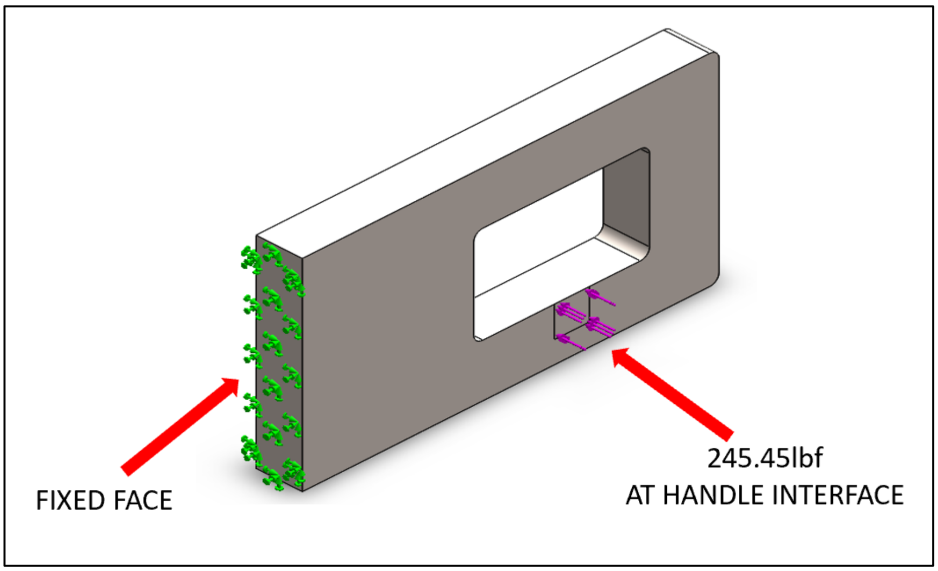


Figure 67: Handle guide loading case showing fixed face (green) and loaded area (purple)

The fixed face of the handle guide is welded to the declined conveyor structure. The loading case presented in Figure 67 highlights the location which the 245.45lbf force is applied. The 245.45lbf force represents half of the maximum load the paddles cylinders are capable of exerting on each of the two guides. Finite element analysis was a great aid in determining the stresses which result from the loading scenario. Hand calculations were deemed unfit for the load case since the applied load results in not only shear and bending, but torsion as well. The load application point is offset vertically from the center of the face perpendicular to the load. The FEA study was conducted with Solidworks 2020 utilizing the settings summarized in TABLE IX.

TABLE IX: HANDLE GUIDE SOLIDWORKS FEA STUDY SETTINGS [7]

Software	Solidworks 2020
Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Automatic transition	Off
Mesh auto loops	Off
Jacobian points	4
Max element size	0.1in
Min element size	0.033in
Material type	316L Stainless steel (Solidworks profile)
Elastic modulus	193GPa
Poisson's Ratio	0.30
Tensile strength	550MPa
Yield strength	137.9MPa
Solver	Direct sparse solver
Adaptive mesh refinement	h-adaptive, 3 loops, 99% target accuracy
Thermal effects	Disabled

The maximum stress observed from the FEA studied occurred at the base of the guide at the point where the component will be welded to the declined conveyor sub-structure. Since the area which exhibited the highest stress value will be covered by weld, the stresses will be distributed through the fillet weld, significantly reducing the value of stress at this location. The convergence study performed resulted in a solution with the singularity point causing divergence in stress and while the deflection still converged. The mesh refinement convergence study can be accessed in the Appendix F if desired. Figure

68 displays the stress gradient exhibited by the guide. The von Mises stress scale was set to max out at the yield stress of the 316L stainless steel.

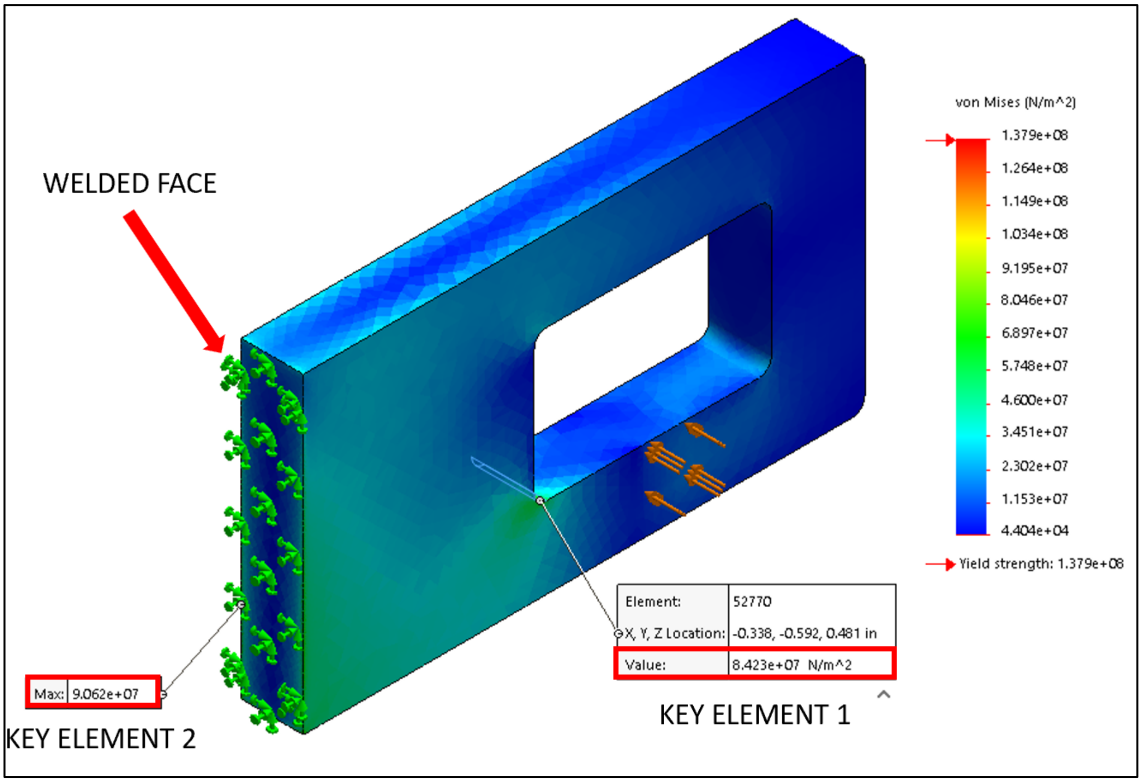


Figure 68: Handle guide stress gradient

Stresses present at key element 2 in Figure 68 indicate the location where the maximum stress was exhibited, however, this location will be welded to the declined conveyor structure, likely eliminating the stress concentration and singularity point. Key element 1 was selected by the team to represent the most critical location to look at stress values. The stress value of 84 MPa resulted in a factor of safety of approximately 1.68. Thus, the guide is fit for implementation when it is considered that the loading conditions were estimated to only occur in the extreme event that 100% of cylinder pushing power being directed along the line of motion of the linear slides. The selected material thickness is 0.5” 316L stainless-steel.

3.3.5 Design – Paddles & Pins

3.3.5.1 Paddle Assembly Overview

The final design for the paddles and their supporting pins (i.e. shafts) was approached with the following objectives:

- Low cost
- Ease of manufacturing
- Long life
- Ease of disassembly and cleaning

These objectives were achieved using a design that consists of a 316L steel pin, Delrin 500CL bushing, 316L stainless steel outer sleeve/bore and a welded 316L tube armature with corresponding eyelets. The paddle assemblies are summarized in the following Figure 69, while the pin is shown later.

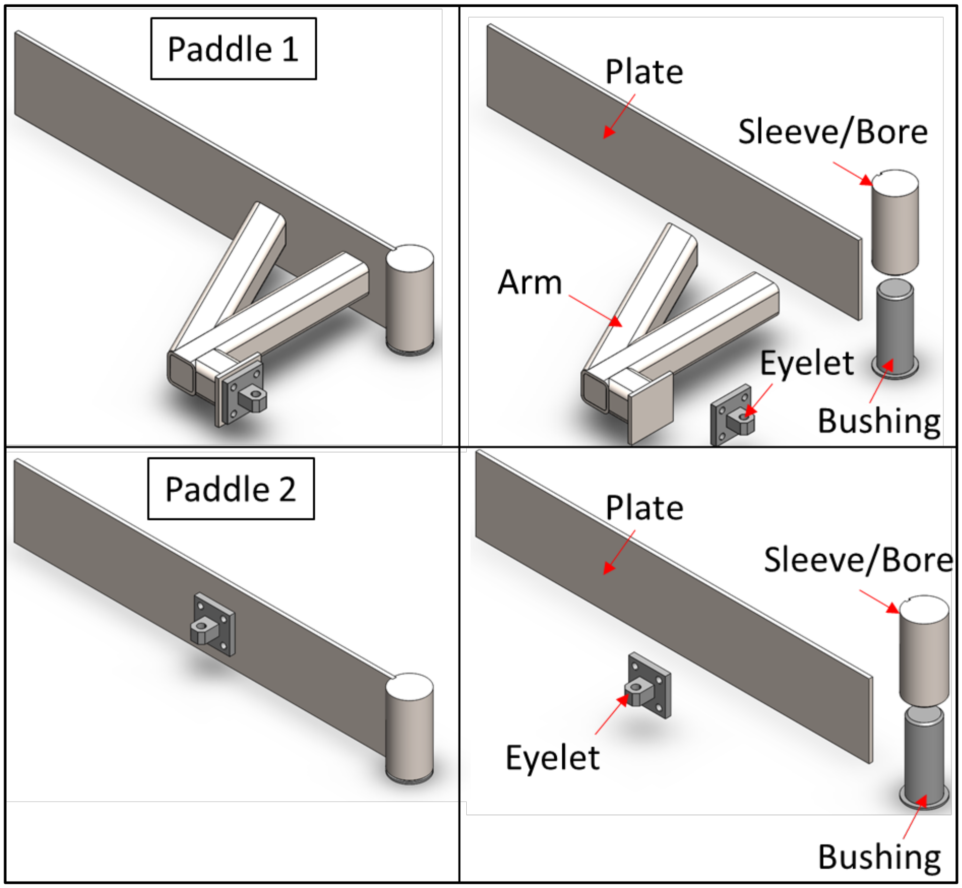


Figure 69: Exploded view of Paddles 1 and 2

There are only a few components for each paddle. The bushing is made from Delrin and has a simple transition fit (H7n6) into the bore. The 316L bore itself has a slot in the side to facilitate the attachment of the 316L plate via welding, to which the armature and eyelet are welded for paddles 1 and 2 respectively. The paddle assembly itself then rests on the pin, since the top of the sleeve/bore and bushing are capped off, and rotates freely using a free running fit (i.e. H9d9) between the bushing and pin. The mounting on the pin is shown next in Figure 70.

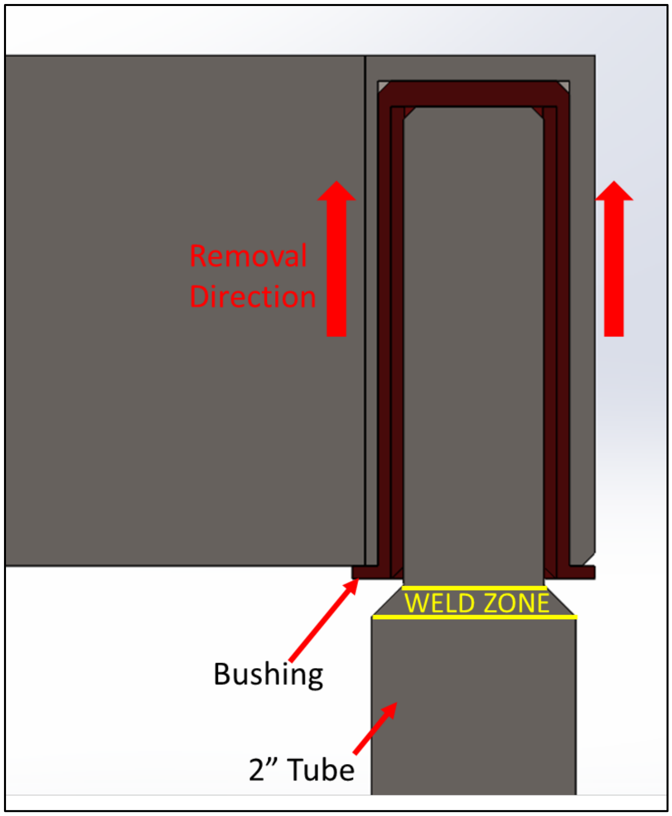


Figure 70: Paddle assembly mounting

Figure 70 demonstrates how the paddle assembly can be simply removed from the pin for cleaning and does not require tools. The eyelet on the paddle mounts to the clevis of the pneumatic cylinders using a 0.5” pin and small cotter pins, which further facilitates the tool-less design and is shown in detail in the later Section 4.3.6.

3.3.5.2 Pin Design & Analysis

The 316L SS pin has an outer diameter of 1.375”, is 5” tall, and has a small 0.125” chamfer around the crown of the pin. Given that the surrounding tube structure is comprised of 2” square tubing, 1.375” is the largest diameter permissible while maintaining an acceptable 5/16” weld at the base, bringing the overall diameter up to 2” [11]. This geometry is shown next in Figure 71.

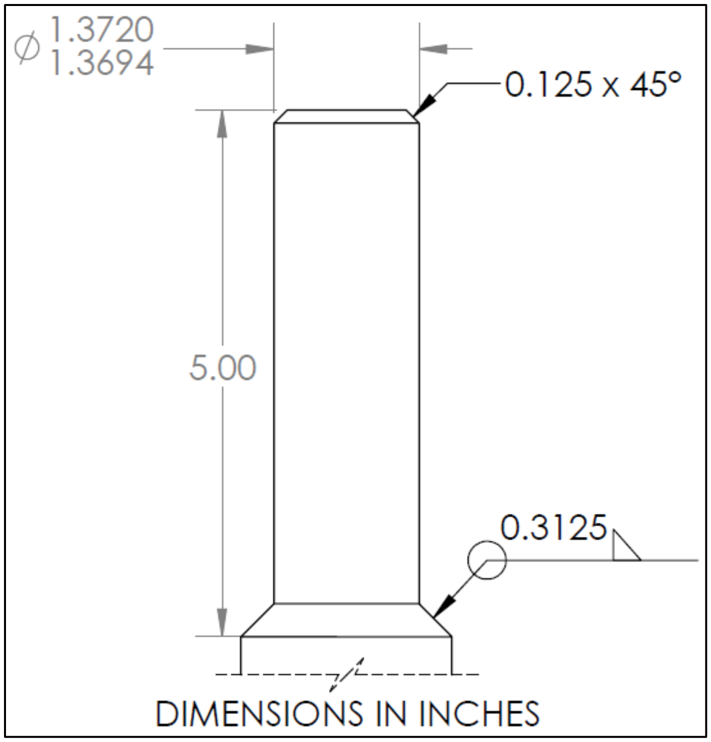


Figure 71: Geometric specifications of paddle pin

The analysis of the pin was restricted to the loading of the weld around the base, as it has a much smaller cross-sectional area and would fail before the main body of the pin. Particularly, the pin was assumed to have a cyclic loading of 490.9lbf distributed perpendicularly to the upper 4.5” of the pin, representing a worst-case scenario of the full force of the pneumatic cylinder being applied directly (2.5” diameter cylinder bore, 100psi). This loading on the pin is shown in the following Figure 72.

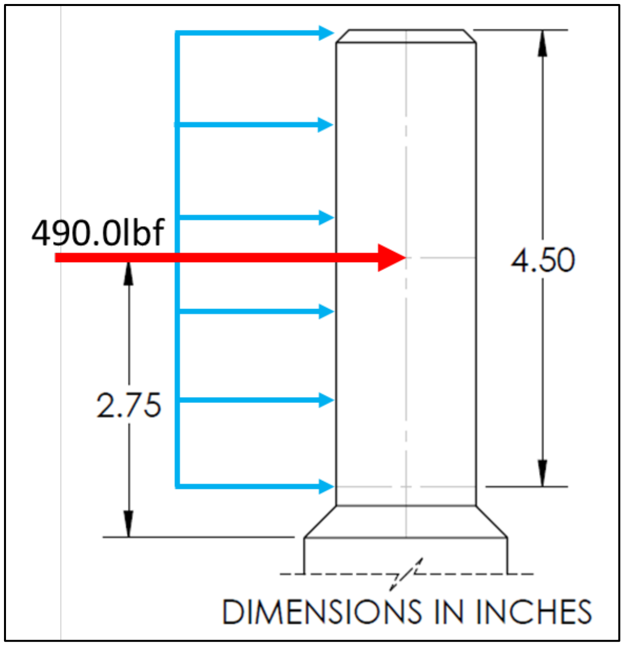


Figure 72: Loading scenario for paddle pin

The fatigue analysis was applied to both the weld itself, and the small area of the parent material (base) adjacent to the weld. The analysis followed the methodology outlined in Shigley's Mechanical Engineering textbook, particularly that of Chapter 7 with respect to welds, shaft analysis, and the application of the Modified Goodman approach [11]. The welding electrode selected and used was the 316/316L-15 from Lincoln Electric, which has a yield and ultimate strength of 68ksi and 90ksi respectively [12]. The datasheet for the electrode has been provided for the reader in Appendix D. Similarly, the selected material for the pin was 316L stainless steel from Atlas Steels, with a yield and ultimate strength of 24.66ksi and 70.34ksi respectively [13]. The datasheet from Atlas Steels is provided for the reader in Appendix D. Table X summarizes the various stress concentration factors, stresses, endurance limit modifying factors, and factors of safety for the static and fatigue loading scenarios, and the hand calculations are provided for the reader in the Appendix C.

TABLE X: STRESS VALUES ON STEEL TUBING, PIN AND WELD

	Steel Tubing & Pin	Weld
Material	316L Stainless Steel (Atlas Steels)	316/316L-15 Electrode (Lincoln Electric)
Yield strength (ksi)	24.66	68
Ultimate strength (ksi)		
Static Loading		
$\tau_{allowable}$ (ksi)	9.862	27
τ_{actual} (ksi)	0.296	2.12
Factor of safety		
Cyclic Fatigue Loading		
Endurance limit modifying factors	$k_a = 0.58$	
Pristine endurance limit	$S_e' = 0.5S_{ut} = 35.17ksi$	
Modified endurance limit	$S_e = k_a k_b k_c k_d k_f S_e' = 9.87ksi$	
Fatigue stress concentration factor	$K_{fs} = 1.5$	
	Steel Tubing & Pin	**Weld**
S_{actual} (ksi)	0.444	3.18
Factor of safety	38.99	5.44

Table X shows the pin with the selected material, weld, and loading scenario passes static loading with a factor of safety in the weld and adjacent material of 12.7 and 33.3 respectively. Similarly, the proposed design passes fatigue loading with a factor of safety in the weld and adjacent material of 5.44 and 38.99. Thus, the pin should be theoretically function indefinitely provided that it is machined, welded, and loaded appropriately, and that it is not subjected to extreme corrosion fatigue. The calculations assumed that the weld has adequate penetration, is ground down, and does not drastically affect the local base material properties. Further, it was assumed that the pin is turned on a lathe to get a smooth surface finish, but the weld was treated to be "as cast" in terms of surface quality. Given that the pin is turned on a lathe for manufacturing and welded to the frame, it doesn't require disassembly, is easy to clean, and easy to manufacture.

3.3.5.3 Bushing Design & Analysis

To facilitate the rotary motion between the paddle and the pin, either a bearing or bushing could have been selected. This was discussed with HyLife and it was determined that a Delrin (Acetal) bushing would be preferred over a roller or needle bearing. The rationale behind this selection was that Delrin bushings are low cost to produce, easy to clean, easy to replace, are considered food-safe, and are considered "dry" bearings. A "dry" bearing or bushing does not require lubrication on a continual basis, but may require an initial lubrication for the wear in period [14]. The bushing shown previously in Figure 71 and Figure 72 was designed based on the following design principles and recommendations from DuPont [14]:

- High shaft hardness and surface quality
- At least 3 axial grooves, as deep as is feasible, and approximately 10% of the shaft diameter
- An absolute minimum diametral clearance of 0.2% of the shaft diameter
- Initial lubrication to facilitate the wear in period
- Protection against dirt ingress

The high shaft hardness and surface quality of the bushing and shaft contribute to an extended service life and more reliable operation. DuPont has found that shaft hardness is the largest contributing factor the bushing life, however this could not be accommodated for with the restriction of 304 and 316 stainless steel [14]. With this in mind, the bushing design was approached with the objective of easy replacement, being substantially overbuilt for the loading conditions, and low cost.

The minimum of 3 axial grooves is suggested to allow for dirt and particles to be removed from the wear surface of the bushing in operation. If the bore of the bushing was completely smooth (i.e. no axial grooves) the dirt and particles would continue to move around between the shaft and the bushing, wearing it out at an accelerated rate. This remains true even if the particles are Delrin itself, similar to how a diamond can cut another diamond. The rationale behind the width of grooves being at least 10% of shaft diameter and as deep as feasible was not elaborated on by DuPont, but was still adhered to in the design of the bushing.

The minimum acceptable diametral clearance between the shaft and the bushing is specified as 0.2% of the shaft diameter, since Delrin has a relatively high coefficient of thermal expansion. This was accounted for in the design of the bushing by using a loose free running fit (H9d9).

To achieve the initial lubrication during the wear in period and to reduce the likelihood of dirt ingress, the bushing was capped and inverted such that any dirt or water can be drained away while the lubricant remains shielded from high pressure spray. The final geometry of the bushing is shown next in Figure 73.

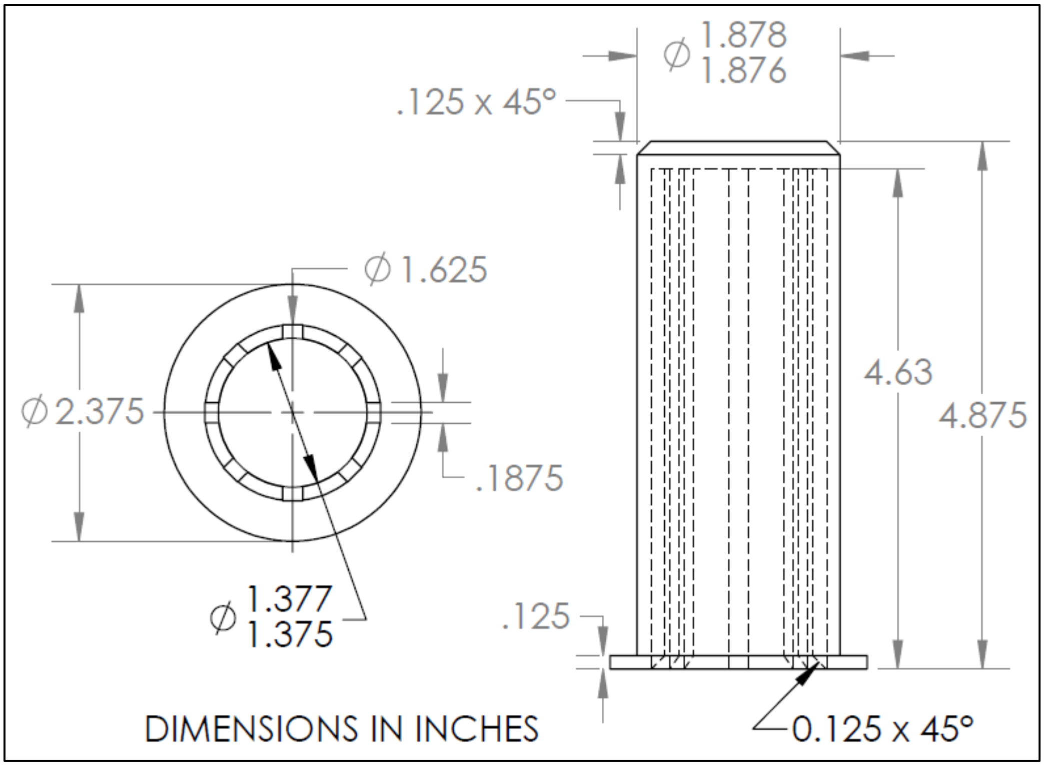


Figure 73: Final geometric specification of the pin

The final bushing design can be manufactured using a combination of turning, boring, and broaching. There are 8 equally spaced internal grooves, each 0.1875” (3/16”) wide, and 0.125” deep. There is a 0.125” symmetric chamfer along crown of the bushing (top) and an additional chamfer on the base of the bushing to facilitate easy pin insertion and insertion of the bushing into the paddle bore itself using a locational transition fit (H7n6). Additionally, a 0.125” thick ring on the bottom allows for removal of the bushing from the paddle bore with a screwdriver or thin spanner.

The suitability of this bushing design to the application was determined using a combination of the equations in the DuPont design guide [15]. It was assumed that the paddle rotates 90 degrees in one second, corresponding to two seconds for a complete paddle cycle (i.e. +90° followed by -90°), which with two paddles, would allow for a 2 second idle time between loins arriving. This corresponds to a rotational speed (when in motion) of 15RPM, which, along with the assumed 490.9lbf applied to the projected area of the bushing from the pin loading analysis, obtains a PV (pressure*velocity) value of 0.90 MPa*m/min, much lower than the maximum allowable 15MPa*m/min for Delrin 500CL [15]. Delrin 500CL was selected because it has a low static and kinetic coefficient of friction of 0.1 and 0.2 respectively, as well as the best wear characteristics in comparison to Delrin 500 and Delrin 900F [15]. The specific calculations regarding the bushing are available for the reader in Appendix C.

It is difficult to predict the actual service life of the bushing, given that it is dependent on the real loading scenario, environmental effects, adherence to DuPonts best practices, and other unknown factors. Thus, the lifespan of this bushing design can only be estimated as adequate but requires testing for more accurate predictions.

3.3.5.4 Paddle Bore Design

The paddle bore is the female metal sleeve in which the bushing is inserted and to which the paddle plate is welded. Its function is to facilitate a connection between the plate, bushing, and the pin to facilitate the paddle assembly's range of angular motion. It is manufactured from 316L stainless steel, and is produced from a single piece of round stock that is turned, bored, and features a 0.255" channel on the side for the plate. The paddle bore is shown next in Figure 74.

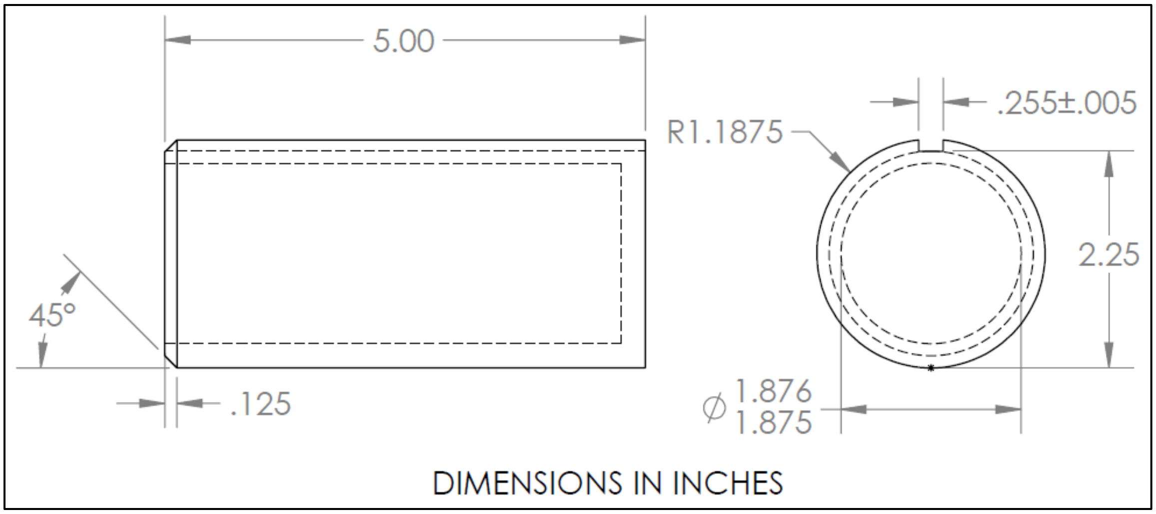


Figure 74: Final geometric specifications of the paddle bore

The paddle bore is 5" long overall, has an outer diameter of 2.375". The internally bored out cavity is 4.75" long by 1.875" diameter. The base (bottom) of the bore has a 0.125" symmetric chamfer along the outer edge to facilitate removal of the bushing with a screwdriver or spanner, and a 0.255" wide by 0.125" deep channel on the outer periphery of the unit to which the paddle plate is inserted and welded. The purpose of the channel is to provide an accurate location for affixing the metal plate and ensuring that the metal plate is square with the paddle bore. To ensure that the steel plate can fit into the channel, a tolerance of 0.005" has been specified for the channel. The paddle bore is anticipated to have a long service life due to no metal on metal contact in motion and a very large weld perimeter for the paddle plate.

3.3.5.5 Paddle Plate Design

The paddle plate is the main contact surface with the loin, pushing and maneuvering the loin on the table as the pneumatic cylinders extend. As was seen previously in Figure 74, the geometry of the plate is a simple rectangular cut of 0.25" 316L steel plate. It measures 26.75" long by 5" tall, maintaining contact with much of the loin. The paddle plate geometry is shown in Figure 75 next.

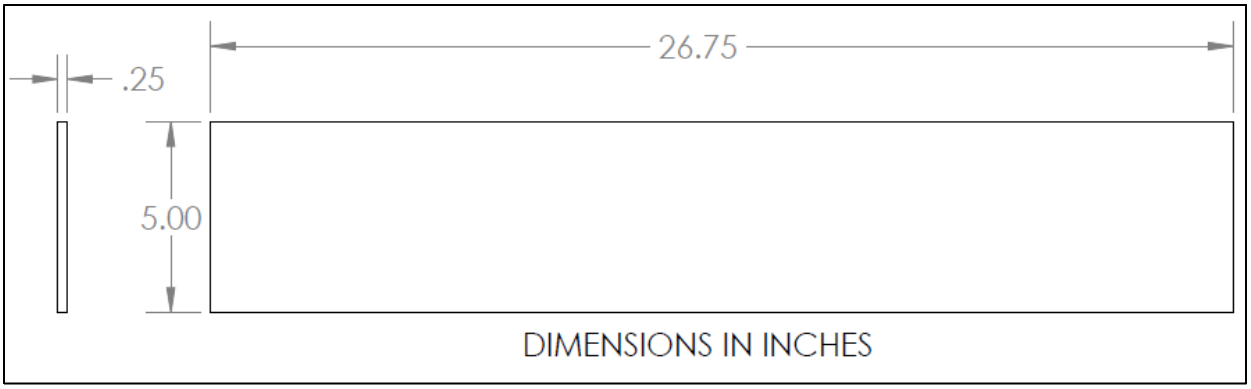


Figure 75: Final geometric specifications of the paddle plate

The paddle was intentionally made shorter than the full length of an average loin to allow for some room between the various moving components. By allowing for some room between the moving components, the chances of jamming are reduced.

The plate thickness of 0.25" was selected to reduce the weight of the paddle and because this is a common thickness used in the HyLife facility. A simple stress analysis on the first paddle was performed to evaluate the capabilities of the 0.25" plate, and the full analysis is provided for the reader in Appendix C. Since the first paddle's supporting arm is the closest to the bushing and pin, it has a larger cantilever beam effect than the second paddle. The loading scenario that was considered is shown next in Figure 76.

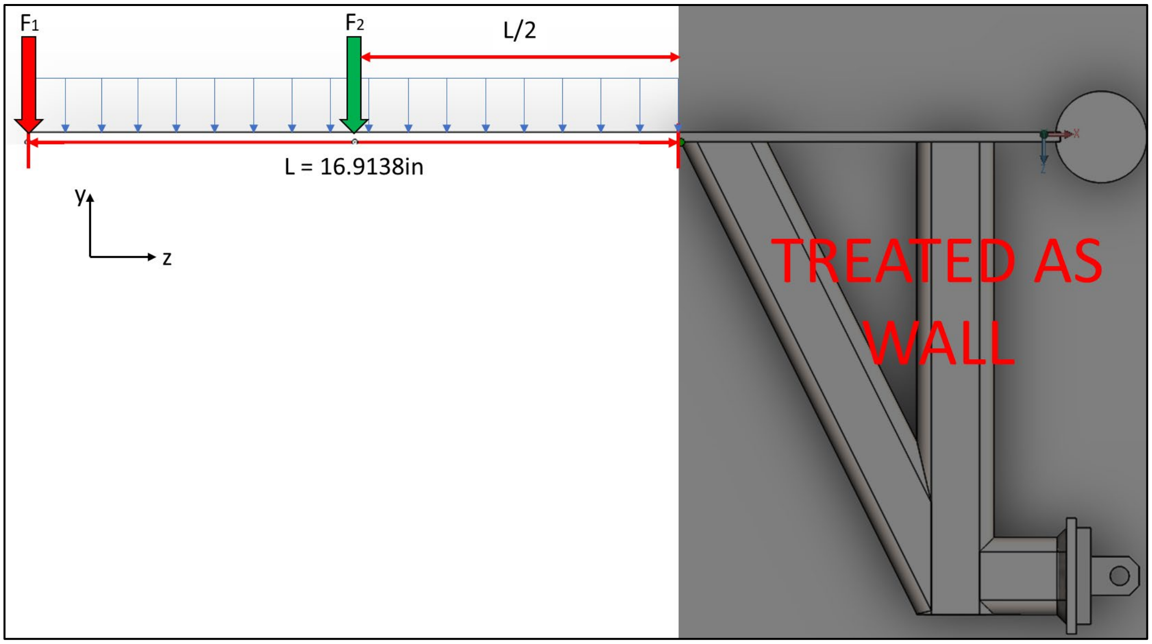


Figure 76: Loading case for the paddle plate

During the site visits, sample loins were dragged across steel sheets and it was noted that the coefficient of friction turned out to be higher than expected. The team did not have a mechanism to determine the coefficient of friction, so it was assumed to equal 1 for both static and dynamic events. The load on the paddle from pushing the loin was assumed to occur in two manners. The first load case is identified previously in Figure 76 as F_1, corresponding to a point load on the end of the paddle when the paddle first contacts the loin. The second load case, F_2, assumed a distributed load on the plate spanning from the tip to the beginning of the paddle arm, hence why it is located at the midspan between both points. To determine a factor of safety for both scenarios, the maximum allowable F_1 and F_2 loads were calculated and compared to the nominal 10kg loin weight. Using the yield strength of Atlas Steels 316L steel, it was found that the maximum allowable static loads are 75.92lbf and 151.84lbf for F_1 and F_2 respectively [13]. This corresponded to a factor of safety of 3.4 and 6.8 for F_1 and F_2.

Fatigue was considered. However, it was realized that fatigue failure is unlikely to occur before yielding for the selected 316L material. The rationale for this was that the endurance limit for the manufacturer's steel was unavailable and thus was assumed to be half the ultimate tensile strength [11]. This assumption resulted in an endurance limit for the 316L steel of 35.17ksi. Given that the yield strength of the 316L steel is 24.65ksi and the endurance limit is approximately 35.17ksi, the 0.25" plate would likely yield before succumbing to fatigue. Since the plate was found to not yield under the assumed conditions, it would therefore be unlikely to fatigue and be a satisfactory design selection.

3.3.5.6 Paddle Arm & Eyelet Design

Each paddle assembly features a different method of connection to the pneumatic cylinders. The first paddle features a 316L stainless steel armature, referred to as the "Paddle Arm". The arm consists of 2" square tubing with a wall thickness of 0.1875" and an EB500 eyelet from Bimba, welded together and then to the paddle plate. This is shown next in Figure 77 [16].

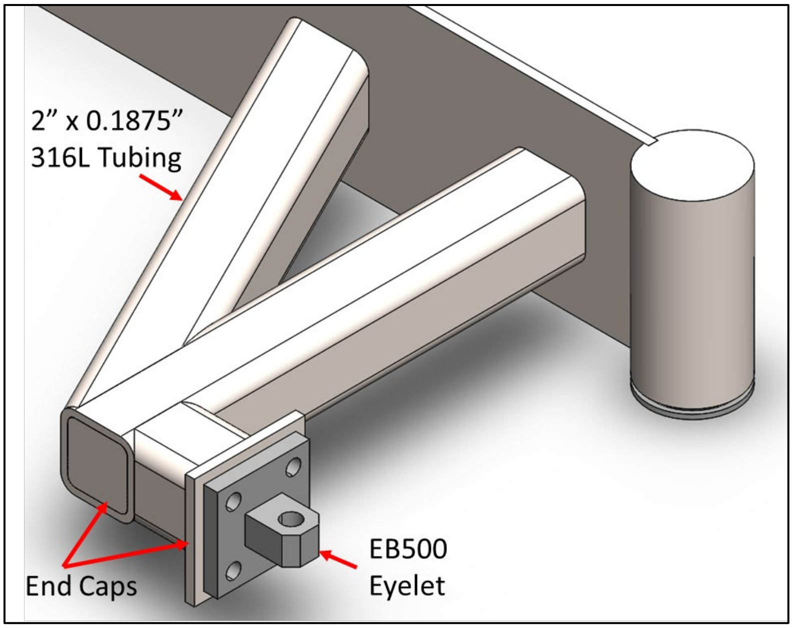


Figure 77: Paddle arm and cylinder connection

The design of the paddle 1 armature provides support for loading in the primary direction of the pneumatic cylinder using the two tubes. The original design for the arm involved the use of a simple 0.375" laser cut plate. However, this would not effectively support vertical loading in the event the cylinder pushes at an angle. By increasing the effective height in the vertical direction, the arm is much more rigid in vertical bending and will sustain the load properly while experiencing less deformation. A side by side comparison of the two designs and the applied loads considered in their design are shown next in Figure 78.

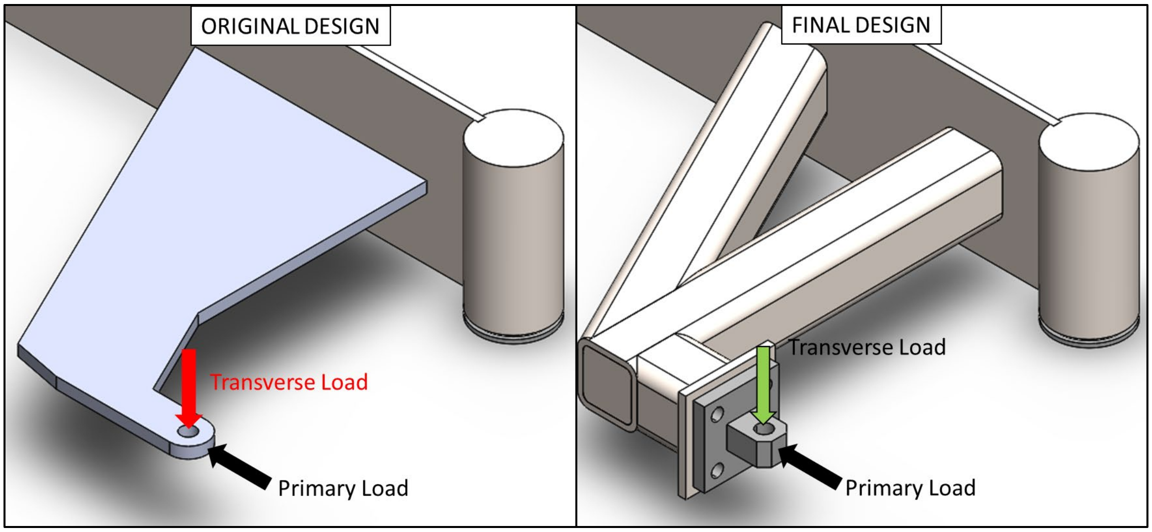


Figure 78: Load cases for original and final designs of paddle 1 armature

Finite element analysis of the original and final arm design was completed to show the variation in stress and total deflection, as well as to select the appropriate arm. Two scenarios were tested for each arm; the first scenario was 490.9lbf in the primary load direction. The second scenario was loading at 5 degrees from the original loading direction, splitting the original load into 42.79lbf in the downward vertical direction and 489.03lbf in the primary direction. In each simulation, the bushing and paddle bore were excluded from the analysis, since the design concern was with the maximum cylinder load applied to the armature and where it interfaces with the paddle plate. Further, the back side of the paddle plate was treated as a fixed support, while the load was applied directly to the inner face of the eyelet. TABLE XI summarizes the settings used in all 4 simulations.

TABLE XI: PADDLE ARMATURE FEA SIMULATION SETTINGS [7]

Software	Solidworks 2020
Mesh type	Solid mesh
Mesher used	Standard mesh
Automatic transition	Off
Mesh auto loops	Off
Jacobian points	4
Element size (max)	0.08in
Tolerance	0.004in
Material type	316L Stainless steel (Solidworks profile)
Elastic modulus	193GPa
Poisson's Ratio	0.3
Tensile strength	550MPa
Yield strength	137.9MPa
Component contacts	Global contact (bonded)
Solver	Direct sparse solver
Adaptive mesh refinement	h-adaptive, 5 loops, 99% target accuracy
Thermal effects	Disabled

In all 4 simulations, it was found that the maximum stress occurred at the sharp intersections of the various components. This was anticipated since the CAD software does not easily model weld beads in an assembly, resulting in sharp corners. A convergence study was run for all 4 simulations, showing a divergence in stress while the peak deflection converges, indicating a good solution with the presence of singularity points (elements with infinite stress). The mesh refinement convergence studies have been provided for the reader in the Appendix F. In all the following figures, the deformation scale was set to 1 and the stress scale maxes out at the yield strength of the material, thereby indicating points of failure in red. The first loading scenario was the primary loading of 490.0lbf, shown next in Figure 79.

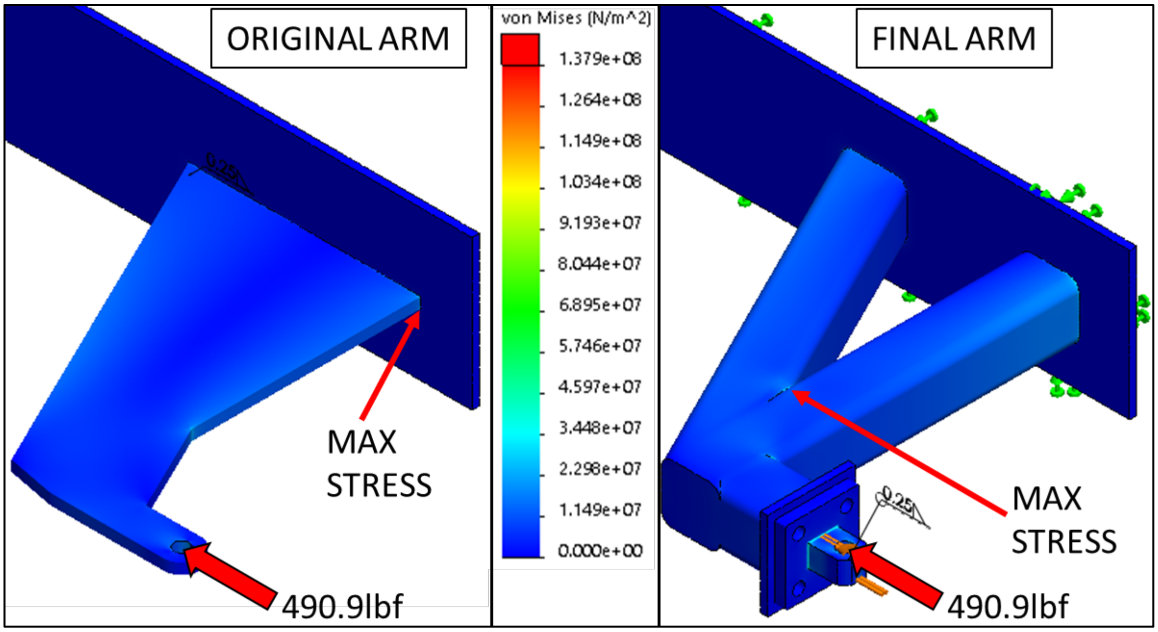


Figure 79: Von Mises stress distribution for original paddle arm (left) and final paddle arm (right) under primary 490.9lbf loading. Deformation scale is 1 to 1 and peak stress locations identified.

Figure 79 shows that the vast majority of each arm is blue, indicating a low stress of approximately 0 to 20MPa. It should be noted however, that the original design had a peak stress of 107MPa in its bottom corner where the arm interfaces with the paddle plate. Additionally, the final arm design had a peak stress of 285MPa along the inner joint between the two tubes coming together. Both points of max stress were contradictory to the rest of what was observable on the arms, indicating the presence of singularity points. This was anticipated due to the large load and theoretically infinite stress at the non-welded sharp corners of intersection. A close view of each max stress element is shown next in Figure 80 and reveals that there are a series of singularity points between each of the parts.

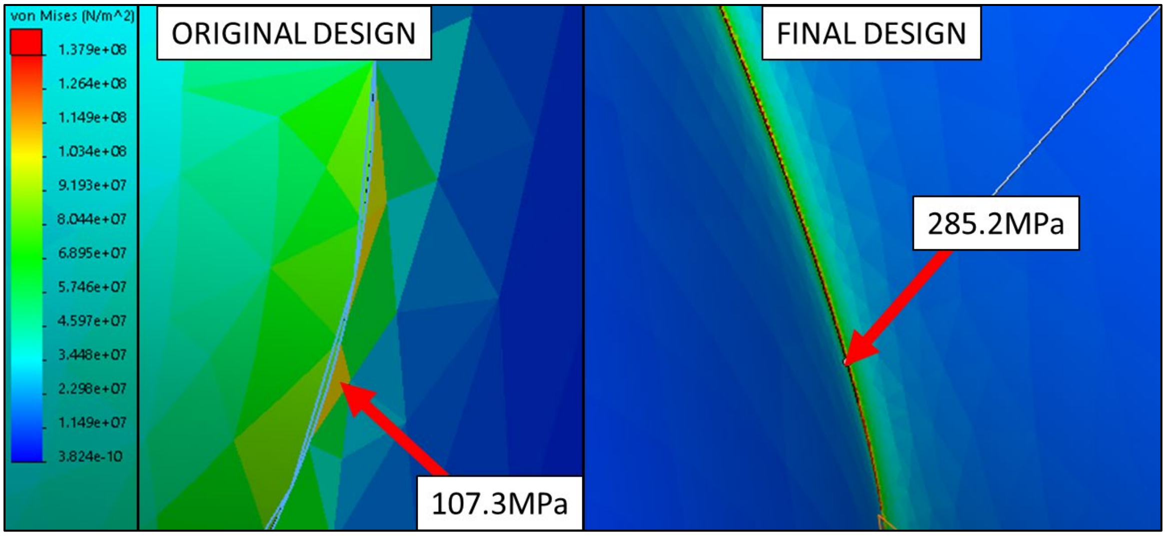


Figure 80: Zoomed in view of peak stress singularity elements on the original paddle arm design (left) and final design (right) under primary loading of 490.0lbf

As mentioned previously, a mesh convergence study was conducted for each simulation, showing convergence in deflection while the stress diverged. Neglecting the singularity points, the rest of each arm showed a low stress of 0 to 20MPa, while the yield strength of the Solidworks 316 stainless steel is approximately 138MPa [7]. Thus, if either design was used, they would be unlikely to fail in terms of the primary loading, provided that the stress concentration between the arm and paddle is alleviated with a weld bead. The actual deflection under the applied load was insignificant, peaking at 0.067mm for the original design and 0.07mm for the final design. The points of peak deflection are identified in Figure 81 next.

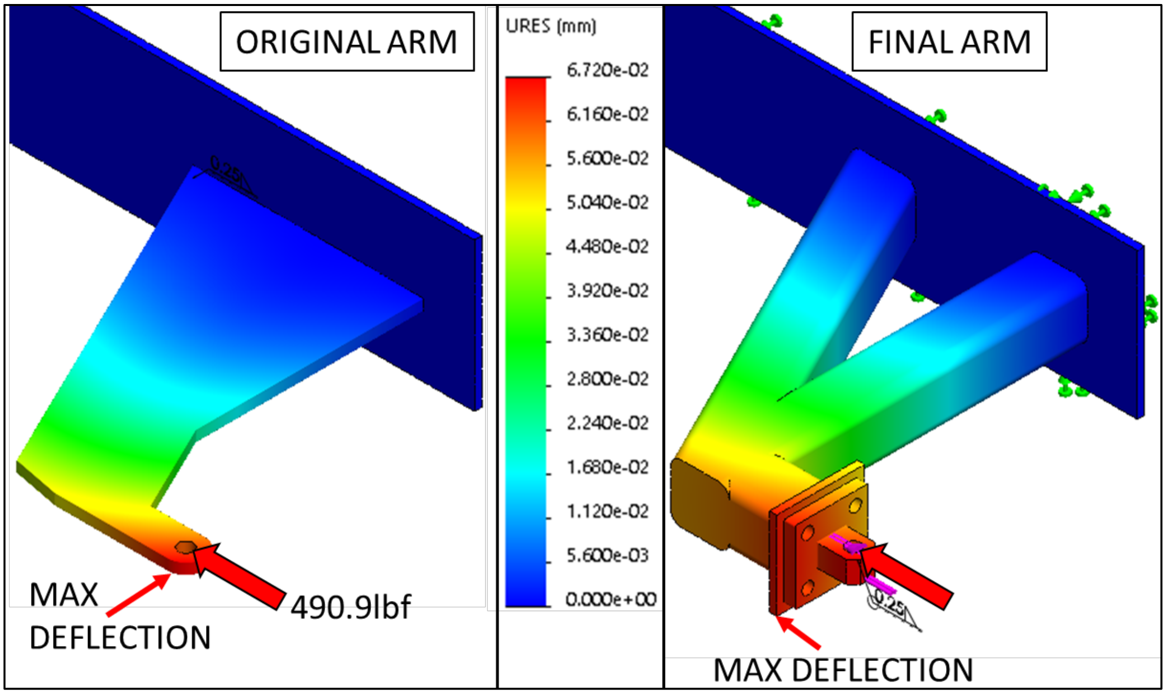


Figure 81: Plot of deflection of the original paddle arm (left) and final arm (right) under primary loading. Deformation scale is 1 to 1. Max deflection for the orignal arm is 0.067mm and 0.07mm for the final arm.

While both designs performed well under primary loading, they behaved quite differently when the load was shifted, pushing downward at a 5-degree angle with respect to the original load. Figure 82 shows the stress distribution corresponding to the inclined loading condition.

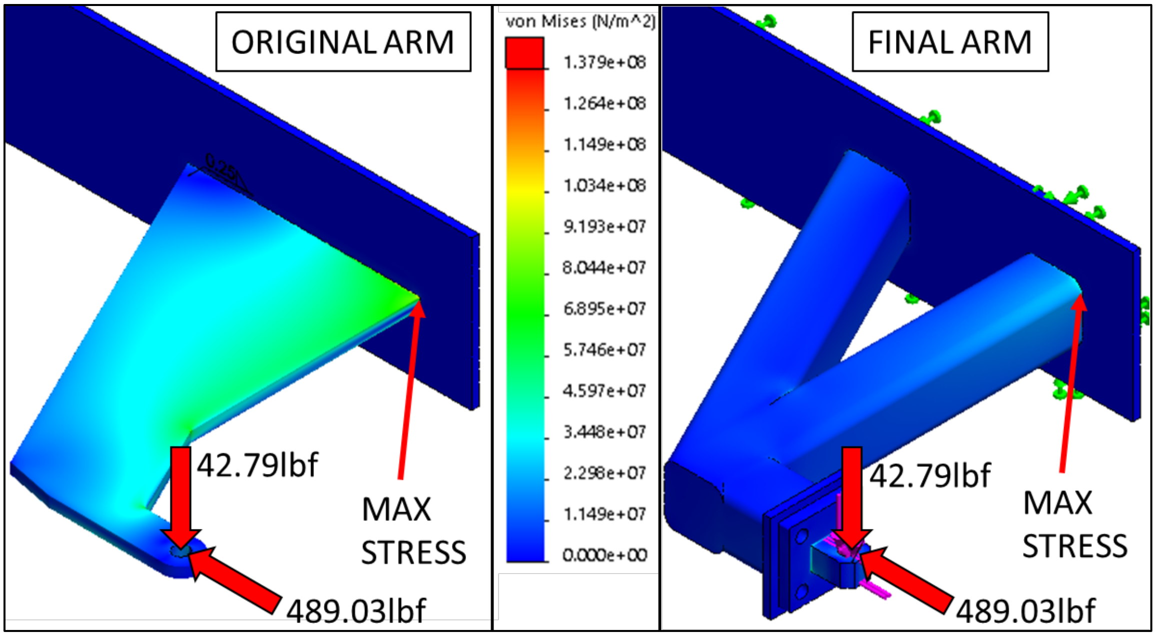


Figure 82: Von Mises stress distribution for original paddle arm (left) and final paddle arm (right) under a 490.9lbf loading at 5 degrees downward from the original direction. Deformation scale is 1 to 1 and peak stress locations identified.

Examination of the original and final arm in the shows that the introduction of a vertical load increased the stress on the top and bottom faces of the arms. The stress was magnified more for the original arm, as anticipated given that the bending stiffness has a cubic relation to the height and is greatly reduced when the material height is reduced. Once again, peak stress occurred at the sharp intersections between components. For the original arm, the peak stress occurred on the top corner of intersection and was found to be 401MPa. The peak stress for the final design was 175.5MPa, once again between the two tubes and on the bottom side this time. The high stress of 175.5MPa on the final arm was localized, much in the same way as the first loading scenario, with much of the final arm below 34MPa. The closeup of each region in Figure 83 next shows the singularity points in question.

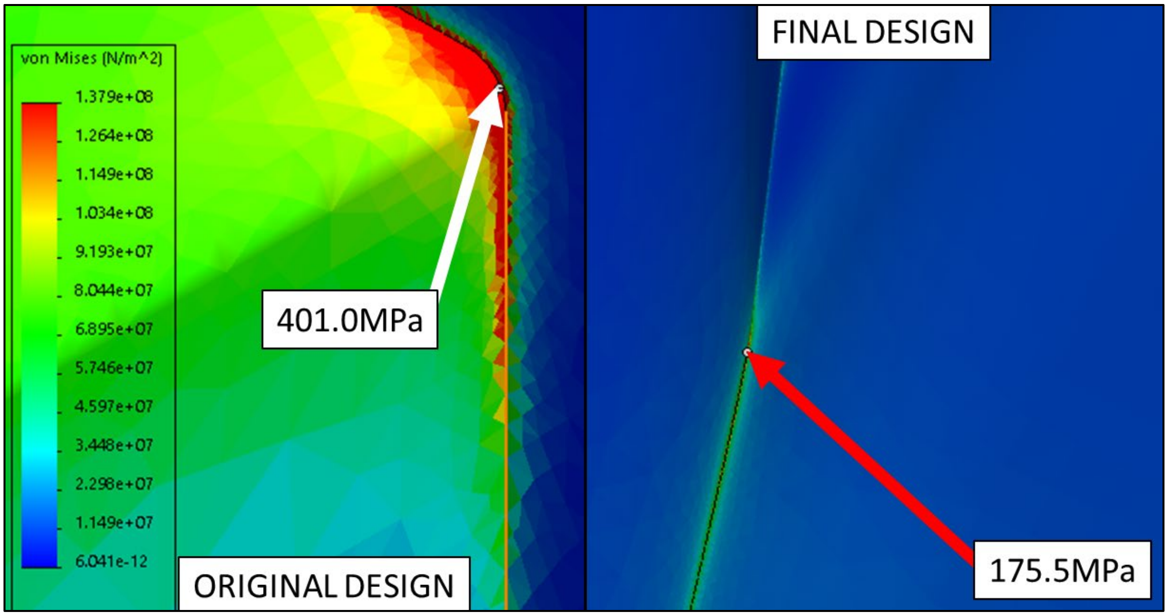


Figure 83: Zoomed in view of peak stress singularity elements on the original paddle arm design (left) and final design (right) under 5 degree downward loading of 490.9lbf

Once again, these singularity points would disappear in the presence of a weld bead. It should be noted however, that the original design had stress upwards of 80 to 100MPa on the top and bottom faces, corresponding to the combined bending loads. Thus, the original design would be sensitive to vertical loading and any increase from the applied vertical load would bring the arm close to yielding. In addition to the high stress, the deflection of the original arm design under the combined load was large compared to the final arm design. The deflection of both designs is shown next in Figure 84.

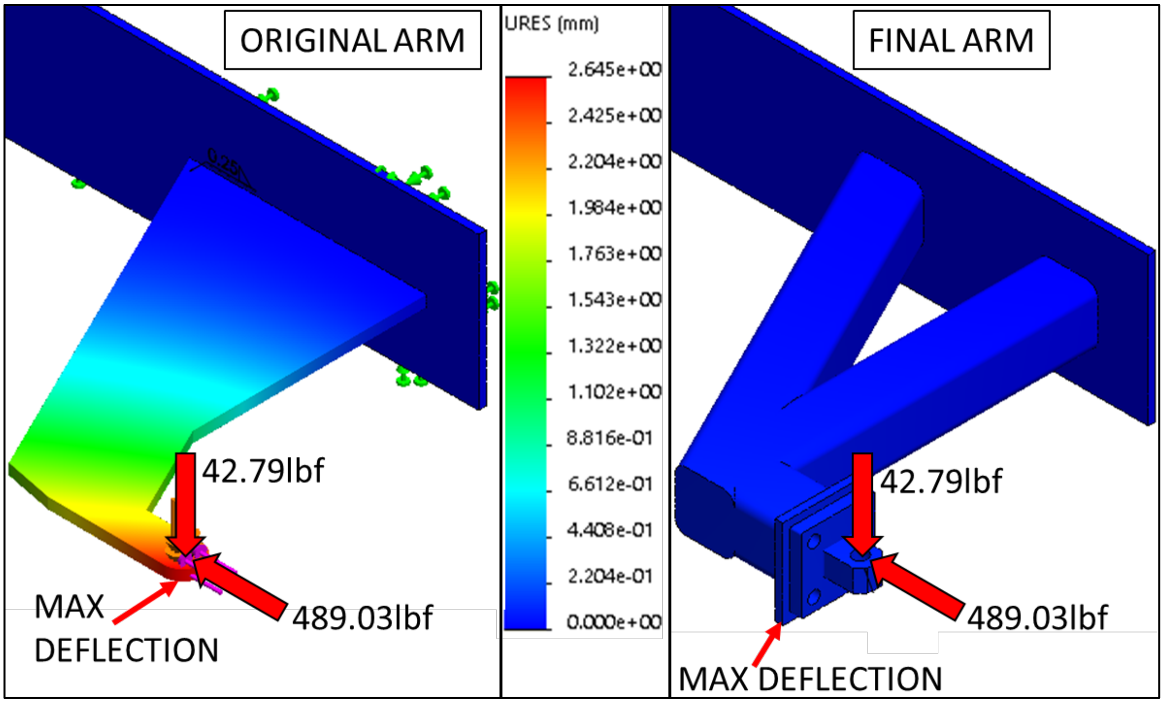


Figure 84: Plot of deflection of the original paddle arm (left) and final arm (right) under 5-degree downward loading of 490.9lbf. Deformation scale is 1 to 1. Max deflection for the orignal arm is 2.645mm and 0.094mm for the final arm.

In Figure 84, the deformation scale for both arms has been set to correspond to the maximum deflection of 2.645mm in the original design. As a result, when the original arm is compared to the final arm design, it is apparent that the final design has much less deflection and is superior in terms of its stiffness with respect to vertical loads. The maximum deflection of the final arm is 0.094mm, which is 3.55% of the original design deflection.

As a result of the comparable performance under the primary load of 490.9lbf and the superior performance under the 5-degree offset load, the final arm design was selected. The final arm design has a weight of 11.12 lbs, which is 4.15lbs heavier than the original design; the heavier final arm is an acceptable trade-off given its better stress and deformation performance.

The second paddle did not require a custom armature to facilitate the required motion, and thus the EB500 eyelet was once again selected from Bimba, corresponding to their repairable stainless-steel line of products. The EB500 eyelet is made from 300 series stainless steel and is shown in detail in Figure 85 next [16].

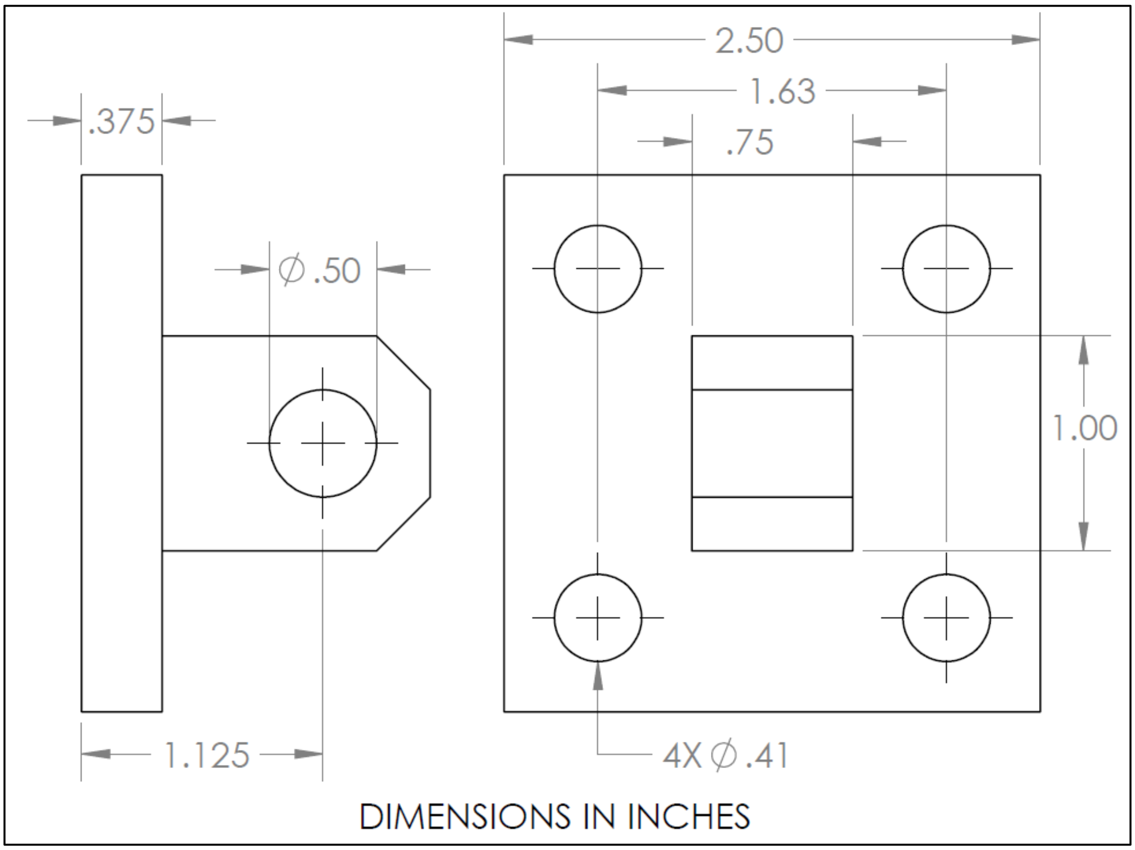


Figure 85: Geometric specifications of the EB500 eyelet

The welded placement of the EB500 on the paddle assembly is shown next in Figure 86.

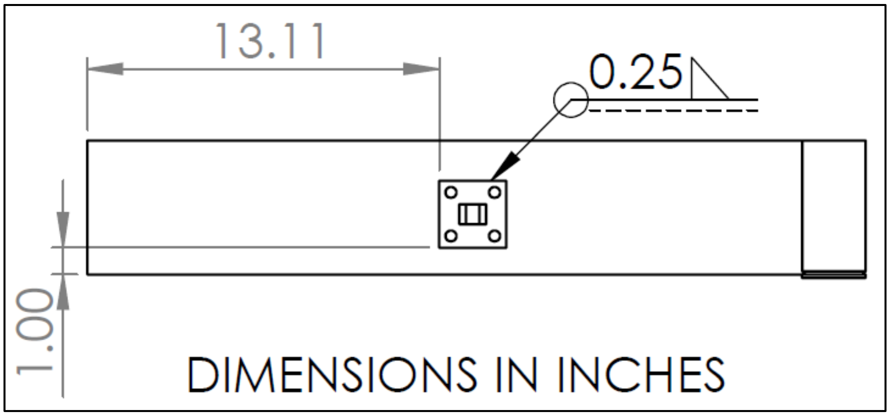


Figure 86: Welded placement of the EB500 on the paddle assembly

The EB500 eyelet does not have a price listed on the Bimba website, and thus the price of the unit was estimated at $40 based on the cost of a similar eye bracket (REF Double-wall pivot bracket MP-17) and the more robust 300 series stainless steel [17].

3.3.6 Design – Cylinder Mounting

In order to rotate the paddles to push the loin it was decided that two pneumatic cylinders would be used. Each of the cylinder would have one end attached to the paddle, and the other end attached to the frame. This section will shows the cylinder mounting orientation, and mounting brackets.

3.3.6.1 Cylinder Orientation

When mounting the cylinders onto the paddles the ideal orientation would be perpendicular to the paddle surface. Due to the inclined conveyor there would be insufficient clearance between the top of the lower conveyor and the cylinder for the loin to pass. This mounting geometry and conflict can be seen in Figure 87.

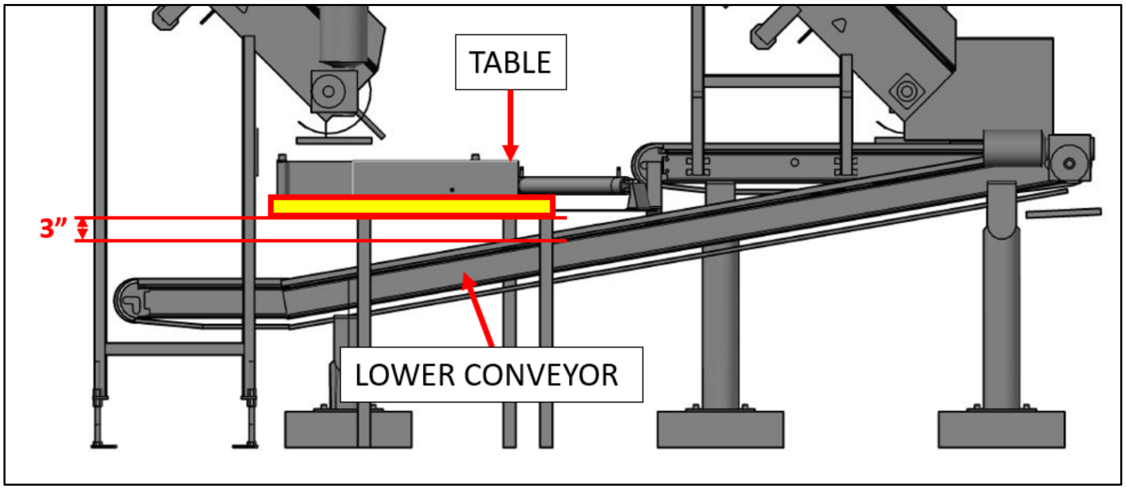


Figure 87: Insufficient space between the lower conveyor and underside of table

Figure 87 shows that with the cylinder perpendicular to the paddle surface would have a maximum of 3” inches between the cylinder mounting point and the conveyor top. Since it was required that there be 12” of clearance between the top of the lower conveyor and any above structure at all times this would not work.

To maintain the required 12” of clearance the cylinders needed to be rotated with mounting locations off to the side. With careful consideration the following cylinder orientation, shown in Figure 88, was selected.

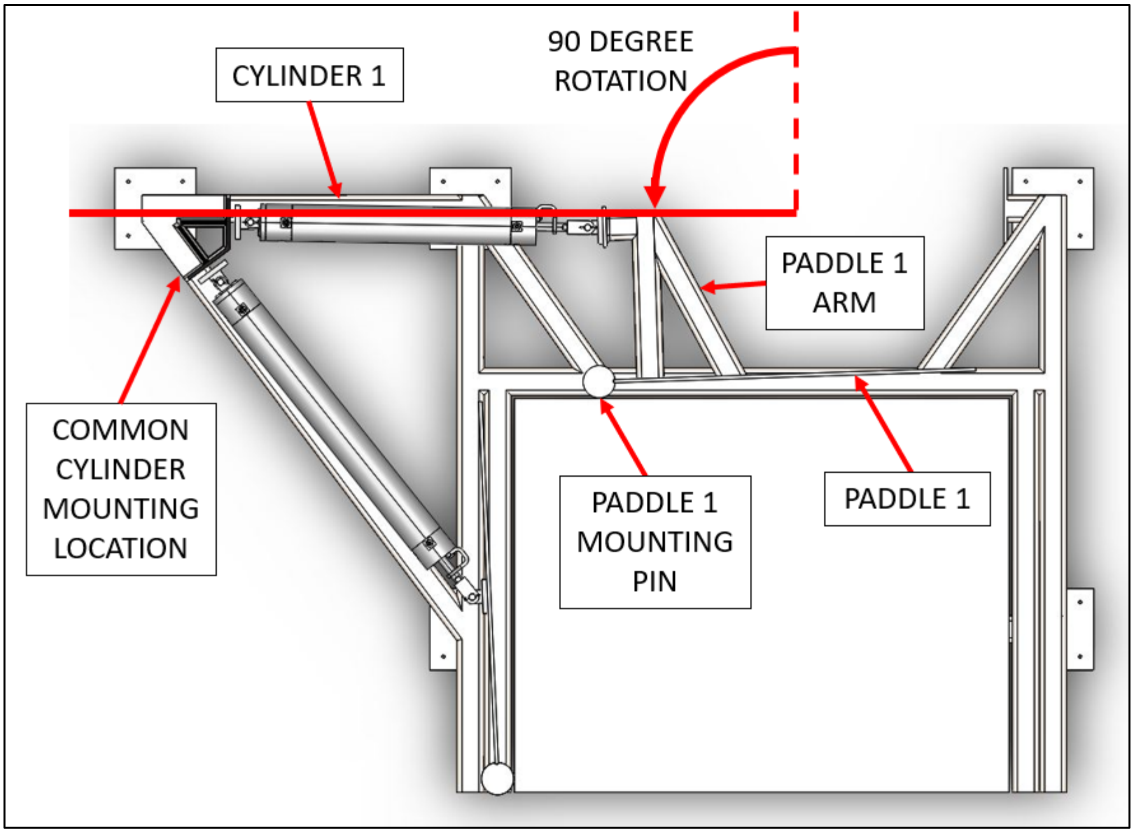


Figure 88: Cylinder reoriented 90 degrees to decrease the overall footprint

Figure 88 shows that the cylinder for paddle 1 was rotated 90 degrees to the side. This position was desirable since both cylinders could then be mounted at one location, decreasing the overall footprint of the design. Due to the orientation of cylinder 1, an arm was designed, as outlined in Section 3.3.5.6, so that the rod end of the cylinder could be connected to the paddle. The arm provided enough clearance for the paddle 1 to rotate 90 degrees without cylinder 1 clashing with the paddle 1 mounting pin. The corner cylinder mounting bracket, the EB500 brackets used to attach the cylinders to the paddles and to the corner cylinder mounting bracket, are discussed next.

3.3.6.2 Cylinder Mounting Brackets

Two different types of bracket were used in the paddle table design. The different mounts are shown in Figure 89.

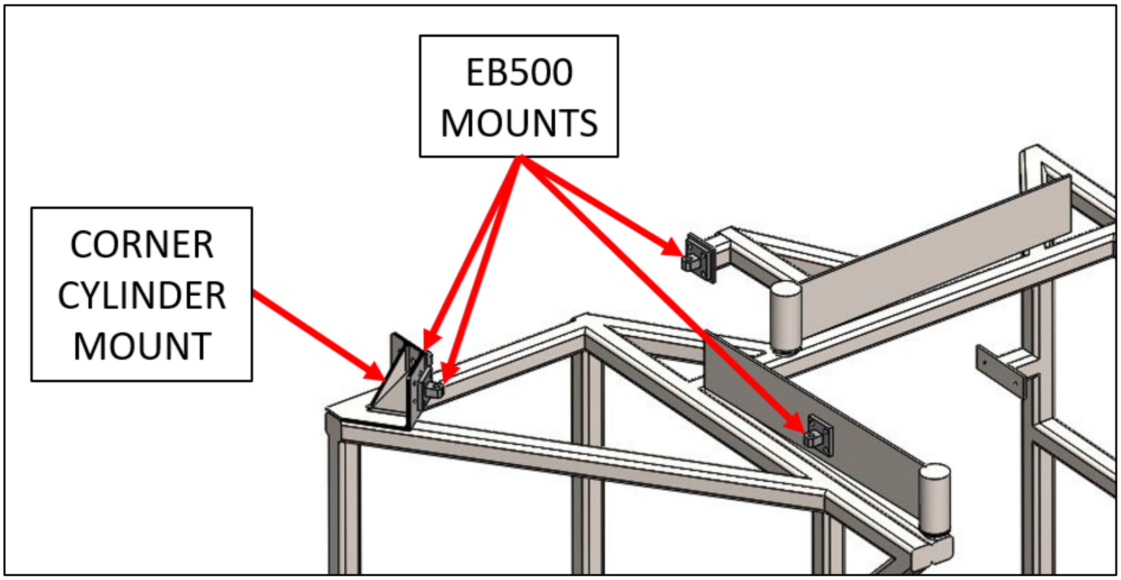


Figure 89: Two types of mounts used on the paddle table identified

The corner cylinder mounting bracket will be fabricated out of 1/4" stainless steel plate due to the intricate geometry, while all other EB500 mounts are selected from a Bimba as discussed next [16].

3.3.6.2.1 Custom Corner Cylinder Mounting Bracket

In order to mount both cylinder at a common location a custom bracket was designed. The bracket was fabricated out of 1/4" 316L stainless steel plate and is shown in Figure 90.

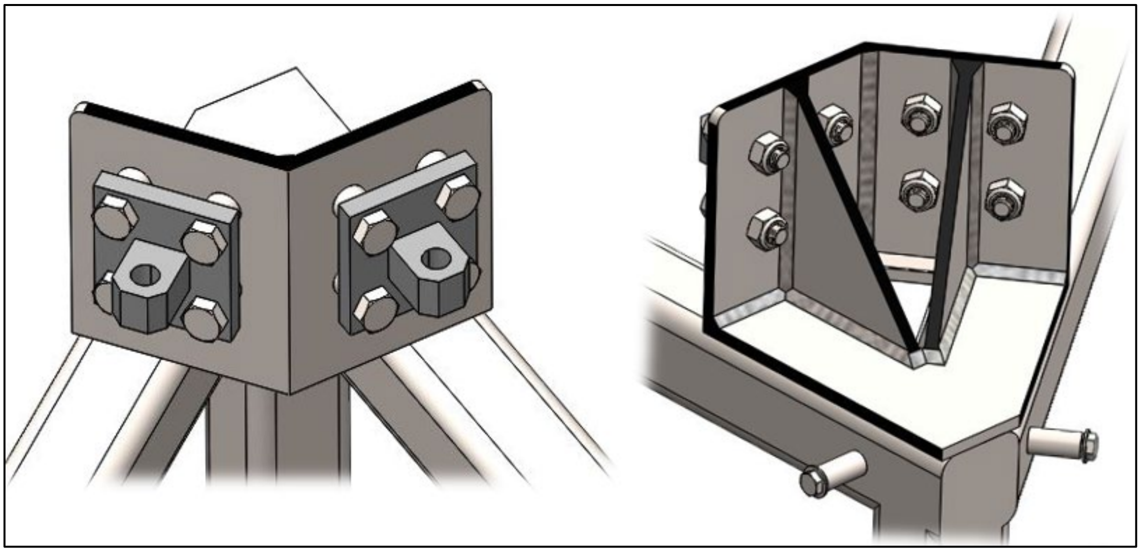


Figure 90: Corner cylinder mount views

The bracket consists of a base plate, two rectangular pieces, and two triangulated pieces. The base plate geometry matches that of the angled square tube support structure to facilitate mounting the bracket to the main support structure. The bracket is to be welded to the support structure around the base plate. It should be noted that a cut-out was included in the base plate so that product would not gather, and so the bracket could be easily cleaned. In addition to the base plate, two rectangular pieces of 316L stainless steel were used so that the cylinders could be attached to the bracket. To increase overall strength and rigidity of the bracket the two rectangular pieces were triangulated back to the base plate.

3.3.6.2.2 EB500 Mounting Bracket

The brackets used to mount the cylinders to the paddles and corner cylinder mounting bracket were the EB500 eyelet bracket from Bimba [16]. The bracket was chosen since it was compact, robust, and mated perfectly with the cylinders which were also specified from Bimba. As mentioned previously the EB500 bracket is made from 300 series stainless steel, so the bracket will be compliant with the various chemicals used during the cleaning process in the final operating environment.

3.3.6.2.3 Mounting Fasteners

The Bimba EB500 brackets are welded onto the paddles/paddle arms, and the custom fabricated corner cylinder mounting bracket is also welded to the main support structure, thus not requiring fasteners. The EB500 brackets used to mount the cap end of the cylinders to the custom fabricated corner cylinder mounting bracket require fasteners for mounting. For the hardware 40 mm long 316 stainless steel M10 standard thread bolts with M10 316 stainless steel nylok nuts are used to attach the EB500 bracket to the corner bracket. Due to the operating food safe environment M10 10mm long stainless steel standoffs are used to create a gap between surfaces to aid in cleaning, and to avoid any buildup occurring [16].

3.3.6.3 Cylinder Costs & Specifications

The two selected pneumatic cylinders are from Bimba's USDA 3-A approved "Repairable Stainless Steel" line of products [18]. This line of pneumatic cylinders is ideal for a meat processing facility due to the food safe washdown rating, sensing capability, and serviceable design. Both cylinders feature magnetic reed switches, the same general specifications, and similar prices. The main difference between the two cylinders is their respective stroke length. The specifications and price of each cylinder are summarized in TABLE XII.

TABLE XII: TECHNICAL SPECIFICATIONS AND PRICING OF SELECTED CYLINDERS [18]

Part Number	RS-MP2-2.50x14-MPR-P-SSP-U-XX	RS-MP2-2.50x19-MPR-P-SSP-U-XX
Bore Diameter (in)	2.5	2.5
Stroke (in)	14	19
Rod Diameter (in)	5/8	5/8
Mounting Style	MP2 Rear Clevis	MP2 Rear Clevis
Cushions	None	None
Magnetic Piston	MPR	MPR
Bumper	None	None
Rod End Style	KK1	KK1
USDA 3-A Approved	Yes	Yes
Extended rod/thread	No	No
Seal & Lubrication	Standard food grade	Standard food grade
Low Friction Seals	No	No
Piston Material	Stainless steel with wearband	Stainless steel with wearband
Air Port	3/8 NPT	3/8 NPT
Proximity Switch	P (sourcing output)	P (sourcing output)
Rod Wiper Material	Standard	Standard
Body materials	316-SS, 303-SS, PTFE, Acetal, urethane, nitrile	316-SS, 303-SS, PTFE, Acetal, urethane, nitrile
Price (CAD)	1616.20	1711.70

Each cylinder requires a threaded clevis mount on the piston rod end and a clevis pin for the front and rear clevis. The required parts come from Bimba once again, with the part numbers, quantity, and price for each summarized in TABLE XIII.

TABLE XIII: QUANTITY AND PRICE OF SELECTED CLEVIS AND PIN [18]

Item / Part Number	Quantity	Price per item
Clevis / SS-RC437 (BIMBA)	2	58.25
Pin / SS-CP500 (BIMBA)	4	16.70

Figure 91 shows the 14" pneumatic cylinder, complete with the clevis mounts and pins.

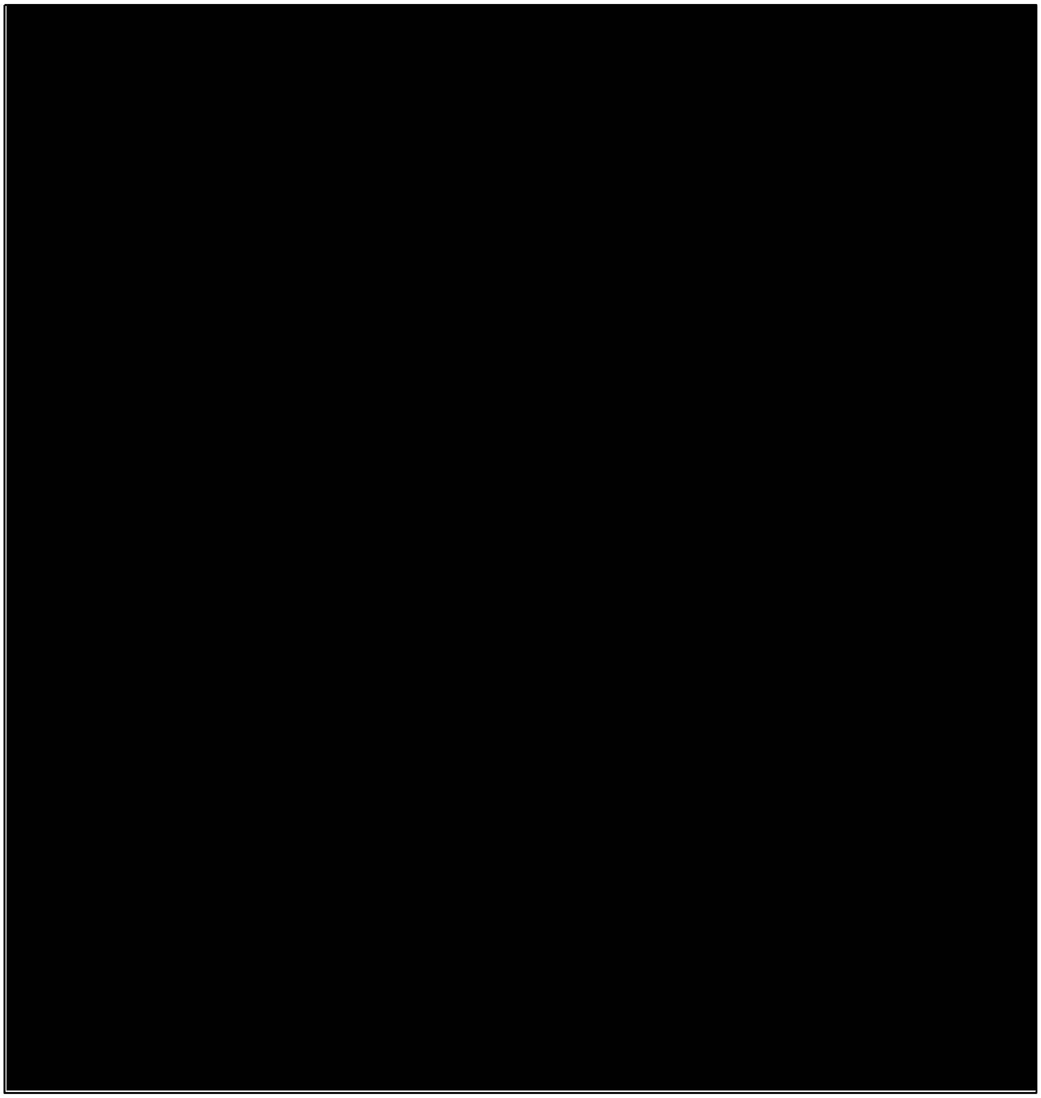


Figure 91: Geometric specifications of pneumatic cylinder, clevis mounts and pins assembly [18]

Given the modular nature of the Bimba cylinder designs, the 19” version of the cylinder is quite similar. The technical drawing for the 19” cylinder is shown in next in Figure 92.

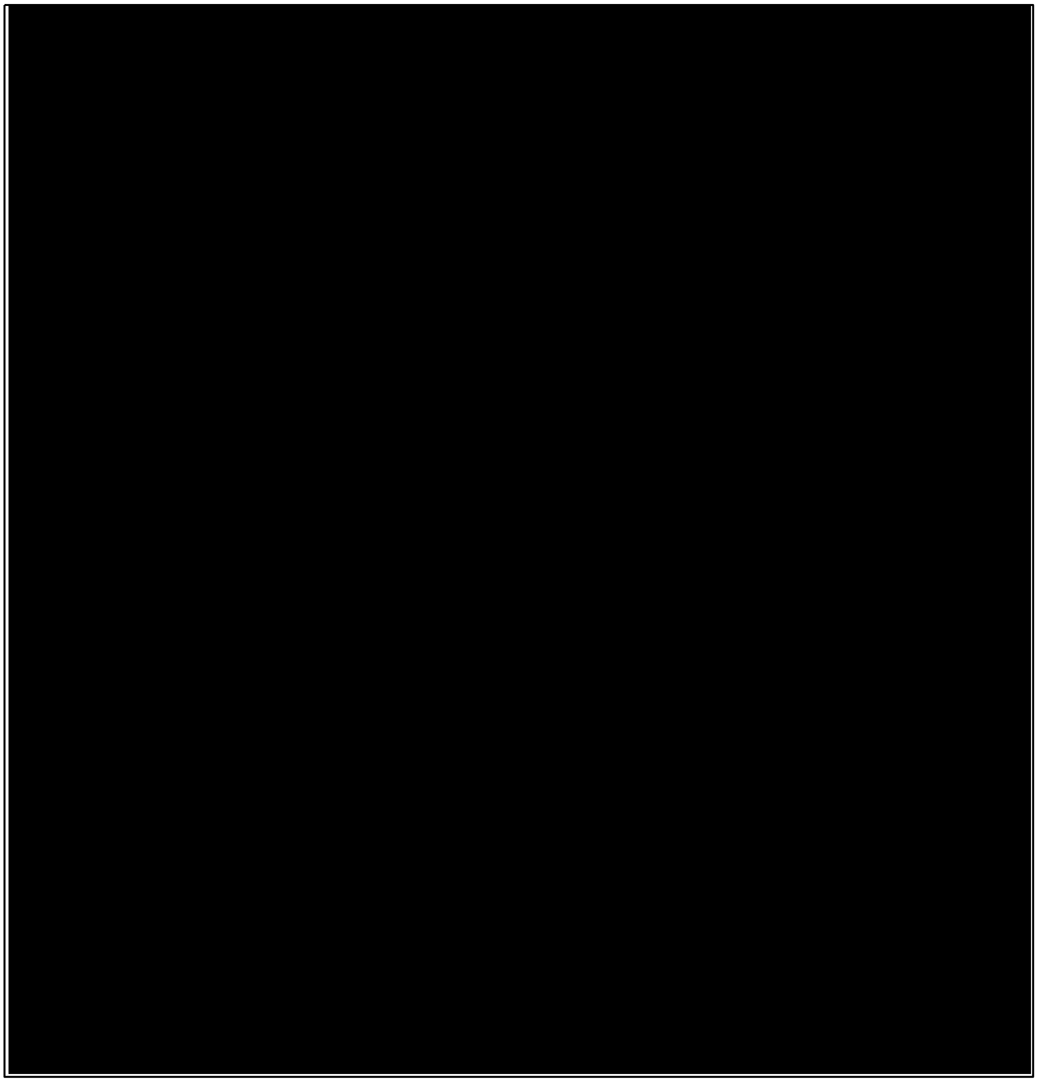


Figure 92: Technical drawing for the 19" cylinder [18]

Since there are many brands and types of solenoid air valves, fittings, and tubing, their selection has been left for future work. Ultimately, their selection is best performed by HyLife in order to maintain consistency across the plant floor. The required sensors are discussed later in Section 3.3.7.

3.3.7 Design – Sensors

To facilitate the final paddle table design, various sensors and pneumatic control are required. As with any industrial automation application, the sensors serve various purposes in the operation of the system at large, particularly:

- Loin detection to trigger the orientation cycle with paddles 1 and 2
- Closed loop monitoring and control for pneumatic cylinders
- System failure or jamming detection

The following sections outline the various sensors used, their installation, cost, wiring, and system logic, along with the pneumatic control methodology. It should be noted that the final design does not have an automatic bypass; any system failure or jamming will cause the paddles to cease operation and notify the operator to clear the system, as opposed to automatically clearing the jam or running in bypass mode. The datasheets for the various sensors are provided for the reader in the Appendix D and the following TABLE XIV shows the assignment of the digital inputs and outputs referenced in the rest of the section.

TABLE XIV: Assignment of digital inputs and outputs

Digital Input (InXX) / Digital Output (OutXX)	Name	Function
In01	Infrared sensor (Allen Bradley)	Loin detection
In02	Reed switch 1	Paddle 1 home position
In03	Reed switch 2	Paddle 1 extended position
In04	Reed switch 3	Paddle 2 home position
In05	Reed switch 4	Paddle 2 extended position
Out01	Solenoid circuit 1-A	Paddle 1 retraction
Out02	Solenoid circuit 1-B	Paddle 1 extension
Out03	Solenoid circuit 2-A	Paddle 2 retraction
Out04	Solenoid circuit 2-B	Paddle 2 extension
Out05	Jamming alarm	Jam detection alarm

3.3.7.1 Integrated Cylinder Sensors

The final design uses two pneumatic cylinders from Bimba. The cylinders, as described earlier, are from the Repairable Stainless Steel (RS) series with magnetic pistons. As such, they use Bimba's normally open RSU-1-Q reed sensors which simply thread into the side of the cylinder body [19]. A reed sensor acts as a magnetic switch where, when in close proximity to the magnetic piston, it relays positive source voltage to the PLC digital input. This is shown schematically in Figure 93 below for the retracted position of the pneumatic cylinder.

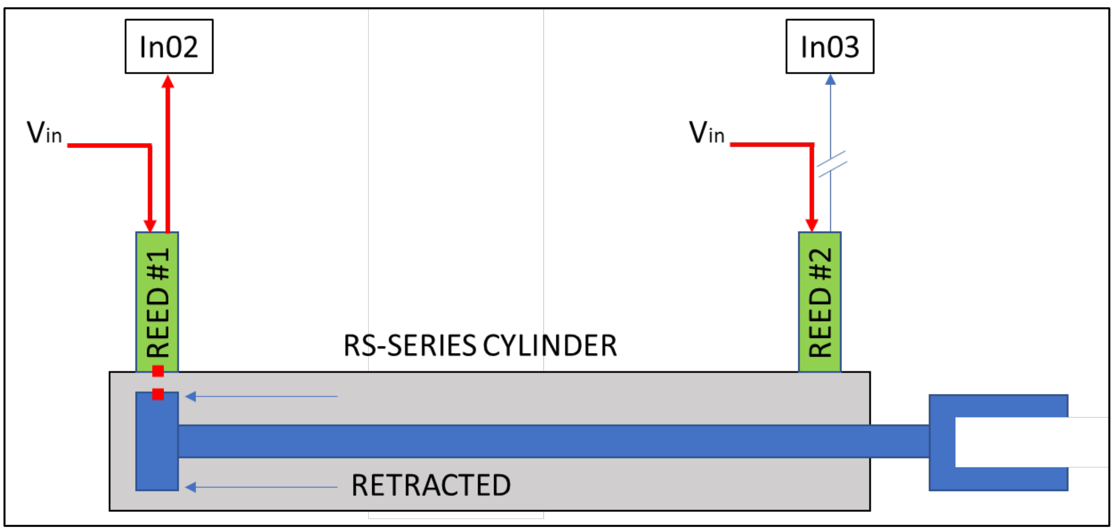


Figure 93: Retracted position of the pneumatic cylinder

From Figure 93 it is seen that the retracted position of the magnetic piston relays the positive source voltage, Vin, to digital input 2 of the PLC. For the PLC, the active state of digital input 2 would correspond to the retracted position in the ladder logic. Similarly, the extended position of the pneumatic cylinder is shown next in Figure 94.

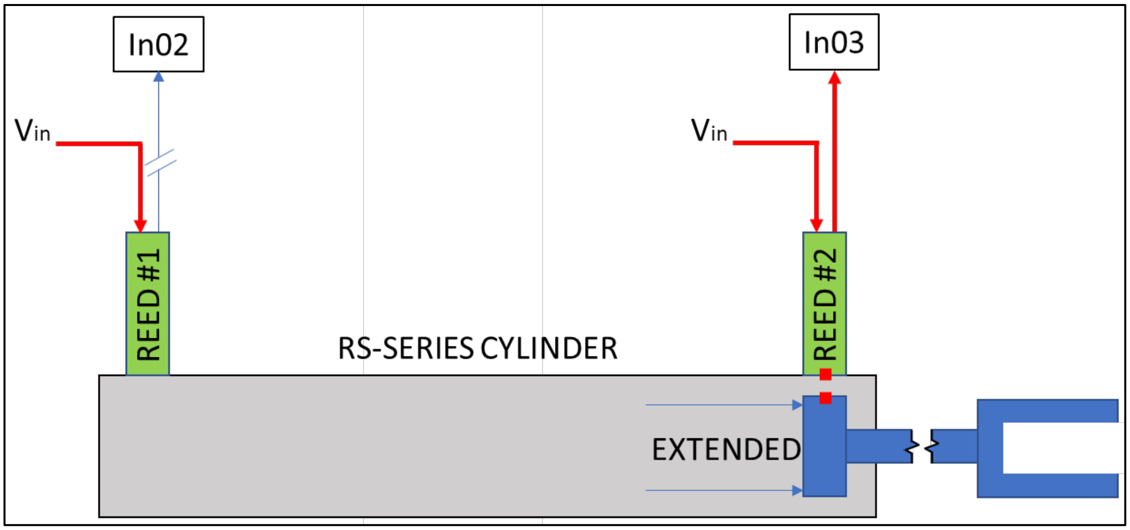


Figure 94: Extended position of the pneumatic cylinder

Figure 94 once again shows the relaying of the source voltage, in this instance from reed switch #2 to digital input #3 of the PLC, corresponding to the extended position of the pneumatic cylinder.

The cost per RSU-1-Q sensor is standard for industrial sensors at $52.05 (USD) per sensor [20]. The overall pinball paddles design requires a total of 4 sensors, corresponding to the two Bimba cylinders used. The RSU-1-Q sensors have an M8 male connector, which are paired with a corresponding female 5-meter shielded cable, C5X-S, for an addition of $52.97 (USD) per cable. The C5X-S cable is an excellent choice for the application of the paddle cylinders, as they have a right-angle connection that facilitates low-profile cable management [20].

3.3.7.2 Pneumatic Control

The use of the two Bimba pneumatic cylinders required some additional components. Particularly, to use the two cylinders, the following are items are required:

- Flexible air tubing

- Fittings
- (2x) 5/3 solenoid valves

The specification of tubing, fittings, and solenoids are left for future work or selection by HyLife, as they are once again components that are on the shelf in their inventory, and the team would like to ensure that standard items are used.

In the previous TABLE XIV, solenoid circuits 1-A, 1-B, 2-A, and 2-B were listed. These are the various pneumatic circuits to control the extension and retraction of the two pneumatic cylinders. To facilitate the two circuits per cylinder, a single 5/3 solenoid valve is required. Thus, two of the valves are required for the two cylinders. A schematic of the 1-A (retracted) circuit is shown for the first cylinder in Figure 95 next.

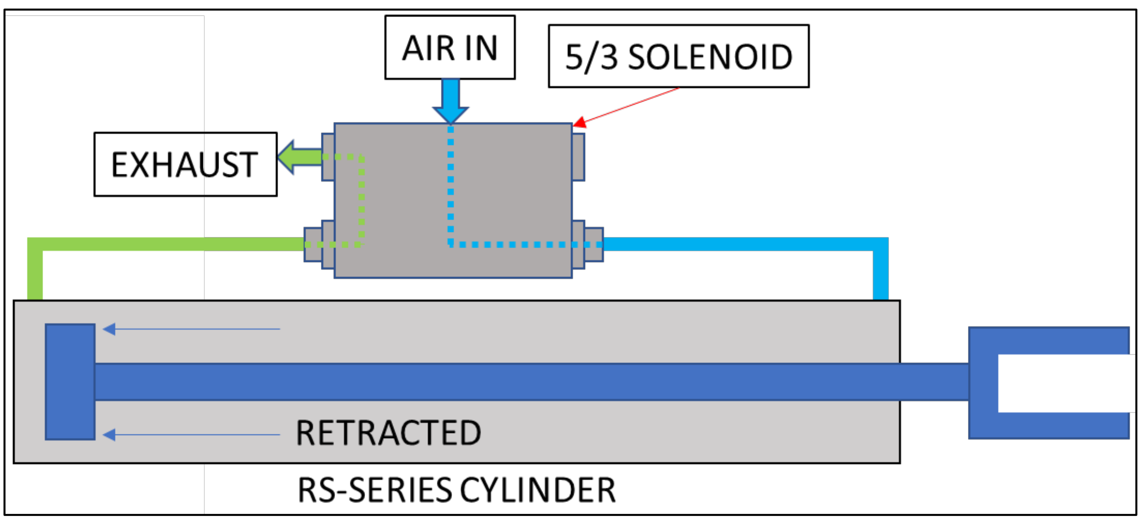


Figure 95: Schematic of the 1-A (retracted) circuit shown for the cylinder 1

Similarly, a schematic of the 1-B (extended) circuit is shown for the first cylinder in Figure 96.

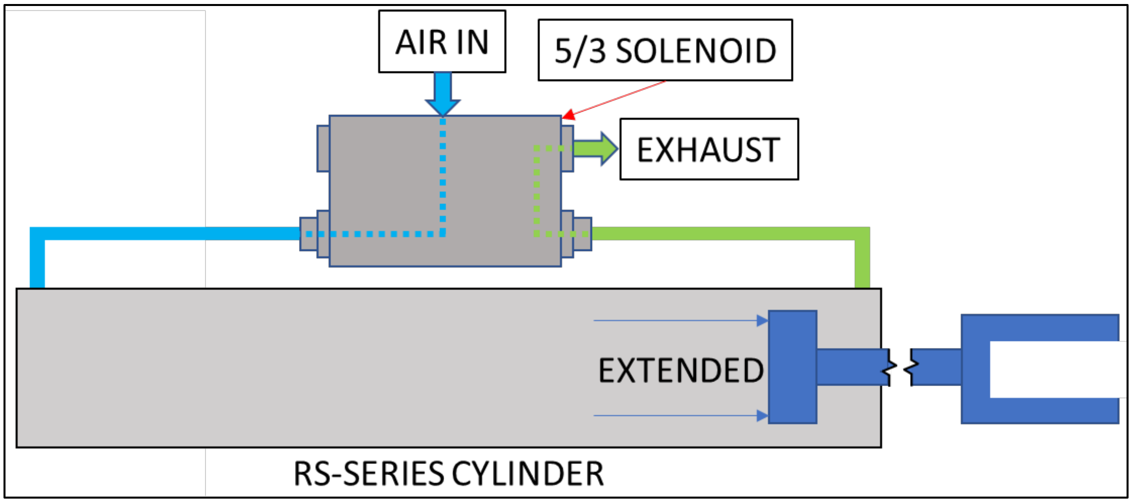


Figure 96: Schematic of the 1-B (extended) circuit shown for the cylinder 1

The schematic for the 2-A and 2-B circuits are the same as the previously shown 1-A and 1-B circuits, thus are not shown here.

3.3.7.3 Proximity Sensor

A method of detecting the arrival of a loin on the paddle table is critical to the success of the paddle table design. There are many sensors that can be used for proximity detection; however, the restriction of contact-less sensors reduces the available methods to optical and ultrasonic. HyLife has traditionally used infrared sensors from Allen Bradley throughout their facility, making them a proven and accepted piece of hardware for the paddle table design. The selected sensor for the detection of the loin falling onto the table is the 42CST-D1MPA3-D4 from Allen Bradley, standard to HyLife's facility [21]. An existing installation of the 42CST-D1MPA3-D4 at the HyLife facility is shown next in Figure 97.

Figure 97: Existing installation of the 42CST-D1MPA3-D4 at the HyLife facility [1]

The sensor features a threaded barrel for mounting through a hole in a steel plate. The major diameter of the thread is 18mm, and both nuts for mounting are included with the sensor [21]. The rear mounted cable is not specified in the manufacturer documentation, and assumed to be supplied by HyLife from their standard inventory.

The 42CST-D1MPA3-D4 is constructed from stainless steel, operates on standard 10-30VDC, and has a sensing range of up to 800mm. It is also ideal for this application due to the simple ferromagnetic teach mode; to train the sensor when an object is actually in sight, a magnet is simply placed on the outer housing of the sensor to trigger the sensor teach mode [22]. Further, the sensor is IP69K, Ecolab and Johnson Diversity rated, making it ideal for food processing facilities. The estimated cost of a 42CST-D1MPA3-D4 sensor is $160 (CAD) based on pricing from Gerrie [22]. Further details regarding the teach mode and specifications of the sensor are provided for the reader in the Appendix D.

The Allen Bradley sensor will be configured in the standard PNP transistor or "sourcing" configuration, like the normally open reed switches in the previous section. This translates to the "switch" of the sensor having supplied and relaying voltage to the digital input of the PLC when a loin is placed in front of the sensing path. The sensor is shown in its idle state, where no output is sent to the PLC in Figure 98.

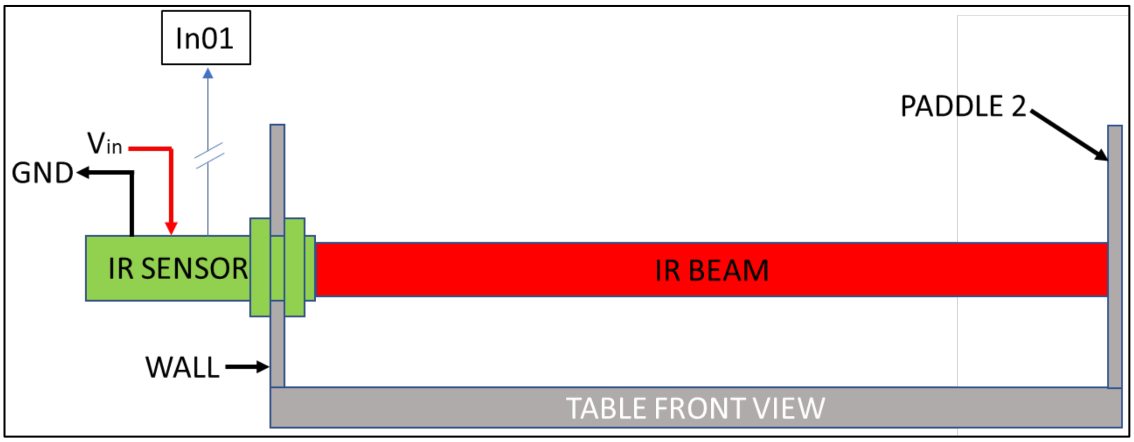


Figure 98: Allen-Bradley IR sensor in idle state

Figure 98 shows that when no loin is in the infrared beam from the sensor, the output to the PLC is in a digital low state. That is, with no loin in the path of the beam, there is no voltage sent to the digital input of the PLC. Figure 99 shows the opposite situation, with a loin in the beam path.

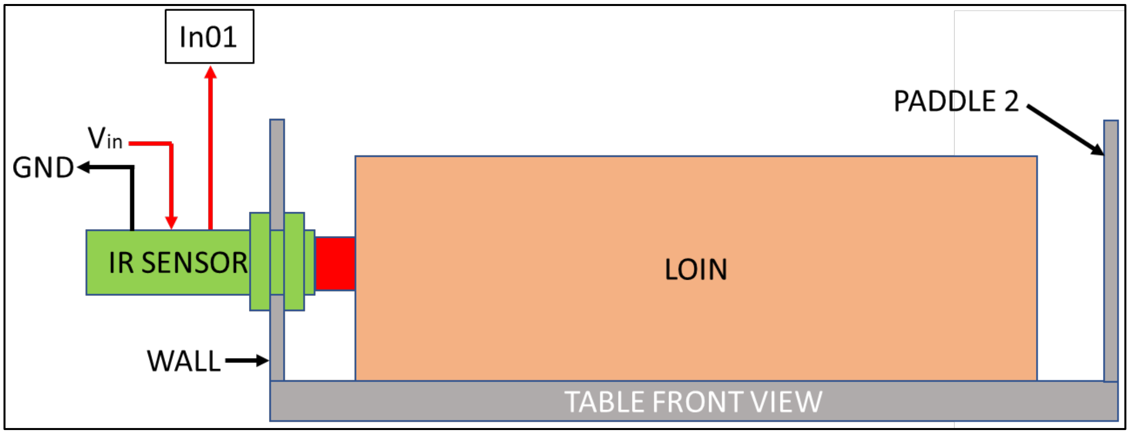


Figure 99: Loin in the IR sensor beam path

With the loin now intercepting the beam path as in Figure 99, the sensor sends a voltage to the digital input of the PLC. The PLC programming recognizes this high digital state as a loin on the table, triggering the sequence of paddle 1 and paddle 2 moving the loin.

3.3.7.4 Flow Chart

Full automation of the final design required the selection of various sensors and consideration for solenoid valves to manipulate the air cylinders. Fundamentally, there are 3 key steps in the actual process:

1. Loin detection
2. Cycling paddle 1 forward and back
3. Cycling paddle 2 forward and back

At first glance, these 3 steps seem straightforward. However, to facilitate the 3 steps in a safe and effective manner, more rigour is necessary to ensure jamming is prevented. It was discussed previously that there is an infrared sensor for loin detection, along with two reed switches on each of the two paddles. These are combined with a PLC and the control of solenoid valves to coordinate the movement of the various components, initiate paddle cycles, and detect jams as they arise. Figure 100 shows the general logic of these in the system.

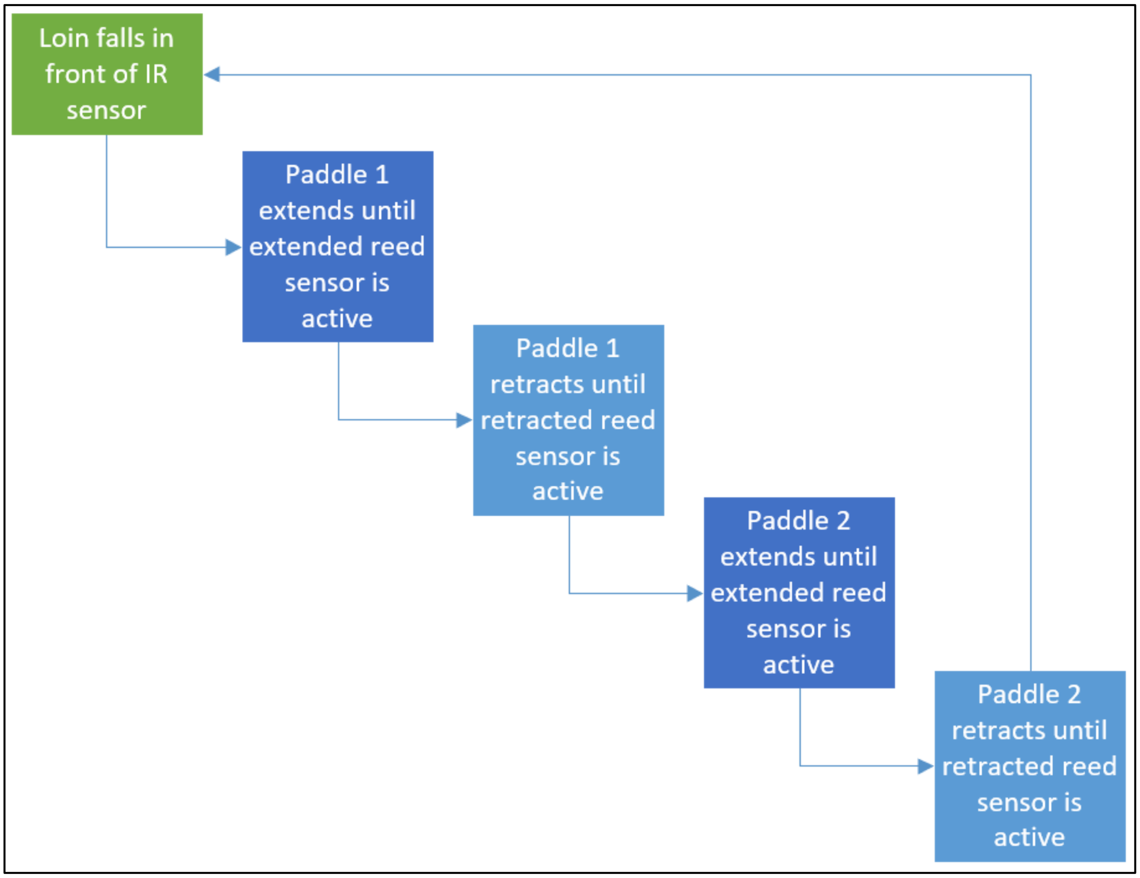


Figure 100: General overview of PLC logic

While the process in Figure 100 is slightly more complicated than the 3 initial steps discussed, it still does not account for the intricacies of the actual final design. As an example, it is unknown how prone the system is to jamming once physically built, but it is known that the final system has a manual bypass method and that the average cycle time is 6 seconds. Thus, if a loin enters the system, triggering a cycle, a 6 second counter is initiated to ensure that the components move to where they need to be within an acceptable time frame. If an arm takes too long to reach an end point (i.e. a loin jam has likely occurred), the timer will expire, the system will abandon the operation by retracting to the home position, and the operator will be notified than an issue has arisen. This is shown in a more formal flowchart next in Figure 101.

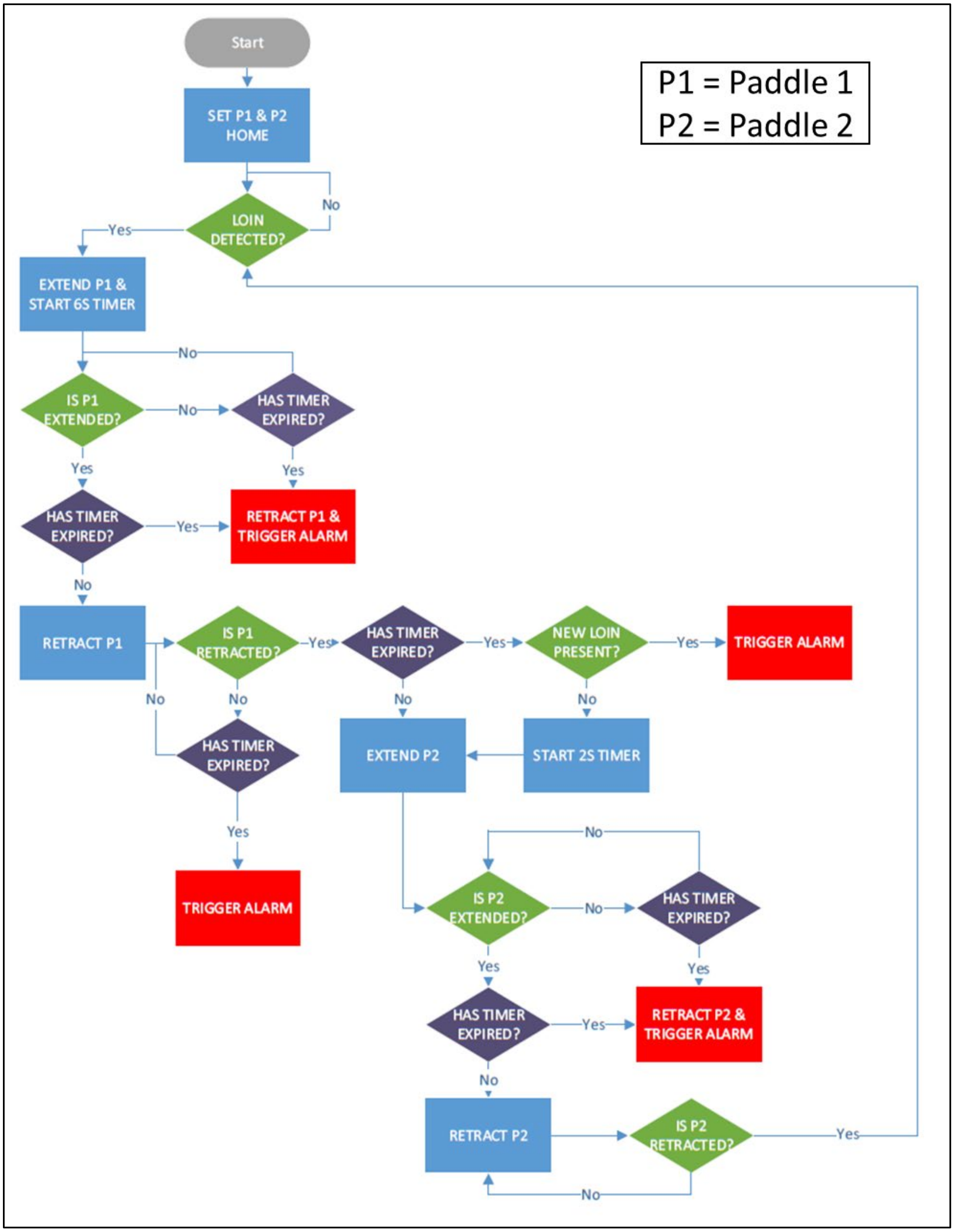


Figure 101: Detailed PLC logic flowchart

The proposed PLC logic has a great deal of loops for timer expiration. Since it is unknown how well the system will perform in general, and particularly how well the infrared sensor can detect new loins, the rigid logic previously shown in Figure 101 has been presented. If the infrared sensor can accurately differentiate between a loin and a paddle, a timer reset or override could be introduced into the flowchart to allow the system to continue to run until an actual loin jam occurs. However, this cannot be accurately quantified until the system is actually installed and thus is not presented here.

3.3.8 Design – Loin Detection Sensor Mounting

For the IR sensor to be securely mounted and accurately detect the presence of a loin, a mounting bracket was created. The mounting bracket also serves as a barrier to stop loins from falling off the side of the table. The bracket is made of 1/4" thick 316L stainless steel plate, and measures 30”x8”. The bracket is shown in Figure 102.

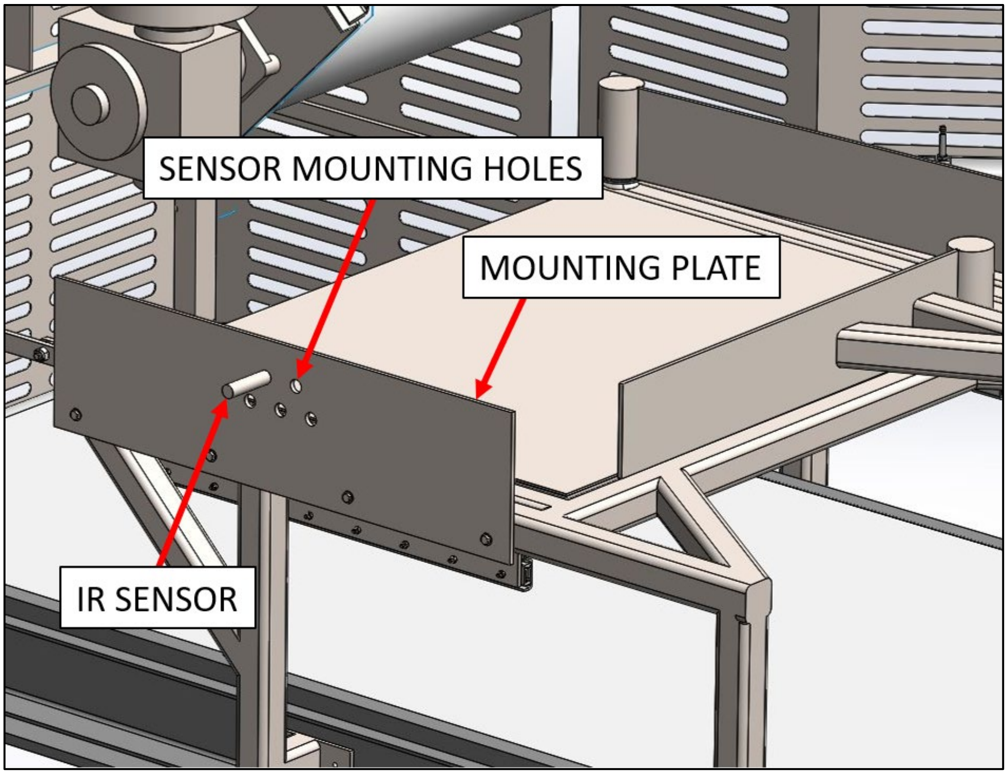


Figure 102: Loin detection sensor mounting plate

Figure 102 shows that the sensor mounting plate is mounted to the main support structure at 4 locations using 1" threaded standoffs. It can also be seen that the mounting plate has 5 different sensor mounting holes. The different sensor mounting holes can be used to reposition the sensor in order to find the optimal mounting location for loin detection. The sensor mounts onto the mounting bracket using an 18mm diameter threaded barrel and a nut on each side of the plate.

3.4 Code and Material Compliance

When designing for the pork processing plant there are strict codes and standards that govern how items are designed and implemented. For this project it was important to ensure that the design was code compliant, and that the selected materials were compliant with the cleaning products used in the facility. This section aims to inform the reader about the actions that were taken to ensure the design was both code compliant and material compliant in all respects.

3.4.1 Code Compliance

For the design to be implemented into the pork processing facility the codes and standards that were outlined in Section 1.9 needed to be met. To ensure code compliance the following steps were taken:

- All surfaces are smooth, free from imperfections, and easily cleaned.
- All areas are easily accessible for inspection, maintenance, and cleaning.
- All surfaces are designed to avoid product and liquid collection.
- All materials used are compliant with codes and standards, such as 304SS and 316SS.
- All hollow areas are hermetically sealed.
- All items can be disassembled for cleaning and inspection using no tools or limited hand tools that are commonly available to maintenance workers.
- All nonremovable items are designed so that there is enough space to clean around equipment.
- All nonremovable items use standoffs to avoid product buildup and to aid in cleaning.
- All items have a minimum of 18" clearance from the floor to allow for proper cleaning.

With all items listed above the design was deemed to be code compliant.

3.4.2 Material Compliance

At the pork processing plant different cleaning products used during the cleaning process. When designing the paddle table, it was important to gather information about each chemical from the corresponding data sheets. The chemical data sheets can be found in Appendix D. With the information about each chemical known, compliant materials could be properly selected. The cleaning products and their associated non-compliant materials from the data sheets are shown in TABLE XV:

TABLE XV: MATERIAL COMPLIANCE [23]

Chemical Name	Chemical Use	Not Compliant With
ECOLAB - BONCHEM BON FOME	Cleaning product	Acids, Metals
ECOLAB - FOAM FORCE LP	Cleaning product	Acids, Metals, Organic materials
ECOLAB - VOTREXX	Sanitizer - Food contact surface	Bases, Metals, Organic materials
ECOLAB - Soil-Off II	Cleaning product	Acids
ECOLAB - XY-12	Sanitizer	Acids, Metals
ECOLAB - WHISPER 400	Sanitizer - Food contact surface	None

After looking at the materials used in the plant, and discussing material selection with the client, the materials were selected. The design used 303 (in limited non food-contact circumstances), 304, 316, and 316L stainless steel, UHMW plastic, nitrile, Teflon, and Delrin 500CL. The only use of the 303 stainless steel was for the EB500 mounting bracket from Bimba. 303 stainless steel is not recommended for use in a food processing facility, as per the *FS119 Sanitary Design and Consumption of Food Equipment* document [3], but the bracket could be machined from 316L stainless steel if so desired.

3.5 Safety Guards

To ensure safe operation of the paddle table it was important to design the safety guards so that the workers could not come into contact with moving components. The safety guards were made of 16-gauge 316L stainless steel and mounted directly to the existing equipment supports. To ensure code compliance was achieved 1/2" standoffs made of 316L stainless steel were used at all safety guard mounting locations. The safety guards were modelled, and can be seen in Figure 103:

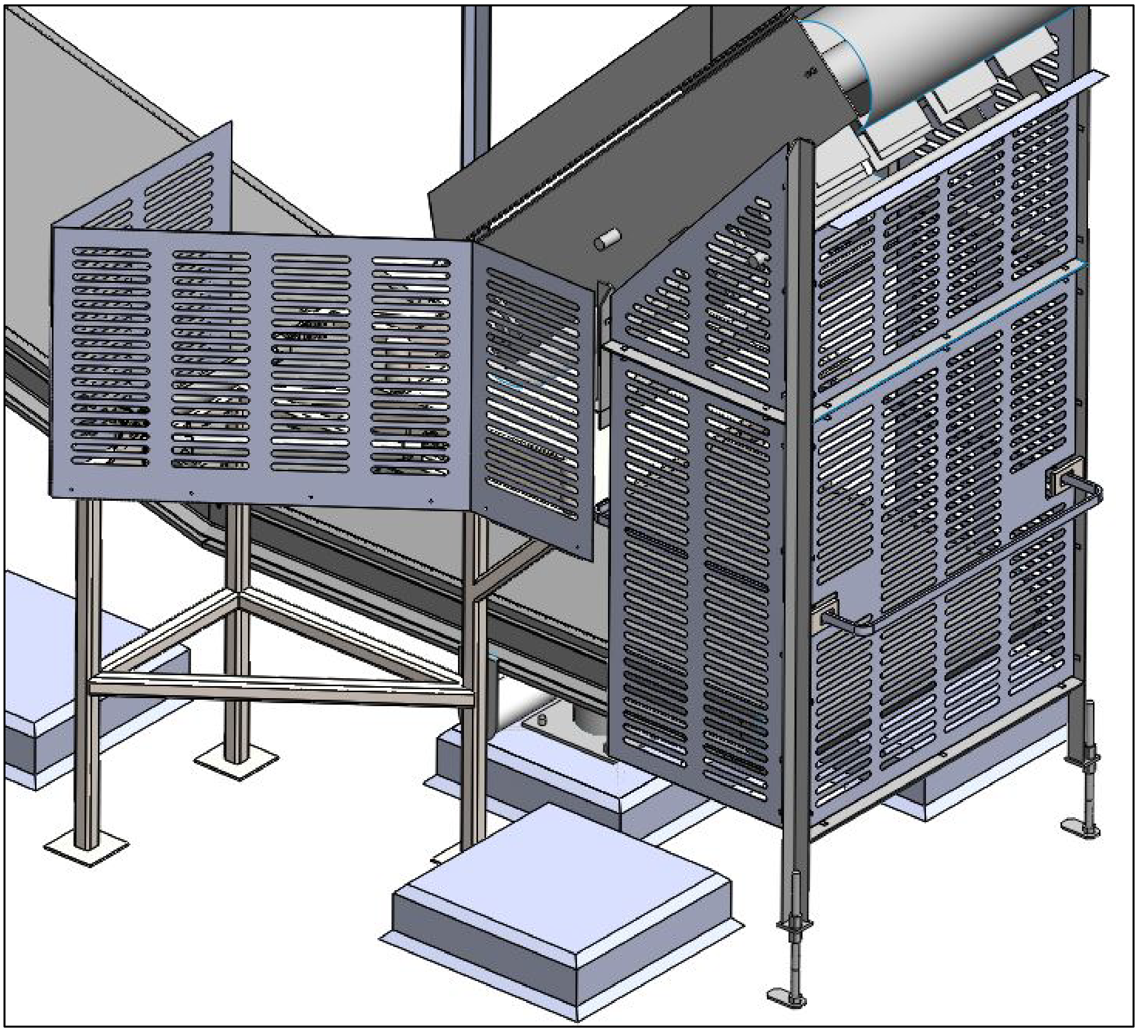


Figure 103: Safety guards

Figure 103 shows that rectangular cut-outs were implemented into the safety guards to allow the HyLife personnel to monitor the area and to decrease the surface area for cleaning. The dimensions of the safety guards can be found in Appendix E.

4 Final Design

After the development phase, the final design consisted of a large assembly that incorporated many components. An overall summary of the final design is provided in this section. First, a functional description of each component and the system as a whole is included. Next, an overview of the final design's compliance with the required project metrics is provided. Analysis of the risks associated with the final design is also included for the client's consideration. Next, a bill of materials is included to provide a comprehensive list of the required parts for implementation of the system. Cost analysis of material procurement and machining is also included. Lastly, technical drawings of the entire assembly and of certain components are included to show critical geometric specifications.

4.1 Design Summary

This section of the report will first outline what is included in the final design, and then discuss how the system operates and is integrated into the existing loin line.

4.1.1 Final Design – Overview and Process Integration

The final paddle table design can be broken down into four main areas consisting of the decline conveyor, lower conveyor, paddle table and bypass feature, and the safety guards. This section will overview what is included in each of the four main areas, including the components used, and a discussion on how the design integrates into the existing process. The main components of the final design are shown in a front isometric render in Figure 104.

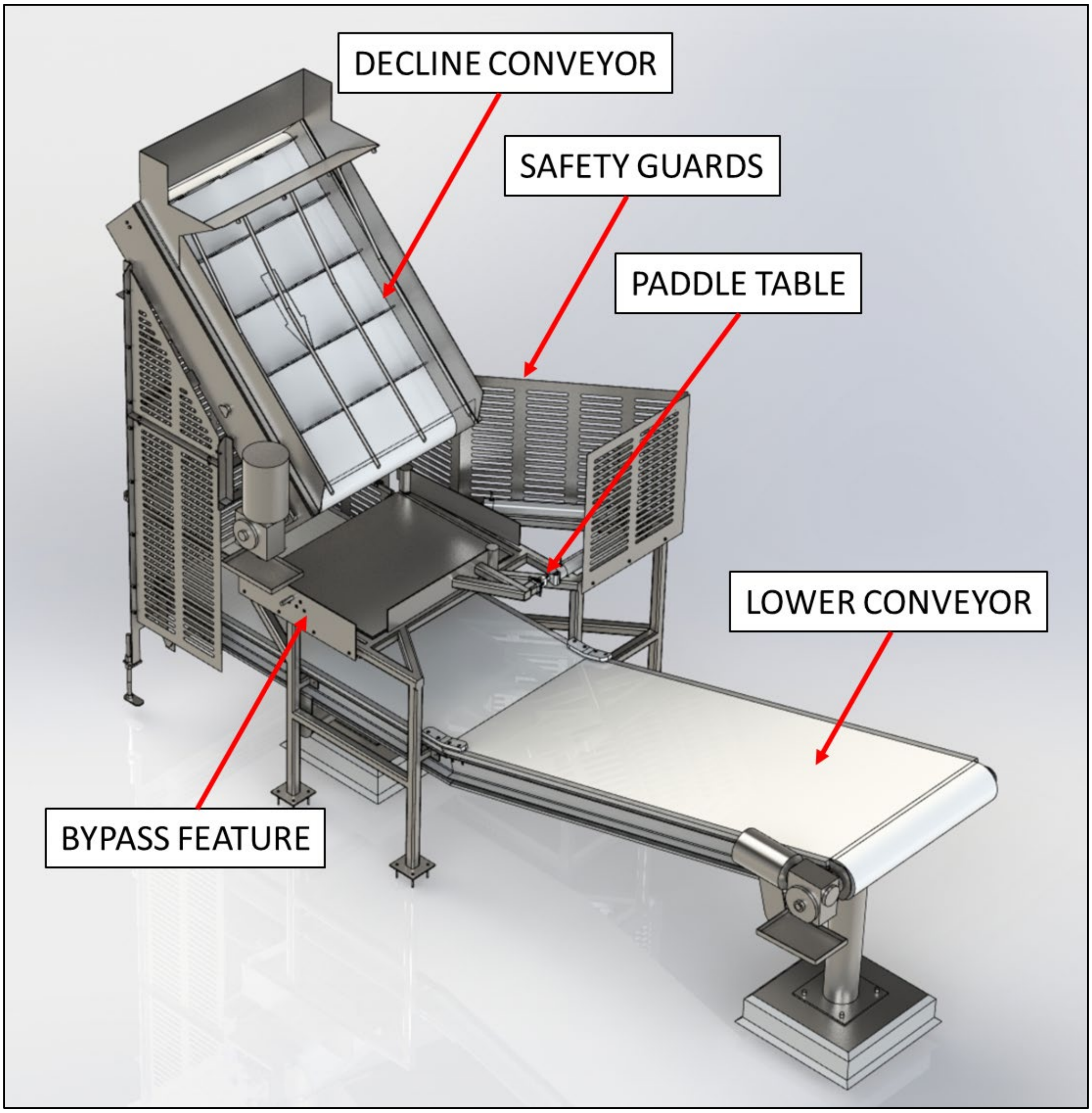


Figure 104: Render of final design - isometric front view

Similarly, the main components of the final design are shown in a rear isometric render in Figure 105.

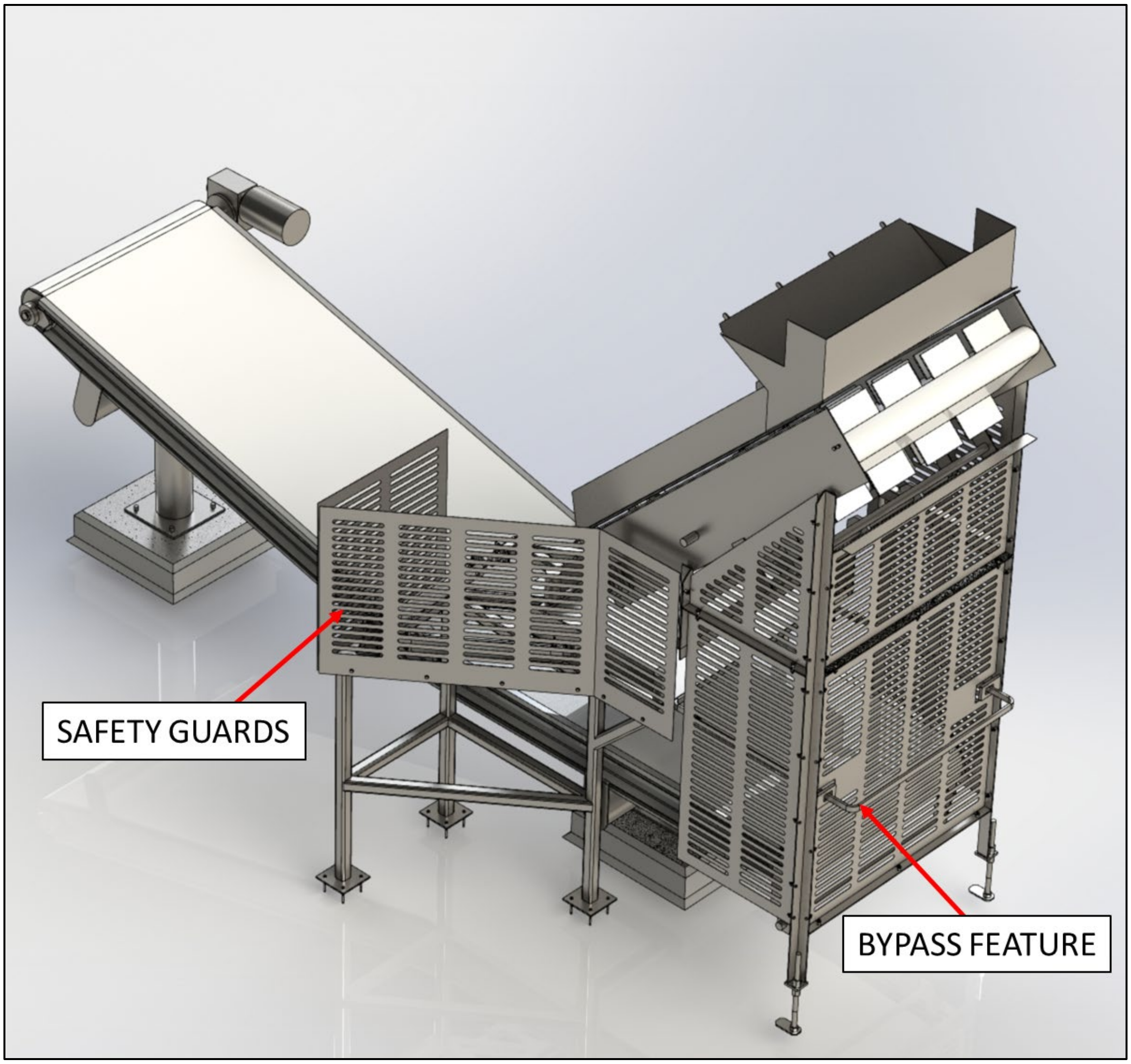


Figure 105: Render of final design - isometric back view

Decline conveyor

The decline conveyor has minor changes from the original design in the HyLife facility. To create enough clearance for the lower conveyor to travel beneath the declined conveyor, a support member needs to be relocated. The relocation of the cross-member is not something that will compromise the structural integrity of the decline conveyor support structure. No other changes to the decline conveyor were made.

Lower conveyor

The lower conveyor is to be lowered by 24” from the existing location. The lower conveyor is inclined at 15-degrees to join back up to the previous transfer location at the weight station. The lower conveyor is 2” narrower than the existing conveyor at 40.5” overall with a 38” wide belt. The narrow conveyor belt was used to fit within the decline conveyor supports with more clearance. The lower conveyor uses a cone top open hinge conveyor belt to grip the loin on the inclined section. The cone top conveyor belt is an 800 series belt from Intralox [5]. The Angled EZ Clean series drive sprockets are used to drive the conveyor belt. To drive the lower conveyor a Model SSM0145CT Keltech 1 HP motor is used in conjunction with a Keltech 90-degree gearbox [24]. The final design of the lower conveyor belt is to be contracted out to Frontmatec for the final design. A preliminary design of the UHMW conveyor belt hold-downs has been proposed. The hold-downs are based on existing hold-downs used at the HyLife facility and are used to keep the conveyor in place at the transition point from flat to 15-degree incline.

Paddle Table with Bypass Feature

The paddle table consists of a welded tube support structure, a sliding table to facilitate bypass in the event of system failure or jams, 2 paddle assemblies, 2 pneumatic cylinders, a mounting bracket for the cylinders, and an infrared sensor for loin detection.

The welded tube support structure is constructed from 2” square 316L steel tubing, with a wall thickness of 0.1875”. There are two 1.375” pins welded to the structure to act as shafts for the paddle assemblies. The food contact surface for the table is 0.125” thick 316L steel sheet. There is a welded corner bracket for mounting the pneumatic cylinders to the tube frame, consisting of 0.25” 316L laser cut plate and two EB500 eyelets from Bimba [16].

The bypass sliding table structure measures 29”x36.5” and is constructed from 1” square 316L steel tubing with a 0.1875” wall thickness. The 1” square tubing structure uses 45-degree joints at the edges of the outer perimeter such that the structure is hermitically sealed. The bypass sliding table has a 1/8” 316L stainless steel top. The sliding bypass table is mounted to the main support structure using custom linear bearing sliders. The linear bearing sliders are series 28, have a 690mm body, and a 700mm stroke. The washdown version of the series 28 linear slide bearing is a custom rendition of the standard series 28. The bypass table handle is made of 1”x0.375” flat bar, and is used to slide the bypass table out of the way.

The paddle assemblies each consist of a paddle plate, paddle bore, bushing, eyelet plates and a welded tube arm in the case of the first paddle assembly. The paddle plate is constructed from 0.25” 316L stainless steel plate and welded to the paddle bore, made from 2.375” round stock 316L stainless steel. A bushing is inserted into the paddle bore and is simply constructed from 2.375” round stock Delrin 500CL. The eyelets are the EB500 model from Bimba, constructed from 303 stainless steel. In addition to the eyelets, the first paddle features a welded 2” square 316L tube arm with a wall thickness of 0.1875” to facilitate the required motion with the pneumatic cylinder.

Each pneumatic cylinder is from the repairable stainless series line from Bimba [18]. Each cylinder is a USDA approved design, with the addition of Bimba’s normally open

RSU-1-Q reed sensors to detect the extended and retracted position of each pneumatic cylinder. There are two cylinders, one featuring a 14” stroke and the other a 19” stroke. Each cylinder features a front and rear clevis with cotter pins for toolless service. In addition to the RSU-1-Q reed sensors, there is one 42CST-D1MPA3-D4 infrared sensor from Allen-Bradley to detect the presence of a loin on the paddle table, and it is simply mounted to the side wall of the paddle table through a hole [21] [19].

The safety guards ensure that workers do not come into contact with the paddle table and conveyors. The safety guards consist of 16-gauge 316L stainless steel sheet metal that is laser cut. The safety guards feature cut-outs so that the workers can view the paddle table and other various components during operation.

4.1.2 Final Design – System Operation

The normal operation of the design starts with loins falling onto the decline conveyor every 6 seconds. Each loin is caught by the paddles on the decline conveyor and is transferred down to the paddle table. Figure 106 shows the loin as it travels down the decline conveyor.

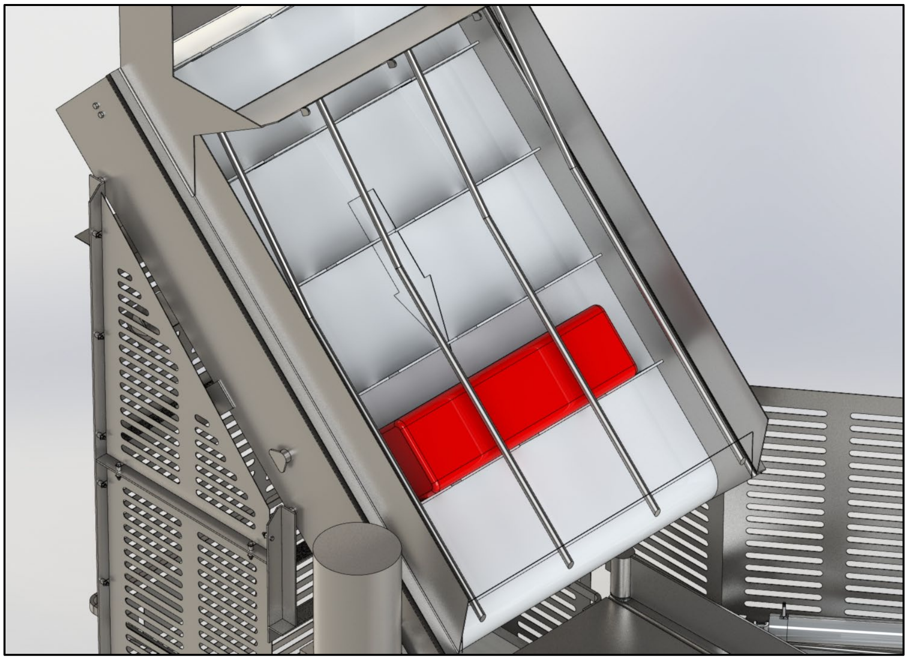


Figure 106: Loin travelling down the decline conveyor

Once the loin drops from the decline conveyor and lands on the paddle table, the IR sensor detects the presence of the loin. This then triggers paddle 1 to be extended by a pneumatic cylinder, thereby rotating the loin by 90 degrees until the loin makes contact with paddle 2, which is in its retracted position. Figure 107 shows the motion of paddle 1.

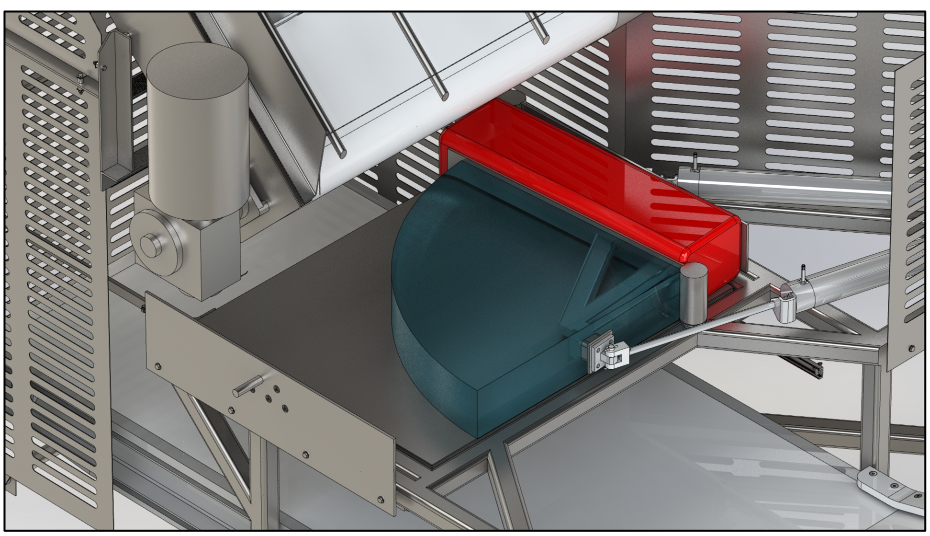


Figure 107: Paddle 1 motion

Paddle 1, then, retracts back to its initial position, which then triggers paddle 2 to be extended by another pneumatic cylinder. By extending paddle 2, the loin is then rotated by another 90 degrees as it falls off the paddle table as shown in Figure 108. At this point, paddle 2 retracts back to its initial position, and the re-orientation of the loin is completed.

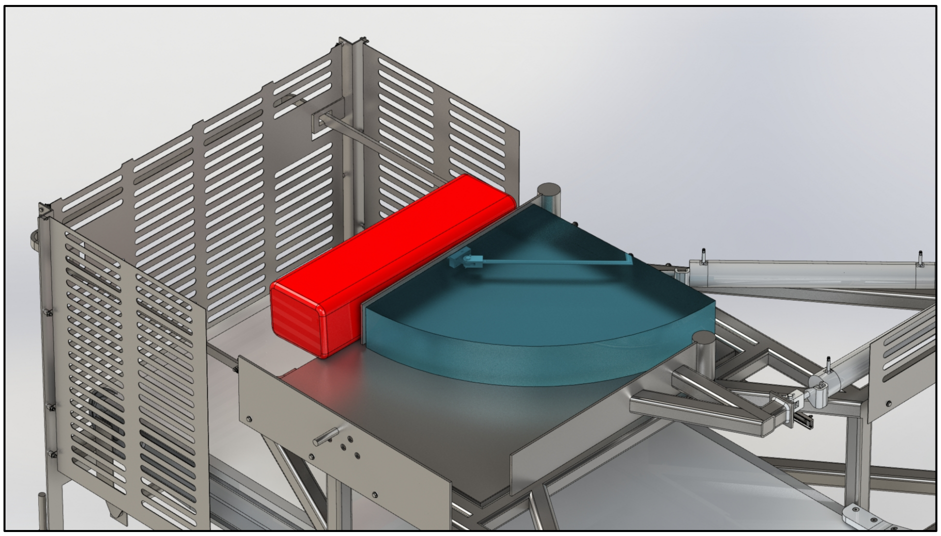


Figure 108: Paddle 2 motion

Once reoriented, the loin travels on the lower conveyor to the weigh station and continues on for further processing on the loin line. The process in this normal operation is then repeated as the loins fall onto the decline conveyor every 6 seconds. A PLC system is used to automate this process by actuating the two cylinders accordingly.

In the event of a stoppage in the loin delivery process at the table, the nearest operator is expected to activate the bypass feature by unlocking the bypass handle. This is done by pulling the handle upward before pulling the handle backward which in turn slides the bypass table back out of the way until it is fully retracted. At this point, the handle hinges downward which allows it to take up less space. This is shown in Figure 109.

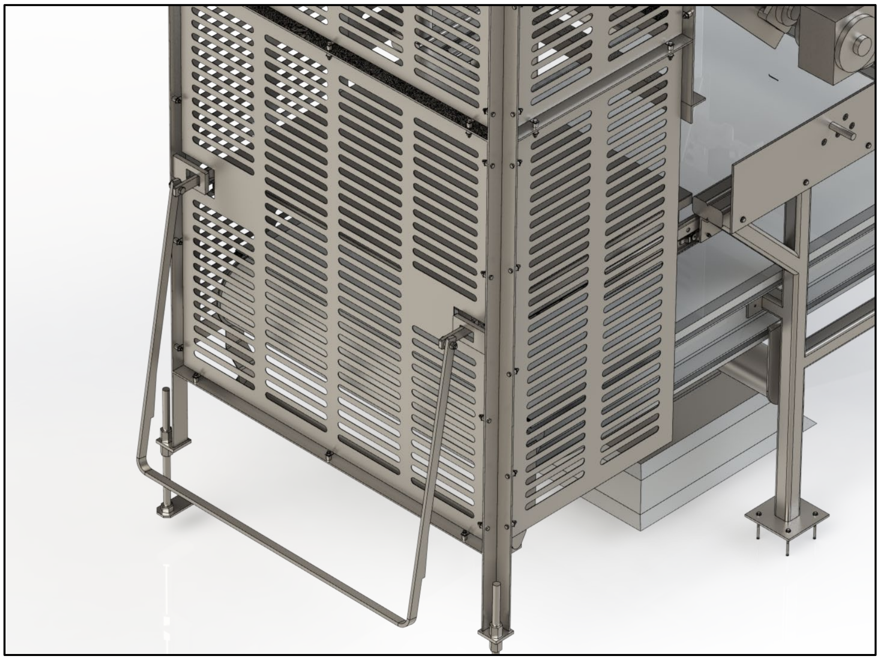


Figure 109: Bypass handle hinged downward

By pulling the handle, the table slides out of its initial position, moving away from the path of the loin as it falls from the decline conveyor. At this point, the loins are free to drop down to the loin line directly from the decline conveyor, and thus the system is in bypass mode. Figure 110 shows the system functioning in bypass mode.

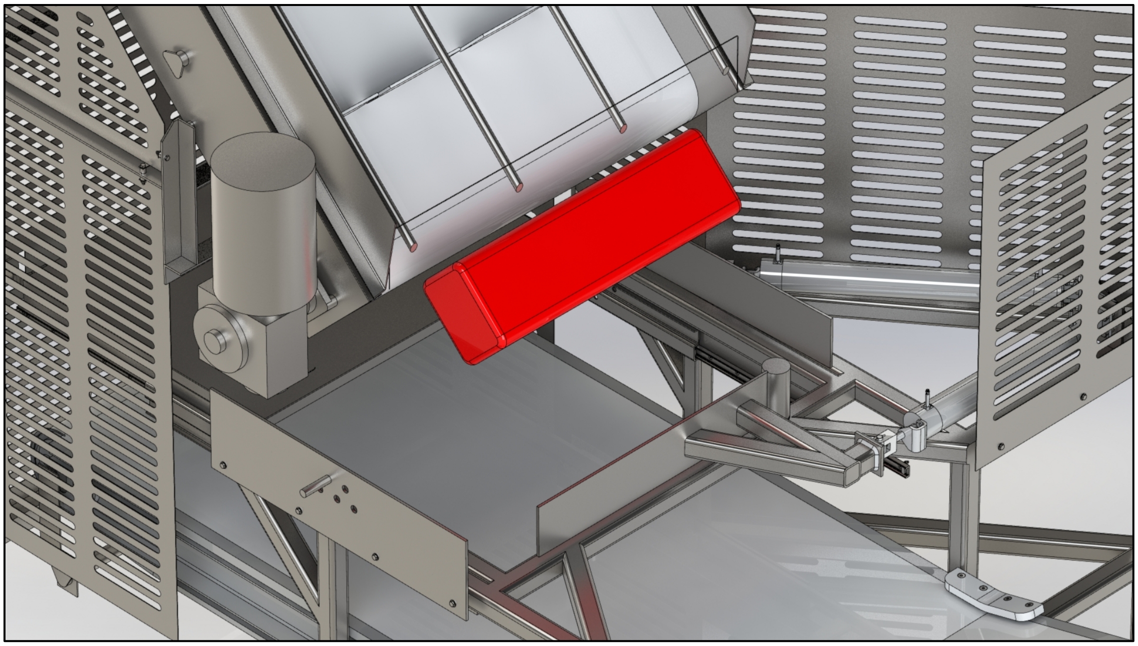


Figure 110: Paddle table in bypass mode

4.2 Final Metrics

At the beginning of the project, metrics that the final design was to meet were established by the team and the client as detailed in Section 1.5. These metrics served as a guide for the team to be able generate a design geared towards the client's needs. TABLE XVI lists the project metrics and the corresponding values for the final design. The items on the list are sorted in descending order of importance, with 5 signifying the highest importance.

TABLE XVI: LIST OF FINAL DESIGN PROJECT METRICS

Metric #	Metric	Imp	Target Value	Actual Value
3	Cleaning water temperature	5	180	180
5	Noise level	5	85	TBD
6	Force from the loin	5	981	981
9	Chemical resistance	5	Pass	Pass
11	Range of permissible cycle times	5	3 to 6	6
12	Full automation	5	Pass	Pass
13	E-Stop/Safety guards/lockout capability	5	Pass	Pass
14	Startup/Stop time	5	60	TBD

Metric #	Metric	Imp	Target Value	Actual Value
15	Manufacturability	5	Pass	Pass
16	Digital input/output communication	5	Pass	Pass
17	BOM/spare parts	5	Pass	Pass
18	CAD model in Inventor	5	Pass	Pass
19	Uptime/reliability	5	100	TBD
20	Variation in discharge angle	5	20	TBD
21	Tools required for service	5	Pass	Pass
22	No tools required for cleaning	5	Pass	Pass
23	Customer satisfaction	5	100%	100%
25	Meets design codes	5	Pass	Pass
7	Endurance/lifespan (rotary, impact, abrasion)	4	450K	TBD
8	Time without ingress from HP washing	4	180	TBD
24	Operational cost	4	2000	TBD
1	Loin dimensions	3	28-30	28-30
2	Weight of loin	3	10	10
4	Time to clean/disassemble	3	15	TBD
10	Cost	2	200K	36,981.23

17 out of the 25 required metrics are achieved by the final design. However, the rest require further testing to determine if the design meets these metrics. The team made the best possible judgement regarding design decisions that affected the metrics that could not be met for certain. For example, the system needs to have a lifespan of around 450,000 cycles. Determining the exact lifespan of the design was difficult, so the team selected the appropriate bushing for the paddle assembly such that the bushing is easily replaceable. This allows for an extended lifetime for the system, since the entire system does not need to be overhauled in the event of a bushing failure. Another metric that is yet to be determined is the variation in discharge angle of the loin once it is pushed off the table by paddle 2. Since the system is automated, the team is confident that the loin discharge angle would be consistent. Similarly, metrics such as noise level, start-up/stop time, time to clean/disassemble, and time without ingress from high-pressure

washing cannot be confirmed without testing. However, the team is confident that the design will pass these metrics as a conservative approach was taken during the development of the overall design.

The final design's reliability in terms of uptime is also difficult to determine from a theoretical standpoint. 100% uptime with the system cannot be realistically achieved, particularly with its automated aspect. As a result, the team integrated the bypass feature, as detailed in Section 3.3.4, which allows for continuous loin processing in the event of system failure. Similarly, the operational cost will have to be determined by the client once the system is implemented, as it is difficult to provide an estimate for this given the team's limited expertise and further testing required.

4.3 Risk Analysis

The initial version of the final design posed risks that could potentially cause effects that are undesirable for the client. The effects that were deemed most critical were: harming the workers, compromising the quality of the loin, and halting the overall loin delivery process. A failure mode and effects analysis (FMEA) was utilized to identify ways that the design can fail, and to eliminate or reduce the risk of failure. At its final version, the designed system is more reliable as a result of the rigorous development phase that it went through. Figure 111 shows each step that the loin goes through in the final design. A side view of the final design is overlaid on the process map as a guide to assist the reader in understanding it.

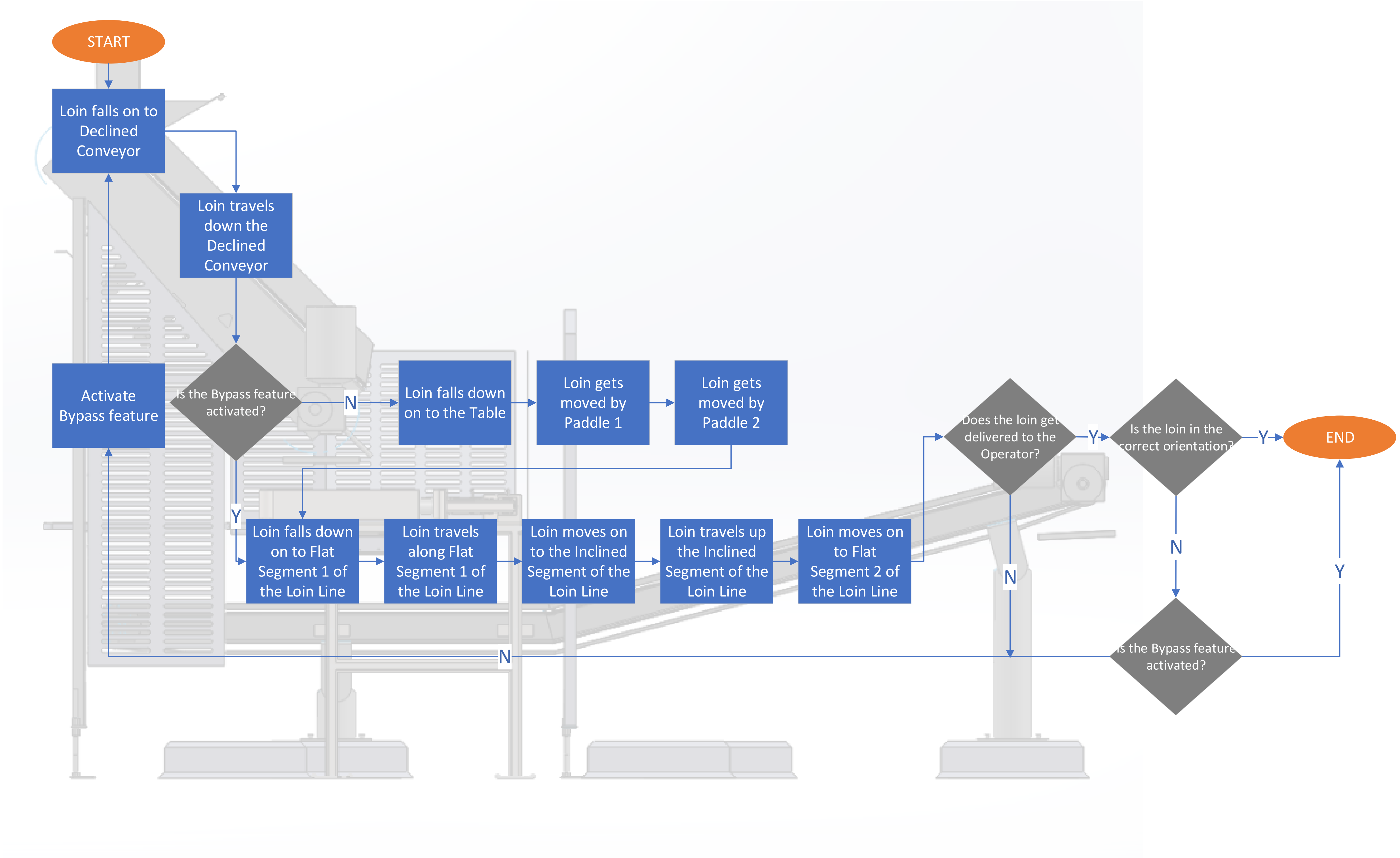


Figure 111: Overall loin delivery process within the final design

The FMEA is summarized in TABLE XVII, which is shown on the next page. Potential failure modes of the design were listed with its corresponding step in Figure 111, with the exception of the cleaning process. To evaluate the significance of each failure mode, the Risk Priority Numbers (RPN) were calculated after the mode was actioned on. The RPN is the product of severity, occurrence, and detection. Each of the three factors used a scale from 1 – 10, with 1 being the unfavourable end. For example, a 10 on the severity scale meant that the effect a mode may expose client to loss, harm or major disruption without warning, while a score of 1 meant no effect to the process. Appendix H provides a detailed explanation for every score on each scale. It is important to note, however, that the scores given were relative estimates to the best of the team's knowledge. For each failure mode, the person responsible for the mitigating the effects of the failure mode and what action is recommended are included. In addition, the failure modes are sorted by process, and that the highest RPN are highlighted in red.

TABLE XVII: FMEA ON FINAL DESIGN

Process Step/ Input	Potential Failure Mode	Potential Failure Effects	Potential Causes	Who is Responsib-le?	Recommend-ed Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
Loin falls down on to the Table	Loin does not fall onto the correct position on the table	Loin will not be oriented properly	Impact of the loin on the Decline Conveyor causing the cleats to be unsynchronized	Operator	Manual re-orientation of loin	5	3	1	15
Loin gets moved by Paddle 1	Paddle 1 does not get actuated	Loin will not be processed	Sensor malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	3	3	36
Loin gets moved by Paddle 1	Paddle 1 swings beyond the intended range of motion	Loin quality will be compromise-ed	Controller error or cylinder malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	3	3	36
Loin gets moved by Paddle 1	Paddle 1 swings beyond the intended range of motion	Worker injury	Controller error or cylinder malfunction	HyLife Foods LP	Integrate signage and raise awareness of hazards with the system	10	1	1	10
Loin gets moved by Paddle 1	Paddle 1 does not retract back into resting position	Loin will not be processed	Controller error or cylinder malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	3	3	36
Loin gets moved by Paddle 2	Paddle 2 does not get actuated	Loin will not be processed	Controller error or cylinder malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	3	3	36

Process Step/ Input	Potential Failure Mode	Potential Failure Effects	Potential Causes	Who is Responsib-le?	Recommend-ed Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
Loin gets moved by Paddle 2	Paddle 2 swings beyond the intended range of motion	Loin quality will be compromise-ed	Controller error or cylinder malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	3	3	36
Loin gets moved by Paddle 2	Worker gets in the way of the paddle	Worker injury	Controller error or cylinder malfunction	HyLife Foods LP	Integrate signage and raise awareness of hazards with the system	10	1	1	10
Loin gets moved by Paddle 2	Loin falls on the floor	Loin does not get processed	Controller error or cylinder malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	1	3	12
Loin gets moved by Paddle 2	Paddle 2 does not retract back to its resting position	Loin does not get processed	Controller error or cylinder malfunction	Supervisor	Use Bypass feature and manual re-orientation of loin	4	3	3	36
Activate Bypass feature	Bypass Handle cannot be pulled	Loin will not be processed	Pieces of the loin get stuck in the Bypass Table mechanism	HyLife Foods LP	Preventative Maintenance	10	1	3	30
Cleaning	Componen-ts breakdown due to cleaning chemical	Loin does not get processed	Material properties for design components deteriorate due to cleaning chemical	Supervisor	Preventive Maintenance	10	1	2	20

Process Step/ Input	Potential Failure Mode	Potential Failure Effects	Potential Causes	Who is Responsib-le?	Recommend-ed Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
Cleaning	Componen-ts breakdown due to cleaning chemical	Loin does not get processed	High pressure water used for cleaning penetrates sensitive components	Supervisor	Preventative Maintenance	10	1	2	20
Cleaning	Residue left on contact surface	Loin quality will be compromise-ed	Cleaning chemical reaches the motors of the conveyor	HyLife Foods LP	Preventative Maintenance	10	1	2	20

The most significant failure modes of the final design were the risks of the paddles not functioning as intended, which is reflected by their RPN. As detailed in the FMEA, these modes are foreseen to have many different causes, such as controller error and cylinder malfunction. The effects of these failure modes potentially lead stoppage in loin processing. To combat these, the bypass table, as discussed in Section 3.3.4, is integrated into the design. This opens a clear path for the loin to go through the system in the event of the paddles malfunctioning. However, activating the bypass feature requires the operators to manually re-orient the loin. Another effect, despite having a lower RPN, would be the paddles potentially harming the workers. To prevent this, the team implemented safety guards which effectively eliminate the risk.

Another significant failure mode is the bypass handle being unable to be pulled when activating the bypass feature, which can be caused by residue getting stuck in the

Sliding Table mechanism. This could potentially lead to loins not being processed, thus having a relatively high RPN. The team recommends the client to enforce the appropriate level of preventative maintenance to detect and prevent this mode from occurring.

Another failure mode of concern is the possibility of components of the design breaking down during cleaning. This could be caused by the high-pressure cleaning water penetrating the sensitive components of the system such as the sensors. Another cause by the materials of the components deteriorating as a result of repetitive cleaning with the cleaning chemicals used by the client. Both causes can potentially downtime if left undetected. During the cleaning process, another failure mode could be improper cleaning of the contact surfaces which include the sliding table, the paddles and the conveyors which leads to compromised loin quality. To combat both modes of failure, it is recommended that appropriate cleaning methods and preventative maintenance be applied to the design.

Overall, a more robust and reliable final design was developed as a result of the risks being identified and acted on. The risks that present safety issues have been essentially eliminated by integrating physical safety guards as well as signage. Furthermore, the risks that can halt the client's production have been eliminated by integrating a bypass feature which allows the loin to go through the design but will require the workers to manually re-orient the loin.

4.4 Bill of Materials (BOM)

The bill of materials for the loin reorientation project has been broken into several components. Each bill of materials section has been selected based on the assigned "area" that the material or part originates from. Some common "area" categories include the bypass system, support structure, safety guards, pins, and paddles. In order to clearly introduce all of the parts required for the installation of the team's design, each area will receive its own table. The item quantity and assigned part number will also be listed within each table, this will allow each item to be quickly cross-referenced against the preliminary engineering drawings. A complete one-piece bill of materials can be found in Appendix G, sorted by area instead of being broken into individual tables as introduced in the following sections. The first area which will be presented is the bypass table section.

4.4.1 Bypass Actuation BOM

The bypass actuation bill of materials includes the bearing slides, mounting hardware, and the bypass actuation handle. This "area" is comprised almost exclusively of components which are dynamic and slide along the static support structure. Components are summarized in TABLE XVIII.

TABLE XVIII: BYPASS ACTUATION BILL OF MATERIALS

BYPASS ACTUATION			
Area	**Component**	**Qty**	**Part Number**
Bypass	Linear Bearing Slides	2	BS01
Bypass	M5 Nylocs	18	BS02
Bypass	M5 Allen Bolts	18	BS03
Bypass	1/2 Bolts	2	BS04
Bypass	1/2 Nylocs	2	BS05
Bypass	Handle Spacer	2	BS06
Bypass	Plate - Handle	1	BS07
Bypass	Plate - Handle Bracket	2	BS08
Bypass	Plate - North Guide	1	BS09
Bypass	Plate - South Guide	1	BS10
Bypass	Outer Slide Mount	2	BS11
Bypass	Inner Slide Mount	2	BS12

4.4.2 Bypass Table BOM

The only other dynamic component which slides with respect to the static support structure which wasn't mentioned in the preceding bypass section is the bypass table structure. This bill of materials includes all materials required for assembling the bypass table itself in TABLE XIX.

TABLE XIX: BYPASS TABLE BILL OF MATERIALS

BYPASS TABLE			
Area	**Component**	**Qty**	**Part Number**
Table Structure	Sheet - Bypass Top	1	BT01
Table Structure	Tube - Mitre Str. 2	2	BT02
Table Structure	Tube - Mitre Str. 3	2	BT03
Table Structure	Tube - Str. 4	4	BT04
Table Structure	Tube - Str. 5	1	BT05

4.4.3 Support Structure BOM

The largest area which has been introduced as an independent bill of materials is the support structure area. The support structure is exclusively comprised of static components which support the bypass table and provided enough stability for the system to slide in and out of the bypass mode. The entire bill of materials can be seen in TABLE XX.

TABLE XX: SUPPORT STRUCTURE BILL OF MATERIALS

SUPPORT STRUCTURE			
Area	**Component**	**Qty**	**Part Number**
Base Structure	Tube - Support Str. 1	2	SS01
Base Structure	Tube - Support Str. 2	2	SS02
Base Structure	Pin	2	SS03
Base Structure	Tube - Support Str. 4	5	SS04
Base Structure	Tube - Support Str. 5	2	SS05
Base Structure	Tube - Support Str. 6	2	SS06
Base Structure	Tube - Support Str. 7	2	SS07
Base Structure	Tube - Support Str. 8	1	SS08
Base Structure	Tube - Support Str. 9	2	SS09
Base Structure	Tube - Support Str. 10	2	SS10
Base Structure	Plate - Side Mount	2	SS11
Base Structure	Plate - Floor Mount	5	SS12
Base Structure	Tube - Support Str. 13	2	SS13
Base Structure	Plate - Corner Gusset	2	SS15
Base Structure	EB500 Mount	2	SS16
Base Structure	Plate - Corner Base	2	SS17
Base Structure	EB500 - M10 SST Bolt	8	SS18
Base Structure	EB500 - M10 SST Nut	8	SS19
Base Structure	EB500 - M10 SST Spacer	8	SS20
Base Structure	Plate - Tube Cap	7	SS21
Base Structure	Concrete Anchor	20	SS22

4.4.4 Safety Guards BOM

The safety guards section is exclusively comprised of the large laser cut sheet metal parts which are placed in all locations which have been exposed due to the proposed design changes the team has made to the system. The entire summary of components can be seen in Table XXI.

TABLE XXI: SAFETY GUARDS BILL OF MATERIALS

SAFETY GUARDS			
Area	**Component**	**Qty**	**Part Number**
Safe Guard	Sheet - Safety Guard 1	1	SG01
Safe Guard	Sheet - Safety Guard 2	1	SG02
Safe Guard	Sheet - Safety Guard 3	2	SG03
Safe Guard	Sheet - Safety Guard 4	1	SG04
Safe Guard	M6 SST - Bolt	33	SG07
Safe Guard	M6 SST - Nyloc Nut	40	SG08
Safe Guard	½” SST - Spacer	47	SG09
Safe Guard	M6 SST Bolt - 45mm	7	SG10
Safe Guard	316L SST - 1" Spacer	13	SG11
Safe Guard	SST - 1/4"-20 Bolt	13	SG12
Safe Guard	1/4" SST - Washer	13	SG13

4.4.5 Paddles and Cylinders BOM

The paddles and cylinders area is closely linked to the support structure area since all of the components are mounted on the static support structure. It is listed separately of the static support structure since it is a complex portion of the design and has been given a unique part number naming convention. The entire bill of materials for the paddles and cylinders can be seen in Table XXII.

TABLE XXII: PADDLE AND CYLINDER BILL OF MATERIALS

PADDLE & CYLINDER			
Area	**Component**	**Qty**	**Part Number**
Paddle & Cylinder	Bimba Pneu. Cyl.	2	PC01
Paddle & Cylinder	Tube - Paddle Tube 1	1	PC02
Paddle & Cylinder	Tube - Paddle Tube 2	1	PC03
Paddle & Cylinder	Sleeve - Paddle Jacket	2	PC04
Paddle & Cylinder	Tube - Paddle Tube 3	1	PC05
Paddle & Cylinder	Plate - Tube Cap	1	SS21
Paddle & Cylinder	Bushing - Delrin	2	PC07
Paddle & Cylinder	Plate - Paddle Face	2	PC08
Paddle & Cylinder	EB500 Mount	2	SS16
Paddle & Cylinder	AB Prox. Sensor	1	PC09
Paddle & Cylinder	Sensor Mount Plate	1	PC10

4.4.6 Lower Conveyor BOM

The bill of materials is limited for the lower conveyor area due to the fact that all of the specific components for the lower conveyor would be specified by consultant responsible for the installation of the system. Many existing conveyors in the HyLife plant were developed by a consultant with experience in the area, this project will be no different, the consultant would be responsible for the full-length bill of materials here. The costing section provides an estimate which is based on the estimated cost per linear foot that HyLife has explained is the common cost which they have incurred in the past for conveyor installations. Table XXIII includes items which are required for the project in the lower conveyor region.

TABLE XXIII: LOWER CONVEYOR BILL OF MATERIALS

LOWER CONVEYOR			
Area	**Component**	**Qty**	**Part Number**
Hold Down	Hold Down Shoe	2	HD01
Hold Down	M8 SST C/S - Bolt	4	HD02
Hold Down	M8 SST - Nut	4	HD03
Hold Down	M10 SST - Spacer	4	HD04
Low Conveyor	Cone Top Belting	N/A	LC01
Low Conveyor	Track Body	N/A	LC02
Low Conveyor	800 Series Sprocket	N/A	LC03
Low Conveyor	Conveyor Spray Bar	N/A	LC04

4.5 Cost Analysis

The final design involves procurement of specific components that are already manufactured, as well as raw materials that need further machining. As a result, both purchasing and labour costs are included in the overall cost analysis. The following series of sections will breakdown each of the main components which the entire is comprised of and their corresponding process for material and manufacture. The pricing component of this design report is a rough representation of the costs which would be incurred if the project is pursued by the client. Given the fact that there is over 60 unique parts which are assembled to create the teams design, shops were not contacted for specific quotes on each part as it would an inefficient use of their time. All costs are provided in US dollars.

4.5.1 Tube Part Cost Breakdown

Breaking down the cost of the tube parts required for the team's design entailed obtaining pricing on a per-foot basis from suppliers. Online quoting was conducted through multiple stainless steel tube providers. One of the key points to mention when reviewing the cost estimates for all components is that the prices were obtained for orders of multiple full-length pieces of stock, not for individual pieces [25] [26]. Since a variety of piece parts are specified to have either 2"x2"x7-gauge square tube or 1"x1"x7-gauge square tube, material can be ordered in the supplier original length. All tube components are specified to be built from 316L stainless steel as mentioned in preceding sections. Since this is a preliminary bill of materials, specific shops were not contacted for exact quotes on individual tube parts. Therefore, a tube part cost estimating convention was put in place to give a rough estimate to the client. Tube parts were priced based on their material, length and number of end features. The number of end features refers to the geometry of the cut on the end of the tube; angled or straight. Since none of the tubes have holes that require laser tube cutting or drilling, there was no need to account for price variations due to the addition of them. It is also should be noted that none of the tube parts require bending, this also eliminates another source of increased pricing. Table

XXIV displays a rough pricing chart for the difference in time and cost which the number of end features has on the price of the tube item. These price estimates were created by the team. The setup time associated with cutting the tube parts has also been assumed to be integrated into the estimates in Table XXIV.

TABLE XXIV: TUBE END FEATURE COST BREAKDOWN

316L SST TUBE FEATURE PRICING		
END FEATURES	TIME [HR]	TIME COST [$]
0	0.17	10.95
1	0.25	12.95
2	0.33	13.95

Even with the addition of a labour cost associated with the number of end features that each tube has, the raw material cost proved to be far more significant in the cost estimating process. The following table, Table XXV, is the product of a spreadsheet which has been configured in such a way that it pulls the tube length from one list, then cross-references it with the material cost and end feature number to arrive at a final part cost.

TABLE XXV: TUBE PART COST BREAKDOWN

Area	Component	Qty	Part Number	Length [in]	Cost Per Item	Total Cost
Base Structure	Tube - Support Str. 1	2	SS01	23.25	33.10	**66.19**
Base Structure	Tube - Support Str. 2	2	SS02	38.62	50.74	**101.47**
Base Structure	Tube - Support Str. 4	5	SS04	41.00	52.00	**260.01**
Base Structure	Tube - Support Str. 5	2	SS05	29.00	38.57	**77.15**
Base Structure	Tube - Support Str. 6	2	SS06	15.61	28.82	**57.64**
Base Structure	Tube - Support Str. 7	2	SS07	29.25	40.81	**81.62**
Base Structure	Tube - Support Str. 8	1	SS08	41.00	50.00	**50.00**
Base Structure	Tube - Support Str. 9	2	SS09	44.00	54.86	**109.72**
Base Structure	Tube - Support Str. 10	2	SS10	2.38	13.22	**26.43**
Base Structure	Tube - Support Str. 13	2	SS13	15.56	28.77	**57.54**
Table Structure	Tube - Mitre Str. 2	2	BT02	29.00	39.16	**78.31**

Area	Component	Qty	Part Number	Length [in]	Cost Per Item	Total Cost
Table Structure	Tube - Mitre Str. 3	2	BT03	36.50	45.67	**91.35**
Table Structure	Tube - Str. 4	4	BT04	34.50	40.94	**163.75**
Table Structure	Tube - Str. 5	1	BT05	13.00	22.25	**22.25**
Paddle & Cylinder	Tube - Paddle Tube 1	1	PC02	5.00	18.71	**18.71**
Paddle & Cylinder	Tube - Paddle Tube 2	1	PC03	5.00	15.71	**15.71**
Paddle & Cylinder	Tube - Paddle Tube 3	1	PC05	2.00	12.86	**12.86**

Table XXV shows that the prices per individual tube part ranges from only $13 to as much as $54 depending the size and end features. The area of each part is included in Table XXV in order to include some context as to where the part will be installed and what similar components it will be interfacing with.

4.5.2 Sheet Metal Part Cost Breakdown

There are a number of sheet metal parts which go into the complete design of the loin reorientation system. Most of the sheet metal parts are very basic with minimal laser cut distance or braking operations required. Sheet metal was used as much as possible in order to cut down on far more expensive machining operations. One of the most significant areas where money was saved by moving towards a sheet metal operation as opposed to a machining operation was the corner bracket where the cap end of the pneumatic cylinders meet. The corner bracket could be machined but instead was specified to be laser cut and then welded. The structural integrity of the sheet metal corner bracket is validated in a preceding section by finite element analysis. The cost estimation process for sheet metal parts was similar to the estimation of tube part costs. The first action when estimating the cost of sheet metal parts was obtaining an online quote for the material required on a per square-foot basis [25] [27]. A wider variety of sheet metals were used than tube sizes. Sheet metal sizes which were utilized include: 0.25”, 0.375”, 0.5”, 7-guage and 16-gauge stainless steel, all of these being of the 316L stainless-steel grade. When estimated the costs associated with laser cutting of parts, the thickness of material, laser cutting hourly cost, laser cutter speed, and nesting/setup time was considered. The hourly price of operation of a laser cutter was found to be $13.00 to $20.00 per hour [28]. The speed of cutting was estimated to be approximately 1.5 meters/hour (~59 inches/min) [29]. The speed of the laser cutter was an estimated for cutting steel with an approximate material thickness of 8mm which is very close to a lot of the material being used. Although it is good that the laser cutter run time cost was estimated, the majority of the cost would be expected to be associated with the setup/nesting of the parts in the sheet. Since the shop which would be doing the laser cutting operations is unknown, it is hard to estimate the exact setup costs associated with each part. Since the team will be utilizing some volume parts made from material which is less common, such as 0.5” 316L stainless steel plate, than standard thinner gauge mild steel, nesting parts may be harder since the shop does not get many orders for those particular items. Therefore, the setup time was estimated on a per part basis. TABLE XXVI summarizes the costs associated with the sheet metal parts which the team has incorporated in their design.

TABLE XXVI: SHEET METAL PART COST

Area	Component	Qty	Part Number	Cost Per Item	Total Cost
Bypass	Plate - Handle	1	BS07	33.75	33.75
Bypass	Plate - Handle Bracket	2	BS08	17.94	35.87
Bypass	Plate - North Guide	1	BS09	20.48	20.48
Bypass	Plate - South Guide	1	BS10	19.18	19.18
Bypass	Outer Slide Mount	2	BS11	15.63	31.25
Bypass	Inner Slide Mount	2	BS12	15.63	31.25
Base Structure	Plate - Side Mount	2	SS11	12.44	24.87
Base Structure	Plate - Floor Mount	5	SS12	16.58	82.90
Base Structure	Plate - Corner Gusset	2	SS15	12.44	24.87
Base Structure	Plate - Corner Base	2	SS17	15.23	30.47
Base Structure	Plate - Tube Cap	7	SS21	12.22	85.53
Safe Guard	Sheet - Safety Guard 1	1	SG01	122.20	122.20
Safe Guard	Sheet - Safety Guard 2	1	SG02	104.30	104.30
Safe Guard	Sheet - Safety Guard 3	2	SG03	114.10	228.20
Safe Guard	Sheet - Safety Guard 4	1	SG04	122.20	122.20
Table Structure	Sheet - Bypass Top	1	BT01	37.65	37.65
Paddle & Cylinder	Plate - Tube Cap	1	SS21	7.12	7.12
Paddle & Cylinder	Plate - Paddle Face	2	PC08	41.55	83.10
Paddle & Cylinder	Plate – Sensor Mount	1	PC10	56.65	56.65

The sheet metal item cost summary in TABLE XXVI is similar to the preceding tube components cost section in that the sheet metal item cost summary breaks down the size of the item, quantity of the part, as well as the area which the part which resides to give context as to where the part is and what other parts it is that it interfaces with.

4.5.3 Remaining Manufactured Part Cost Breakdown

The remaining manufactured components which do not have the volume of sheet and tube components include components which require lathing and machining processes. For example, the bushings which interface with the paddle pins and allow the paddles to rotate smoothly and freely require broaching after being turned on a lathe to achieve the desired geometries. Table XXVII summarizes the manufactured components which remain and their respective cost estimates.

TABLE XXVII: MACHINED COMPONENT COST SUMMARY

Area	Component	Qty	Part Number	Cost Per Item	Total Cost
Base Structure	Pin	2	SS03	113.71	**227.42**
Hold Down	Hold Down Shoe	2	HD01	151.83	**303.65**
Paddle & Cylinder	Sleeve - Paddle Jacket	2	PC04	113.71	**227.42**
Paddle & Cylinder	Bushing - Delrin	2	PC07	103.12	**206.25**

All manufactured components have now been introduced and given a cost estimate. The next step in the costing process is to introduce all the purchased parts and their respective costs. After summarizing the purchased parts, the costs associated with the installation of all new components and the removal of the components for the existing system in order to account for as many costs which may arise as possible.

4.5.4 Vendor Part Cost Breakdown

All purchased item which do not require cost estimations with regards to how they are manufactured are summarized in the following section. The parts which are summarized in the following section include fasteners, spacers/standoffs, pneumatic cylinders, sensors, mounting equipment, and conveyor related items. This section will also touch upon the pricing involved in the outsourcing of the lower conveyor design. It has been mentioned previously in the report that the lower conveyor, like other conveyors in the plant, have been outsourced to consultants such as Frontmatec. Pricing with regards to what Frontmatec often charges for similar conveyors to what the team would like to implement has been discussed with the client. In summary, a rough estimate for a flat a conveyor would yield a price tag of around $1,500 per linear foot. Since the team has specified that the conveyor have both inclined and flat sections the price would likely rise due to the increase in complexity. The team expects that the price per linear foot would be closer to a value to $1,700. To be more specific, the pricing associated with the conveyor will be measured on a conveyor path basis, meaning that the linear foot will be measured on the conveyor itself at floor level. Table XXVIII summarizes all the purchased parts involved required for design implementation.

TABLE XXVIII: PURCHASED COMPONENTS COST BREAKDOWN [18] [16] [5] [30]

Area	Component	Qty	Part Number	Cost Per Item	Total Cost
Bypass	Linear Bearing Slides	2	BS01	900.00	1800.00
Bypass	M5 Nyloks	18	BS02	0.12	2.19
Bypass	M5 Allen Bolts	18	BS03	0.38	6.83
Bypass	1/2 Bolts	2	BS04	0.70	1.39
Bypass	1/2 Nyloks	2	BS05	2.26	4.52
Bypass	Handle Spacer	2	BS06	20.02	40.04
Base Structure	EB500 Mount	2	SS16	24.60	49.20
Base Structure	EB500 - M10 SST Bolt	8	SS18	0.75	6.02
Base Structure	EB500 - M10 SST Nut	8	SS19	0.82	6.55
Base Structure	EB500 - M10 SST Spacer	8	SS20	3.39	27.12
Base Structure	Concrete Anchor	20	SS22	7.00	139.95
Safe Guard	M6 SST - Bolt 30mm	33	SG07	0.33	10.89
Safe Guard	M6 SST - Nylok Nut	40	SG08	0.65	26.08
Safe Guard	1/2" SST - Spacer	47	SG09	2.05	96.35
Hold Down	M8 SST C/S - Bolt	4	HD02	2.53	10.12
Hold Down	M8 SST - Nut	4	HD03	0.30	1.19
Hold Down	M10 SST - Spacer	4	HD04	3.39	13.56

Area	Component	Qty	Part Number	Cost Per Item	Total Cost
Low Conveyor	Cone Top Belting	1	LC01	24460.00	24460.00
Low Conveyor	Track Body	*	LC02	*	*
Low Conveyor	800 Series Sprocket	*	LC03	*	*
Low Conveyor	Conveyor Spray Bar	*	LC04	*	*
Paddle & Cylinder	Bimba Pneu. Cyl.	2	PC01	1711.70	3327.90
Paddle & Cylinder	EB500 Mount	2	SS16	24.60	49.20
Paddle & Cylinder	AB Prox. Sensor	1	PC09	160	160.00
Paddle & Cylinder	M6 SST Bolt - 45mm	7	SG10	2.05	14.35
Paddle & Cylinder	316L SST - 1" Spacer	13	SG11	3.79	49.27
Paddle & Cylinder	SST - 1/4"-20 Bolt	13	SG12	0.21	2.78
Paddle & Cylinder	1/4" SST - Washer	13	SG13	0.03	0.43

From the costing sections, the area corresponding to the location of each of the parts is noted in the table before revealing its price in order to provided context as to where the part is installed. The fields in Table XXVIII contain an asterisk are subcomponents involved in the lower conveyor build. Individual pricing on these conveyor sub-components are not individually priced out since their cost is included in the linear foot pricing estimate for the entire unit.

4.5.5 Structure Assembly and Implementation Cost Breakdown

Structure assembly costs are associated with the preparation, welding, anchoring, and similar processes involved in the final implementation of the loin reorientation in the processing plant. The disassembly of the existing loin reorientation system can also be included in this section since it is an inevitable cost associated with the implementation of a new system. System installation would likely take place over a weekend when there is downtime in the loin line, therefore operations involved in the implementation of the design would be time sensitive in order to eliminate any downtime. High level cost estimates were created for each of the operations listed above and are summarized in

Table XXIX. Cost estimates are based on the estimated time required to complete each task with a labour cost of $225/Hr [31].

TABLE XXIX: SYSTEM INSTALLATION COST

Job Details	Estimated Cost [$]
Existing System Removal	600.00
Support Structure & Table Welding	1800.00
Pneumatic Component Installation	600.00
Safety Guard Installation	500.00
TOTAL	**3500.00**

Table XXIX summarizes the main components involved in the implementation process aside from the costs associated with the build-up of the lower conveyor which is being contracted out. The costs associated with the lower conveyor build-up has been integrated into the purchased part costing section which precedes the current section. The cost estimates associated with the installation of components of the team's design are purely high-level cost estimates only for the purposes of a rough budget.

4.5.6 Final Cost Summary

With all elements which contribute the total cost of the build and installation of the design introduced, the final cost can be summated and introduced. TABLE XXX summarizes the cost total by the component area without the assembly costs associated with the overall installation of the device. Keeping in mind that the proposed project budget was $200,000, the team was able to come in an at a much lower dollar figure.

TABLE XXX: TOTAL COST OF EACH COMPONENT

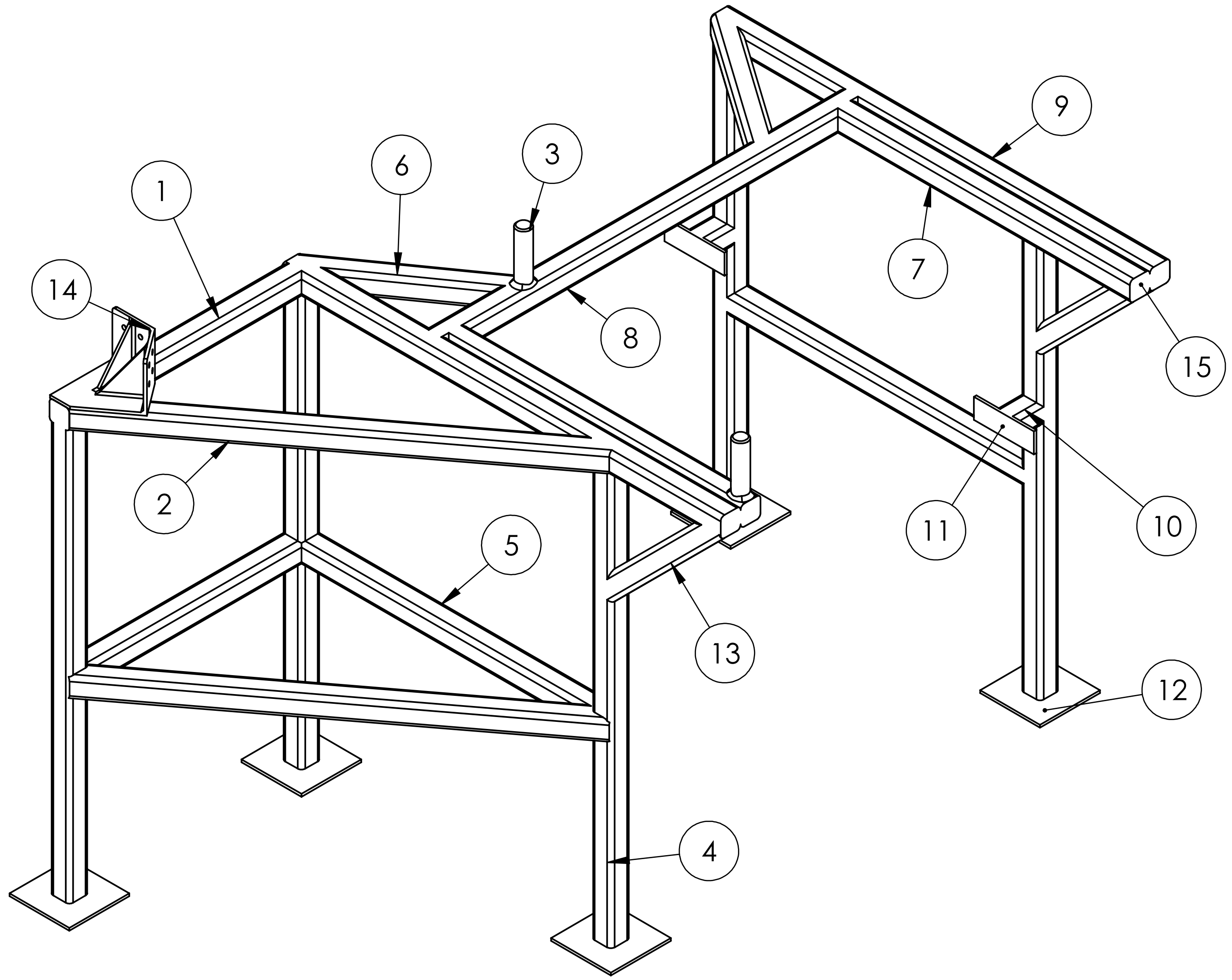
Area	Total Cost [$]
Bypass	2026.75
Base Structure	1592.68
Safe Guard	710.22
Table Structure	393.31
Low Conveyor	24650.00
Paddle & Cylinder	4108.28
Total	**$ 33 481.23**

As mentioned in the design assembly, the total cost of assembly is $33,500. The combined total of individual component pricing and assembly cost yields a total price of **$36 981.23**. Additional information regarding the process of developing cost estimates for manufactured components can be found in Appendix G.

4.6 Engineering Drawings

Engineering drawings have been made for all the piece parts required for the assembly of the loin reorientation device with the exception of purchased items. The engineering drawings included within this section are exclusively assembly drawings which solely call out the items which belong to each major component of the design. Drawings of individual piece parts are available in Appendix E.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SS01	TUBE - SUPPORT STR. 1	1
2	SS02	TUBE - SUPPORT STR. 2	2
3	SS03	PIN - CYLINDER MOUNTING	2
4	SS04	TUBE - SUPPORT STR. 4	5
5	SS05	TUBE - SUPPORT STR. 5	2
6	SS06	TUBE - SUPPORT STR. 6	2
7	SS07	TUBE - SUPPORT STR. 7	2
8	SS08	TUBE - SUPPORT STR. 8	1
9	SS09	TUBE - SUPPORT STR. 9	2
10	SS10	TUBE - SUPPORT STR. 10	2
11	SS11	PLATE - SIDE MOUNT	2
12	SS12	PLATE - FLOOR MOUNT	5
13	SS13	TUBE - SUPPORT STR. 13	2
14	SA-SS02	ASSY - CORNER BRKT	1
15	SS21	PLATE - TUBE END CAP	7



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.X = ± .01
.XX = ± .005
ANGLES = ± 1°

3RD ANGLE PROJECTION

DO NOT SCALE DRAWING

TITLE: SUPPORT STRUCTURE - SUB ASSY

PART NUMBER:

BASE TABLE - ASSY

COMMENTS:

SIZE: **B**

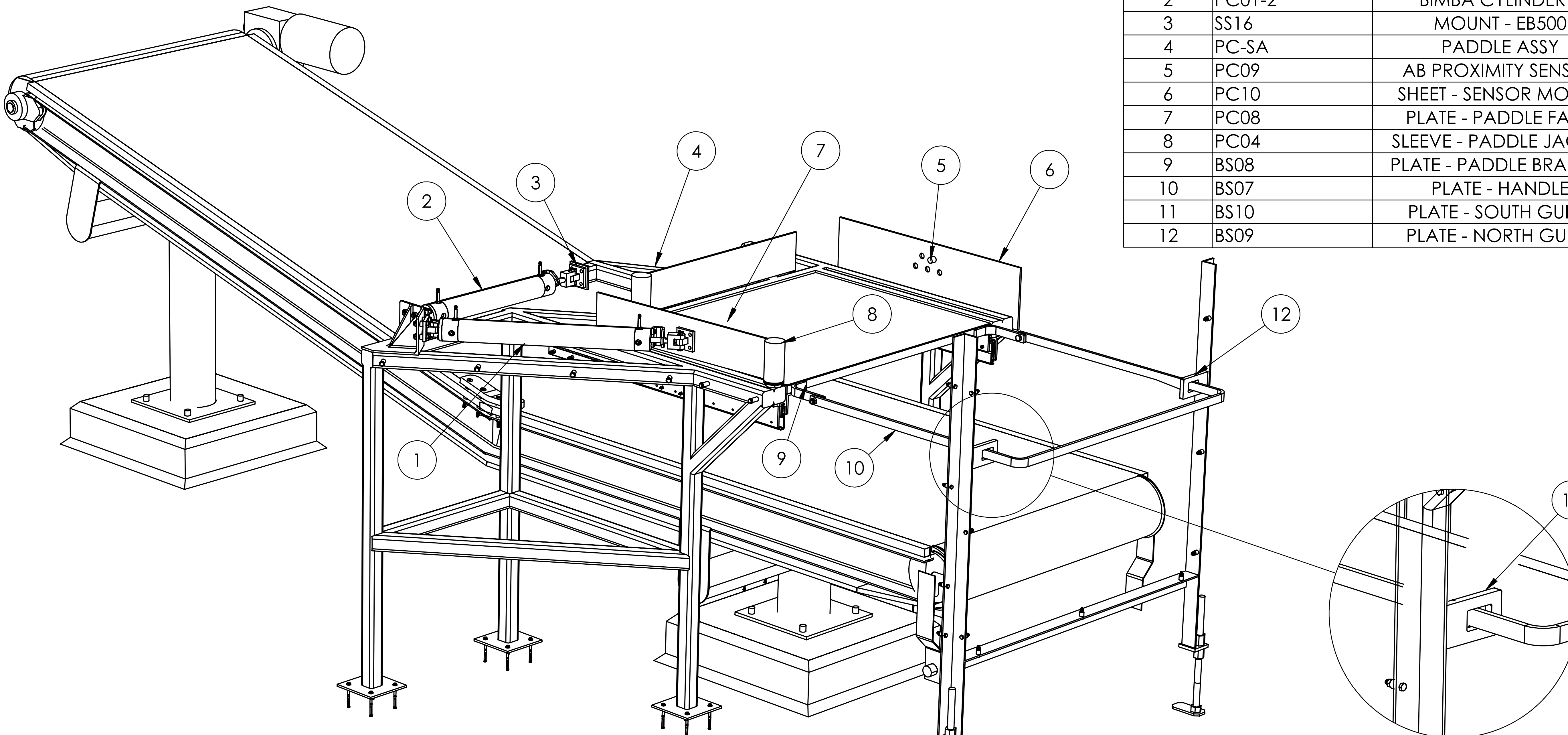
DWG. NO.

REV

WEIGHT:

SHEET 1 OF 2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	PC01	BIMBA CYLINDER 1	1
2	PC01-2	BIMBA CYLINDER 2	1
3	SS16	MOUNT - EB500	2
4	PC-SA	PADDLE ASSY	1
5	PC09	AB PROXIMITY SENSOR	1
6	PC10	SHEET - SENSOR MOUNT	1
7	PC08	PLATE - PADDLE FACE	2
8	PC04	SLEEVE - PADDLE JACKET	2
9	BS08	PLATE - PADDLE BRACKET	2
10	BS07	PLATE - HANDLE	1
11	BS10	PLATE - SOUTH GUIDE	1
12	BS09	PLATE - NORTH GUIDE	1



DETAIL A
SCALE 1 : 6

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3RD ANGLE PROJECTION

DO NOT SCALE DRAWING

TITLE: SUB ASSY - BYPASS AND PADDLE SYSTEM

PART NUMBER: BP-PC-SUB ASSY

COMMENTS:

SIZE: B

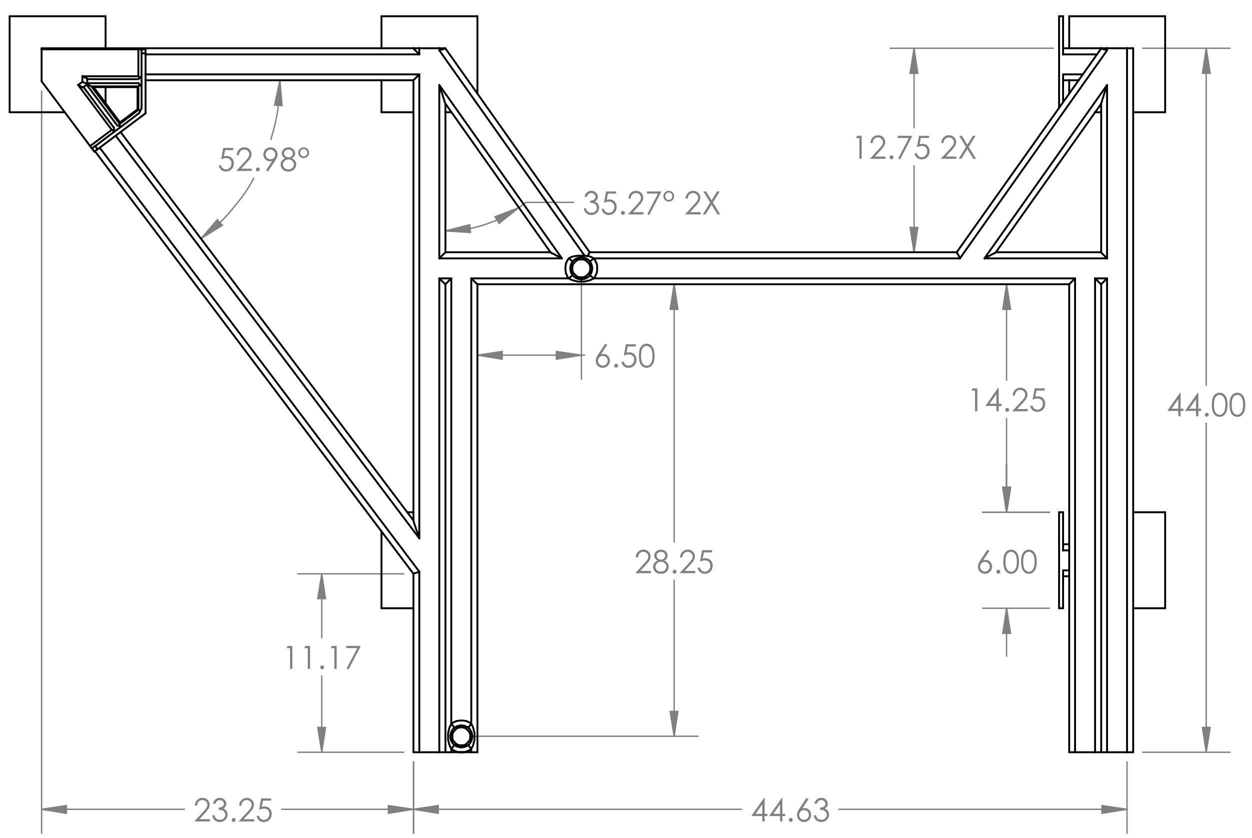
DWG. NO.

REV

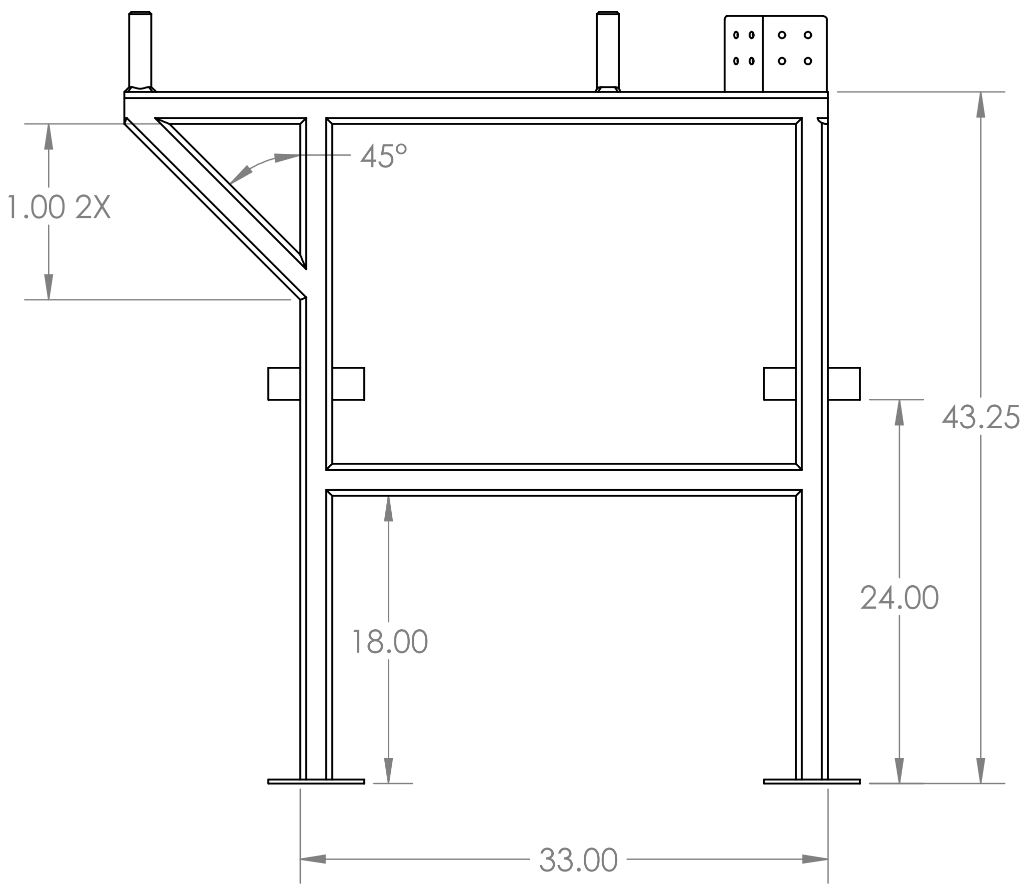
WEIGHT:

SHEET 1 OF 2

TOP



LEFT-SIDE



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.XX = ± .005
ANGLES = ± 1°

3RD ANGLE PROJECTION

DO NOT SCALE DRAWING

TITLE:
TITLE HERE

PART NUMBER:
SUB ASSY - BYPSDD

COMMENTS:

SIZE
B

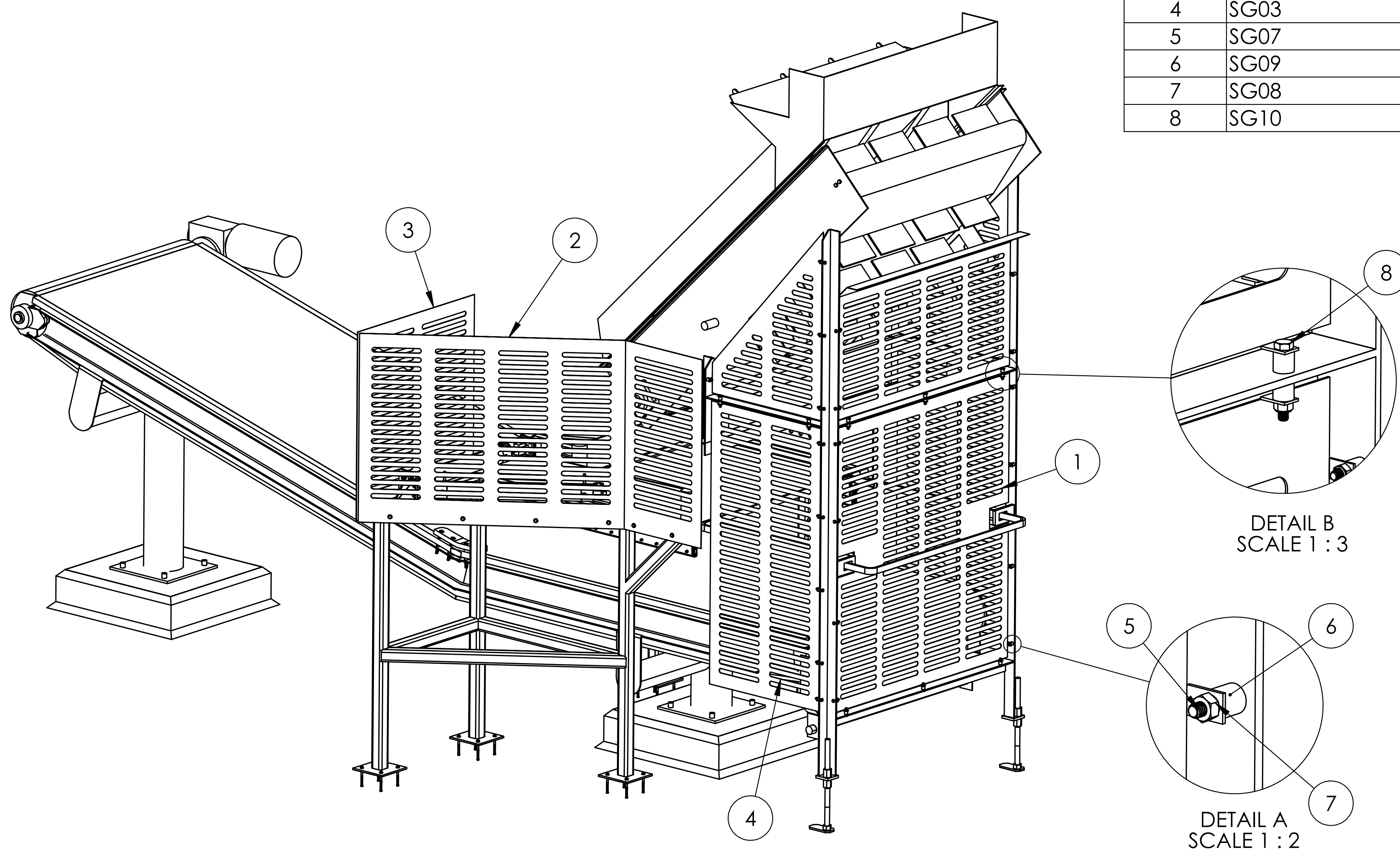
DWG. NO.

REV

WEIGHT:

SHEET 2 OF 2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SG04	SHEET - SAFETY GAURD 4	1
2	SG01	SHEET - SAFETY GAURD 1	1
3	SG02	SHEET - SAFETY GAURD 2	1
4	SG03	SHEET - SAFETY GAURD 3	2
5	SG07	M6 SST - BOLT 30MM	33
6	SG09	0.5" SST - SPACER	47
7	SG08	M6 SST - NYLOC NUT	40
8	SG10	M6 SST - 45MM BOLT	13



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ANGLES = ± 1°

3RD ANGLE PROJECTION

DO NOT SCALE DRAWING

TITLE: SAFETY GUARDS - SUB ASSY

PART NUMBER: SAFETY GUARDS - ASSY

COMMENTS:

SIZE **B**

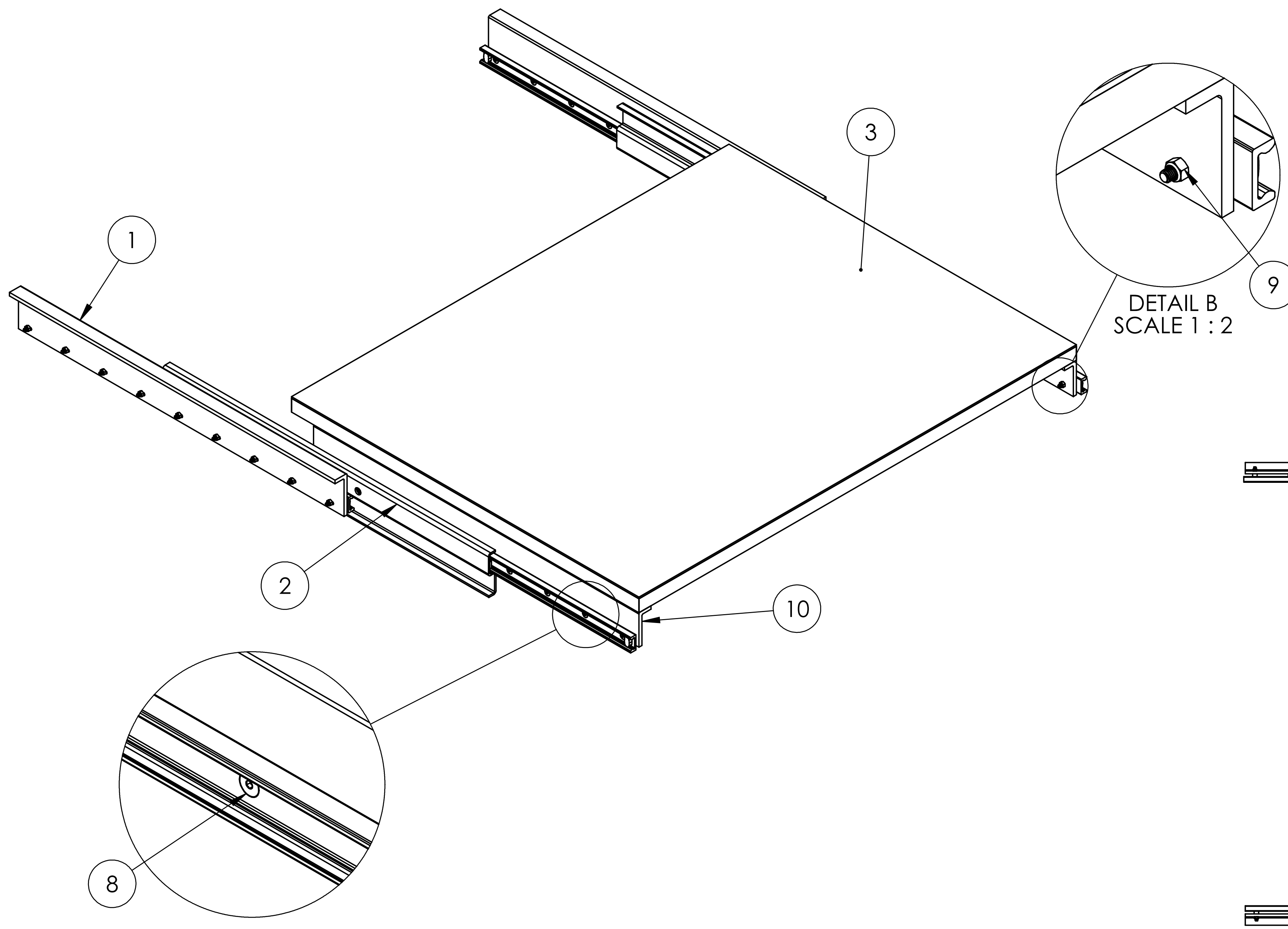
DWG. NO.

REV

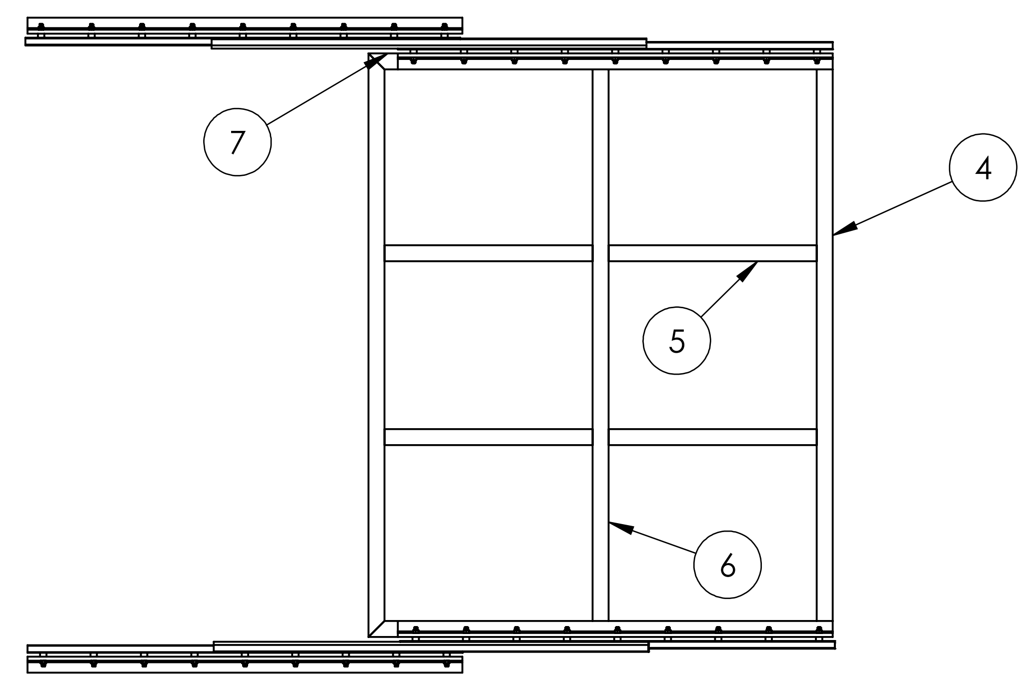
WEIGHT:

SHEET 1 OF 2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	BS11	BRACKET - OUTER SLIDE	1
2	BS01	LINEAR SLIDE	2
3	BT01	SHEET - BYPASS TOP	2
4	BT03	TUBE - MITRE STR. 3	5
5	BT05	TUBE - STR. 5	2
6	BT04	TUBE - STR. 4	2
7	BT02	TUBE - MITRE STR. 3	2
8	BS04	C/S 1/2" BOLT	1
9	BS05	1/2" NYLOC	2
10	BS12	BRACKET - INNER SLIDE	2



DETAIL A
SCALE 1 : 2



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.X = ± .01
.XX = ± .005
ANGLES = ± 1°

3RD ANGLE PROJECTION

TITLE: BYPASS TABLE - SUB ASSY

PART NUMBER: SUB DRW - SLIDING TABLE

COMMENTS:

SIZE: **B**

DWG. NO.

REV

WEIGHT:

SHEET 1 OF 2

5 Conclusion

The team designed an automated pork loin reorientation system for HyLife Foods LP that rotates a pork loin 180 degrees. The system was designed to eliminate the poor ergonomics and 1.8 seconds of nonvalue added time from the existing manual reorientation process on the north loin line at their Neepawa, MB facility. The system was designed with approved materials and satisfies the FDA 2017, FS119, and AMI standards for foodsafe production. The entire design costs $36,981.23 (USD), which meets the $200,000 (CAD) limit specified by the client. The system designed by the team automatically re-orients the loin by utilizing two pneumatically actuated paddles. The first paddle rotates the loin 90 degrees on a table, followed by an additional 90 degrees with the second paddle, pushing the loin backwards off of the bypass table onto the conveyor underneath the table. The loin is then delivered to the operators further along the conveyor in the desired orientation. To facilitate the paddle table design and bypass mechanism, the existing lower conveyor must be lowered 24” to provide clearance between the loin, table, decline and lower conveyor. The conveyor itself has been designed to a conceptual level based on the existing conveyor CAD model provided to the team, and is expected to be designed and implemented by the company contracted by HyLife to build it. Further, the selection of wiring, tubing, solenoids, and air fittings have been left to future work since they are standard inventory items in the HyLife facility. To ensure operator safety, safety guards have been designed to surround all moving components. Downtime is minimized with a manual bypass feature. The manual bypass consists of a sliding table that moves backwards, out of the way of the loin as it drops off the decline conveyor. The loin passes through the space vacated by the retracted table, thus landing directly on the lower conveyor and is delivered to the operators in its initial orientation. To operate the bypass, the operator needs to only lift the bypass handle and pull the table back, at which point the handle folds down out of the way when fully retracted.

Lastly, the design is complete and the project deliverables have been obtained. Component specifications, drawings, CAD models, cost analysis, and a functional description of the design have been provided to allow the client to implement the system if desired. The target specifications which were established at the onset of the project are mostly met, with the exception of a few that are dependent on testing. The following specifications require the physical system to be built for their evaluation:

- Noise level
- Startup/stop time
- Uptime and reliability
- Variation in loin discharge angle
- Endurance and lifespan of components
- Time without ingress from high pressure washing
- Operational cost
- Disassembly and cleaning time

Moving forward with this design our team has a few recommendations pertaining to areas of the design that would require further investigation before implementation. Such areas would include calibration of the air pressure to the cylinders, commissioning of the PLC system, and contacting Frontmatec. The plant air pressure is set at 100 PSI, but through the use of a regulator, the air pressure feeding the pneumatic cylinders should be reduced to provide only what is required. The regulated air pressure would result in decreased force from the cylinders, but may result in a more controlled motion and less wear and tear on components. A PLC flowchart has been presented within this report, but further testing and debugging of the logic would be required upon installation. Debugging may include the addition of more sensors or controls in the PLC logic to permit increased uptime and reduced false alarms. In addition to the recommendations there are two future work items. The first future work item involves HyLife reaching out to Frontmatec to coordinate the final design of the lower conveyor based upon the proposed design, as discussed earlier. The second future work item would be to spec out all wiring, air supply tubing, fittings, and solenoids.

6 References

[1] E. D. T. 7, *Site Photos,* Neepawa, 2019.

[2] AMI Foundation, "2014 Sanitary Equipment Design Taskforce," AMI Foundation, Washington, DC, 2014.

[3] R. H. S. a. D. J. Erickson, "Sanitary Design and Construction of Food Equipment," Institute of Food and Agricultural Sciences (IGES), Florida, 2014.

[4] FDA U.S. Food & Drug Administration , "2017 Food Code," FDA U.S. Food & Drug Administration , College Park, MD 20740, 2017.

[5] Intralox, "2019 MODULAR PLASTIC CONVEYOR BELTS ENGINEERING," [Online]. Available: https://intraloxpublic.myrevbase.com/v?lang=en. [Accessed 11 11 2019].

[6] Keltech, "IP69K Motors," [Online]. Available: http://www.keltechltd.com/products/id/31. [Accessed 17 11 2019].

[7] Dassault Systems, *Solidworks Software,* 2020.

[8] Linear Positioning Systems, "Stainless Steel Linear Bearing - Washdown Ready," TPA Motion, [Online]. Available: https://www.linearpositioningsystems.com/stainless-steel-linear-bearings.html. [Accessed 15 November 2019].

[9] T RACE Linear Technologies, "Linear & Telescopic Slides Catalog 2017," T RACE, [Online]. Available: https://www.linearpositioningsystems.com/pdf/trace/telerace-2017-full-catalog.pdf. [Accessed 18 Novemeber 2019].

[10] L. P. Solutions, "Waterproof Actuators," [Online]. Available: https://www.linearpositioningsystems.com/waterproof-actuator.html. [Accessed 14 November 2019].

[11] J. K. N. Richard G. Budynas, Shigley's Mechanical Engineering Design - Tenth Edition, New York: McGraw Hill Education, 2015.

[12] Lincoln Electric, "Stainless Alloy Electrodes - ER316/316L," Lincoln Electric, [Online]. Available: https://www.lincolnelectric.com/en-

ca/Consumables/Pages/product.aspx?product=Products_Consumable_StainlessNickelandHighAlloy-Lincoln-LincolnER316316L(LincolnElectric). [Accessed 25 November 2019].

[13] Atlas Steels, "Atlas Steels - Grade Data Sheet - 316 316L 316H," January 2011. [Online]. Available: http://www.atlassteels.com.au/documents/Atlas_Grade_datasheet_316_rev_Jan_2011.pdf. [Accessed 21 Novemeber 2019].

[14] Dupont, "Delrin - The High Performance Acetal Resin," [Online]. Available: https://www.dupont.com/products/delrin.html. [Accessed 21 November 2019].

[15] Dupont, "Dupont - General Design Principles - Module 1: Chapter 8," [Online]. Available: https://www.dupont.com/content/dam/dupont/products-and-services/plastics-polymers-and-resins/thermoplastics/documents/General%20Design%20Principles/General%20Design%20Principles%20for%20Bearings.pdf. [Accessed 22 November 2019].

[16] Bimba , "Tie-Rod Eye Bracket," [Online]. Available: https://www.bimba.com/Products-and-Cad/Actuators/Inch/Accessories/Mounting-Brackets/Pivot-Brackets-Eye-Brackets/NFPA-Tie-Rod-Eye-Bracket-TATASTDFMTRAMS-Series. [Accessed 21 November 2019].

[17] Bimba, "Double-Wall® NFPA "MP-4" Pivot Bracket," [Online]. Available: https://www.bimba.com/Products-and-Cad/Actuators/Inch/Accessories/Mounting-Brackets/Pivot-Brackets-Eye-Brackets/Double-Wall-NFPA-MP-4-Pivot-Bracket-Bimba-DW-Series. [Accessed 18 11 2019].

[18] Bimba, "Repairable Stainless Round Cylinders," [Online]. Available: https://www.bimba.com/Products-and-Cad/Actuators/Inch/NFPA/Guided-Thrusters/NFPA-Repairable-Stainless. [Accessed 3 Novemeber 2019].

[19] Bimba, "Magnetic Switch Products," [Online]. Available: https://www.bimba.com/sites/default/files/Library%20Archives/Catalogs/Bimba/PFL-0119_Pneumatic-Switches.pdf. [Accessed 5 November 2019].

[20] TSI Solutions, "Bimba Proximity Sensor," TSI Solutions, [Online]. Available: https://www.tsisolutions.us/itemdetail/RSU-1-Q. [Accessed 13 November 2019].

[21] Rexel USA, "Allen-Bradley 42CSS-D1MPA3-D4 CYLINDRICAL," Rexel USA, [Online]. Available: https://www.rexelusa.com/usr/Root-Category/Control%2C-

Automation/Sensors/Photoelectric---High-Performance/Diffuse-Reflective-Sensors/Allen-Bradley-42CSS-D1MPA3-D4-CYLINDRICAL/p/410899. [Accessed 12 November 2019].

[22] Gerrie , "https://www.gerrie.com/2362111/Product/Allen-Bradley-Rockwell-Auto-42CST-D1MPA3-D4," [Online]. Available: https://www.gerrie.com/2362111/Product/Allen-Bradley-Rockwell-Auto-42CST-D1MPA3-D4. [Accessed 10 11 2019].

[23] Ecolab, "Ecolab Products Home," Ecolab, [Online]. Available: https://en-ca.ecolab.com/. [Accessed 3 November 2019].

[24] Matrix Solutions , "Keltech SSM0145CT," Matrix Solutions, [Online]. Available: https://www.industrialmatrix.com/Listing/72729. [Accessed 21 November 2019].

[25] Metals Depot, "Home Page," Metals Depot, [Online]. Available: https://www.metalsdepot.com/. [Accessed 22 November 2019].

[26] Ryerson Metals, "Stainless-Steel Tube," Ryerson Metals, [Online]. Available: https://www.ryerson.com/catalog/107117. [Accessed 22 November 2019].

[27] R. Metals, "Stainless-Steel Plate," Ryerson Metals, [Online]. Available: https://shop.ryerson.com/catalog/search/107113. [Accessed 22 November 2019].

[28] McHone Industries, Inc., "How Much Does Laser Cutting Steel Cost Per Inch?," McHone Industries, Inc., 7 10 2019. [Online]. Available: https://blog.mchoneind.com/blog/how-much-does-laser-cutting-steel-cost. [Accessed 28 11 2019].

[29] COHERENT rofin, "Laser Cutting of Mild Steel," COHERENT rofin, [Online]. Available: https://www.rofin.com/en/applications/laser-cutting/mild-steel/. [Accessed 28 11 2019].

[30] McMaster-Carr, "Fastening & Joining," McMaster-Carr, [Online]. Available: https://www.mcmaster.com/. [Accessed 19 November 2019].

[31] CRAFTJACK, "How Much Does Metal Welding Cost?," improvenet, [Online]. Available: https://www.improvenet.com/r/costs-and-prices/metal-welding-cost. [Accessed 28 11 2019].

APPENDIX A

CLIENT EVALUATION

Table of Contents

1 Concept 1 Evaluation

Concept Evaluation Form

Concept Number: 1 Evaluated By: AADY TOM THOMAS Date: 22 OCT 19

Rate the following on a scale of 1 to 5, with 1 being "strongly disagree" and 5 being "strongly agree".

1. The design is durable.	1	2	3	4	5
2. The design is easy to clean.	1	2	3	4	5
3. The design is rugged.	1	2	3	4	5
4. The design is ~~in~~sensitive to loin size and orientation.	1	2	3	4	5
5. The design minimizes loin drop distance and potential loin damage.	1	2	3	4	5
6. The cost for this design would be acceptable.	1	2	3	4	5
7. The design is of minimal complexity in terms of number of moving parts.	1	2	3	4	5
8. The design is of minimal complexity in terms of reorienting the loin.	1	2	3	4	5
9. The design would be reliable.	1	2	3	4	5
10. The design has potential for a bypass function and would not impede production in an emergency situation.	1	2	3	4	5

Total Score: 35 **/ 50**

1

CONCEPT 1

Comment Section

Pros are:

POSITIVE RE-ORIENTATION (IF MATERIAL PRESENTED PROPERLY)
RE-USE OF CURRENT CONVEYORS AND DECLINE

Cons are:

HIGH POTENTIAL OF JAMMING
DIFFICULT AREA TO ACCESS

Items to change/redesign:

- ACCOMODATION FOR BYPASS (SLIDE OR FLIP OUT OF THE WAY?)
-

Additional Comments:

THIS IS THE PREFERRED CONCEPT.

2

2 Concept 2 Evaluation

Concept Evaluation Form

Concept Number: 2 Evaluated By: AADY TOM THOMAS Date: 22 OCT 19

Rate the following on a scale of 1 to 5, with 1 being "strongly disagree" and 5 being "strongly agree".

1. The design is durable. 1 2 3 4 5
2. The design is easy to clean. 1 2 3 4 5
3. The design is rugged. 1 2 3 4 5
4. The design is insensitive to loin size and orientation. 1 2 3 4 5
5. The design minimizes loin drop distance and potential loin damage. 1 2 3 4 5
6. The cost for this design would be acceptable. 1 2 3 4 5
7. The design is of minimal complexity in terms of number of moving parts. 1 2 3 4 5
8. The design is of minimal complexity in terms of reorienting the loin. 1 2 3 4 5
9. The design would be reliable. 1 2 3 4 5
10. The design has potential for a bypass function and would not impede production in an emergency situation. 1 2 3 4 5

Total Score: 33.5 **/ 50**

1

Comment Section

Pros are: · NO CHANGE TO DROP
· SIMPLE RE-ORIENTATION (MAYBE DIFFICULT EXECUTION)
· BY-PASS IS VERY EASY

Cons are: · INITIAL ORIENTATION IS VERY CRITICAL.
· HIGH TORQUE REQUIRED TO ROTATE LOINS AT PRODUCTION SPEEDS.
· GAURDING WOULD NEED TO BE EXTENSIVE DUE TO FORCES INVOLVED.

Items to change/redesign:

· CONTINUOUS ROTATION VS RECIPROCAL MOTION

Additional Comments:

GREAT CONCEPT. PROBABLY TOO DIFFICULT TO EXECUTE.

2

APPENDIX B

CONCEPTS

Table of Contents

List of Tables

1 Top 8 Concepts

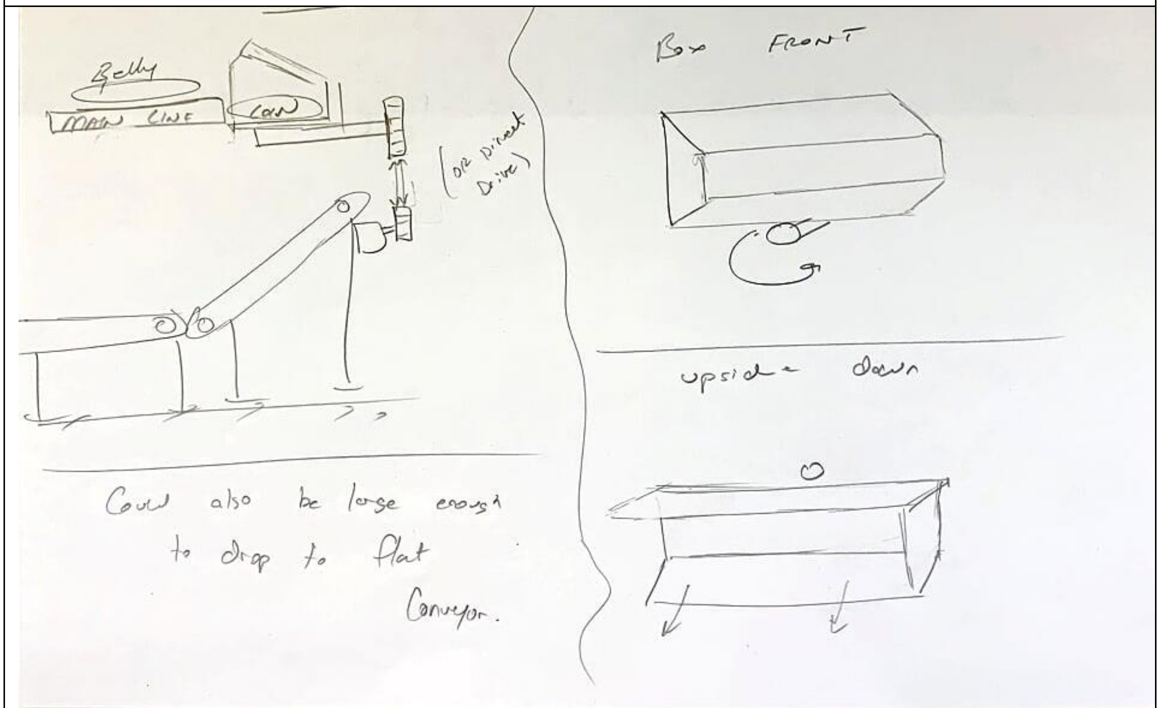
The top 8 concepts are listed in Table I:

Table I: TOP 8 CONCEPTS

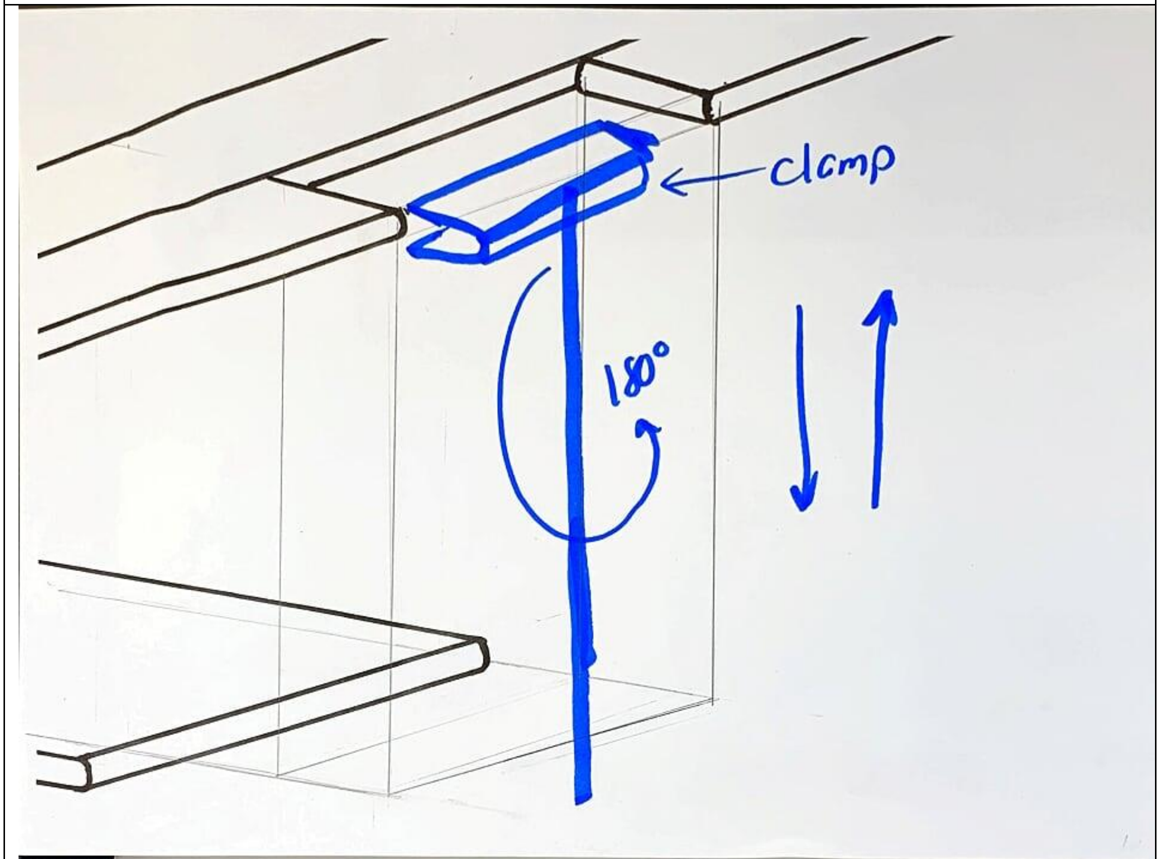
Concept Number	Concept Name
10	Loin Rota-Drop
11	Clamping Mechanism
12	Helix Conveyor
13	Conveyor/Turntable Design
14	Bite & Turn
15	Pinball Paddles
16	The Loinbine
20	Loin Chute

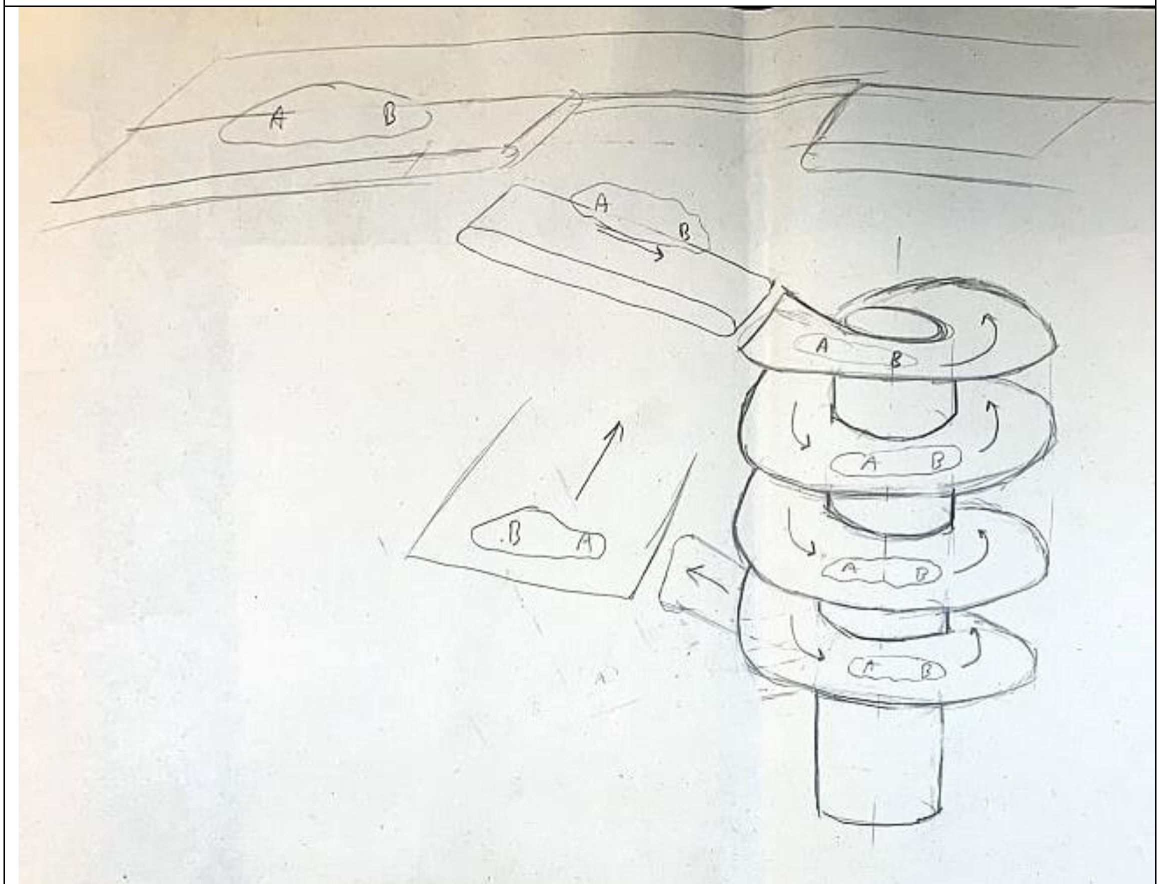
The sketches for each of the top 8 concepts are shown next with the concepts unique feature and function explained:

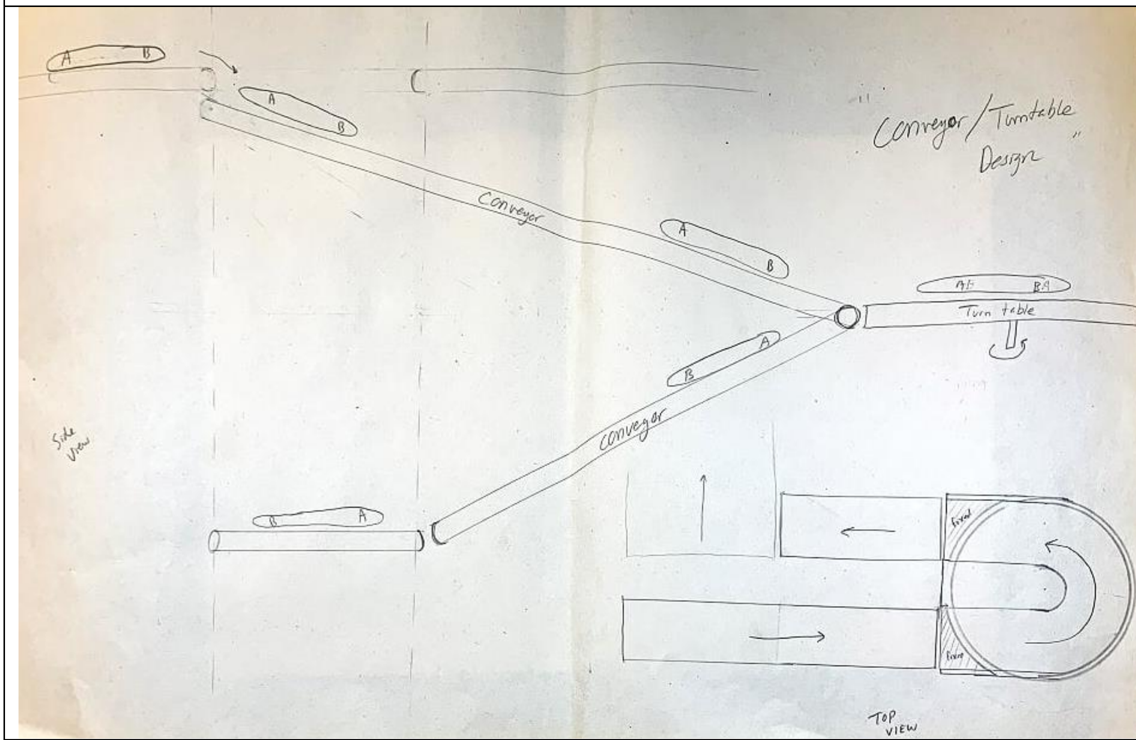
Concept 10 - Loin Rota-Drop

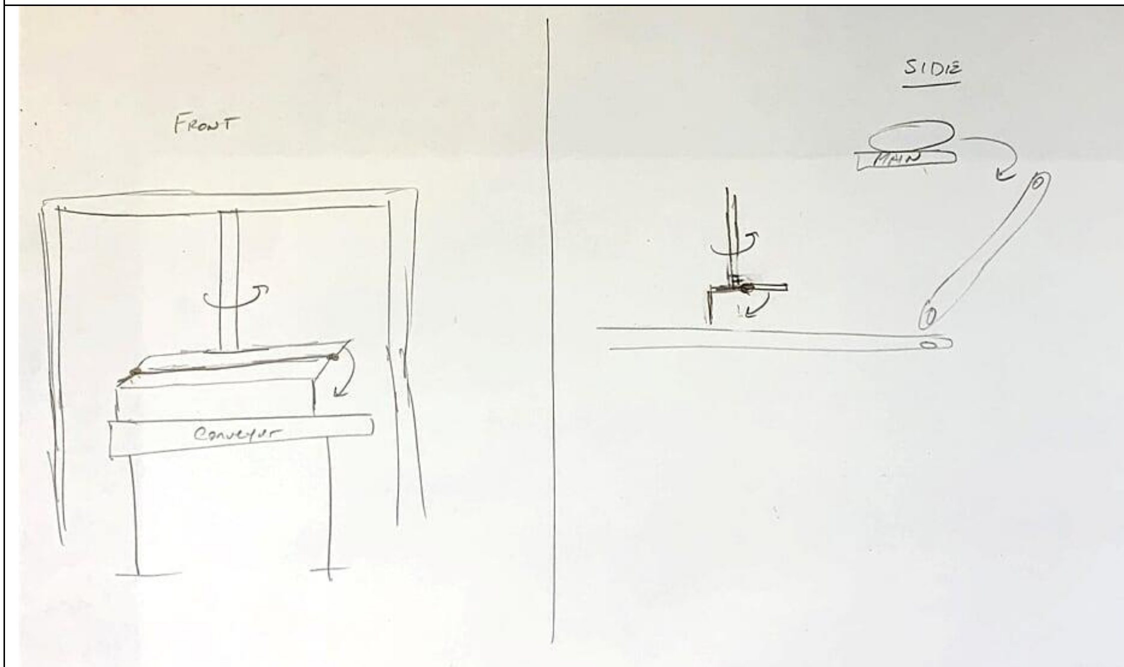


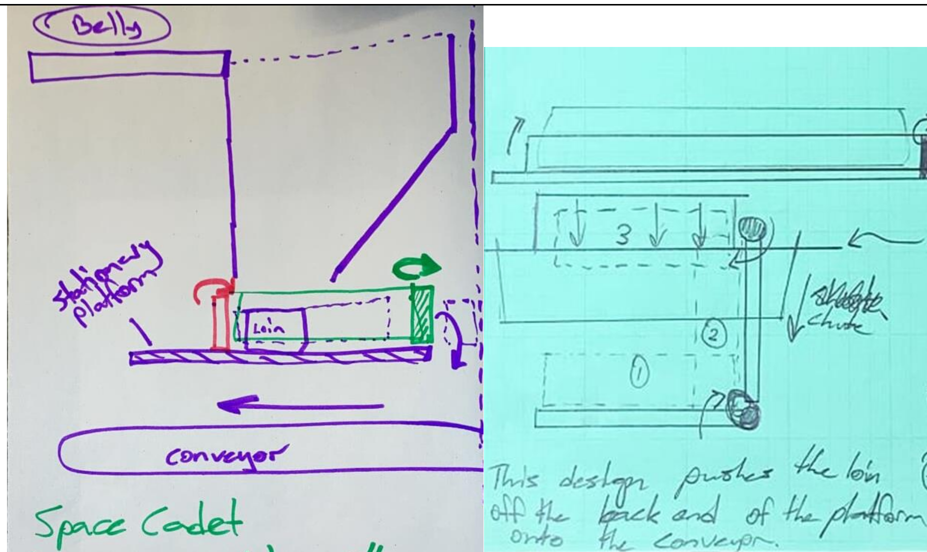
Feature	Rotating loin accept & release box
Function	The design is intended to accept the loin off of the main conveyor before rotating about the axis shown in the sketch. By dropping the loin after the 180 degree rotation is complete, the loin has been oriented correctly.

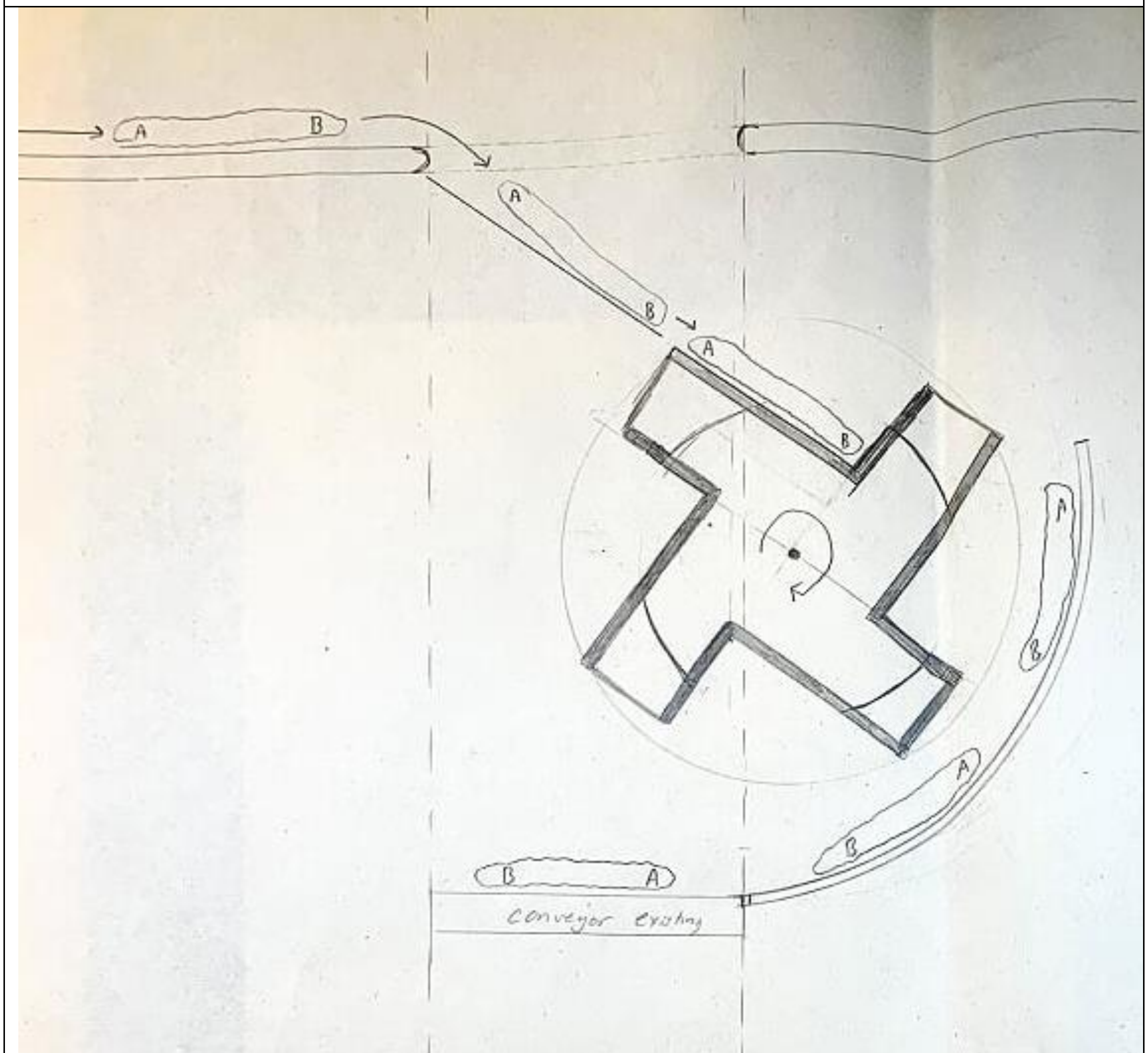
Concept 11 - Clamping Mechanism	
	
Feature	Clamping Mechanism
Function	The clamp would grab the loin and then travel downward while making a 180-degree motion turn to reorient the loin.

Concept 12 - Helix Conveyor	
	
Feature	Helical Conveyor System
Function	The loin would travel down the helical conveyor to reorient the loin.

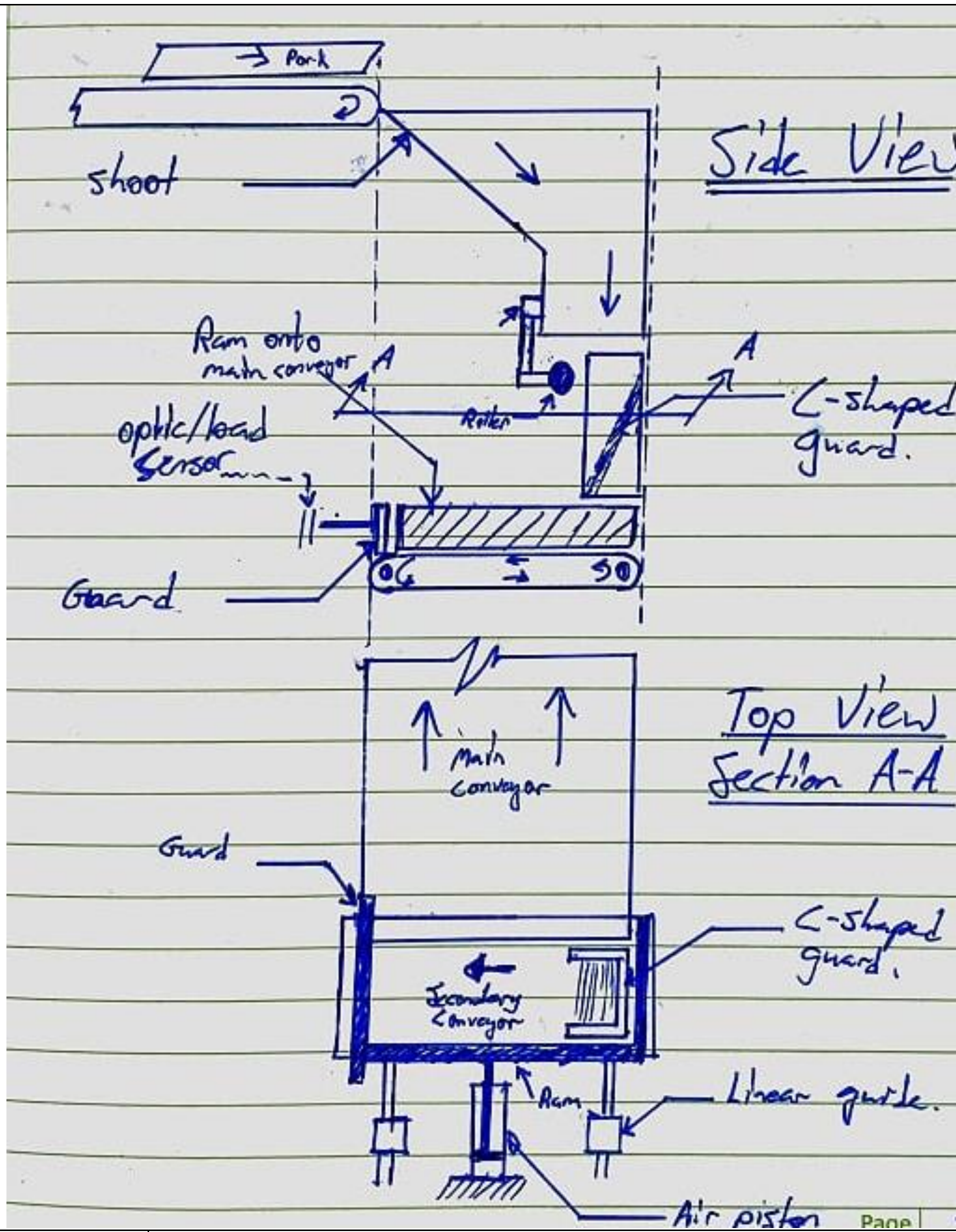
<table>
<tr><td colspan="2">Concept 13 - Conveyor/Turntable Design</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Feature</td><td>Turntable Design</td></tr>
<tr><td>Function</td><td>The loin would travel down the conveyor where the turntable would reorient the loin by 180 degrees.</td></tr>
</table>

Concept 14 - Bite & Turn	
	
Feature	Clamping and turning motions
Function	The bite and turn method traps the loin when it arrives at the device. After trapping the loin, it is turned 180 degrees then released. The conveyor takes the loin away after release.

Concept 15 - Pinball Paddles	
	
Feature	Two perpendicular paddles on a stationary platform
Function	The loin falls down the chute onto a stationary table, wherein the first paddle rotates 90 degrees, followed by the perpendicular paddle rotating an additional 90 degrees to push the loin backwards off the platform onto a moving conveyor.

Concept 16 - The Loinbine	
	
Feature	Rotating wheel with slots for the loin
Function	The loin would drop into the holder on the rotating wheel. Then as the wheel rotates clockwise the loin would fall from the holder where it would travel down a slide to reach the lower conveyor. The wheel/slide would reorient the loin.

Concept 20 - Loin Chute



Feature	Simple Chute
Function	This concept was very simple from the fact that the main component of this design was a large chute. The loin would then fall down the chute onto a conveyor which would bring the loin into position. Then a ram would transfer the loin onto the main conveyor.

2 Weighted Decision Matrix

The weighted decision matrix used to evaluate the 8 top concepts is shown in Table II.

Table II: WEIGHTED DECISION MATRIX

		Concept															
		10 Loin Rota-Drop		11 Clamping Mechanism		12 Helix Conveyor		13 Conveyor/Turn Table Design		14 Bite & Turn		15 Pinball Paddles		16 The Loinbine		20 Loin Chute	
Selection Criteria	**Weight**	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Reliability	0.18	3	0.54	3	0.54	3	0.54	5	0.89	4	0.71	4	0.71	4	0.71	5	0.89
Cost	0.04	2	0.07	3	0.11	2	0.07	3	0.11	5	0.18	3	0.11	4	0.14	4	0.14
Complexity	0.11	2	0.21	3	0.32	5	0.54	3	0.32	4	0.43	3	0.32	4	0.43	4	0.43
Safety	0.25	3	0.75	4	1.00	4	1.00	4	1.00	4	1.00	5	1.25	4	1.00	5	1.25
Ease of Integration	0.11	2	0.21	3	0.32	3	0.32	3	0.32	5	0.54	3	0.32	4	0.43	4	0.43
Commisioning Time	0.18	2	0.36	2	0.36	5	0.89	4	0.71	3	0.54	3	0.54	4	0.71	4	0.71
Cleaning/Maintenance	0.14	2	0.29	2	0.29	2	0.29	3	0.43	5	0.71	5	0.71	4	0.57	4	0.57
	TOTAL SCORE	2.43		2.93		3.64		3.79		4.11		3.96		4.00		4.43	
	RANK	8		7		6		5		2		4		3		1	
	CONTINUE ?	No		No		No		No		Yes		Yes		Yes		Yes	

APPENDIX C

CALCULATIONS

Table of Contents

List of Figures

1 Table Support Structure Calculations

The table leg analysis is simplified to a structural column with one fixed end, and one free end. A load *P* is applied axially downward on the top of the column. The table leg was composed of 2" square tubing with 0.1875" wall thickness. The tube material was 316L stainless steel. The 316L stainless steel properties $\sigma_{yield} = 24.65ksi$, and modulus of elasticity $E = 27992.3ksi$ came from Atlas Steels [1]. This loading case is shown next in Figure 1.

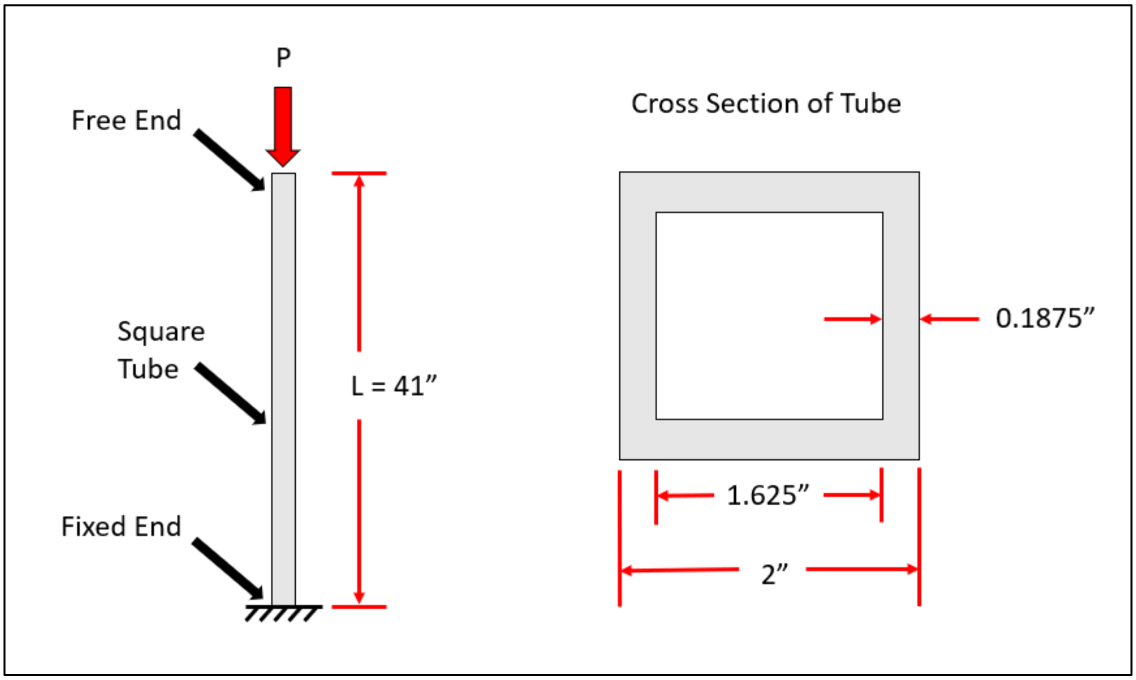


Figure 1: Load scenario diagram for the table support structure for buckling and compression analysis

The first calculation is to determine the load at which the column would fail at due to compression. To calculate the load, P, the following equation is used:

$$P = (\sigma_{yield})(A)$$

Where σ_{yield} is the yield strength of the material, and A is the cross-sectional area of the tube. The cross-sectional area is calculated as follows:

$$A = (OD)^2 - (ID)^2 = (2")^2 - (1.625")^2 = 1.36\ in^2$$

With the cross-sectional area known the max load in compression is calculated as:

$$P = \left(\sigma_{yield}\right)(A) = (24.65ksi)(1.36\ in^2) = 33{,}500\ lbs$$

Therefore, the square tube fails due to compression at a load of 33,500 lbs.

The second calculation is to determine the load at which the column would fail at due to buckling. Due to the loading scenario of one fixed end, and one free end, the effective length L of the column is equal to 2L.

To calculate the critical buckling load the moment of inertia is first calculated as:

$$I = \frac{{b_o}^4}{12} - \frac{{b_i}^4}{12} = \frac{(2in)^4}{12} - \frac{(1.625in)^4}{12} = 0.7523\ in^4$$

It should be noted that due to the symmetry of the square tube the moment of inertia is the same about the x and y axes.

With the moment of inertia known, the critical buckling is calculated as follows:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} = \frac{\pi^2(27992.3\ psi)(0.7523\ in^4)}{[(2)(41\ in)]^2} = 30{,}900\ lbs$$

With a critical buckling load of 30,900 lbs, it is deemed that the structural table leg would fail first due to buckling.

2 Bypass Table Calculations

The calculations regarding the structural integrity of the bypass table tube structure have been verified by creating a load case which is comprised of only one 36.5” tube with two fixed ends. The load case is intended to show an extreme case using the same 316L stainless steel tubing that has been selected for the tube structure. The intent is to show that if this particular tube can withstand the expected maximum load case, then surely the entire tube frame can as well, more efficiently. A total distributed load of 100kg was applied, this representing approximately 10 jammed loins in addition to the weight of the structure itself. The following is a series of calculations which result in the maximum bending stress the tube will see under the previously stated loading conditions. The loading scenario under consideration is shown next in Figure 2.

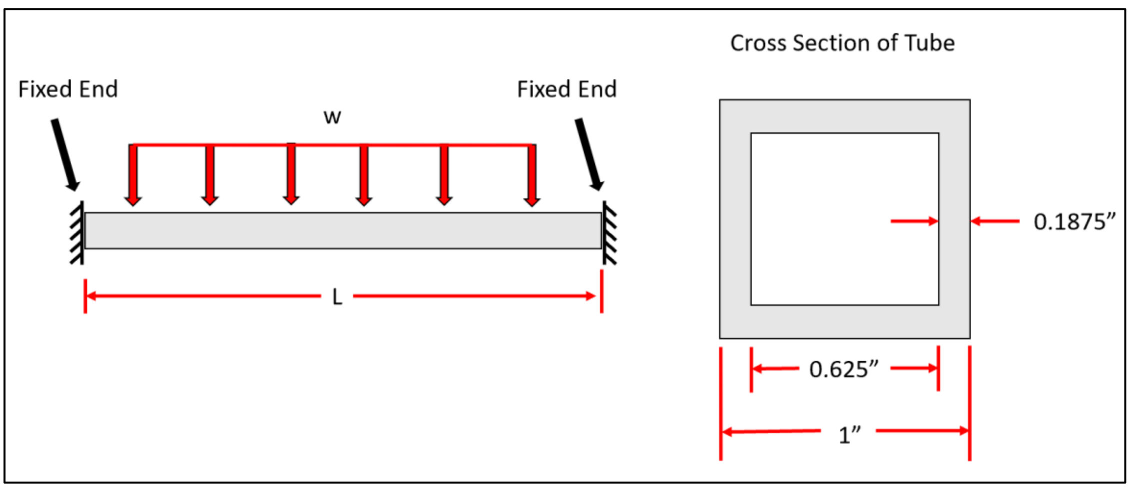


Figure 2: Bypass table distributed loading scenario

The moment of inertia for the 1” square tube selected for the application is calculated next as:

$$I = \frac{1}{12}(b_o h_o^3 - b_i h_i^3) = \left(\frac{1}{12}\right)(0.0254m^4 - 0.0159m^4 = 2.936 * 10^{-8}\ m^4$$

The neutral axis is located at the location, *c*, with a value shown next as:

$$c = 0.0127\ m$$

The length of tube, L, is 0.927m and the equivalent force at the center of the tube, F, is 981 N. The maximum moment experienced by the tube can be calculated as follows:

$$M = \frac{FL}{8} = \frac{(981N)(0.927m)}{8} = 113.67\ Nm$$

With the maximum moment established, the maximum bending stress can be calculated as seen next:

$$\sigma_{bend} = \frac{Mc}{I} = \frac{(113.67Nm)(0.0127m)}{2.936 * 10^{-8}\ m^4} = 49.169\ MPa$$

With a maximum bending stress in the tube calculated, the factor of safety can be calculated using the yield strength of 316L [2] steel as:

$$n = \frac{170.0}{49.169} = 3.45$$

With a factor of safety of 3.45 and a stress value far less than half of the ultimate strength of 316L stainless steel, the tube structure successful comes in lower than the endurance and yielding points of 316L stainless steel under tough theoretical load scenarios [2].

3 Bypass Handle Compression and Buckling Calculations

Analysis of the bypass handle in compression is broken down in the following section. This is the detailed calculations referenced in Section 3.3.4 The analysis of the bypass handle was simplified to be a beam, fixed at both ends, compressively loaded. Compression and buckling failure modes are considered. The cross-section of the bypass handle is 0.375" by 1" for a length of 25.625". The tube material was 316L stainless steel. The 316L stainless steel properties $\sigma_{yield} = 24.65ksi$, and modulus of elasticity $E = 27992.3\ ksi$ came from Atlas Steels [1].

The first calculation was to determine the load at which the column would fail at due to compression. To calculate the load, P, the following equation was used:

$$P = (\sigma_{yield})(A)$$

Where σ_{yield} is the yield strength of the material, and A is the cross-sectional area of the tube. The cross-sectional area was calculated as follows:

$$A = bh\ = (0.375)(1") =\ 0.375\ in^2$$

With the cross-sectional area known the max load in compression was calculated as:

$$P = (\sigma_{yield})(A) = (24.65ksi)(0.375\ in^2) = 9{,}244\ lbs$$

Therefore, the bypass slide would fail due to compression at a load of 9,244 lbs.

The second calculation was to determine the load at which the column would fail at due to buckling. Due to the loading scenario of two fixed ends the effective length L of the column was equal is simply L. The k-value for this double fixed-end buckling scenario will be 0.5.

To calculate the critical buckling load the moment of inertia was calculated for bending about both the X and Y axes. Figure 3 next shows the cross-section, loading case and the orientation of the X and Y axes.

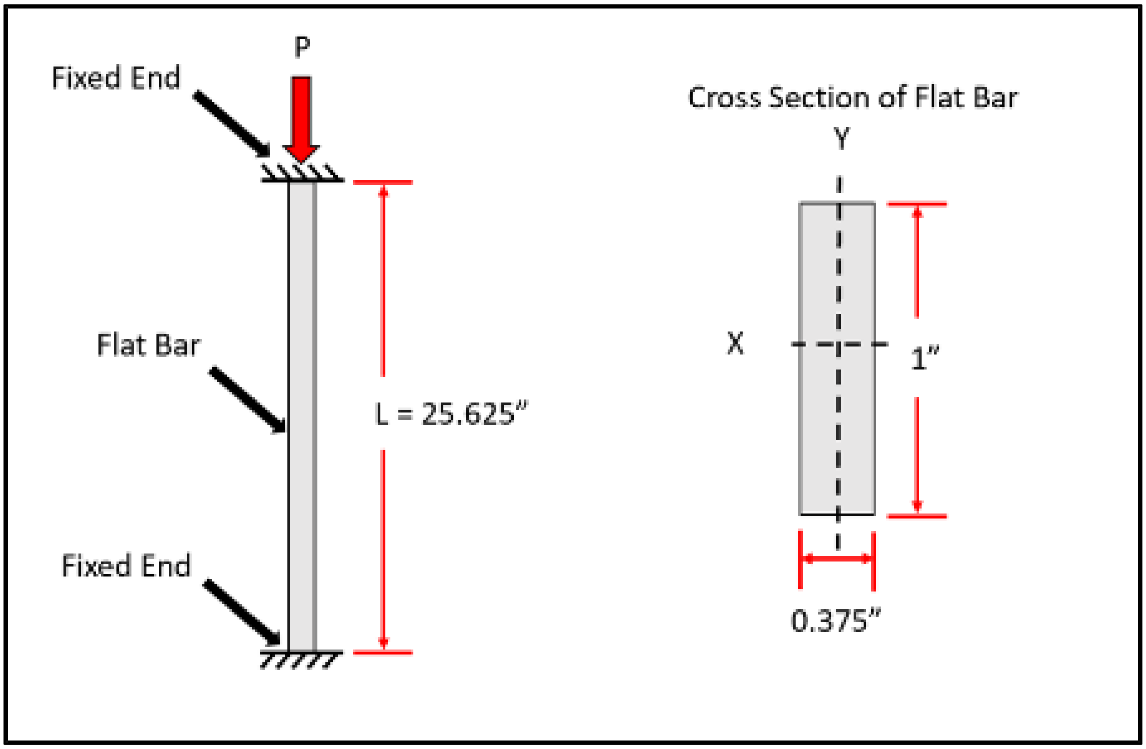


Figure 3: Bypass handle loading case

Moments of inertia of inertia, I_X and I_Y are calculated next,

$$I_X = \frac{bh^3}{12} = \frac{(0.375in)(1in)^3}{12} = 0.03125\ in^4$$

$$I_Y = \frac{bh^3}{12} = \frac{(1in)(0.375in)^3}{12} = 0.00439\ in^4$$

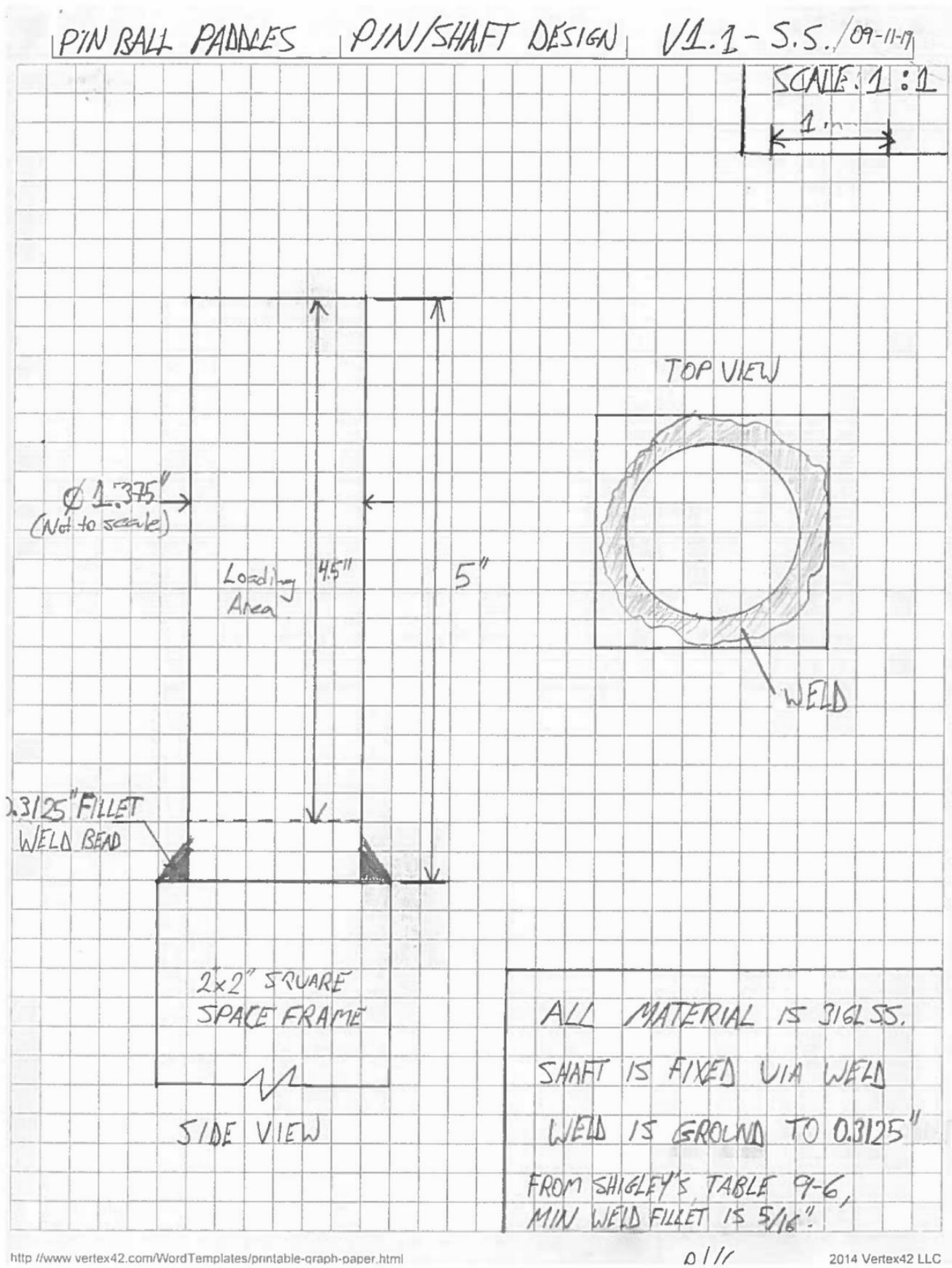
Next, the critical buckling load for both bending about the X and Y axes can be calculated. The lowest value of the two can be evaluated against the estimated maximum load that the bypass handle will experience.

$$P_{cr,X} = \frac{\pi^2 E I_X}{(KL)^2} = \frac{\pi^2(27992.3\ psi)(0.03125\ in^4)}{[(0.5)(25.625\ in)]^2} = 52{,}590\ lb$$

$$P_{cr,Y} = \frac{\pi^2 E I_Y}{(KL)^2} = \frac{\pi^2(27992.3\ psi)(0.00439\ in^4)}{[(0.5)(25.625\ in)]^2} = 7{,}397\ lb$$

Seeing that the minimum critical buckling is experienced when occurring about the Y-axis, this was the value compared directly against the estimated maximum force that the system will exert on the bypass handle.

4 Paddle Pin Calculations



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Cylinder: BIMBA RS - 2.5in BORE

HOUSE AIR IS $\approx$ 100 PSI

Assuming that the cylinder loads the shaft directly (worst case loading), the transmitted load is:

$$F = P \times A = 100\,PSI \times \frac{\pi}{4}(2.5)^2\,in^2$$

$$\therefore \underline{\underline{F = 490.9\,lbf}}$$

This load is assumed to increase from zero to 490.9 lbf and return back to zero, following a sine wave pattern with a period of 2sec. This allows for 2sec of idle time between the two paddles at a nominal 6sec cycle time.

The shaft has a diameter of 1.375in, a 0.3125in fillet weld on the base, and OAL of 5inches.

The moment of inertia, I, of the shaft is:

$$I = \frac{\pi}{64} d^4 = \frac{\pi}{64}(1.375)^4\,in^4$$

$$\therefore \underline{\underline{I = 0.1755\,in^4}}$$

Note that $c = d/2 = 0.6875in$ for the shaft

Shaft Area $A = \frac{\pi}{4} d^2 = \frac{\pi}{4}(1.375)^2 = 1.485\,in^2$

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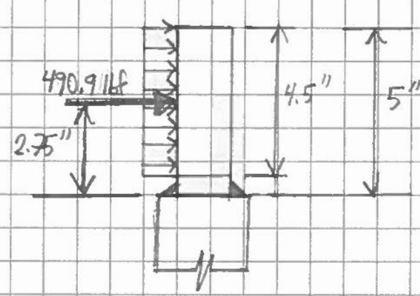
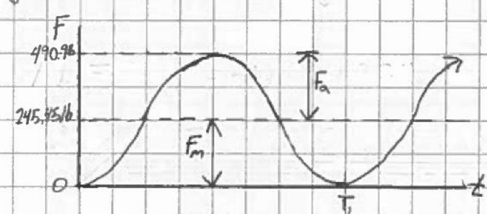
The shaft will have a bearing load transferred to the upper 4.5" which is assumed to be uniform from top to bottom:



The uniform load is approximated to occur as a point load of 490.9 lbf at 2.75in above the square tubing.

The load cycle looks like:



$$M_a = M_m = \frac{WL}{2} = \frac{490.9\ \text{lbf} \times 2.75\text{in}}{2}$$

$$\therefore M_a = M_m = 675\ \text{in-lbf}$$

$$M_{min} = 0\ \text{inlbf}$$

$$M_{max} = M_a + M_m = 1350\ \text{inlbf}$$

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The selected electrode is LINCOLN ELECTRIC'S 316/316L-15. (E90XX)

$S_y = \sigma_y = 68\ ksi$ $\quad \varepsilon_{ut} = 0.38\ in/in.$

$S_{ut} = \sigma_{ut} = 90\ ksi$

From table 9-2 (Shigley's) $\rightarrow A_u = 1.414\pi h r = 1.414 \times \pi \times 5/16 \times 0.6875\ in^2$

$$\underline{\underline{A_u = 0.9543\,in^2}}$$

$$I_u = 1.414\pi h r^3 = 1.414 \times \pi \times 5/16 \times 0.6875^3\ in^4$$

$$\therefore \underline{\underline{I_u = 0.4511\ in^4}}$$

From Table 9-4; (Shigley's) $\tau_{max_{weld}} = 0.30 S_{ut} = 0.30 \times 90 ksi \Rightarrow \underline{\underline{\tau_{max_{weld}} = 27\ ksi}}$

$$\tau_{max_{base}} = 0.40 S_{y,base} = 0.40 \times 24.6564 ksi \Rightarrow \underline{\underline{\tau_{max_{base}} = 9.862\ ksi}}$$

Atlas steels 316L

From Table 9-5: (Shigley's) $K_{fs} = 1.5$

Equation 9-4(a); (Shigley's) $\tau'_{max} = \frac{V_m}{A} = \frac{490.9\ lbf}{0.9543\ in^2} = \underline{\underline{0.514\ ksi}}$ (transverse)

9-4(d): $\tau''_{max} = \frac{Mc}{I_u} = \frac{1350 \times 0.6875\ lbf\text{-}in}{0.4511\ in^4} = \underline{\underline{2.057\ ksi}}$ (normative)

9-4(e): $\tau_{total} = (0.514^2 + 2.057^2)^{1/2} = \underline{\underline{2.120\ ksi}}$ (Combined vectors)

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Thus, from a static perspective: $\tau_{total} = 2.120\,ksi \ll 27\,ksi = \tau_{max,weld}$

The shear on the top of the 2in square tube is

$$\tau_{tube} = \frac{V_{max}}{A_{bore}} = \frac{490.9\,lbf}{\frac{\pi}{4}(2^2 - 1.375^2)\,in^2} = 0.296\,ksi << 9.862\,ksi = \tau_{max,bore}$$

The shaft and weld pass peak static loading. We now shift the analysis to fatigue using the modified goodman approach (DE-Goodman, Shigley's).

From table 6-2: (Shigley's) $a = 39.9$ $b = -0.995$ (as Forged, Weld)

Surface Factor: $K_a = a S_{ut}^{b} = 39.9 \times 70.3^{-0.995}$ $S_{ut,316L} = 485\,MPa = 70.3\,ksi$

$$K_a = 0.58$$

Size factor: $K_b = 0.879 d^{-0.107} = 0.879(1.375)^{-0.107}$

$$K_{b_1} = 0.85$$

However, K_{b_1} assumes a rotating shaft. For non-rotating circular rounds

$$d_e = 0.370\,d = 0.370(1.375) = 0.5088\,in.$$

$$K_{b_e} = 0.879(0.5088)^{-0.107}$$

$$K_{b_e} = 0.945$$

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Loading Factor: $k_c = 0.59$ (eqn. 6-26, Shigley's, Torsion/shear)

Temperature Factor: $k_d = 1.0$ (eqn, 6-27 is valid for $T \geq 70F$)

Reliability Factor: $k_e = 0.868$ (95%, table 6-5, shigley's)

Misc. Affects: $k_f = 1$

$S_e' \approx 0.5 S_{ut} = 0.5(70.34 \text{ ksi})$ (Assumed from Shigley's eqn. 6-8 $S_{ut} \leq 200$ ksi)

$S_e' \approx 35.17$ ksi. (pristine)

$S_e = k_a k_b k_c k_d k_e k_f S_e'$

$S_e = (0.58)(0.945)(0.59)(1.0)(0.868)(1.0)(35.17)$

$\underline{\underline{S_e = 9.87 \text{ ksi}}}$ (modified endurance limit)

The fatigue SCF increases the stress such that

$\sigma_{m_{weld}} = \sigma_{a_{weld}} = k_{fs}\left(\frac{\tau_{total}}{2}\right) = 1.5\left(\frac{2.12}{2}\right) = \underline{\underline{1.59 \text{ ksi}}}$ (weld)

$\sigma_{m_{tube}} = \sigma_{a_{tube}} = k_{fs} \frac{\tau_{tube}}{2} = 1.5\left(\frac{0.296}{2}\right) = \underline{\underline{0.222 \text{ ksi}}}$ (tube)

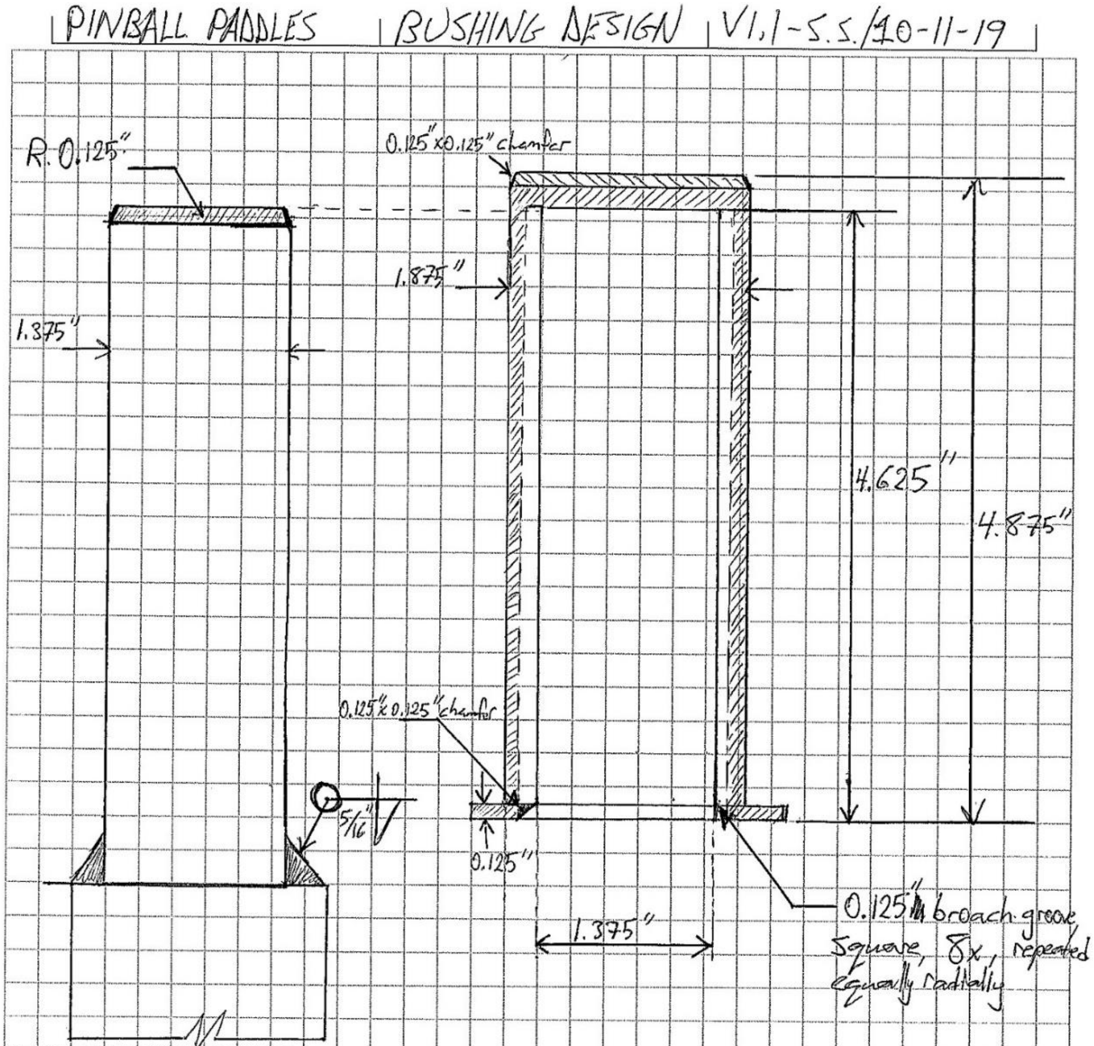
Factor of Safety: (DE-Goodman)

$n_{weld} = \frac{1}{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}}} = \frac{1}{\frac{1.59}{9.87} + \frac{1.59}{70.34}}$ $\boxed{n_{weld} = 5.44}$

$n_{tube} = \frac{1}{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}}} = \frac{1}{\frac{0.222}{9.87} + \frac{0.222}{70.34}}$ $\boxed{n_{tube} = 38.99}$

Both the weld and parent metal pass with FOS of 5.44 and 38.99 respectively. Design is approved

5 Bushing Calculations



Projected bearing surface is: $f = d \times l = 1.375'' \times 4.5'' = 6.188\,in^2$

Specific pressure: $p = \frac{P}{d \times l} = \frac{490.9\,lbf}{6.188\,in^2} = 79.34\,psi$

$p = 79.34\,psi = 0.547\,MPa$.

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The peripheral speed requires the number of cycles per minute (RPM) for continuous rotation. However, the operation is discontinuous with a rotation of +90° and −90° over the course of 2sec, every 6 seconds.

When in motion, the angular speed is thus: $\omega = \frac{90^\circ}{1\,sec.} = 0.25\,\frac{rev}{sec.}$

and in terms of RPM, we find: $\underline{\underline{n = 15\,RPM}}$.

The peripheral speed is then calculated as:

$$V = \frac{d \times n \times \pi}{1000} = \frac{1.375\,in \times 25.4\,\frac{mm}{in} \times 15\,RPM \times \pi}{1000}$$

$$V = \underline{\underline{1.646}}\,\left(\frac{m}{min}\right)$$

The P-V value is then found as:

$$PV = pV = 0.547\,(MPa) \times 1.646\,\left(\frac{m}{min}\right)$$

$$\therefore \boxed{PV = \underline{\underline{0.90}}\,\left(\frac{MPa \cdot m}{min}\right)} \ll 15\,\frac{MPa \cdot m}{min}\ \text{(Delrin 500CL)}$$

From the DuPont bearing design guide, this PV is so low that it is acceptable for all 6 curves in Fig 7.08, despite corresponding to the high PV curves 2 & 3. (Delrin on ground stainless steel). For delrin 500CL, the max PV is 15 MPa·m/min, thus this bushing passes.

Lastly, the Delrin 500CL has $\mu_s = 0.10$ and $\mu_k = 0.20$.

2/2

6 Paddle Plate Calculations

The following Figure 4 and calculations concern the bending load experienced by the paddles while pushing the loin. The first paddle has a longer length under bending, thus experiences the highest stress. If the first paddle is capable of sustaining the loads, the second will therefore be able to as well.

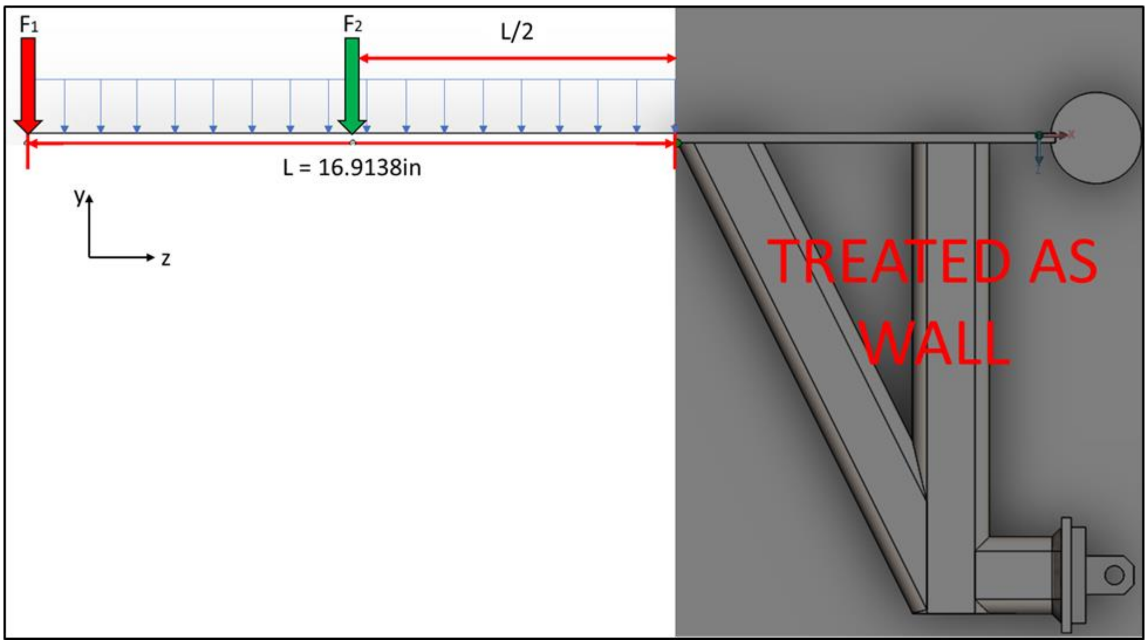


Figure 4: Paddle plate load scenario

The average loin weight is 10kg. Conversion into pound-force is calculated as follows:

$$F_{loin} = 10kg * 2.20462\frac{lbf}{kg} = 22.05lbf$$

The moment of inertia for the paddle under the two loading scenarios is calculated for the rectangular cross-section as:

$$I_{xx} = \frac{1}{12}bh^3 = \left(\frac{1}{12}\right)(5in)(0.25in)^3 = 6.51 * 10^{-3}\ in^4$$

The stress in a beam under bending is simply calculated as:

$$\sigma_{yy} = \frac{My}{I_{xx}} = \frac{FL_{eff}y}{I_{xx}}$$

Where M is the bending moment and simplifies to force times effective length. The value of y corresponds to the distance from the neutral axis to the top or bottom surface. The previous equation normally has a negative sign, but the negative has been omitted since the magnitude of the stress is the only concern. Rearranging for force, we find that:

$$F = \frac{\sigma_{yy} I_{xx}}{L_{eff}y}$$

Substituting the yield stress of 24.6564 ksi from Atlas Steels 316L, the height from the neutral axis of y = 0.125in, the moment of inertia I_{xx}, and length L, the maximum allowable force at the end of the paddle is [1]:

$$F_1 = \frac{(24.6564 * 10^3)(6.51 * 10^{-3})}{16.9138 * 0.125} = 75.92\ lbf$$

The corresponding factor of safety for this end load is:

$$n_1 = \frac{F_1}{F_{loin}} = \frac{75.92}{22.05} = 3.443$$

Since the bending moment is equal to the force times distance, the distributed loading scenario has half the bending moment about the base of the cantilever and thus half the bending stress. Therefore, the maximum allowable load F_2 and factor of safety for the distributed load are:

$$F_1 = \frac{(24.6564 * 10^3)(6.51 * 10^{-3})}{\frac{16.9138}{2} * 0.125} = 151.84\ lbf$$

And,

$$n_2 = \frac{151.84}{22.05} = 6.886$$

Thus, under the scenario described, a 0.25" plate can sustain the load from pushing the 10kg loin, whether it is loaded at the end or the 10kg load is distributed across the span of 16.9138in.

This analysis has been based on the premise of static yield characteristics and has neglected fatigue failure. The datasheet from Atlas Steels does not provide an endurance limit for the 316L steel, thus the endurance limit was assumed to be half the ultimate tensile strength. In doing so, the endurance limit is calculated as:

$$S_e = 0.5 * S_{ult} = 0.5 * 485\ MPa * 0.145 \frac{ksi}{MPa} = 35.17 ksi$$

Examining the endurance limit and the yield strength, it is apparent that the yield strength is lower than the proposed endurance limit. Therefore, yielding theoretically occurs before fatigue. Given that the static loading found no yield to occur, a 0.25" plate should be sufficient for the design.

7 References

[1] Atlas Steels, "Atlas Steels - Grade Data Sheet - 316 316L 316H," January 2011. [Online]. Available: http://www.atlassteels.com.au/documents/Atlas_Grade_datasheet_316_rev_Jan_2011.pdf. [Accessed 21 Novemeber 2019].

[2] J. K. N. Richard G. Budynas, Shigley's Mechanical Engineering Design - Tenth Edition, New York: McGraw Hill Education, 2015.

APPENDIX D

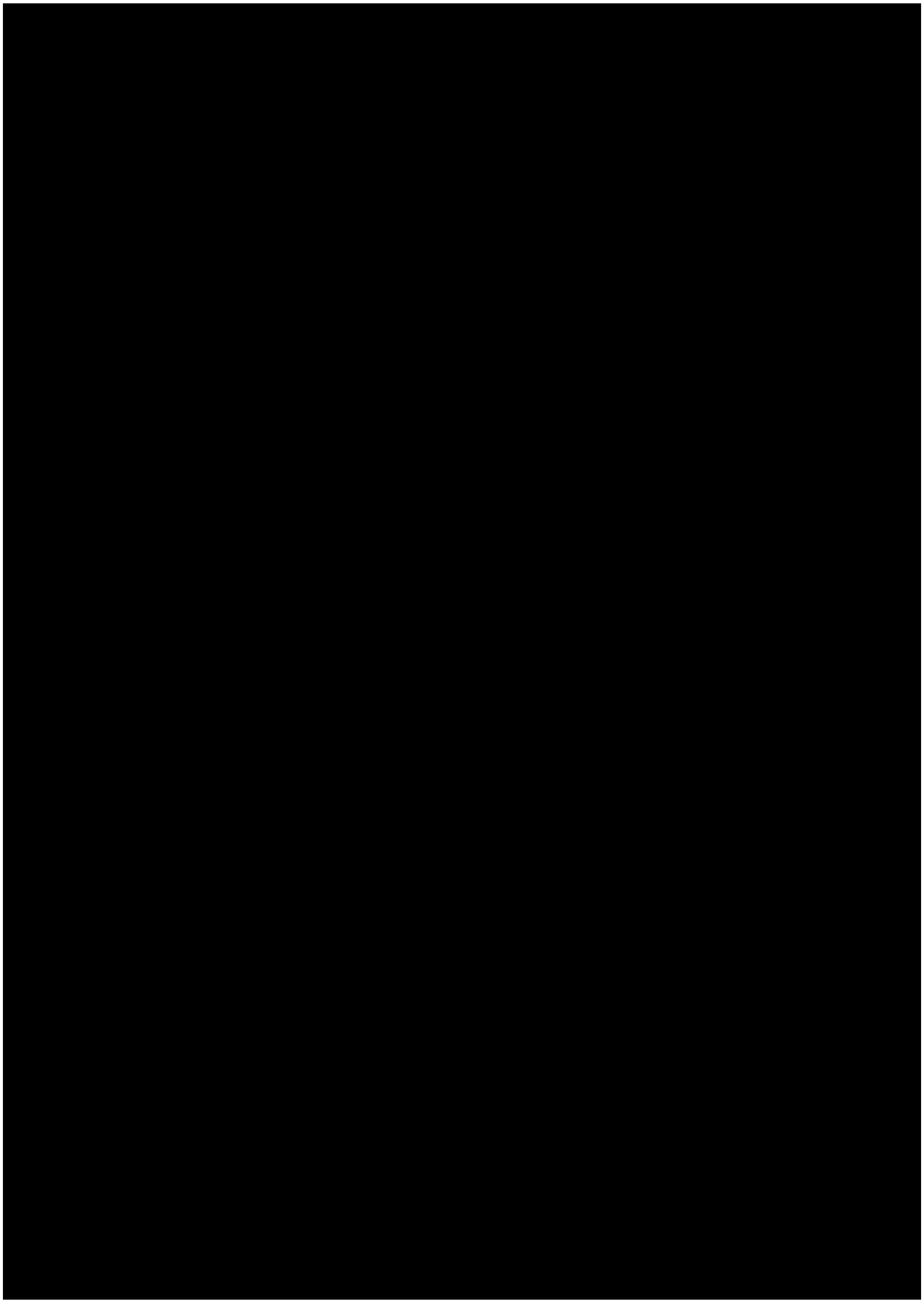
Specifications Sheets

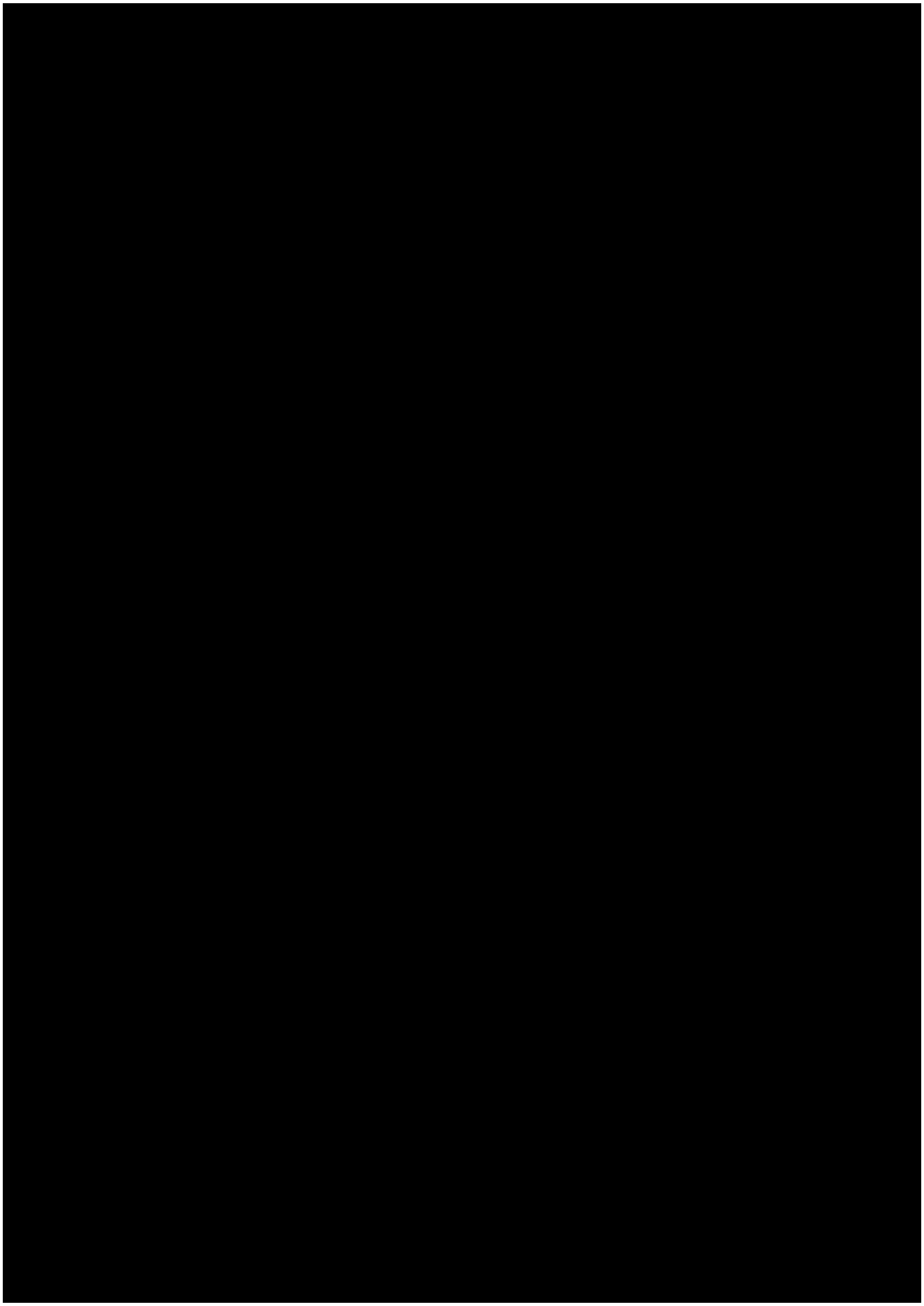
Table of Contents

1 Cleaning Chemicals [1]

The following six chemicals are used to clean the equipment in HyLife Foods LP's facilities.

1.1 BONCHEM BON FOME





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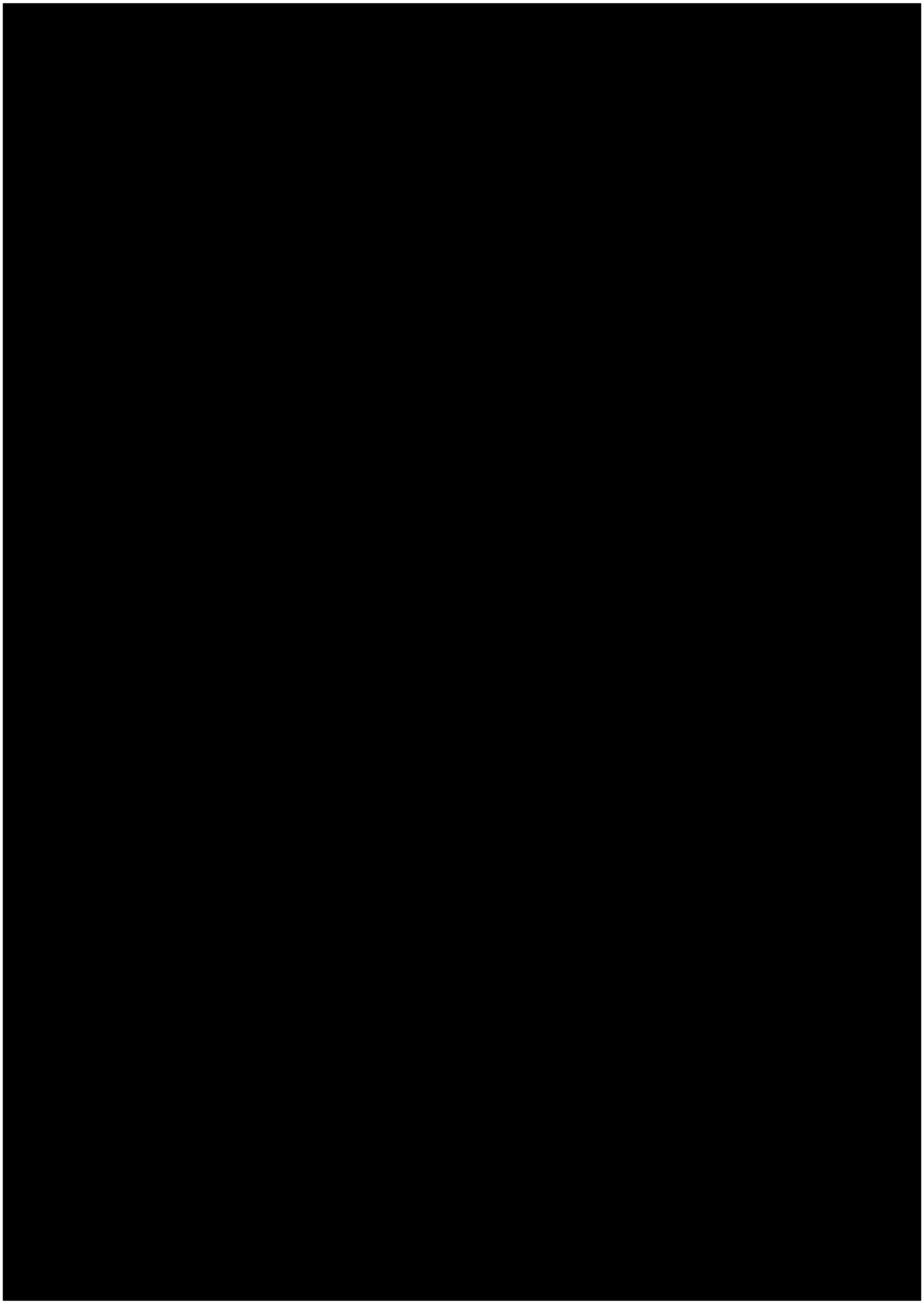

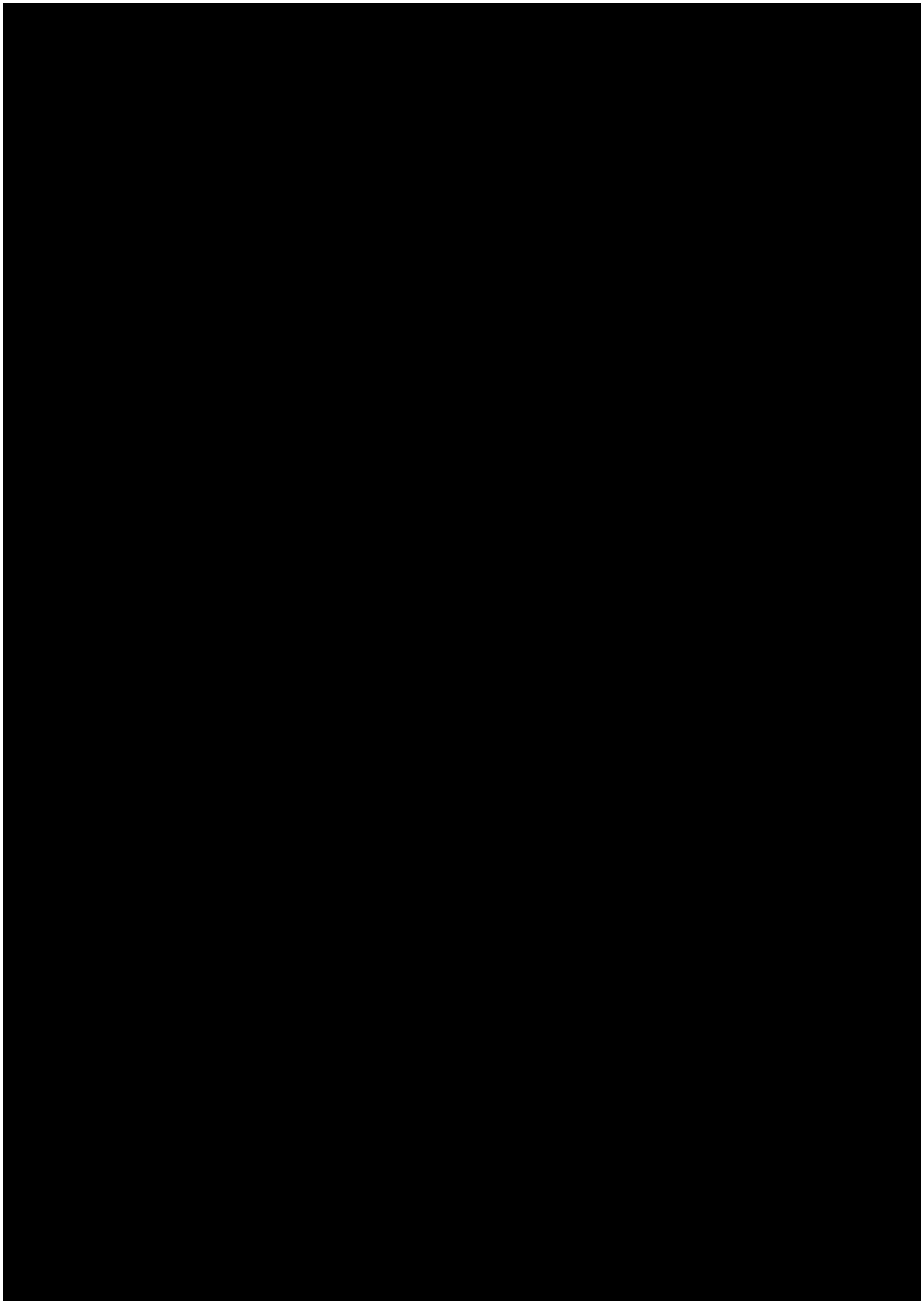

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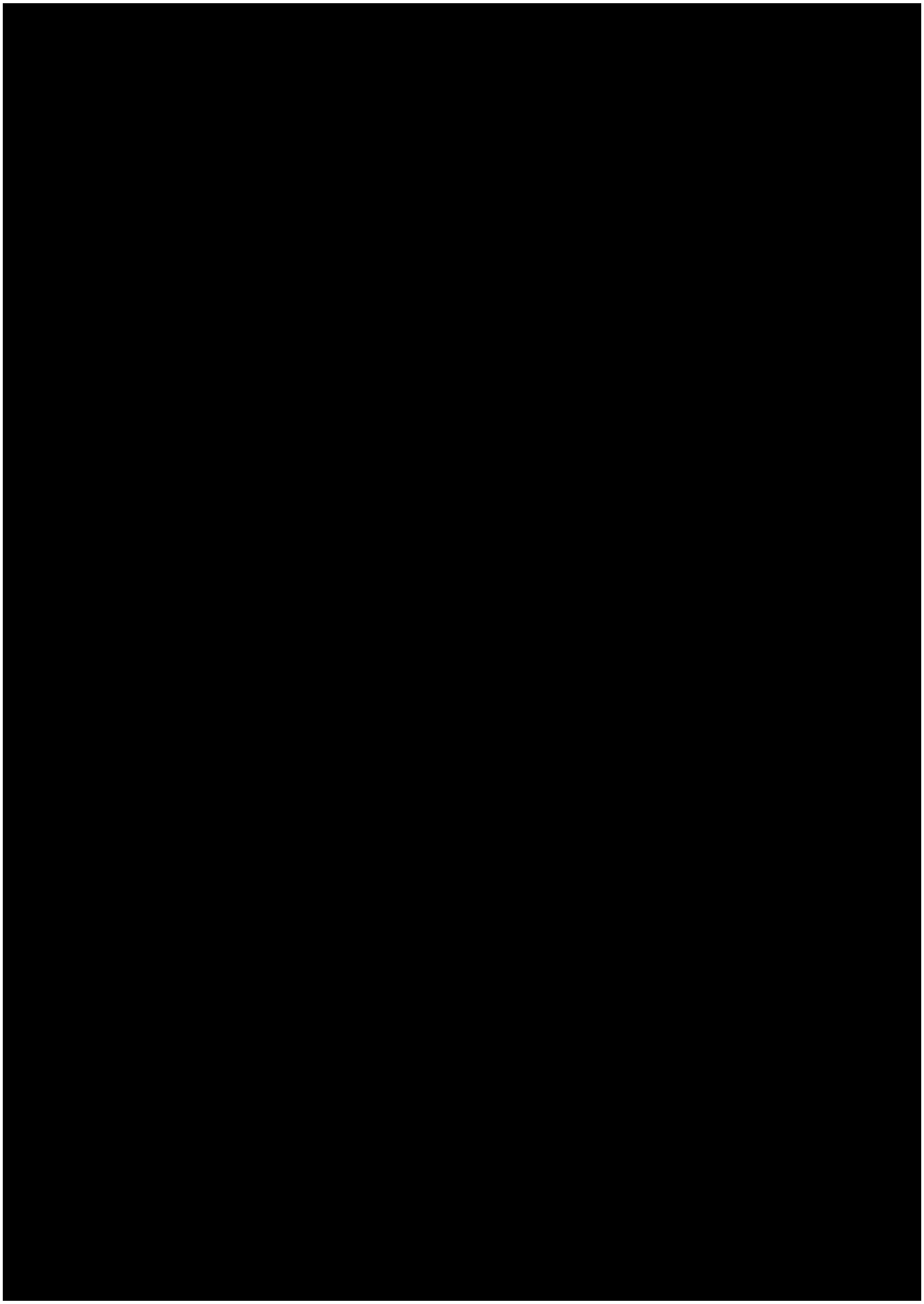

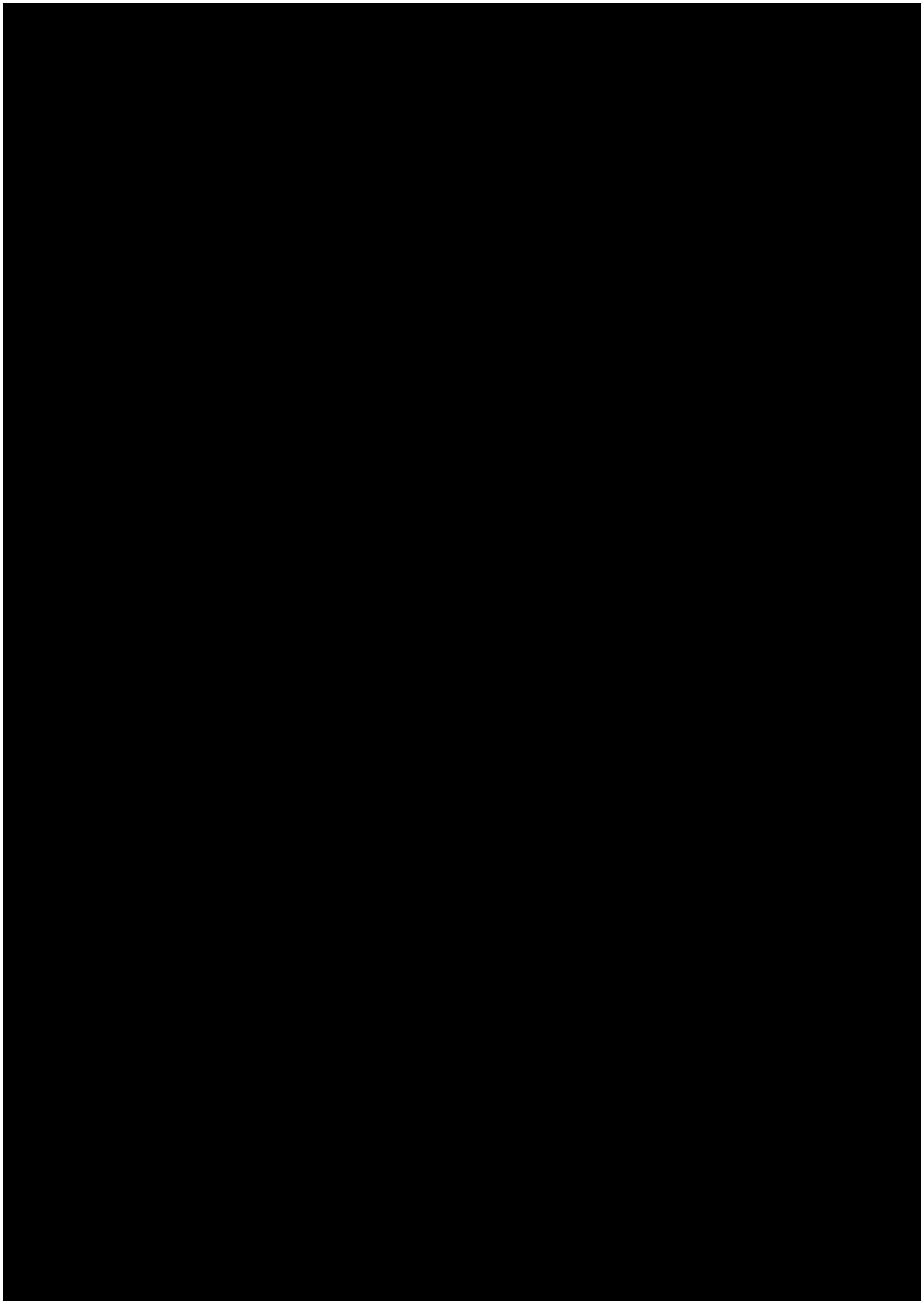

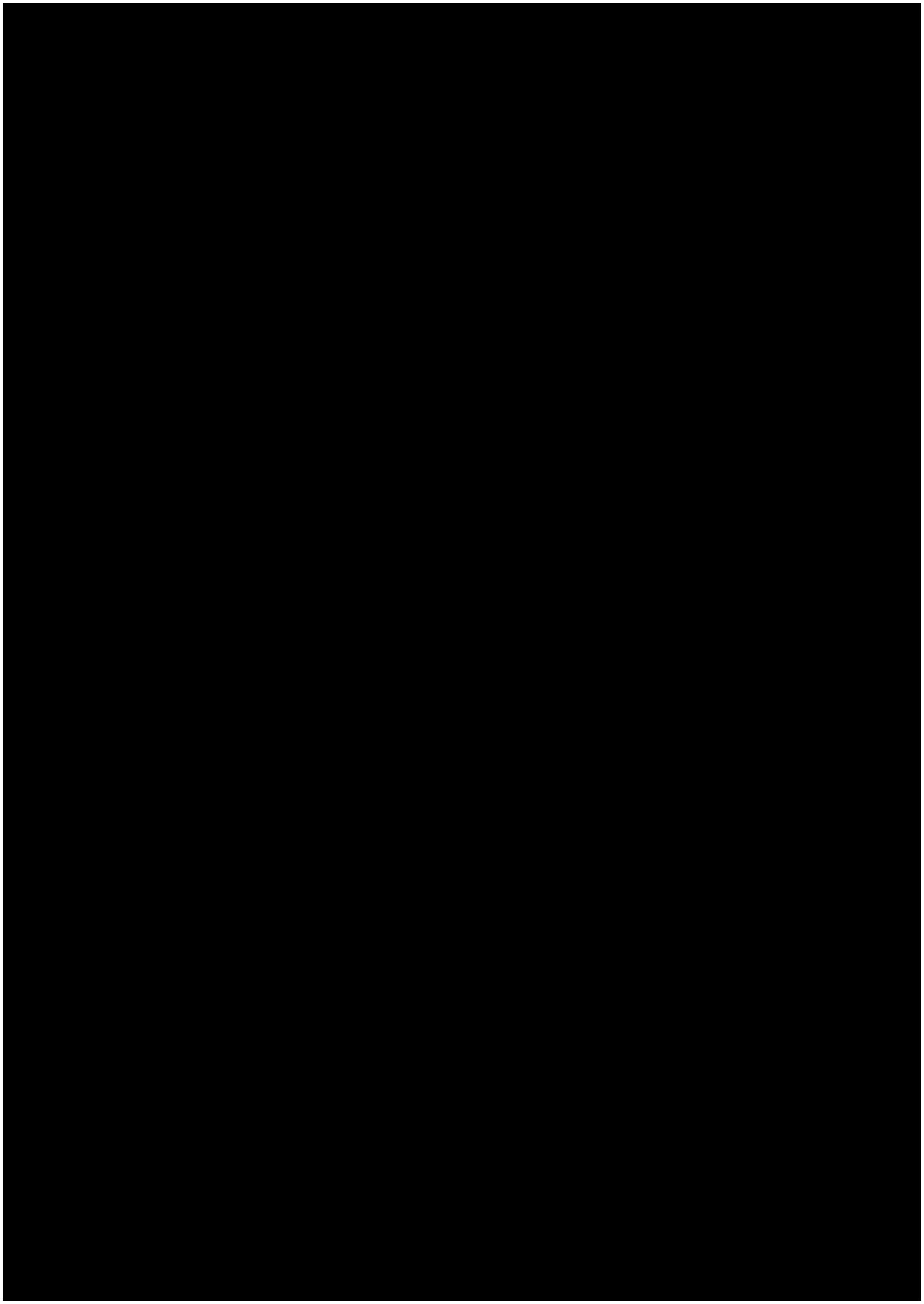

1.2 FOAM FORCE LP

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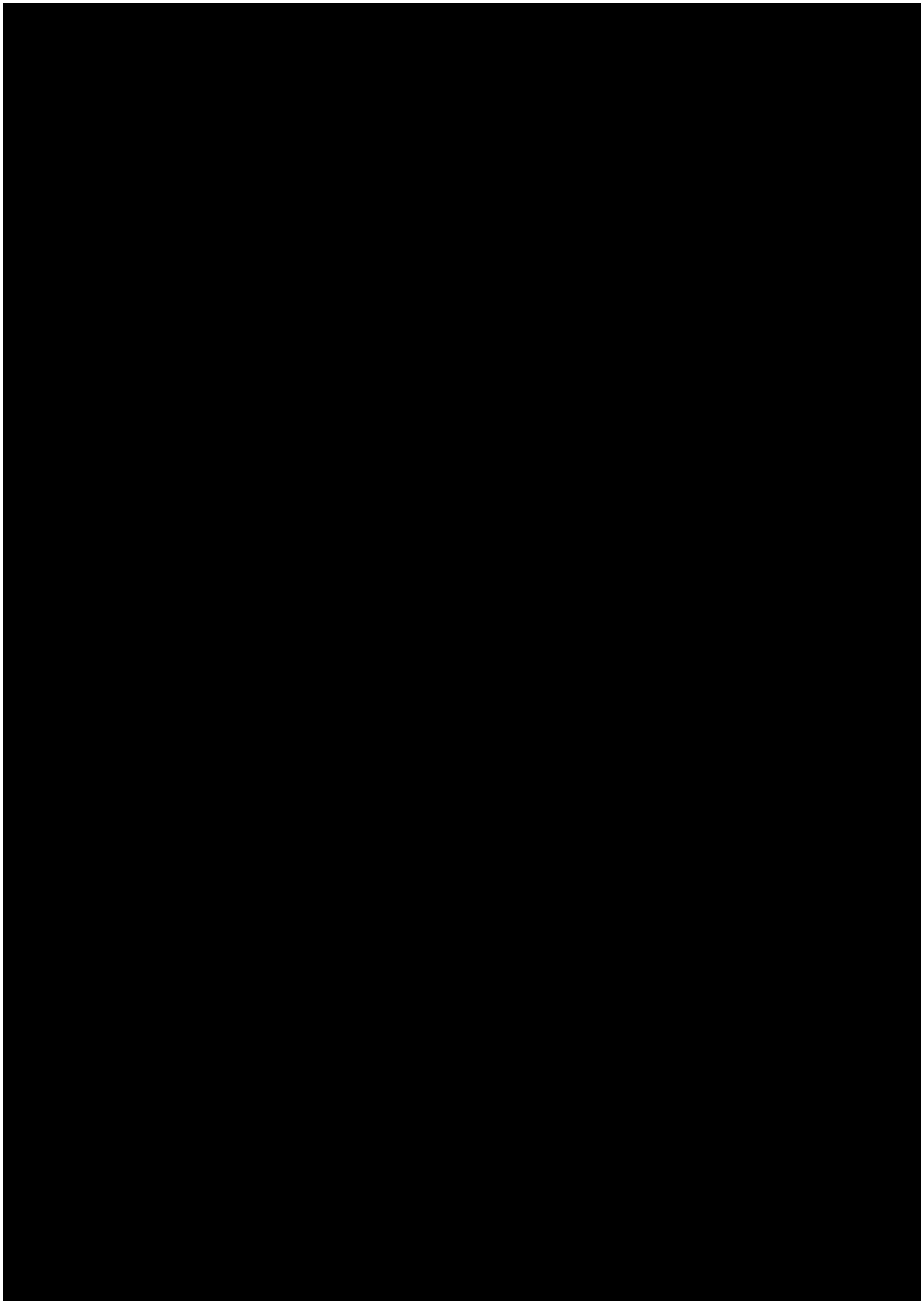

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[redacted]

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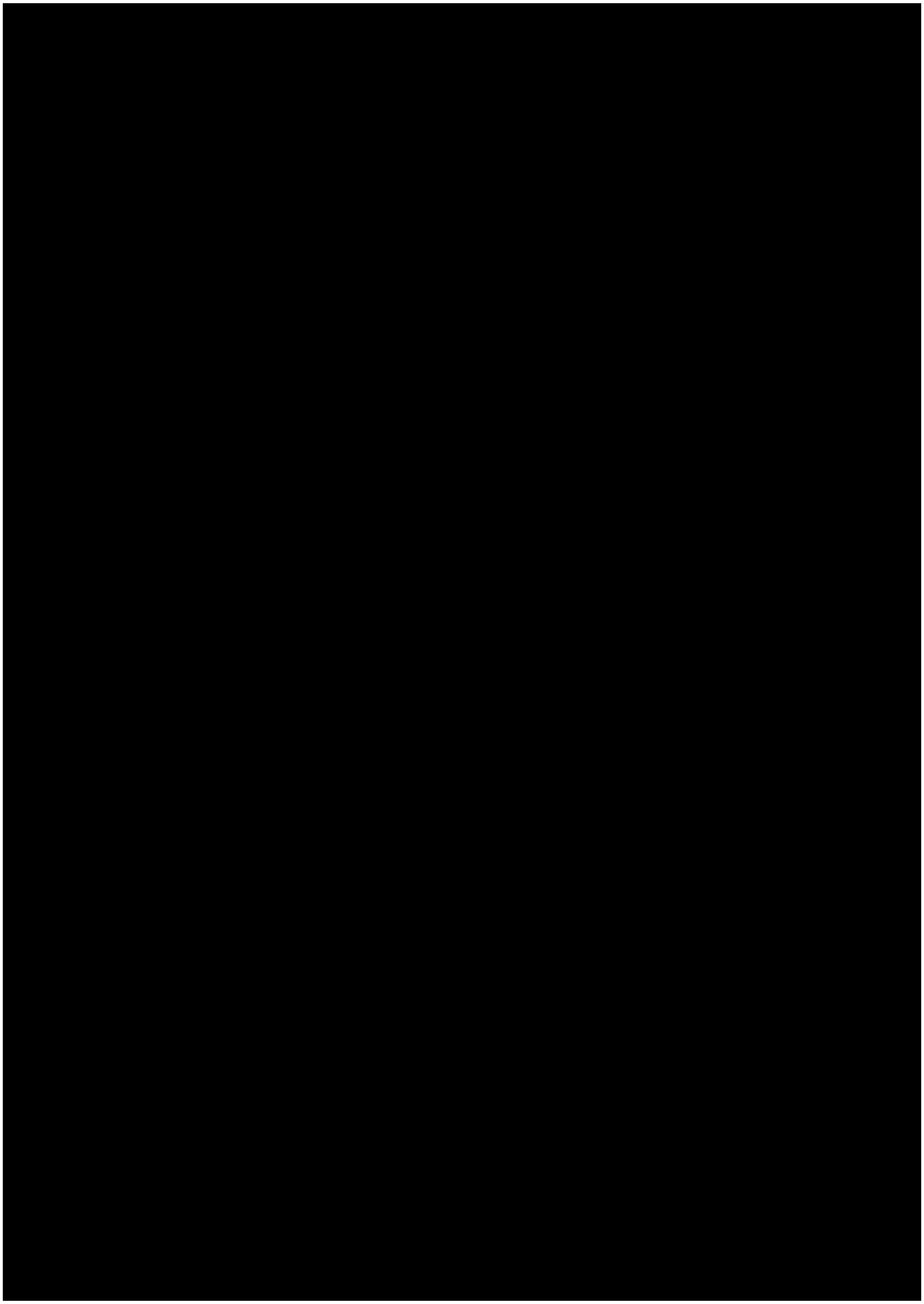

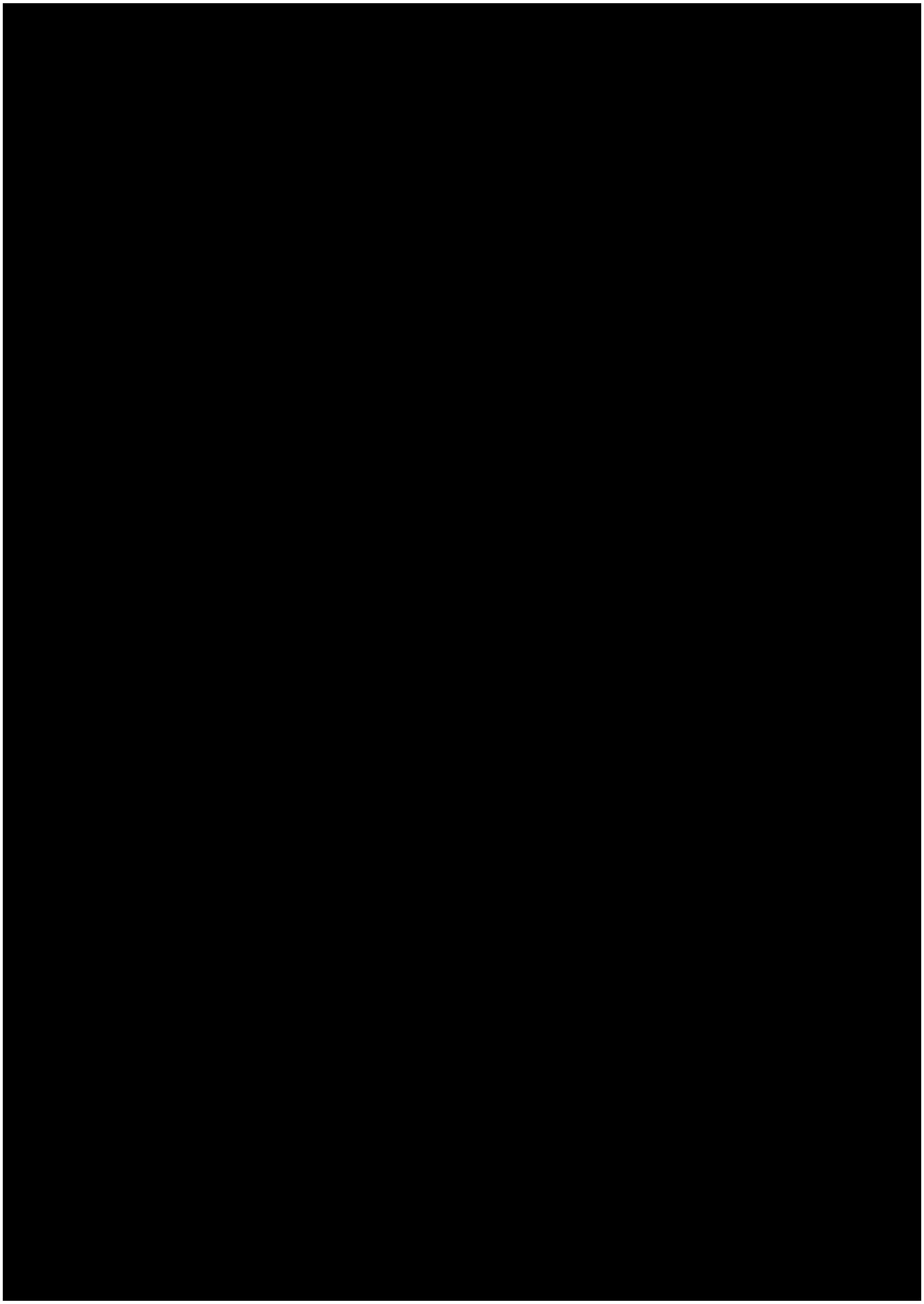

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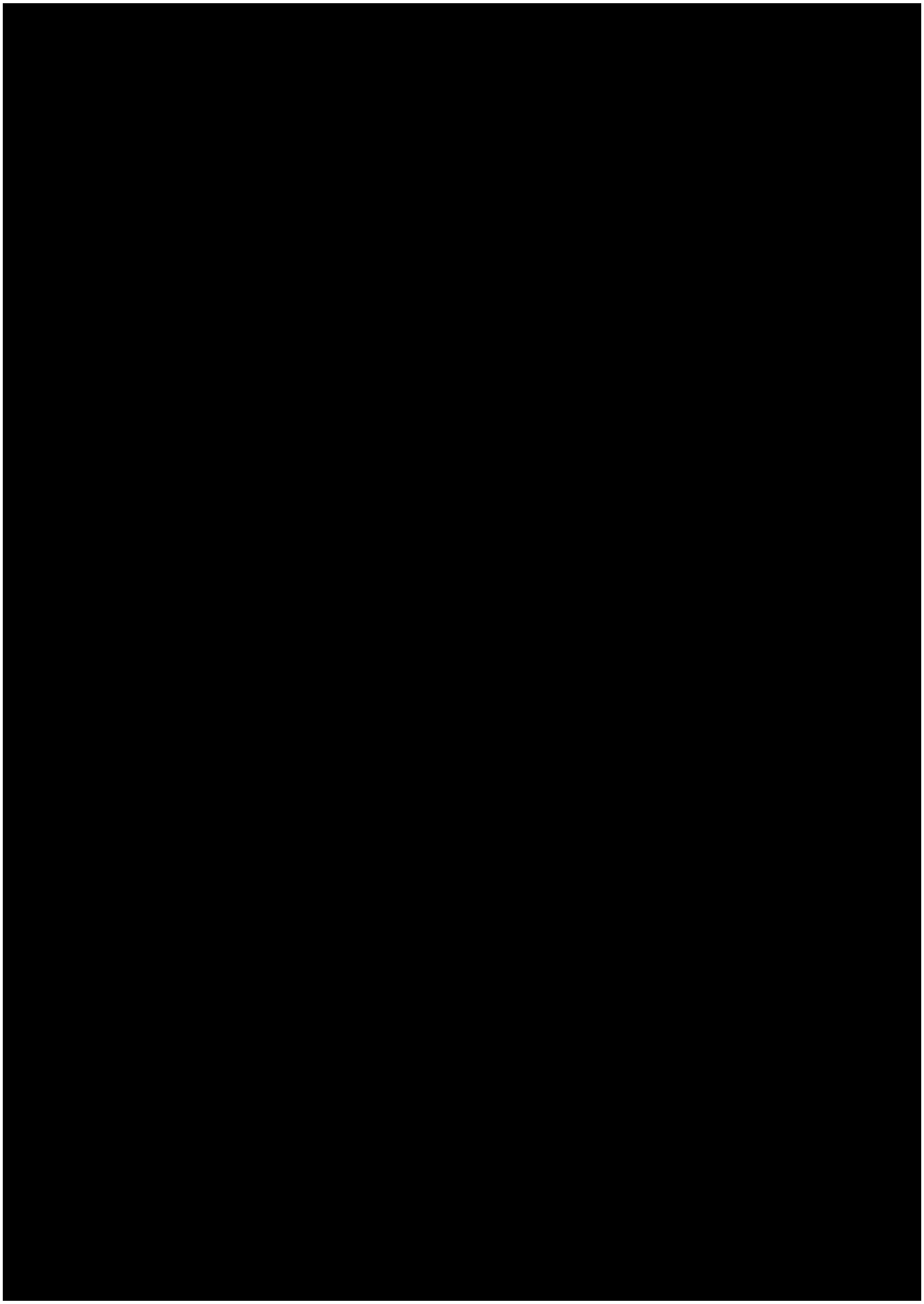

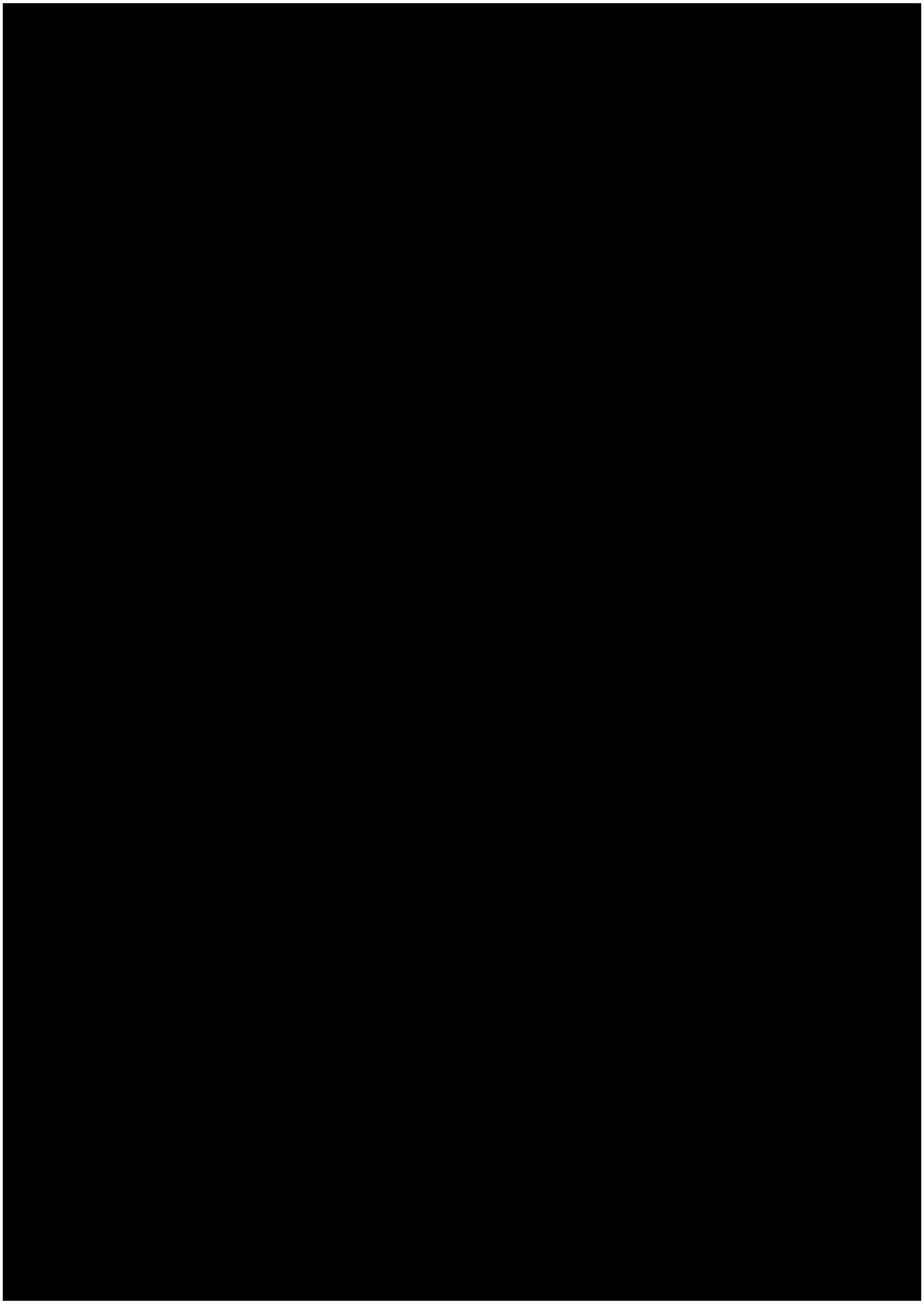

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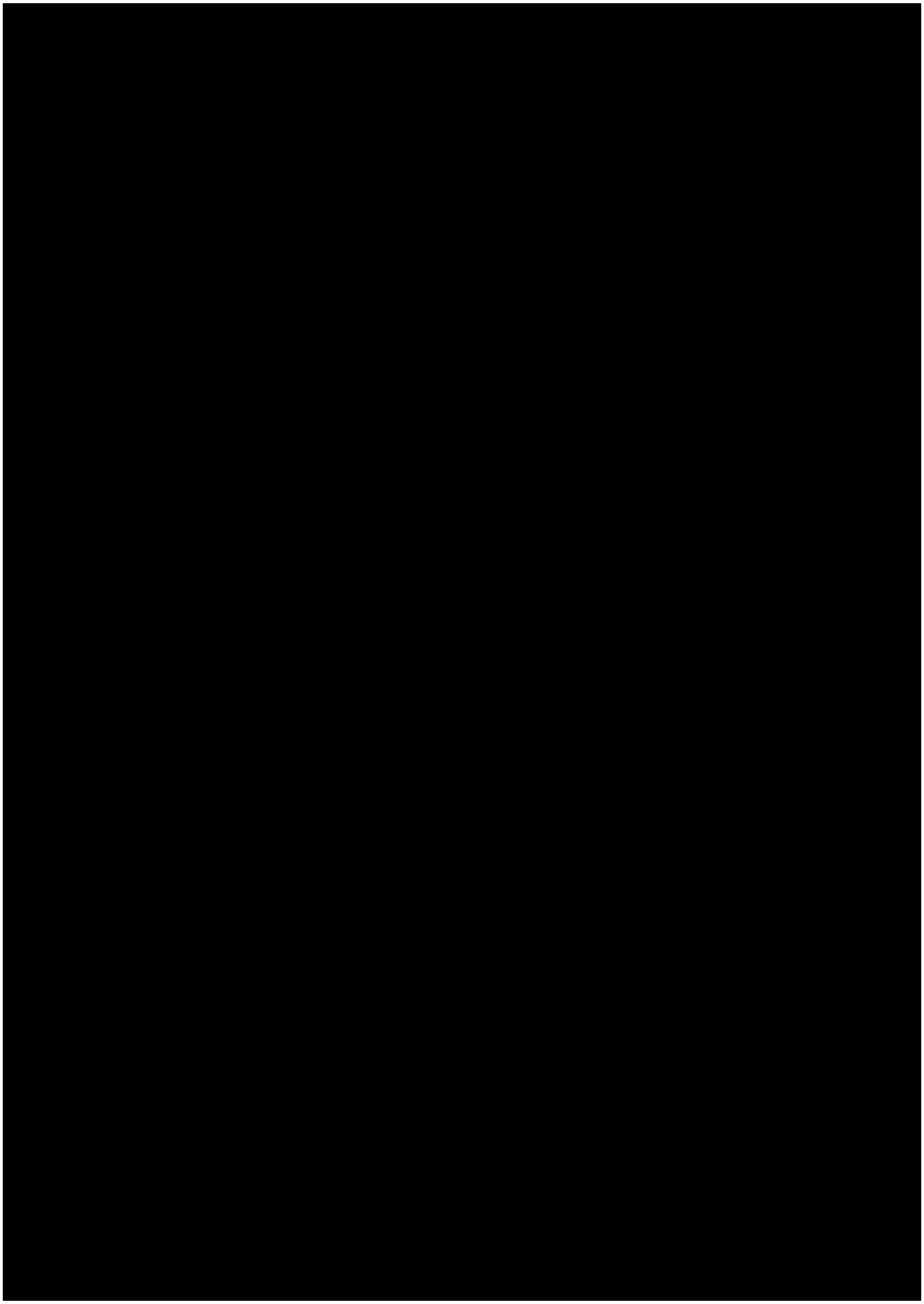

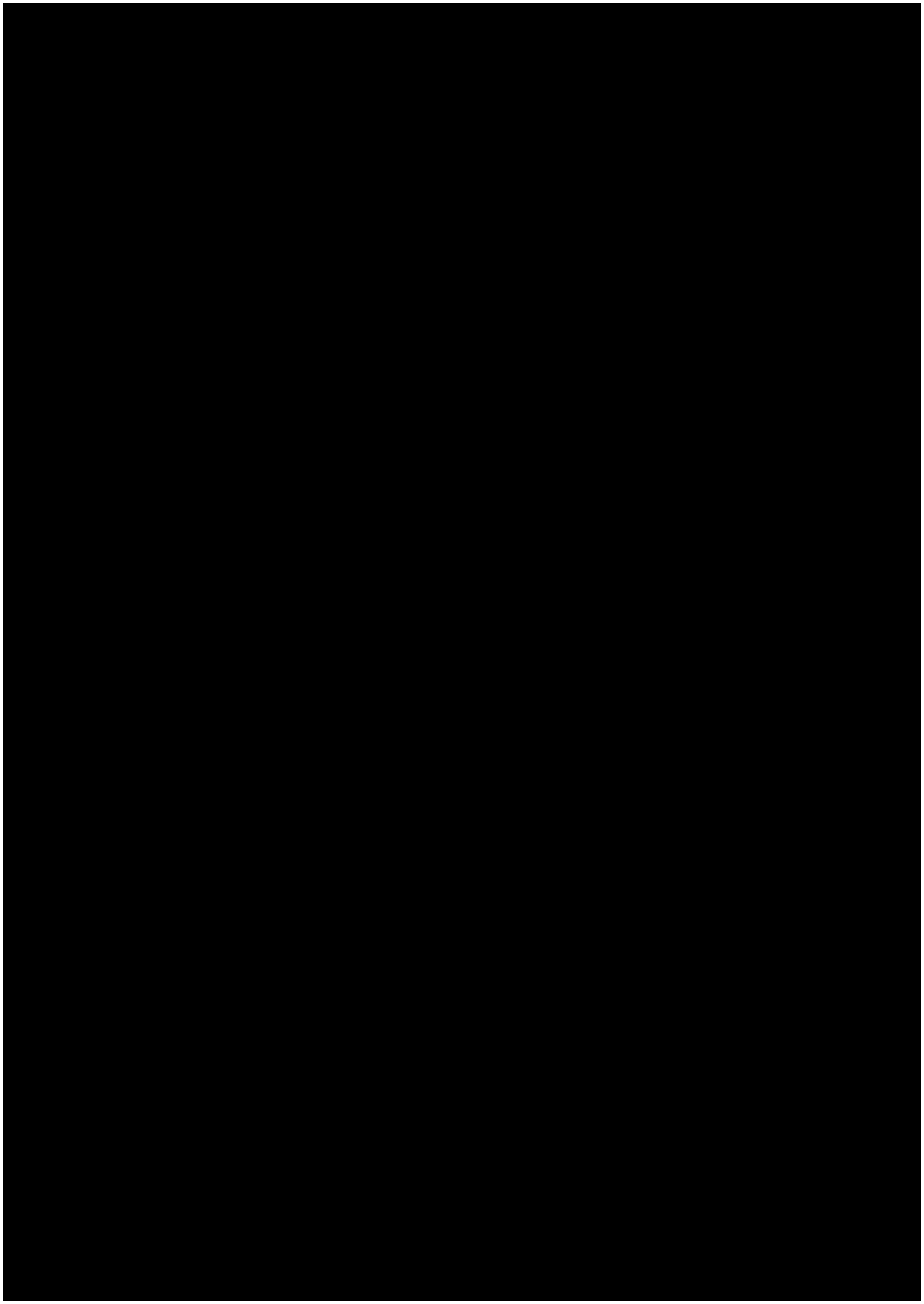

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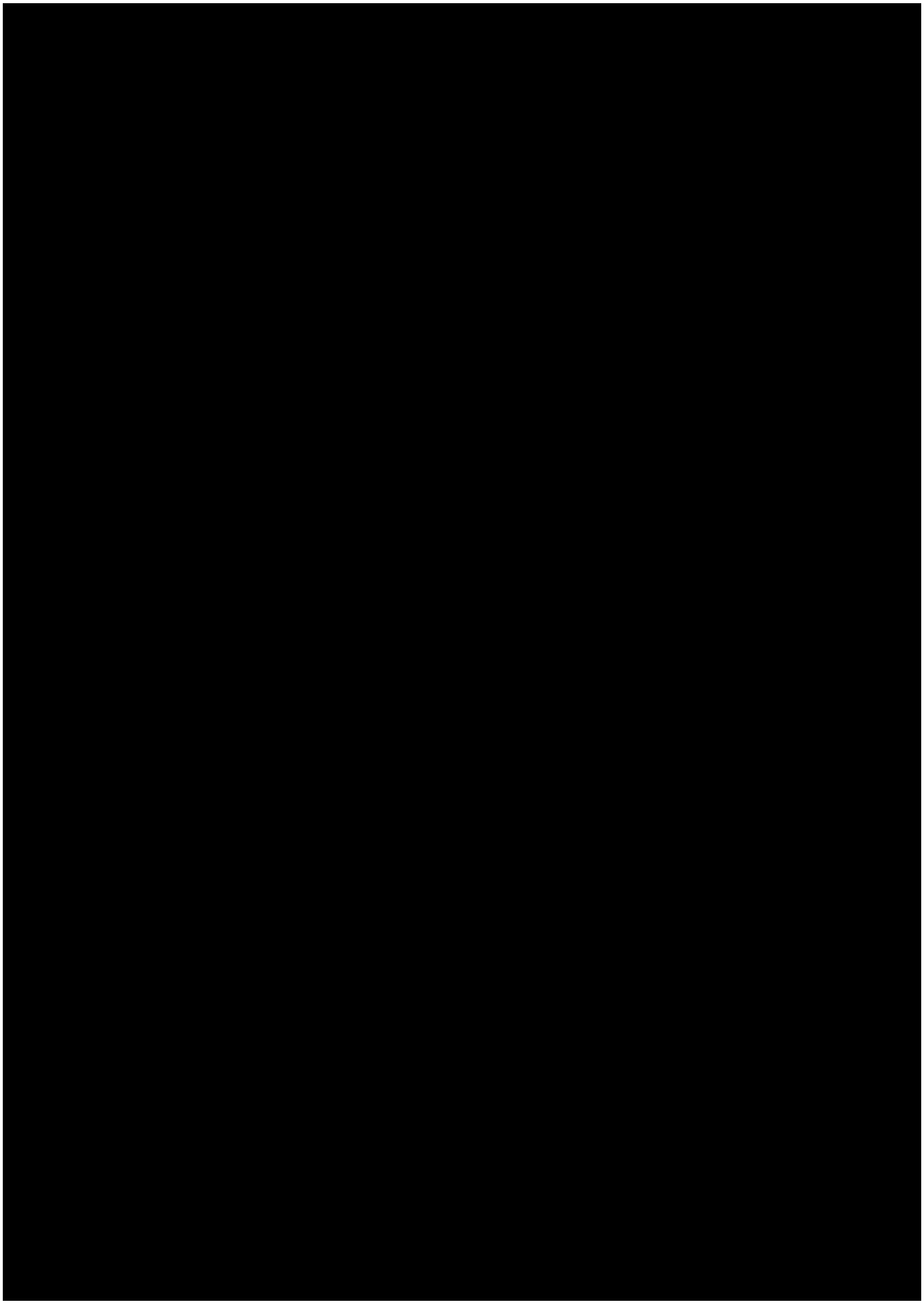

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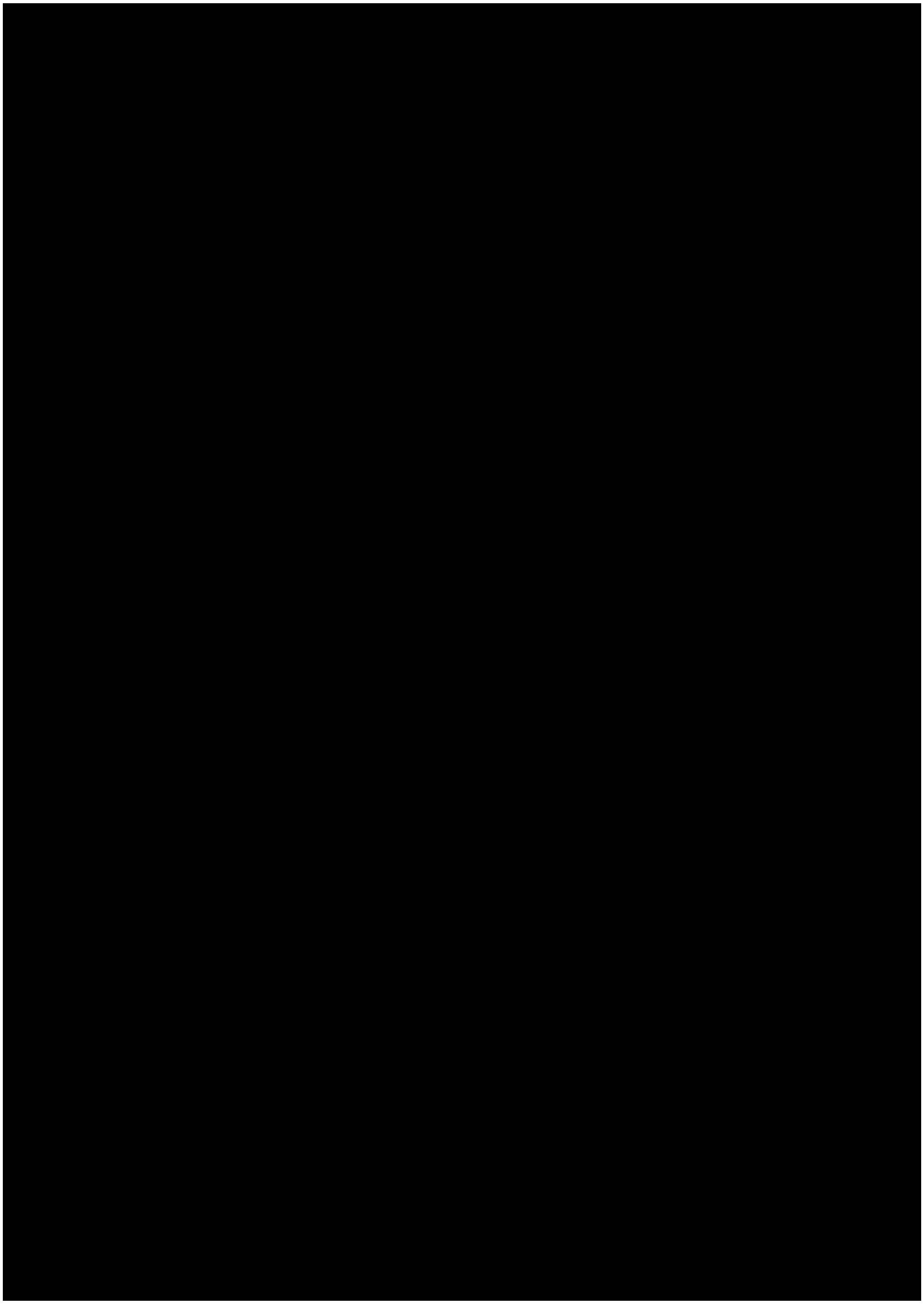

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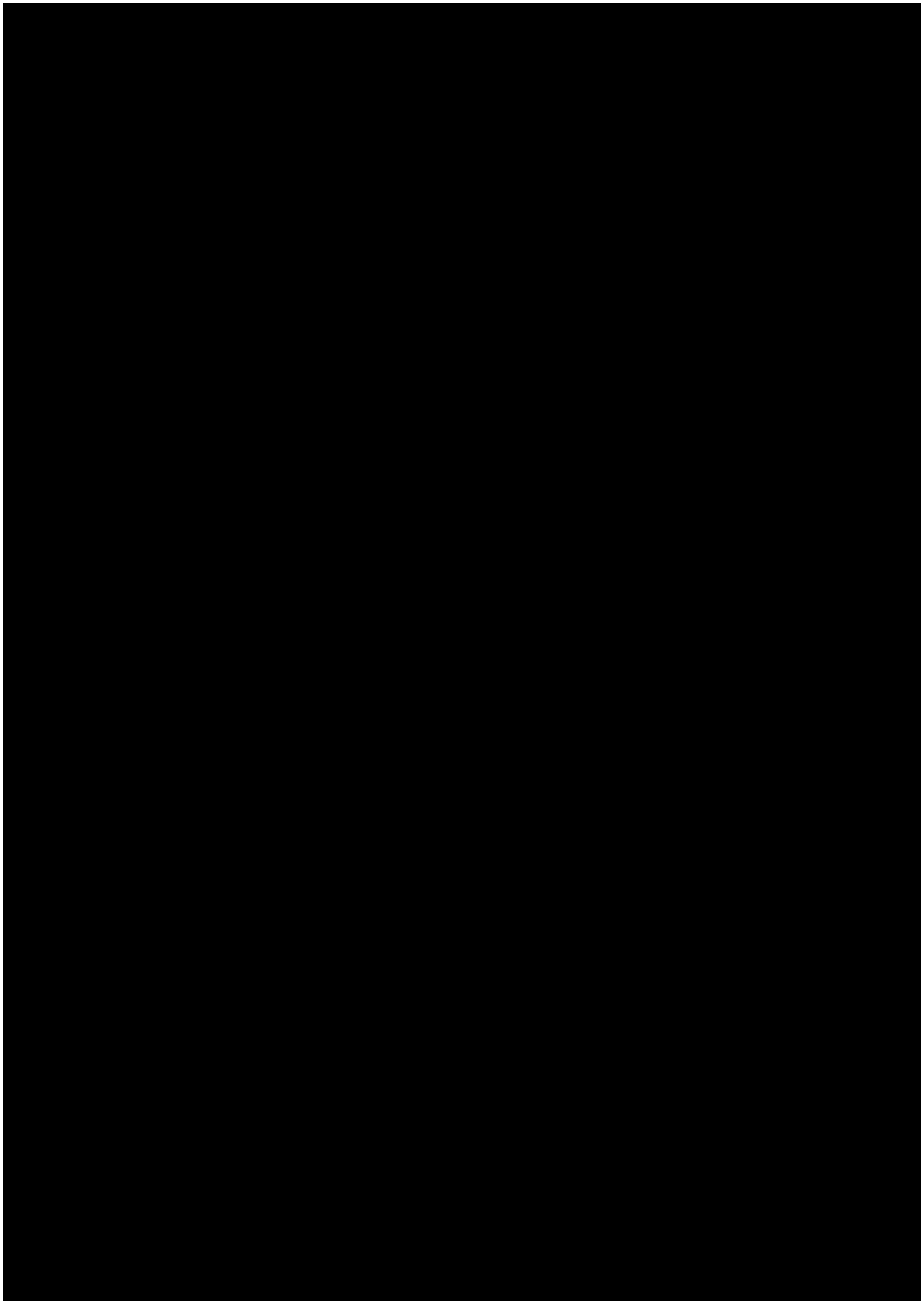

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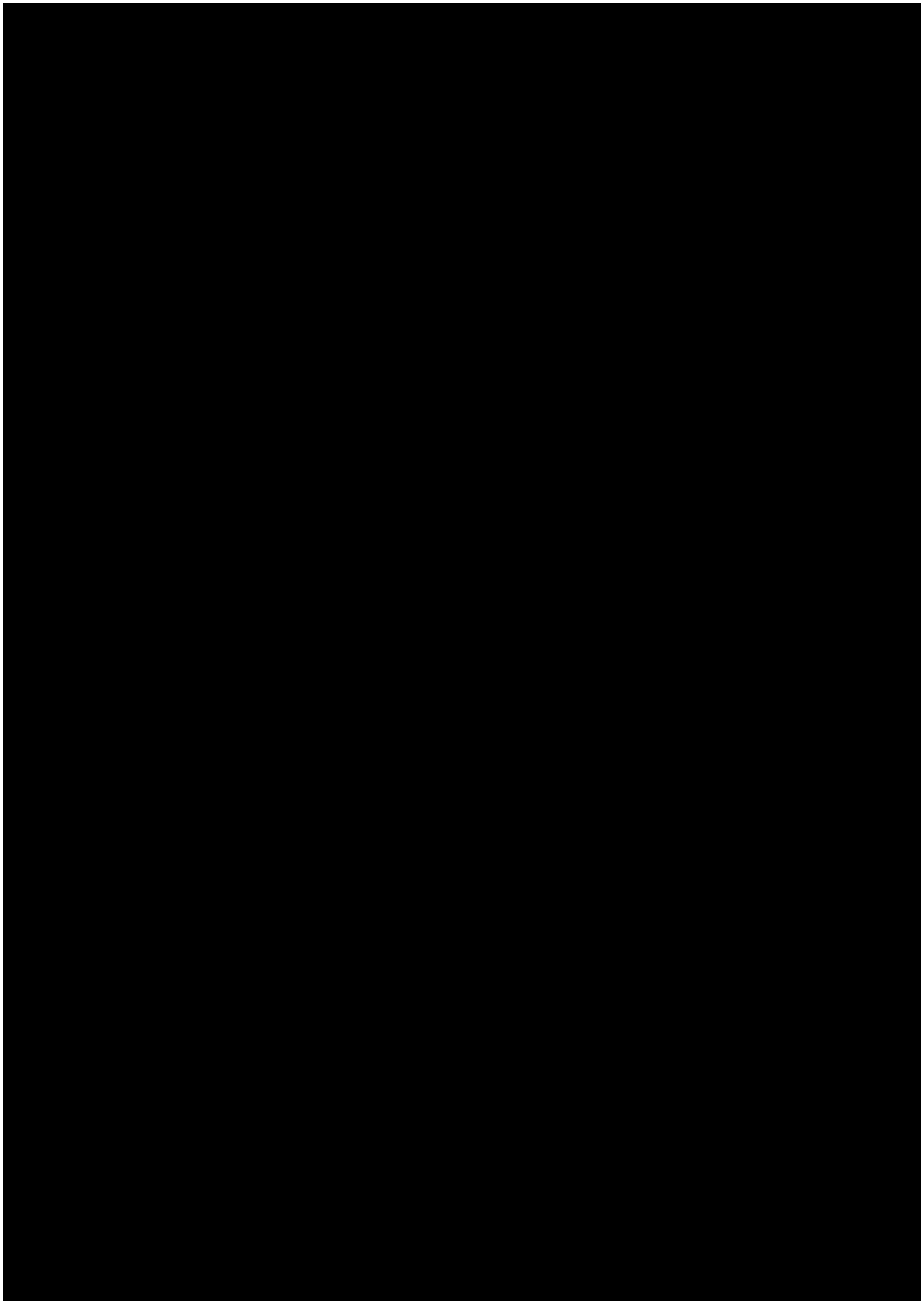

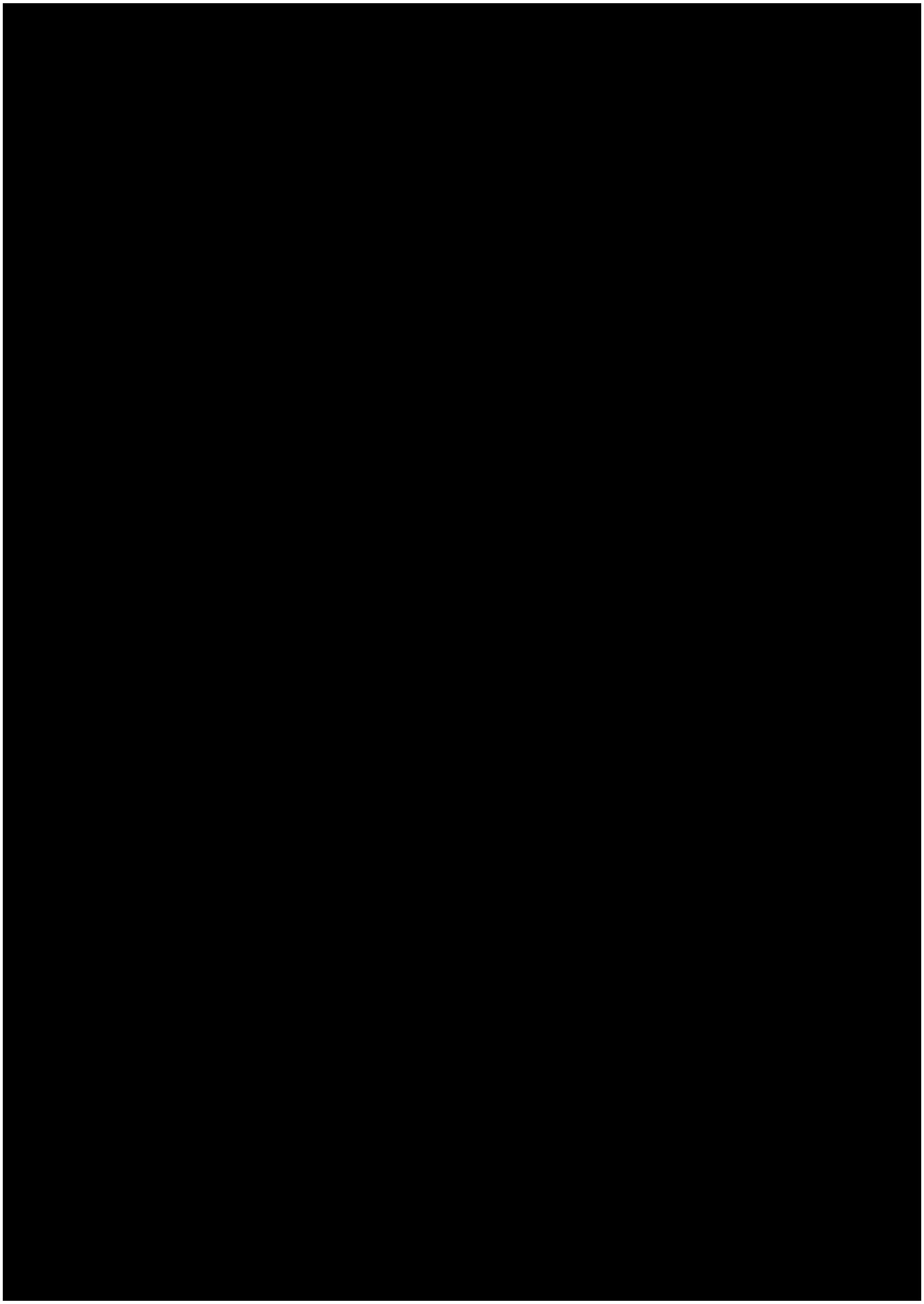

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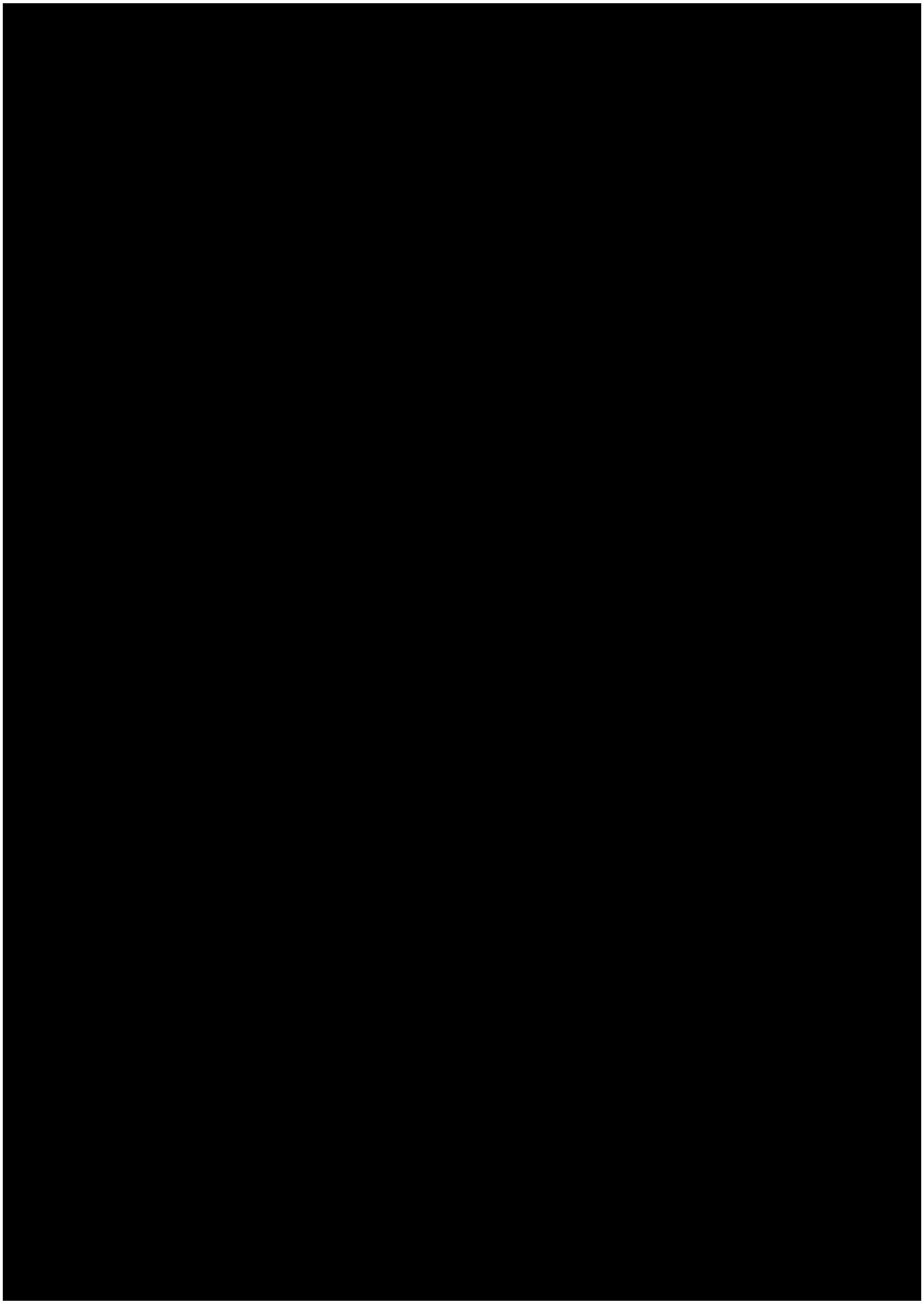

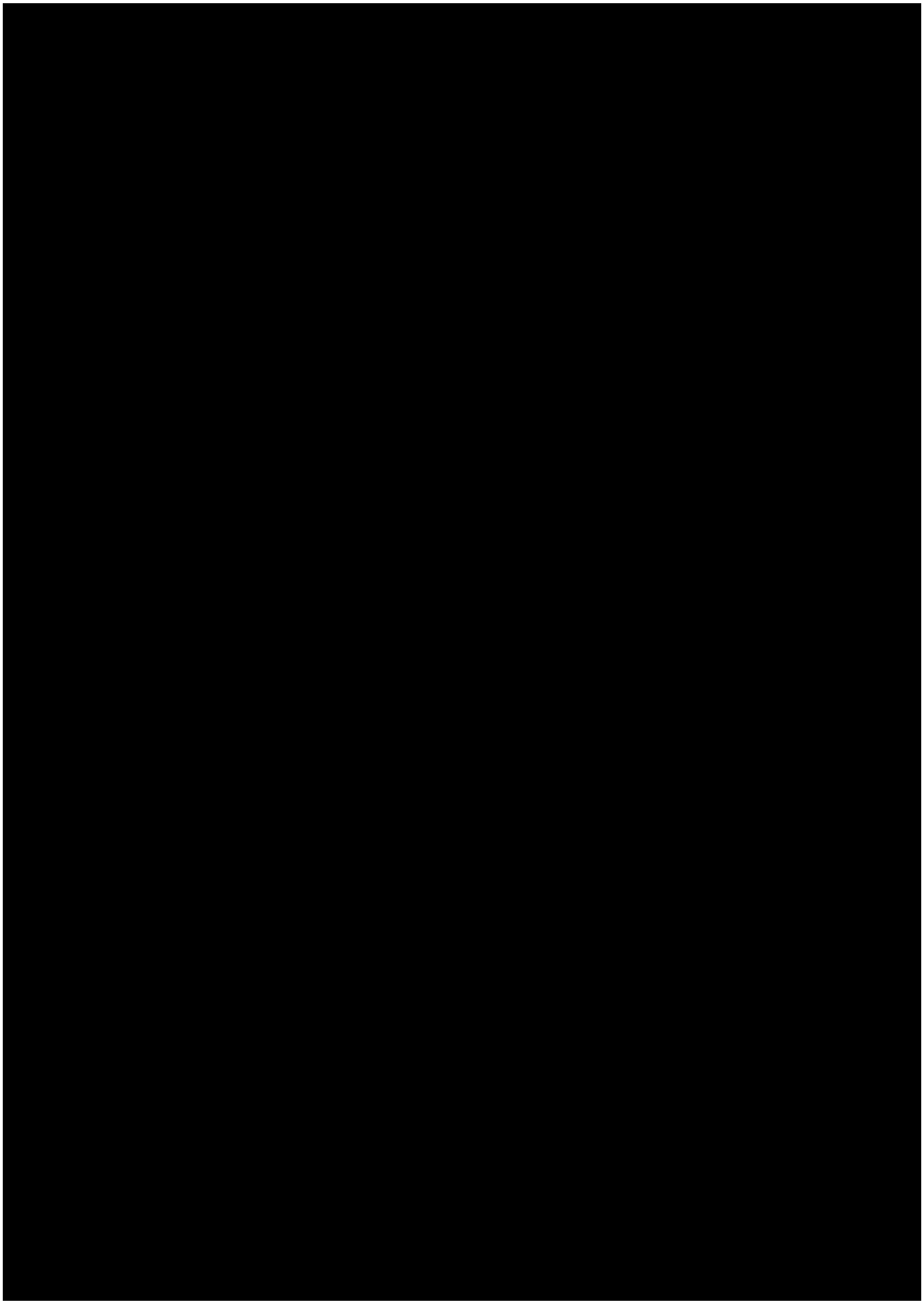

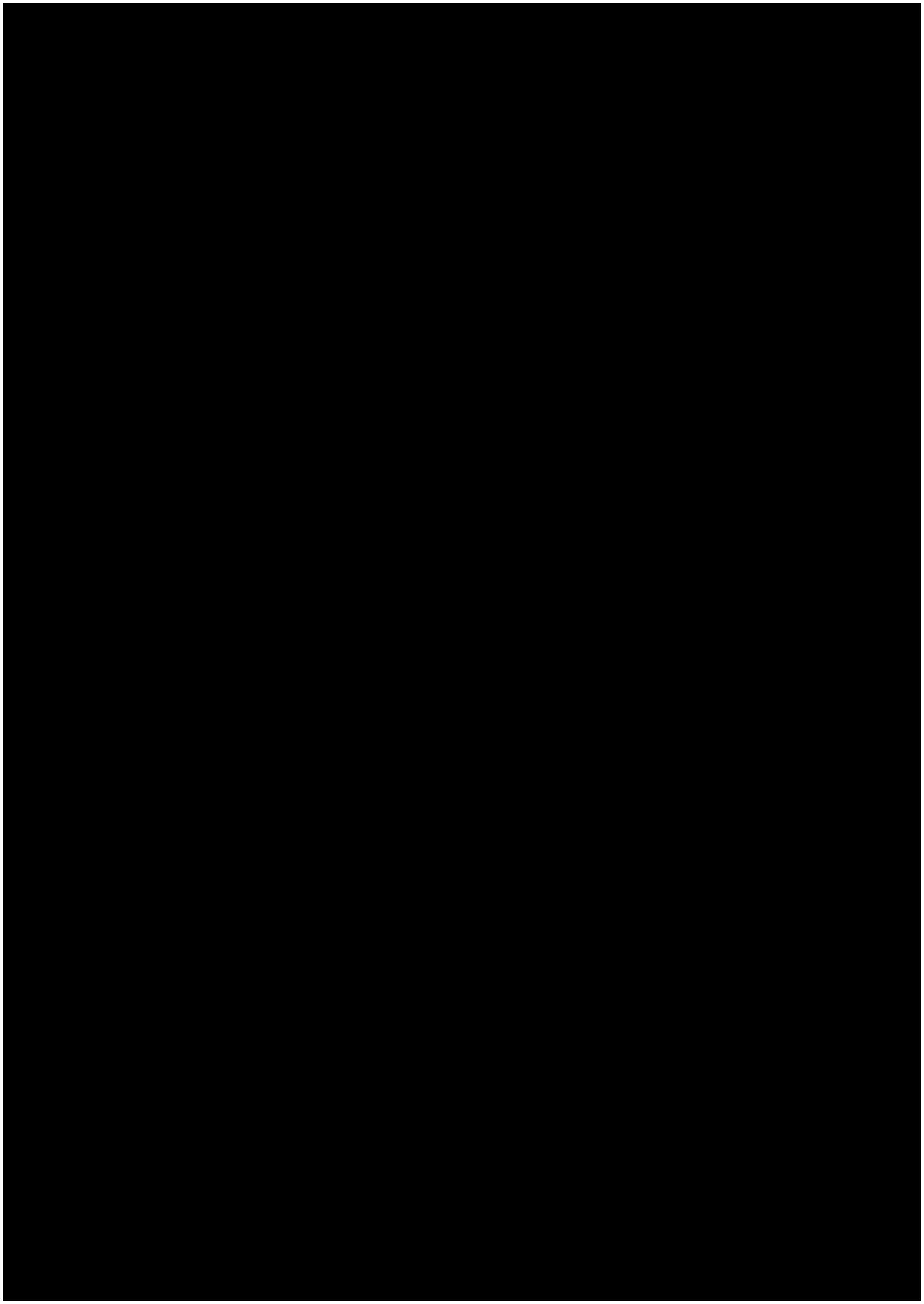

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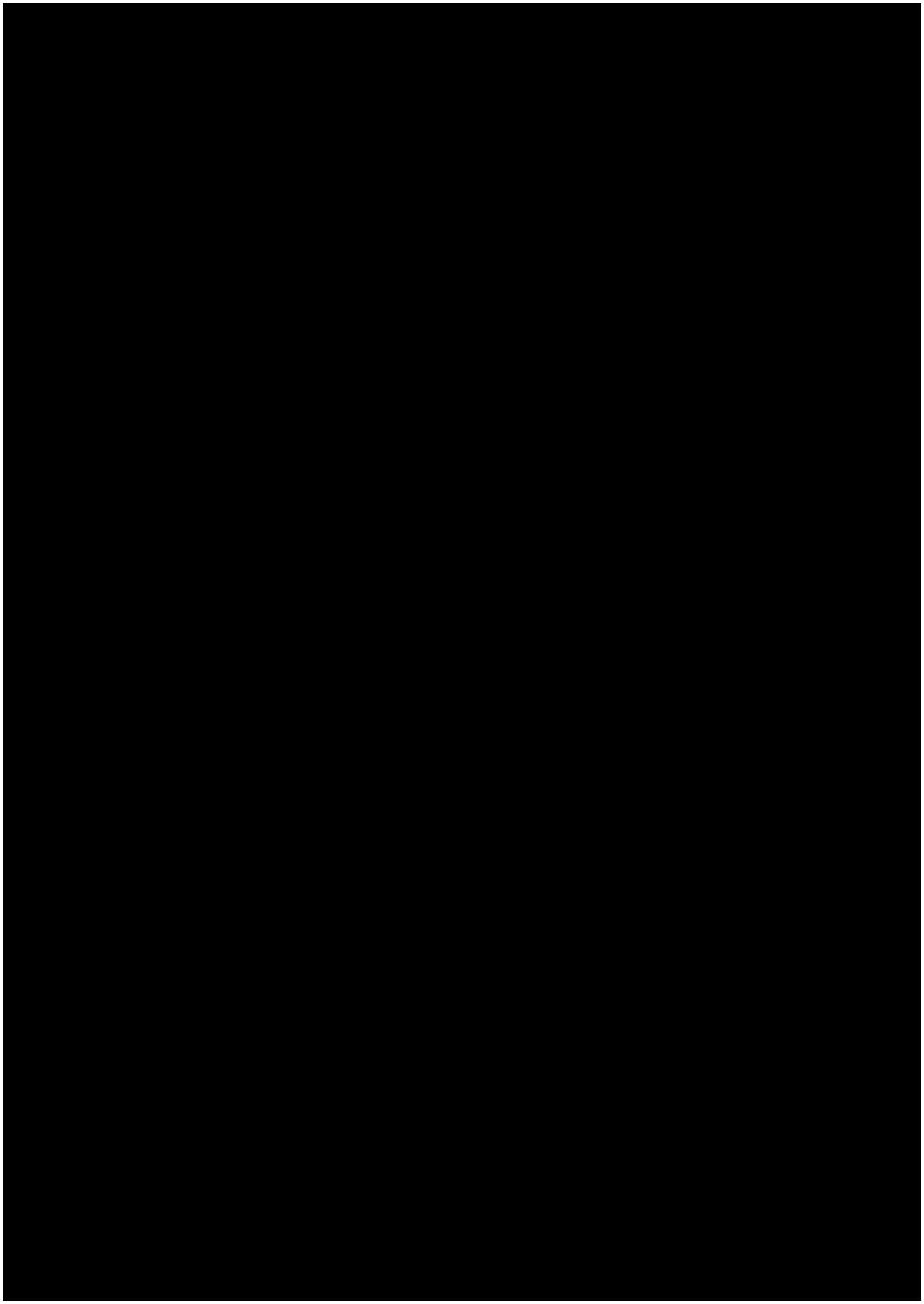

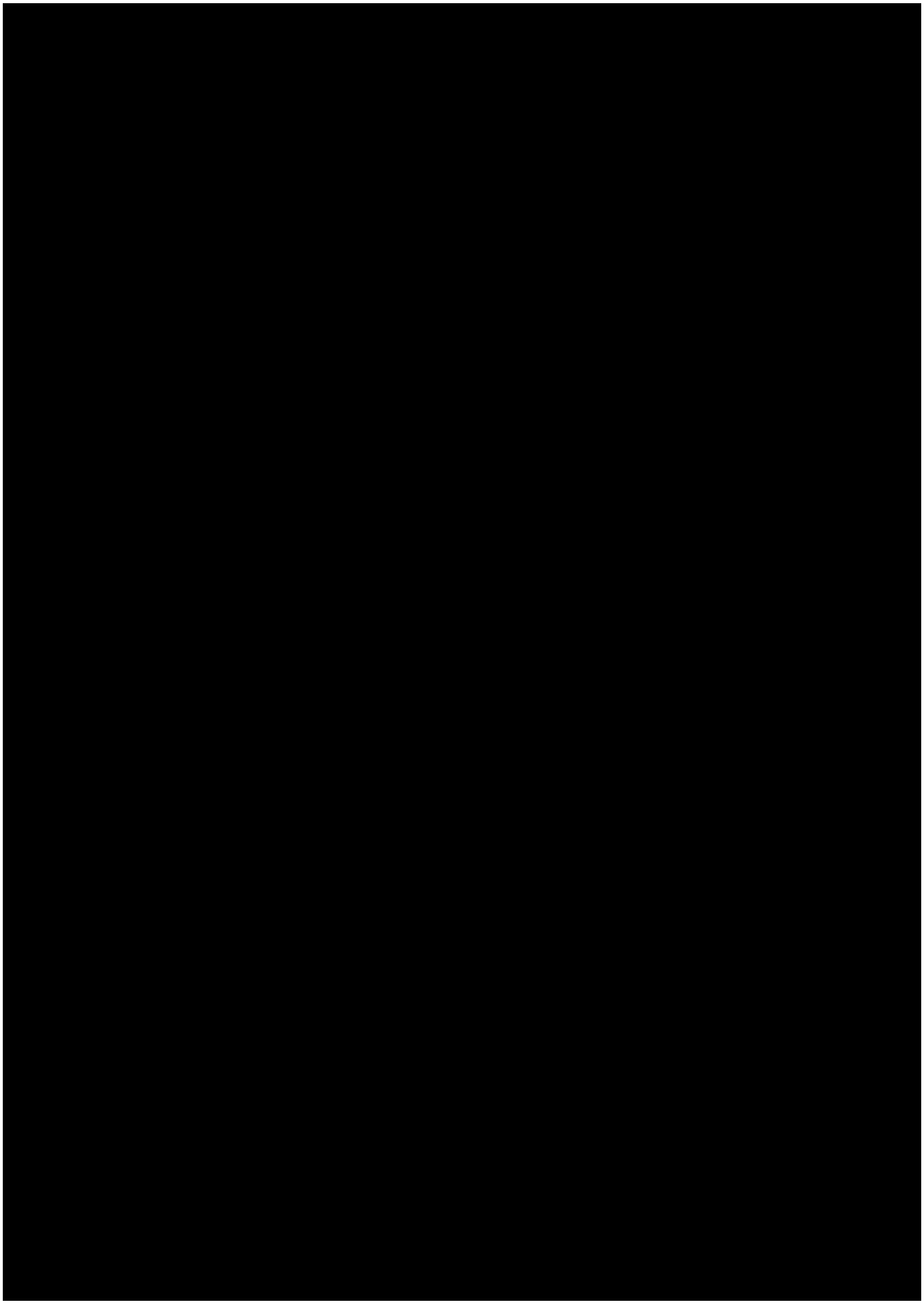

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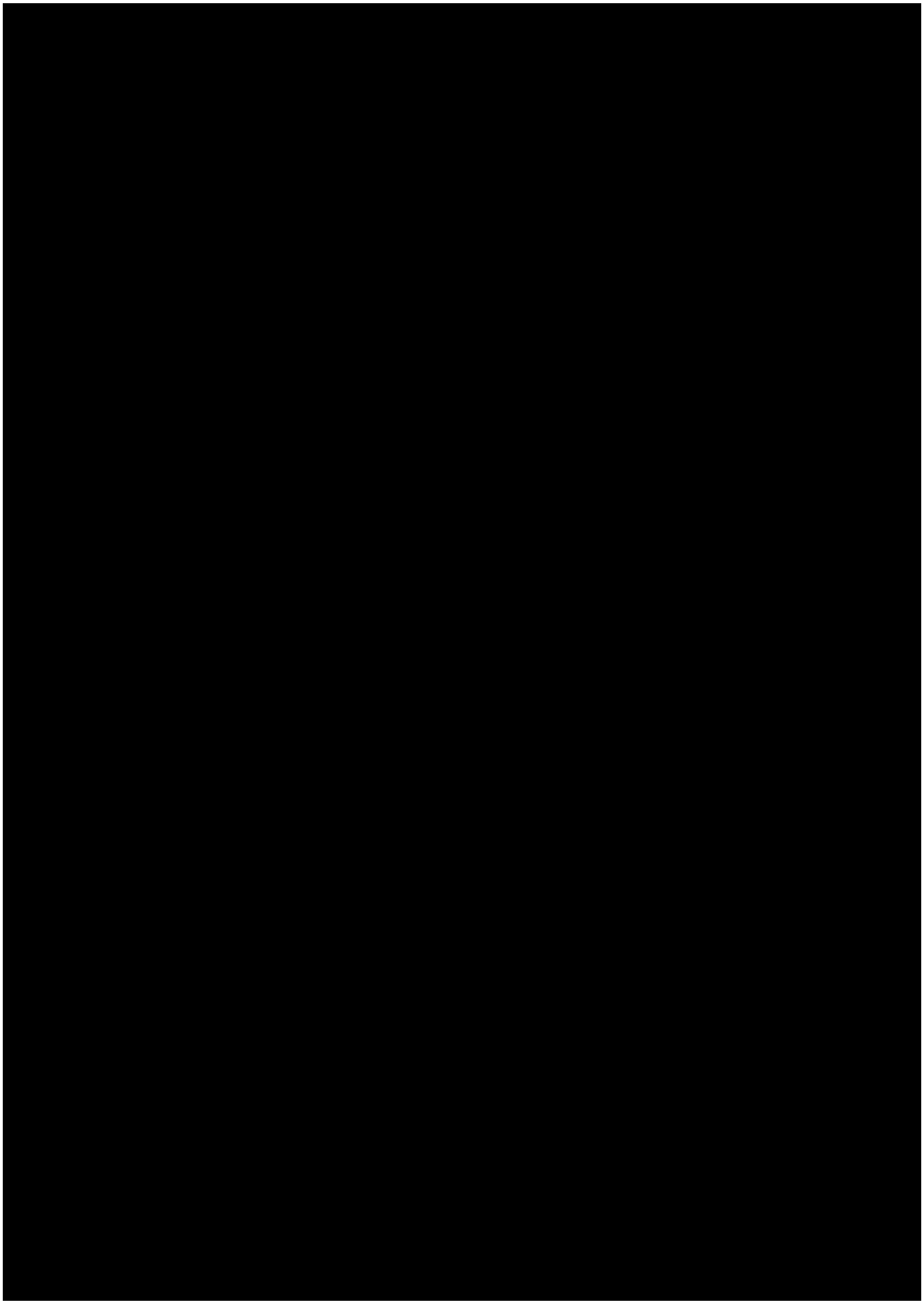

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2 EZ Clean Sprockets [2]

[redacted]

3 Cone Top Belt [2]

[redacted]

4 Electrodes [3]

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5 References

[1] Ecolab, "Ecolab Products Home," Ecolab, [Online]. Available: https://en-ca.ecolab.com/. [Accessed 3 November 2019].

[2] Intralox, "2019 MODULAR PLASTIC CONVEYOR BELTS ENGINEERING," [Online]. Available: https://intraloxpublic.myrevbase.com/v?lang=en. [Accessed 11 11 2019].

[3] Lincoln Electric, "Stainless Alloy Electrodes - ER316/316L," Lincoln Electric, [Online]. Available: https://www.lincolnelectric.com/en-ca/Consumables/Pages/product.aspx?product=Products_Consumable_StainlessNickelandHighAlloy-Lincoln-LincolnER316316L(LincolnElectric). [Accessed 25 November 2019].

APPENDIX E

ENGINEERING DRAWINGS

PART NUMBER

BS07

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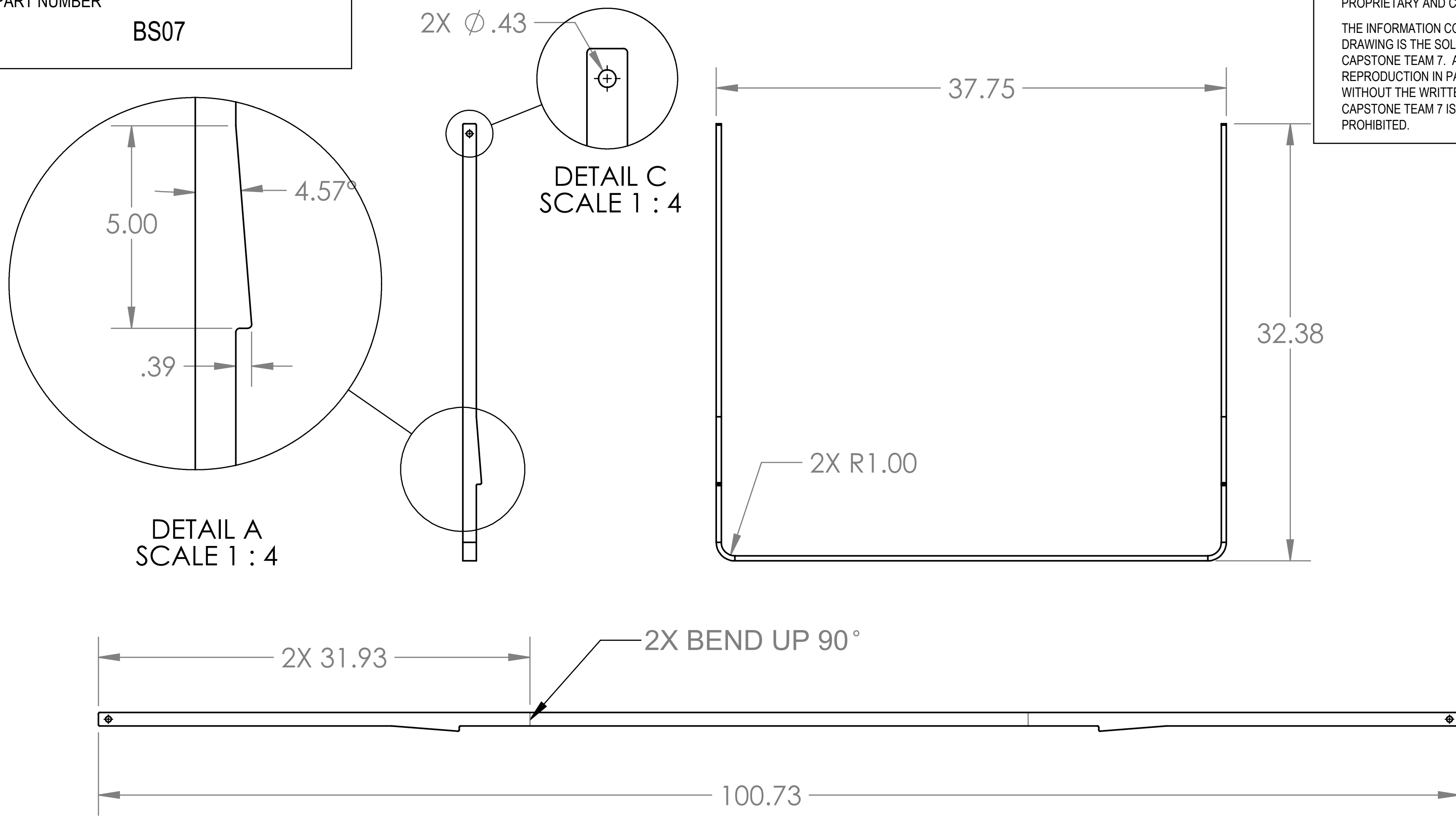

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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

TITLE

HANDLE - BYPASS TABLE

MATERIAL

0.375" THK 316L SST PLATE

COMMENTS:

NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

BS08

PROPRIETARY AND CONFIDENTIAL

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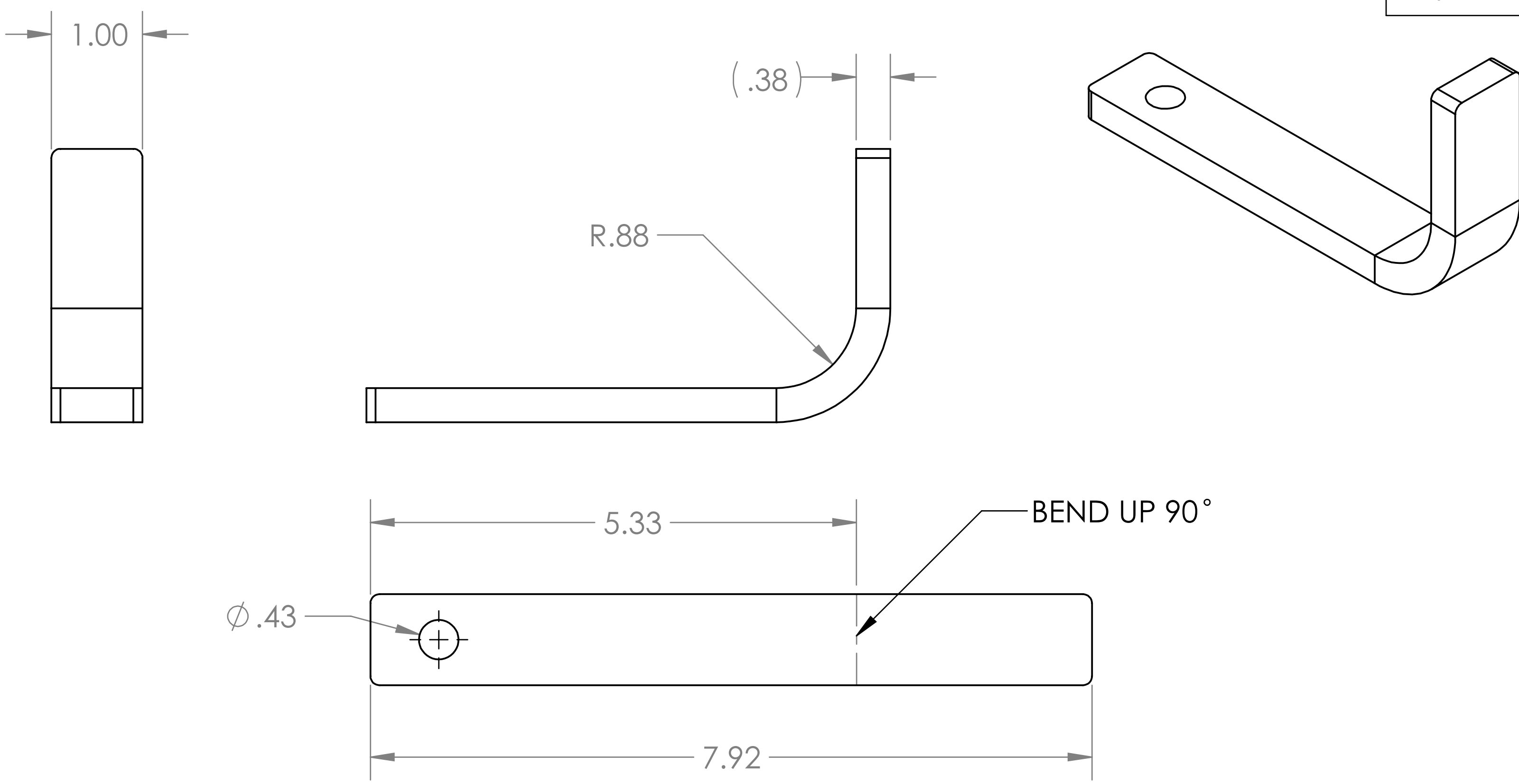

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.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

BRACKET - SLIDE RAIL

MATERIAL

0.375" THK 316L SST PLATE

COMMENTS:

NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

SOLIDWORKS Educational Product. For Instructional Use Only.

PART NUMBER
BS09

PROPRIETARY AND CONFIDENTIAL

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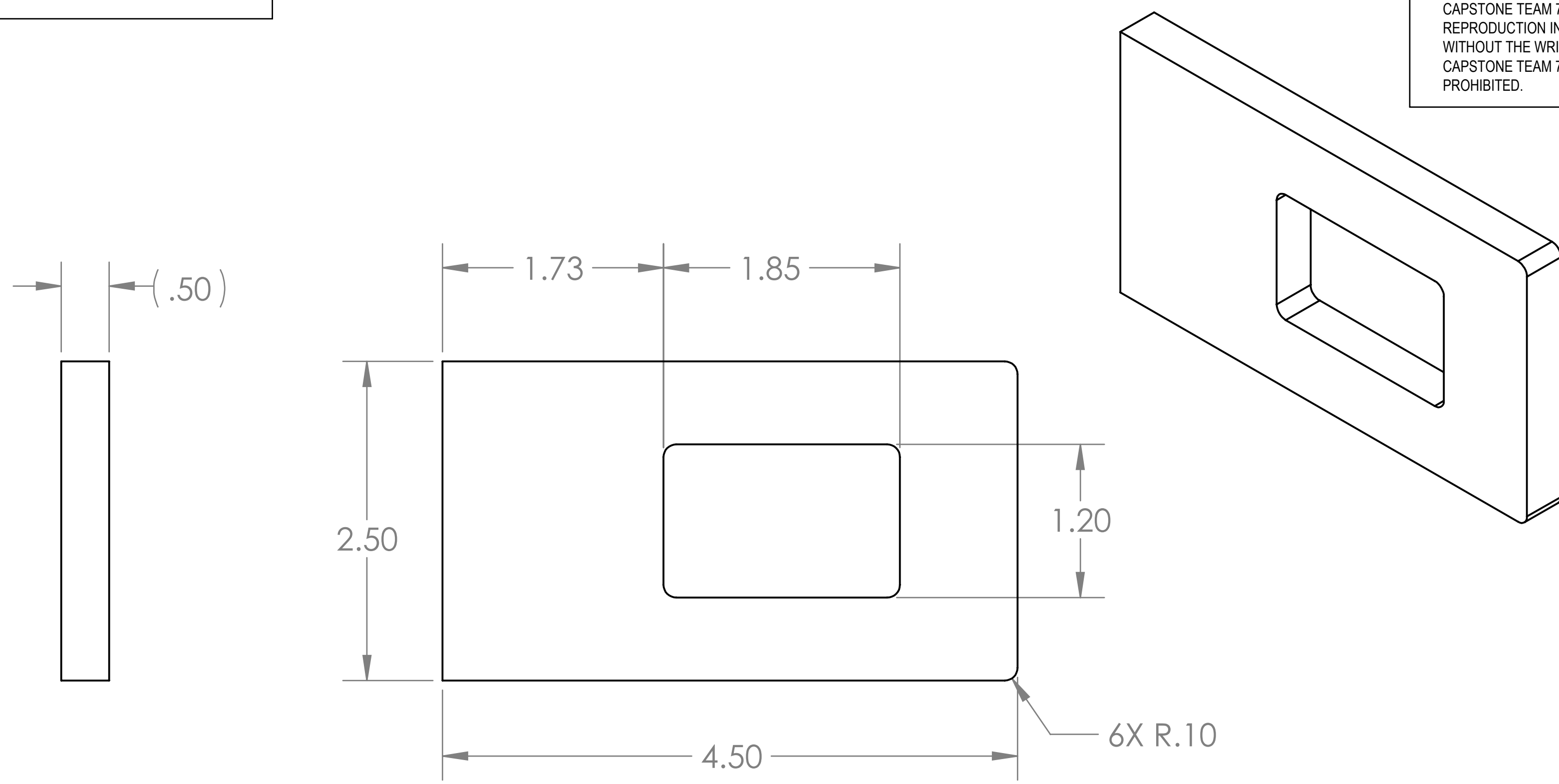

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- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE
BRACKET - NORTH GUIDE

MATERIAL
0.375" THK 316L SST PLATE

COMMENTS:

NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

BS10

PROPRIETARY AND CONFIDENTIAL

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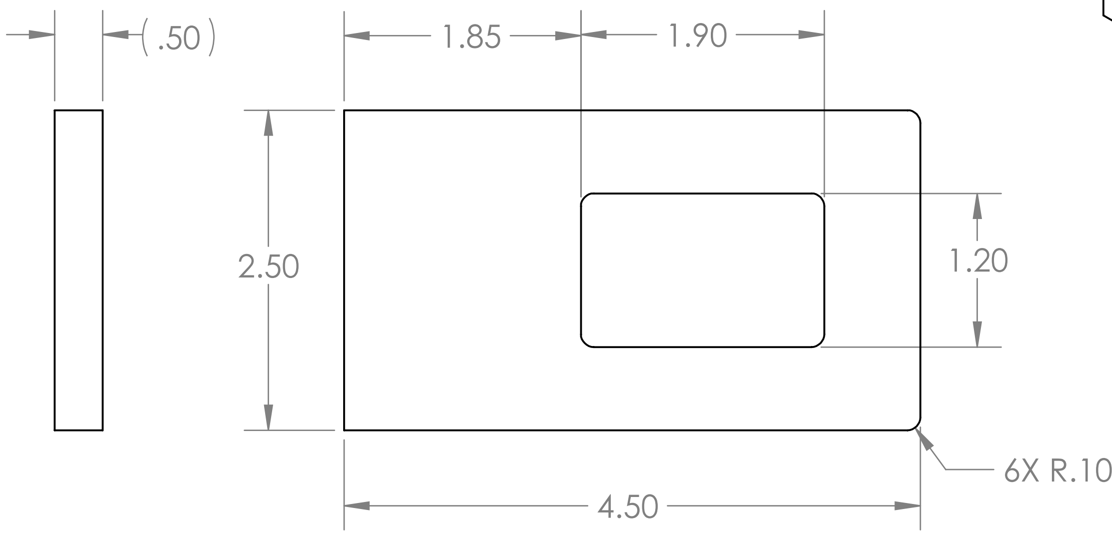

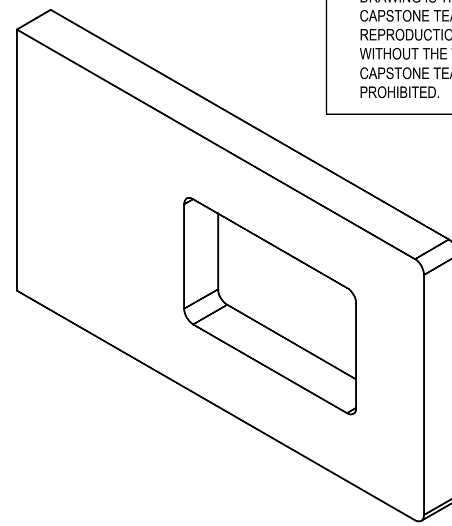

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ISSUE	REVISION	DRAWN	DATE

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- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

BRACKET - SOUTH GUIDE

MATERIAL

0.375" THK 316L SST PLATE

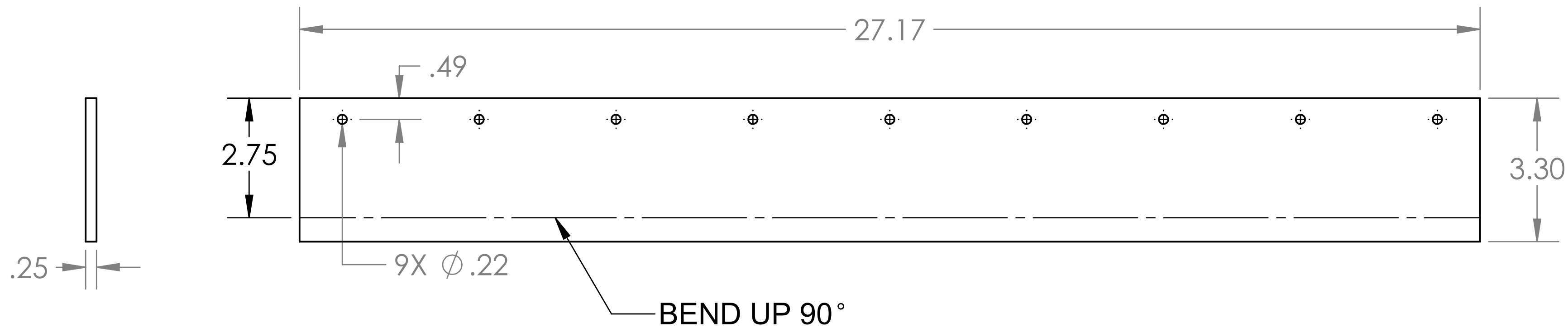
COMMENTS:

NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER
BS11



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- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE
BRACKET - SLIDER MOUNT

MATERIAL
0.25" THK 316L SST PLATE

COMMENTS:

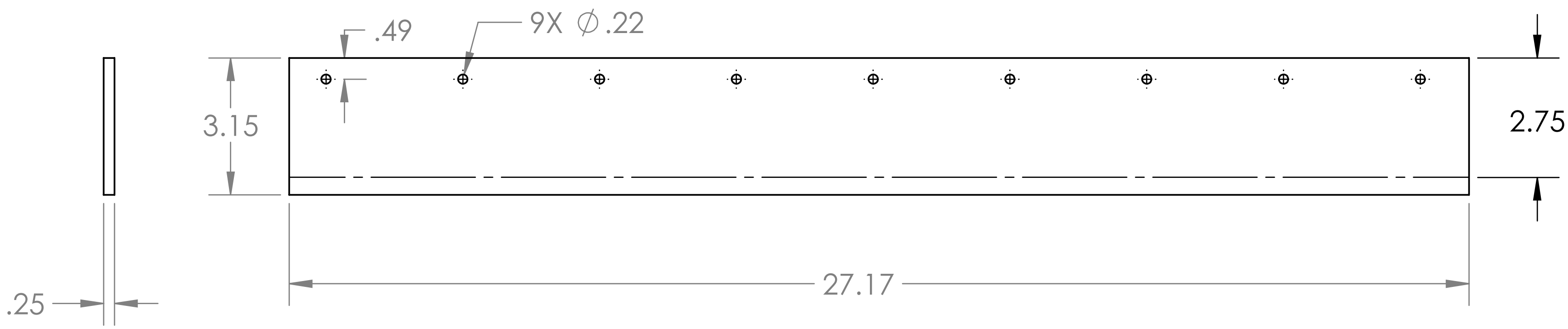
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

BS12



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- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

BRACKET - SLIDER MOUNT

MATERIAL

0.25" THK 316L SST PLATE

COMMENTS:

NEXT ASSEMBLY

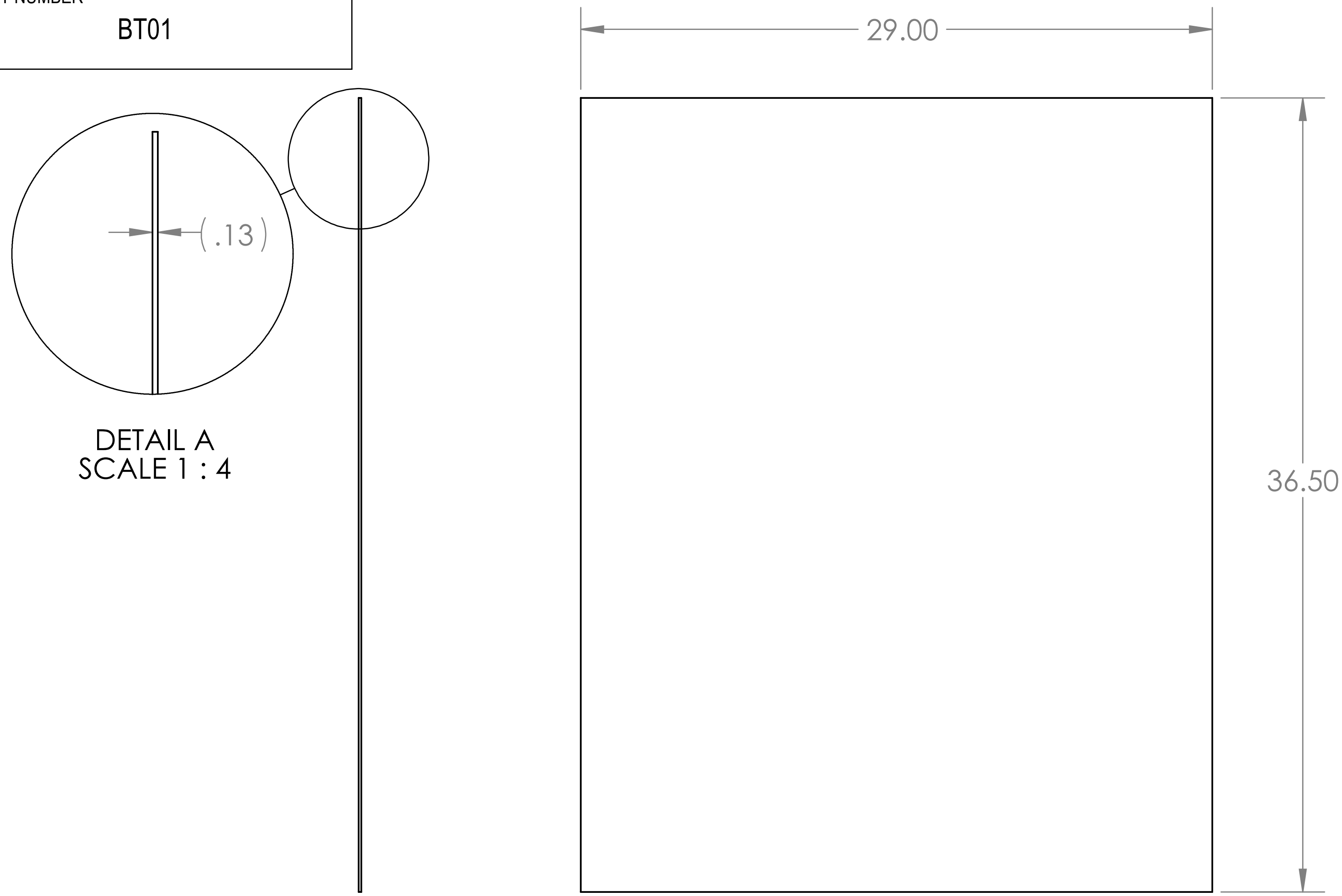
SIZE A

SHEET 1 OF 1

PART NUMBER

BT01

PROPRIETARY AND CONFIDENTIAL



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TOLERANCES:
- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

SHEET - BYPASS TABLE

MATERIAL

0.125" 316L SST SHEET

COMMENTS:

NEXT ASSEMBLY

SIZE **A**

SHEET 1 OF 1

PART NUMBER

BT02

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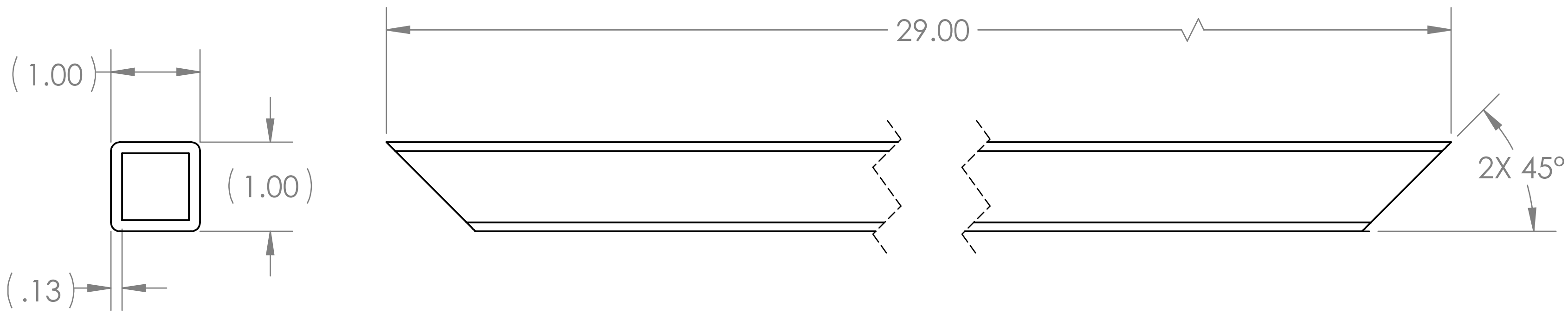

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TOLERANCES:
- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

TUBE - SHORT MITRE

MATERIAL

1" X 1" X 7GA. 316L SST TUBE

COMMENTS:

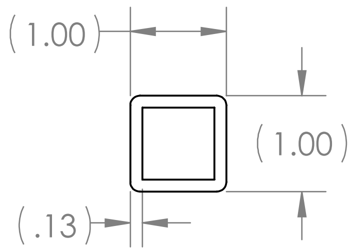
NEXT ASSEMBLY

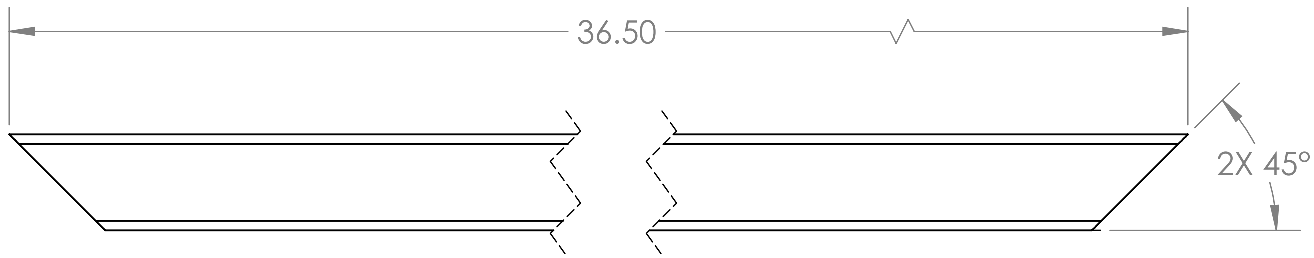
SIZE A

SHEET 1 OF 1

PART NUMBER

BT03





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A	PRELIMINARY DRAWING CREATED	TEAM 7	11/22/2019	FINISH
ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

TUBE - LONG MITRE

MATERIAL

1" X 1" X 7GA. 316L SST TUBE

COMMENTS:

NEXT ASSEMBLY

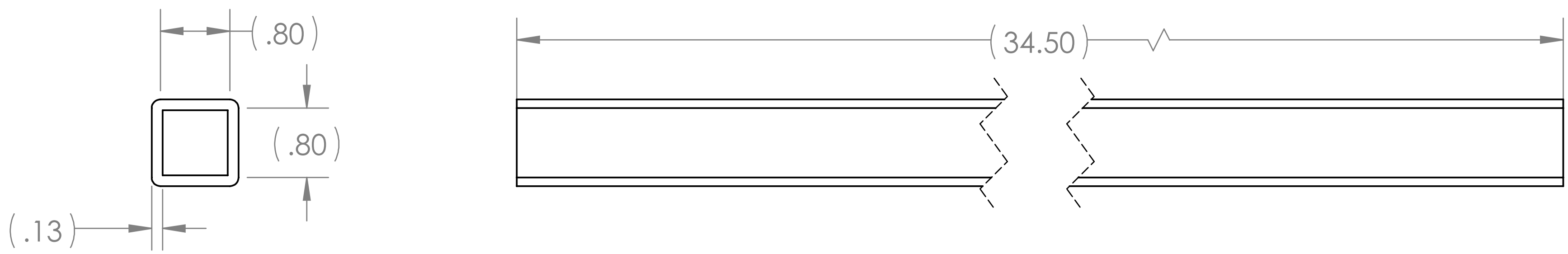
SIZE **A**

SHEET 1 OF 1

PART NUMBER

BT04

PROPRIETARY AND CONFIDENTIAL



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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

TUBE - BYPASS MIDDLE LONG

MATERIAL

1" X 1" X 7GA. 316L SST TUBE

COMMENTS:

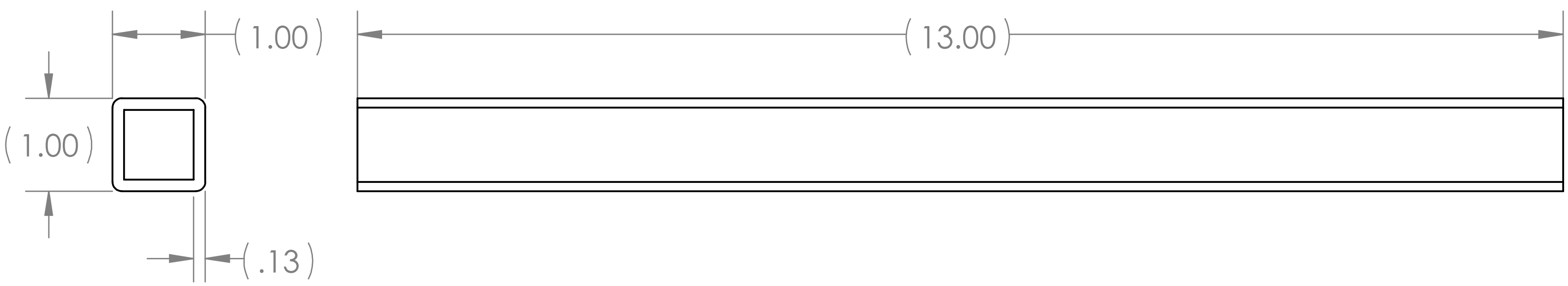
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

BT05



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ISSUE	REVISION	DRAWN	DATE

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TOLERANCES:
- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

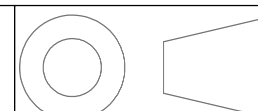
TITLE

TUBE - BYPASS TABLE SHORT

MATERIAL

1" X 1" X 7GA. 316L SST TUBE

COMMENTS:



NEXT ASSEMBLY

SIZE **A**

SHEET 1 OF 1

PART NUMBER

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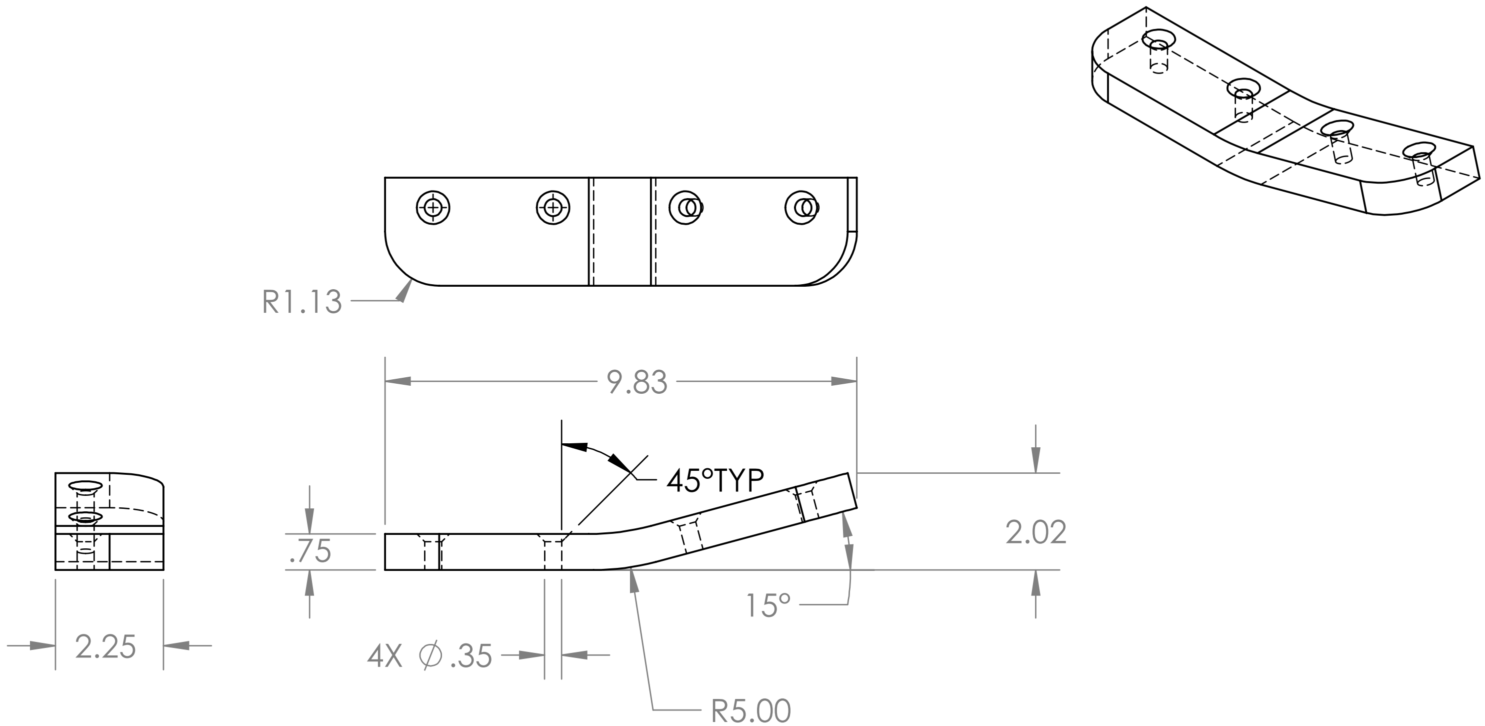

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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

TUBE - PADDLE MOUNT 2

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

NEXT ASSEMBLY

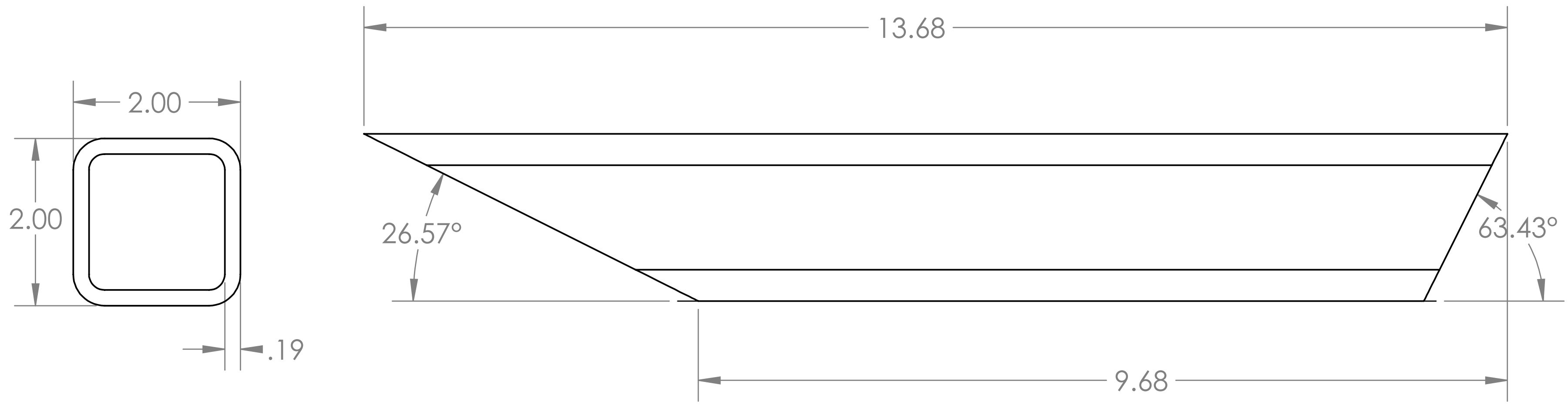
SIZE A

SHEET 1 OF 1

PART NUMBER

PC02

PROPRIETARY AND CONFIDENTIAL



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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

TUBE - PADDLE MOUNT 3

MATERIAL

2"X2"X7GA. 316L SST TUBE

COMMENTS:

NEXT ASSEMBLY

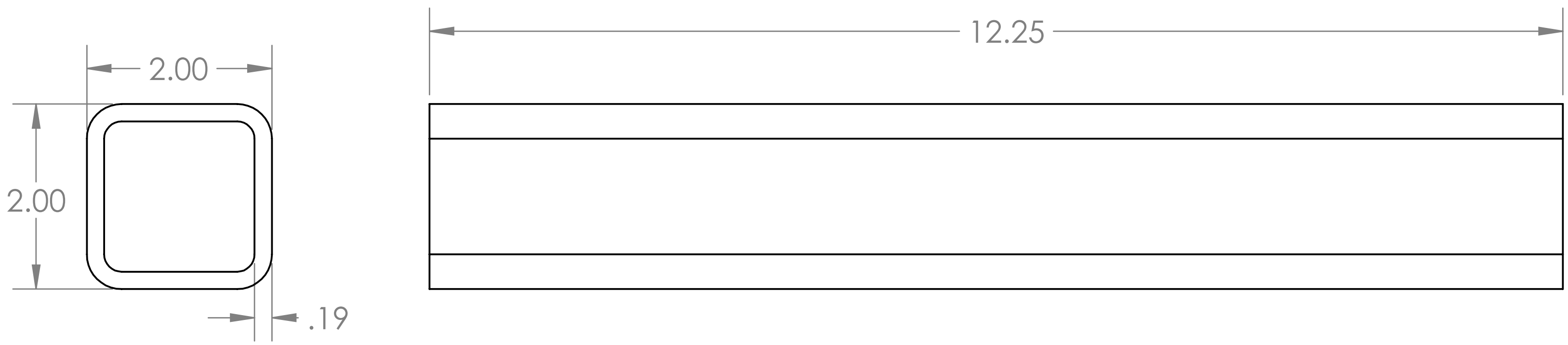
SIZE A

SHEET 1 OF 1

PART NUMBER

PC03

PROPRIETARY AND CONFIDENTIAL



A	PRELIMINARY DRAWING CREATED	TEAM 7	11/30/2019
ISSUE	REVISION	DRAWN	DATE

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TOLERANCES:
- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

TUBE - PADDLE MOUNT 2

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

NEXT ASSEMBLY

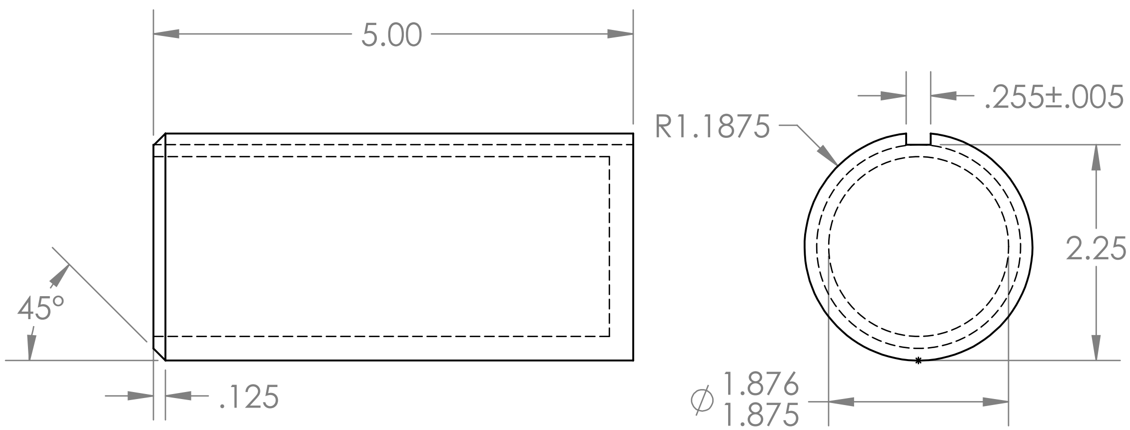
SIZE A

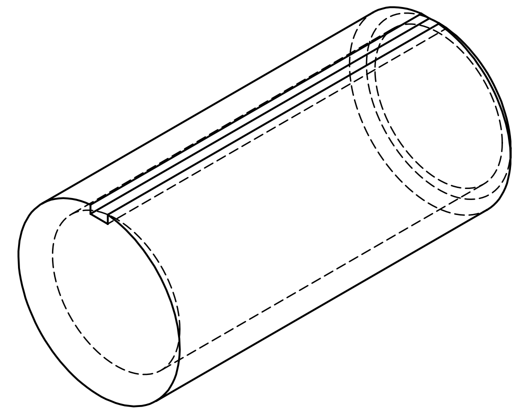
SHEET 1 OF 1

PART NUMBER

PC04

PROPRIETARY AND CONFIDENTIAL





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A	PRELIMINARY DRAWING CREATED	TEAM 7	11/22/2019	FINISH TBD
ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

PADDLE BORE CAP

MATERIAL

316L SST ROUND STOCK SIZE TBD

COMMENTS:

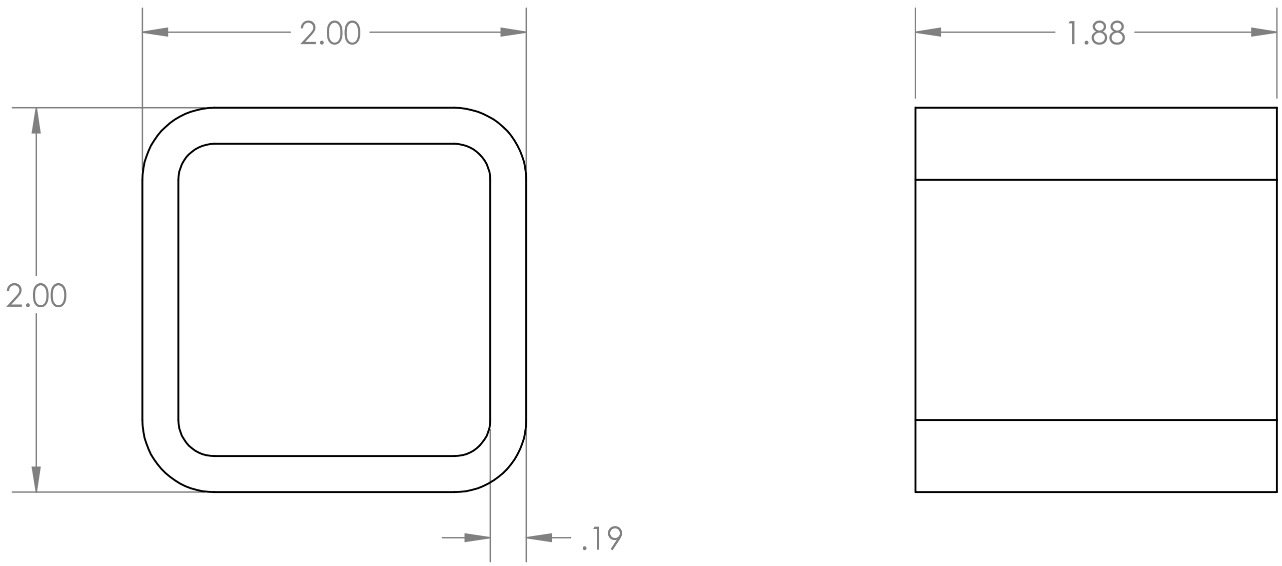
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

PC05



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ISSUE	REVISION	DRAWN	DATE

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TOLERANCES:
- = ± .1
.X = ± .01
.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

TUBE - PADDLE MOUNT 1

MATERIAL

2"X2"X7GA. 316L SST TUBE

COMMENTS:

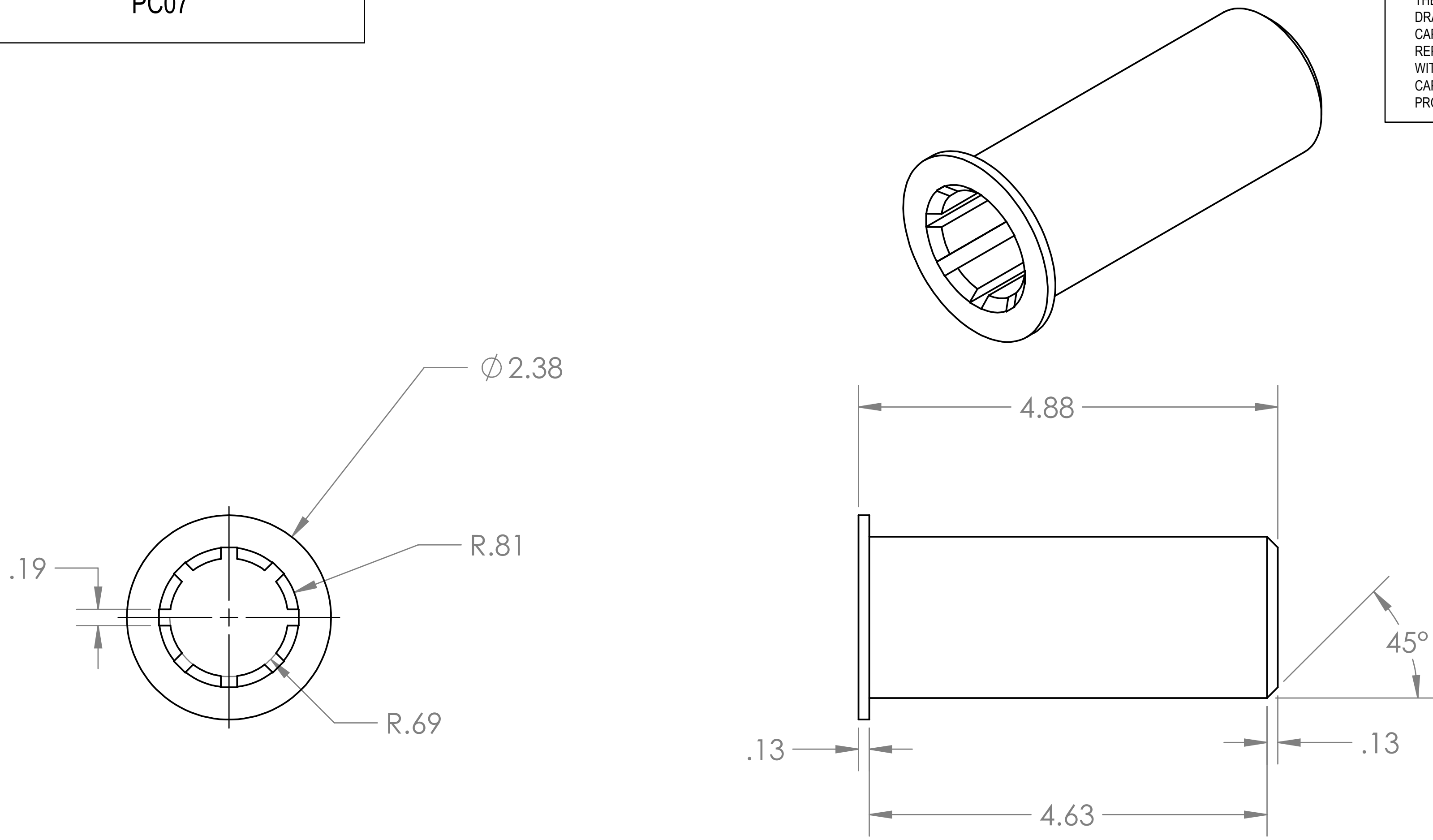
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

PC07



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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

PADDLE BUSHING

MATERIAL

DELRIN

COMMENTS:

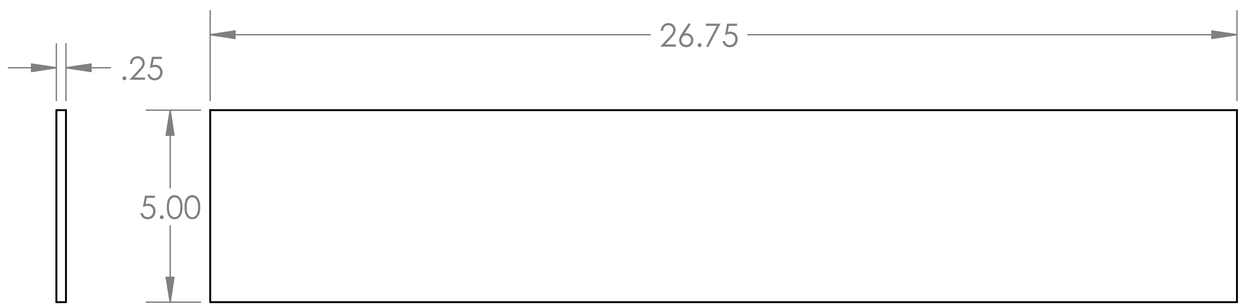
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

PC08



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.XX = ± .005
ANGLES = ± 1°

FINISH
TBD

DO NOT SCALE DRAWING

TITLE

PADDLE PLATE

MATERIAL

316L SST PLATE 0.25"

COMMENTS:

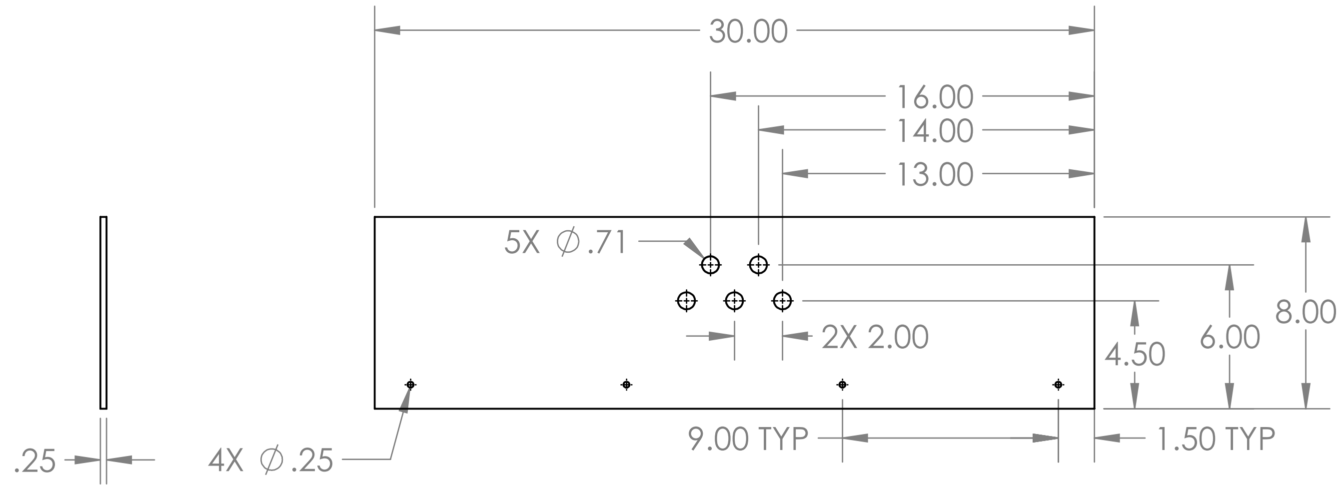
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

PC10



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ANGLES = ± 1°

FINISH

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TITLE

SHEET - SENSOR MOUNT

MATERIAL

.25" 316L SST PLATE

COMMENTS:

NEXT ASSEMBLY

SIZE A

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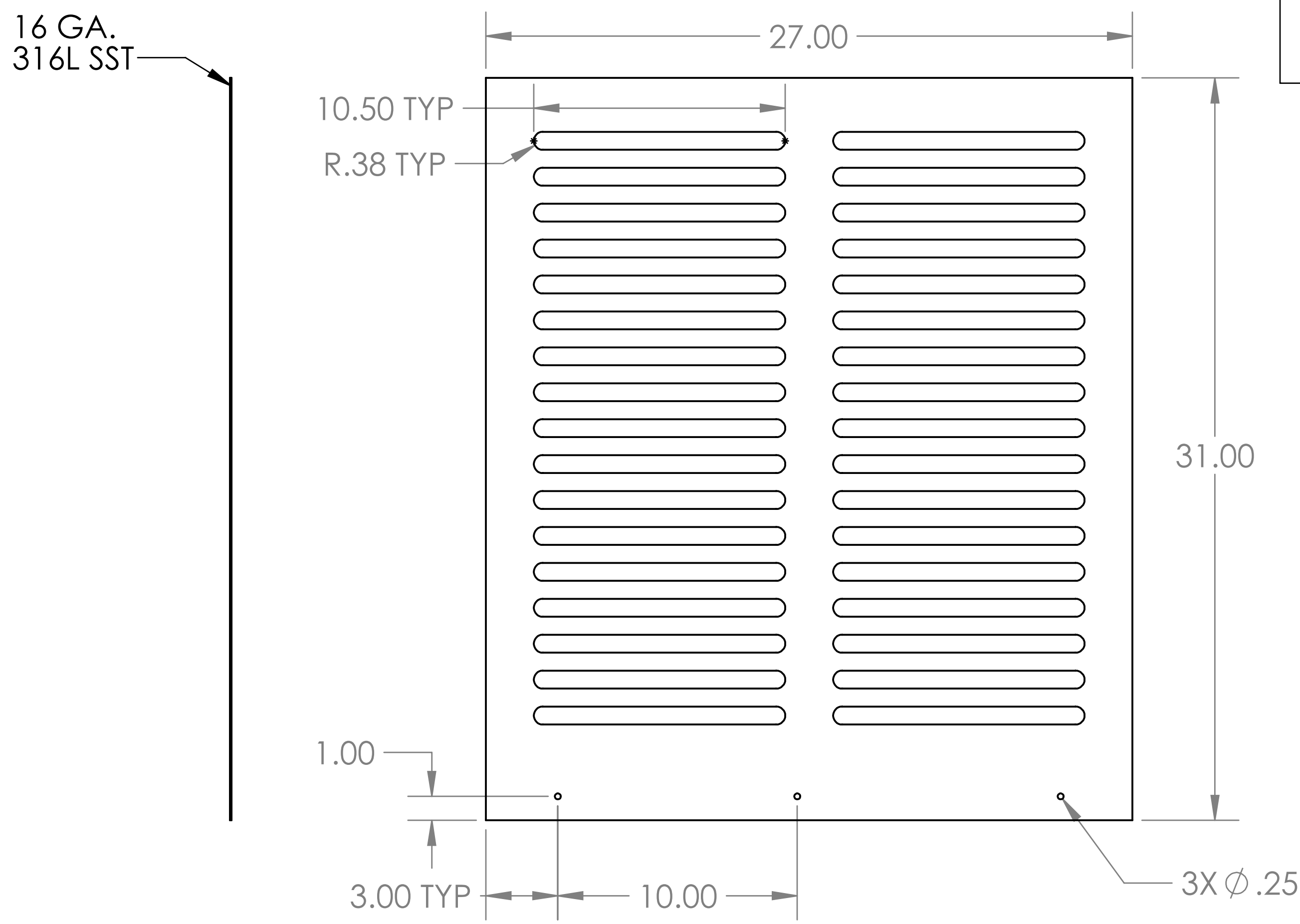
PART NUMBER

SG01



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TITLE

SHEET - SAFETY GUARD 1

MATERIAL

16 GA. 316L SST SHEET

COMMENTS:

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SIZE A

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PART NUMBER

SG02

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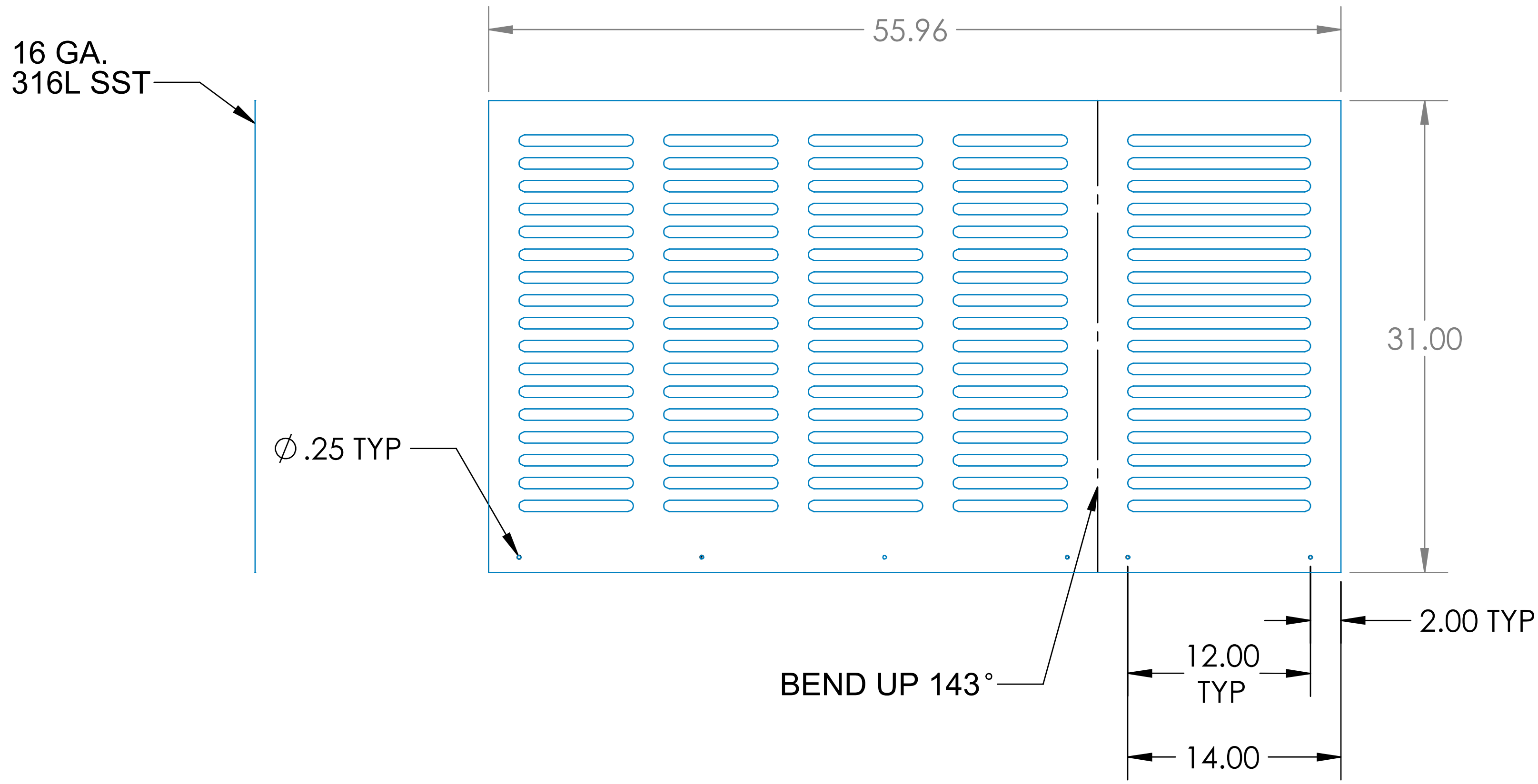

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TITLE

SHEET - SAFETY GUARD 2

MATERIAL

16 GA. 316L SST SHEET

COMMENTS:

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PART NUMBER

SG03

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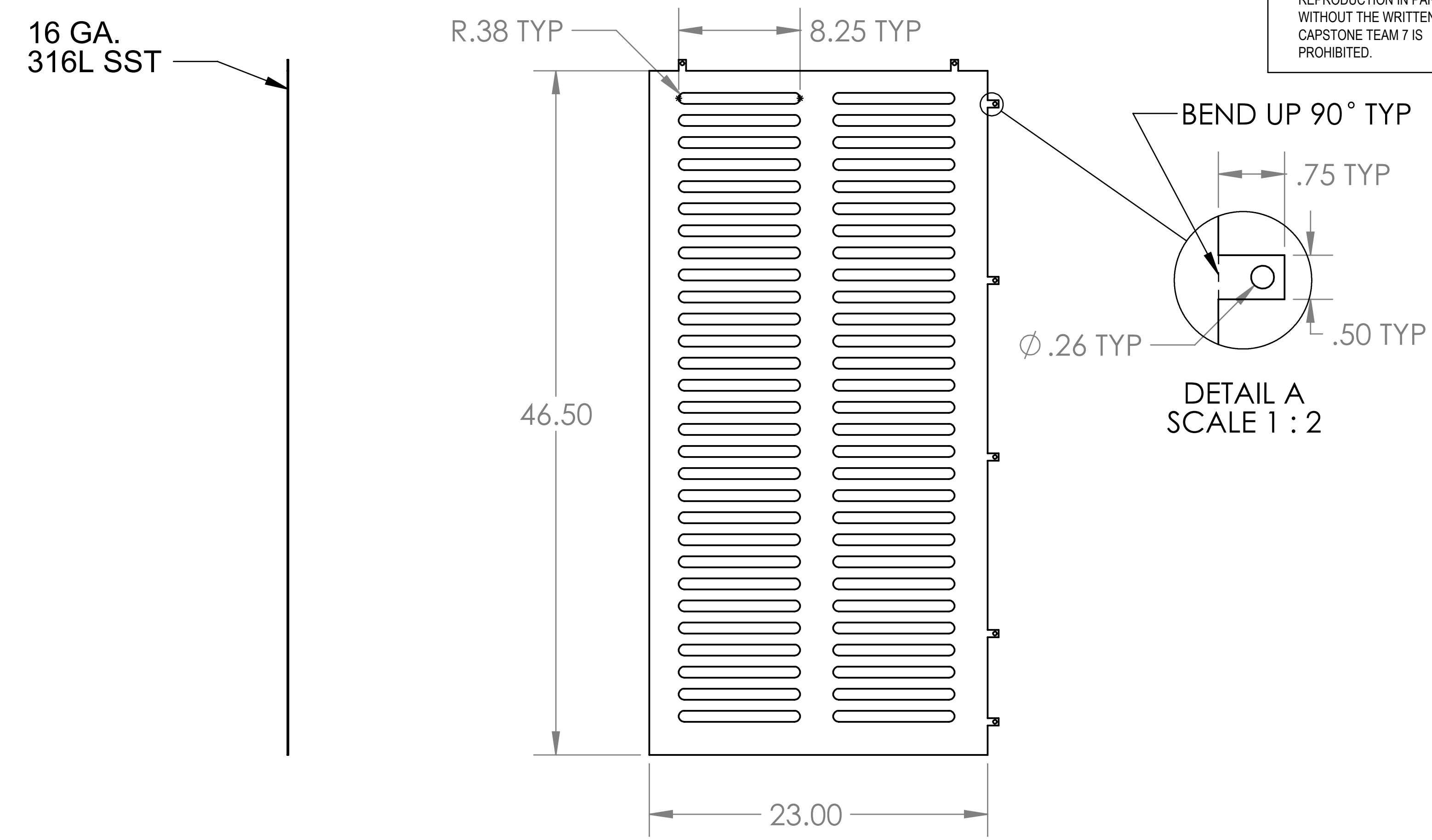

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TITLE

SHEET - SAFETY GUARD 3

MATERIAL

16 GA. 316L SST SHEET

COMMENTS:

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PART NUMBER

SG04

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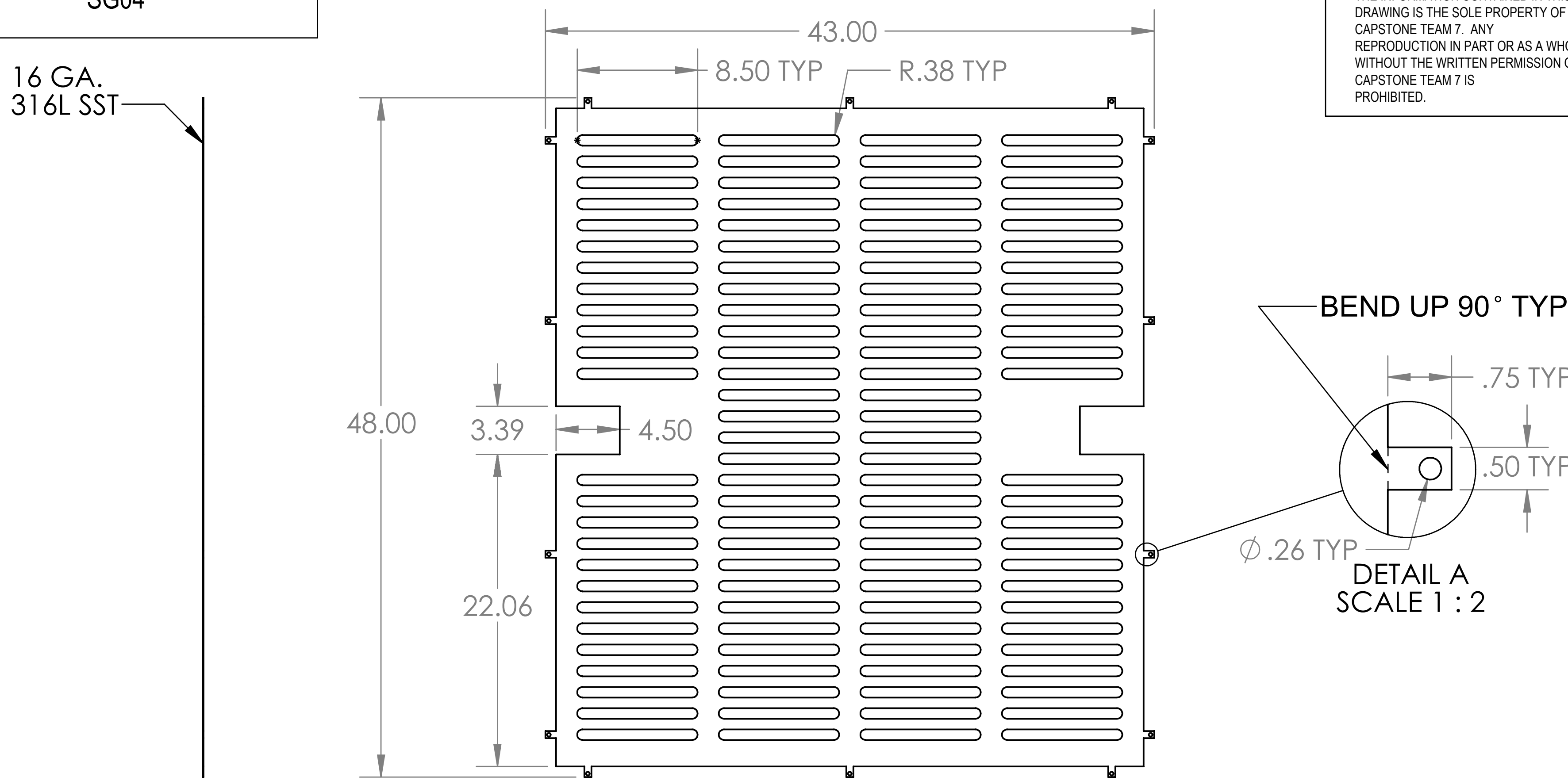

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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

TITLE

SHEET - SAFETY GUARD 4

MATERIAL

16 GA. 316L SST SHEET

COMMENTS:

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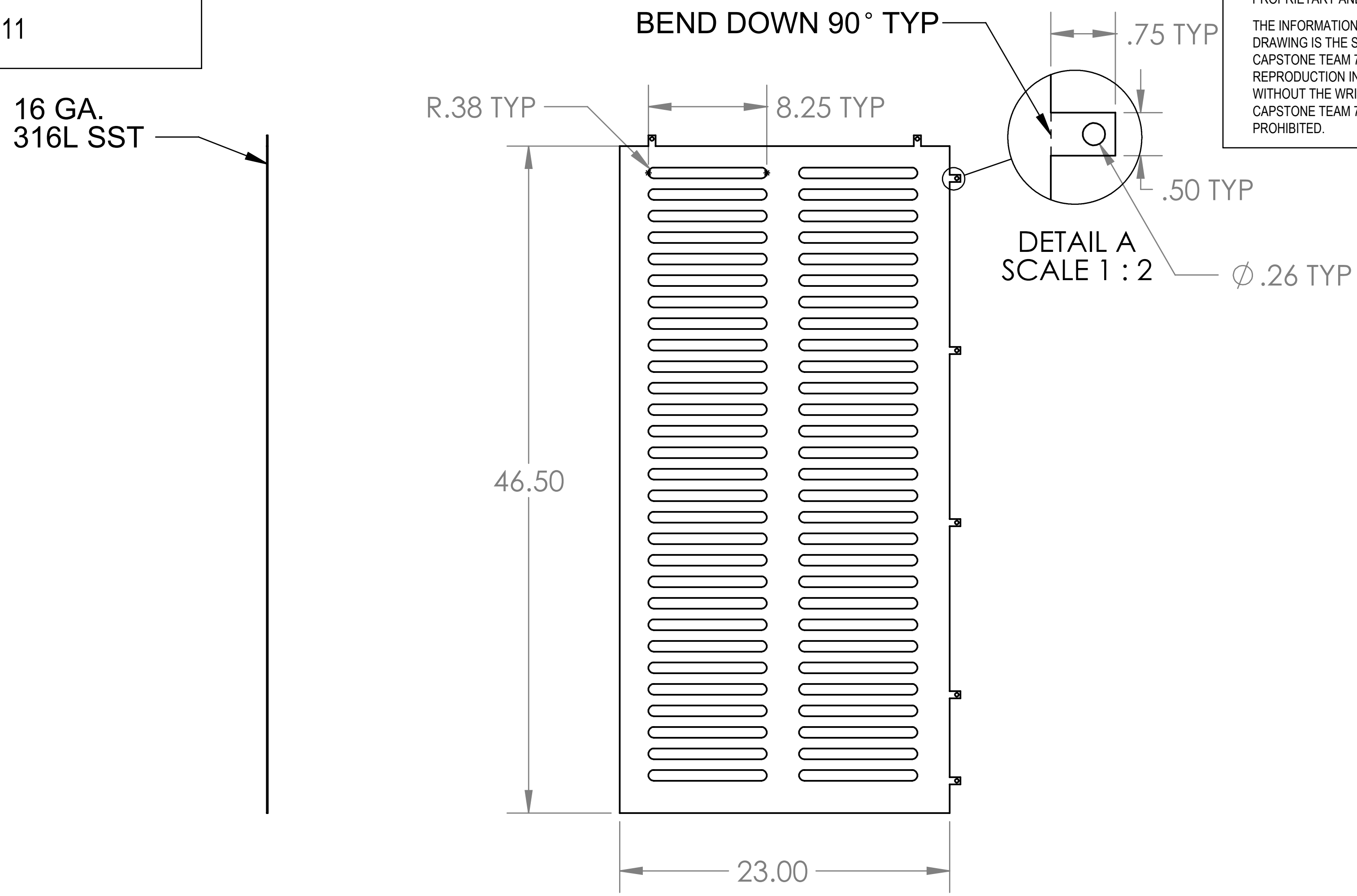
SHEET 1 OF 1

PART NUMBER

SG11



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TITLE

SHEET - SAFETY GUARD 11

MATERIAL

16 GA. 316L SST SHEET

COMMENTS:

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PART NUMBER

SS01

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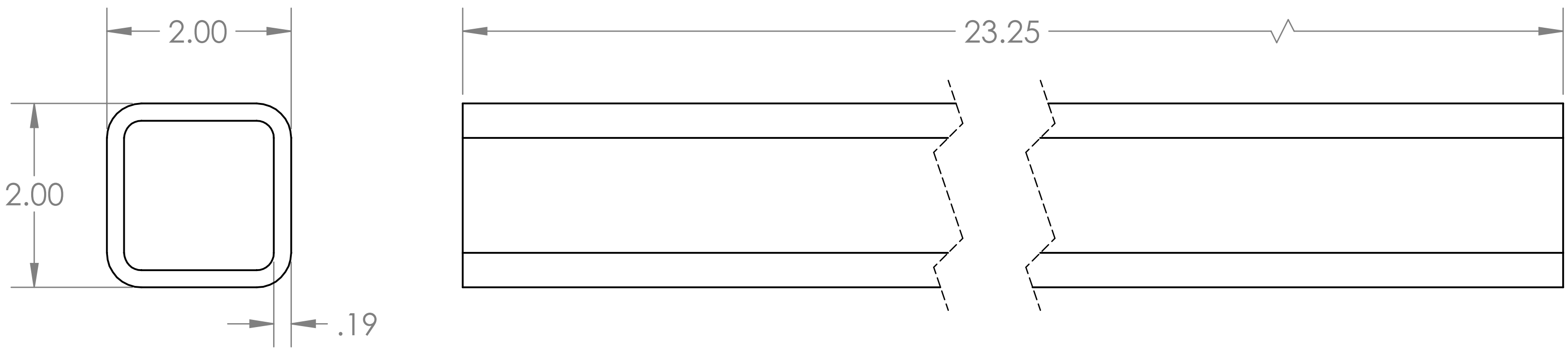

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FINISH

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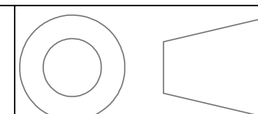
TITLE

TUBE - SUPPORT STR. 1

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:



NEXT ASSEMBLY

SIZE **A**

SHEET 1 OF 1

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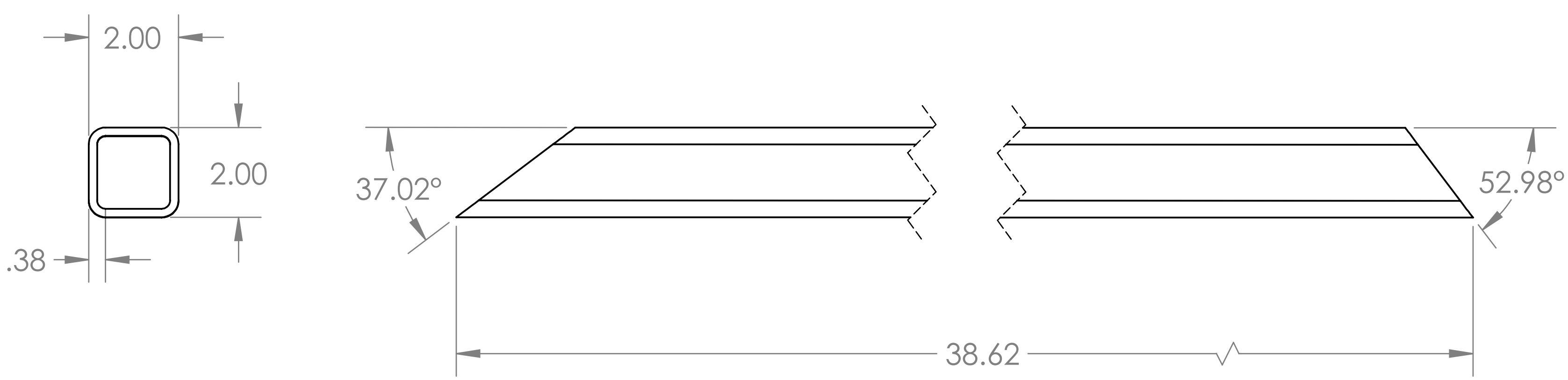
PART NUMBER

SS02



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TITLE

TUBE - SUPPORT STR. 2

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

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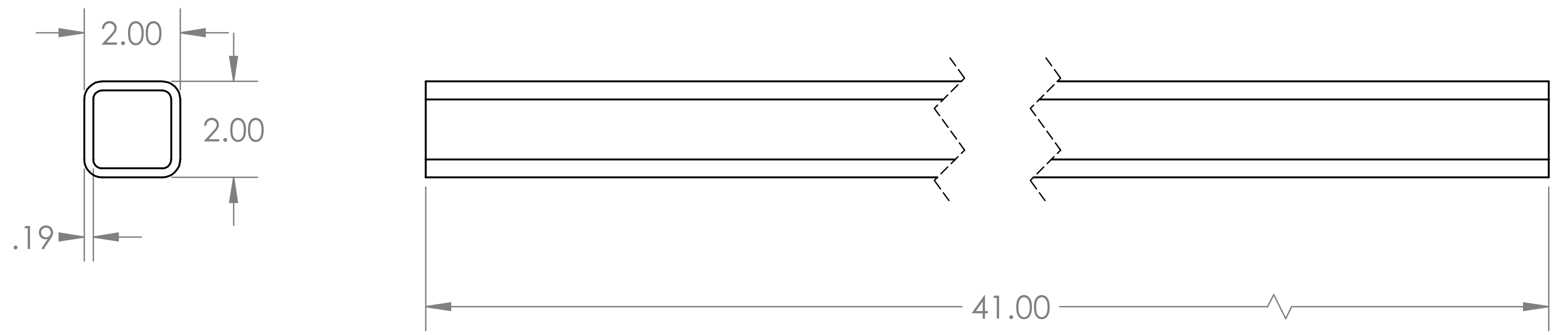
SIZE A

SHEET 1 OF 1

PART NUMBER

SS04

PROPRIETARY AND CONFIDENTIAL



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TITLE

TUBE - SUPPORT STR. 4

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

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SIZE A

SHEET 1 OF 1

PART NUMBER

SS05

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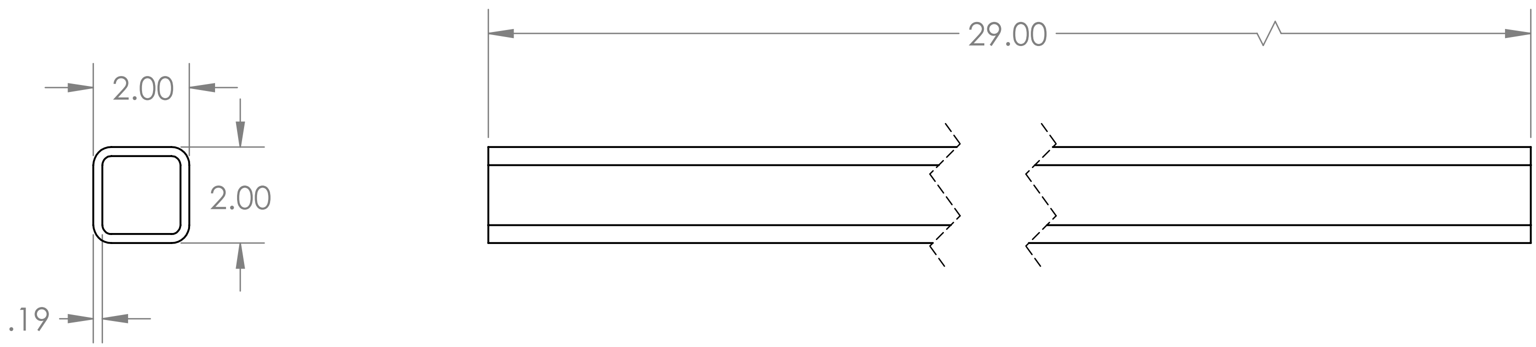

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TITLE

TUBE - SUPPORT STR. 5

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

NEXT ASSEMBLY

SIZE **A**

SHEET 1 OF 1

PART NUMBER

SS06

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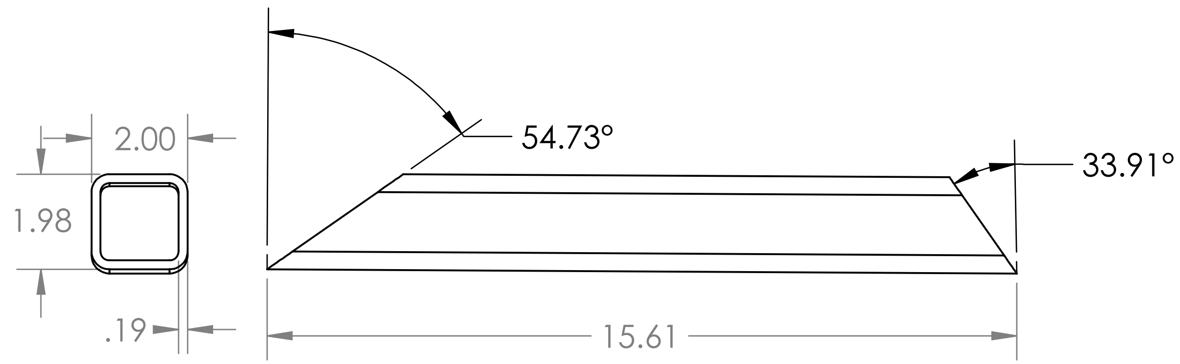

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ISSUE	REVISION	DRAWN	DATE	DO NOT SCALE DRAWING

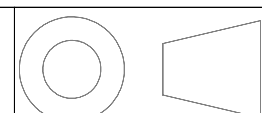
TITLE

TUBE - SUPPORT STR. 5

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:



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SS07

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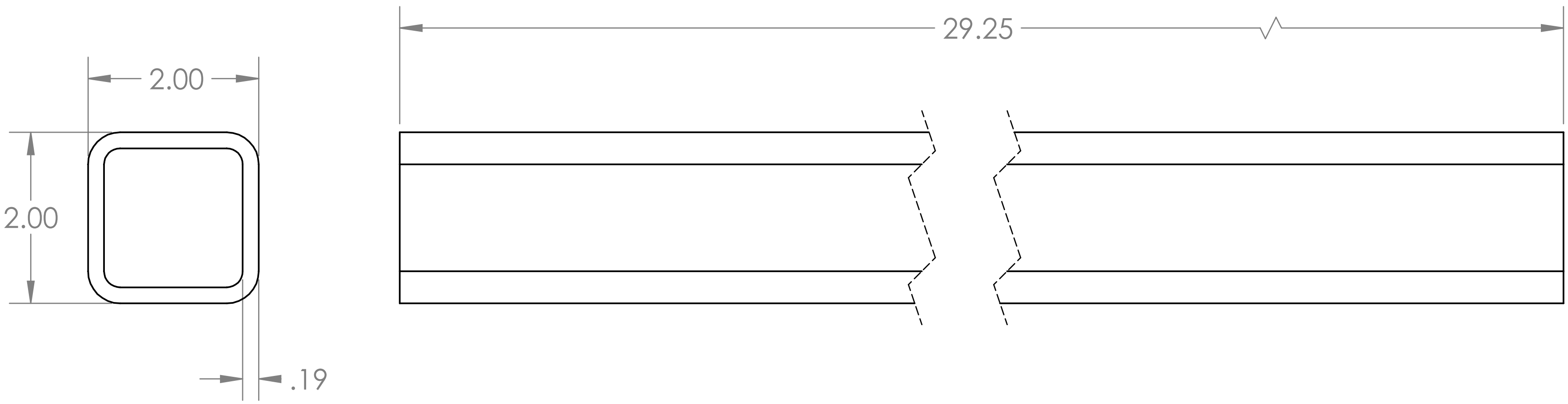

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.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

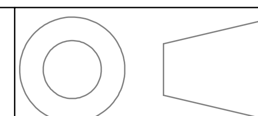
TITLE

TUBE - SUPPORT STR. 7

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:



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PART NUMBER

SS08

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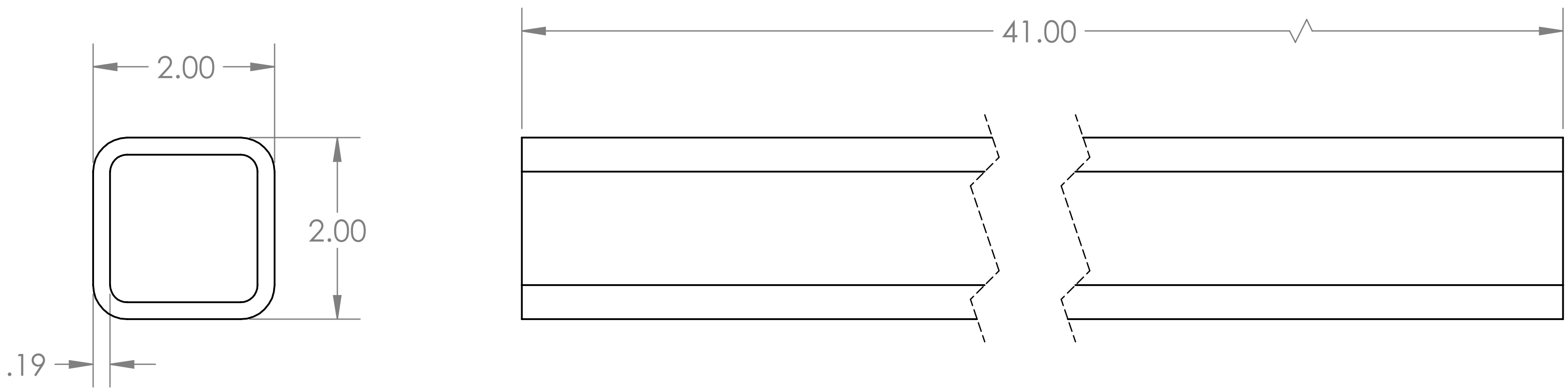

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TITLE

TUBE - SUPPORT STR. 8

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

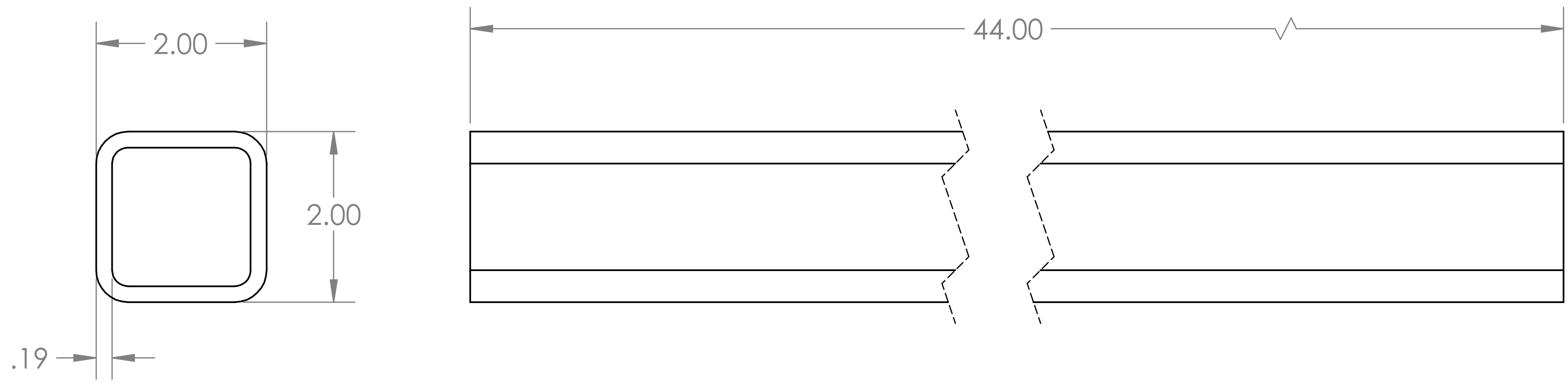
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

SS09



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ANGLES = ± 1°

FINISH

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TITLE

TUBE - SUPPORT STR. 9

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

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SIZE A

SHEET 1 OF 1

PART NUMBER

SS10

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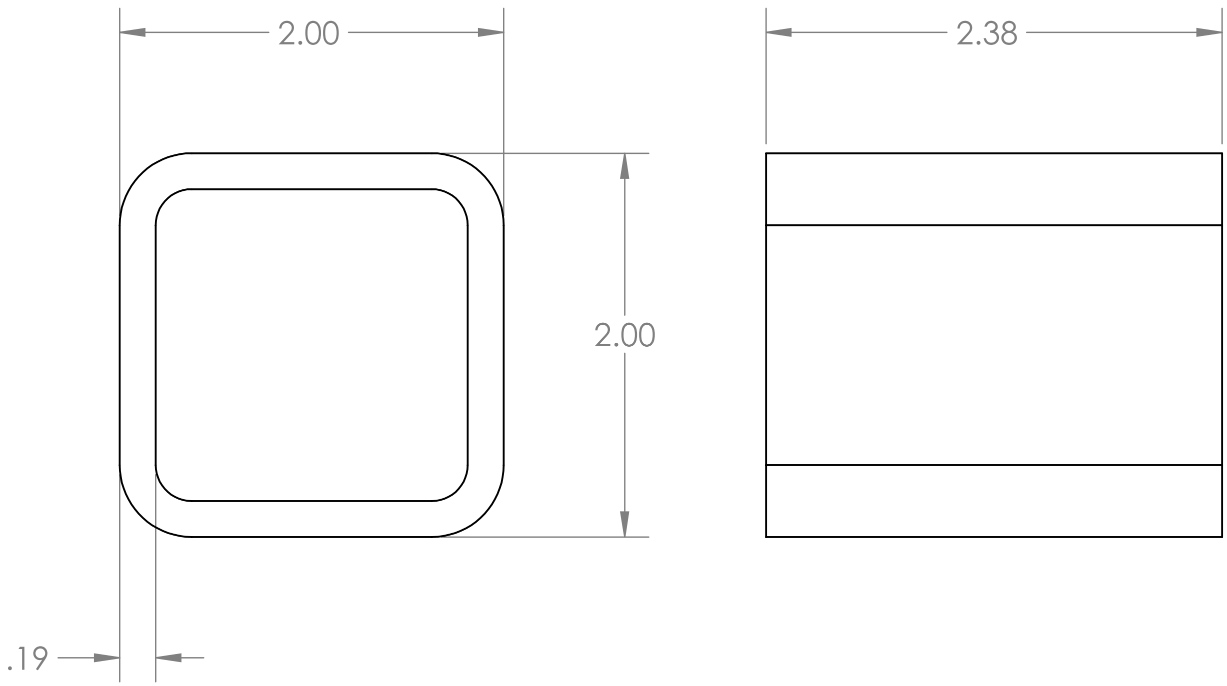

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.XX = ± .005
ANGLES = ± 1°

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TITLE

TUBE - SUPPORT STR. 10

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

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SIZE A

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SS11

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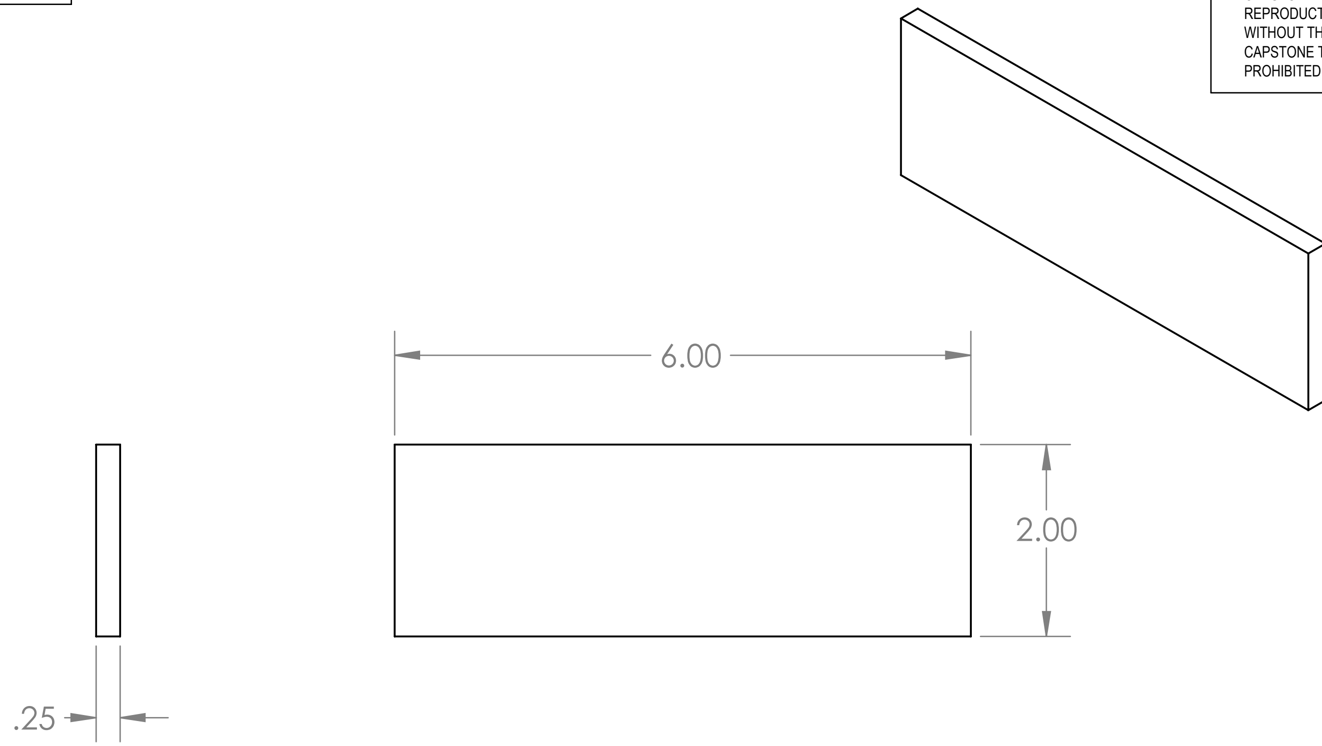

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TITLE

PLATE - SIDE MOUNT

MATERIAL

0.25" 316L SST PLATE

COMMENTS:

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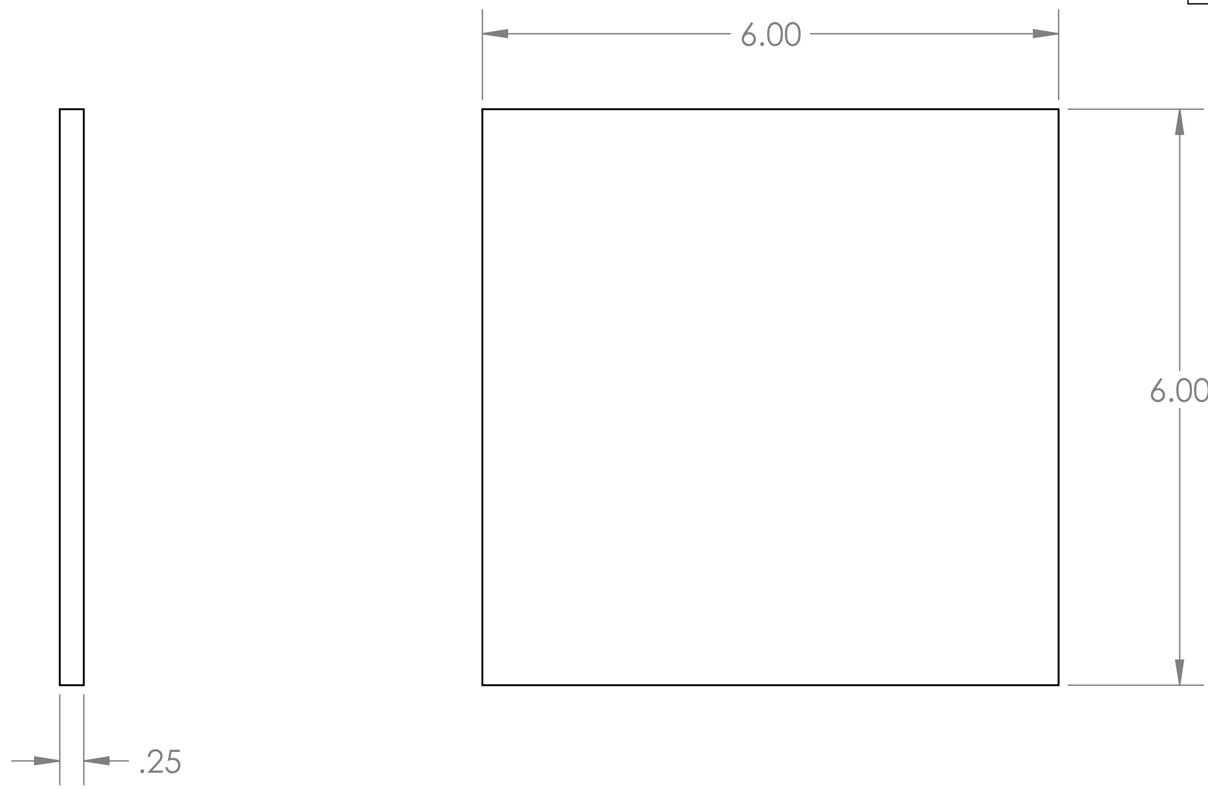
PART NUMBER

SS12



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.XX = ± .005
ANGLES = ± 1°

FINISH

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TITLE

PLATE - FLOOR MOUNT

MATERIAL

0.25" 316L SST PLATE

COMMENTS:

NEXT ASSEMBLY

SIZE A

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SS13

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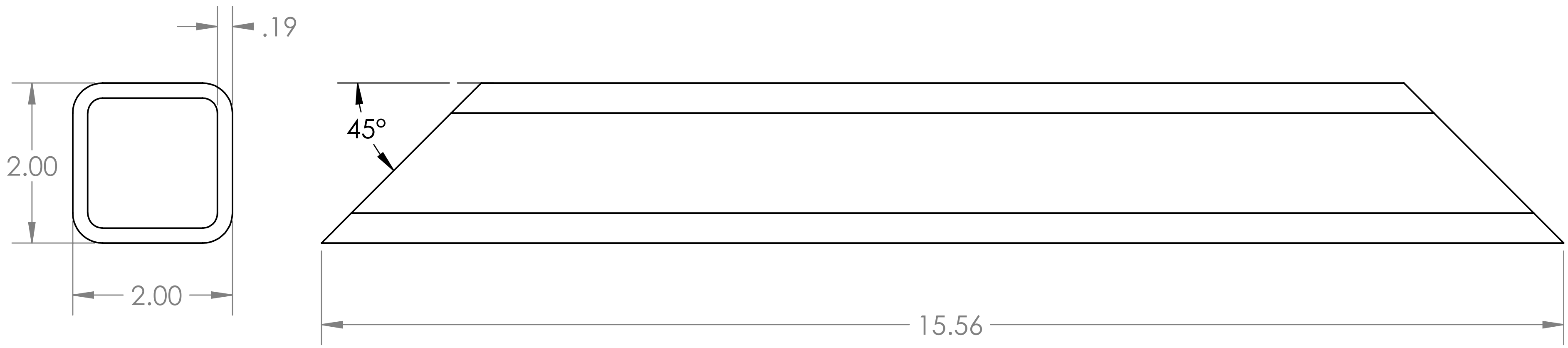

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.XX = ± .005
ANGLES = ± 1°

FINISH

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TITLE

TUBE - SUPPORT STR. 1

MATERIAL

2" X 2" X 7GA. 316L SST TUBE

COMMENTS:

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SIZE A

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SS14

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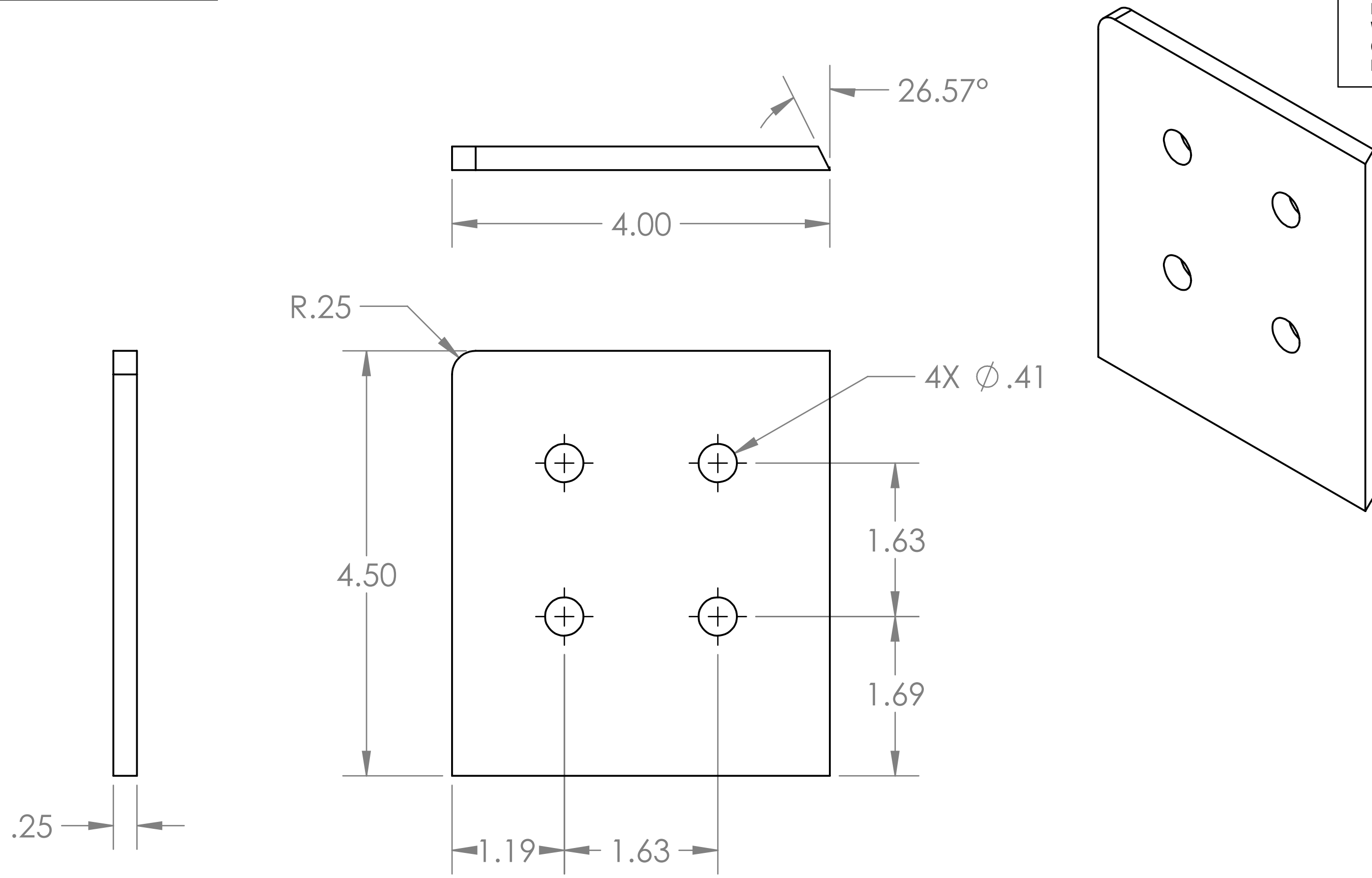

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TITLE

PLATE - SEAL PLATE

MATERIAL

0.25" 316L SST PLATE

COMMENTS:

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SS15

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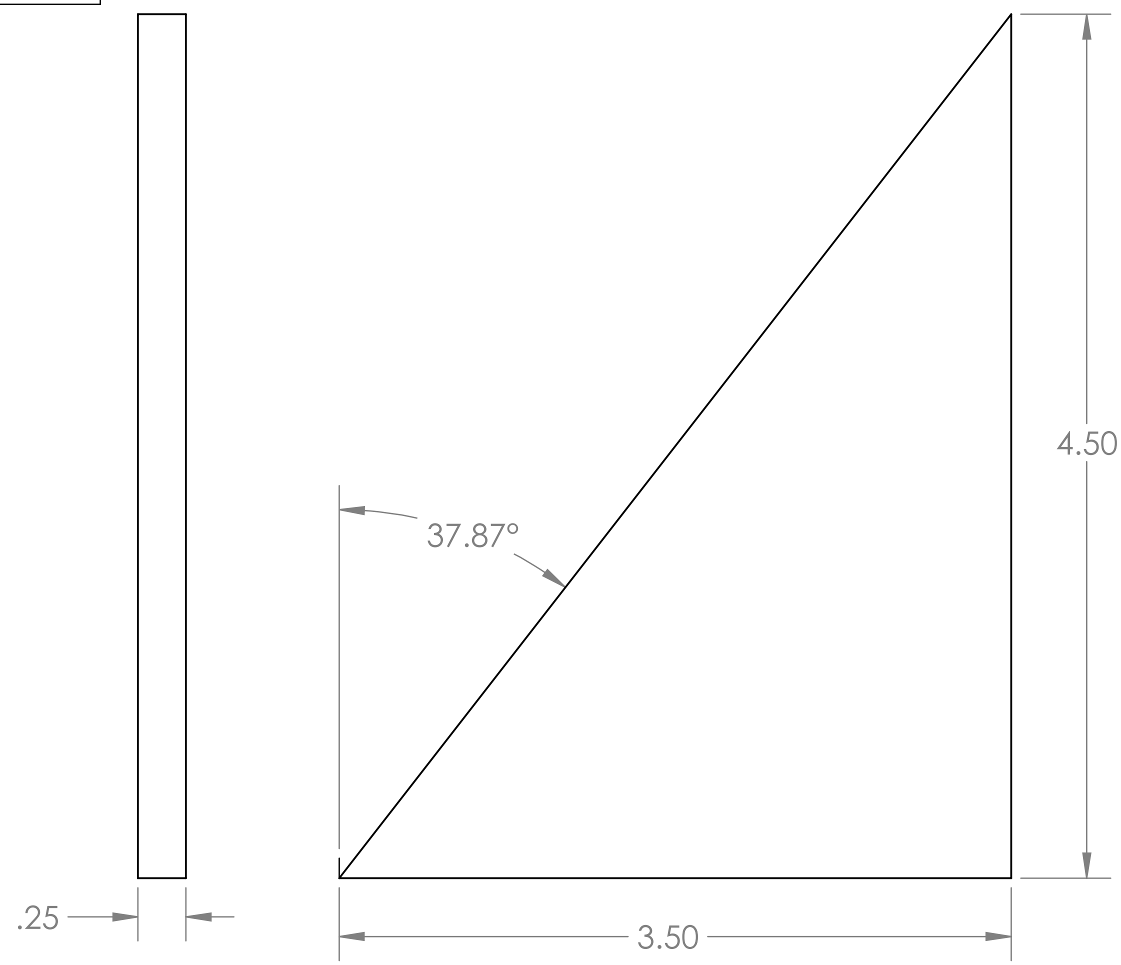

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ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

TITLE

PLATE - CYL BRKT GUSSET

MATERIAL

0.25" 316L SST PLATE

COMMENTS:

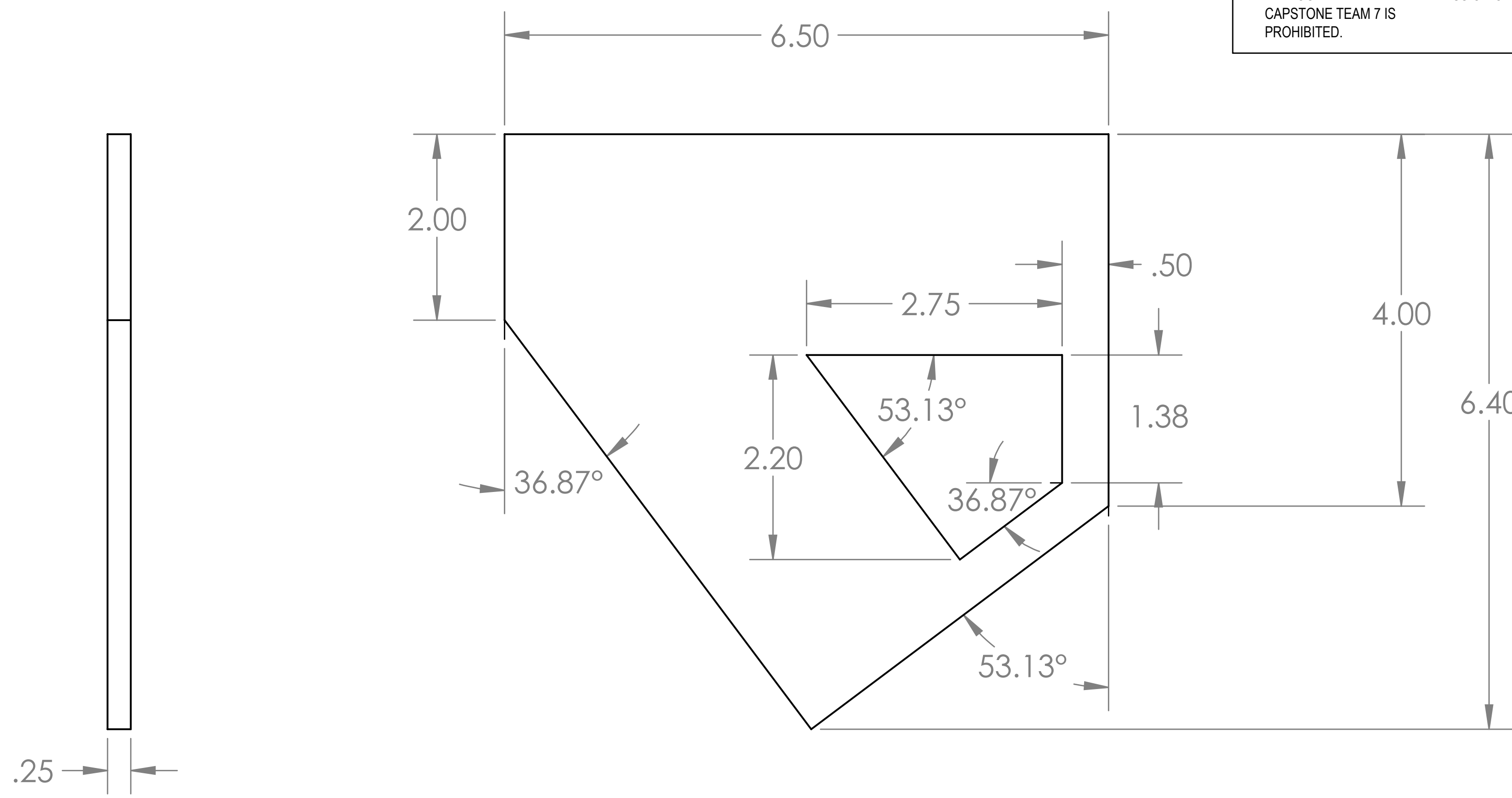
NEXT ASSEMBLY

SIZE A

SHEET 1 OF 1

PART NUMBER

SS17



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.XX = ± .005
ANGLES = ± 1°

FINISH

DO NOT SCALE DRAWING

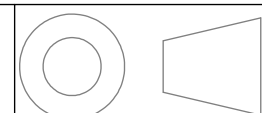
TITLE

PLATE - CYL BRKT BASE

MATERIAL

0.25" 316L SST PLATE

COMMENTS:



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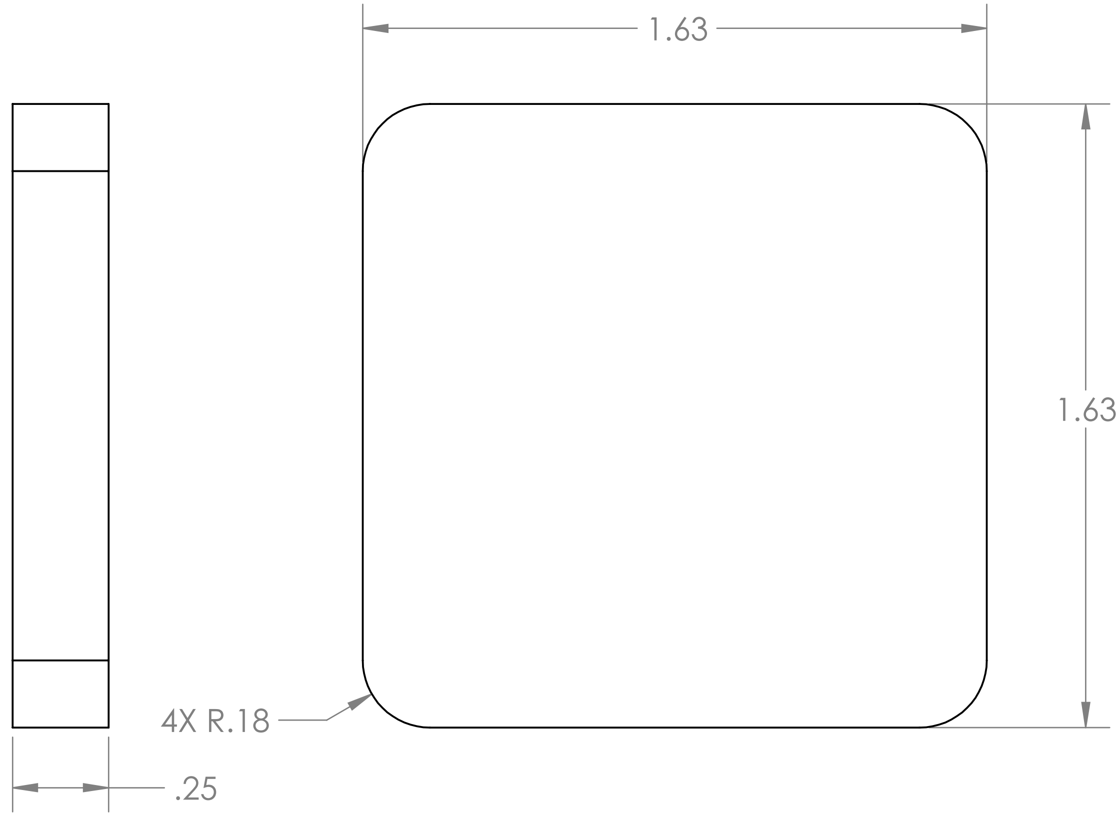
SIZE A

SHEET 1 OF 1

PART NUMBER

SS21



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TITLE

PLATE - SEAL PLATE

MATERIAL

0.25" 316L SST PLATE

COMMENTS:

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APPENDIX F

FEA

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List of Tables

1 Support Structure FEA

Finite element analysis was used to assess the support structure when loaded by the extension of paddle 1 and 2 respectively. When either paddle is blocked by a loin or held in place, most or all of the load from each cylinder is transferred to the pins. When the first cylinder pushes on the arm of paddle 1, it transfers the full load to the pin in the direction of the cylinder extension. When the second cylinder pushes on paddle 2, only a portion of the load is transferred to the pin due to the cylinder loading angle.

With a supply of 100psi air, each of the two cylinders can exert up to 490.9lbf. The 100psi air supply represents the maximum pressure available in the plant and thus was used as a worst-case loading scenario. The forces for each loading scenario consist of a force onto the paddle mounting pin, and a force onto the cylinder corner mounting bracket. The forces are outlined next in Figure 1.

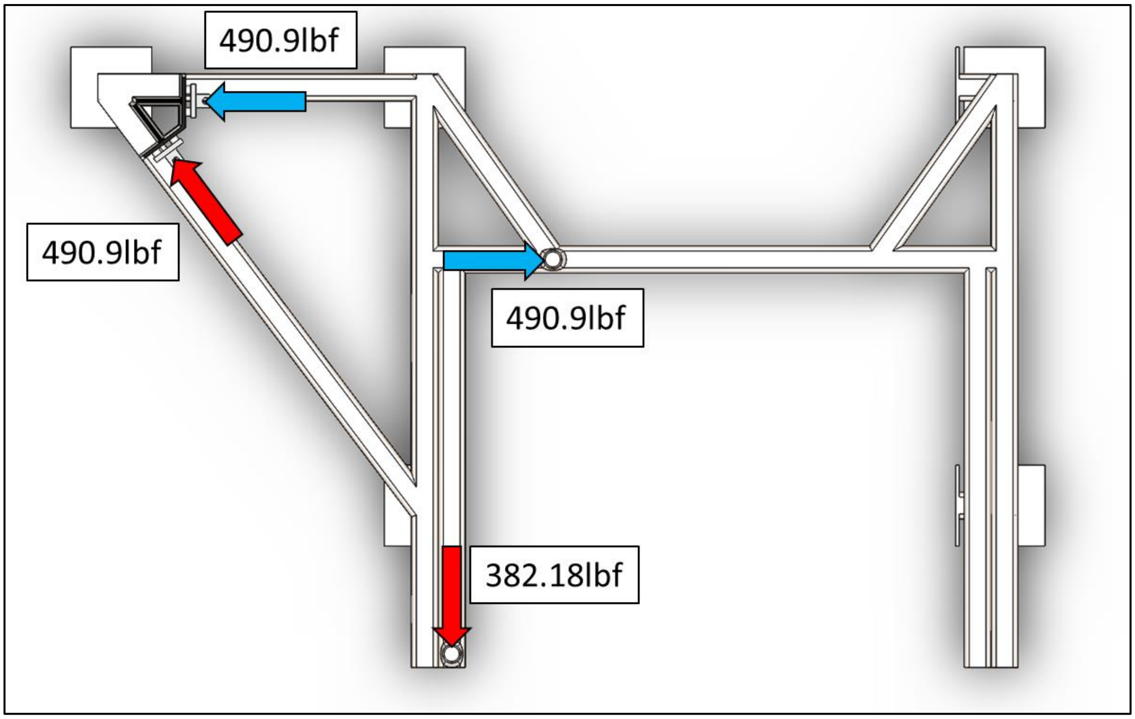

Figure 1: Top view of paddle table structure with forces for paddle 1 loading (blue) and paddle 2 loading (red)

As shown in Figure 1, the blue arrows indicate loading scenario 1, for which there is 490.9lbf applied to the bracket and the pin. The 490.9lbf on the pin is due to the cylinder being parallel to the first paddle, and the assumption that the paddle is held in place. For loading scenario 2 there is a force of 490.9lbf on the cylinder mounting bracket, but only 382.18lbf applied to the pin due to the direction of cylinder extension with respect to the paddle. In the second loading scenario, the pin only experiences the y-component of this force, being 382.18lbf.

In the simulation of both loading scenarios, a mesh convergence study was run and common settings were used in the simulation setup [1]. These settings are shown next in TABLE I.

TABLE I: SUPPORT STRUCTURE FEA SETTINGS

Software	Solidworks 2020
Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Automatic transition	Off
Mesh auto loops	Off
Jacobian points	4
Max element size	0.5in
Min element size	0.01in
Material type	316L Stainless steel (Solidworks profile)
Elastic modulus	193GPa
Poisson’s Ratio	0.3
Tensile strength	550MPa
Yield strength	137.9MPa
Component contacts	Global contact (bonded)
Solver	Direct sparse solver
Adaptive mesh refinement	h-adaptive, 5 loops, 99% target accuracy
Thermal effects	Disabled

Additionally, common boundary conditions were used. The bottom of the support structure feet and the sides were considered fixed geometry, as shown alongside the force vectors in Figure 2 next.

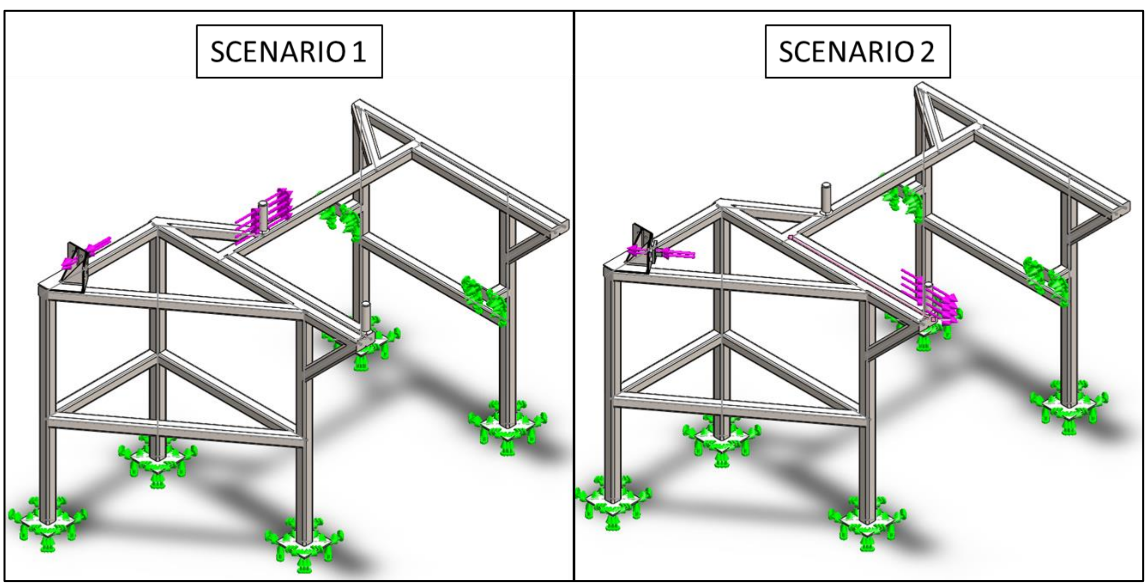

Figure 2: Force vectors (purple) and fixed boundaries (green) for paddle 1 loading (left) and paddle 2 loading (right)

1.1 Loading Scenario 1 – Paddle 1 Extension

As described prior, the first scenario involved loading the corner cylinder mount and the first paddle pin with 490.9lbf in opposite directions. It was determined from preliminary finite element analysis that most of the structure is below the yield stress. This is shown next in Figure 3.

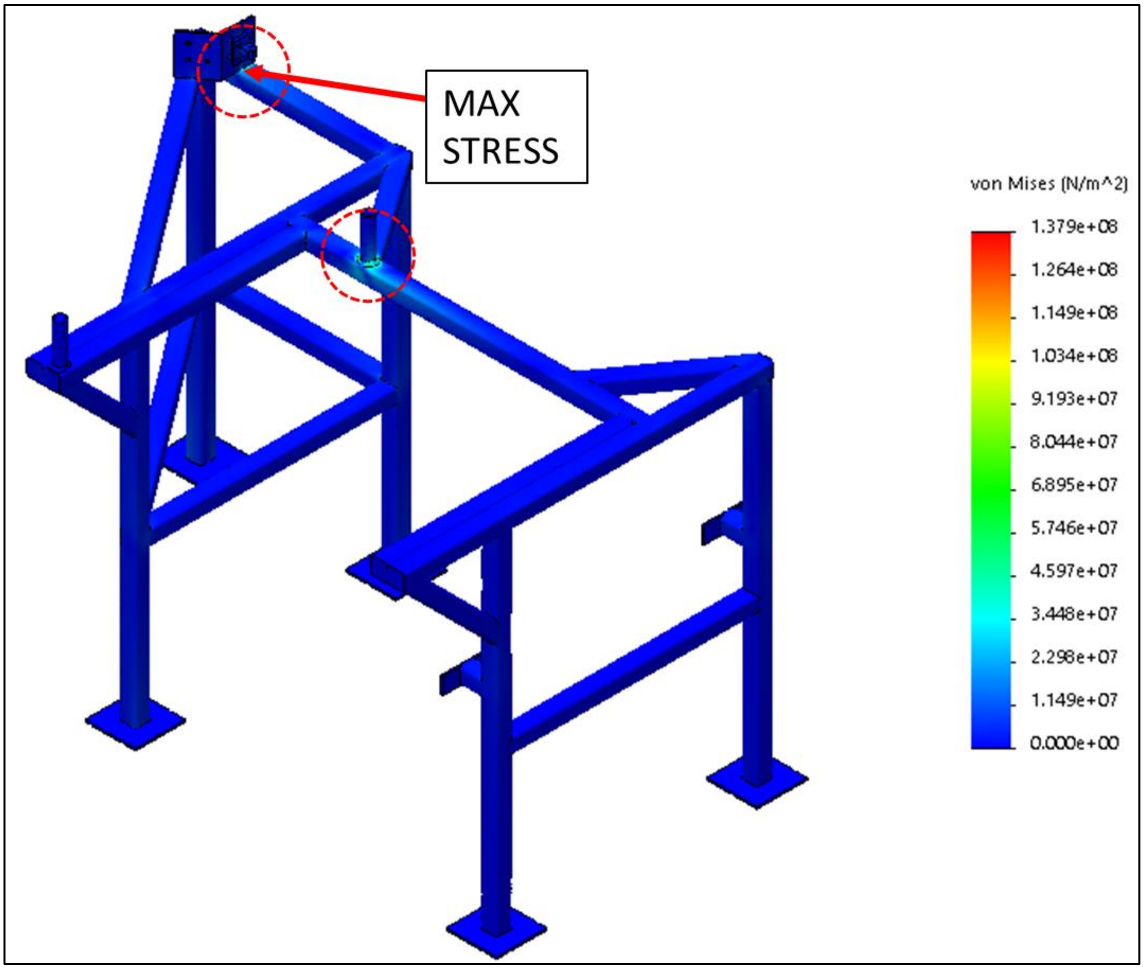

Figure 3: Von Mises stress distribution for table support structure under loading scenario 1. Deformation scale is 1 to 1 and peak stress locations are circled in red.

Figure 3 shows two points of high stress, circled in red. Other locations where components met were also found to have high stress, however the two circled locations experienced the highest stress. A closer view of the two points of interest is shown in Figure 4.

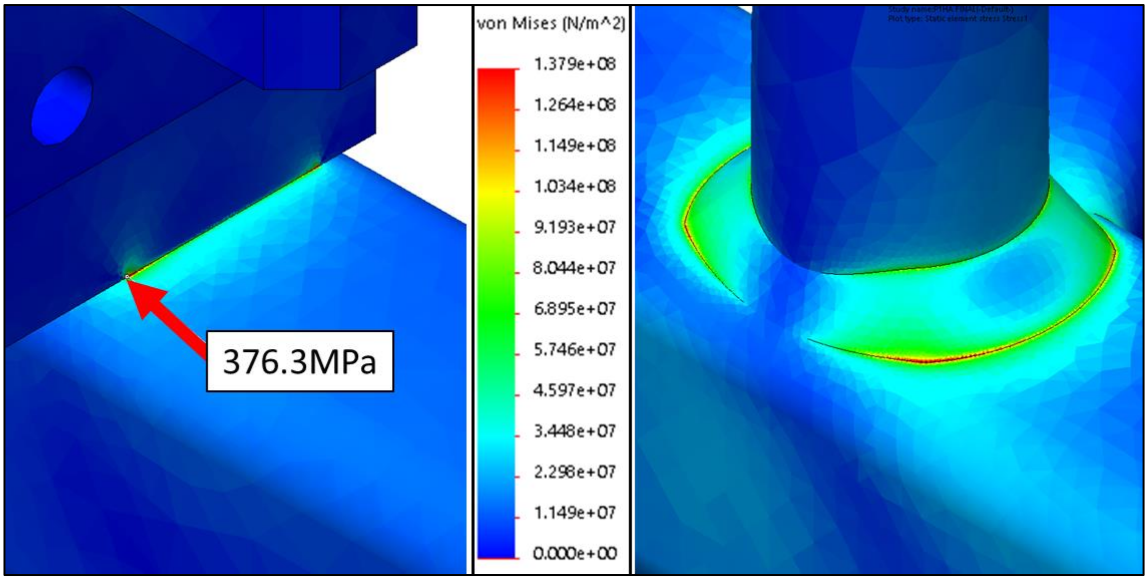

Figure 4: Singularity points from loading scenario 1 on the cylinder corner mounting bracket (left) and paddle pin 1 (right)

From Figure 4, it is seen that the previously circled areas of high stress have a small group of elements with extremely high stress, while the surrounding elements are below yield. The elements of extremely high stress are singularity points as a result a sharp intersection between components and were confirmed to be such by a mesh convergence study. That is, the convergence study showed that as the number of elements increased (i.e. mesh refinement in areas of rapidly changing stress), the stress diverged while the deflection converged. The convergence study is shown next in Figure 5.

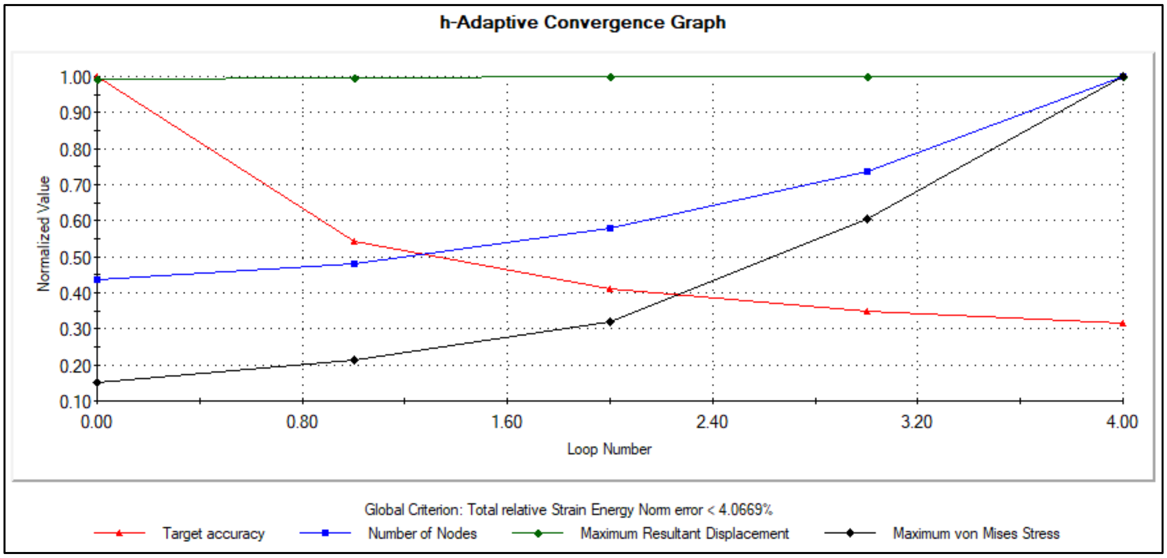

Figure 5: h-adaptive convergence graph for table support structure loading scenario 1

Since the singularity points would be eliminated with welds and the rest of the structure was found to be well below the yield strength of the 316L steel, the support structure should be able to withstand the loading from the first air cylinder. The maximum deflection corresponding to the load of 490.9lbf was found to be 0.5313mm and is shown next in Figure 6.

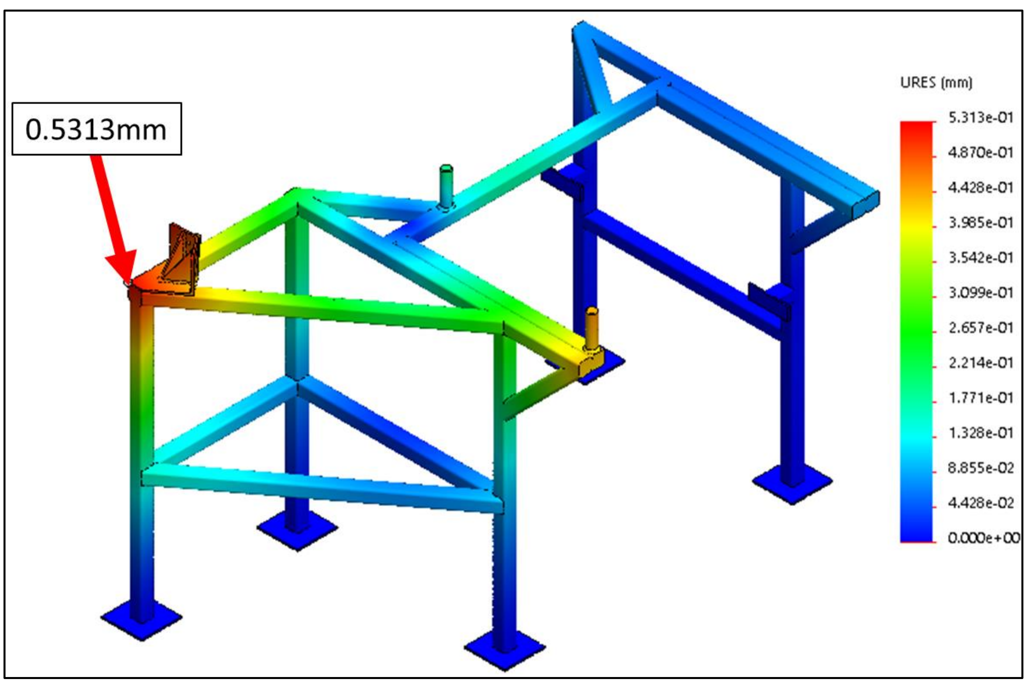

Figure 6: Plot of support structure deflection under loading scenario 2. Peak deflection of 0.5313mm occurs on the corner cylinder bracket. Global deformation scale is 1 to 1.

1.2 Loading Scenario 2 – Paddle 2 Extension

As described prior, the second scenario involved loading the corner cylinder mount with 490.9lbf and the second paddle pin with 382.18lbf. It was determined from preliminary finite element analysis that most of the structure is below the yield stress. This is shown once again in Figure 7 next.

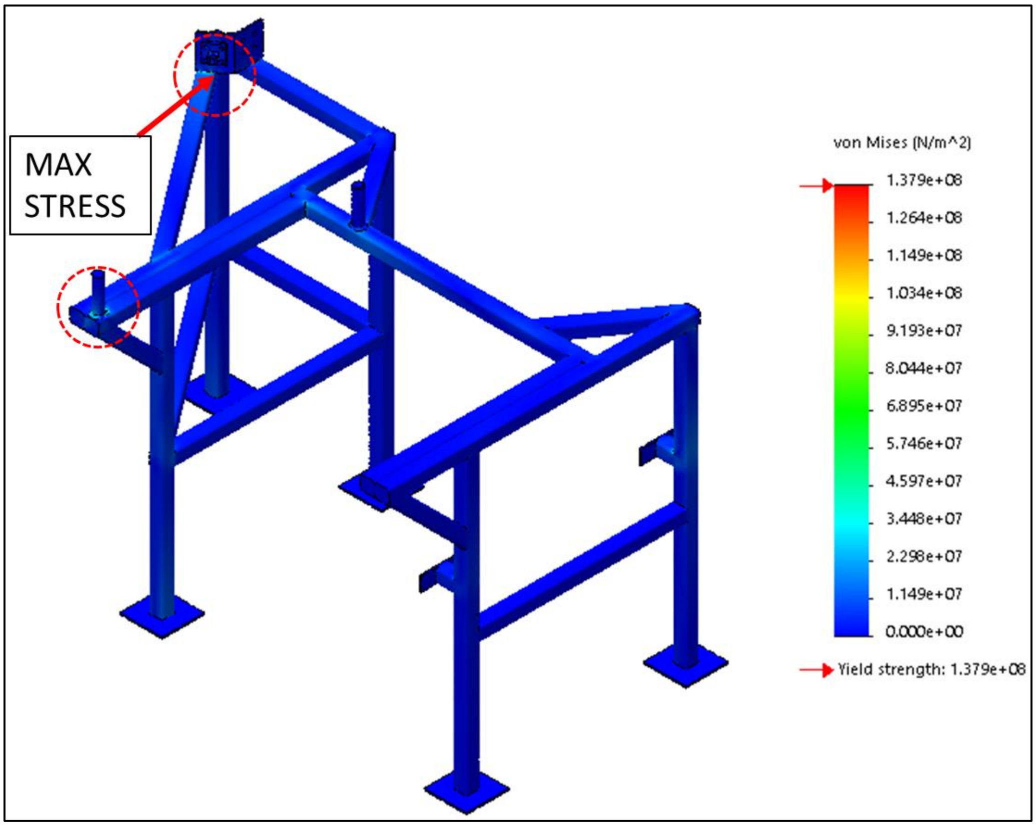

Figure 7: Von Mises stress distribution for table support structure under loading scenario 2. Deformation scale is 1 to 1 and peak stress locations are circled in red.

Figure 7 shows two points of high stress, circled in red. Other locations where components met were again found to have high stress, however the two circled locations experienced the highest stress. A closer view of the two points of interest is shown in Figure 8 next.

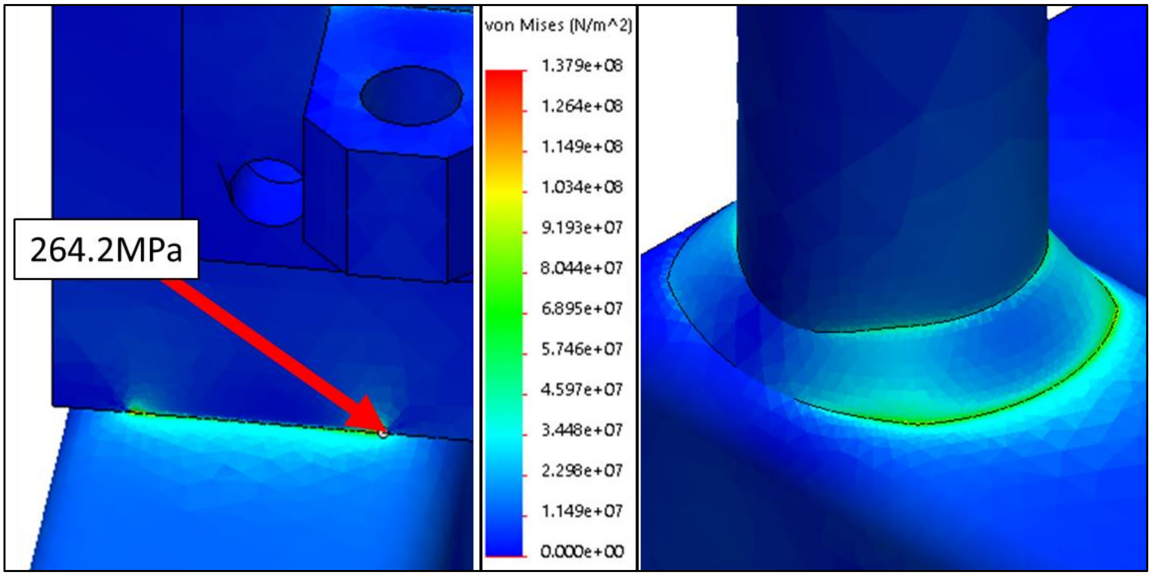

Figure 8: Singularity points from loading scenario 2 on the cylinder corner mounting bracket (left) and paddle pin 2 (right)

From Figure 8, it is seen that the previously circled areas of high stress have singularity points again, which were confirmed again with a mesh convergence study. The convergence study is shown next in Figure 9.

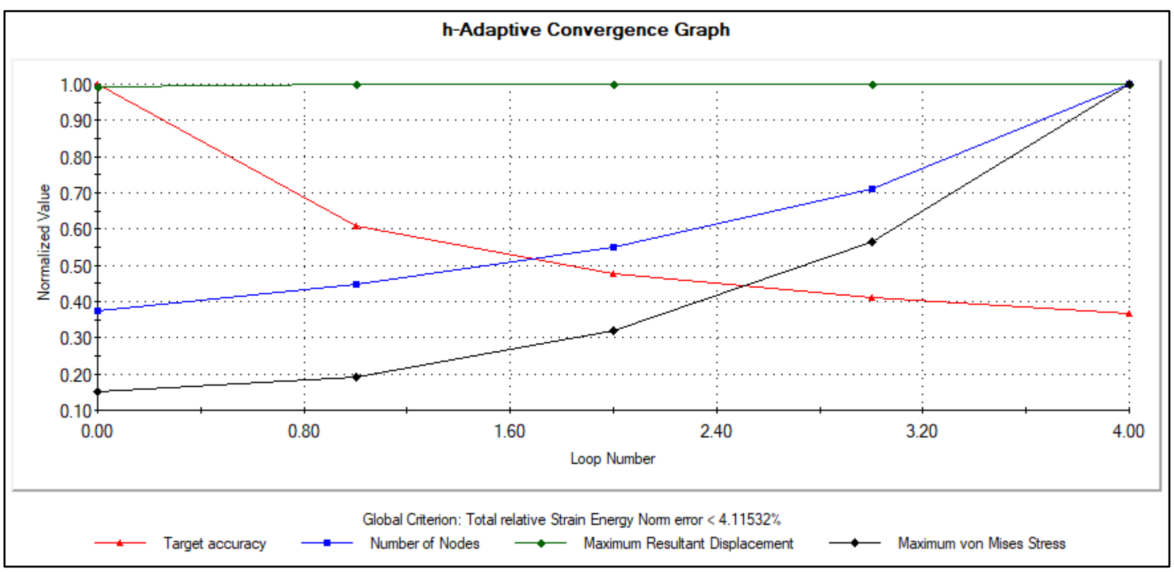

Figure 9: h-adaptive convergence graph for table support structure loading scenario 2

Since the singularity points would again be eliminated with welds and the rest of the structure was found to be well below the yield strength of the 316L steel, the support structure should be able to withstand the loading from the second air cylinder. The maximum deflection corresponding to the load was found to be 1.069mm and is shown next in Figure 10.

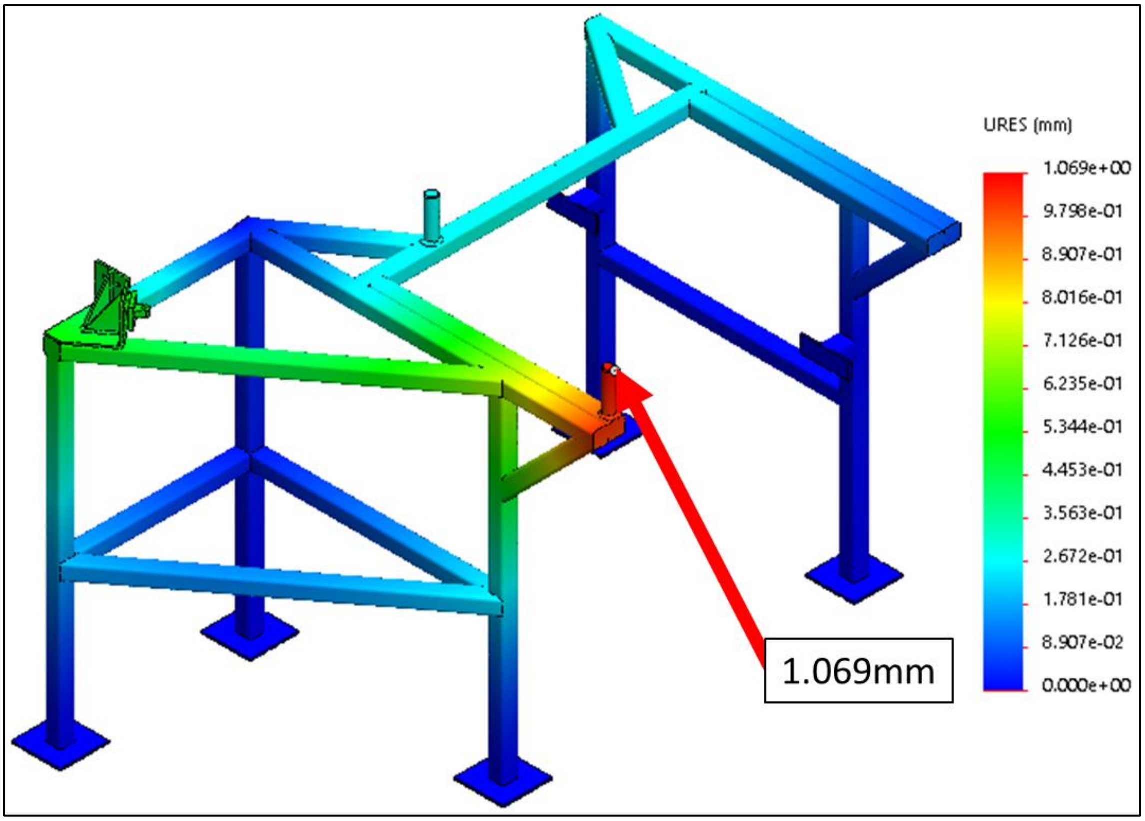

Figure 10: Plot of support structure deflection under loading scenario 2. Peak deflection of 1.069mm occurs on paddle pin 2. Global deformation scale is 1 to 1.

2 Handle Guide FEA

Finite element analysis was performed on the handle guide since hand calculations were cumbersome in the presence of shear, bending, and torsion. The worst-case scenario of 245.45lbf applied to the handle guide was considered, since either cylinder could apply 490.9lbf across the two guides. The welded end of the handle guide was treated as a fixed boundary while the interface area between the handle and the guide was used to apply the force of 245.45lbf. The following Figure 11 shows the area of the guide which interfaces with the sliding handle notch.

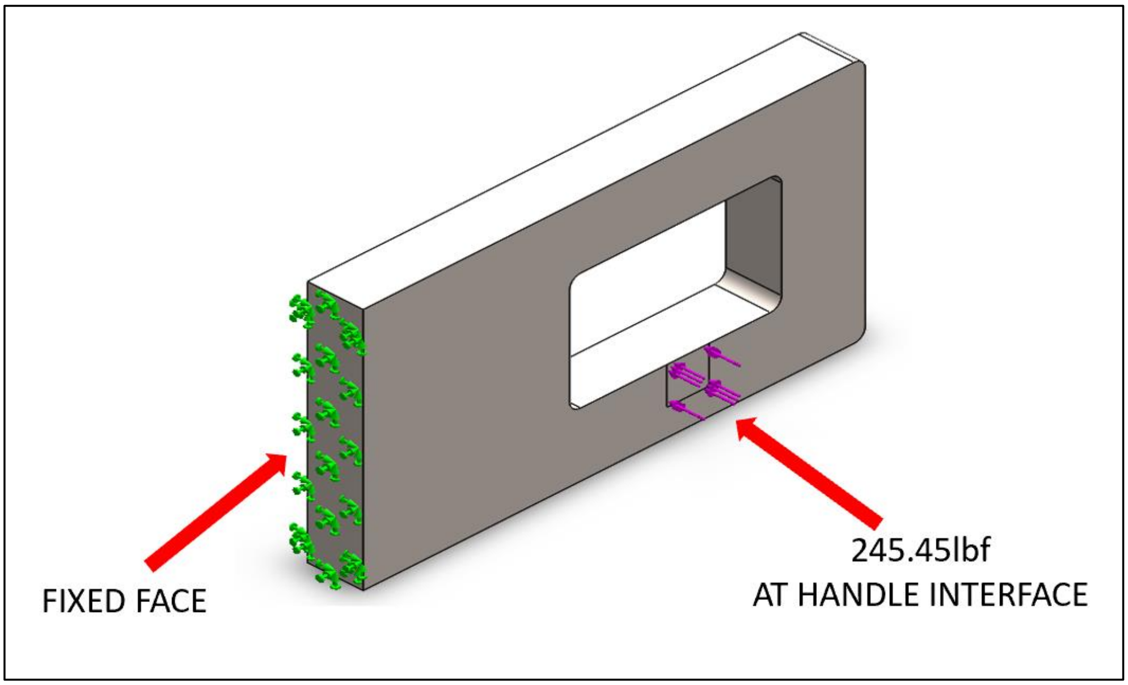

Figure 11: Fixed boundary (green) and force vector (purple) for handle guide loading case

The FEA study was conducted with Solidworks 2020 [1] utilizing the settings summarized in TABLE II below.

TABLE II: HANDLE GUIDE FEA SETTINGS

Software	Solidworks 2020
Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Automatic transition	Off
Mesh auto loops	Off
Jacobian points	4
Max element size	0.1in
Min element size	0.033in
Material type	316L Stainless steel (Solidworks profile)
Elastic modulus	193GPa
Poisson's Ratio	0.30
Tensile strength	550MPa
Yield strength	137.9MPa
Solver	Direct sparse solver
Adaptive mesh refinement	h-adaptive, 3 loops, 99% target accuracy
Thermal effects	Disabled

The maximum stress observed from the FEA studied occurred at the base of the guide at the point where the component will be welded to the declined conveyor sub-structure. Since the area which exhibited the highest stress value will be covered by weld, the stresses will be distributed through the fillet weld, significantly reducing the value of stress at this location. A convergence study run resulted in a solution with a singularity point ultimately yielding divergence in stress and deflection convergence. Figure 12 displays the stress gradient exhibited by the guide. The stress scale was set to max out at the yield stress of the 316L stainless-steel.

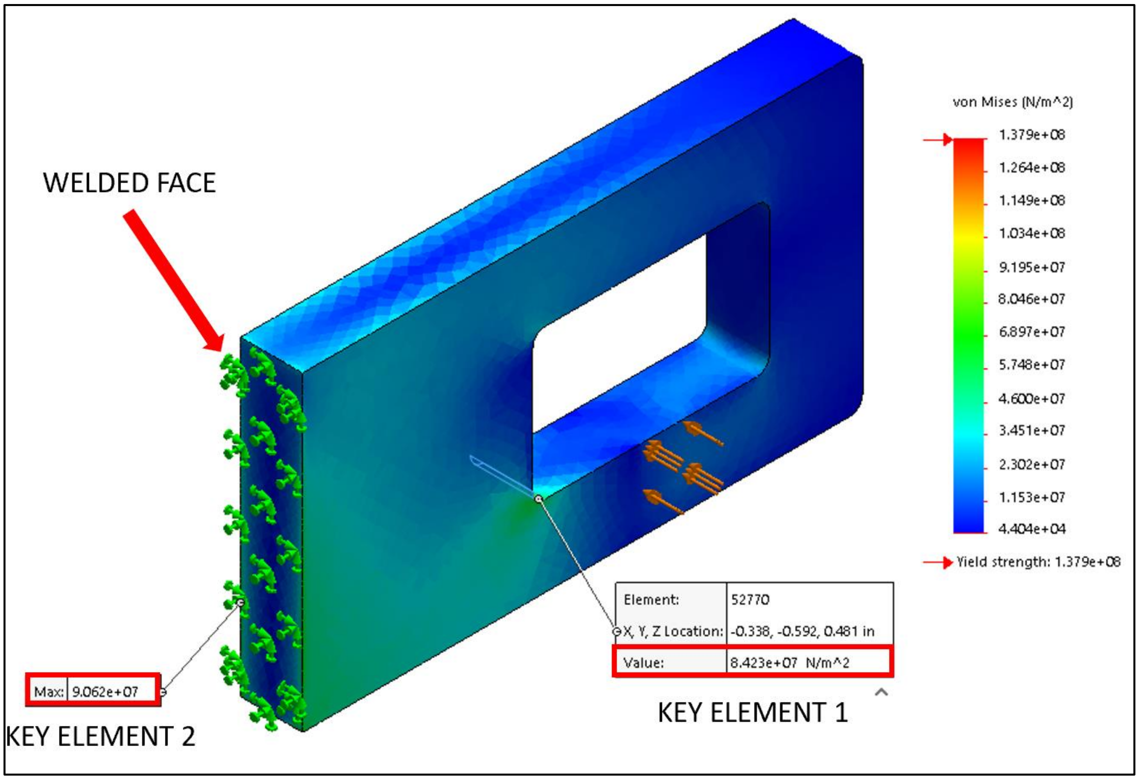

Figure 12: Von Mises stress distribution for the handle guide under 245.45lbf loading. Deformation scale is 1 to 1 and peak stress locations identified.

Key element 2 in Figure 12 indicates the location where the maximum stress was exhibited, however, this location will be welded to the declined conveyor structure, eliminating the stress concentration. Key element 1 was determined to be the next highest stress present in the simulation. The stress value of 84 MPa resulted in a factor of safety of approximately 1.68. At this point, the team deemed the guide fit for implementation considering the loading conditions were estimated to only occur in the extreme event that 100% of cylinder pushing power is directed along the line of motion of the linear slides. The following Figure 13 shows the h-adaptive convergence results for the handle guide simulation.

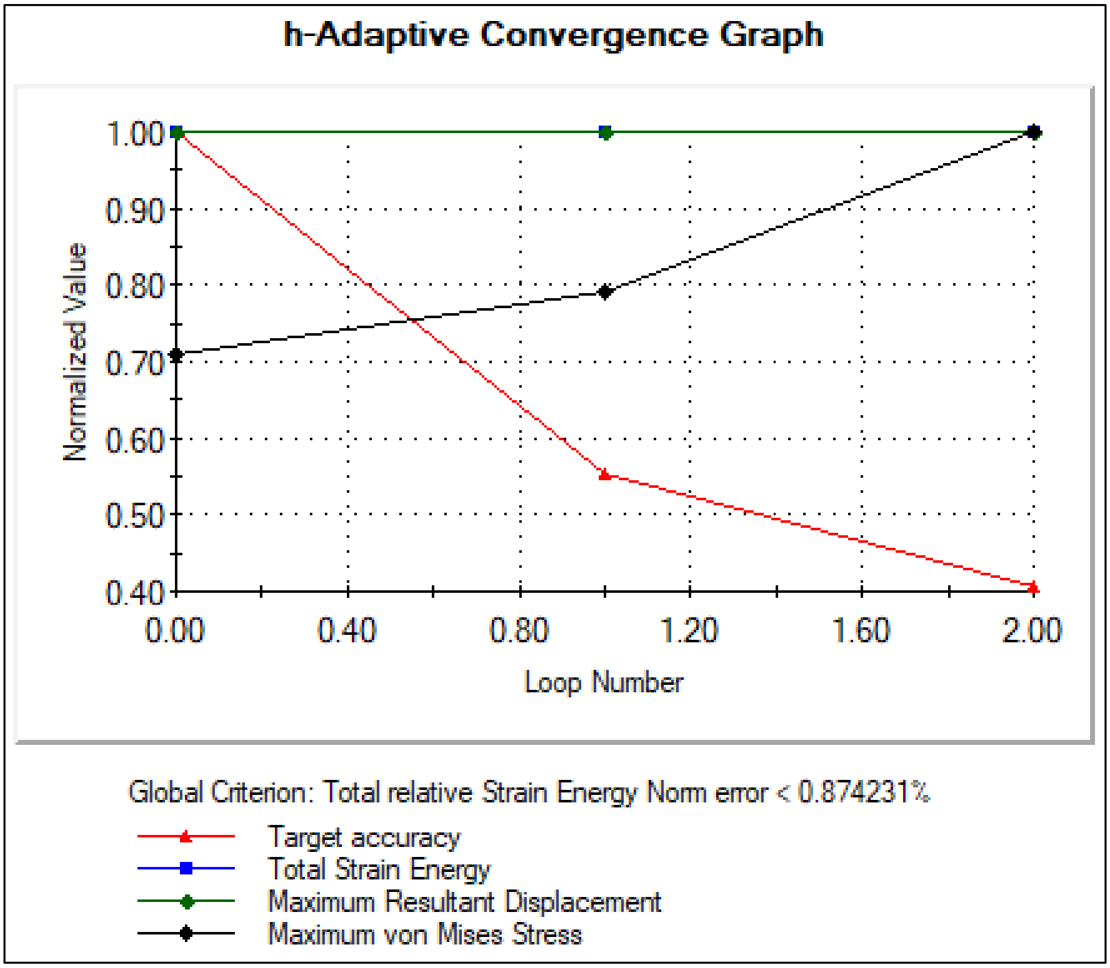

Figure 13: h-adaptive convergence graph for handle guide simulation

3 Paddle Arm FEA

The design of the paddle 1 armature provides support for loading in the primary direction of the pneumatic cylinder using the two tubes. The original design for the arm involved the use of a simple 0.375” laser cut plate. However, this would not effectively support vertical loading in the event the cylinder pushes at an angle. By increasing the effective height in the vertical direction, the arm is much more rigid in vertical bending and will sustain the load properly while experiencing less deformation. A side by side comparison of the two designs and the applied loads considered in their design are shown next in Figure 14.

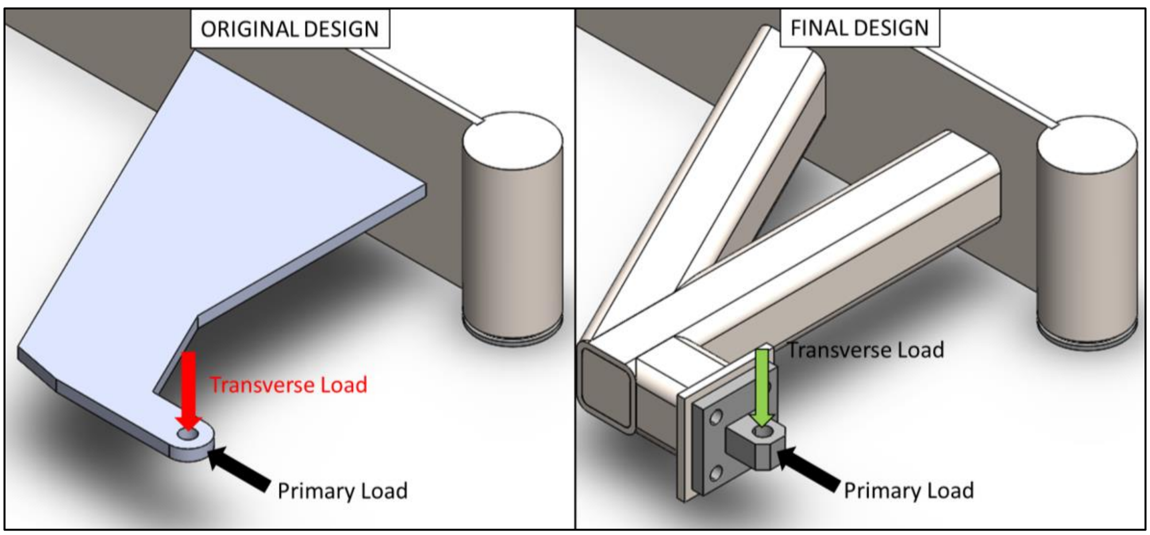

Figure 14: Load cases for original and final designs of paddle 1 armature

Finite element analysis of the original and final arm design was completed to show the variation in stress and total deflection, as well as to select the appropriate arm. Two scenarios were tested for each arm; the first scenario was 490.9lbf in the primary load direction. The second scenario was loading at 5 degrees from the original loading direction, splitting the original load into 42.79lbf in the downward vertical direction and 489.03lbf in the primary direction. In each simulation, the bushing and paddle bore were excluded from the analysis, since the design concern was with the maximum cylinder load applied to the armature and where it interfaces with the paddle plate. Further, the back side of the paddle plate was treated as a fixed support, while the load was applied directly to the inner face of the eyelet. TABLE III summarizes the settings used in all 4 simulations [1].

TABLE III: PADDLE ARMATURE FEA SIMULATION SETTINGS

Software	Solidworks 2020
Mesh type	Solid mesh
Mesher used	Standard mesh
Automatic transition	Off
Mesh auto loops	Off
Jacobian points	4
Element size (max)	0.08in
Tolerance	0.004in
Material type	316L Stainless steel (Solidworks profile)
Elastic modulus	193GPa
Poisson's Ratio	0.3
Tensile strength	550MPa
Yield strength	137.9MPa
Component contacts	Global contact (bonded)
Solver	Direct sparse solver
Adaptive mesh refinement	h-adaptive, 5 loops, 99% target accuracy
Thermal effects	Disabled

In all 4 simulations, it was found that the maximum stress occurred at the sharp intersections of the various components. This was anticipated since the CAD software does not easily model weld beads in an assembly, resulting in sharp corners. A convergence study was run for all 4 simulations, showing a divergence in stress while the peak deflection converges, indicating a good solution with the presence of singularity points (elements with infinite stress). In all the following figures, the deformation scale was set to 1 and the stress scale maxes out at the yield strength of the material, thereby indicating points of failure in red. The first loading scenario was the primary loading of 490.0lbf, shown next in Figure 15.

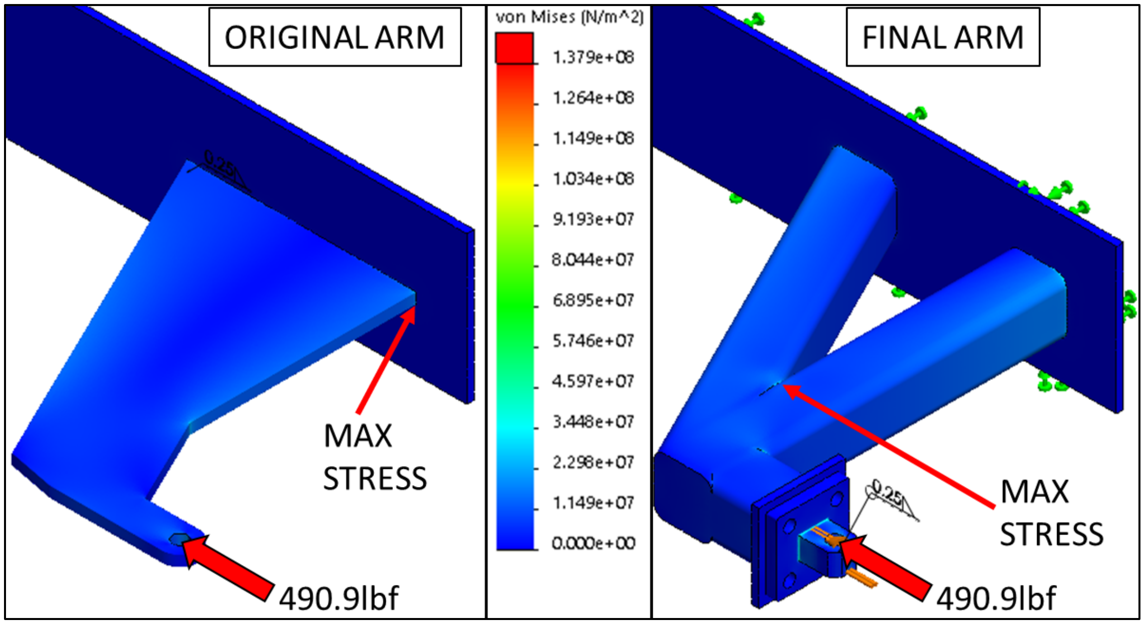

Figure 15: Von Mises stress distribution for original paddle arm (left) and final paddle arm (right) under primary 490.9lbf loading. Deformation scale is 1 to 1 and peak stress locations identified.

Figure 15 shows that much of each arm is blue, indicating a low stress of approximately 0 to 20MPa. It should be noted however, that the original design had a peak stress of 107MPa in its bottom corner where the arm interfaces with the paddle plate. Additionally, the final arm design had a peak stress of 285MPa along the inner joint between the two tubes coming together. Both points of max stress were contradictory to the rest of what was observable on the arms, indicating the presence of singularity points. This was anticipated due to the large load and theoretically infinite stress at the non-welded sharp corners of intersection. A close view of each max stress element is shown next in Figure 16 and reveals that there are a series of singularity points between each of the parts.

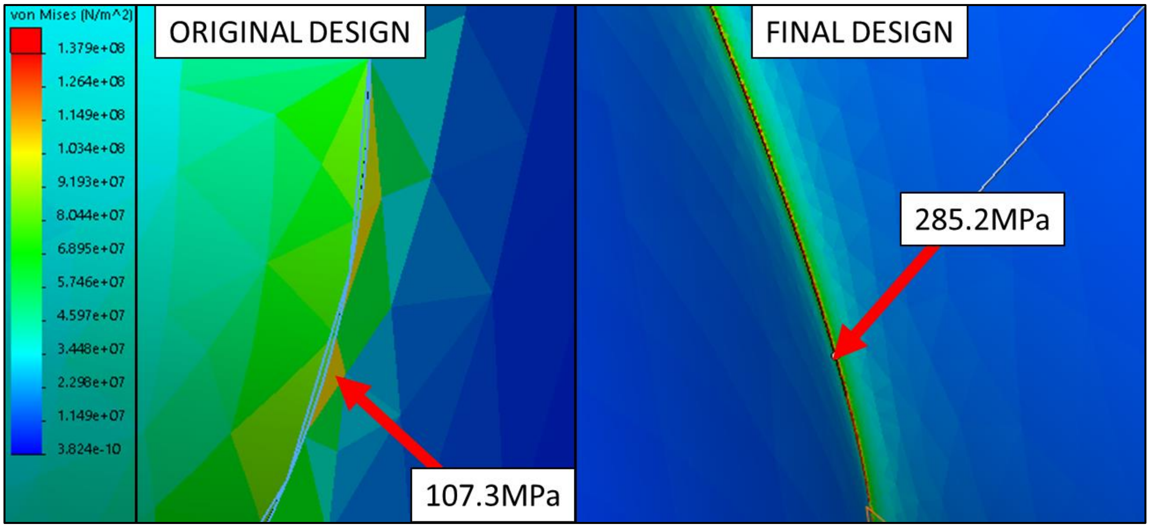

Figure 16: Zoomed in view of peak stress singularity elements on the original paddle arm design (left) and final design (right) under primary loading of 490.0lbf

As mentioned previously, a mesh convergence study was conducted for each simulation, showing convergence in deflection while the stress diverged. Neglecting the singularity points, the rest of each arm showed a low stress of 0 to 20MPa, while the yield strength of the Solidworks 316 stainless steel is approximately 138MPa. Thus, if either design was used, they would be unlikely to fail in terms of the primary loading, provided that the stress concentration between the arm and paddle is alleviated with a weld bead. The convergence study for the original and final arm under the primary loading are shown in Figure 17 next.

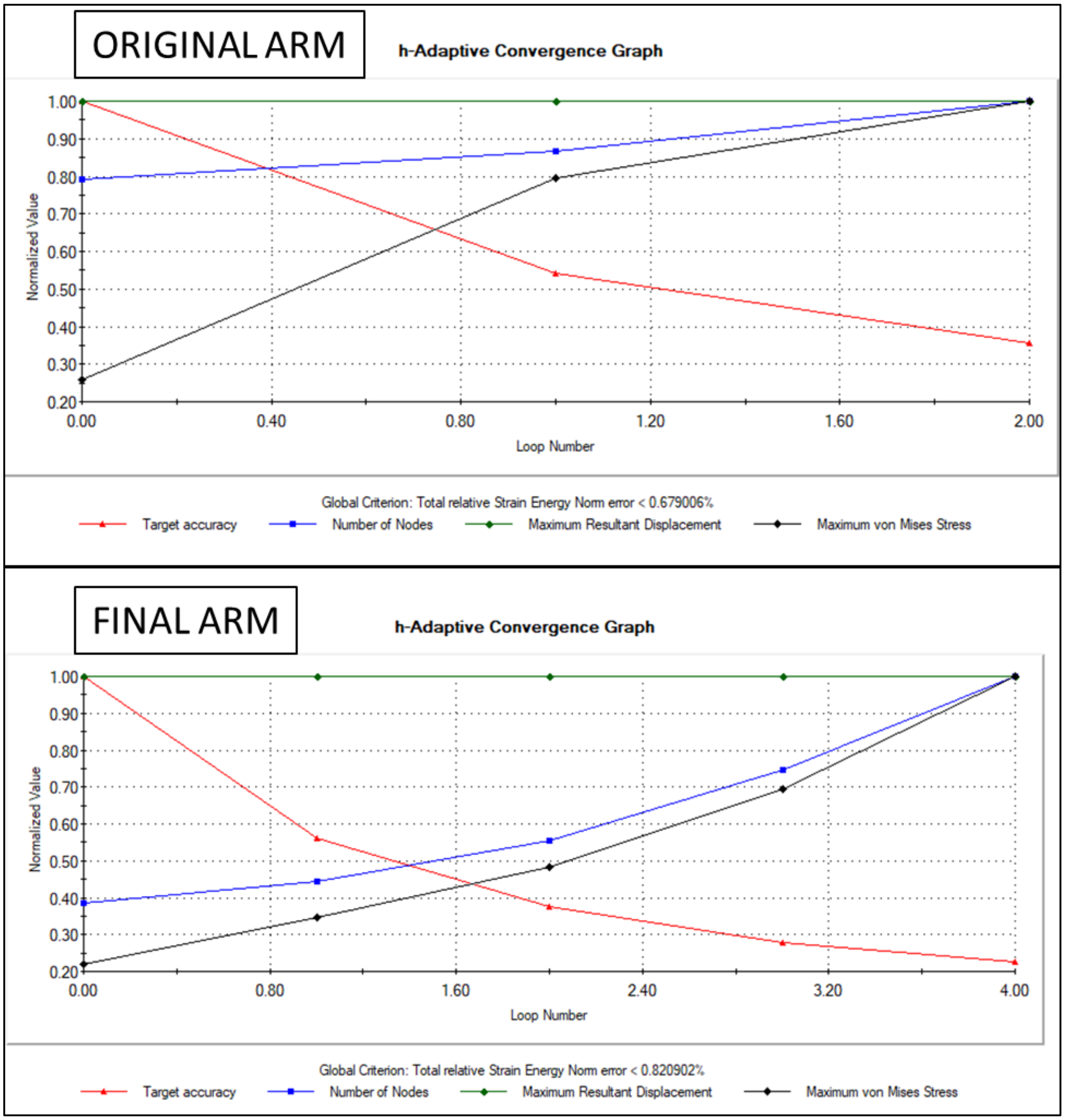

Figure 17: h-adaptive convergence graphs for primary loading of original paddle arm design (top) and final arm design (bottom)

The actual deflection under the applied load was insignificant, peaking at 0.067mm for the original design and 0.07mm for the final design. The points of peak deflection are identified in Figure 18 next.

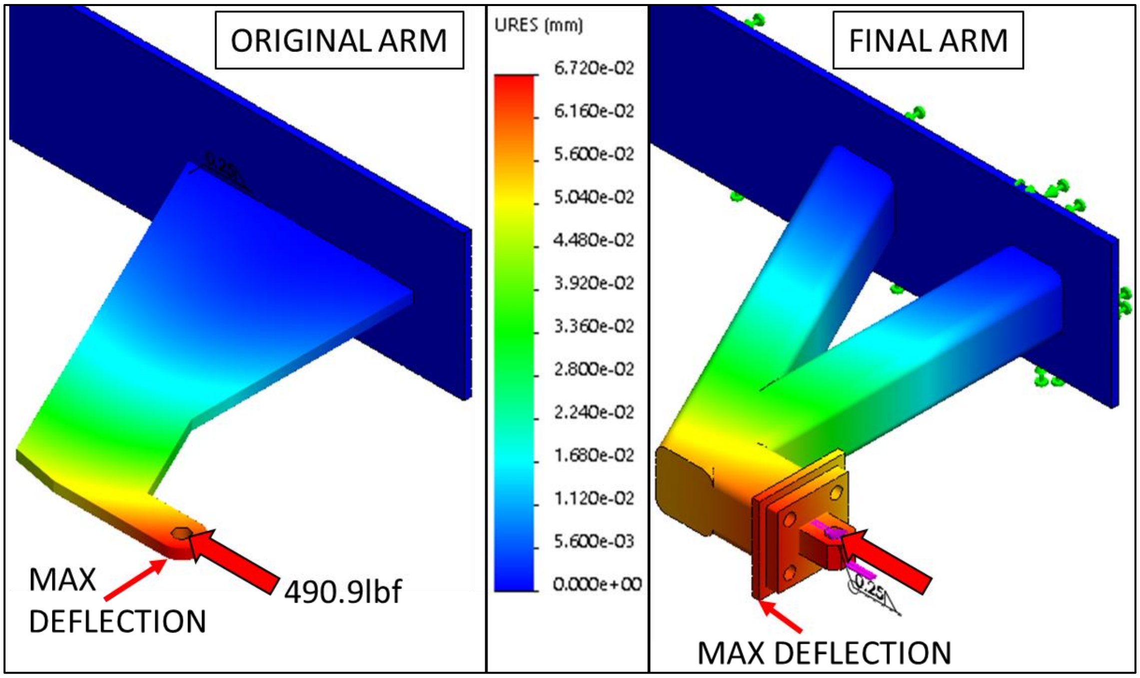

Figure 18: Plot of deflection of the original paddle arm (left) and final arm (right) under primary loading. Deformation scale is 1 to 1. Max deflection for the orignal arm is 0.067mm and 0.07mm for the final arm.

While both designs performed well under primary loading, they behaved quite differently when the load was shifted, pushing downward at a 5-degree angle with respect to the original load. Figure 19 shows the stress distribution corresponding to the inclined loading condition.

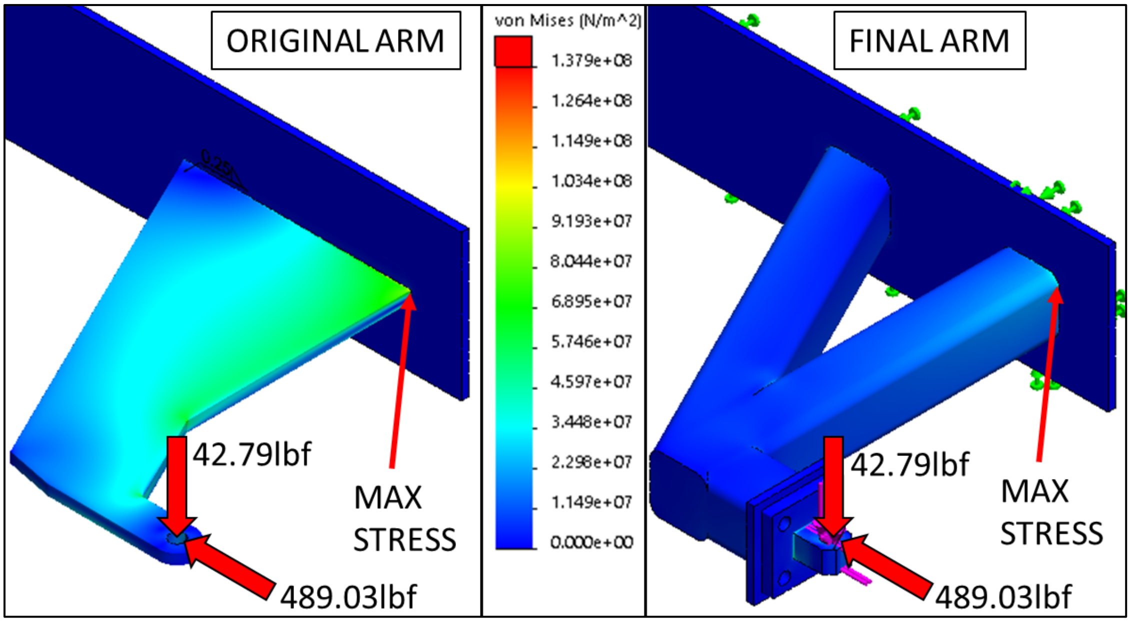

Figure 19: Von Mises stress distribution for original paddle arm (left) and final paddle arm (right) under a 490.9lbf loading at 5 degrees downward from the original direction. Deformation scale is 1 to 1 and peak stress locations identified.

Examination of the original and final arm in the shows that the introduction of a vertical load increased the stress on the top and bottom faces of the arms. The stress was magnified more for the original arm, as anticipated given that the bending stiffness has a cubic relation to the height and is greatly reduced when the material height is reduced. Once again, peak stress occurred at the sharp intersections between components. For the original arm, the peak stress occurred on the top corner of intersection and was found to be 401MPa. The peak stress for the final design was 175.5MPa, once again between the two tubes and on the bottom side this time. The high stress of 175.5MPa on the final arm was localized, much in the same way as the first loading scenario, with much of the final arm below 34MPa. The closeup of each region in Figure 20 next shows the singularity points in question.

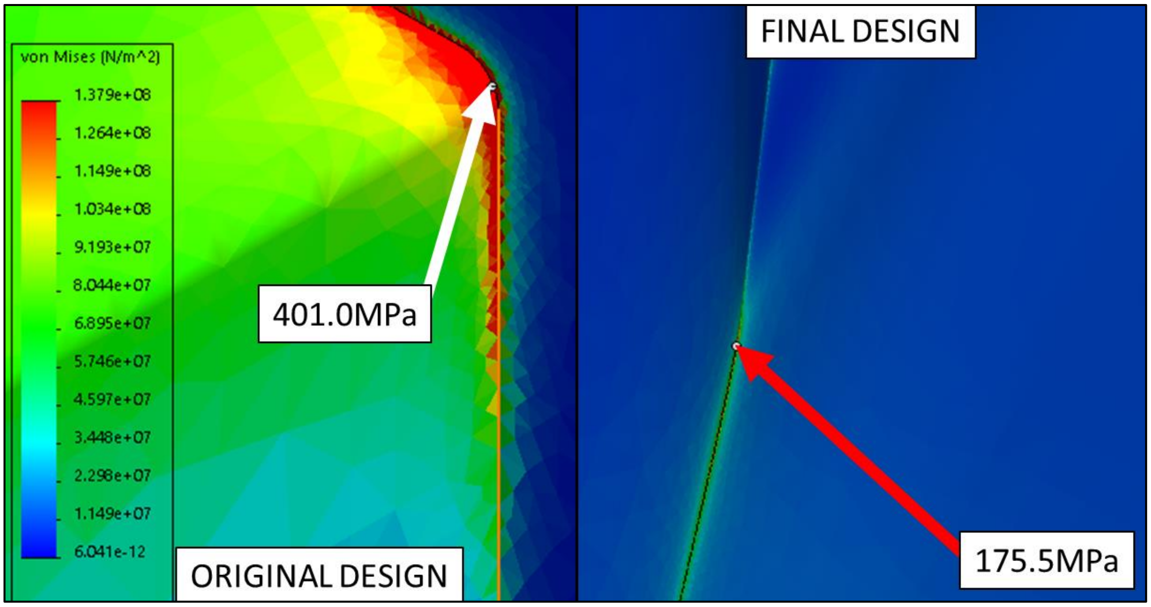

Figure 20: Zoomed in view of peak stress singularity elements on the original paddle arm design (left) and final design (right) under 5 degree downward loading of 490.9lbf

Once again, these singularity points would disappear in the presence of a weld bead. It should be noted however, that the original design had stress upwards of 80 to 100MPa on the top and bottom faces, corresponding to the combined bending loads. Thus, the original design would be sensitive to vertical loading and any increase from the applied vertical load would bring the arm close to yielding. The following Figure 21 shows the convergence plots for both the original and final design under the 5 degree loading scenario.

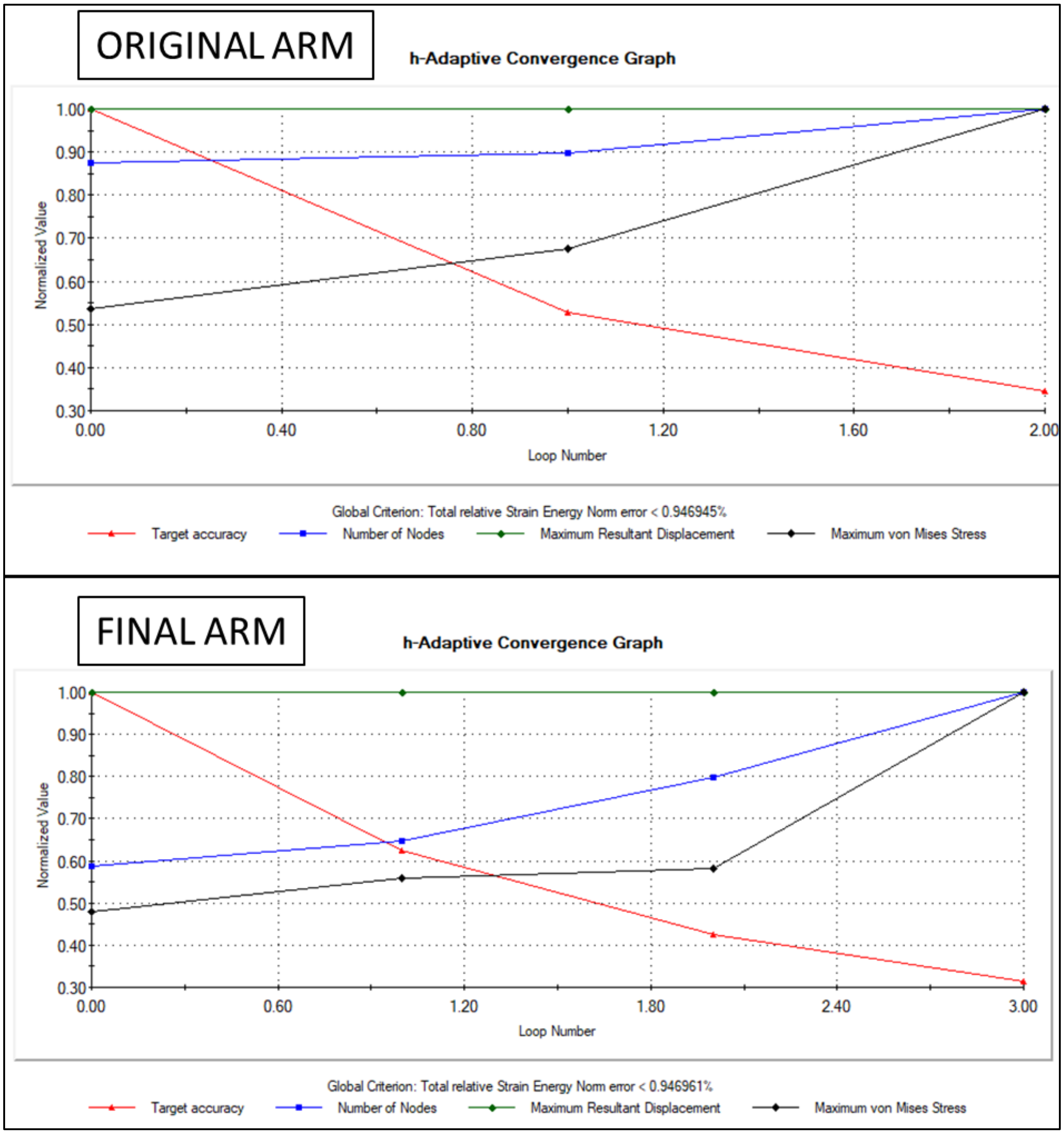

Figure 21: h-adaptive convergence graphs for 5-degree downward loading of 490.9lbf of original paddle arm design (top) and final arm design (bottom)

In addition to the high stress, the deflection of the original arm design under the combined load was large compared to the final arm design. The deflection of both designs is shown next in Figure 22.

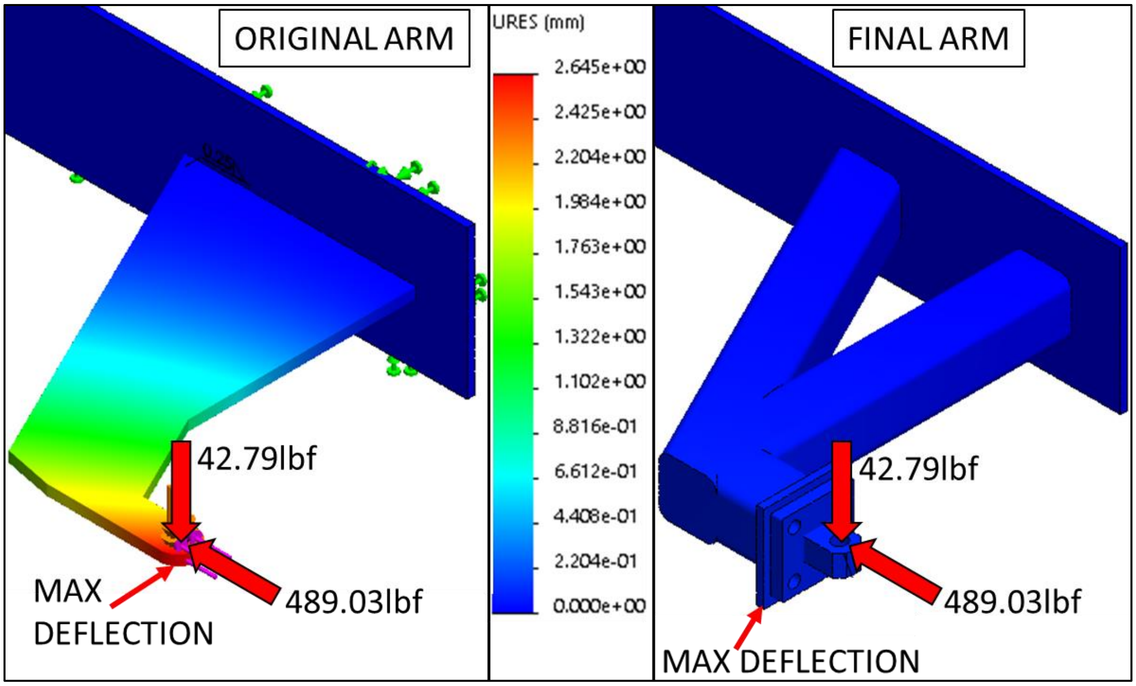

Figure 22: Plot of deflection of the original paddle arm (left) and final arm (right) under 5-degree downward loading of 490.9lbf. Deformation scale is 1 to 1. Max deflection for the orignal arm is 2.645mm and 0.094mm for the final arm.

In Figure 22, the deformation scale for both arms has been set to correspond to the maximum deflection of 2.645mm in the original design. As a result, when the original arm is compared to the final arm design, it is apparent that the final design has much less deflection and is superior in terms of its stiffness with respect to vertical loads. The maximum deflection of the final arm is 0.094mm, which is 3.55% of the original design deflection.

4 References

[1] Solidworks Corp, Dassault Systèmes, 1995.

APPENDIX G

COST

List of Tables

Loin Reorientation System Cost Analysis

A summary of all components which are required for the build of the team's design can be seen in Table II. The table sorts the parts according to the area which it resides in the design in order to make it easier to determine what other parts it interfaces with. The part number of each item is also included in the table, note that the part numbers prefix references the parts area designation. The material and manufacturing costs have also been appended to the parts list. The manufacturing cost was obtained for tube parts by taking the material which was they are to be cut from then determining the number of end features that the part has. The number of end features that the tube has determines the part complexity and is reflected when calculating the manufacturing cost. Similarly, the cost of sheet metal parts was also calculated based on the raw material size and complexity. The greater the laser cut length, the higher the parts manufacturing cost. All purchased components within the master cost spreadsheet bypass the manufacturing and material cost columns since the they are directly purchased.

The materials which are specified to be used in for all manufactured components in the team's design have are summarized in Table I. Gathering specific quotes on certain raw materials proved to be difficult for some items since the selection of 316L grade stainless-steel products much smaller than a 304-grade or similar product. The cost estimates which were created take into account the sizes of 316L stainless-steel that was able to be sourced as well as similar stainless steel products which feature the correct size but are a different grade.

Table I: RAW MATERIAL SUMMARY

Material Type	Dimensions	Notes	Pricing [USD]
Round Bar	0.4995" Dia.	316L SST [1]	$30.47
Tube	2" X 2" 7 Ga.	316L SST*	$11.43
Tube	1" X 1" 7 Ga.	316L SST*	$10.43
Sheet	0.25" Thk.	316L SST*	$15.95
Sheet	0.375" Thk.	316L SST*	$20.95
Sheet	0.5" Thk.	316L SST*	$25.95
Sheet	1/8" Thk.	316L SST*	$8.95
Sheet	16GA	316L SST*	$8.95
Block	As Required	UHMW HDPE [2]	$103.65
Rod	As Required	Delrin – Acetal [2]	$6.95

Items in Table I which contain an asterisk did not have specific pricing on steel supplier websites. These material costs were estimated based on similar materials such as 304L stainless tubing [3] [4] [1] [5]. Table II contains the full one-piece bill of materials along with the cost estimates for all the individual components.

Table II: FINAL DESIGN COST SHEET

Area	Component	Qty	Part Number	Part Cost	Total Cost
Bypass	Linear Bearing Slides [6]	2	BS01	900.00	**1800.00**
Bypass	M5 Nylocs [7]	18	BS02	0.12	**2.19**
Bypass	M5 Allen Bolts [7]	18	BS03	0.38	**6.83**
Bypass	1/2 Bolts [7]	2	BS04	0.70	**1.39**
Bypass	1/2 Nylocs [7]	2	BS05	2.26	**4.52**
Bypass	Handle Spacer [7]	2	BS06	20.02	**40.04**
Bypass	Plate - Handle	1	BS07	33.75	**33.75**
Bypass	Plate - Handle Bracket	2	BS08	17.94	**35.87**
Bypass	Plate - North Guide	1	BS09	20.48	**20.48**
Bypass	Plate - South Guide	1	BS10	19.18	**19.18**
Bypass	Outer Slide Mount	2	BS11	15.63	**31.25**
Bypass	Inner Slide Mount	2	BS12	15.63	**31.25**
Base Structure	Tube - Support Str. 1	2	SS01	33.10	**66.19**
Base Structure	Tube - Support Str. 2	2	SS02	50.74	**101.47**
Base Structure	Pin	2	SS03	113.71	**227.42**
Base Structure	Tube - Support Str. 4	5	SS04	52.00	**260.01**

Area	Component	Qty	Part Number	Part Cost	Total Cost
Base Structure	Tube - Support Str. 5	2	SS05	38.57	**77.15**
Base Structure	Tube - Support Str. 6	2	SS06	28.82	**57.64**
Base Structure	Tube - Support Str. 7	2	SS07	40.81	**81.62**
Base Structure	Tube - Support Str. 8	1	SS08	50.00	**50.00**
Base Structure	Tube - Support Str. 9	2	SS09	54.86	**109.72**
Base Structure	Tube - Support Str. 10	2	SS10	13.22	**26.43**
Base Structure	Plate - Side Mount	2	SS11	12.44	**24.87**
Base Structure	Plate - Floor Mount	5	SS12	16.58	**82.90**
Base Structure	Tube - Support Str. 13	2	SS13	28.77	**57.54**
Base Structure	Plate - Corner Gusset	2	SS15	12.44	**24.87**
Base Structure	EB500 Mount [8]	2	SS16	24.60	**49.20**
Base Structure	Plate - Corner Base	2	SS17	15.23	**30.47**
Base Structure	EB500 - M10 SST Bolt [7]	8	SS18	0.75	**6.02**
Base Structure	EB500 - M10 SST Nut [7]	8	SS19	0.82	**6.55**
Base Structure	EB500 - M10 SST Spacer [7]	8	SS20	3.39	**27.12**
Base Structure	Plate - Tube Cap	7	SS21	12.22	**85.53**
Base Structure	Concrete Anchor	20	SS22	7.00	**139.95**
Safe Guard	Sheet - Safety Guard 1	1	SG01	122.20	**122.20**
Safe Guard	Sheet - Safety Guard 2	1	SG02	104.30	**104.30**
Safe Guard	Sheet - Safety Guard 3	2	SG03	114.10	**228.20**
Safe Guard	Sheet - Safety Guard 4	1	SG04	122.20	**122.20**
Safe Guard	M6 SST - Bolt 30mm [7]	33	SG07	0.33	**10.89**
Safe Guard	M6 SST - Nyloc Nut [7]	40	SG08	0.65	**26.08**
Safe Guard	1/2" SST - Spacer [7]	47	SG09	2.05	**96.35**
Table Structure	Sheet - Bypass Top	1	BT01	37.65	**37.65**
Table Structure	Tube - Mitre Str. 2	2	BT02	39.16	**78.31**
Table Structure	Tube - Mitre Str. 3	2	BT03	45.67	**91.35**
Table Structure	Tube - Str. 4	4	BT04	40.94	**163.75**
Table Structure	Tube - Str. 5	1	BT05	22.25	**22.25**
Hold Down	Hold Down Shoe	2	HD01	151.83	**303.65**
Hold Down	M8 SST C/S - Bolt [7]	4	HD02	2.53	**10.12**
Hold Down	M8 SST - Nut [7]	4	HD03	0.30	**1.19**
Hold Down	M10 SST - Spacer [7]	4	HD04	3.39	**13.56**
Low Conveyor	Cone Top Belting [9]	1	LC01	24650.00	**24650.00**
Low Conveyor	Track Body	0	LC02	0.00	**0.00**
Low Conveyor	800 Series Sprocket [9]	0	LC03	0.00	**0.00**
Low Conveyor	Conveyor Spray Bar	0	LC04	0.00	**0.00**

Area	Component	Qty	Part Number	Part Cost	Total Cost
Paddle & Cylinder	Bimba Pneu. Cyl. [10]	2	PC01	1711.70	**3327.90**
Paddle & Cylinder	Tube - Paddle Tube 1	1	PC02	18.71	**18.71**
Paddle & Cylinder	Tube - Paddle Tube 2	1	PC03	15.71	**15.71**
Paddle & Cylinder	Sleeve - Paddle Jacket	2	PC04	113.71	**227.42**
Paddle & Cylinder	Tube - Paddle Tube 3	1	PC05	12.86	**12.86**
Paddle & Cylinder	Plate - Tube Cap	1	SS21	7.12	**7.12**
Paddle & Cylinder	Bushing - Delrin	2	PC07	103.13	**206.26**
Paddle & Cylinder	Plate - Paddle Face	2	PC08	41.55	**83.10**
Paddle & Cylinder	EB500 Mount [8]	2	SS16	24.60	**49.20**
Paddle & Cylinder	AB Prox. Sensor [11]	1	PC09	160.00	**160.00**
Paddle & Cylinder	Sensor Mount	1	PC10	56.65	**56.65**
Safe Guard	M6 SST Bolt - 45mm[7]	7	SG10	2.05	**14.35**
Safe Guard	316L SST - 1" Spacer [7]	13	SG11	3.79	**49.27**
Safe Guard	SST - 1/4"-20 Bolt[7]	13	SG12	0.21	**2.78**
Safe Guard	1/4" SST - Washer[7]	13	SG13	0.03	**0.44**

References

[1] Ryerson Metals, "Ryerson Metals - Round Bar," [Online]. Available: https://shop.ryerson.com/catalog/search/107100103. [Accessed 25 November 2019].

[2] Curbell Plastics, "Material Shop," Curbell Plastics, [Online]. Available: https://www.curbellplastics.com/Shop-Materials. [Accessed 22 November 2019].

[3] Clinton Aluminium, "Products Page," [Online]. Available: https://www.clintonaluminum.com/products/. [Accessed 25 November 2019].

[4] Midwest Steel Supply, "Stainless Steel Tube," Midwest Steel Supply, [Online]. Available: https://www.midweststeelsupply.com/store/304stainlesssteelsquaretube. [Accessed 22 November 2019].

[5] Metals Depot, "Home Page," Metals Depot, [Online]. Available: https://www.metalsdepot.com/. [Accessed 22 November 2019].

[6] Linear Positioning Systems, "Stainless Steel Linear Bearing - Washdown Ready," TPA Motion, [Online]. Available: https://www.linearpositioningsystems.com/stainless-steel-linear-bearings.html. [Accessed 15 November 2019].

[7] McMaster-Carr, "Fastening & Joining," McMaster-Carr, [Online]. Available: https://www.mcmaster.com/. [Accessed 19 November 2019].

[8] Bimba , "Tie-Rod Eye Bracket," [Online]. Available: https://www.bimba.com/Products-and-Cad/Actuators/Inch/Accessories/Mounting-Brackets/Pivot-Brackets-Eye-Brackets/NFPA-Tie-Rod-Eye-Bracket-TATASTDFMTRAMS-Series. [Accessed 21 November 2019].

[9] Intralox, "Modular Plastic Belting," Intralox, [Online]. Available: https://www.intralox.com/products/belts-and-accessories/modular-plastic-belting. [Accessed 7 November 2019].

[10] Bimba, "Repairable Stainless Round Cylinders," [Online]. Available: https://www.bimba.com/Products-and-Cad/Actuators/Inch/NFPA/Guided-Thrusters/NFPA-Repairable-Stainless. [Accessed 3 Novemeber 2019].

[11] TSI Solutions, "Bimba Proximity Sensor," TSI Solutions, [Online]. Available: https://www.tsisolutions.us/itemdetail/RSU-1-Q. [Accessed 13 November 2019].

APPENDIX H

FMEA

Table of Contents

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1 Failure Modes and Effects Analysis (FMEA)

A FMEA is used in the Final Design Report (FDR) to analyze the risks associated with the final design. The FMEA evaluates the significance of failure modes by assigning each one with a Risk Priority Number (RPN), which is a factor of severity, occurrence, and detection. For each of these factors, a score an appropriate score is given to every failure mode to generate the RPN. Furthermore, scales from 1-10 were used for the scoring of each of the factors, which are modified versions of the scales provided in GoLeanSixSigma [1]. The following subsections outline these scales.

1.1 Severity Scale

Table I shows the severity scale that was used for the FMEA in the FDR. A scale of 1-10 is used, with 1 being the lowest severity of the failure mode effect.

Table I: SEVERITY SCALE USED IN FMEA ON FINAL DESIGN IN FDR

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur **without** warning	10
Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur **with** warning	9
Very High	Major disruption of service involving client interaction, resulting in either associate re-work or inconvenience to client	8
High	Minor disruption of service involving client interaction and resulting in either associate re-work or inconvenience to clients	7
Moderate	Major disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	6

Effect	Criteria: Severity of Effect	Ranking
Low	Minor disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	5
Very Low	Minor disruption of service involving client interaction that does not result in either associate re-work or inconvenience to clients	4
Minor	Minor disruption of service not involving client interaction and does not result in either associate re-work or inconvenience to clients	3
Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associate re-work or inconvenience to clients	2
None	No Effect	1

1.2 Occurrence Scale

Table II shows the severity scale that was used for the FMEA in the FDR. A scale of 1-10 is used, with 1 being the lowest occurrence rate of the failure mode.

Table II: OCCURRENCE SCALE USED FOR FMEA ON FINAL DESIGN IN FDR

Probability of Failure	Per Item Failure Rates	Ranking
Very High: Failure is almost inevitable	1 in 2	10
	1 in 8	9

Probability of Failure	**Per Item Failure Rates**	**Ranking**
High: Generally associated with processes similar to previous processes that have often failed	1 in 20	8
	1 in 40	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	1 in 80	6
	1 in 400	5
	1 in 1000	4
Low: Isolated failures associated with similar processes	1 in 4000	3
Very Low: Only isolated failures associated with almost identical processes	1 in 20,000	2
Remote: Failure is unlikely. No failures associated with almost identical processes	<1 in 20,000	1

1.1 1.3 Detection Scale

Table III shows the severity scale that was used for the FMEA in the FDR. A scale of 1-10 is used, with 1 being the lowest likelihood of detection of the failure mode.

Table III: DETECTION SCALE USED FOR FMEA ON FINAL DESIGN IN FDR

Detection	Criteria: Likelihood the existence of a defect will be detected by process controls before next or subsequent process, -OR- before exposure to a client	Ranking
Absolute Certainty of Non-Detection	Current controls will not or cannot detect the failure	10
Very Remote	Very remote likelihood current controls will detect failure mode	9
Remote	Remote likelihood current controls will detect failure mode	8
Very Low	Very low likelihood current controls will detect failure mode	7
Low	Low likelihood current controls will detect failure mode	6
Moderate	Moderate likelihood current controls will detect failure mode	5
Moderately High	Moderately high likelihood current controls will detect failure mode	4
High	High likelihood current controls will detect failure mode	3
Very High	Very high likelihood current controls will detect failure mode	2
Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1

2 References

[1] E. Swan, "GoLeanSixSigma.com," GoLeanSixSigma, 9 February 2012. [Online]. Available: https://goleansixsigma.com/failure-modes-effects-analysis-fmea/. [Accessed 22 November 2019].