Bag Splitting Hopper

Nutrien Rocanville Potash (**NRP**)

MECH 4860 – Engineering Design

Final Report

Advisor: Vern Campbell, P. Eng

Date: December 4, 2019

Team: #30 – Depressant Bulk Aggregate Guarding Solutions

Project Manager: Trevor Rusk ___________________________________

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LETTER OF TRANSMITTAL

December 4, 2019

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Dear Dr. Labossiere:

Please see enclosed final design report, titled 'Bag Splitting Hopper' This report is co-authored by Team 30, consisting of the following mechanical engineering undergraduates: Trevor Rusk (Project Manager), Lianne Dupont (Communications Director), Liam Knudson (Logistics Coordinator) and Anthony Dziedzic (Secretarial Director).

This report details the proposed design solution to NRP's operator safety concern. The current and proposed support structure will be analyzed mathematically, and numerically using finite element analysis (FEA). Details of the proposed design include engineered component and assembly drawings, including a bill of materials (BOM), and a cost analysis.

The team would like to acknowledge the help received during the design and writing processes from advisors, instructors and professors. Advisor, Vern Campbell, assisted the team in developing a strategy to clearly understand the client requests and provided his professional experience and advice for design guidance and report delivery. Technical Communications Instructor, Aidan Topping, assisted in formatting and communications of the technical report. Professor, Dr. Paul Labossiere, answered all our questions and concerns regarding the phases and content of the report, as well as course objectives.

Yours truly,

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Trevor Rusk (PM)

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Lianne Dupont (CD)

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Liam Knudson (LC)

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Anthony Dziedzic (SD)

EXECUTIVE SUMMARY

Nutrien Rocanville Potash (NRP) is a Saskatchewan based producer of potash fertilizer that wished to address safety concerns associated with the reagent addition process. This process currently requires operators to work to underneath a suspended 1000 [kg] load without a safeguard, putting them in a serious injury or fatality risk. The objective of this project was to develop a design by December 4th that reduces the time the operator spends in the "line-of-fire" from 57 to 0 seconds, increases the height adjustability of the current support structure from 7 to 18 inches, provides the operators the ability to stop product flow for maintenance, and maintains the required ultimate factor of safety (FOS) of 5.

Customer needs were used to identify components of the design that would be required to achieve the target specifications which included: a structural safeguard, bag opening method, bag closing method and a height adjust feature. Team brainstorming sessions produced a number of potential design solutions for each design component. A rigorous multistep screening and evaluating process was then applied until a final design concepts remained. The Bag Splitting Hopper was chosen as the concept the team would move forward with as it best met the customer's needs.

A Failure Mode and Effects Analysis was conducted by the team to strengthen weak areas of the design which added additional components to the overall design. A 3D model of the design was created to meet the initial and newly discovered requirements. Analytical analysis of the material strength and ergonomics of the structure was then conducted, followed by numerical analysis to corroborate the

analytical results and explore areas for optimization. After the design was complete, material and fabrication quotes were collected and came within budget. The team then compiled all information needed by the customer into this report for them to make an informed decision moving forward.

The team achieved the project objectives by developing a design that: completely removed the operator from the line of fire, increased the bag height adjustability to 12” and added 15” of additional adjustability for the entire structure, utilized a slide gate and chute for complete flow control, with all parts meeting or exceeding the required FOS of 5. The team exceeded the project objectives by increasing the overall efficiency of the unloading process and coming in 13% underbudget at $21,810 CAD making it a viable option for the client to pursue. Finally, all required deliverables were made available by the deadline of December 4th, 2019, successfully completing the project.

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GLOSSARY

BOM:	Bill of Materials
Cost:	Estimated purchase, installation, maintenance and future replacement costs.
COC:	Current Operating Condition
Design Maintenance:	Maintenance associated with designed components.
Duration of Process Training:	Estimated time and difficulty of training the current and future operators to safely conducting process.
FEA:	Finite Element Analysis
FMEA:	Failure Mode and Effects Analysis
FOS:	Factor of Safety
Installation Cost:	Only considers the cost to integrate the final design into the current system.
NRP:	Nutrien Rocanville Potash
Operator Safety:	The safety of the operator during any process they may be conducting.
Operator Satisfaction:	A subjective metric that the process operators will apply to the final design to ensure the design the team selects is satisfactory.
PM:	Preventative Maintenance
Primary Support System:	Current system used to suspend depressant bag above hopper via the eyelets of the depressant bag.
Process Length:	The estimated time to conduct normal process with the final design.
Product Containment:	How well the entire system mitigates spilled product.
RPN:	Risk Priority Number

SIF:	Serious Injury or Fatality
SS:	Stainless Steel
VOC:	Voice of the Customer
WDM:	Weighted Decision Matrix
WS:	Weighted Score

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1 INTRODUCTION

Nutrien Rocanville Potash (**NRP**), located in Rocanville, Saskatchewan, is the largest of Nutrien's six potash operations. NRP mines raw mineral ore 1000 [m] below the surface and uses a milling process to produce potash fertilizer for the world market.

This report includes problems identified, project objectives, concepts generated, concepts scored, detailed design, maintenance and future work recommendations.

1.1 PROJECT BACKGROUND

NRP has identified safety risks with the addition of a depressant into the floatation process. The depressant is supplied in 1000 [kg] bulk bags, which are suspended above a process hopper using a stainless steel (**SS**) support structure. Depressant bags need to be changed by operators every 24 hours to meet production demands. The bags are moved using an overhead crane and a bulk bag hoist fixture. Figure 1 shows the operator lowering a new bag onto the support structure.

Figure 1: New bulk bag being installed using overhead crane and lifting device

The bags are suspended above the hopper via the **primary support system** which involves hanging the bag from the bag hoist fixture via the bag's eyelets. The safety risk occurs when the operator must work under the suspended bag to untie and open the outlet during the bag change process. Currently, there are no safeguards in place to prevent a serious injury or fatality (**SIF**) in the event of structural failure of the primary support system or bag. Figure 2 depicts the operator reaching under the flocculant bag to untie and open the outlet, putting them in what NRP calls the "line-of-fire." Note, the depressant bag change process is identical to flocculant bag change process. Only flocculant bag change was observed during site visits due to production schedules.

Figure 2: Flocculant bag being opened by operator

The process in which depressant is introduced into the milling operation is illustrated using the flowchart displayed in Figure 3. The process consists of all steps involved in loading a depressant bag into the support structure, opening the bag and closing the bag for unplanned maintenance. Tasks that have a SIF potential are circled in red and are the focus of the project.

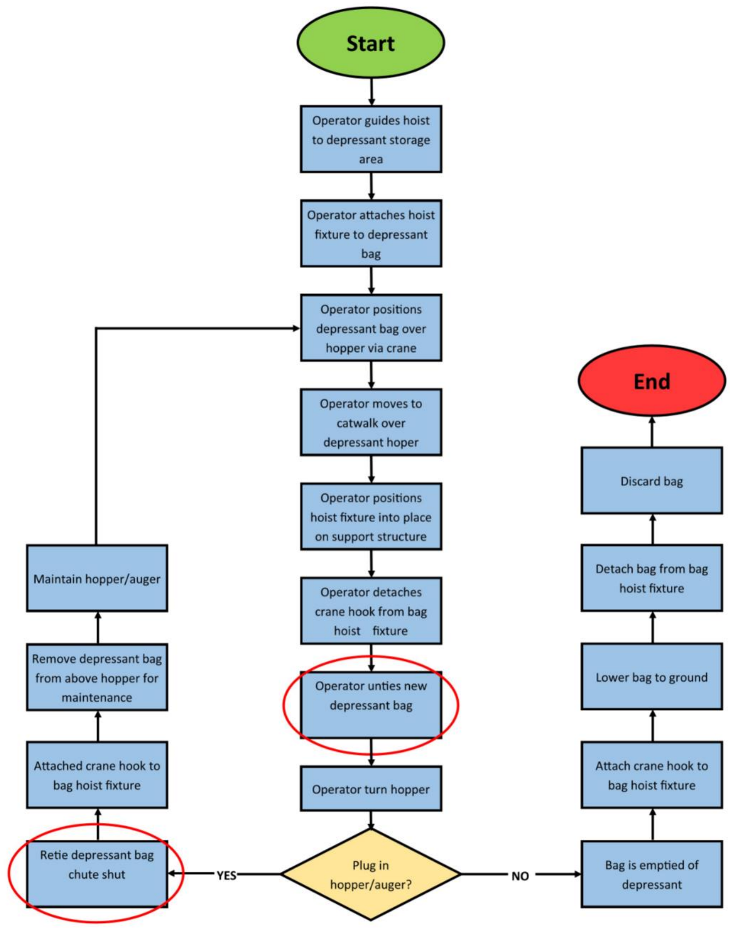

Figure 3: Reagent addition process flowchart with dangerous tasks circled in red

Additionally, the existing support structure has insufficient height adjustability as there is only 7 [in] available to increase the clearance between the bottom of the bag and top of the process hopper, restricting the operators' access. Therefore, an improved height adjustment concept must be incorporated into the design. The existing depressant support system used is shown in the drawing in Figure 4, provided by NRP. The depressant support system is in a standalone building referred to as the "reagent building" by NRP.

[redacted]

Figure 4: NRP depressant support system and process mixing hopper [1]

Another problem occurs when downstream equipment requires unplanned maintenance. In order to provide access to the affected areas, the opened bags must be lifted out of the process hopper. Attempting to retie the bags using the outlet ties is extremely difficult due to the weight of the depressant, and also requires the operator to once again be in the “line-of-fire.” For these reasons, the bags are left untied when being removed, causing the remainder of the bag to be spilt. The spill is contained by floor drains so there are no environmental impacts, but it does create a significant slip and fall hazard due to its texture and can take hours of cleaning to remediate the safety concern. The inability to reseal the depressant bags results in the loss of the remaining depressant, safety hazard, time spent cleaning up and reduced production efficiency. This spillage has a low frequency of occurrence, but NRP wants to determine a solution.

The priorities specified by the client, NRP, for this project are as follows:

1. Safety
2. Ease of Use and Design Simplicity
3. Efficiency
4. Maintenance
5. Cost

1.2 PROJECT OBJECTIVES AND SCOPE

To ensure success of the team's design, project objectives and scope were defined and approved by NRP to ensure all the design needs are addressed sufficiently.

1.2.1 PROJECT OBJECTIVES

The project goal is to provide safety improvements by designing a system that:

- Reduces operator time in the "line of fire" from 57 seconds to 0
- Increases support structure height adjustability from 7 [in] to 12 [in]
- Provides safe and simplistic way to open new bag, isolate and control flow

The project completion date is December 4, 2019. The following client deliverables are provided:

- A detailed design report with the following content:
    - Structural analysis of integrated final design
    - Design methodology
    - Cost analysis
    - Considerations for maintenance and operations
    - Recommendations for out-of-scope improvements
- Verification of designed components using finite element analysis (**FEA**)
- Engineered component, weldment and assembly drawings of final design
- Bill of Materials (**BOM**) of all designed components

1.2.2 PROJECT SCOPE

The project scope for the depressant system includes:

- Depressant support structure and containment
- Method for opening a new bag, flow control and isolation
- Increase height adjustability for a safeguard and access improvement

The following items are not within the scope of this project and will not be altered:

- Downstream equipment (process hopper, feed auger, etc.)
- Lower hopper support structure and mixing hopper
- Flocculant bulk bag equipment (depressant design can be utilized)
- Overhead crane

1.3 CONSTRAINTS AND LIMITATIONS

There are a number of constraints and limitations that the team considered to ensure that the design integrates within the current process without disruption. TABLE I contains constraints and limitations imposed on the project based on the needs of the process owners and process performers, as well as the needs of the current design and process. Once a conceptual design was selected, a number of additional design specific constraints were established.

TABLE I: CONSTRAINTS AND LIMITATIONS

No.	Constraint/Limitation	Implication
1	Must use bags provided by NRP.	We are required to develop a design that utilizes the NRP depressant bags.
2	Cannot introduce any bag fragments into mixing hopper.	This will impose limitations on how the bag may be opened as bag fragments can become lodged in the mixing auger located underneath the bag.
3	Mixing hopper cannot be altered.	The support structure must be designed to accommodate the existing hopper structure without modification.
4	Drawings must be provided in DWG format for NRP drafter review.	NRP has final review of drawings prior to fabrication and install.
5	Materials used in design must not be damaged by a corrosive environment.	The materials used in the construction of the structural design must have corrosion resistant properties that are suited for the environment of the reagent building. This will restrict material selection and will likely increase the cost of materials.
6	The function of the design must not be compromised by exposure to outdoor environments.	Materials used in design must be suited to exposure to outdoor elements such as rain, snow, wind, heat and cold winter air.

No.	Constraint/Limitation	Implication
7	The operators must not find the design difficult or cumbersome to use.	Operators will need to be consulted on the design and they must find it easy and comfortable to use. Operators approval is needed in order for success.
8	Design must integrate into current design and may not impede function of existing design or disrupt process.	Must not disrupt any function of the existing structure. This will restrict the placement of any additional structures or devices.
9	Design must fit within design footprint of 64 [in] L X 64 [in] W.	Design must fit within the footprint the of existing Depressant Support Structure which is dictated by catwalk located above mixing hopper.
10	Cost of design and design implementation may not exceed $25,000 CAD.	NRP has provided an increased budget to 25,000 CAD from 15,000 CAD due to project scope and design potential.
11	Design must be manually operated.	NRP requires a manual design as proof of concept before they will invest in automatic designs. Automatic hydraulic, pneumatic and electrical systems may not be implemented in the team's final design.
12	NRP turnaround from September 20th – October 21st.	Reduced access to process performers during this time as production at NRP is scaled back during turnarounds for maintenance.
13	NRP plant is located 373 [km] from University of Manitoba.	Due to large distance to the process site, the team had limited opportunities for site visits, and thus relied heavily on the project champion to obtain information throughout project.
14	There must be a minimum of 8 [in] between mixing hopper and safeguard.	Clearance constraint will restrict the depth and overall height of safeguard design.
15	Crane hook attached to lifting jig must be accessible by operator standing on catwalk without use of additional step or ladder.	Restricts total height of the design, specifically the upper supports.

No.	Constraint/Limitation	Implication
16	The operator may not stand any higher than 4 [ft] off the ground while on a ladder.	Restricts height of any design features that must be accessed by the operator for operational or maintenance purposes.
17*	Design must be able to accommodate untying depressant bags with flap as an auxiliary method of opening.	Design must provide operator access to the underside of the depressant bag. Bag splitter must be easily removable.
18*	Operator must be able to untie a depressant bag without being in the line of fire.	Access to underside of bag must be placed below safeguard device.
19*	Design must have lower height adjustment.	Additional design feature is required that enables the height of the safeguard hopper relative to the floor.
20*	NRP requires a minimum FOS of 5 for the design.	The allowable stress must meet the FOS of 5.

* Constraints determined after concept design selection

1.4 TARGET SPECIFICATIONS

During the project definition phase, NRP needs were prioritized and corresponding technical specifications were generated based on the voice of the customer (**VOC**). The needs and specifications were reviewed and approved by NRP then analyzed in a House of Quality in Appendix A to ensure all client needs were sufficiently met. The needs and specifications were used to select the final design concept and address parts of the design that needed to be improved through the final design.

1.4.1 CLIENT NEEDS

Operator safety and obtaining operator approval are NRP's number one priority for this design project, and thus, will be the team's primary focus during the design development stage. Other project needs have lower priority, such as the design's cost effectiveness. These lower priority design needs will still be pursued but will give way to higher priority needs, as necessary. All needs, compiled in TABLE II, were ranked using NRP's priorities outlined in Section 1.1.

TABLE II: CUSTOMER NEEDS

#	Need	Priority
1	Improve operator safety	5
2	Approved for use by shift operators	5
3	Raise bag supports	4
4	Work for a long time in a corrosive environment	4
5	Intuitive for other shift operators to conduct process	4
6	Improve operator ergonomics	3
7	Close the bag for removal when there is still product left	3
8	Improve or maintain current efficiency	3
9	Easy to maintain	3
10	Cost effective compared to original process	2

1.4.2 SPECIFICATION TABLE

The current, marginal and optimal operating conditions for each metric were determined based on the needs of the process owners and performers. Combining the metrics and their respective targets in TABLE III yielded the specifications.

TABLE III: PROJECT SPECIFICATIONS

Metric #	Need #	Metric	Units	Current	Marginal	Optimal
1	1,2,6,8	Time operator spends under suspended load	s	~ 57	0	0
2	2,3,5,6	Height adjustment range of bag supports	in	0	8	12+
3	1,3,4,9	Endurance limit of bag supports	Cycles	?	9125	20,000
4	1,2,5,6,8,10	Time to open bag	s	~ 55	< 55	< 10
5	1,5,6,7,8,9,10	Time to close bag	s	1800	< 55	< 10
6	1,5,7,8,10	Product lost during maintenance	kg	1000	< 20	< 0.5
7	3,4,7,9,10	Design and installation cost	CAD $	0	25,000	< 15,000
8	1,2,3,5,6,7,8	Operator satisfaction	Subj.	Low	High	High
9	4,8,9,10	Maintenance duration	h	0	< 2	0.5
10	2,5,7,8,10	Duration of process training	min	30	< 120	< 30
11	2,4,8,9,10	Maintenance frequency	times/year	0	2	1

NRP approved increasing the project budget to $25,000 from $15,000 to maximize the potential of the proposed design. The budget increase became necessary after features desired by the client or operators, such as making the design compatible for both disposable and reusable bulk bags, as well as provide a bag and hopper height adjustment feature. The team also separated the maintenance specification into two metrics: duration and frequency of the maintenance. In doing so, the team could better identify how potential concepts would need to be maintained and impacts to existing process and production.

2 CONCEPT GENERATION

Concepts were generated through external and internal research. External research involved finding manufactured or off-the-shelf solutions. Internal research involved concepts generated via team brainstorming and how the concepts can work as a system for the process.

To aid concept generation, an Ishikawa cause and effect diagram, Figure 5, was used to categorize the design metrics to address the client's needs. The metrics were categorized by individual design components that would be required in order to meet the project objectives.

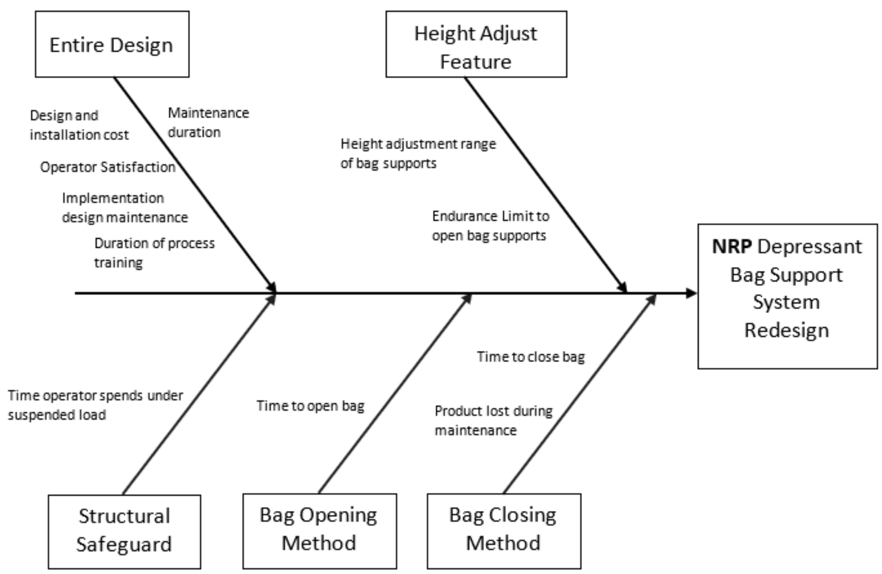

Figure 5: Ishikawa cause and effect diagram

As shown in Figure 5, the design metrics were organized into four design component categories with a fifth category, "Entire Design," capturing metrics that must be addressed by every component within the design. From the Ishikawa diagram, the design is comprised of four critical design components which are defined in TABLE IV.

TABLE IV: CRITICAL DESIGN COMPONENTS

Design Component	Component Description
Structural Safeguard	A secondary device to support depressant bag and prevent worker injury in event of failure of the primary support system.
Bag Opening Method	A method to safely and efficiently open the depressant bags, achieved through a device or a various processes.
Bag Closing Method	A method that would enable the operators to temporarily stop the flow of depressant, allowing for maintenance without product loss.
Height Adjust Feature	Provide the operator's means to adjust the height of the primary bag support system to accommodate for varying bag sizes.

Using the defined design components, the team began the process of brainstorming potential solutions for each component. Additional concepts were also determined through external research and information provided by NRP after they contacted their sister Nutrien Potash sites for feedback of existing solutions that could be utilized. All the concepts generated through brainstorming, internal research, external research and NRP contacting sister Nutrien Potash sites for potential solutions are summarized in an Idea Box as shown, TABLE V.

TABLE V: IDEA BOX

Parameter			
Opening System	Closing System	Safeguard	Height Adjustability
• Manually Cut • Manually Untie • Fledbag® Original • Vibra Screw Inc.™ Bag Splitter®	• Mechanical Cinch/Iris Valve • Manual Cinch • Fledbag® Easy • Fledbag® Original • Slide Door • Mechanical Clamp	• Grating with Hole • Steel Tubing • Chains • Cable • Hopper • Nothing • Vibra Screw Inc.™ Bulk Bag Unloader®	• Manual Pin/Bolt adjustment • Motor Hydraulic • Manual Hydraulic • Pneumatic actuated • Electric actuated • Rack and pinion

3 CONCEPT SELECTION

Concept selection consisted of four distinct stages: initial concept screening, concept scoring, concept combination and selecting a final design concept. The initial concept screening reduced the number of design ideas, based on constraints and limitations, and concept scoring used a weighted decision matrix (**WDM**) to rank the concepts. Concepts were then combined, and practical combinations were screened and scored to determine the top system design concept. The top system design concept was selected for final design and illustrated, for visual purposes. A description of all individual design concepts is shown in Appendix B.

3.1 CONCEPT SCREENING

Combining design solutions for each parameter yielded 1,008 potential designs. To facilitate the evaluation of the combined conceptual designs, it was necessary to reduce the number of potential design solutions for each parameter using a two-step screening process.

First, the design solutions were screened using the scope, constraints and limitations established in conjunction with the clients at the onset of the project. The Vibra Screw Inc.™ Bag Unloader® was eliminated as a potential safeguard as it would require modification of the lower hopper support system due to the deviation in vertical column spacing between the two systems, violating constraint #9. The height adjustment solutions actuated automatically via a hydraulic, pneumatic or electric system were removed since NRP needs a manual solution as per constraint #11.

The second step of the screening process involved evaluating how each design solution met the needs of the customer and design metrics. WDMs were used to evaluate the design concepts for each individual component. Unique selection criteria were developed for each individual design component based on the customer needs as well as the components technical function. After being approved for use by NRP, the WDMs were used to identify the best design solutions for each design component, which further facilitated the comparison of combined design concepts.

3.2 CONCEPT SCORING

To determine the scoring weights of the criteria, the team compared the criteria to one another. The weights of each criterion were determined by calculating the number of "hits" for that criterion, divided by the total number of possible "hits". Once the weights of each selection criteria were determined, the team moved into scoring the ideas, based on their selected design criterion. Criteria weights were reviewed and approved by NRP prior selecting the final concept.

As shown previously in TABLE V, the team split the system into various categories, each satisfying specific needs for the design. The design ideas that survived the screening process were scored, based on the design criteria. While evaluating each design solution using the WDMs, a correlation score of 0, 1, 3 or 9 was assigned. The magnitude and definition of the correlation scores, displayed in TABLE VI, follows the Lean Six Sigma standard practice for evaluating solutions using a WDM [2].

TABLE VI: GENERAL SCORING CORRELATIONS

Correlation Scores	
Conceptual design is unable to meet customer requirement	0
Conceptual design has a weak ability to meet customer requirement	1
Conceptual design has a moderate ability to meet customer requirement	3
Conceptual design has strong ability to meet customer requirement (ideal scenario)	9

To eliminate poor designs, the team developed a criterion to interpret the final weighted score for each design, analyzed using the weighted decision matrices. This criterion used the definitions provided in TABLE VI to compare the weighted score (**WS**), of each design to the performance of the Current Operating Condition (**COC**). The criterion is as follows:

Design worse than COC: $\langle 0 \leq WS < 3.00 \rangle$

Design equivalent to COC: $\langle WS = 3.00 \rangle$

Design better than COC: $\langle 3.00 < WS < 9.00 \rangle$

Ideal Design: $\langle WS = 9.00 \rangle$

In order to ensure that the final design improved the performance relative to the current design, only concepts with a score greater than 3.00 were carried through to system scoring of the design concept selection process. All scores that are 3.00 or less were eliminated. Criteria weights and WDMs for each design component can be found in Appendix C.

3.3 CONCEPT COMBINATION

Concepts with a weighted score greater than 3.00 moved into concept combination, TABLE VII. In this phase, the Idea Box would be used to combine all compatible individual concept ideas which were then scored using an additional weighted decision matrix to determine the best conceptual design.

TABLE VII: SCREENED CONCEPT IDEA BOX

Parameter			
Opening System	Closing System	Safeguard	Height Adjustability
• Manually Untie • Fledbag® Original • Vibra Screw Inc.™ Bag Splitter®	• Fledbag® Easy • Fledbag® Original • Slide Door • Clamp	• Grating with Hole • Steel Tubing • Hopper	• Manual Pin/Bolt adjustment

3.3.1 SYSTEM SCREENING

As concepts were combined using the Idea Box, TABLE VII, an issue arose as some of the ideas could not be practically combined with others. Therefore, system concepts were screened to remove ideas that were not practical, as justified in TABLE VIII.

TABLE VIII: CONFLICT JUSTIFICATIONS

Conflict	Reasoning
Vibra Screw Inc.™ Bag Splitter® cannot be combined with Grating with Hole and Steel Tubing.	The Bag Splitter® may result in product overflow as Grating with Hole and Steel Tubing do not contain the product.
Vibra Screw Inc.™ Bag Splitter® cannot be combined with the Fledbag® Easy and Clamp.	The Bag Splitter® pierces the bag, removing the possibility of reclosing the bag outlet.
Slide Door cannot be combined with Manually Untie for the Grating with Hole and Steel Tubing.	Slide Door may result in product overflow as Grating with Hole and Steel Tubing do not contain the product.
Fledbag® Original cannot be combined with an opening method.	Fledbag® Original has its own opening method.
Fledbag® Easy can only be used with manual untie opening method.	Fledbag® Easy must be manually clamped to the bag outlet before untied.

3.3.2 SYSTEM SCORING

With the possible concept combinations verified by the final combination screening process, the remaining combined design concepts were evaluated using a final system scoring matrix. The determination of the weights for each criterion can be found in Appendix D. The system scoring matrix was used to identify the final system design concept that was carried into final detailed design.

As shown in TABLE IX, the best design, based on the weighted score, is the Vibra Screw Inc.™ Bag Splitter®, Slide Door and Manual Pin/Bolt, henceforth known as the Bag Splitting Hopper.

TABLE IX: SYSTEM SCORING

Design Idea				Criteria							Weighted Score
				Operator Safety	Process Length	Design Maintenance	Product Containment	Installation Cost	Operator Satisfaction*	Duration of Process Training	
Safeguard	**Opening**	**Closing**	**Height Adjustment**	0.25	0.18	0.14	0.07	0.11	0.21	0.04	
Grating with Hole	Manually Untie	Fledbag® Easy	Manual Pin/Bolt	3	1	9	9	9	1	3	4.14
Grating with Hole	Fledbag® Original		Manual Pin/Bolt	9	1	3	3	9	3	3	4.79
Grating with Hole	Manually Untie	Clamp	Manual Pin/Bolt	3	3	3	3	9	1	9	3.43
Steel Tubing	Manually Untie	Fledbag® Easy	Manual Pin/Bolt	3	1	9	9	3	1	3	3.50
Steel Tubing	Fledbag® Original		Manual Pin/Bolt	9	1	3	3	3	3	3	4.14
Steel Tubing	Manually Untie	Clamp	Manual Pin/Bolt	3	3	3	3	3	3	9	3.21
Hopper	**Vibra Screw Inc.™ Bag Splitter®**	**Slide Door**	**Manual Pin/Bolt**	**9**	**9**	**1**	**9**	**1**	**9**	**3**	**6.79**
Hopper	Manually Untie	Fledbag® Easy	Manual Pin/Bolt	3	1	3	9	3	1	3	2.64
Hopper	Fledbag® Original		Manual Pin/Bolt	9	1	3	3	3	3	3	4.14
Hopper	Manually Untie	Slide Door	Manual Pin/Bolt	3	3	3	9	3	9	9	4.93
Hopper	Manually Untie	Clamp	Manual Pin/Bolt	3	3	3	3	3	3	9	3.21

*Operator Satisfaction was scored by the NRP reagent operators

3.4 CONCEPTUAL DESIGN OPTIMIZATION

The Bag Splitting Hopper was the selected concept for the project, based on NRP needs, objectives, constraints and limitations, as determined in Section 3.3.2, TABLE IX. The Bag Splitting Hopper design concept is described, was optimized to meet all NRP needs, and failure mode and effects analysis (**FMEA**) was performed.

3.4.1 CONCEPTUAL DESIGN DESCRIPTION

The final design concept consisted of an unloading hopper for the safeguard with a Vibra Screw Inc.™ Bag Splitter® bolted into the unloading hopper and a slide door as seen in Figure 6. The Vibra Screw Inc.™ Bag Splitter® is used to puncture a new bag and split it open allowing product to flow without the need for the operator to untie the bag. A hopper panel is removed to show internal detail, Figure 6. A slide door mounted to the discharge of the unloading hopper with a discharge chute (not presented) to direct flow into the mixing hopper and prevent overflow, beneath (not presented).

Figure 6: Bag splitting hopper final design concept

3.4.2 CONCEPTUAL DESIGN OPTIMIZATION

Prior to beginning the final design, the Bag Splitting Hopper concept was analyzed to ensure it will adequately meet all of NRP's needs. One issue is that two decision criteria were assigned a correlation score of 1, the installed cost and design maintenance, indicating that the NRP needs associated were not sufficiently met.

The cost of the design was improved significantly by producing an engineered design for portions of the bag splitting hopper such as the vertical support structure and hopper. Designing these components drastically reduced costs associated with outsourcing engineering work as well as improved the flexibility of the design. Designing major components of the Bag Splitting Hopper also achieved cost savings through utilization of NRP preferred fabricators and material suppliers.

To improve the maintenance of the final design, Failure Mode and Effects Analysis (**FMEA**) was applied to the conceptual design to identify potential failure modes that may affect the accessibility of the design for maintenance. Providing a second degree of height adjustment, the addition of an access door and designing removable bin walls vastly improved the accessibility of the design for maintenance purposes.

These alterations helped increase the correlation scores of the installed cost and design maintenance from 1 to 3, validating the selection of the Bag Splitting Hopper design concept.

3.4.3 FAILURE MODE AND EFFECTS ANALYSIS

Before the final design process began, preliminary design work was done to identify any additional design features that may not have been captured by the conceptual design process or from the VOC. Some design features required to prevent structural or functional failure were design specific and could not be considered prior to selecting a final design concept.

FMEA was performed on the Bag Splitting Hopper design concept to pre-emptively identify potential failure modes that would compromise the safety or function of the design. Additionally, FMEA facilitated assessing the risk of these potential failure modes and prioritized corrective actions to mitigate the risks to an acceptable level.

Failure modes found to have a Risk Priority Number (**RPN**) greater than 100 were considered to have an unacceptable level of risk and required implementation of additional design or process control to reduce the risk. The seven failure modes found to have an RPN greater than 100 and their corresponding corrective actions are summarized in TABLE X. Remaining FMEA results as well as an explanation of the FMEA methodology can be found in Appendix E.

Five failure modes identified risks that may impede the function of the reagent addition process. Properly sourcing a slide door and implementing a preventative maintenance routine will prevent the hopper door becoming stuck open or closed, complicating the reagent process. Removable hopper side walls will be required in the upper bin section to provide operator's access to the Vibra Screw Inc.™ Bag Splitter® for maintenance purposes. An outlet chute extending between the outlet of the safeguard hopper and the lower mixing hopper will be needed to prevent material overflow.

One key design change that was applied is to provide operators the ability to access and untie bags with chutes in the event of complications with the Vibra Screw

Inc.™ Bag Splitter®. This design change was critical because it expands the scope of the design, imposing additional design constraints with respect to the design space and design function.

Two failure modes addressed risks pertaining to operator safety. A handrail must be added to the upper portion of the design to prevent operators from falling onto the bag splitter. Finally, requiring the design to accommodate bags with chutes complicates the operator's ability to safely access the outlet chute due to the height of the design. Providing the ability to adjust the height of the hopper reduced this risk.

TABLE X: FMEA ITEMS WITH RPN GREATER THAN 100

Item	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/Mechanism(s) of Failure	Occurrence	Current Design Controls	Detection	RPN	Recommended Action(s)	Action Results			
										Sev.	Occ.	Det.	RPN
Mixing Hopper	Mixing hopper overflows	Product loss, depressant creates slip hazard	5	No effective method to meter product flow, prevent mixing hopper from over filling	10	Side walls on mixing hopper, operator observation	3	150	Design chute that attaches to bottom of safeguard hopper allowing dense depressant to build up in chute, metering flow.	5	3	3	45
Slide Door	Slide Door inoperable, stuck open	No way to isolate depressant flow for maintenance	4	Unable to close door	7	Actuation of door	9	252	Operate slide door once a week, slide door selected must be designed for bulk powder service	4	4	3	48
Slide Door	Slide Door inoperable, stuck closed	Depressant flow stops, affecting production	8	Unable to open door	4	Actuation of door	9	288	Operate slide door once a week, slide door selected must be designed for bulk powder service	8	4	3	96
Catwalk	Fall risk associated with opening for depressant	Operator can fall into safeguard hopper and possibly onto Vibra Screw Inc™ Bag Splitter®, causing a severe injury or death	10	No safety rails present to prevent fall	3	Opening is visible and marked by four posts	4	120	Install handrail to improve detectability of hole and decrease likely hood of a fall into the hopper	10	2	2	40
Vibra Screw Inc™ Bag Splitter®	Vibra Screw Inc.™ Bag Splitter® does not properly pierce depressant bag	Depressant flow stops or is reduced, affecting production.	7	Splitter incompatible with NRP depressant bags.	5	Operator observation	3	105	Make the splitter removable so Nutrien may switch revert back to untying bags. Add access panel to allow operator ability to untie bags.	7	1	3	21
Hopper	Unsatisfactory design height of safety hopper	Operator is unable to reach access door or slide door. Operator not permitted to work beyond 4 feet above ground.	7	Hopper height is too high. Hopper height not adjustable if needed to revert back to untying bags.	10	Operator observation, measurement	3	210	Design hopper to be have an adjustable height, to ensure comfortable operation for all.	7	2	3	14
Hopper	Vibra Screw Inc.™ Bag Splitter® inaccessible.	The Bag Splitter® may not be removed for maintenance or to switch to bag's with outlets	8	Hopper walls impede operator's access to Bag Splitter®.	10	Operator observation.	3	240	Make hopper side walls in upper bin removable for easy access to Bag Splitter®.	8	2	3	48

4 FINAL DESIGN DETAILS

The final design details for the Bag Splitting Hopper are provided in Section 4. To ensure the design performs as intended, analysis of the new Bag Splitting Hoper design was performed through selecting applicable off-the shelf solutions, application of relevant engineering calculations and FEA to validate the designs. Material properties of designed components is specified, design stress is defined, and engineering results are provided.

4.1 DESIGN OVERVIEW

The final design incorporates the safeguard, opening, closing and height adjustment requirements, as well as the modifications made to satisfy the FMEA. All tubing, sheet metal and hardware of the Bag Splitting Hopper are made of 316 SS construction. Figure 7 displays the final design in its entirety.

Figure 7: Final Design

4.1.1 SAFEGUARD

The support structure, designed by the team bolts to the NRP's existing lower structure surrounding the mixing hopper below. The support structure design is constructed of 4 [in], 3 [in] and 2.5 [in] 316 SS square tubing with a wall thickness of 0.25 [in], welded together at the joints and pined at the height adjustments. The hopper bottom is constructed with 0.125 [in] 316 SS sheet to ensure minimum deflection under full load and has all seams welded to eliminate product leakage.

Due to the results of the FMEA, fall arrest bars, highlighted in green in Figure 8, were added to the top of the structure to eliminate the risk of an operator falling into the hopper if there is no bag present. These bars double as lift points for installation and ease of hopper height adjustments. Figure 8 displays the designed safety support structure, including the added fall arrest bars highlighted in green.

Figure 8: Safety support structure with fall arrest bars highlighted

4.1.2 OPENING

Due to NRP's requirement for the design to work with both reusable and disposable bags, the design incorporates two opening methods: splitting for disposable bags and manually untying for reusable bags.

4.1.2.1 SPLITTING FOR DISPOSABLE BAGS

The Vibra Screw Inc.™ Bag Splitter® concept is the intended design for this project. The splitter opens the bag by simply lowering the bag onto the splitter, as seen in Figure 9.

Figure 9: Vibra Screw Inc.™ Bag Splitter® model

To reduce cost, the team designed a bag splitter based on the Screw Inc.™ Bag Splitter® dimension. NRP informed the team that they would prefer to purchase a Vibra Screw Inc.™ Bag Splitter® because it has been proven at Nutrien Vanscoy and will ensure no production interruptions due to splitter performance.

The FMEA raised maintenance concerns for this design as work done within the hopper would require the operator to climb over the hoper wall. Making the walls removable eliminates the maintenance risk, as well as ensures operator safety while installing or removing the Vibra Screw Inc.™ Bag Splitter®. The walls weight 7 [kg] and are designed to be lowered by hand onto a flat landing along the perimeter of hopper, as shown in Figure 10.

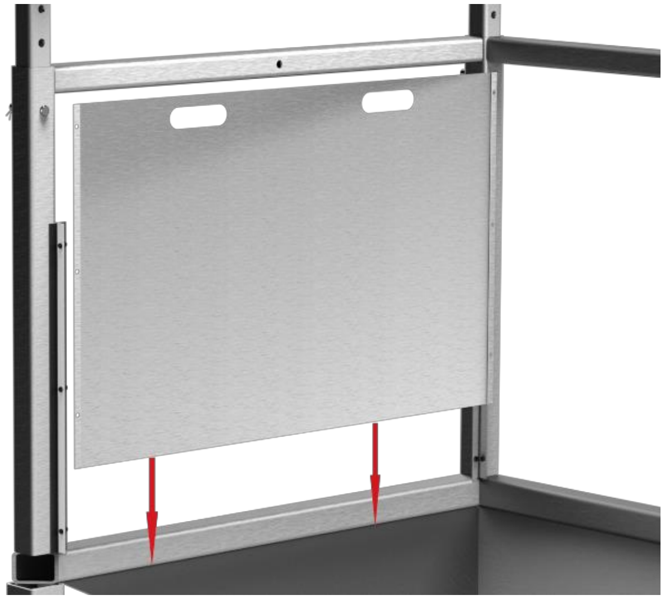

Figure 10: Wall placement

The removable hopper walls are supported along the perimeter by mounted flanges and lower support structure, highlighted green as seen in Figure 11.

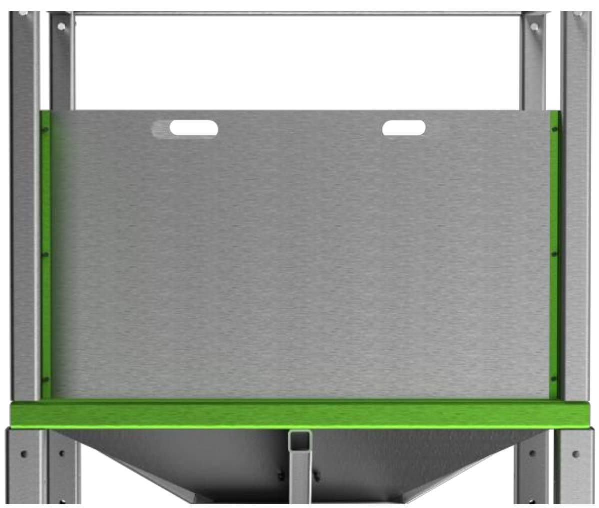

Figure 11: Wall rear supports

Weld nuts are integrated into the hopper walls which allow the hopper walls to bolt onto the side mounting flanges. Therefore, the amount of hardware the operator needs is reduced, mitigating the risk of hardware falling into the mixing hopper below, and improves maintenance accessibility.

4.1.2.2 UNTYING FOR REUSABLE BAGS

To allow the operator to safely untie the bag while remaining out of the "line-of-fire," an access door was added to the bottom of the hopper, Figure 12. When using reusable bags, the bag splitter must be removed and the splitter bolt holes in the hopper must be plugged to ensure product containment.

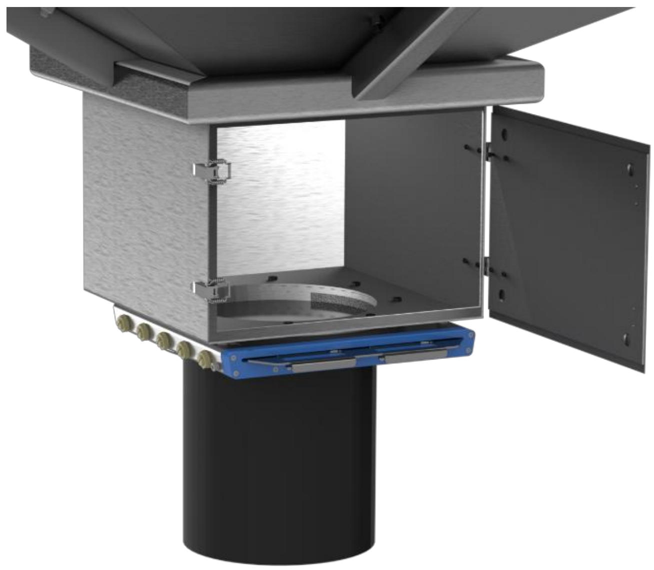

Figure 12: Access door

This door also provides access for maintenance to remove the slide door valve and for operations to remove any clumps from the powder blocking flow.

4.1.3 CLOSING

The slide door selected for the final design is the Mucon™ DSV® 12 Slide Gate, which is an off-the-shelf engineered solution, designed for bulk powder service with lockout-tagout hole integrated. Mucon™ DSV® 12 Slide Gate is shown in Figure 13. The Mucon™ DSV® 12 Slide Gate and required gaskets are items stocked by Schenck Process.

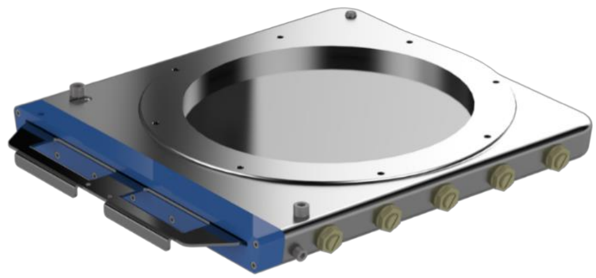

Figure 13: Mucon™ DSV® 12 Slide Gate Valve [3]

A chute must be attached to the discharge of the Mucon™ DSV® 12 Slide Gate to direct depressant flow and prevent overflow of the mixing hopper below. Superchute® Non-Static Vinyl canvas with flange was selected for the design as it is designed for bulk powder service, keeps cost low, while maintaining functionality and easy of use. Superchute® Non-Static Vinyl with HMWPE flange, as shown in Figure 14, mounts to the bottom flange of the Mucon™ DSV® 12 Slide Gate.

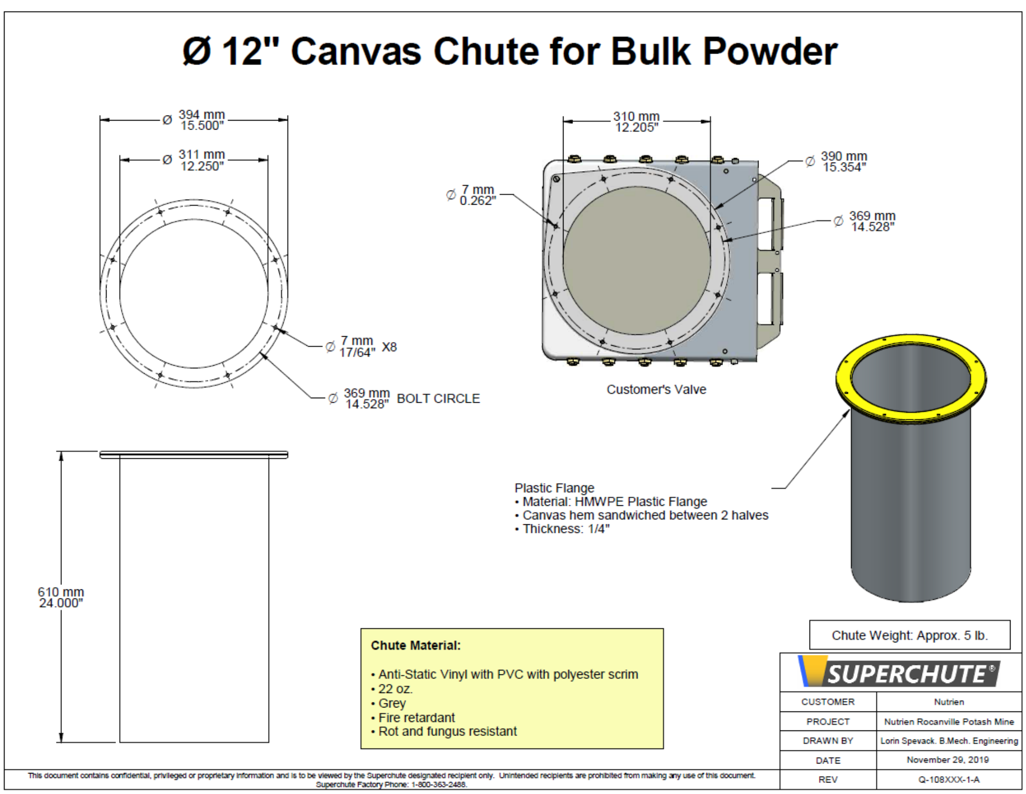

Figure 14: Superchute® non-static vinyl chute with flange [4]

4.1.4 HEIGHT ADJUSTMENT

The Bag Splitting Hopper design features a two-degrees of freedom height adjustment system. The upper adjustment raises and lowers the bag height, relative to the designed hopper. This design recapitulates NRP's original design using a 2.5 [in] tube inserted into a 3 [in] tube, pinned together. The design was improved by vertically raising the pin location, so the operator does not have to bend to down to adjust the height. This design improvement also allows the adjustment tubes to be shorter and lighter, mitigating the risk of operator strain. These upper adjustments have 12 [in] of travel with 4 [in] intervals to ensure that the bag jig can be rested on the supports when using the splitter or opening the bag by hand. The adjustment is shown in Figure 15.

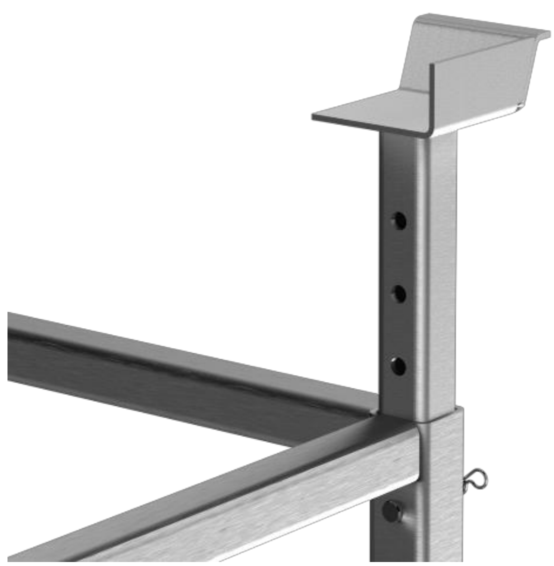

Figure 15: Upper Height Adjustment

The lower adjustment allows entire designed hopper assembly to be raised and lowered, in reference to the ground. The adjustment mimics the upper adjustment but uses a 4 [in] outer tube and a 3 [in] inner tube. The difference in tube sizes was designed to allow clearance, to mitigate binding when adjusting the lower height adjustment. The various increments for the height adjustment was done to ensure that the height was optimal, if the operator had to manually untie a bag, or to be able to raise the structure out of the way for conducting maintenance on the mixing hopper. As shown in Figure 16, the maximum height adjustability of the lower adjustments is 15 [in] in 3 [in] intervals.

Figure 16: Lower Height Adjustment

Pins designed for the both upper and lower height adjustments are ¾ [in] 316/316L SS.

4.2 DESIGN METHODOLOGY

Once the required design features were established through the conceptual design and FMEA processes, the detailed design of the individual components began. A design methodology was developed and followed to ensure that each facet of the design complied with the client's expectations and achieved the required design goals. The design methodology follows the structure outlined in Figure 17.

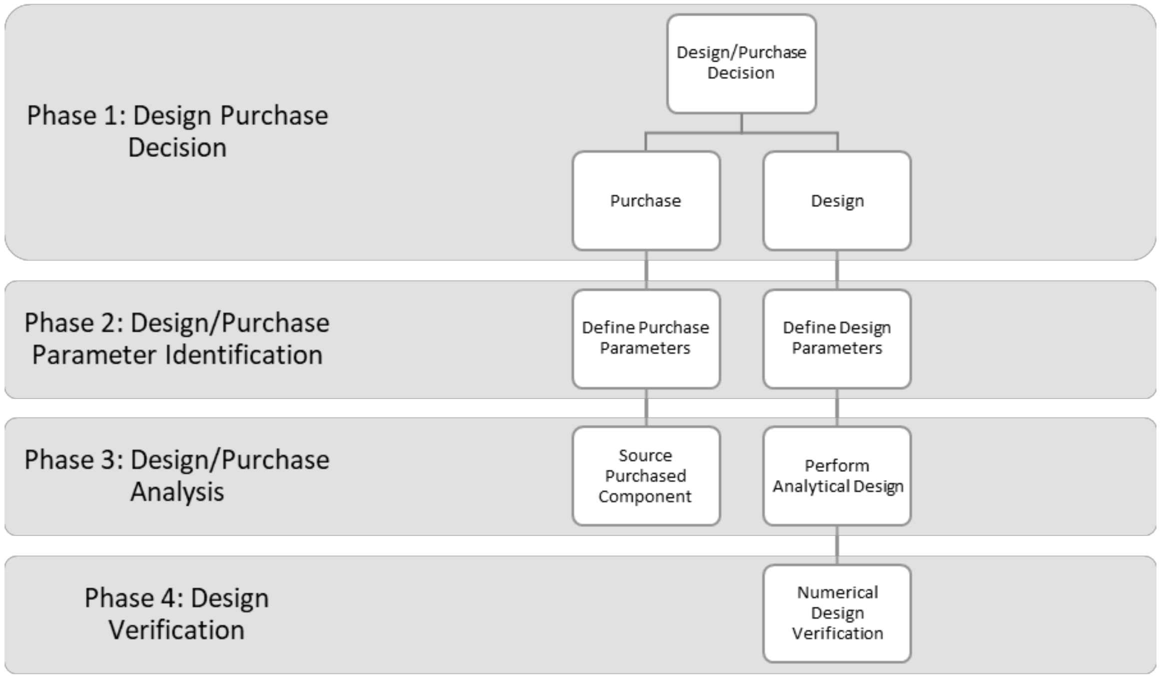

Figure 17: Design methodology structure

For each component used in the design, the first phase of the design process was to establish whether the component should be purchased or designed by the team. Each decision was unique to the specific component, but generally considered the design complexity, cost and compatibility with the design constraints.

In the second phase of the design process, the parameters and constraints relevant to the design where established to ensure the design's compliance with the VOC. These parameters and constraints were used to either guide the design process or help select an appropriate sourced component.

In the third phase of the design process, analytical decisions were made using the parameters and constraints identified in the second phase to make a design decision.

The final phase of the design process was specific to designed components. After the design had been produced analytically, numerical analysis tools such as FEA were applied to verify the analytical results.

4.3 OFF-THE-SHELF COMPONENTS

Several off-the-shelf engineered solutions were found through external research. Based on the cost, quality and applicability, off-the-shelf engineered solutions were selected for final design or removed respectively.

Off-the shelf support structures and hoppers were sourced but the cost exceeded the budget drastically, thus and in-house engineered support structure and hopper design were provided.

4.3.1 VIBRA SCREW INC.™ BAG SPLITTER®

The Vibra Screw Inc.™ Bag Splitter® is a proven solution to open disposable bags, currently implemented at Nutrien Vanscoy, and can be purchased at a reasonable price of $5500 CAD. Although this component was designed by the team and could be fabricated, NRP expressed their preference to purchase the Bag Splitter® from Vibra Screw Inc.™ to reduce in-house design risk and liability, as well as purchasing a spare to store in NRP warehouse.

4.3.2 MUCON™ DSV® 12 SLIDE GATE

The Mucon™ DSV® 12 Slide Gate valve was selected due to superior product quality compared to other off-the-shelf engineered solutions for this specific application. The Mucon™ DSV® 12 Slide Gate is available for a price of $1100 CAD each with required gaskets and is specifically designed for bulk powder hopper discharge applications.

4.3.3 SUPERCHUTE®

The Superchute® Non-Static Vinyl chute with flange was selected due the low cost of the Superchute® at $450 CAD, while providing the required product containment without requiring engineering design and fabrication. Superchute® Non-Static Vinyl chute is made of a flexible canvas material allowing easy access for maintenance and operations.

4.4 DESIGNED COMPONENTS ANALYSIS

The designed components were determined through means of analytical and numerical (FEA) analysis. Due to the limited budget of $25,000 CAD and NRP needs, a customized support structure needed to be engineered by the design team. The existing support structure was analyzed to benchmark existing performance and stress to gauge components for the final designed support structure. Due to the additional weight introduced with the design, analysis was performed on the lower support structure to ensure all values are below the allowable design stress. Appendix F describes the detailed analytical methodology used for design and Appendix G details analytical results of the existing support structure used for benchmarking.

4.4.1 FACTOR OF SAFETY RESULTS

Using the material properties for 316L SS from Appendix F, the allowable normal and shear stresses are summarized in TABLE XI. 316L was used over 316 because it has lower strength properties and the metal supplier uncertainty between 316 or 316L SS. Therefore, 316L was used to ensure a safe design for the worst-case scenario.

TABLE XI: ALLOWABLE STRESS FOR 316L SS AND GRADE 5 BOLT

316L SS Normal [ksi]	316L SS Shear [ksi]
14	8.4

4.4.2 SUPPORT STRUCTURE ANALYTICAL RESULTS

The support structure refers to all tube members within the design. This section summarizes the analytical results of the support structure.

4.4.2.1 FATIGUE RESULTS

The fatigue limit for 20,000 cycles and the endurance limit results for 316/316L SS Normal Stress and Shear Stress are summarized in TABLE XII. See Appendix F for background on endurance and fatigue limit calculations.

TABLE XII: FATIGUE AND ENDURANCE LIMIT RESULTS

Material	Fatigue Limit [ksi]	Endurance Limit [ksi]	Allowable Stress [ksi]
316L SS Normal	33.06303	14.24633	14
316L SS Shear	23.25804	12.33507	8.4

The design normal stress for 316/316L SS is defined as 14 [ksi], since the fatigue limit, 33.06 [ksi], is greater than the allowable normal stress defined by the FOS.

The design shear stress for 316/316L SS bolt is defined as 8.4 [ksi], since the fatigue limit, 23.26 [ksi] is greater than the allowable shear stress defined by the FOS.

4.4.3 AXIAL STRESS

The axial stress maximum in the designed support structure, including the mass of the design (500 [kg]), depressant (1000 [kg]), lifting jig (70 [kg]) and bag (3 [kg]) is 0.52353 [ksi], well below the normal design stress for 316/316L SS of 14 [ksi].

4.4.3.1 BUCKLING RESULTS

To ensure the 316/316L SS support columns can adequately support the load, the critical buckling load, P_{cr}, was determined for the upper and lower supports. The column load applied, P_{load}, was compared the P_{cr} to determine the buckling FOS. The buckling results of the final design upper height adjustment columns is shown in TABLE XIII for a fixed-free column (C = 0.25).

TABLE XIII: FINAL DESIGN UPPER HEIGHT ADJUSTMENT BUCKLING RESULT

P_{cr} [lbf]	P_{load} [lbf]	FOS	Column End Conditions (C)	Moment of Inertia [in^4]	Length [in]
137,075.7588	632.313	216.78	0.25	1.55597	28

The buckling results of the final design upper support structure columns buckling result is summarized in TABLE XIV for a fixed-fixed column (C = 1).

TABLE XIV: FINAL DESIGN UPPER SUPPORT STRUCTURE COLUMN BUCKLING RESULT

P_{cr} [lbf]	P_{load} [lbf]	FOS	Column End Conditions (C)	Moment of Inertia [in^4]	Length [in]
349,344.1841	632.313	552.47	1.00	2.79327	47

Both, the upper height adjustment columns and upper support structure, exceed the critical buckling load significantly, as shown by the FOS in TABLE XIII and TABLE XIV. The design incorporates the same-size columns as they are proven to be reliable, in terms of strength and lifespan.

The existing lower support structure was analyzed to ensure it can support its current weight (1000 [kg] of depressant, 70 [kg] jig and 3 [kg] bulk bag), along with the mass of the final design (500 [kg]). Buckling of the lower support structure, which the final design rests on, was performed for a fixed-fixed column (C = 1), as shown in TABLE XV, to ensure each column can support the final design and existing load.

TABLE XV: LOWER SUPPORT STRUCTURE CRITICAL BUCKLING RESULTS

P_{cr} [lbf]	P_{load} [lbf]	FOS	Column End Conditions (C)	Moment of Inertia [in^4]	Length [in]
109,368.0985	907.998	120.45	1.00	2.79327	84

Comparing the critical buckling load, 109,368.1 [lbf], to the load applied to the lower support structure, 907.998 [lbf], results in a FOS of 120.45.

Therefore, all designed columns and lower support structure exceeds the FOS of 5, as required by NRP, and will support the required load with no safety concerns.

4.4.3.2 HOPPER HEIGTH ADJUSTMENT PINS

NRP requested the unloading hopper have a lower height adjustment feature, in addition to the upper height adjustment. The pin size and material for both, the lower and upper height adjustment, were determined. The lower height adjustment pins support the entire weight of the final design (500 [kg]), depressant (100 [kg]), bag (3 [kg]) and bag jig (70 [kg]). 316/316L SS bolts were selected for the lower height adjustment pins to eliminate galvanic corrosion and improve corrosion resistance. The force on each pin is shared between the four columns and distributed between two holes in each hollow square tube. The designed pin strength results for the hopper height adjustment pins are summarized in TABLE XVI.

TABLE XVI: HOPPER HEIGTH ADJUSTMENT PIN STRESS RESULTS

Shear Stress [ksi]	Bearing Stress [ksi]	Force [lbf]	Bolt Diameter [in]
1.02764	3.22844	453.9992	0.75

A stress concentration factor (K) was applied to the shear and bearing stress to ensure the hopper height adjustment pins meet the allowable design shear stress of 8.4 [ksi] for 316/316L SS, as summarized in TABLE XVII.

TABLE XVII: HOPPER HEIGHT ADJUSTMENT PINS WITH STRESS CONCENTRATION

Shear Stress [ksi]	Bearing Stress [ksi]	K
2.62049	8.23252	2.55

Therefore, ¾ [in] 316/316L SS bolts were selected for the hopper height adjustment pins since both shear and bearing stress, are below the allowable design shear stress for 316/316L SS of 8.4 [ksi]. To simplify manufacturing, store spare parts and ensure smaller pins aren't installed on the lower height adjustment, ¾ [in] 316/316L SS bolts are selected for the upper height adjustment pins, as well. The stress in the bag height adjustment pins is less than the hopper height adjustment pins, as they are under less stress due to the increase in weight of the design, as summarized in TABLE XVIII and TABLE XIX.

TABLE XVIII: BAG HEIGHT ADJUSTMENT PIN STRESS RESULTS

Shear Stress [ksi]	Bearing Stress [ksi]	Force [lbf]	Bolt Diameter [in]
0.71563	2.24822	316.156362	0.75

TABLE XIX: BAG HEIGHT ADJUSTMENT PINS WITH STRESS CONCENTRATION

Shear Stress [ksi]	Bearing Stress [ksi]	K
1.82486	5.73297	2.55

4.4.4 SUPPORT STRUCTURE NUMERICAL RESULTS

SolidWorks was used to conduct two different loading studies, regarding the strength of the safety structure tubing. The first study simulated the bag lifting jig resting on the upper support plates. The second study simulated lifting the whole structure while holding a full bag of depressant, as shown in Figure 18 and Figure 19, respectively.

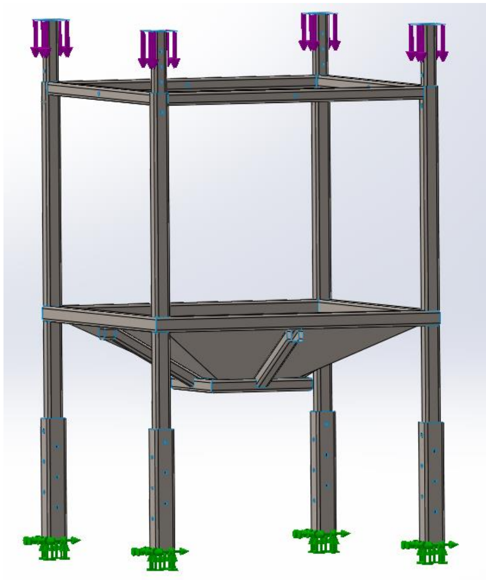

Figure 18: Study one loading

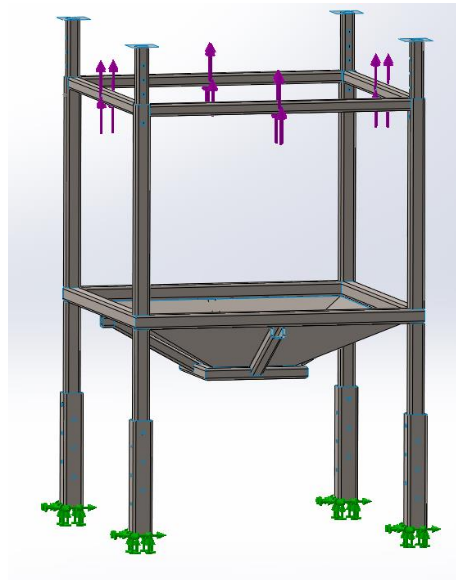

Figure 19: Study two loading

To ensure the structures met the required FOS of 5, both studies were conducted with an applied load five time greater than the actual load currently applied to the structures. As shown in TABLE XX, the stress exhibited in the support structure design is far below the ultimate tensile strength. Therefore, the numerical and analytical results agree.

TABLE XX: SUPPORT STRUCTURE FEA RESULTS

Study	Applied Load [kg]	Max Stress [Pa]	Max Displacement [mm]
Bag Jig Loading	5000	1.256e+08	4.636e-01
Structure Lift Loading	7340	3.256e+08	3.298

Full descriptions of the FEA for both studies can be found in Appendix H.2.1 and Appendix H.2.2, respectively.

4.4.5 HOPPER DESIGN

The initial stage for designing the hopper was to determine geometry of the hopper, based on factors including customer constraints, flow properties and operator accessibility. Once the shape of the hopper was established, two loading scenarios where analyzed to anticipate the pressures that would be present in hopper during operation.

4.4.5.1 DESIGN OR SOURCE DECISION

The design or source decision, as it pertains to the hopper portion of the design, is heavily dependent on a number of design specific customer constraints defined in TABLE I. The many constraints imposed on this portion of the design make it a highly customized component that would not be available for purchase of an off-the-shelf product. If the hopper design was outsourced, a custom design would be required, adding an additional engineering cost to the design. For this reason, the team designed the hopper to reduce the overall project cost and engineering fees.

4.4.5.2 HOPPER DESIGN OVERVIEW

The Hopper design consists of four distinguishable sections:

- **Upper Bin Section:** The upper section of hopper consisting of 4 vertical removable walls.
- **Hopper Section:** Hopper section consisting of 4 slopped walls forming and inverted square pyramid that will funnel depressant to opening at the center of the hopper. This section of the design will be used to mount the Vibra Screw Inc.™ Bag Splitter®.
- **Lower Bin Section:** Small section located directly underneath the hopper section, which is required to allow access to the underside of the depressant bags and facilitate mounding the slide door underneath the hopper. Consists of 4 vertical

walls, one of which will house an access door allowing operators to reach and untie a depressant bag from underneath the safeguard. Will also contain mounting flange for slide door.

- **Structural Support**: Structural support consisting of HSS tubbing that will reinforce sheet metal used in construction of other hopper components. Will also be used to mount hopper to lower height adjust and upper supports.

4.4.5.3 HOPPER DESIGN SPACE

The hopper design envelope is physically constrained by the existing lower support structure, the size of the depressant bag, as well as some of the client's constraints. The design envelope is constrained by the dimensions listed in TABLE XXI:

TABLE XXI: HOPPER DESIGN ENVELOPE PHYSICAL CONSTRAINTS

Dimension Name	Symbol	Description	Min Value	Max Value
Bin Width	W	Width of bin and hopper opening. Constrained by width between vertical tubes of upper support structure and width of depressant bag.	44 [in]	54 [in]
Bottom Hopper Opening	d	Width of opening at the bottom of the hopper as well as width of Lower Bin. Must accommodate maximum bag outlet chute size.	16 [in]	NA
Chute Height	H_c	Distance between bottom of slide door (mounted to bottom of bottom bin) and the top of the lower mixing hopper. Space is needed to allow operator access to lower mixing hopper for maintenance purposes.	8 [in]	24 [in]
Total Height	H_{Max}	Maximum allowable height of the entire design. Restricts max height of vertical hopper walls relative to floor.	NA	173 [in]

The dimensions outlined in TABLE XXI, as well as the hopper sections defined in Section 4.4.5.2, are displayed in Figure 20.

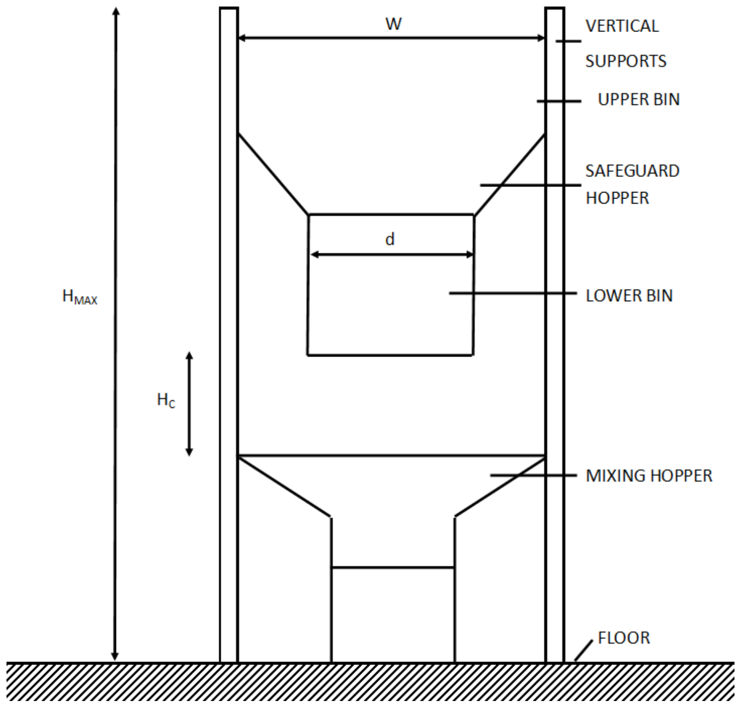

Figure 20: Hopper design envelope

4.4.5.4 HOPPER AND BIN SECTION DESIGN

The bin and hopper sections were fully defined geometrically by establishing the parameters displayed in Figure 21:

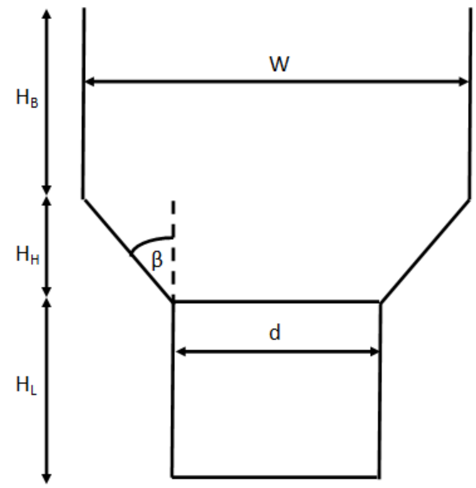

Figure 21: Hopper and bin design parameters

The geometry of the hopper and bins was designed to support the entire volume of the depressant bag to prevent product overflow while remaining as vertically compact as possible to meet the design's height restrictions.

The hopper inclination angle (β) was a critical parameter that influenced many conflicting aspects of the design's performance, including the material flowability and the operator's accessibility to the bottom of the bag to untie bags with chutes when the bag splitter is not being used. To compromise between these two important properties, the hopper was made as steep as possible to maximize material flow while remaining accessible to the operator. Specific details on how each of the hopper and bin geometric parameters were determined may be found in Appendix I.1.

The hopper and bin section dimensions are summarized in TABLE XXII:

TABLE XXII: HOPPER AND BIN SECTION DIMENSION SUMMARY

Symbol	Description	Value
W	Bin Width	54 [in]
d	Bottom Hopper Opening	18 [in]
H_L	Height of lower bin section.	16.116 [in]

β	Hopper Inclination Angle	60°
H_H	Height of Hopper	10.39 [in]
H_B	Height of Upper Bin	32.875[in]

The hopper inclination angle of 60° was determined using anthropometric reach measurements and produced a design that may be accessed by 95% of the male population and 40% of the female population. Unfortunately, due to ergonomic and geometrical constraints, it was not feasible to capture a larger proportion of the female population. However, this design is intended to use the Vibra Screw Inc.™ Bag Splitter® as the primary method of opening the bag, which does not require the operator to access the bottom of the bag and is, therefore, operable by people of any stature.

With the design space for the hopper and bin sections determined, the exact shape and thickness of the sheet metal components were determined during the CAD phase of the design.

4.4.5.5 HOPPER STRUCTURAL SUPPORT DESIGN

The structural support of the hopper will be made to reinforce the sheet metal hopper to ensure operator safety when operators are required to work underneath the hopper. The structural support will be composed of steel tubing with a square cross-section to facilitate manufacturing, as the flat faces of the tube easily rest along the outside of the hopper walls. The structural supports follow the profile of the hopper and are placed in the center of the plate, to minimize deflection and reinforce the Vibra Screw Inc.™ Bag Splitter® during the piercing procedure. The exact placement and sizing of the beams was determined during the modelling portion of the design process.

4.4.5.6 HOPPER STRESS CALCULATIONS

To estimate the stresses presented in the hopper during operation, two scenarios were analyzed to ensure the hopper's walls were sufficiently built for strength. The first situation corresponds to the scenario in which the depressant bag has been pierced by the Bag Splitter® and the depressant will partially fill the hopper. The weight of the depressant exerts pressure onto the walls of the hopper. The second situation corresponds to the depressant bag resting on the slopped walls of the hopper, which occur when the operators are required to manually untie the bag, or if the eyelets failed and depressant bag fell into the hopper.

4.4.5.6.1 HOPPER FILLING AND DISCHARGING WALL PRESSURES

The analysis covered in this section is based on the situation in which the hopper is filled with depressant material. A hopper stress calculation software called the Silo Stress Tool [5], developed by Dietmar-Schulze, was used to determine the pressure applied to the hopper and bin walls when filled with depressant.

The Dietmar-Schulze Silo Stress Tool [5] requires the hopper dimensions established in Section 4.4.5.4 as input parameters. Additionally, a number of material properties for the Guar Gum powder were needed to capture the powder's frictional behavior in response to a dynamic loading condition. The Silo Stress Tool program [5] provided graphical and tabulated results for the normal wall pressure (σ_w) as well as the mean vertical stresses (σ_v), occurring in the cross-section of the hopper.

Analysis of stresses in a hopper is a complicated process due to the complex nature of internal particle friction in a dynamic environment. Therefore, a number of assumptions were made to facilitate the hopper stress calculations and application of the Silo Stress Tool [5]. Specifics regarding the loading assumptions as well as details outlining the calculation of Guar Gum material properties are available in Appendix I.2.

The input parameters required by the Silo Stress Tool [5] are detailed in TABLE XXIII. The program requires metric inputs, so metric dimensions are provided in both imperial and metric when applicable:

TABLE XXIII: SILO STRESS TOOL INPUT PARAMETERS [5]

Variable	Description	Value (Imperial)	Value (Metric)
ρ_b	Guar Gum Bulk Density	0.02423 [lbs/in^3]	670.65 [kg/m^3]
Ø	Internal Friction Angle	39.80°	
K	Lateral Pressure Angle	0.3959	
H_F	Filling Height	50.918 [in]	1.293 [m]
H_B	Height of Upper Bin	32.875 [in]	0.835 [m]
θ_w	Wall Friction Angle	29.683°	
W	Bin Width	54 [in]	1.372 [m]
β	Hopper Inclination Angle	60°	
d	Bottom Hopper Opening	18 [in]	0.457 [m]
H_L	Height of Lower Bin Section.	16.116 [in]	0.409 [m]

The parameters listed in TABLE XXIII where input to into the Silo Stress Tool [5], as shown in Figure 22. Inputting these parameters in the software produced the graphical and tabulated stress and pressure results, as shown in Figure 23.

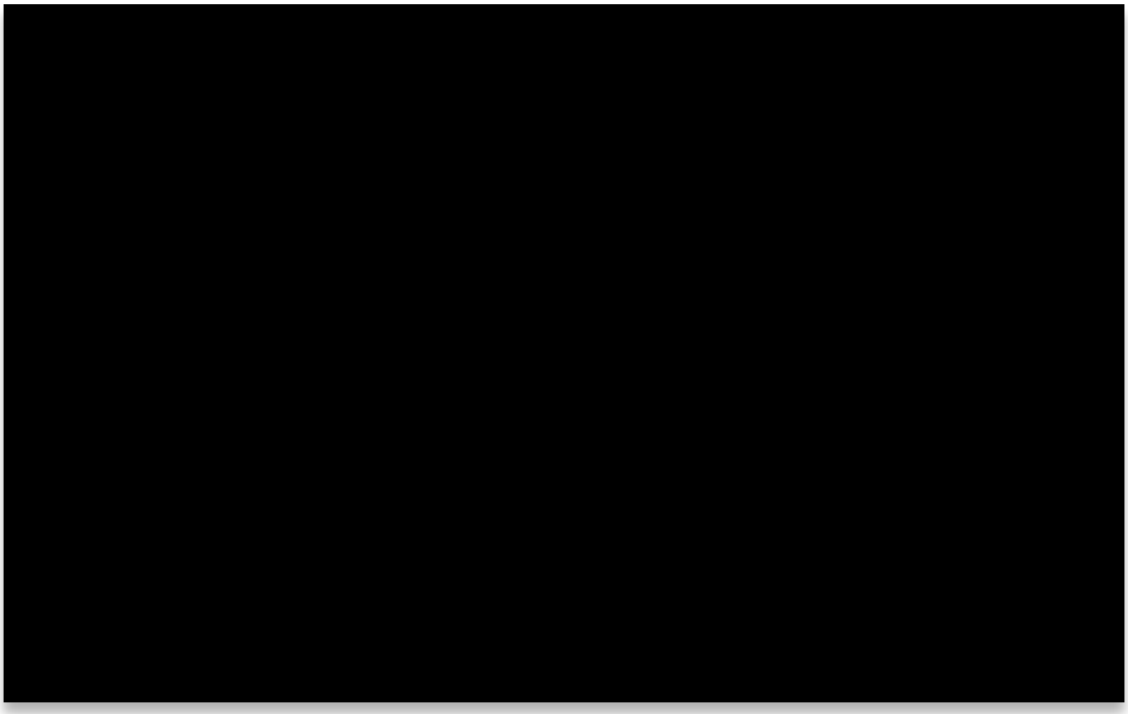

Figure 22: Silo Stress Tool parameter input window [5]

Figure 23: Silo Stress Tool hopper stress results, max stresses circled in red [5]

According to Figure 23, the maximum normal wall pressure, plotted in blue, occurs at the interface of the hopper and the lower bin, with a peak value of σ_w = 4107 [Pa].

The mean vertical stress, plotted in black, were found to be consistently larger in magnitude than the normal wall pressure. The largest average vertical stress occurs in the lower bin section with a peak value of σ_v = 4639 [Pa] at the outlet. The results of this analysis were then applied to the design model, using FEA, to determine a proper sheet metal thickness for the hopper and bin walls.

4.4.5.6.2 Hopper Bag Support Stresses

Should the primary support system fail, the hopper would be required to support the entire weight of the depressant bag. To ensure the hopper does not fail, the normal wall pressure exerted by the depressant bag was analyzed for this scenario. The calculations were based on a contact interface between the bag and the hopper when a full bag is sitting within the hopper. The team selected a 4 [in] contact patch width (C_T) as a conservative estimate, based on observations and measurements that were taken on site. For this analysis, the bag was assumed to sit at the height where the width of the hopper becomes equivalent to the average depressant bag width (W_b).

Figure 24 depicts the shape of the bag contact area that will exist on the sloped face of the hopper wall. Figure 25 shows the bag contact area from the cross-sectional perspective as the bag settles into the slope of the hopper, being fully supported by the hopper walls.

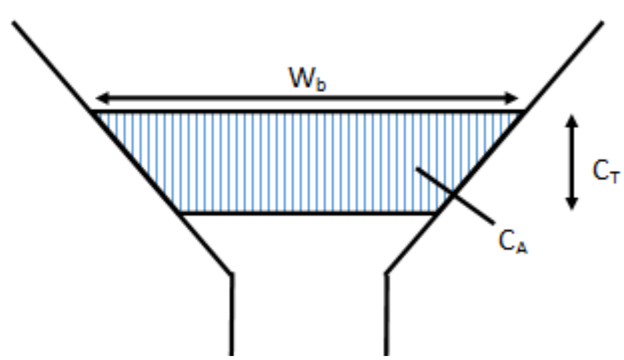

Figure 24: Normal view of sloped hopper wall showing wall-bag contact patch

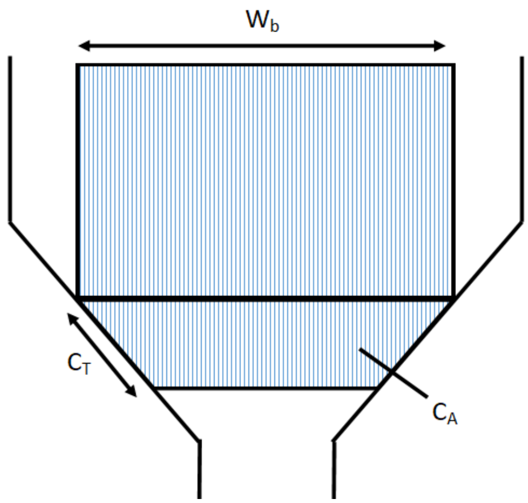

Figure 25: Cross sectional view of hopper showing wall-bag contact patch

Using a contact patch width of 4 [in] resulted in a total contact area (A_T) of 659.56 [in^2] between the hopper and the depressant bag. Using this area, the weight of the depressant bag and the hopper inclination angle (β) the total normal wall pressure (σ_W) applied to the hopper at the contact patch was found to be 2.9 [psi] (20000 [Pa]). Details regarding these calculations may be found in Appendix I.3.

The pressure normal to the hopper wall was then applied to the design model for the specified contact patch to conduct FEA. The FEA process finalized the sheet metal thickness required for the lower hopper.

4.4.6 HOPPER NUMERICAL ANALYSIS RESULTS

FEA was conducted on the hopper to verify the hopper bottom and side wall material wall thickness was selected appropriately.

4.4.6.1 HOPPER BOTTOM RESULTS

The first two hopper studies take place on the hopper bottom and analyze 11 [ga], 16 [ga], and 22 [ga] material thickness. The first study analyzed loading the entire hopper to simulate a full depressant bag emptied into it. The second study analyzed hopper bag load which required the creation of a 4 [in] ring within the hopper that emulated the surface contact between the hopper and a bag if the bag was dropped directly onto the hopper bottom. Pressures used for these studies were taken from the analytical calculations completed in section 4.4.5, and were both for worst-case scenarios. The loading conditions of these studies are shown in Figure 26 and Figure 27 respectively.

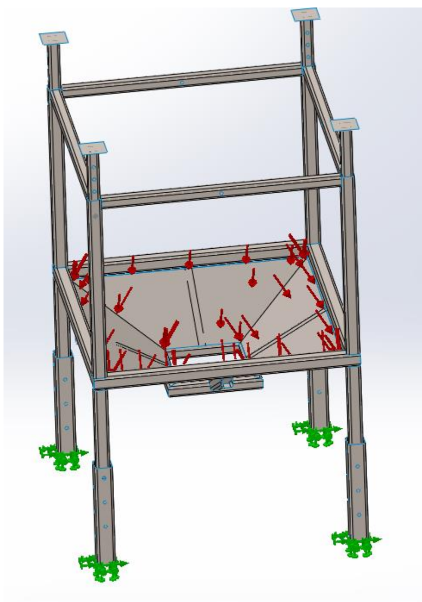

Figure 26: Entire hopper loading

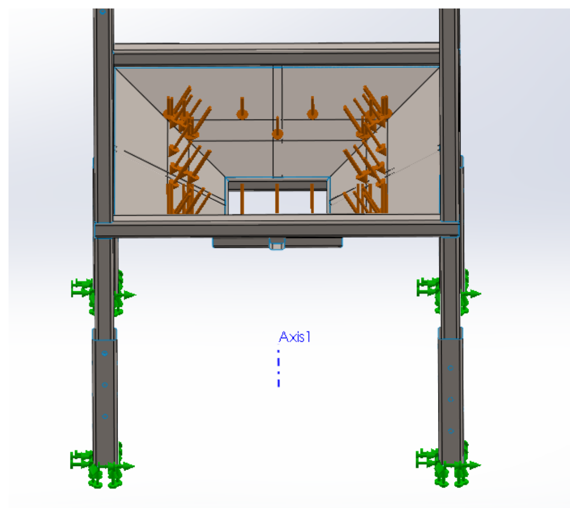

Figure 27: Hopper bag loading

TABLE XXIV displays the results of both tests. Since the 22 [ga] material did not meet the required FOS for the entire hopper loading study, it was not considered when conducting the hopper bag loading study.

TABLE XXIV: HOPPER BOTTOM FEA RESULTS

Study	Applied Pressure [Pa]	Thickness [in]	Displacement [mm]	Max Stress [Pa]	Avg. Stress [Pa]	FOS
Entire Hopper Loading	4,106	0.125	0.4	1.852×10^7	1.08×10^7	31
		0.062	3.065	7.596×10^7	4.431×10^7	7.6
		0.031	21.3	2.865×10^7	1.724×10^8	2
Hopper Bag Loading	23,510	0.125	0.7	4.594×10^7	2.68×10^7	18.5
		0.062	5.14	1.837×10^8	9.184×10^7	4.6

The results in TABLE XXIV reinforce that the optimal selection is 11 [ga] or 0.125 [in] thick material for the hopper bottom. The optimal selection is due to the low amount of displacement of the material, ensuring that it will continue to work correctly over the lifespan of the design. The first and second hopper bottom study are shown in in Appendices I.3.1 and I.3.2, respectively.

4.4.6.2 HOPPER SIDE WALLS RESULTS

The removable side walls are made of 22 [ga] material to ensure they are light enough to lift, comfortably. To ensure that the hopper side walls will not fail if the system is misused and by filling the hopper to the top of the walls, stress analysis was performed using the parameters in Figure 28 and Figure 29 show the stress and displacement distributions, respectively.

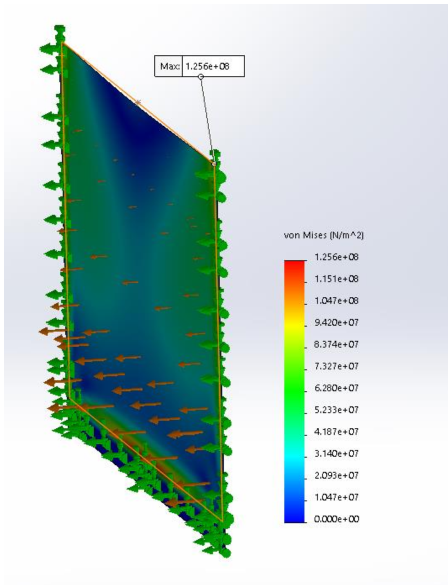

Figure 28: Wall loading stress distribution

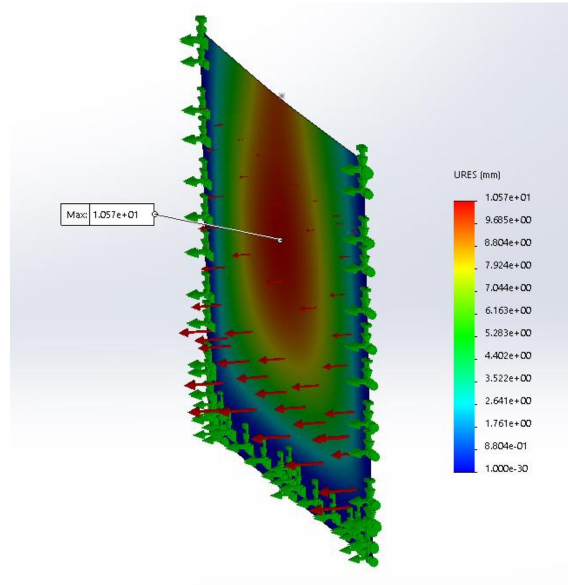

Figure 29: Wall loading displacement distribution

The maximum stress of 1.256×10^8 [Pa] yielded a FOS of 4.6 which is below the requirement of 5. The max displacement of 10.6 [mm] also raises small concerns. However, the side walls are primarily to keep operators from contacting the splitter, as well as contain depressant in the hopper. The failure of the hopper side walls is not a direct safety concern and is unlikely, due to the extreme loading conditions required for failure. Therefore, the team is considering a FOS of 4.6 acceptable for the hopper side walls and the 22 [ga] material is acceptable. For a full description of this analysis refer to Appendix I.3.3.

4.5 COST ANALYSIS

A detailed cost was performed on the final design to estimate the material, fabrication and installation of the Bag Splitting Hopper. The full BOM is provided in TABLE XXV, followed by a cost analysis of the selected vendors, suppliers and fabricators, and the installation of the design, estimated using NRP labor rates provided.

4.5.1 BOM

TABLE XXV: BAG SPLITTING HOPPER BOM

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_T2	HOPPER PERIMETER	4
2	DSS_T4	BAG ADJUST OUTTER TUBE	4
3	DSS_P2	WALL MOUNT	8
4	DSS_T9	FALL GUARD	4
5	DSS_T3	HOPPER ADJUST INNER TUBE	4
6	DSS_T6	HOPPER UPPER SUPPORT	4
7	DSS_T7	HOPPER ANGLES SUPPORT	4
8	DSS_T8	HOPPER LOWER SUPPORT	4
9	DSS_P6	HOPPER HINGE SIDE	1
10	DSS_P7	HOPPER BOTTOM	1
11	DSS_P8	SLIDE DOOR SPACER	1
12	DSS_P15	HOPPER LATCH SIDE	1
13	DSS_P16	HOPPER SOLID WALL	1
14	DSS_P13	HOPPER DOOR SIDE	1
15	DSS_P3	SIDE WALL	4
16	93560A140	WELD NUT	24
17	DSS_T1	HOPPER ADJSUTMENT OUTTER TUBE	4
18	DSS_P1	MOUNTING PLATE	4
19	DSS_T5	BAG ADJUSTMENT TUBE	4
20	DSS_P4	JIG REST PLATE(1)	2
21	DSS_P5	JIG REST PLATE(2)	2
22	92401A765	316 Stainless Steel	8
23	1528A23		2
24	1528A23		2
25	6148A160_CORNER-MOUNT COMPRESSION SPRING DRAW LATCH	LATCH	2
26	Splitter main		4
27	Splitter plate		4
28	93180A617	SS Carriage Bolt, 1/2"-13 Thread, 1 1/2" Length	8
29	90715A165	Nylon-Insert Locknut , 1/2"-13 Thread Locknut	8

30	93190A536	SS Hex Screw 1/4"-20 Thread, 3/8"Long	24
31	91500A242	SS Flat Head Phillips, #10-24 Thread, .5in Long	8
32	94150A335	SS Hex Nut, M4 x 0.7 mm Thread	8
33	90257A011	SS Hex Nut, #10-24 Thread	8
34	90116A207	SS Pan Head Phillips, M4 x 0.7 mm Thread, 10mm Long	8
35	75812612A.stp		1
36	75812614A.stp		1
37	75812613A.stp		1
38	80353035A - M5 Capscrew - 35 Lng.stp		9
39	Gland_Packing-300.stp		1
40	Serial_Plate.stp		1
41	Serial_Pin.stp		2
42	80565010A - M6 Pan Hd Screw - 10 Lng.stp		2
43	80400405A - M6 Washer - Int Shake.stp		2
44	80356040A - M10 Capscrew - 40 Lng.stp		2
45	75806651A.stp		10
46	80133672A - M16 x 1.5P Flanged Locknut.stp		10
47	80355010A - M8 Capscrew - 10 Lng.stp		2
48	SD_DOOR		1
49	93635A318	Stainless Steel Hex, M8 x 1.25 mm Thread, 20mm Long	8
50	93635A310	Stainless Steel Hex, M8 x 1.25 mm Thread, 12mm Long	8
51	DSS_P14	DOOR OUTER	1
52	DSS_P12	DOOR SEAL	1
53	DSS_P10		1
54	DSS_P9		1

4.5.2 MATERIAL AND FABRICAITON

The final design cost includes materials, fabrication, off-the-shelf items and installation estimate. NRP suggested Goodman Steel LTD, Parkland Manufacturing LTD, and Saskatoon Metal Manufacturing as metal suppliers and fabricators, as these companies currently supply and are familiar to NRP. Quotes were received from each of the suggested vendor, as well as other vendors in Canada and U.S.A. The lowest suggested quotes were selected for the cost analysis.

Saskatoon Metal Manufacturing quoted the material and fabrication, with pickling and passivation, of the final design at $13,400 CAD, excluding taxes and shipping with a 3- to 4-week delivery, after receiving the purchase order. Appendix J displays all the quotes obtained for various off-the-shelf products, materials and manufacturing of the Bag Splitting Hopper design. The drawing package, including assembly, weldments and part drawings of the Bag Splitting Hopper can be found in Appendix K.

The total material cost for the final design using Saskatoon Metal Manufacturing material and fabrication quote, Vibra Screw Inc™ Bag Splitter® quote, Schenck Process quote for Mucon™ DSV® 12 Slide Gate with gaskets, and Superchute® Non-Static Vinyl chute with flange is summarized in TABLE XXVI.

TABLE XXVI: FINAL DESIGN MATERIAL AND FABRICATION COST ESTIMATE

Company	Quoted	Cost [CAD]
Saskatoon Metal Manufacturing	Material and Fabrication	$13,400
Vibra Screw Inc.™	Bag Splitter®	$5500
Schenck Process	Mucon™ DSV® 12 Slide Gate	$1100
Superchute®	Discharge Chute with Flange	$450
TOTAL COST ESTIMATE = $20,450 CAD*		

*Excluding Taxes and Shipp

The total material and fabrication cost for the final design is estimated to be $20,450 CAD, excluding taxes and shipping. All parts have a lead time less than 4 weeks.

4.5.3 INSTALLATION

NRP provided a labor wage ($85/hour) to estimate the installation cost. It is estimated that the final design can be installed in 8 hours with two workers. This estimate results in a $1,360 CAD installation cost, bringing the final design total to $21,810 CAD.

NRP has the final decision rights on the selected supplier and fabricator of the final design. The team selected the above material suppliers and fabricators to meet the budget of $25,000 CAD.

4.6 MAINTENANCE CONSIDERATIONS

The team suggest an annual preventative maintenance (**PM**) to sharpen the splitting edge of the Bag Splitter® to ensure optimal performance and reduce the risk of tearing the bag, and the risk of unwanted bag fibers entering the mixing hopper. Also, a spare Bag Splitter® can be purchased from Vibra Screw Inc.™ and stored in a warehouse at NRP, in the event of premature failure.

To ensure the slide door does not get stuck, opened or closed, the team suggests operations manually operate the slide door, as a weekly PM, to ensure the valve is free of product build-up. If a weekly PM is determined to be too frequent, the PM frequency could be decreased to a monthly PM. A spare Mucon™ DSV® 12 Slide Gate Valve and gaskets can be purchased from Schenck Process, and stored in an NRP warehouse, in the event of premature failure.

5 RECOMMENDATIONS

If the Vibra Screw Inc.™ Bag Splitter® used in the design works as intended, Nutrien Potash should introduce this to other Potash sites, to reduce the cost per unit by purchasing in bulk. Additionally, standardizing the reagent addition process across Nutrien Potash will improve the safety of operators working at any site.

If the implementation of the Vibra Screw Inc.™ Bag Splitter® is successful, NRP should completely adopt bulk bags without chutes. This method of bag opening is a safer alternative to untying bags, with or without the safeguard in place.

Prior to implementing a design for the flocculant system, stress calculations should be performed to ensure the design provided is acceptable. The need for additional analysis is due to the differences in the material properties such as density, internal friction angle and wall friction angles. It is recommended that NRP only use the design for its intended purpose. Using the design to support loads in excess of 1000 [kg] or for materials other than Guar Gum is discouraged as it could potentially result in design failure.

The Mucon™ DSV® 12 can be converted to an electrically or pneumatically actuated valve by simply purchasing the kit from Schenck Process. This would allow further process improvements and system automation. Linear actuators, hydraulic or pneumatic cylinders may also be used to facilitate the adjustment of the design's height.

To ensure the sustained success of the design, the performance of the design should be continuously tracked and monitored. A plan of corrective action should be produced to make adjustments to the design in the event of non-conformance with the performance metrics being monitored.

6 CONCLUSION

The Bag Splitting Hopper design provided to NRP was developed through a systematic engineering design process. The project was defined based on NRP's needs, objectives and priorities determined at the project kick-off meeting on September 16, 2019 at the NRP mill site. A project definition report was submitted and approved by NRP, to enter the next phase of the project: concept development.

Concepts were generated, based on NRP's needs, objectives and priorities, through internal and external research. To ensure the project objectives were attained, the concept ideas were separated into four defined design components: safeguard, opening method, closing method and height adjustment. Concepts were screened based on the constraints and limitations, defined by NRP, and scored using a series of WDMs.

Concepts were then combined into systems and unpractical systems were screened. Remaining systems were scored through a WDM that aligning with NRP needs, objectives and priorities. The WDM reduced the final design concepts to the single best concept for the project's application: Bag Splitting Hopper.

FMEA was performed on the Bag Splitting Hopper design concept to optimize the concept prior to final detailed design. Areas of concern were address, as required, and recommended actions were implemented to ensure the design met NRP needs, objectives and priorities.

The final design phase implemented the recommended actions assigned from the FMEA. Analytical and numerical engineering analysis was performed to determine the final design of the Bag Splitting Hopper. Engineered off-the-shelf solutions were implemented for the closing method and opening method, Mucon™ DSV® 12 and Vibra Screw Inc.™ Bag Splitter®, respectively, to ensure optimal process performance and endurance. The support structure and hopper were design by the team, to reduce outside engineering costs and provide a customized design, as per NRP request.

For the designed support structure and hopper, the allowable design normal stress was defined as 14 [ksi] and allowable design shear stress of 8.4 [ksi] for 316/316L SS. The maximum normal stress in the designed support structure was 0.53 [ksi], well below the design stress. The buckling analysis resulted in a FOS of 120.45 in the lower support structure. The 316/316L SS pins, designed for the lower height adjustment, has a shear stress of 2.62 [ksi] and a bearing stress of 8.23 [ksi], both below the allowable design shear stress of 8.4 [ksi].

The design meets all the metrics targeted by the team, as shown in TABLE XXVII.

TABLE XXVII: DESIGN METRICS WITH TARGETS AND DESIGNED VALUES

Metric	Description	Targeted	Designed
1	Time Operator Under Bag	0 seconds	0 seconds
2	Height Adjustment Range	12 [in]+	12 [in]
3	Endurance Limit of Design	20,000 cycles	∞ cycles
4	Time to Open Bags	< 10 seconds	< 10 seconds
5	Time to Close Bags	< 10 seconds	< 10 seconds
6	Product Lost During Maintenance	< 0.5 kg	0 kg
7	Design Cost Installed	$25,000 CAD	$21,810 CAD
8	Operator Satisfaction	High	High
9	Maintenance Duration	0.5 hours	0.5 hours
10	Duration of Training	0.5 hours	0.5 hours
11	Maintenance Frequency	Annual	Annual

The team provided NRP with a final detailed design report, FEA of the existing and suggested design, engineering drawings of the design assembly, weldments and components, BOM, and cost analysis of the required material, fabrication and installation of the Bag Splitting Hopper.

7 LESSONS LEARNED

While participating in the Nutrien project for MECH 4860, the team learned a wide variety of skills applying engineering analysis to a real-world problem. The multifaceted project required application of skills relating to project management, team work, communication, systematic design and design verification.

The team gained experience applying systematic engineering design tools such as FMEA, weighted decision matrix and ranking criteria to make fact-based engineering decisions. Additionally, the team became much more familiar with computational design tools, primarily CAD and FEA. Both the CAD and FEA helped the team learn more about the software, along with troubleshooting analysis software in general.

In addition to engineering tools, the team became well versed in project management skills. The design required many components to be sourced, which required the team to consider factors such as costs, logistics and budgeting of time and resources. Obtaining quotes from various suppliers provided valuable experience interacting with vendors in a professional manner.

Finally, the project stressed the importance of communication with the client and the process performers. Early in the project, lack of frequent client meetings resulted in poor communication, which impeded the team's ability to quickly obtain information. Constant communication with the client and operators gave invaluable information about the process that facilitated the design process. Considering the voice of the customer for each design decision, the team was able to develop a successful design that satisfied the client and operators' requirements.

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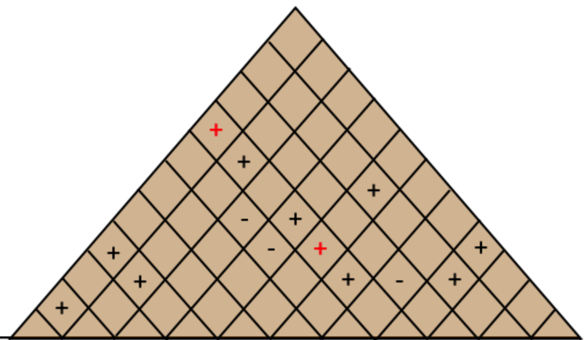
APPENDIX A – HOUSE OF QUALITY

NRP needs were related to the metrics in a House of Quality, Figure A.1. Metrics were determined to be either maximized or minimized, based on the project objectives. Metrics were cross referenced to NRP needs to determine their relationship and respective weights. If a need was not sufficiently addressed by a metric, a metric was added to ensure all NRP needs are addressed.

The most important metrics identified were "Operator satisfaction" and "Time operator spends under suspended load". These metrics were crucial for ensuring the design solution would be used by the operators and close the performance gap concerning operator safety. The only metrics with negative correlations were "Design and installation cost" and three other metrics. The team was able to justify these metrics, as the cost of the solution was a low priority need.

Correlation	
+ (red)	Strong Positive Correlation
+	Positive Correlation
-	Negative Correlation
- (red)	Strong Negative Correlation
Direction of Improvement	
▲	Increase
▼	Decrease
Relationships	
✪	Strong Relationship (9)
●	Medium Relationship (3)
○	Weak Relationship (1)



House of Quality
Nutrien Depressant Bag Handling System

	Maximize or Minimize Metric Value		▼	▲	▲	▼	▼	▼	▼	▲	▼	▼	▼
		Engineering Metrics	Time operator spends under suspended load	Height adjustment range of bag supports	Endurance limit of bag supports	Time to open bag	Time to close bag	Product Containment	Design and installation cost	Operator satisfaction	Maintenance Duration	Durration of process training	Maintenance Frequency
	Customer Needs / Importance		1	2	3	4	5	6	7	8	9	10	11
1	Improve operator safety	5	✪	○	●	○	○	○		✪			
2	Approved for use by shift operators	5	✪	○		○				✪		○	○
3	Raise bag supports	4		✪	○				●	●			
4	Work for a long time in a corrosive environment	4			✪				●		○		●
5	Intuitive for other all shift operators to conduct process	4		○		○	○	○		○		✪	
6	Improve operator ergonomics	3	●	●		●	●			✪			
7	Close the bag for for maintenance	3					✪	✪	○	●		○	
8	Improve or maintain current efficiency	3	○			✪	●	●		○	○	○	✪
9	Easy to maintain	3			○		✪		○		✪		✪
10	Cost effective compared to original process	2				●	○	●	✪		○	○	○
		Units of Measure	Seconds	Inches	Cycles	Seconds	Seconds	Kg	CAD $	Subjective	Hours	Minutes	Instances per/year
		Importance	102	59	58	68	83	51	48	145	36	49	72
		Weight %	13%	8%	8%	9%	11%	7%	6%	19%	5%	6%	9%

Figure A.1: House of Quality

APPENDIX B – DESIGN CONCEPTS

The design concepts developed by the team through internal and external research are shown in the following section.

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B.1 SAFEGUARD DESIGN CONCEPTS

The safeguard design concepts developed are a grating with hole, steel tubing, hopper, chain, cables, nothing and Vibra Screw Inc™ Bulk Unloader®. Visuals of each concept and details about the concepts are shown in TABLE B.I.

TABLE B.I: SAFEGUARD DESIGN CONCEPT NAME, DETAILS AND VISUAL

Safeguard Design Concepts	Details	Visual
Grating with Hole	Utilize metal grating currently used in the construction of the walking platform above depressant hopper. A hole would be cut in the center to provide access to the opening chute on the bottom of the depressant bag.	
Steel Tubing	A steel structure that would serve as a safeguard in event the bag eyelets fail. Steel beams welded to one another would prevent bag from falling and protect operators and equipment underneath bag. Center portion of design can be used to mount auxiliary opening/closing device.	

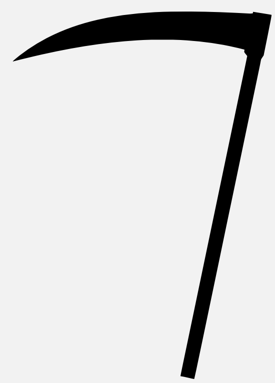
Safeguard Design Concepts	Details	Visual
Hopper	Design would consist of a hopper constructed out of sheet metal supported by a steel tube frame. Hopper shape would function as a secondary support for the underside of the depressant bag as well as a method of directing depressant flow that minimizes product loses.	
Chains	Secondary support system consisting of chains that support the depressant bag laterally as well as axially. This system would be suspended from the same support structure that currently supports the depressant bags via pins through the bag eyelets.	
Cable	Similar design to chains, however, it consists of heavy-duty cable rather than steel chain links. Has potential to have fewer binding issues than chain links.	

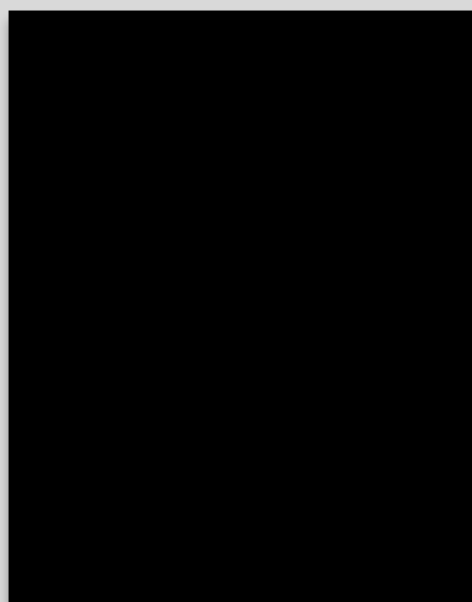
Safeguard Design Concepts	Details	Visual
Nothing	No safeguard would be required if an opening and closing solution could be incorporated that not require the operator to go underneath the suspended bag.	
Vibra Screw Inc™ Bulk Unloader® [1]	Similar to the hopper design, but an off-the-shelf solution.	

B.2 OPENING DESIGN CONCEPTS

The opening design concepts developed are manually cut, manually untie, Fledbag® Original and Vibra Screw Inc.™ Bag Splitter®. Visuals of each concept and details about the concepts are shown in TABLE B II.

TABLE B II: OPENING METHOD DESIGN CONCEPT NAME, DETAILS AND VISUAL

Opening Design Concept	Details	Visual
Manually Cut	The operator uses a hand tool to cut a slit in the bag. The device would consist of a blade to cut the bag attached to an extension to keep the operator out of the line of fire.	
Manually Untie	Flap and chute on bottom of the bag manually untied by operator, allowing product to flow through chute. This is the current operating procedure used in the reagent addition process. This solution would require a safeguard to effectively remove operator from line of fire.	

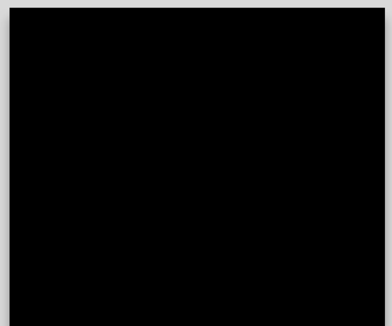
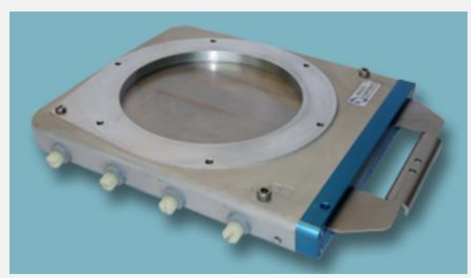
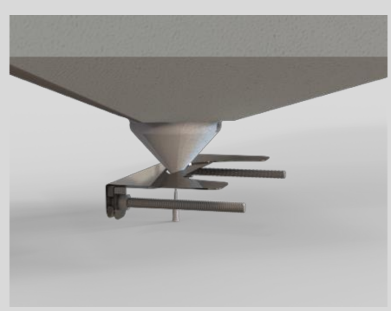
Opening Design Concept	Details	Visual
Fledbag® Original [2]	The Fledbag® Original be setup on the ground. The operator would then lower the bag onto the Fledbag®, piercing the bag. The tabs on the Fledbag® would keep it fixed in the bottom of the bag. The bag would then be moved to the support structure and lowered into place. The operator would then open the bottom of the Fledbag® releasing the product into the mixing hopper. For a visual representation of the installation refer to **Error! Reference source not found.**.The safety structure would have to be designed to allow the bag to be rest inside without contacting the Fledbag®. The Fledbag® does impede the current process as it would need to be cut out of the bag when the bag is empty.	
Vibra Screw Inc.™ Bag Splitter® [3]	The Vibra Screw Inc.™ Bag Splitter® works as a large spearhead piercing the bottom of the bag as it is lowered onto it. This design can only be bolted into a hopper safety structure as there needs to be a way to contain the product after the bag has been opened. The Vibra Screw Inc.™ Bag Splitter® is an efficient opening method. However, it is not meant for reusable bags. Therefore, bags without outlets must be sourced.	

B.3 CLOSING DESIGN CONCEPTS

The closing design concepts developed are Mechanical Cinch/Iris Valve, Manual Cinch, Fledbag® Easy, Fledbag® Original, Slide Door or Gate and Mechanical clamp. Visuals of each concept and details about the concepts are shown in TABLE B.III.

TABLE B.III: CLOSING METHOD DESIGN CONCEPT NAME, DETAILS AND VISUAL

Closing Design Concept	Details	Visual
Mechanical Cinch/Iris Valve [4]	Cinch that would be operated via a mechanical device that would lower required effort to operate. Cinch would be fixed about the depressant bag's structure and can be used to close or even control flow rate. An Iris valve would be the ideal device and can be used in-line where desired.	
Manual Cinch	Cinch that would be used by the operator to manually close outlet chute of the depressant bag. Could consist of chute straps that are integrated into existing bag or an auxiliary design that could be mounted to outside of bag chute.	

Closing Design Concept	Details	Visual
Fledbag® Easy [5]	The Fledbag® Easy would stop product flow via the operator manually closing the integrated shutoff valve. The Fledbag® Easy can only be integrated with the Manual Untie opening process. This is because the device needs to be installed onto the bag chute before the chute is opened. This results in adding extra steps in the opening process.	
Fledbag® Original [2]	The Fledbag® Original would stop product flow via the operator manually closing the integrated shutoff valve. After the bag is emptied the device would require the operator to manually cut it out of the bag.	
Slide Door [6]	The design would be integrated into a Hopper Safety structure as a means to control and isolate flow from the hopper. The slide door could work by moving in linearly into the close position. A off the shelf engineering Slide Gate could be utilized as well.	
Mechanical Clamp	Design would consist of clamping device that would cease depressant flow by clamping depressant bag chute shut. May be used to close bag or meter product flow. Clamp could consist of independent system or may be fixed to safeguard structure if possible.	

B.4 HEIGHT ADJUSTABILITY CONCEPTS

The height adjustment design concepts are manual pin/bolt, hydraulic actuation -manual and rack and pinion. Visuals of each concept and details about the concepts are shown in TABLE B.IV.

TABLE B.IV: HEIGHT ADJUSTMENT DESIGN CONCEPT NAME, DETAILS AND VISUAL

Height Adjustability Concept	Details	Visual
Manual Pin/Bolt Adjustment	Current method used by NRP. Upper supports consist of steel tubes with holes drilled at specified increments. Upper supports are inserted into lower vertical supports and are constrained via bolts or pins. New supports would require additional length.	
Hydraulic Actuation - Manual	Design would consist of a hydraulic cylinder(s) that are actuated via a manual handle and release valve. Works in similar way to floor jack. Cylinders would extend when actuated, raising the upper supports to desired height.	
Rack and Pinion	Design would consist of pinion actuated via a rotating handle. When the handle is turned, the pinion turns and raises upper supports by meshing to rack mounted to lower inside portion of upper support.	

B.5 WORKS CITED

[1] "Bulk Bag Unloader," Vibra Screw Incorporated, [Online]. Available: http://www.vibrascrew.com/schematics/17820-SD.pdf. [Accessed 19 October 2019].

[2] Fledbag, "Fledbag® Original," Fledbag®, [Online]. Available: https://www.fledbag.com/en/fledbag-original.html. [Accessed 18 October 2019].

[3] "Bag Splitter®," Vibra Screw Inc.™, [Online]. Available: http://www.vibrascrew.com/schematics/S114_BBU_17832-SD.pdf. [Accessed 19 October 2019].

[4] "AD Series® Iris Valve," Mucon™, [Online]. Available: https://www.mucon.com/en/products/iris-valves/series-ad-iris-valve-2. [Accessed 19 October 2019].

[5] Fledbag, "Fledbag® Easy," FledBag®, [Online]. Available: https://www.fledbag.com/en/fledbag-easy.html. [Accessed 18 October 2019].

[6] "DSV Slide Gate® Valve," Mucon™, [Online]. Available: https://www.mucon.com/en/products/slide-valves/dsv-slide-gate-valve. [Accessed 23 October 2019].

APPENDIX C – INDIVIDUAL CONCEPT SCORING

Individual concepts, which surpassed the screening process, were scored to determine the best design idea for the respective category (safeguard, opening method, closing method and height adjustment). This section details the rankings used to select designs, the determination of the weights of the criteria, and the weighted decision matrices (WDMs).

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C.1 CRITERIA RANKING JUSTIFICATION

A justification table outlining the team's definition for each correlation score, corresponding to each decision criteria used in the concept scoring weighted decision matrices may be found in TABLE C.I.

TABLE C.I: CRITERIA STRENGTH RANKING JUSTIFICATION

Criteria	Criteria Strength Justification		
	1	3	9
Ease of Use	Operator is required to exert a considerable amount of effort and technique while conducting daily tasks using the proposed combined system.	Operator is required to exert a minimal amount of effort t while conducting daily tasks using the proposed combined system.	Operator is not required to exert any physical effort, while conducting daily tasks using the proposed combined system.
Ease of Use [Opening]	Operator must exert a fair degree of physical effort or is required to physically work for greater than 10s to open bag.	Operator is required to exert a minimal amount of physical effort for a brief period of time (<10 seconds).	Operator is not required to exert any physical effort.
Ease of Use [Closing]	Operator must exert a substantial degree of effort to close or closing takes longer than 10 seconds	Operator is required to exert a moderate amount of physical effort for a brief period of time (<10 seconds).	Operator is required to exert a minimal amount of physical effort for a brief period of time (<10 seconds).

Criteria	Criteria Strength Justification		
	1	3	9
Ease of Maintenance	Design requires more substantial maintenance or more frequent maintenance (> 1 occurrence/year).	Design requires minimal maintenance under normal operation. Maintenance frequency is minimal (< 1 occurrence/year).	Design requires no maintenance.
Reliability	Design may have some potential to break or require premature replacement before the retirement of the support structure design. Design may also have some potential risk pertaining to not working as intended.	Design has minimal potential to break and should have a long product lifetime. The design is very likely to work as intended consistently.	Design is extremely unlikely to break and has a long-projected lifetime. Design is guaranteed to work as intended consistently.
Cost	Design requires a significant cost to purchase and implement relative to other design concepts.	Design requires a moderate cost to purchase and implement relative to other design concepts.	Design requires minimal cost to purchase and implement.
Storage	Device requires storage and may be bulky, heavy or otherwise difficult to store.	Device will need to be stored, but is small, compact and easy to locate when needed.	Requires no storage of device.
Process Integration	Design that requires of implementation of additional process steps or decreases efficiency of current process.	Design that does neither improves the reagent addition process nor adds additional steps.	Design that removes process steps from reagent addition process or improves efficiency.

Criteria	Criteria Strength Justification		
	1	3	9
Ease of Installation	Requires a substantial degree of time and effort to install design.	Requires a moderate degree of time and effort to install design.	Requires no installation to implement design.
Operator Safety	Operator has more significant risk of minor injury such as falls, pinches or cuts. Risk is larger than should be considered acceptable.	Operator is completely safe from significant injury or death but has small potential to be exposed to minor safety hazards such as pinch points or falls from ladder.	Operator is completely removed from safety risk while operating design.
Product Containment	Product loss of greater than 20 kg throughout reagent addition process.	Product loss greater than 0.5 kg, but less than 20 kg throughout reagent addition process.	Less than 0.5 kg (0.05%) of product loss throughout reagent addition process.
Installed Cost	Total cost of components, fabrication and installation is likely to exceed $12,500 CAD.	Total cost of components, fabrication and installation is likely between $10,000 and $12,500 CAD.	Total cost of components, fabrication and installation is <$10,000 CAD.
Operator Satisfaction	Operator dislikes design.	Operator is indifferent to design.	Operator is very satisfied design.
Duration of Process Training	Training require exceeds 30 minutes.	Training required is less than 30 minutes.	No additional training is required.
Process Length	Duration of reagent addition process is increased.	Duration of reagent addition process is maintained.	Duration of reagent addition process is reduced.

C.2 SAFEGUARD SCORING

Safety, reliability and ease of use, are of most importance in the design of the Safeguard concept, respectively, followed by maintenance, as shown in TABLE C.II. These weights are an accurate representation of the project objectives, as defined by the project champion and mentioned in Section 1.1, are safety, ease of use, efficiency and maintenance, respectively.

TABLE C.II: SAFEGUARD CRITERIA WEIGHTS

	Safeguard	A	B	C	D	E	F	G
	Criteria	Ease of Use	Ease of Maintenance	Reliability	Safety	Cost	Ease of Installation	Process Integration
A	Ease of Use	A	A	C	D	A	A	A
B	Ease of Maintenance		B	C	D	B	B	H
C	Reliability			C	D	C	C	C
D	Safety				D	D	D	D
E	Cost					E	F	G
F	Ease of Installation						F	G
G	Process Integration							G
	Total Hits	5	3	6	7	1	2	3
	Weightings	0.19	0.11	0.22	0.26	0.04	0.07	0.11

The Safeguard concepts that passed the screening process were scored, using the weights of the respective criteria, as shown in TABLE C.III. The design ideas with a weight score of greater than 3.00 would move into the next design phase of combining concepts as part of the overall system. As shown in TABLE C.III, three designs will move on: Grating with Hole, Steel Tubing and Hopper, respective of their weighted scores.

TABLE C.III: SAFEGUARD SCORING

Design Idea	Criteria							Weighted Score
	Ease of Use	Ease of Maintenance	Reliability	Safety	Cost	Ease of Installation	Process Integration	
Safeguard	0.19	0.11	0.22	0.26	0.04	0.07	0.11	
Grating with Hole	9	3	9	9	3	1	3	6.44
Steel Tubing	9	3	9	9	1	1	3	6.37
Chains	3	3	3	3	9	3	1	2.67
Cable	3	3	3	3	9	3	1	2.67
Hopper	9	1	9	9	1	1	1	6.15
Nothing	9	9	0	0	9	9	9	3.00

C.3 OPENING METHOD SCORING

As shown in TABLE C.IV, safety, reliability and ease of opening are of most importance in the design of the Opening Method concept, respectively, followed by ease of maintenance. These weights are similar to those attained in the table for the Safeguard criteria weights, TABLE C.III. The agreement of important criteria strengthens the support of the primary project objectives: safety, ease of use, efficiency and maintenance.

TABLE C.IV: OPENING METHOD CRITERIA WEIGHTS

	Opening	A	B	C	D	E	F	G
	Criteria	Ease of Opening	Ease of Maintenance	Reliability	Safety	Cost	Storage	Process Integration
A	Ease of Opening	A	A	C	D	A	A	A
B	Ease of Maintenance		B	C	D	B	B	G
C	Reliability			C	D	C	C	C
D	Safety				D	D	D	D
E	Cost					E	F	G
F	Storage						F	G
G	Process Integration							G
	Total Hits	5	3	6	7	1	2	4
	Weightings	0.18	0.11	0.21	0.25	0.04	0.07	0.14

Using the weights of the respective criteria, TABLE C.IV, the Opening Method concepts that passed the screening process were scored in TABLE C.V. As shown by the weighted scores in TABLE C.V, Vibra Screw Inc.™ Bag Splitter®, Manually Untie and Fledbag® Original, moved into the phase of combining the design ideas as part of a system.

TABLE C.V: OPENING METHOD SCORING

Design Idea	Criteria							Weighted Score
	Ease of Opening	Ease of Maintenance	Reliability	Safety	Cost	Storage	Process Integration	
Opening	0.18	0.11	0.21	0.25	0.04	0.07	0.14	
Manually Cut	1	3	0	0	3	3	1	0.75
Manually Untie	1	9	9	1	9	9	3	4.07
Fledbag® Original	9	3	3	3	1	1	1	3.50
Vibra Screw Inc.™ Bag Splitter®	9	3	3	9	1	9	9	6.14

C.4 CLOSING METHOD SCORING

The Closing Method design criteria weights, shown in TABLE C.VI, once again identify the team's priorities as being safety, reliability, ease of closing and ease of maintenance. These highly weighted criteria further validate the team's primary project objectives of safety, ease of use, efficiency and maintenance.

TABLE C.VI: CLOSING METHOD CRITERIA WEIGHTS

	Closing	A	B	C	D	E	F	G	H
	Criteria	Ease of Closing	Ease of Maintenance	Reliability	Safety	Cost	Storage	Ease of Installation	Process Integration
A	Ease of Closing	A	A	C	D	A	A	A	A
B	Ease of Maintenanc e		B	C	D	B	B	B	H
C	Reliability			C	D	C	C	C	C
D	Safety				D	D	D	D	D
E	Cost					E	F	G	H
F	Storage						F	F	H
G	Ease of Installation							G	H
H	Process Integration								H

Total Hits	6	4	7	8	1	3	2	5
Weightings	0.17	0.11	0.19	0.22	0.03	0.08	0.06	0.14

Based on the weights of the criteria determined in TABLE C.VI, respectively, the Closing Method design ideas that passed the screening process were scored in TABLE C.VII. Four Closing Method design ideas moved into the next phase, having a weighted score greater than 3.00: Fledbag® Easy, Fledbag® Original, Slide Door and Clamp, respectively.

TABLE C.VII: CLOSING METHOD SCORING

Design Idea	Criteria								Weighted Score
	Ease of Closing	Ease of Maintenance	Reliability	Safety	Cost	Storage	Ease of Installation	Process Integration	
Closing	0.17	0.11	0.19	0.22	0.03	0.08	0.06	0.14	
Mechanical Cinch	3	3	3	3	3	3	3	3	2.58
Manual Cinch	1	9	3	1	9	9	9	3	2.64
Fledbag® Easy	9	3	9	3	3	1	3	1	4.47
Fledbag® Original	9	3	3	3	3	1	9	9	4.42
Slide Door	9	3	3	3	3	9	1	9	4.42
Clamp	9	3	3	3	3	3	1	9	4.42

C.5 HEIGHT ADJUSTMENT SCORING

The Height Adjustment design criteria weights, shown in TABLE C.VIII, display the team's priorities as safety and reliability. However, rather than ease of use being third, it is ranked fourth, with cost being ranked third. The decrease in weight for the "Ease of Use" criterion is due to the fact that height is rarely adjusted. Therefore, the team determined that, in this case, being cost effective was more important than the ease of use for a design that is rarely modified.

TABLE C.VIII: HEIGHT ADJUSTMENT CRITERIA WEIGHTS

	Height Adjustment	A	B	C	D	E	F
	Criteria	Ease of Use	Ease of Maintenance	Reliability	Safety	Cost	Ease of Installation
A	Ease of Use	A	A	C	D	E	A
B	Ease of Maintenance		B	C	D	E	B
C	Reliability			C	D	C	C
D	Safety				D	D	D
E	Cost					E	E
F	Ease of Installation						F
	Total Hits	3	2	5	6	4	1
	Weightings	0.14	0.10	0.24	0.29	0.19	0.05

As shown in TABLE C.IX, based on the weighted scores determined in TABLE C.VIII, only one Height Adjustment design idea moved into the concept combination design idea phase: Manual Pin/Bolt, which is the same as the existing method.

TABLE C.IX: HEIGHT ADJUSTMENT SCORING

Design Idea	Criteria						Weighted Score
	Ease of Use	Ease of Maintenance	Reliability	Safety	Cost	Ease of Installation	
Height Adjustment	0.14	0.10	0.24	0.29	0.19	0.05	
Manual Pin/Bolt	1	9	9	3	9	9	6.14
Hydraulic Actuation - Manual (Jack)	3	3	3	3	3	1	2.90
Rack and Pinion	3	1	3	3	3	1	2.71

APPENDIX D – SYSTEM SCORING CRITERIA WEIGHTS

As shown in TABLE D.I, the highest weighted criteria, based on the metrics established in the House of Quality, Appendix A, are operator safety, operator satisfaction and process length, respectively. These highly weighted criteria support the top two priorities, as specified by NRP in Section 1.1: safety and ease of use.

TABLE D.I: SYSTEM CRITERIA WEIGHTS

	Final	A	B	C	D	E	F	G
	Criteria	Operator Safety	Process Length	Design Maintenance	Product Containment	Installation Cost	Operator Satisfaction	Duration of Process Training
A	Operator Safety	A	A	A	A	A	A	A
B	Process Length		B	B	B	B	F	B
C	Design Maintenance			C	C	C	F	C
D	Product Containment				D	E	F	D
E	Installation Cost					E	F	E
F	Operator Satisfaction						F	F
G	Duration of Process Training							G

Total Hits	7	5	4	2	3	6	1
Weightings	0.25	0.18	0.14	0.07	0.11	0.21	0.04

APPENDIX E – FAILURE MODE AND EFFECTS ANALYSIS

Failure mode and effects analysis (FMEA) was performed by the team to identify potential design failures. The failure modes identified were ranked, based on severity, occurrence and detection, which were multiplied together, resulting in a risk priority number (RPN). Based on the RPN, the failure modes were deemed acceptable, or unacceptable, for which corrective actions were determined and the RPN was re-evaluated.

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E.1 FMEA METHODOLOGY

The team conducted FMEA by conceiving a list of potential failure modes that may affect the various components of the hopper design. For each failure mode, potential causes and effects of the failure were identified. The team then evaluated the severity of the failures' effect, the probability of the causes' occurrence and the detectability of the failures. After careful discussion, a score of 1 to 10 was assigned to each of these metrics based on specific scoring criteria developed by the team. The scoring criteria for a failure's severity, occurrence and detectability can be found in TABLE E.I.

The risk associated with each scenario was calculated using an RPN that is the product of the scores assigned to the device's severity, occurrence and detection scores:

$$RPN = Severity \cdot Occurence \cdot Detection \quad \text{Equation 1}$$

Failure modes that had RPNs greater than 100 were considered a great risk and required the team to propose new design or process controls to reduce the risk. After developing corrective actions for high-risk failure modes, the severity, occurrence and detection of the augmented design were reevaluated to recalculate the RPN. The entire FMEA process was conducted as a collaborative team effort and involved consultation with the client and process operators to validate the analytic decisions made by the team. Additionally, the FMEA process was a continuous activity conducted throughout the final design process, with amendments being made regularly as new information was obtained.

E.2 CRITERIA RANKING

The criterion definitions that compose the severity, occurrence and detectability rating scales were established for the specific application for which the Bag Splitting Hopper design was intended. As a result, the risk rating for each of the three RPN components accurately defined the risk from the team's and NRP's perspectives. Each criteria ranking was defined by a 1-10 scale with 1 corresponding to low risk and 10 corresponding to extreme risk.

The severity portion of the RPN refers to the magnitude of the failure mode's consequences. This criterion considers the risk associated with operator safety and ergonomics but also considers the risk to the process and process equipment. When selecting a risk ranking for a specific failure mode, the severity of the risk was considered from both the operator safety and process perspectives, and the most severe consequence are selected.

The opportunity portion of the RPN gages the likelihood of a given failure mode occurring, in a specific period of time. The scale of the occurrence was based on the cycle time of the reagent addition process, as well as the 50-year life expectancy of the design.

The detection RPN metric captures the likelihood of detecting a potential failure before it occurs. Score for a specific failure mode is assigned based on the design controls in place that are used to preemptively identify failure modes.

TABLE E.I: FMEA SEVERITY, OCCURRENCE AND DETECTION RANKINGS

SEVERITY

Description	*Design*	*Ranking*
VERY HIGH Likelihood of Destruction of Support System and/or Mixing Components (**WITHOUT** Warning) and/or Death or Permanent Disability.	***Hazardous w/o Warning***	**10**
VERY HIGH Likelihood of Destruction of Support System and/or Mixing Components (**WITH** Warning) and/or Death or Permanent Disability.	***Hazardous with Warning***	**9**
HIGH Likelihood System/Process is **INOPERABLE** (Loss of Primary Function) and/or Operator Injury Resulting in Long-Term Disability (Exceeding 1 Year).	***Very High***	**8**
HIGH Likelihood System/Process is OPERABLE, but at a **REDUCED** Level of Performance and/or Operator Injury Resulting in Short-Term Disability (Between 1 Month to 1 Year). *Customer is Very Dissatisfied.*	***High***	**7**
MODERATE Likelihood System/Process is **OPERABLE**, but Comfort/Convenience Item(s) are **INOPERABLE** and/or Short-Term Disability (Less Than 1 Month) or Light-Duty Work. *Customer is Dissatisfied.*	***Moderate***	**6**
LOW Likelihood System/Process **OPERABLE**, but Comfort/Convenience Item(s) are Operable at a **REDUCED** Level of Performance and/or Operator Suffering Minor Injury Requiring **OFF-SITE** Attention, but no Lost Time (ie. stitches, slip, etc.). *Customer is Somewhat Dissatisfied.*	***Low***	**5**
Fit & Finish/Squeak & Rattle Item Varies or Does Not Conform and/or Operator Suffering Minor Injury Requiring **ON-SITE** Attention, but no Lost Time (ie. minor cut, pinch, etc.). *Defect Noticed by **MOST** Operators **(>75%).***	***Very Low***	**4**
Fit & Finish/Squeak & Rattle Item Varies or Does Not Conform and/or an Ergonomic Discomfort. *Defect Noticed by **HALF** of the Operators **(50%)**.*	***Minor***	**3**
Fit & Finish / Squeak & Rattle Item Varies or Does Not Conform and/or Reduced Ease of Actuation. *Defect Noticed by **DISCRIMINATING** Operators **(<25%).***	***Very Minor***	**2**
No Discernable Effect.	***None***	**1**

Notes: Severity is a RELATIVE RANKING, within the scope of the individual FMEA

OCCURRENCE

	CNH Proposal for Low Volume Applications			
Probability of Failure	***Possible Failure Rates***	***Frequency (cycles)***	***Frequency (%)***	***Ranking***
Very High: *Persistent Failures*	Failure occurs daily	1/1	100%	10
High: *Frequent Failures*	Failure occurs weekly	1/7	14%	9
	Failure occurs monthly	1/30	2%	8
Moderate: *Occasional Failures*	Failure occurs semi-annually	1/180	1%	7
	Failure occurs annually	1/365	0.5%	6
Low: *Relatively Few Failures*	Failure occurs bi-annually	1/730	0.2%	5
	Failure occurs every five years	1/1800	0.056%	4
	Failure occurs once a decade	1/3650	0.027%	3
Remote: *Failure is Unlikely*	At least one instance of failure during the intended lifespan	1/20,000	0.010%	2
	Less than one instance of failure during the intended lifespan	<1/20,000	<0.010%	1

Notes: Occurrence = Likelihood that specific cause mechanism or Variability will occur during design life.
Ranking Number has a relative meaning rather than an absolute value.
Must be applied consistently during the FMEA

DETECTION

	Criteria: Likelihood of Detection by Design Control	***Ranking***
Almost Impossible	Design Control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control.	10
Very Remote	Very remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	9
Remote	Remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	8
Very Low	Very Low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	7
Low	Low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	6
Moderate	Moderate chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	5
Moderately High	Moderately High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	4
High	High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	3
Very High	Very High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	2
Almost Certain	Design Control will almost certainly detect a potential cause/mechanism and subsequent failure mode	1

E.3 LOW-SCORING FMEA

The failure modes that had RPN values of less than 100 were deemed to have acceptably low risk, and therefore did not require corrective actions. These failure modes are outline in TABLE E.II.

TABLE E.II: FMEA ITEMS WITH RPN LESS THAN 100

Item	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/Mechanism(s) of Failure	Occurrence	Current Design Controls	Detection	RPN
Depressant Bag	Eyelet(s) Failure	Bag falls without warning into safeguard hopper. May prevent produce from flowing out of hopper.	5	Design defect in bag	3	Safeguard hopper	5	75
Depressant Bag	Eyelet(s) Failure	Piercing Target Missed, flow of material cannot be controlled	5	Design defect in bag	3	Current Design Controls	5	75
Vibra Screw	Piercing Target Missed	Flow of material out of the bag cannot be controlled.	5	Uncontrolled decent	5	Hopper walls, vertical supports acting as visual, physical guides.	2	50
Vibra Screw	Piercing Target Misaligned	Potential for bag to not be completely emptied	2	Uncontrolled decent	5	Hopper walls, vertical supports acting as visual, physical guides.	2	20
Height Adjustment	Pin Failure	Bag falls into hopper	3	Overloading or wear	1	Routine visual inspection by operator	1	3
Height Adjustment	Vertical member buckles.	Bag is dropped, potential for structure to fall	10	Overloading or wear	1	Routine visual inspection by operator	1	10

APPENDIX F – SUPPORT STRUCTURE ANALYSIS METHODOLOGY

The analytical methodology used to design the support structure is detailed in Appendix F sections below. This includes the material properties for materials involved in design, factor of safety to calculate the allowable stress, fatigue analysis to ensure the structure can withstand the required cyclic loading, axial stress, buckling, and height adjustment pin strength.

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F.1 MATERIAL PROPERTIES

316L SS material properties, TABLE F.I, were used since they are less than 316 SS to ensure design stability and we cannot guarantee which supplier NRP will choose for 316 or 316L SS materials.

TABLE F.I: MATERIAL PROPERTIES FOR 316L SS [1]

Yield Strength [ksi]	Ultimate Strength [ksi]	Shear Strength [ksi]	Modulus of Elasticity [ksi]
25	70	42	27,992

The material properties for grade 5 bolts are summarized in TABLE F.II.

TABLE F.II: GRADE 5 BOLT SHEAR MATERIAL PROPERTY [2]

Ultimate Shear [ksi]
75

F.2 FATOR OF SAFETY

To ensure the design performs is a harsh mining environment, a factor of safety was applied. NRP standard factor of safety is 5 which was applied to our design. The allowable normal and shear stress are calculated from Equation 2 and Equation 3 [3].

$$\sigma_{allowable} = \frac{\sigma_{ultimate}}{5}$$ Equation 2

$$\tau_{allowable} = \frac{\tau_{ultimate}}{5}$$ Equation 3

F.3 FATIGUE

The support structure experiences cyclic loading, since the bags are changed every 24 hours to meet production. First, the endurance limit is calculated to define the fatigue limit. The endurance limit, S_e, is calculated from Equation 4 and Equation 5 [3].

$$S_e = k_a k_b k_c k_d k_e k_f S'_e \quad \text{Equation 4}$$

$$S'_e = 0.5\, S_{ut} \;\; for\; S_{ut} \leq 200\; ksi \quad \text{Equation 5}$$

where k_a is the surface factor, k_b is the size factor, k_c is the load factor, k_d is the temperature factor, k_e is the reliability factor, k_f is miscellaneous effects factor.

The surface factor, k_a, is calculated from Equation 6.

$$k_a = a S_{ut}^b \quad \text{Equation 6}$$

where a and b are determined using TABLE F.III. Hot rolled values were used because it is standard manufacturing process [4].

TABLE F.III: PARAMETERS FOR SURFACE MODIFICATION FACTOR, k_a [3]

[redacted]

The size factor, k_b, and load factor, k_c, is determined for axial loading conditions from Equation 7 and Equation 8.

$$k_b = 1\; for\; axial\; loading \quad \text{Equation 7}$$

$$k_c = 0.85\; for\; axial\; loading \quad \text{Equation 8}$$

The temperature factor, k_d, is calculated from Equation 9 with T = 70°F.

$$k_d = 0.975 + 0.432(10^{-3})T_F - 0.115(10^{-5})T_F^2 + 0.104(10^{-8})T_F^3 - 0.595(10^{-12})T_F^4 \quad \text{Equation 9}$$

where $70 \leq T_F \leq 1000$°F

The reliability factor, k_e, is calculated from Equation 10.

$$k_e = 1 - 0.08z_a \qquad \text{Equation 10}$$

where z_a is determined using TABLE F.IV below. 99.99% reliability was used.

TABLE F.IV: RELIABILITY FACTORS, k_e FOR 8% STANDARD DEVIATION [3]

[redacted]

To ensure the design performs for 50 years, approximately 20,000 cycles a fatigue limit was calculated from the endurance limit, Equation 11, Equation 12 and Equation 13. The fatigue limit will be compared to the allowable stress defined by the factor of safety, and the lower of the two values is the design stress. [3]

$$S_f = aN^b \qquad \text{Equation 11}$$

$$a = \frac{(fS_{ut})^2}{S_e} \qquad \text{Equation 12}$$

$$b = -\frac{1}{3}\log\left(\frac{fS_{ut}}{S_e}\right) \qquad \text{Equation 13}$$

where N is number of cycles, f is determined using Figure F.1 and S_{ut} is ultimate stress.

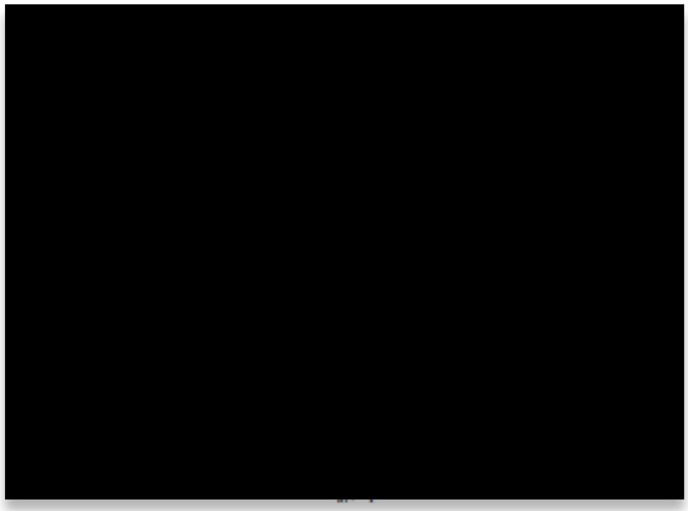

Figure F.1: Fatigue strength fraction, f, from S_{ut} [3]

F.4 AXIAL STRESS

The axial stress in the 316 SS support structure was calculated from Equation 14 to ensure the design can support the load and weight of the design. [3]

$$\sigma = \frac{F}{A} \qquad \text{Equation 14}$$

where F is the force per column and A is the cross-sectional area for the bag height adjustment columns.

F.5 BUCKLING

To ensure the existing structure can support the required load of 1000 kg plus additional weight of the bag and lifting device, buckling analysis was performed on the bag height adjustment columns. The critical buckling load, P_{cr}, was calculated from Equation 15. [3]

$$P_{cr} = \frac{C\pi^2 EI}{l^2} \qquad \text{Equation 15}$$

where C is the column end conditions, E is modulus of elasticity, I is the second moment of inertia and l is the column length. The load per bag height adjustment column was determined by adding the weight of the depressant (1000 kg), the weight of the bag (3 kg) and the weight of the bag lifting jig (70 kg) and dividing by 4.

Further buckling analysis was performed for eccentric loading using Equation 16, to ensure the worst-case scenario is still below the allowable stress. [5]

$$\sigma_{max} = \frac{P}{A}\left[1 + \frac{ec}{r}\sec\left(\frac{\pi}{2}\sqrt{\frac{P}{P_{cr}}}\right)\right]$$ Equation 16

where P is the load, A is the cross-sectional area, e is the eccentric loading distance, c is the distance to the neutral axis, r is the radius of gyration and P_{cr} is the critical buckling load.

F.6 HEIGHT ADJUSTMENT PIN STENGTH

To ensure the height adjustment pins do not fail, shear and bearing stress were calculated from Equation 17 and Equation 18. A stress concentration was then applied to the shear and bearing stress failure does not occur. [3]

$$\tau = \frac{F}{A}$$ Equation 17

where τ is the shear stress, F is the force and A is the cross-sectional area.

$$\sigma = -\frac{F}{A}$$ Equation 18

where σ is the bearing stress, F is the force and A = td, t is the plate thickness and d is the pin diameter.

Applying a stress concentration, K, due a hole in a plate, Figure F.2, increases the shear and bearing stress.

Figure F.2: Bar in tension or simple compression with a transverse central hole [3]

The maximum shear and bearing stress after applying the stress concertation factor, K is calculated from Equation 19 and Equation 20. [3]

$$\tau_{max} = K_{ts}\tau_0 \quad \text{Equation 19}$$

$$\sigma_{max} = K_t\sigma_0 \quad \text{Equation 20}$$

F.7 WORKS CITED

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APPENDIX G – EXISTING SUPPORT STRUCTURE ANALYSIS

The existing support structure, Figure 4, was analyzed, as requested by NRP, to determine the strength. This strength was used, by the team, as a benchmark for the new support structure design. The new support structure design must meet or exceed the existing support structure strength and lifespan.

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G.1 ANALYTICAL RESULTS

To ensure there is no issue with the current design, engineering calculations and FEA were performed. No further optimization will be performed if the design is determined to be satisfactory to ensure no unforeseen risks are introduced into the system and since weight reduction is not a requirement. Any components of concern were addressed as required.

G.1.1 FACTOR OF SAFETY

The allowable stress, based on the minimum FOS of 5, as defined by NRP is summarized in TABLE G.I.

TABLE G.I: 316L SS AND GRADE 5 BOLT ALLOWABLE STRESS FROM FOS

316L SS Normal [ksi]	316L SS Shear [ksi]	Grade 5 Shear [ksi]
14	8.4	15

G.1.2 FATIGUE RESULTS

The fatigue results, using analytical methodology from Appendix F, is summarized TABLE G.II

TABLE G.II: ANALYTICAL FATIGUE RESULTS

Material	Fatigue Limit [ksi]	Endurance Limit [ksi]	Allowable Stress [ksi]
316L SS Normal	33.06303	14.24633	14
316L SS Shear	23.25804	12.33507	8.4
Grade 5 Shear	34.67176	14.52622	15

G.1.3 AXIAL STRESS RESULTS

The results for the stresses in the support structure is summarized in TABLE G.III.

TABLE G.III: 316 SS BAG SUPPORT STRUCTURE AXIAL STRESS RESULTS

Axial Stress [ksi]	Design Stress [ksi]
0.37291	14

The maximum axial stress, 0.37291 [ksi] is well below the design stress for 316 SS of 14 [ksi], thus accepted.

G.1.4 BUCKLING RESULTS

Dimensions of existing bag height adjustment columns are shown in TABLE G.IV.

TABLE G.IV: BAG HEIGHT ADJUSTMENT COLUMN DIMENSIONS

Base [in]	Width [in]	Thickness [in]
2.5	2.5	0.1875

Buckling results for the bag height adjustment columns are shown in TABLE G.V.

TABLE G.V: BAG HEIGH ADJUSTMENT COLUMN CRITICAL BUCKLING LOAD RESULTS

Critical Load [lbf]	Applied Load [lbf]	FOS	Column End Conditions	Moment of Inertia [in^4]	Length [in]
55510.01803	632.31273	87.789	0.25	1.55597	44

The results are accepted since the critical buckling load is well below the load applied, 591.62 [lbf]. The bag height adjustment factor of safety for buckling is 87.789.

The results for eccentric buckling, assuming the load is applied at the edge of the bag height adjustment columns, is summarized in TABLE G.VI.

TABLE G.VI: ECCENTRIC BUCKLING RESULTS FOR MAXIMUM STRESS

Max Stress [ksi]	Eccentric Loading Distance [in]	Radius of Gyration [in]	Area [in^2]
0.25842	1.25	0.94717	1.73438

Results are accepted since the max stress is well below the allowable design stress of 14 [ksi].

G.1.5 HEIGHT ADJUSTMENT PIN STRENGTH RESULTS

Results for the bag height adjustment bolt strength is summarized in TABLE G.VII.

TABLE G.VII: BAG HEIGHT ADJUSTMENT PIN SHEAR AND BEARING STRESS RESULTS

Shear Stress [ksi]	Bearing Stress [ksi]	Force [lbf]	Area [in^2]	Bolt Diameter [in]
1.10944	2.61404	275.7	0.24850	0.5625

Results for bolt shear stress and bearing stress after applying the stress concentration of 2.5, is summarized in TABLE G.VIII.

TABLE G.VIII: BAG HEIGHT ADJUSTMENT PIN STRESS WITH STRESS CONCENTRATION

Shear Stress [ksi]	Bearing Stress [ksi]	K
2.77359	6.53511	2.5

Result accepted since the shear and bearing stress are below grade 5 bolt design stress of 15 [ksi].

G.2 NUMERICAL RESULTS

A model of the currently implemented support structure was modeled in 3D, using SolidWorks, based on the dimensions in the drawing of the current support structure provided by NRP. Static, buckling and fatigue studies, using FEA in SolidWorks, were performed on the model. These studies analyzed the strength of the current support structure, which is currently implemented at NRP. These results determined where, if any, the design should be strengthened to support the current load, along with the added load of the suggested design, the Bag Splitting Hopper.

The following parameters were used for the FEA static and buckling studies:

- Fixtures:
  - Fixed bottom face of each of the four base plate
- Load:
  - Total load of 1073 [kgf] on the four support plates where the jig rests:
    - Depressant weight: 1000 [kg]
    - Jig weight: approximately 150 [lbs] ≈ 70 [kg]
    - Depressant bag weight: 3 [kg]
  - Gravity force of 9.81 [m/s^2]
    - Gravity takes into consideration the weight of the 316 SS structure, itself.
- Mesh:
  - Curvature-based mesh
  - Maximum mesh element size: 0.25 [in]
  - Minimum mesh element size: 0.050 [in]
  - Minimum number of elements in a circle: 8
  - Element size growth ratio: 1.6

- Material: “AISI 316 Stainless Steel Sheet (SS)”
  - Properties are shown in Figure G.1

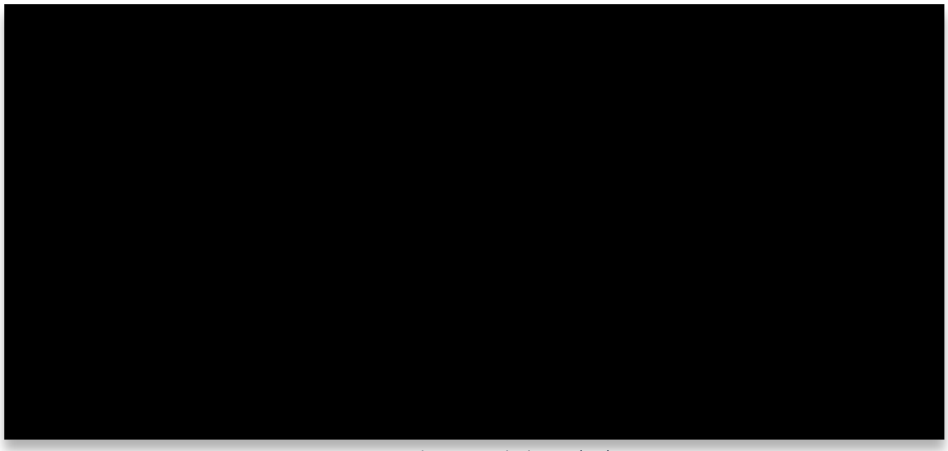

Figure G.1: AISI 316 Stainless Steel Sheet (SS) Properties

The modelled support structure used for FEA, including the fixture and load parameters, is shown in Figure G.2.

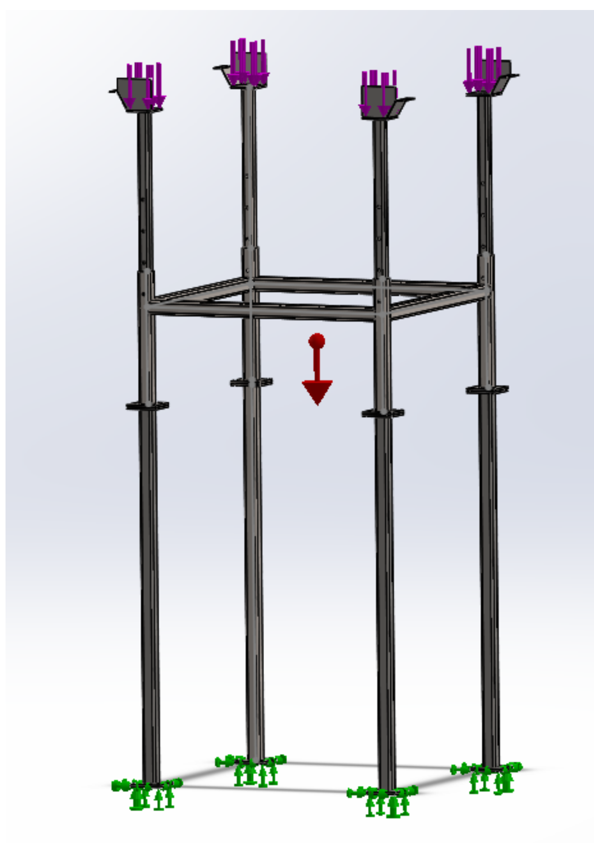

Figure G.2: Current support structure fixtures and loads

G.2.1 CONVERGENCE

To ensure the maximum and minimum mesh element sizes used were an accurate representation of the analyses, a mesh convergence study was performed. Data was obtained from FEA, based on the input of maximum and minimum mesh element size, as shown in TABLE G.IX.

TABLE G.IX: FEA MESH CONVERGENCE STUDY DATA

Maximum Mesh Element Size [in]	Minimum Mesh Element Size [in]	# of Nodes	# of Elements	Peak Displacement [x10^{-2} mm]	% Error*
4	0.80	232363	117710	7.096	-
2	0.40	585011	296865	7.326	3.14
1	0.20	1000972	559709	7.402	1.03
0.5	0.10	1105162	559709	7.433	0.42
0.375	0.075	1404366	726301	7.436	0.04
0.35	0.070	1566078	818032	7.445	0.12
0.325	0.065	1794357	949890	7.456	0.15
0.3	0.060	2108673	1142082	7.456	0.00
0.275	0.055	2567835	1431286	7.459	0.04
0.25	0.050	3340556	1917348	7.467	0.12

*Data was not obtained from FEA and was calculated manually

Using the data obtained in SolidWorks, the following plot, Figure G.3, was generated. As observed from the mesh convergence data and plot, a maximum and minimum mesh element size of 0.5 [in] and 0.10 [in], respectively, is sufficient for accurate analysis data, having a percent error of less than 1%. Therefore, the maximum and minimum mesh element size of 0.25 [in] and 0.050 [in], respectively, used for the analysis accurately represent the FEA static and buckling analyses.

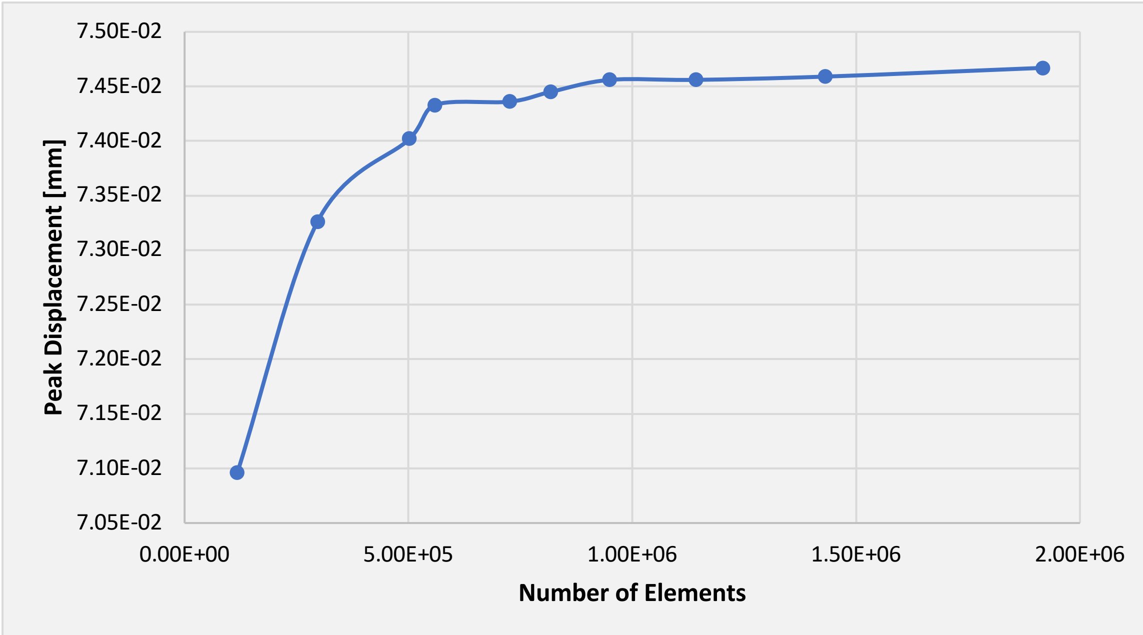

Figure G.3: FEA mesh convergence study plot

G.2.2 FEA STRESS ANALYSIS

As shown in Figure G.4, the max stress exhibited in the support structure is 2.241 [ksi], which is located on the top of the support plates, whereas the stresses in the legs of the supports are on the scale of 8.202×10^{-6} to 0.37734 [ksi]. The yield stress for 316 SS, using the material for 316 SS Sheet in SolidWorks, is 2.5 [ksi]. Thus, the stresses exhibited in the support structure will not fail due to the axial stresses.

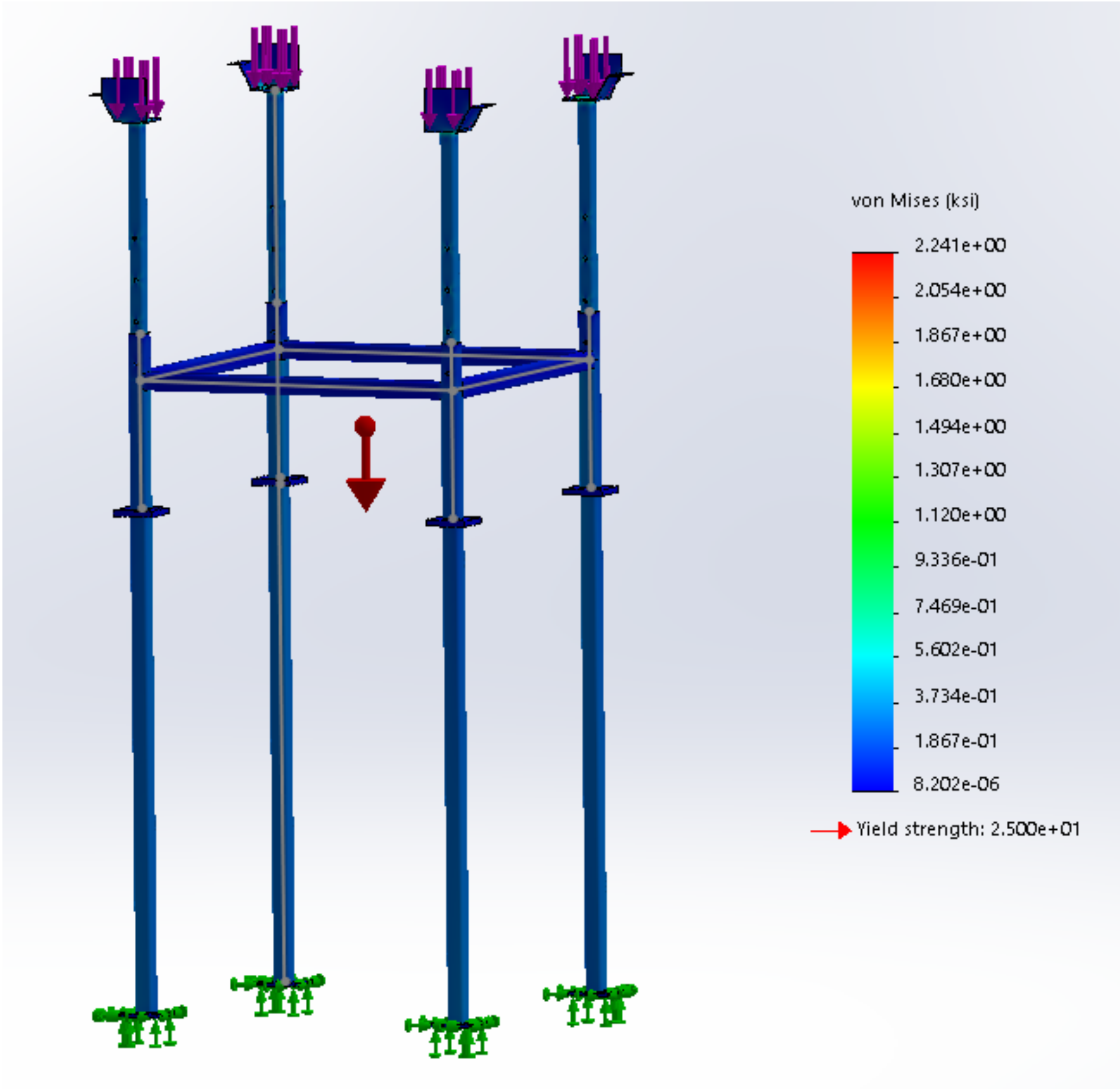

Figure G.4: Current support structure FEA stress analysis

G.2.3 FEA FOS ANALYSIS

The FOS in the current support structure, as shown in Figure G.5, displays that the minimum FOS is 9.864, which is much larger than the minimum requirement, given by NRP, of a FOS of 5. These results further support the conclusion that the current support structure will not fail due to axial stresses.

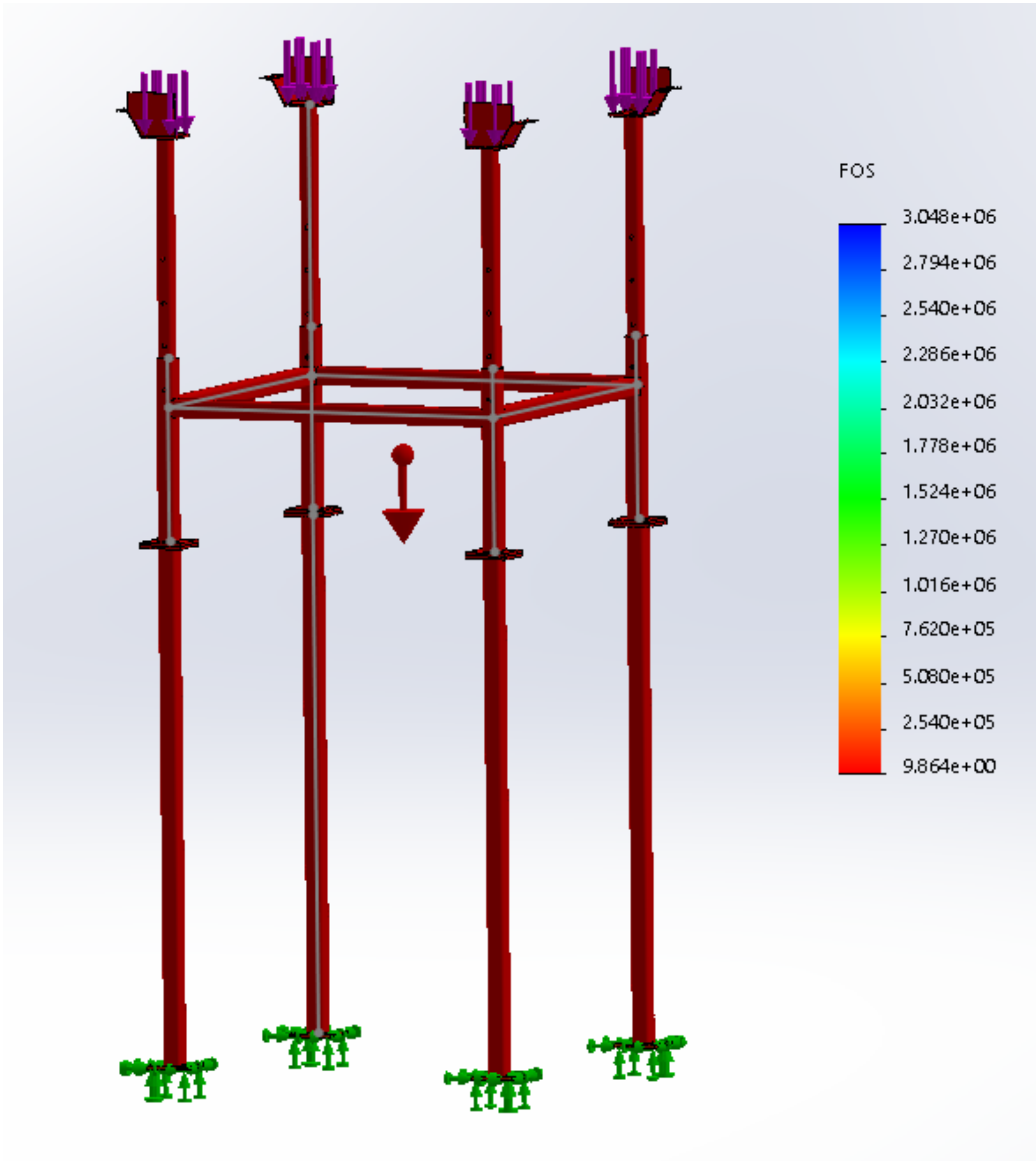

Figure G.5: Current support structure FEA FOS analysis

G.2.4 BUCKLING STUDY

The team performed a SolidWorks FEA buckling study on the current support structure, as shown in Figure G.6, which resulted in a buckling FOS of 73.61. Thus, the current support structure will not fail due to buckling.

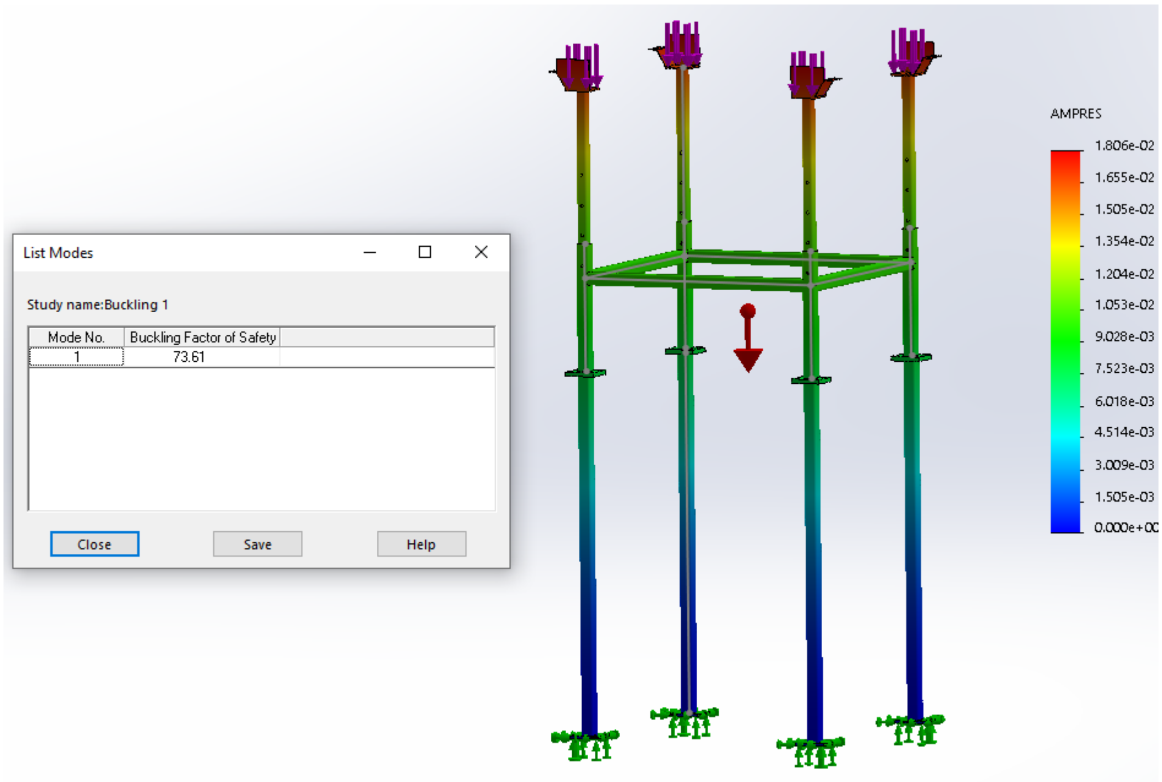

Figure G.6: Current support structure FEA buckling analysis

G.2.5 FATIGUE STUDY

A fatigue study was performed on the current support system. However, as shown in Figure G.7, the stresses in the structure remain below the S-N curve. Therefore, the current support structure will not fail due to fatigue.

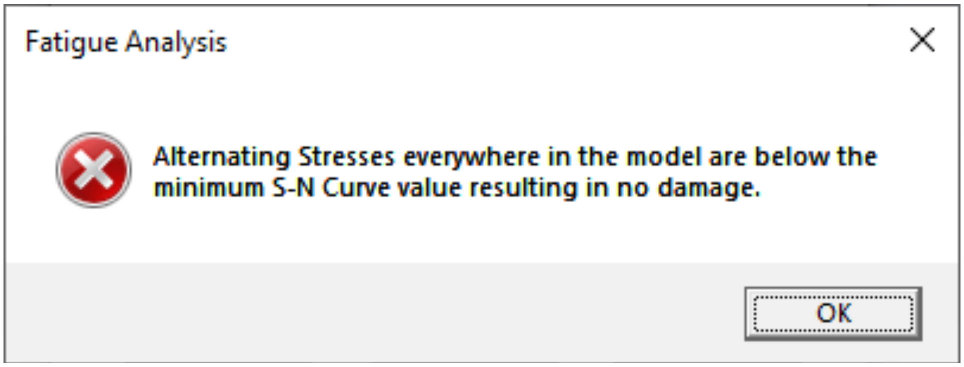

Figure G.7: Current support structure FEA fatigue analysis

The current support structure will not fail due to axial stresses, buckling or fatigue, based on the static, buckling and fatigue FEA studies performed in SolidWorks. Therefore, there are no safety concerns for the current support structure, assuming a maintenance plan has been created and is being followed.

APPENDIX H – SUPPORT STRUCTURE DESIGN

The analytical and numerical analysis variables are detailed below. This includes the endurance limit variables, fatigue limit variables, FEA selected variables, FEA for hopper bag loading scenario, FEA for structure lifting scenario

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H.1 ANALYTICAL ANALYSIS

The endurance limit variables, shown in TABLE H.I through TABLE H.III, were used to calculate the fatigue limit. Using the analytical methodology from Section F.3, the following values were determined.

TABLE H.I: 316L SS NORMAL ENDURANCE LIMIT VARIABLES CALCULATED

ka (surface)	kb (size)	kc (load)	kd (temp)	ke (reliability)	kf (misc)
0.68168	1	0.85	1	0.70248	1

TABLE H.II: 316L SS SHEAR ENDURANCE LIMIT VARIABLES REUSLTS

ka (surface)	kb (size)	kc (load)	kd (temp)	ke (reliability)	kf (misc)
0.98372	1	0.85	1	0.70248	1

TABLE H.III: GRADE 5 BOLTS SHEAR ENDURANCE LIMIT VARIABLES RESULTS

ka (surface)	kb (size)	kc (load)	kd (temp)	ke (reliability)	kf (misc)
0.64874	1	0.85	1	0.70248	1

Using the above endurance limit variables, the endurance limit was calculated. With the endurance limit known, the fatigue limit for each respective material and stress was found. The variables, shown in TABLE H.IV through TABLE H.VI, were used to calculate the fatigue limit respectively.

TABLE H.IV: 316L SS NORMAL STRESS FATIGUE LIMIT VARIABLES

a	N	b
278.59805	20000	-0.21521

TABLE H.V: 316L SS SHEAR STRESS FATIGUE LIMIT VARIABLES

a	N	b
115.83556	20000	-0.16212

TABLE H.VI: GRADE 5 BOLT SHEAR STRESS FATIGUE LIMIT VARIABLES

a	N	b
313.65693	20000	-0.22238

H.2 NUMERICAL ANALYSIS

Numerical analysis of the proposed design structure underwent FEA to mitigate any design risks. The model was analyzed with height adjustments set to their max setting to create a worst-case loading scenario. Since the model is relatively large the solid model was converted to a surface model and contacts between surfaces were implemented. Finally, the material was set to SolidWorks material, “AISI 316 Stainless Steel Sheet (SS)” who’s properties can be seen in Figure H.1.

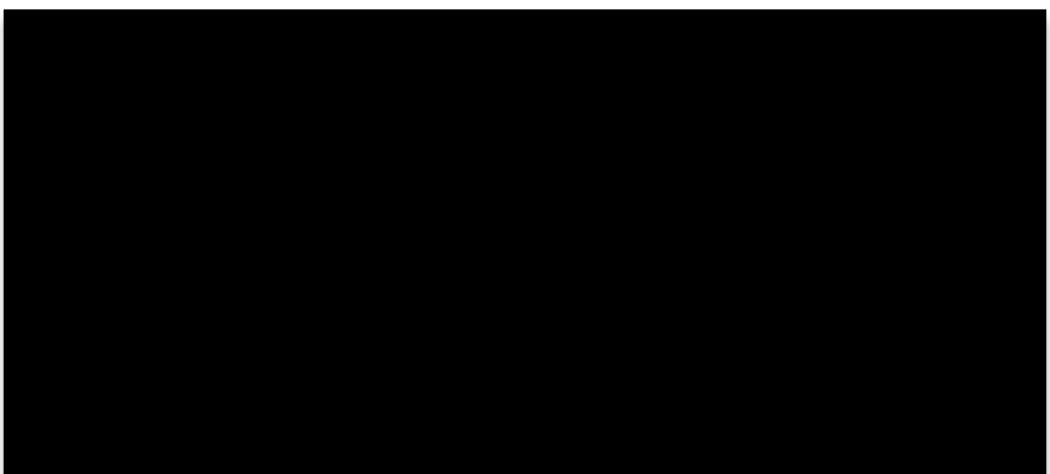

Figure H.1: AISI 316 Stainless Steel Sheet (SS) properties

H.2.1 BAG JIG LOADING

The first loading scenario was set up to imitate the bag lift jig being placed on the upper jig rests with the bag free hanging. The bottom of the structure was fixed while the upper rests had a total downward load of 5000 [kg] applied which can be seen in Figure H.2. This heavier load was to ensure that the minimum ultimate FOS of 5 was met.

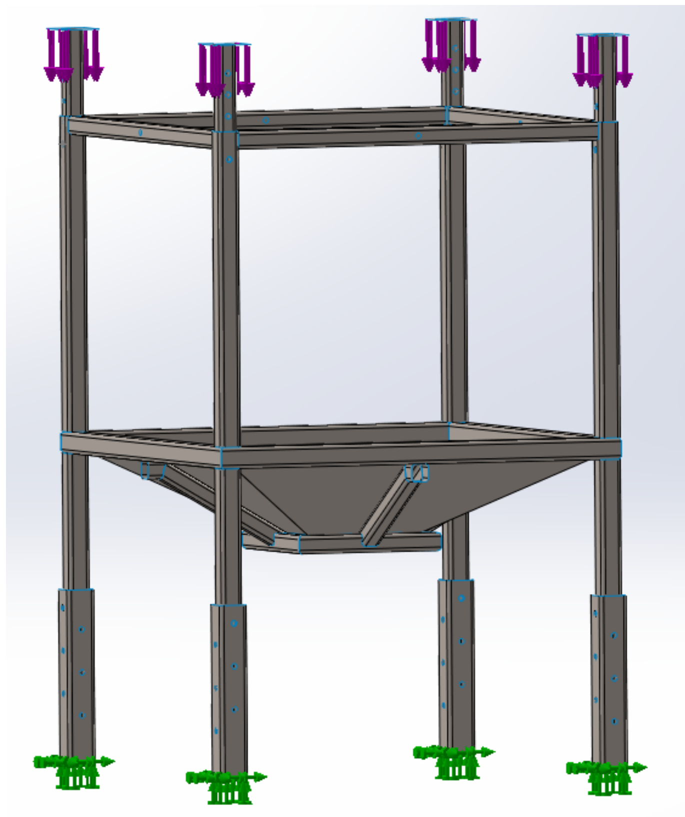

Figure H.2: Bag jig loading conditions

The maximum stress was found to be 1.256×10^{8} [Pa] and the max displacement was found to be 4.636×10^{-1} [mm]. The distribution of the stress and the displacement can be seen in Figure H.3 and Figure H.4, respectively.

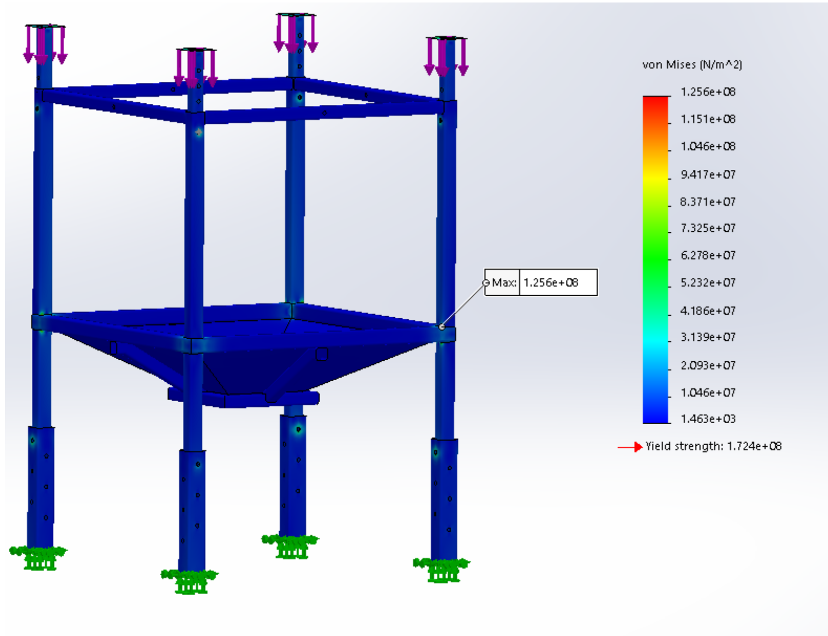

Figure H.3: Bag jig loading stress distribution

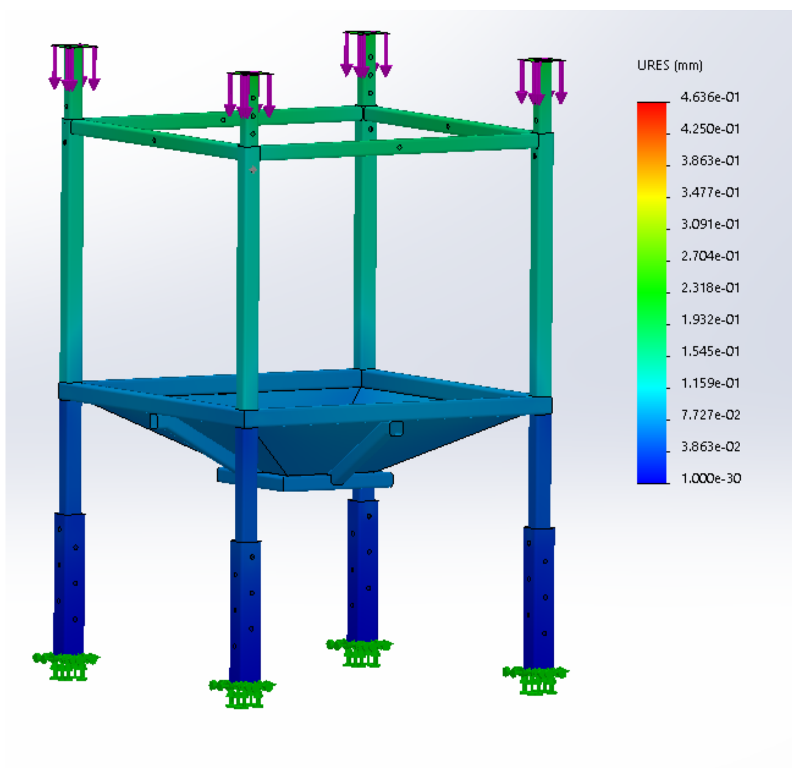

Figure H.4: Bag jig loading displacement distribution

It can be seen in the stress distribution that the stresses throughout the majority of the model were very low. This is due to some of the contacts in the model not behaving exactly as welded connection would and creating stress risers. Even with considering this stress riser the structure surpasses the FOS of 5.

H.2.2 STRUCTURE LIFT LOADING

The structure is designed to be lifted by the holes in the made in the fall protection bars of the hopper. Therefore, the worst-case scenario would be having to lift the hopper while it is full resulting in a 1468 [kg] load. To simulate this the structure bottoms were fixed as in the previous study and an upward load of 7340 [kg] was applied to the lifting holes seen in Figure H.5.

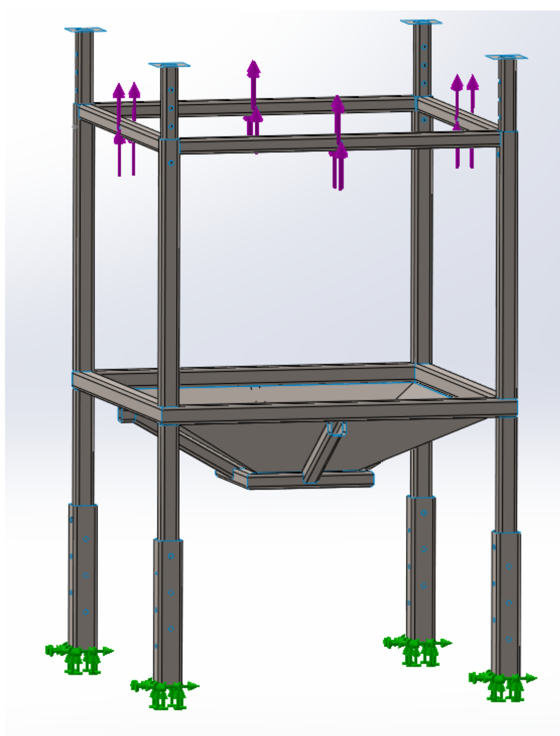

Figure H.5: Structure lift loading conditions

APPENDIX I – HOPPER DESIGN ANALYSIS

This section will show the calculations used to determine the geometry of the hopper design, as well as the methods used to analyze the pressures that will be applied to the hopper during operation. Finally, the hopper wall stresses calculated analytically will be applied using FEA to determine the stresses present in the hopper's components and finalize features of the design such as the sheet metal thickness.

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I.1 HOPPER GEOMETRY ANALYSIS

The size and shape of the hopper and bin sections may be fully determined by establishing the dimensions outlined in TABLE I.I.

TABLE I.I: HOPPER AND BIN DIMENSIONS

Symbol	Description
W	Bin Width
d	Bottom Hopper Opening
H_L	Height of Lower Bin Section.
β	Hopper Inclination Angle
H_H	Height of Hopper
H_B	Height of Upper Bin

The hopper was designed to support the entire volume of one full depressant bag. The dimensions of the depressant bags used by Nutrien are displayed in Figure I.1.

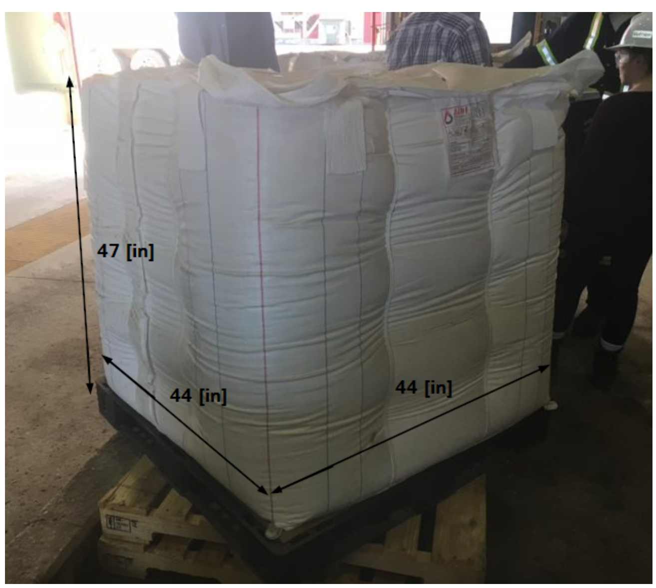

Figure I.1: Depressant bag dimensions

The volume of the bag (V_B) was found using the following equation:

$$V_B = 44 \cdot 44 \cdot 47 = 90{,}992\ in^3$$

The volume of the upper bin (V_B) will have a square cross section and is a function of the bin width (W) and the bin height (H_B) described by Equation 21:

$$V_U = W^2 \cdot H_B \qquad \text{Equation 21}$$

Likewise, the volume of the Lower Hopper Bin (V_L) is defined by Equation 23:

$$V_L = d^2 \cdot H_L \qquad \text{Equation 22}$$

The volume of the hopper portion (V_H) was found using Equation 24 which describes the volume of a square pyramid with a flat top:

$$V_H = \frac{1}{3}(W^2 + Wd + d^2)H_H \qquad \text{Equation 23}$$

Therefore, the total volume of the design (V_T) is represented by Equation 24:

$$V_T = V_U + V_H + V_L = W^2 \cdot H_B + \frac{1}{3}(W^2 + Wd + d^2)H_H + d^2 \cdot H_L \qquad \text{Equation 24}$$

The total volume of the design must be greater than the volume of the depressant bag so it can support the entirety of the bag's volume:

$$V_T > V_B$$

$$W^2 \cdot H_B + \frac{1}{3}(W^2 + Wd + d^2)H_H + d^2 \cdot H_L \ > 90{,}992\ in^3 \qquad \text{Equation 25}$$

Making the design's total volume larger than that of the bag will compensate for foreign entities that may be taking up space within the hopper such as the Vibra Screw

Inc.™ Bag Splitter®, the depressant bag and material built up in the corners of the hopper which is called ratholing [1]. The relation shown in Equation 25 was used to determine the parameters needed to dimension the hopper and bin sections.

I.1.1 BIN WIDTH (W)

Maximizing the volume of the upper bin is advantageous as it has the largest volume of the three hopper sections that contain material. It is also desirable for the design to be compact vertically to ensure that the all aspects of the design are accessible from either the floor or the catwalk. For these reasons, the volume of the upper bin was maximized most efficiently by maximizing the Bin Width (W) and holding the Bin Height (H_B) variable as shown in Equation 26:

$$\uparrow V_U = \uparrow W^2 \cdot H_B$$ Equation 26

The maximum value of the Bin Width is 54 [in] which is constrained by the distance between the vertical support tubes at the periphery of the design. Thus W = 54 [in].

I.1.2 BOTTOM HOPPER OPENING (d)

The Bottom Hopper opening defines both the opening at the bottom of the Hopper Section as well as the width of the 4 walls that form the Lower Bin Section. Since this design must accommodate the ability to untie bags with outlet flaps as per constraint #18, the value of d must be sufficiently large to allow the largest bag outlet chute, 16 [in], to pass through. Thus, the bottom hopper opening was required to be 16 [in] or greater.

Minimizing the size of the lower bin would improve the operator's ability to access and maintain the lower mixing hopper which is located directly underneath the lower bin. Therefore, according to Equation 22 , the size of the lower bin was minimized by keeping the value of d as small as possible.

The value of d was made larger than 16 [in] to give the operator some room to untie the depressant bag and navigate around the outlet chute. By providing an extra 2 [in] of clearance the operator was given enough access to manipulate the outlet chute. Therefore, the value of d was selected to be 18 [in].

I.1.3 HEIGHT OF LOWER BIN SECTION (H_L)

As mentioned previously, the design was made as compact vertically as possible, but would also allow the operators to easily access the bottom of the depressant bags to untie if needed. The height of the Lower Bin Section was a function of the access door, housed in the lower bin section, as well as reinforcement members, and mounting flanges for the slide door at the bottom of the bin. These details were finalized during the CAD portion of the design, determining the height of the lower bin section:

$$H_L = 16.116"$$ Equation 27

I.1.4 HOPPER INCLINATION ANGLE (B)

The hopper inclination angle was complicated and lengthy to determine as it is a critical factor that influences many operational features of the design. The angle is measured from the vertical and relates to how steep the hopper is. A shallow hopper is desirable because:

- A shallow hopper results in a vertically compact design, reducing the overall height of the design.
- The contact patch between the hopper wall the depressant bag is maximized for shallow hoppers, reducing the shear stress in the hopper wall in the event the primary support system fails, requiring the hopper walls to support the weight of the depressant bag.
- A shallow hopper will provide operators easier access to the bottom of the bag in the event that the Vibra Screw Inc.™ Bag Splitter® is not being used, and they need to manually untie the bag via the opening chutes.

However, there are some properties of steep hoppers that are also desirable: a steep hopper is more likely to produce mass flow rather than funnel flow, meaning material will continuously flow without becoming stagnant and building up [1]. Additionally, a steep hopper facilitates the deformation of the depressant bags as they empty and sag downwards, easing the ability of product to flow out of the depressant bag and into the hopper.

Of all the design considerations associated with hopper inclination angle, the accessibility of the depressant bag and the product flow are the most important according to the VOC. The accessibility of the depressant bag directly affects customer metrics #4 and #8 and the product flow will affect metrics #8, #9 and #11. To compromise between these two conflicting needs, the hopper was designed to be as steep as possible (minimal hopper inclination angle) to maximize product flow, while remaining within the ergonomic reach of the operators.

To determine the operator's ability to access the underside of the bag, a model shown in Figure I.2 was produced using anthropometric measurements to establish the bounds of the operator's reach. The model simulates an operator, standing on a ladder, reaching through the opening in the lower bin section and up through the bottom of the hopper to access the chute at the bottom of the depressant bag. In order to reach the center of the bag, the operator might be required to lean in slightly. Additionally, the model will ensure that the operator will be able to just see the center of the bag, as they untie it. This is accomplished by producing a straight line from the operator's eyes to the center of the bag and having the line pass through a point that represents the upper edge of the access door which represents the boundary of the operator's field of vision.

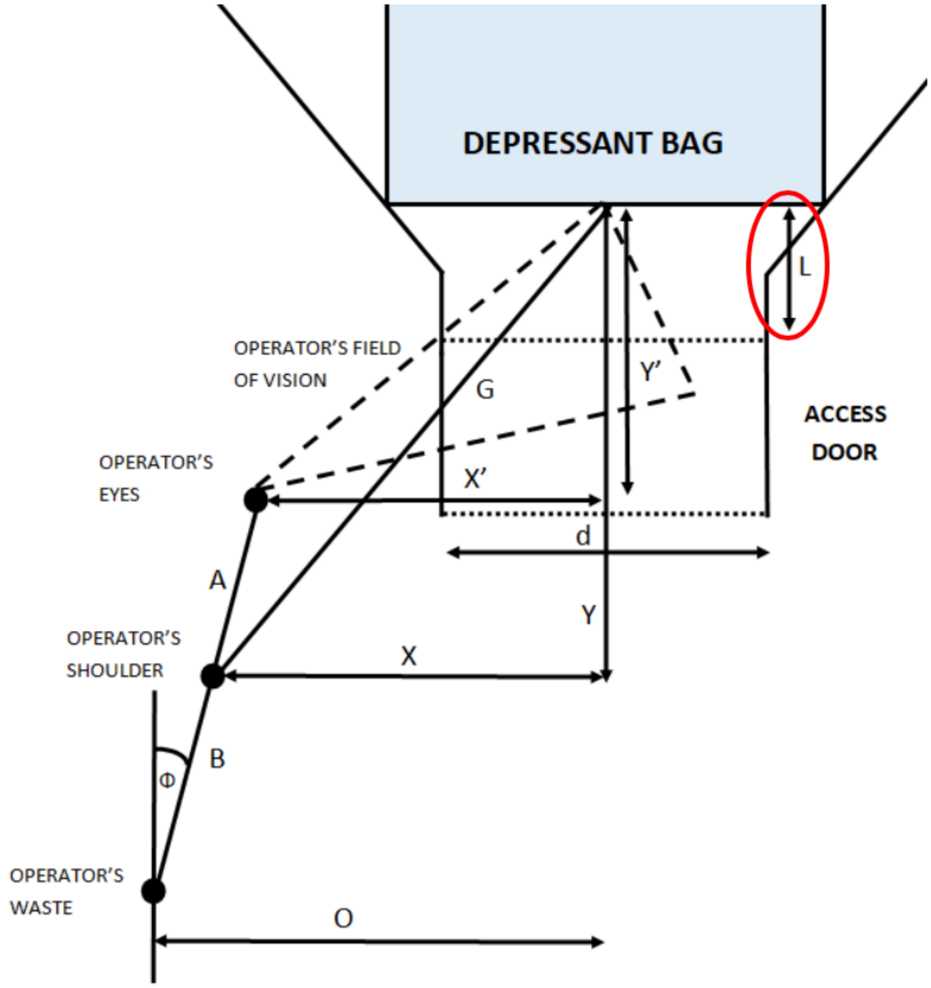

Figure I.2: Operator hopper reach model

The variable of interest, L (circled in red), quantifies how high up into the hopper the operator would be able to reach, which is the limiting factor in determining the hopper inclination angle.

The following parameters, shown in TABLE I.II, are needed to determine the operator's reach:

TABLE I.II: OPERATOR'S REACH PARAMETERS

Symbol	Description
L	Distance from top of access door to bottom of depressant bag. Quantifies how high up into the hopper the operator is able to reach.
d	Bottom Hopper Opening
G	Operator Functional Grip Reach, Extended (accounts for shoulder extension)
F	Distance from elbow to center of grip
U	Distance from shoulder to elbow
n	Functional Grip Reach Scaling Factor
ϴ	Elbow bend angle
E	Operator eye height (standing straight) from floor
S	Operator shoulder height (standing straight) from floor
A	Linear distance between operator’s eyes and shoulder
B	Linear distance between operator’s waist and shoulders
Φ	Operator Back Flexion
X	Horizontal distance from operator’s shoulder to center of depressant bag
Y	Vertical distance from operator’s shoulder to bottom of depressant bag
X’	Horizontal distance from operator’s eyes to center of depressant bag
Y’	Vertical distance from operator’s eyes to bottom of depressant bag
O	Distance from center of hopper to outside of lower support system’s vertical members (existing structure)

A number of assumptions and simplifications were required to make the model solvable which include the following:

- The operator's eyes and shoulder are assumed to be in line with one another
- The ladder is positioned as closely as possible to the outside members of the lower support structure, located 30 [in] from the center of the hopper (measurement taken from existing structure)
- The operator's waist is aligned with the outside edge of the lower support system making the waist 30 [in] from center of hopper
- Back and neck are kept straight as operator leans in, making the waist, shoulder and eyes all aligned

A number of anthropometric measurements were defined to establish values for the body measurements used in the model. Relevant measurements taken from a large population of North American males produced are shown in TABLE I.III.

TABLE I.III: ANTHROPOMETRIC MEASUREMENTS OF NORTH AMERICAN MALES [2]

Percentile	Eye Height, E [in]	Shoulder Height, S [in]	Functional Grip Reach (Extended), G [in]	Shoulder to Elbow Length, U [in]	Elbow to Grip Length, F [in]	Shoulder to Waist Length, B [in]
1	58.43	51.13	28.69	12.94	12.70	12.85
2	59.14	51.82	29.00	13.12	12.85	13.11
3	59.14	52.25	29.34	13.24	12.95	13.27
5	59.58	52.82	29.70	13.39	13.08	13.49
10	60.17	53.68	30.25	13.64	13.3	13.84
15	61.05	54.26	30.63	13.80	13.45	14.07

The team designed for the 5th percentile of males, which would produce a design that accommodates 95% of the male population (as males above the 5th percentile would have longer reach). Unfortunately, designing for the 5th percentile of males will only accommodate the top 40% of the female population. Due to the rather long horizontal distance from the center of the depressant bag to the edge of the existing design, it is not feasible to produce a design that captures a larger proportion of the female population.

It is likely that the operator would need to have a slight bend at the elbow to reach the bottom of the bag via the access door. To account for this bend, a scaling factor, n, was applied to the extended functional grip. The reach of the operator relative to their shoulder was found using Equation 28:

$$G = nG_{max}$$ Equation 28

The value of the grip reach scaling factor (n) was determined by comparing the reach of a straight arm (R_S) to that of an arm with a slight bend (R_B) as shown in Equation 29:

$$n = \frac{R_B}{R_S}$$ Equation 29

R_S is the reach of a straight arm described by Equation 30:

$$R_S = U + F$$ Equation 30

Where U is the shoulder to elbow length and F is the elbow to grip length. It is important to not confuse R_S with G, which is the extended function grip reach used to calculate the operators total reach. R_S only accounts for the reach of the arm but fails to capture the ability of the shoulder to extend in the direction of one’s reach, which will increase the total functional reach [2]. For this reason, G is used to calculate the operator's reach rather than R_s, requiring the use of n.

Figure I.3 shows the functional reach of a bent arm (R_B) as a function of the angle (ϴ) between the upper arm (U) and the forearm (F).

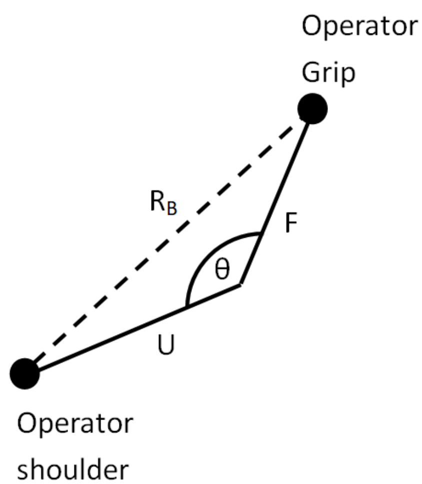

Figure I.3: Reach of bent arm

As seen in Figure I.3, the reach of a bent arm (R_B) was found using the cosine law in conjunction with anthropometric measurements of the upper arm and forearm:

$$R_B = \sqrt{U^2 + F^2 - 2UFcos(\theta)} \quad \text{Equation 31}$$

Where ϴ is the angle between the upper arm and the forearm. Thus, Equation 31 becomes:

$$n = \frac{\sqrt{U^2 + F^2 - 2UFcos(\theta)}}{U + F} \quad \text{Equation 32}$$

For a design to accommodate 95% of the male population, the 5th percentile values of U and F may be used as recorded in TABLE I.III:

$$U = 13.39\ [in]$$

$$F = 13.08\ [in]$$

The value of n should accommodate the arm being bent up to 30 degrees, thus the arm bend angle should be:

$$\theta = 150°$$

Substituting known values into Equation 32, the value of n is determined:

$$n = \frac{\sqrt{13.39^2 + 13.08^2 - 2(13.39)(13.08)cos(150)}}{13.39 + 13.08} = 0.966$$

The horizontal distance from the operator's shoulder to the center of the depressant bag (X) is a function of the distance from the hopper to the ladder (O) as well as the horizontal distance between the operator's waist and shoulder (B):

$$X = O - B\sin\varphi$$

Equation 33

For an ergonomic design, it is recommended that operators not exceed 45 degrees of back flexion [3], which is the angle from the vertical that is produced as the operator leans forward. For this reason, the operators back flexion, φ was selected to be 35 degrees, 10 degrees less than the maximum back flexion. Substituting known values into Equation 33 gives the value of X:

$$X = 30 - (13.49)\sin(35) = 22.262\ [in]$$

As seen in Figure I.2, X, Y and G combine to make a right-angle triangle. Therefore, the vertical distance from the operator's shoulder to the bottom of the depressant bag (Y) may be found using the Pythagorean Theorem:

$$Y = \sqrt{G^2 - X^2} \quad \text{Equation 34}$$

Substituting Equation 28 into Equation 34 and substituting known values gives the value of Y:

$$Y = \sqrt{(nG_{max})^2 - X^2} = \sqrt{[(0.966)(29.7)]^2 - 22.262^2} = 18.098\ [in]$$

The horizontal and vertical distances from the operator's eyes to the bottom center of the depressant bag, X' and Y' were found using X and Y and the distance between the operator's shoulders and eyes (A):

$$X' = X - Asin\varphi \quad \text{Equation 35}$$

$$Y' = Y - Acos\varphi \quad \text{Equation 36}$$

The distance between the operator's eyes and shoulder (A) is not a standard anthropometric measurement and must be found by subtracting the operator's shoulder height (S) from their eye height (E). To capture 95% of the male population, value of A was found to be:

$$A = E - S = 59.58 - 52.82 = 6.76\ [in]$$

Substituting in known values, X' and Y' was found:

$$X' = 22.262 - (6.76)\sin(35) = 18.385\ [in]$$

$$Y' = 18.098 - (6.76)\cos(35) = 12.561\ [in]$$

Finally, the vertical distance that the operator is able to reach up into the hopper, L was found by relating two like triangles:

$$\frac{Y'}{X'} = \frac{L}{d/2} \quad \text{Equation 37}$$

Rearranging and inputting known values gives the following:

$$L = \frac{(18)12.561}{2(18.385)} = 6.149\ [in]$$

Now that the operator's reach has been established, the hopper inclination angle may be found. The hopper inclination angle (β) will be found using the geometry shown in Figure I.4.

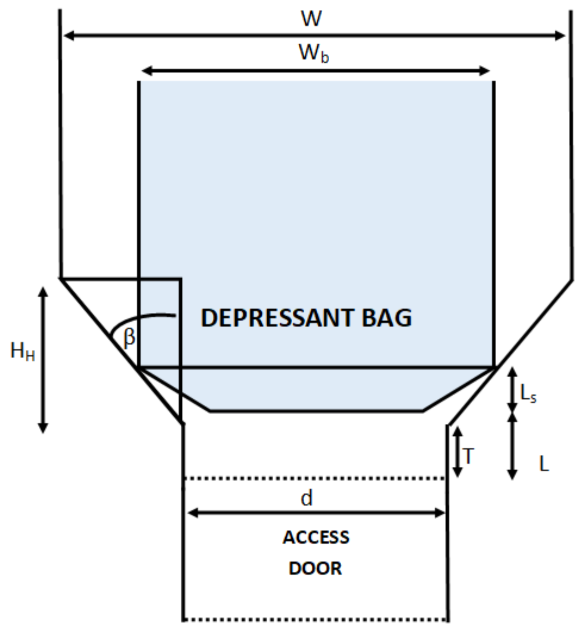

Figure I.4: Hopper inclination angle model

As seen in Figure I.4, the hopper inclination angle was modeled for a scenario where the depressant bag is lowered until it is supported by the hopper walls, providing a safeguard for the operators to safely untie the depressant bag. Important factors that influence the inclination angle include the following:

- The vertical distance the center of the depressant bags sags under the weight of the depressant (L_S) was measured at 5 [in] on average for a bag with an outlet.
- The width of depressant bag (W_b) was measured to be 44 [in].

- The distance between the bottom of the hopper and the top of the access door (T). This distance was determined during the CAD modeling design phase to be 3.013 [in].

Based on the geometry shown in Figure I.4, the bag inclination angle was found using Equation 38:

$$\beta = Tan^{-1}\left(\frac{W_b - d}{2(L - T + L_S)}\right) \quad \text{Equation 38}$$

Substituting known values:

$$\beta = Tan^{-1}\left(\frac{44 - 18}{2(6.149 - 3.013 + 5)}\right) = 57.96°$$

The off the shelf Vibra Screw Inc.™ Bag Splitter® is designed to fit into a hopper with a bag inclination angle of 60° which is roughly 2° greater than the calculated value. To avoid the increased cost associated with producing an additional part to adapt the Vibra Screw Inc.™ Bag Splitter® into the hopper design, a hopper inclination angle of 60° was selected for the design. This was an acceptable adjustment as increasing the hopper inclination angle reduces the steepness of the hopper, improving the accessibility of the design without a noticeable effect on the hopper flow.

I.1.5 HEIGHT OF HOPPER (H_H)

The height of the hopper may be found using the geometry in Figure I.4 and similar principles used to find the hopper inclination angle. Equation 39 was used to find the height of the hopper:

$$H_H = \frac{W - d}{2\tan\beta} \quad \text{Equation 39}$$

Substituting known values:

$$H_H = \frac{54 - 18}{2\tan(60)} = 10.392\ [in]$$

I.1.6 HEIGHT OF UPPER BIN (H_B)

With all the other variables needed to calculate the volume of the hopper established, the height of the upper bin was found using Equation 25:

$$W^2 \cdot H_B + \frac{1}{3}(W^2 + Wd + d^2)\left(\frac{W - d}{2\tan\beta}\right) + d^2 \cdot H_L > 90{,}992\ in^3$$

Substituting known values:

$$54^2 \cdot H_B + \frac{1}{3}[54^2 + (54)(18) + 18^2](10.39) + 18^2(16.116) > 90{,}992\ in^3$$

$$H_B > 24.41\ in$$

The height of the upper bin must be taller than this value to account for the volume of the Vibra Screw Inc.™ Bag Splitter®, depressant bag and ratholing as was discussed earlier. The height of the upper bin was finalized to be 32.875 [in] during the modeling phase of the final design.

I.2 HOPPER FILLING AND DISCHARGING WALL PRESSURE ANALYSIS

This section will analyze the loading scenario in which the hopper is filled with depressant material, which exerts pressure on the walls of the hopper.

I.2.1 FILLING HEIGHT (H_M)

The filling height of the material in the hopper relative to the outlet is a critical metric used to determine the stresses present in the hopper walls. This metric was found by summing the heights of the 3 hopper sections: the upper bin, hopper and lower bin:

$$H_F = H_{B_{min}} + H_H + H_L \qquad \text{Equation 40}$$

Substituting known values:

$$H_F = 24.41 + 10.392 + 16.116 = 50.918\ [in]$$

I.2.2 GUAR GUM BULK DENSITY (ρ_b)

The bulk density of the Guar Gum is a material property that is dependent on the compaction of the powder. To calculate the bulk density of the Guar Gum the following equation was used:

$$\rho_b = \frac{M_B}{V_B} \qquad \text{Equation 41}$$

Where M_B is the mass of the depressant bag and V_B is the volume of the depressant bag. The mass of the bag is 1003 kg (includes weight of depressant and bulk bag). Substituting known values:

$$\rho_b = \frac{2204.62\ [lbs]}{90{,}992\ [in^3]} = 0.02423 \left[\frac{lbs}{in^3}\right] = 670.65 \left[\frac{kg}{m^3}\right]$$

I.2.3 LATERAL PRESSURE RATIO (K)

The lateral pressure ratio is a material property that is needed to relate the stresses normal to the hopper walls to the lateral stresses [4]. There are many different methods to calculate the lateral pressure ratio; European standard EN 1991-4 (2007) [4] defines this value as:

$$K = 1.1(1 - sin\emptyset) \qquad \text{Equation 42 [4]}$$

Where Ø is the internal friction angle of Guar Gum. The internal friction angle was assumed approximately equivalent to the material's angle of repose [5], which for Guar Gum is equal to 39.80° [6]. Substituting known values into Equation 42:

$$K = 1.1(1 - \sin(39.8)) = 0.3959$$

I.2.4 WALL FRICTION ANGLE (θ_w)

The coefficient of friction (μ) is a material property that relates to the frictional behavior that exists between the Guar Gum and the wall of the hopper. For Guar Gum stored in a hopper made with steel walls, the co-efficient of friction is 0.57 [6]. The wall friction angle was found using the wall friction angle:

$$\theta_w = \tan^{-1}(\mu) \qquad \text{Equation 43 [6]}$$

Substituting known values:

$$\theta_w = \tan^{-1}(0.57) = 29.683°$$

I.2.5 INTERNAL HOPPER STRESSES

Analysis of stresses in a hopper is a complicated process due to the complex nature of internal particle friction in a dynamic environment. Therefore, a number of assumptions were made to facilitate the hopper stress calculations:

- Assumption 1: Bulk density of Guar Gum remains constant throughout hopper

In reality, the bulk density of the Guar Gum would vary throughout the hopper, with material at the top of the hopper having a lower density and the material at the bottom having a much higher density due to compaction. This assumption is necessary because there is no imperial data available to anticipate the compaction of Guar Gum under load.

- Assumption 2: Bulk density of Guar Gum is equivalent to bulk density of powder in depressant bag

It is likely that once the Guar gum is released from the depressant bag the density of the Guar Gum may change slightly, however it is difficult to anticipate in what way this will change. For this reason, it will be assumed that the density of the powder throughout the hopper will be equivalent to the density of the powder in the depressant bag.

- Assumption 3: Powder at the top surface of the bin will be level

Stress calculations are based on cross sectional area of material in hopper bin. To simplify calculations, it will be assumed that the material on the top surface will be level when in reality filling would produce a conical heap.

- Assumption 4: Presence of Vibra Screw Inc.™ Bag Splitter® will be neglected

Vibra Screw Inc.™ Bag Splitter® would take up portion of internal volume of hopper but software and calculations are unable to take this into consideration, however effects of this simplification would likely be negligible.

- Assumption 5: Hopper will be loaded with entire contents of depressant bag

The calculations were conducted for the worst-case scenario. Therefore, the hopper was designed to support an entire depressant bag's contents.

I.3 HOPPER BAG SUPPORT PRESSURE CALCULATIONS

The length of the hopper slope (L_H) is a function of the hopper inclination angle (β), and the hopper height (H_H) as shown in the following equation:

$$\cos(\beta) = \frac{H_H}{L_H} \quad \text{Equation 44}$$

Rearranging for L_H and substituting known values:

$$L_H = \frac{H_H}{\cos(\beta)} = \frac{10.39}{\cos\,(60)} = 20.78\ [in]$$

Figure I.5 depicts the normal view to the sloped hopper wall with the contact patch area highlighted in blue.

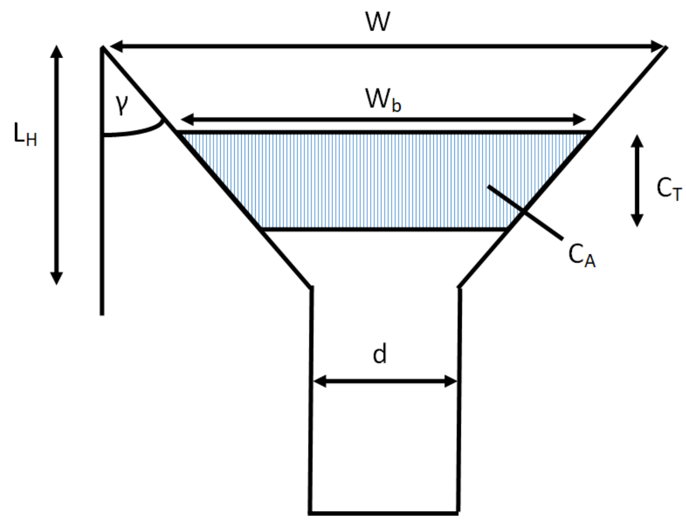

Figure I.5: Hopper contact patch area geometry

The angle γ may be found using Figure I.5:

$$\gamma = \tan^{-1}\left(\frac{W-d}{2L_H}\right) \quad \text{Equation 45}$$

Figure I.5 was also was used to find the area of the contact patch for one hopper wall (C_A) using the following formula:

$$C_A = W_b \cdot C_T - C_T^2 \tan(\gamma) \quad \text{Equation 46}$$

Combining Equation 45 and Equation 46 gives the following equation:

$$C_A = W_b \cdot C_T - C_T^2\left(\frac{W-d}{2L_H}\right) \quad \text{Equation 47}$$

Substituting known values gives the following:

$$C_A = 44(4) - 4^2\left(\frac{54-18}{2(20.78)}\right) = 162.14\ [in^2]$$

The total area of the hopper supporting the weight of the depressant bag (A_T) was found using the following equation:

$$A_T = 4C_A \quad \text{Equation 48}$$

Substituting the area of the hopper wall contact patch gives:

$$A_T = 4(162.14) = 659.56\ [in^2]$$

Figure I.6 shows the normal wall pressure that is applied to the hopper contact patch in response to the weight of the depressant bag.

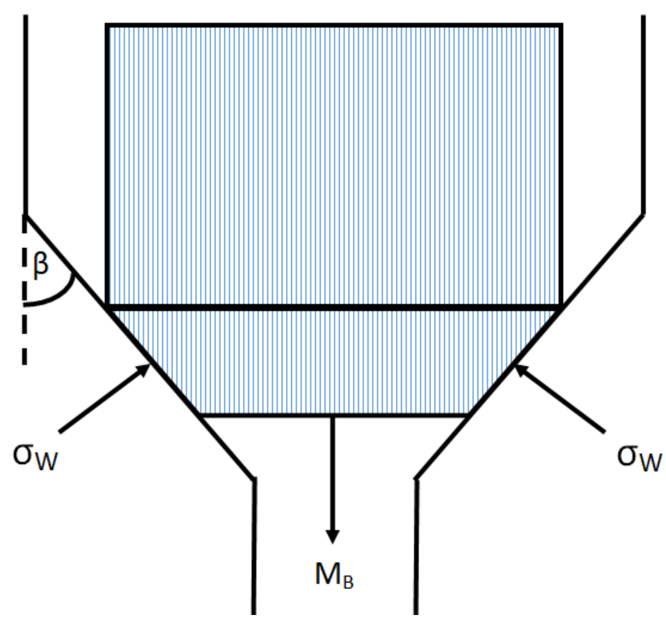

Figure I.6: Normal wall pressure acting on hopper-bag contact patch

The pressure acting normal to the hopper wall (σ_w) for this scenario was found using the following equation determined using Equation 49:

$$\sigma_w = \frac{M_B}{A_T}\cos(90 - \beta) \quad \text{Equation 49}$$

Where M_B is the mass of the full depressant bag. Substituting known values into Equation 49 gives:

$$\sigma_w = \frac{2204.62\ [lb]}{659.56\ [in^2]} \cos\left(90 - 60\right) = 2.895\ psi = 19959\ Pa$$

I.4 NUMERICAL ANALYSIS

FEA was applied to the CAD model on the hopper bottom and removable sides to determine whether the sheet metal thickness selected was sufficient or if it could be optimized. The results of the hopper pressure analysis were utilized to apply pressure to the hopper face.

I.4.1 HOPPER FILLING AND DISCHARGE LOADING

This analysis was used to simulate a scenario where an entire depressant bag is emptied into the hopper. The bottom of the structure was fixed in place and a pressure of 4107 [Pa], as determined in Section I.2, was applied normal to the hopper face as seen in Figure I.7.

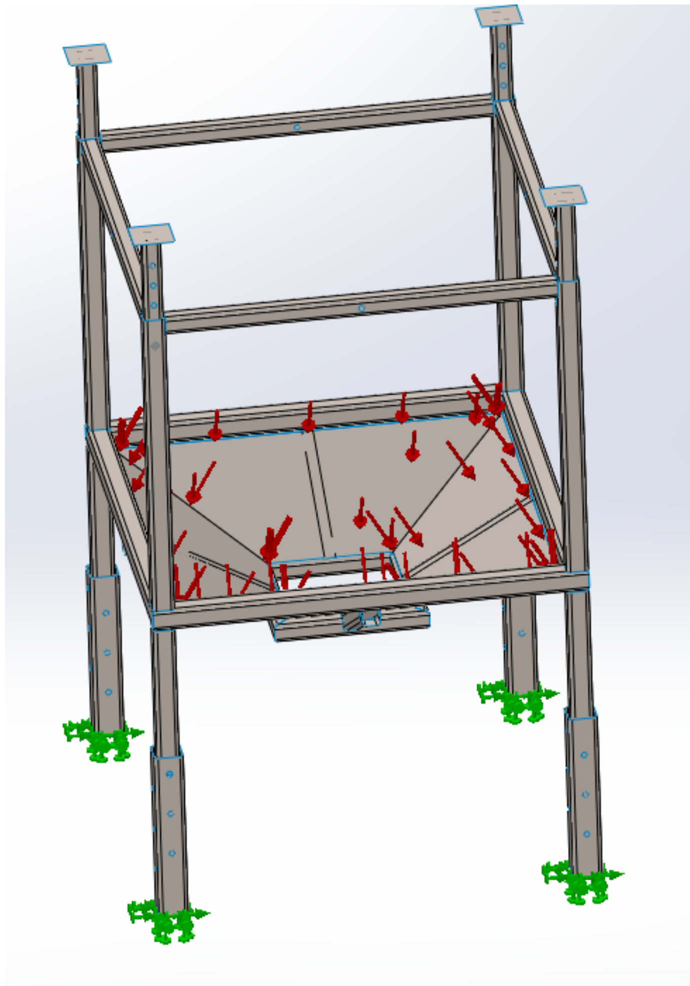

Figure I.7: Entire hopper loading conditions

The study was conducted with standard hopper material thicknesses of 0.125 [in] (11ga), 0.062” (16ga), and 0.031” (22ga) to determine how varying the wall thickness would affect the wall stress and displacement that results from filling the hopper with 1000 kg of Guar Gum. Through all the studies, the stress and displacement models had the same distribution on the hopper. The stress and displacement plots for a thickness of 0.125” can be seen in Figure I.8 and Figure I.9, respectively.

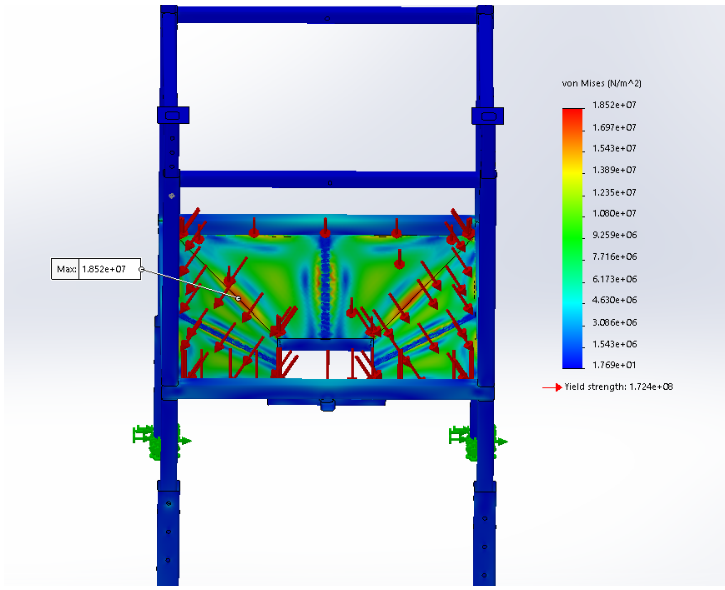

Figure I.8: Entire hopper loading stress distribution

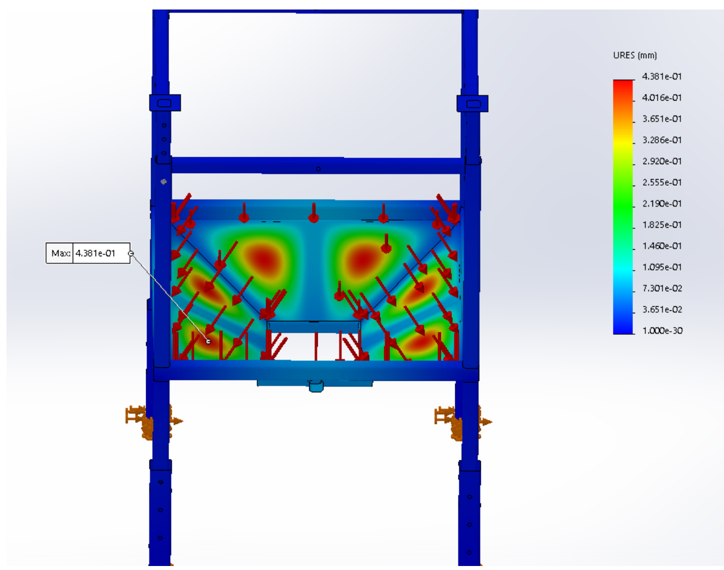

Figure I.9: Entire hopper loading displacement distribution

The results of all the hopper loading studies can be seen in TABLE I.IV.

TABLE I.IV: HOPPER BOTTOM THICKNESS COMPARISON

Thickness [in]	Displacement [mm]	Max Stress [Pa]	Avg. Stress [Pa]	FOS
0.125	0.4	1.852×10^7	1.08×10^7	31
0.062	3.065	7.596×10^7	4.431×10^7	7.6
0.031	21.3	2.865×10^7	1.724×10^8	2

From the results in TABLE I.IV, it can be concluded that in this scenario a thickness of 0.062 [in] would be sufficient for static loading while maintaining a FOS above 5. Although, a thickness of 0.125 [in] is suggested to mitigate any deformation of the hopper.

I.4.2 HOPPER BAG LOADING

This analysis was used to simulate a scenario where a bag is dropped directly onto the hopper. The team assumed that the bag would deform to have 4 [in] contact patch with the hopper around the perimeter of the bag. Therefore, the hopper surface was split into 4inch wide sections that a normal wall pressure of 19,959 [Pa] calculated in Section I.2.5, and the bottom legs of the structure were fixed as seen in Figure I.10.

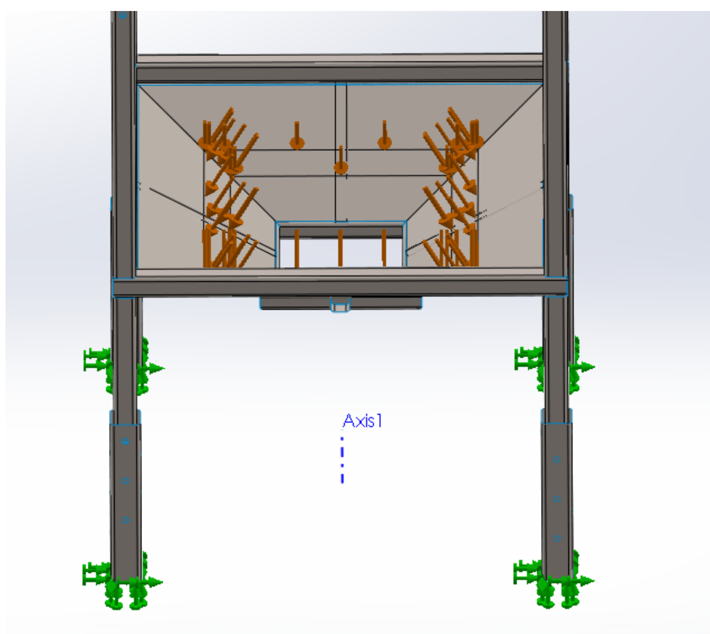

Figure I.10: Hopper bag loading conditions

Hopper walls composed of 0.031 [in] thick sheet metal was determined not to meet the FOS requirement and was therefore not considered for this test. As seen in TABLE I.V, this loading scenario yielded greater stresses in the hopper bottom than hopper filling and discharging loading scenario.

TABLE I.V: HOPPER BAG LOADING RESULTS

Thickness [in]	Displacement [mm]	Max Stress [Pa]	Avg. Stress [Pa]	FOS
0.125	0.7	4.594×10^7	2.68×10^7	18.5
0.062	5.14	1.837×10^8	9.184×10^7	4.6

Since the 0.062 [in] thickness material does not meet the FOS requirement it was removed from consideration. Therefore, the team concluded that 11 [ga] material should be used for the hopper bottom to ensure no failure occurs. If cost is an issue any material thicker than 16 [ga] will suffice if a FOS less than 5 is acceptable.

I.4.3 WALL LOADING

This analysis was used to simulate a scenario where the hopper is full to the top of the side walls to ensure that they are thick enough to not buckle under the load. A surface model wall with the same dimensions as the real wall was created and the supported edges were fixed. A non-uniform load was applied to the face using the following equation to vary the load on the wall location to simulate the stress distribution found using the Silo Stress Tool.

$$\rho \cdot g \cdot y = Pressure \qquad \text{Equation 50}$$

$$657 \cdot 9.81 \cdot y = Pressure$$

Figure I.11 shows the applied load to the model.

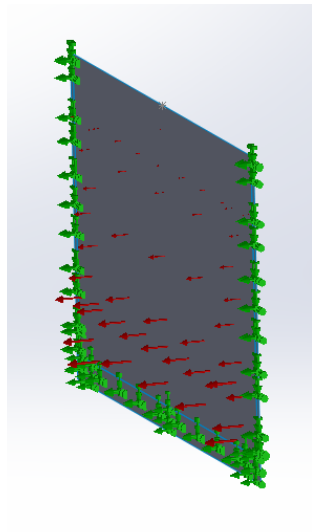

Figure I.11: Wall loading

The max stress and displacement were found to be 1.256×10^8 [Pa] and 10.6 [mm] respectively. This resulted in a FOS of 4.6 which does not meet the target factor of safety of the rest of the system. However, since this is a situation that should not occur during regular operation and is very close to the FOS. For reference the stress and displacement distributions can be seen Figure I.12 and Figure I.13.

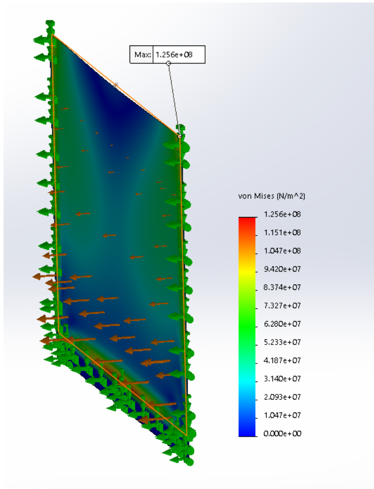

Figure I.12: Wall loading stress distribution

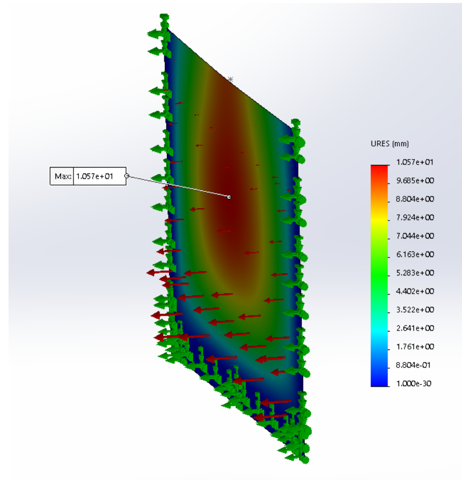

Figure I.13: Wall loading displacement distribution

I.5 Works Cited

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APPENDIX J – QUOTES

Quotes were received from material suppliers, NRP suggested fabricators and off-the shelf solution vendors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

J.1 SASKATOON METAL MANUFACTURING

Saskatoon Metal Manufacturing provided a material and fabrication quote, Figure J.1, for the support structure and hopper designed.

[redacted]

Figure J.1: Saskatoon Metal Manufacturing material and fabrication quote in $CAD

J.2 PARKLAND MANUFACTURING LTD

Parkland Manufacturing LTD provided a material and fabrication quote, Figure J.2, for the support structure and hopper designed.

[redacted]

Figure J.2: Parkland Manufacturing LTD material and fabrication quote in $CAD

J.3 GOODMAN STEEL LTD

Goodman Steel LTD provided a material quote, Figure J.3. A fabrication quote was unable to be received before the required report submission, December 4, 2019.

[redacted]

Figure J.3: Goodman Steel LTD material quote in $CAD

J.4 NEW WEST METALS INC.

New West Metal Inc. provided a material quote and material cost breakdown, Figure J.4 and TABLE J.I.

[redacted]

Figure J.4: New West Metals Inc. material quote and cost breakdown email in $CAD

TABLE J.I: NEW WEST METALS INC. MATERIAL QUOTE AND COST BREAKDOWN

[redacted]

J.5 VIBRA SCREW INC.™

Vibra Screw Inc.™ provided a quote for both, the Bag Splitter®, Figure J.5, and the complete design of the bag splitting hopper, including the Bag Splitter®, Figure J.6 through Figure J.9.

[redacted]

Figure J.5: Vibra Screw Inc.™ Bag Splitter® email quote in \$USD

[redacted]

Figure J.6: Vibra Screw Inc.™ Bag Splitting Hopper complete quote in $USD (1 of 4)

[redacted]

Figure J.7: Vibra Screw Inc.™ Bag Splitting Hopper complete quote in $USD (2 of 4)

[redacted]

Figure J.8: Vibra Screw Inc.™ Bag Splitting Hopper complete quote in $USD (3 of 4)

[redacted]

Figure J.9: Vibra Screw Inc.™ Bag Splitting Hopper complete quote in $USD (4 of 4)

J.6 SCHENCK PROCESS

Schenck Process provided the quote for the Mucon™ DSV® 12 Slide Gate Valve, Figure J.10.

[redacted]

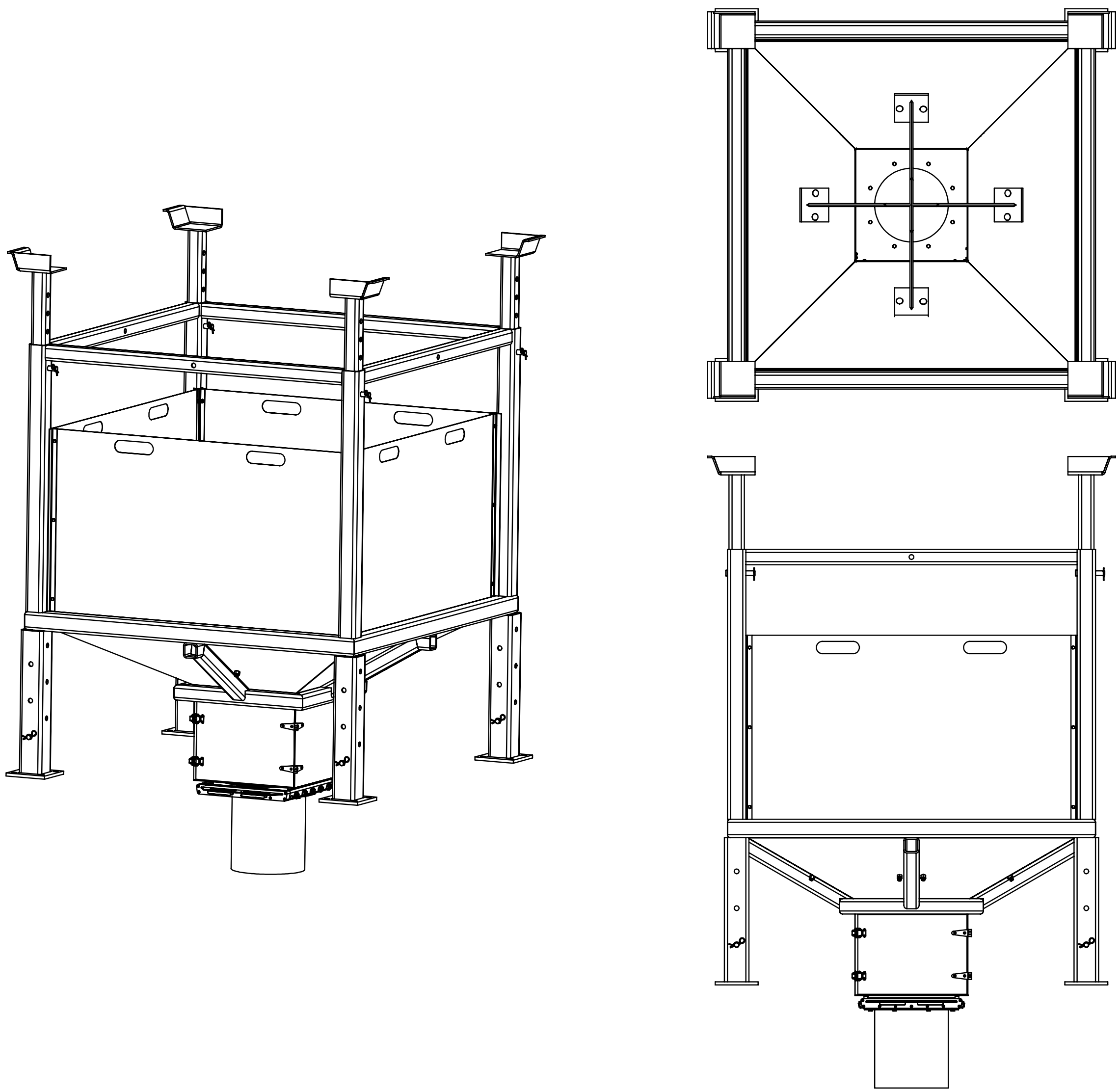
Figure J.10: Schenck Process email quote is $USD

J.7 SUPERCHUTE®

Superchute® provided a quote for the discharge chute with mounting flange.

[redacted]

Figure J.11: Superchute email quote in $CAD



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2	DSS_ASM_03	SIDEWALL ASSEMBLY	4
3	DSS_ASM_01	LOWER STRUCTURE MOUNT	4
4	DSS_ASM_04	BAG HIEGHT ADJUSTER(1)	2
5	DSS_ASM_07	BAG HIEGHT ADJUSTER(2)	2
6	92401A765	316 Stainless Steel	8
7	Hinge_ASM	HINGE	2
8	6148A160_CORNER-MOUNT COMPRESSION SPRING DRAW LATCH	LATCH	2
9	Vibra Screw Splitter Asembly	Splitter	1
10	93180A617	SS Carriage Bolt, 1/2"-13 Thread, 1 1/2" Length	8
11	90715A165	Nylon-Insert Locknut , 1/2"-13 Thread Locknut	8
12	93190A536	SS Hex Screw 1/4"-20 Thread, 3/8"Long	24
13	91500A242	SS Flat Head Phillips, #10-24 Thread, .5in Long	8
14	94150A335	SS Hex Nut, M4 x 0.7 mm Thread	8
15	90257A011	SS Hex Nut, #10-24 Thread	8
16	90116A207	SS Pan Head Phillips, M4 x 0.7 mm Thread, 10mm Long	8
17	SLIDE DOOR		1
18	93635A318	Stainless Steel Hex, M8 x 1.25 mm Thread, 20mm Long	8
19	93635A310	Stainless Steel Hex, M8 x 1.25 mm Thread, 12mm Long	8
20	DSS_ASM_05	DOOR	1
21	DSS_ASM_06	OUTLET CHUTE	1

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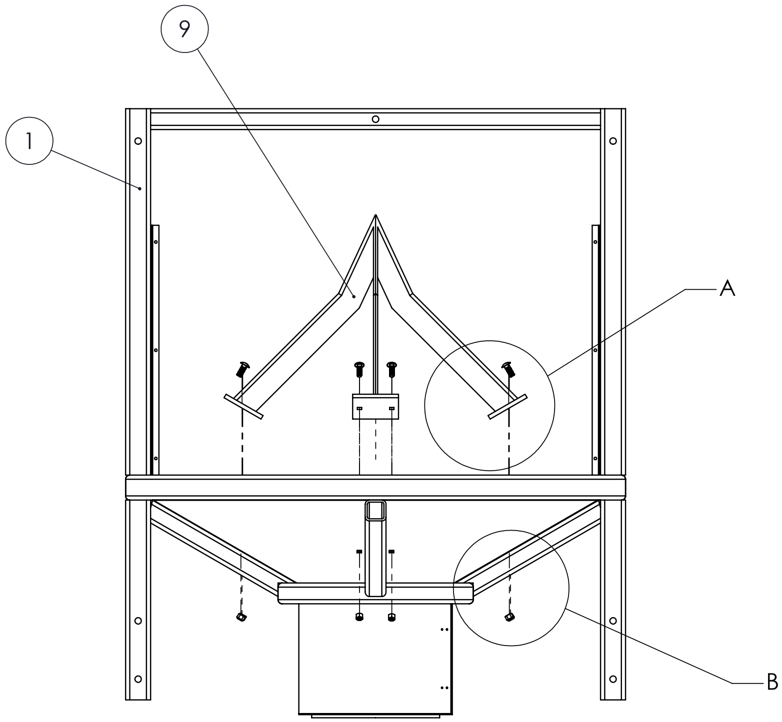

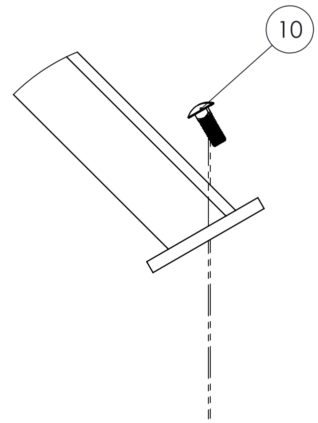

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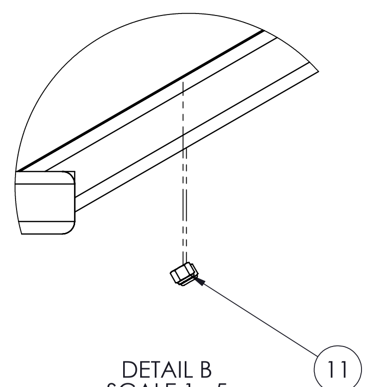

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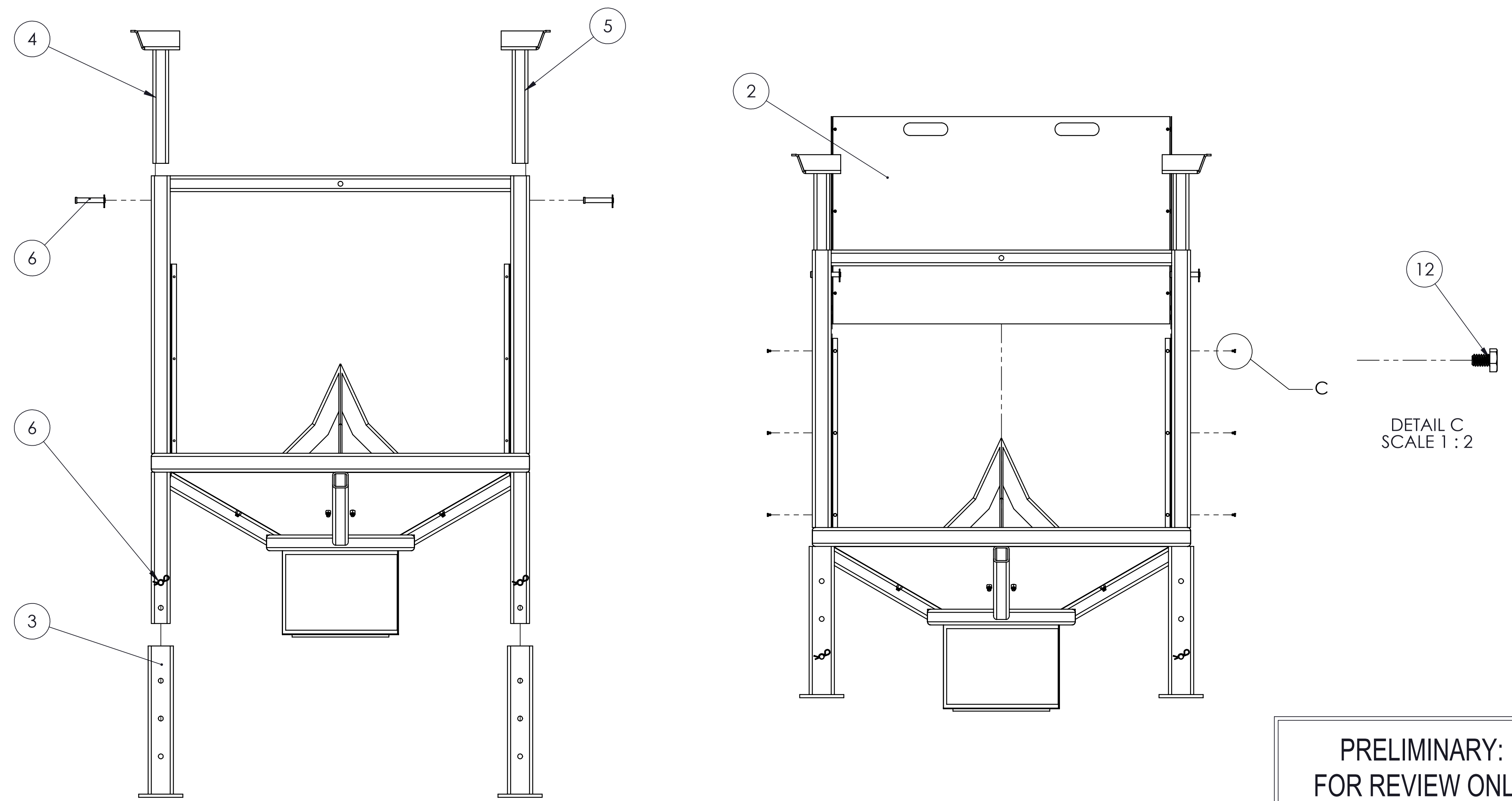

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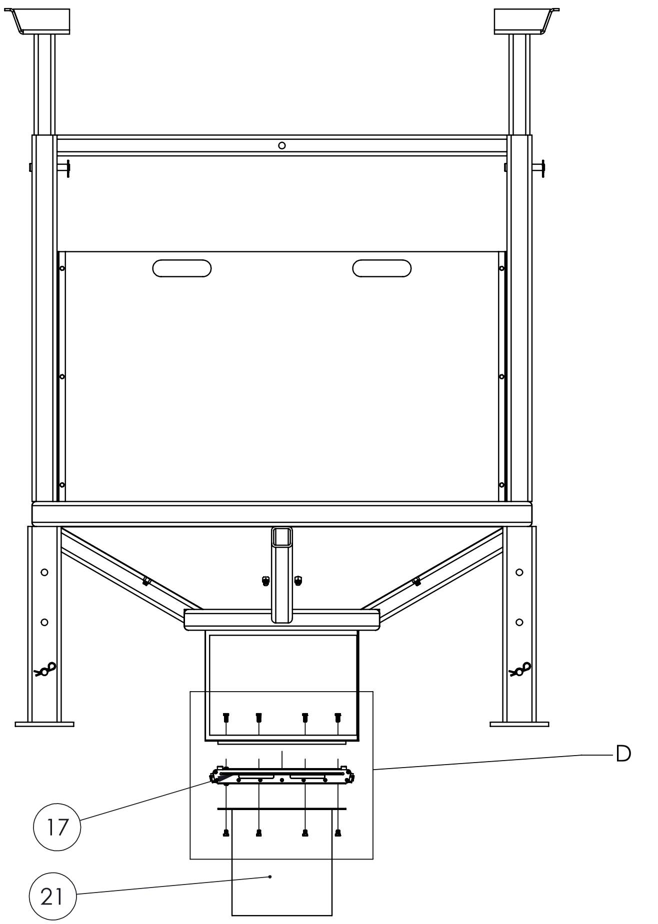

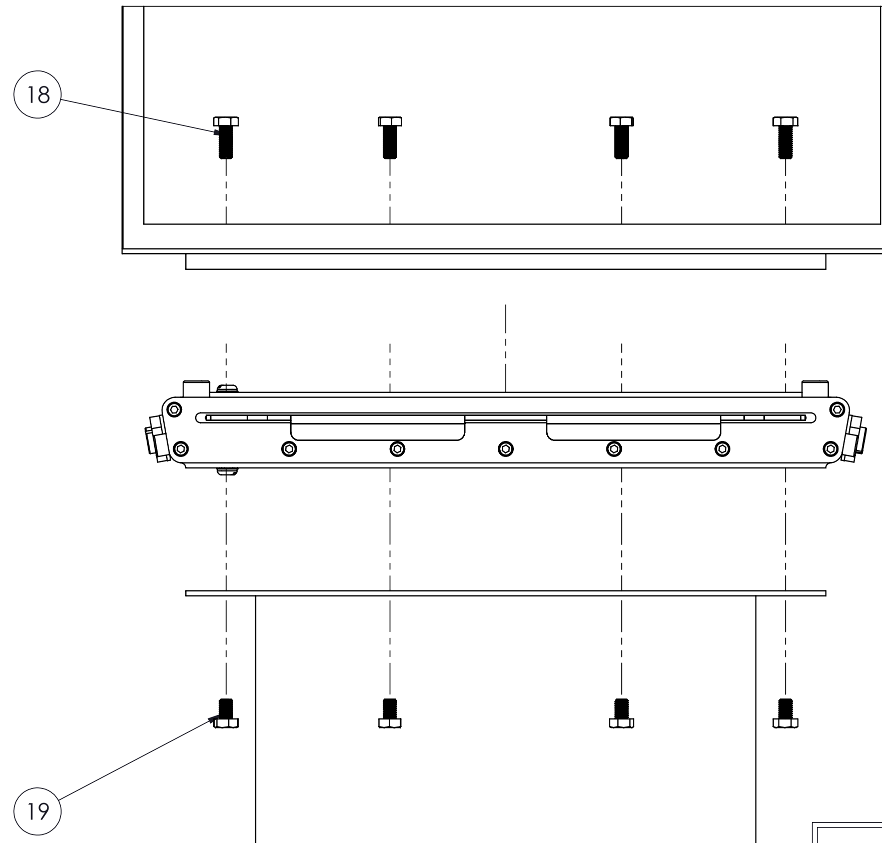

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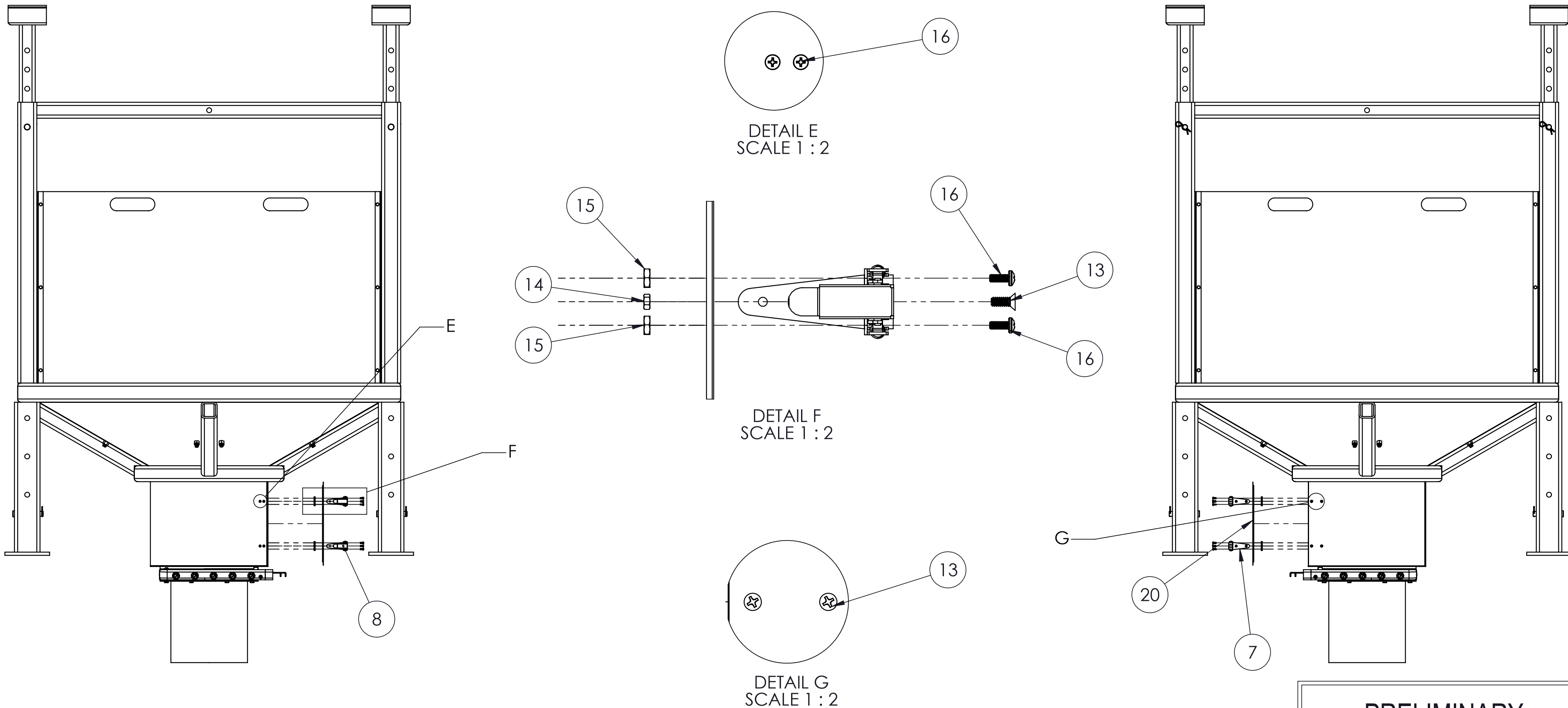

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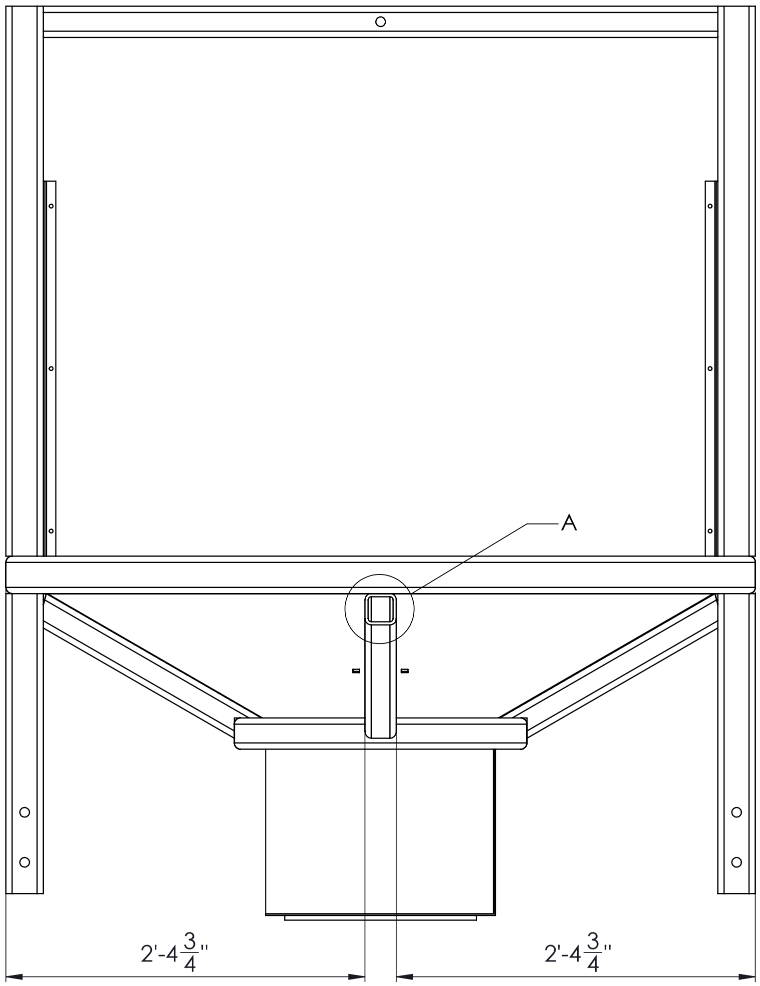

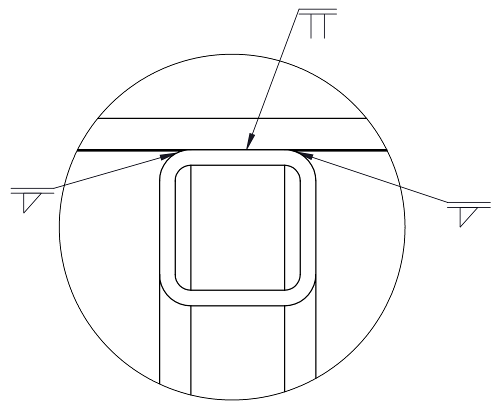

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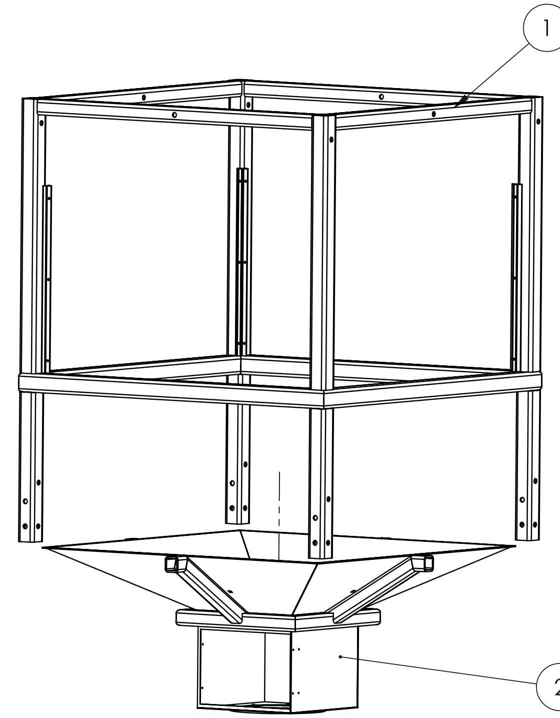

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DSS_ASM_02

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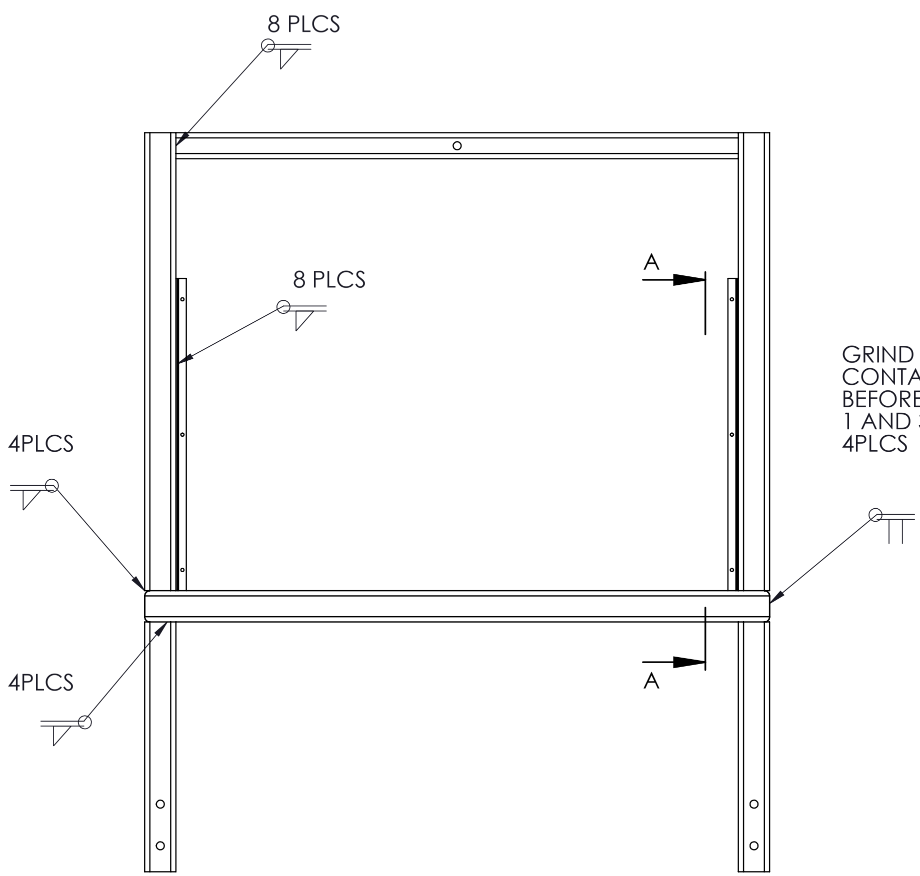
5	DSS_T3	HOPPER ADJUST INNER TUBE	4



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1 AND 3
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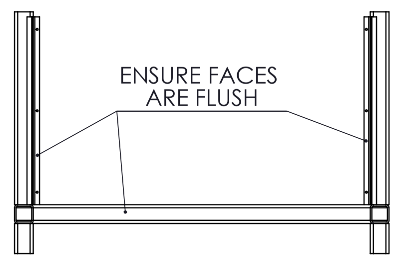

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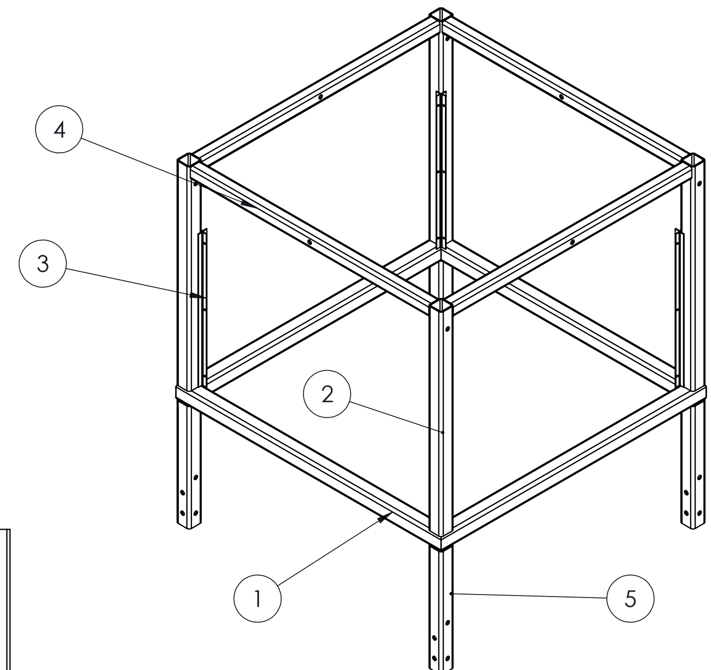

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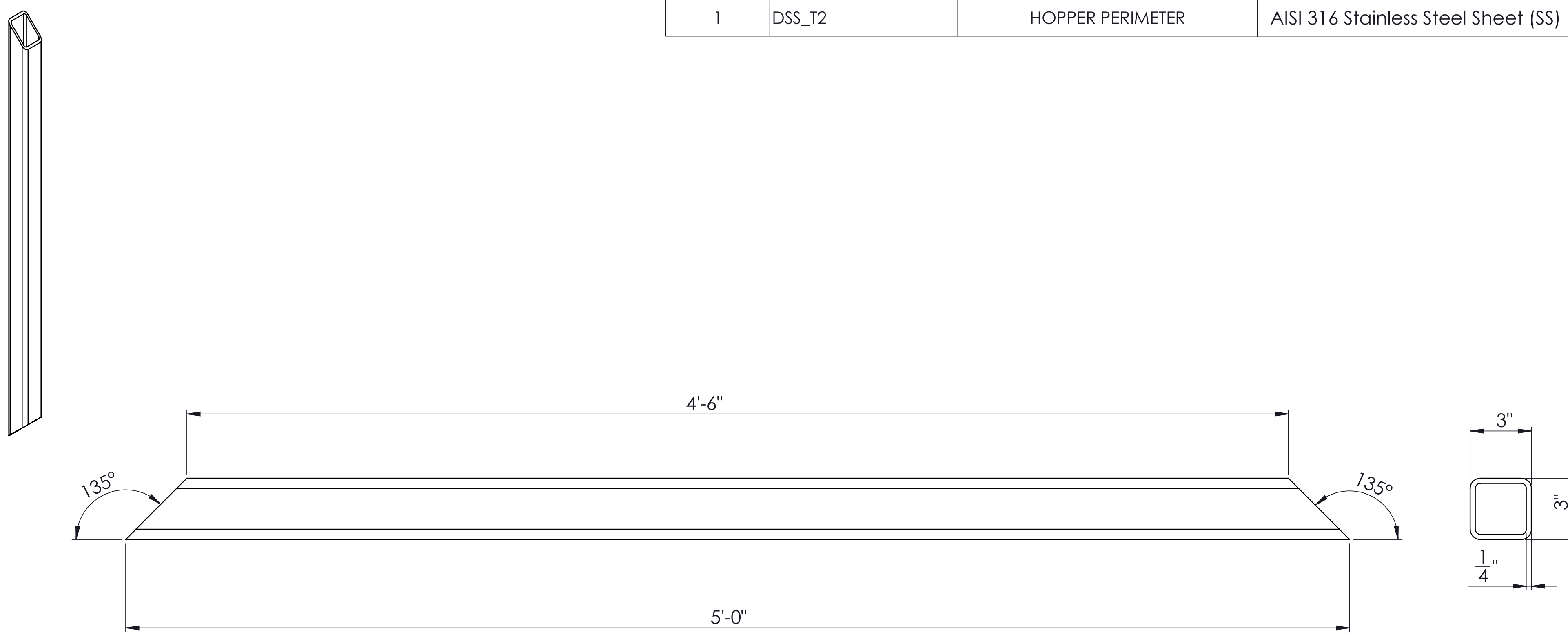

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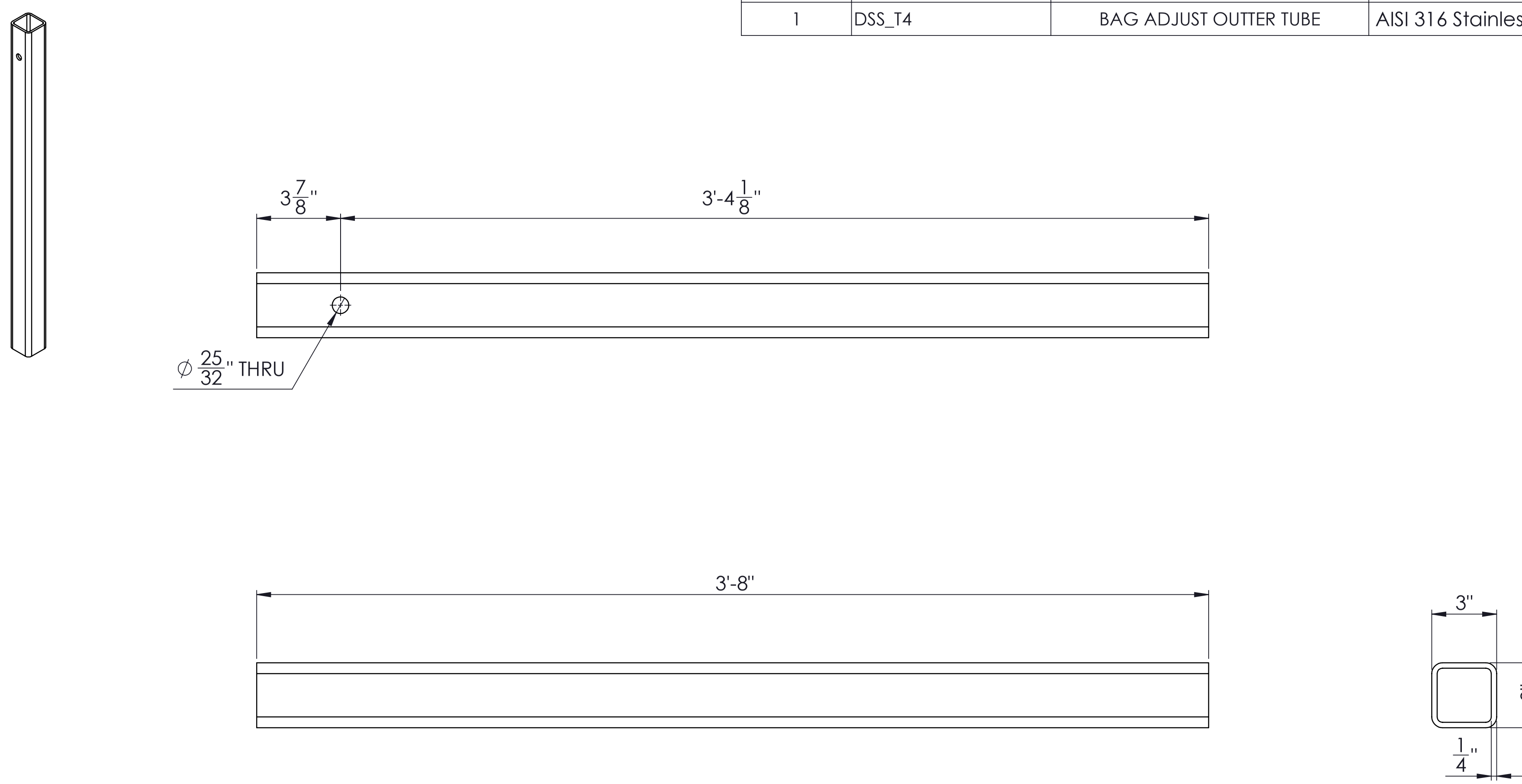

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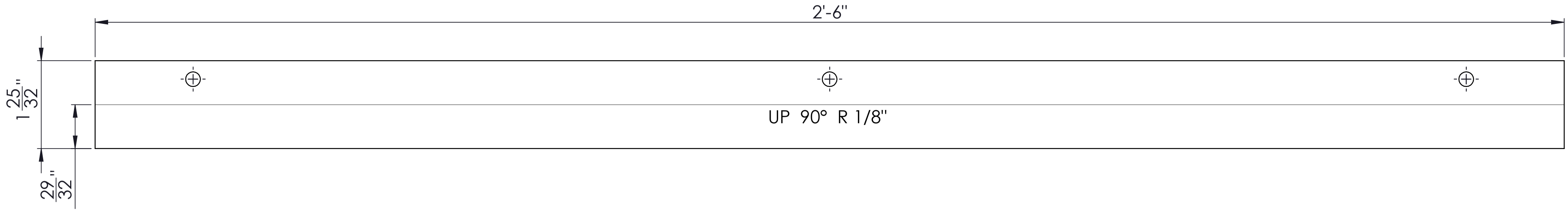

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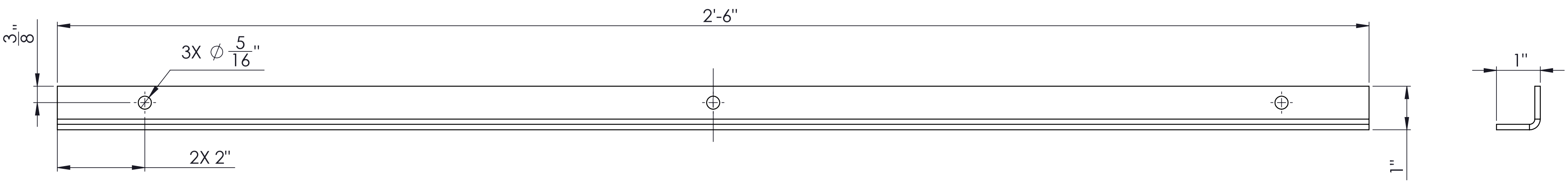

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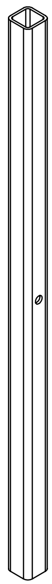

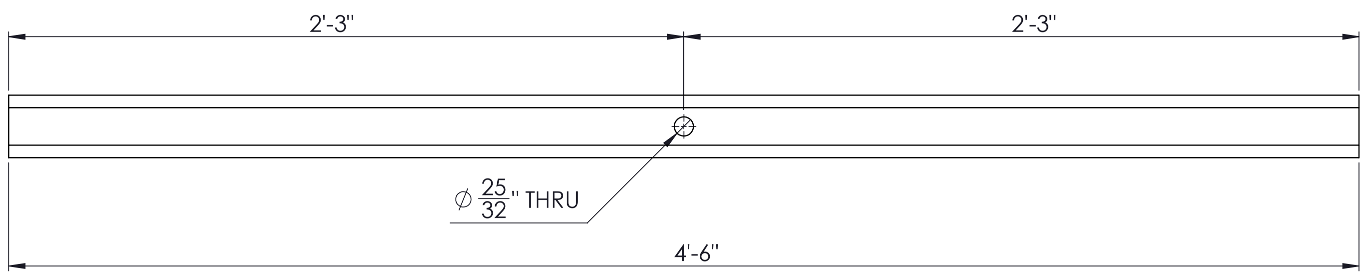

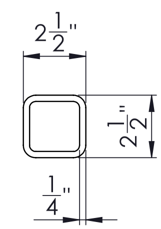

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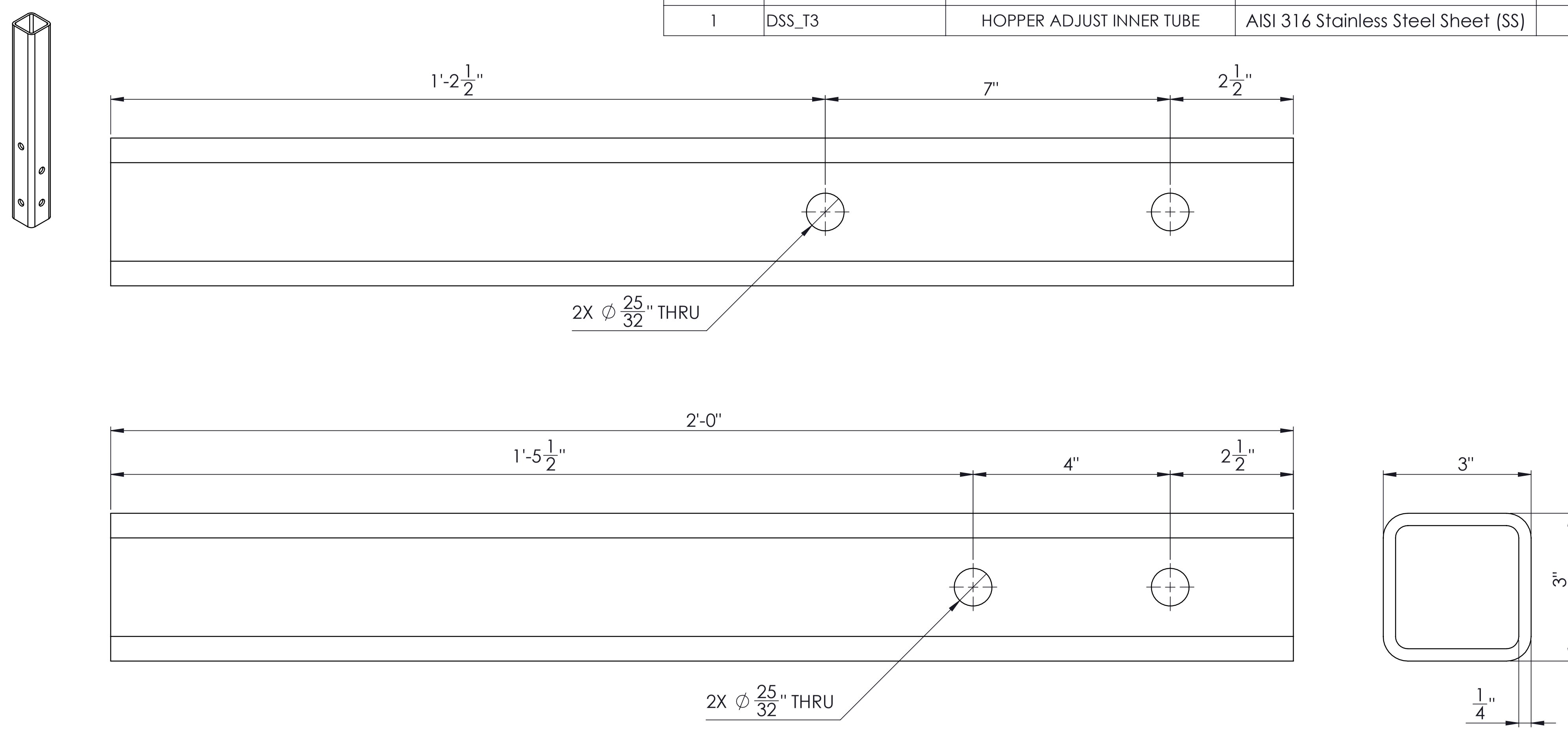
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_T3	HOPPER ADJUST INNER TUBE	AISI 316 Stainless Steel Sheet (SS)	1



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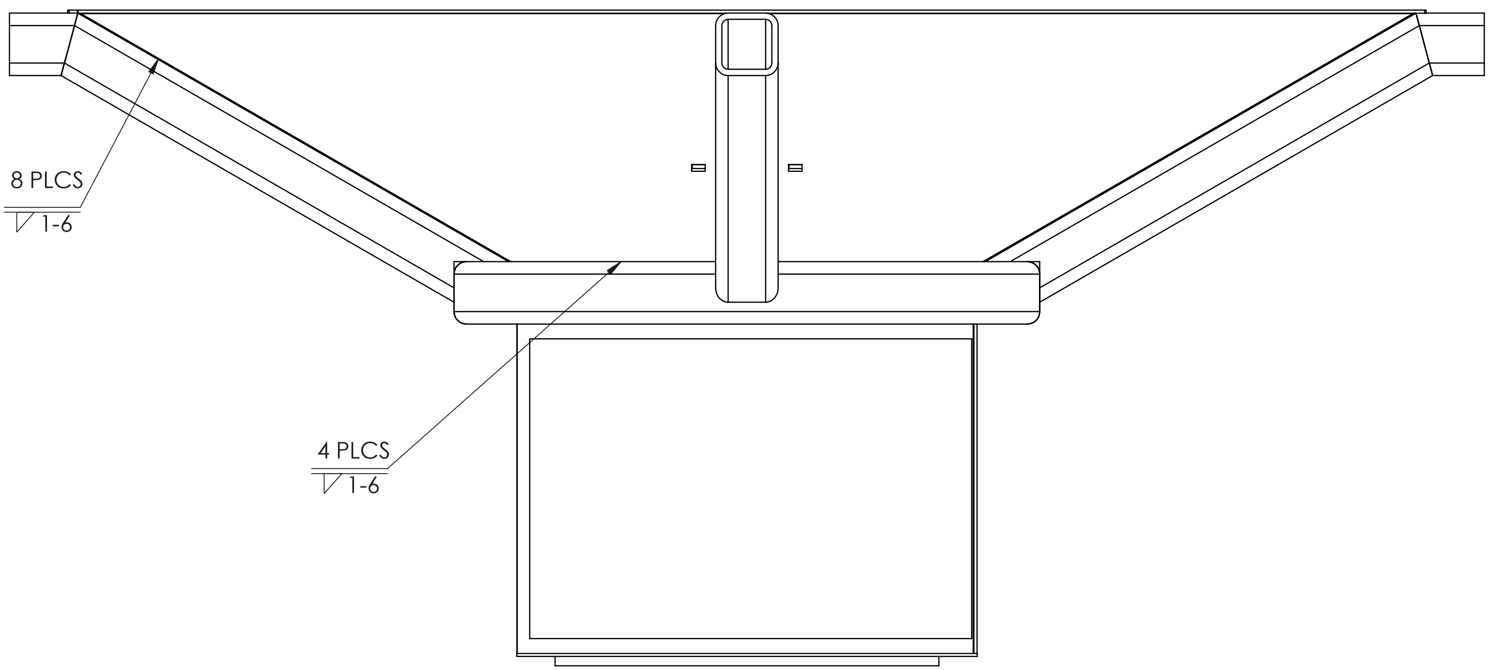
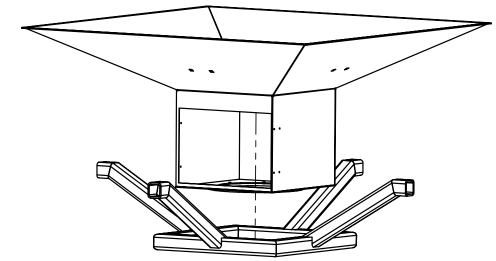
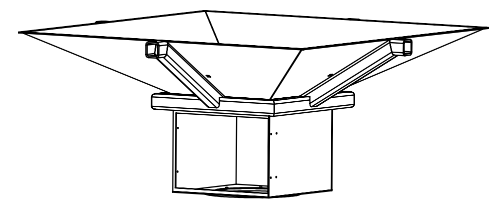
Proj.No. S-4???
Dwg.No. ???-?-???
Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_ASM_02_1	HOPPER SUPPORTS	1
2	DSS_ASM_02_2	HOPPER WALLS	1







NOTE: -INSERT HOPPER FROM TOP
-ORIENTATION NOT IMPROTANT

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DSS_ASM_02_4

Proj.No. S-4???

Dwg.No. ???-?-???

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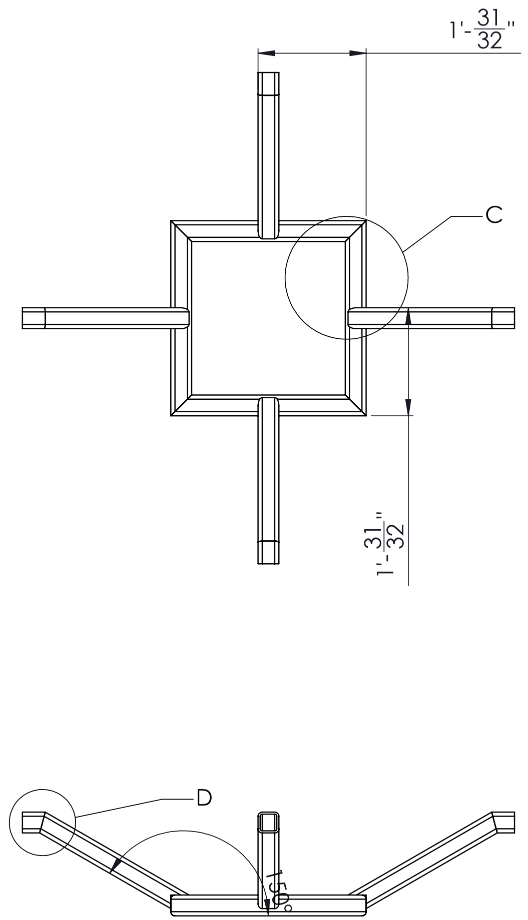
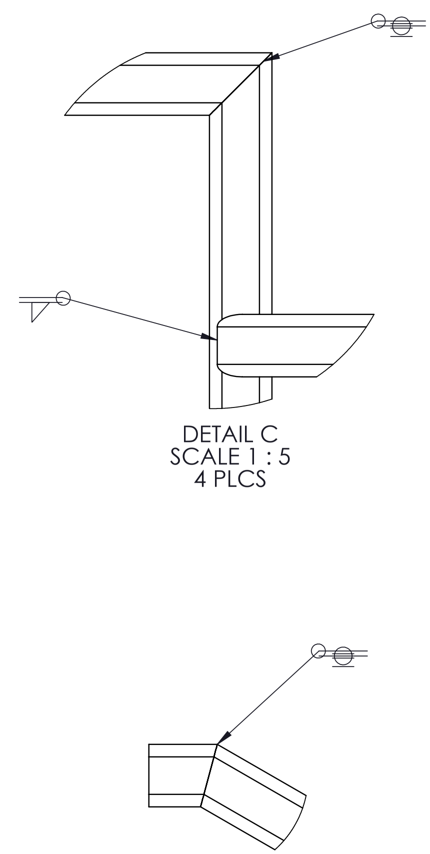
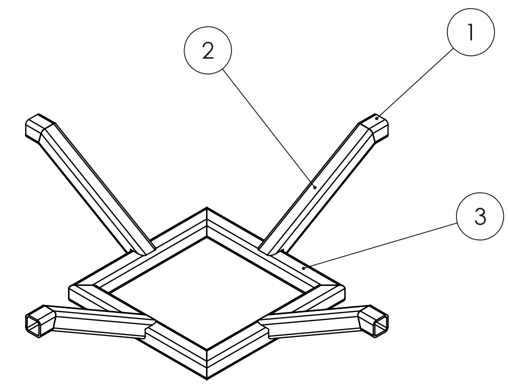


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_T6	HOPPER UPPER SUPPORT	4
2	DSS_T7	HOPPER ANGLES SUPPORT	4
3	DSS_T8	HOPPER LOWER SUPPORT	4



DETAIL C
SCALE 1 : 5
4 PLCS

DETAIL D
SCALE 1 : 5
4 PLCS



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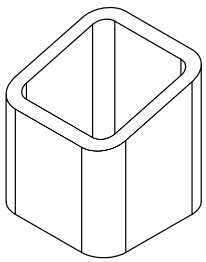
DSS_ASM_02_1

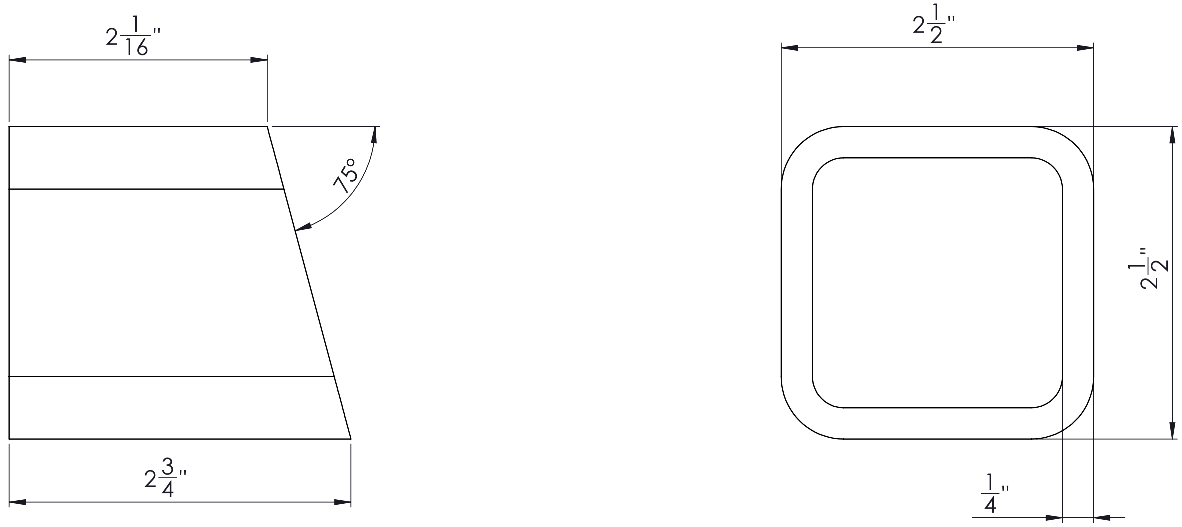
Proj.No. S-4???

Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_T6	HOPPER UPPER SUPPORT	AISI 316 Stainless Steel Sheet (SS)	1





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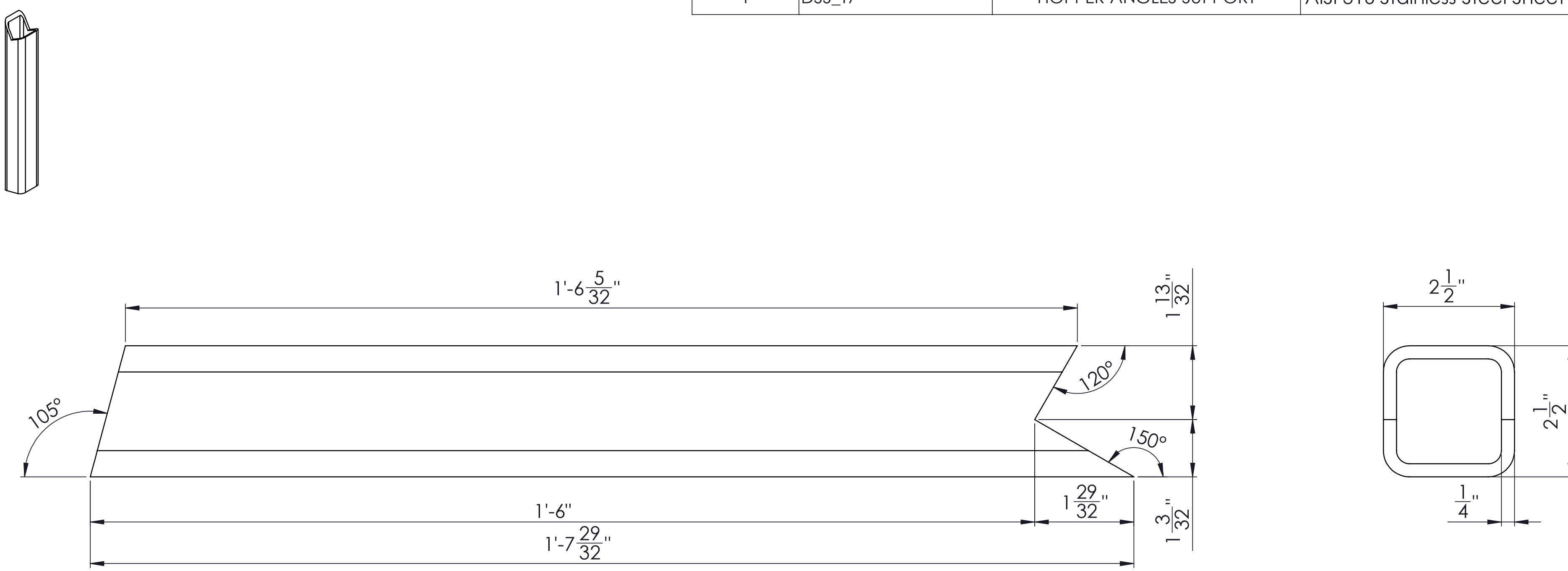
Proj.No. S-4???

Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_T7	HOPPER ANGLES SUPPORT	AISI 316 Stainless Steel Sheet (SS)	1



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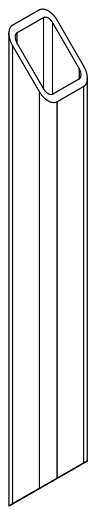
4						Approved:	

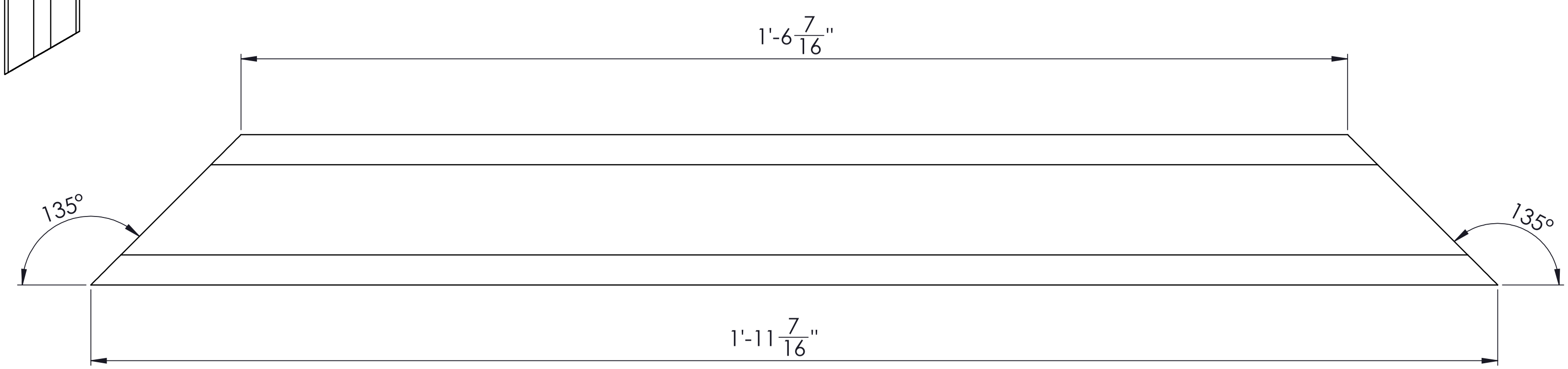
Proj.No. S-4???

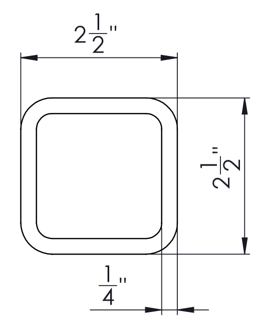
Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_T8	HOPPER LOWER SUPPORT	AISI 316 Stainless Steel Sheet (SS)	1







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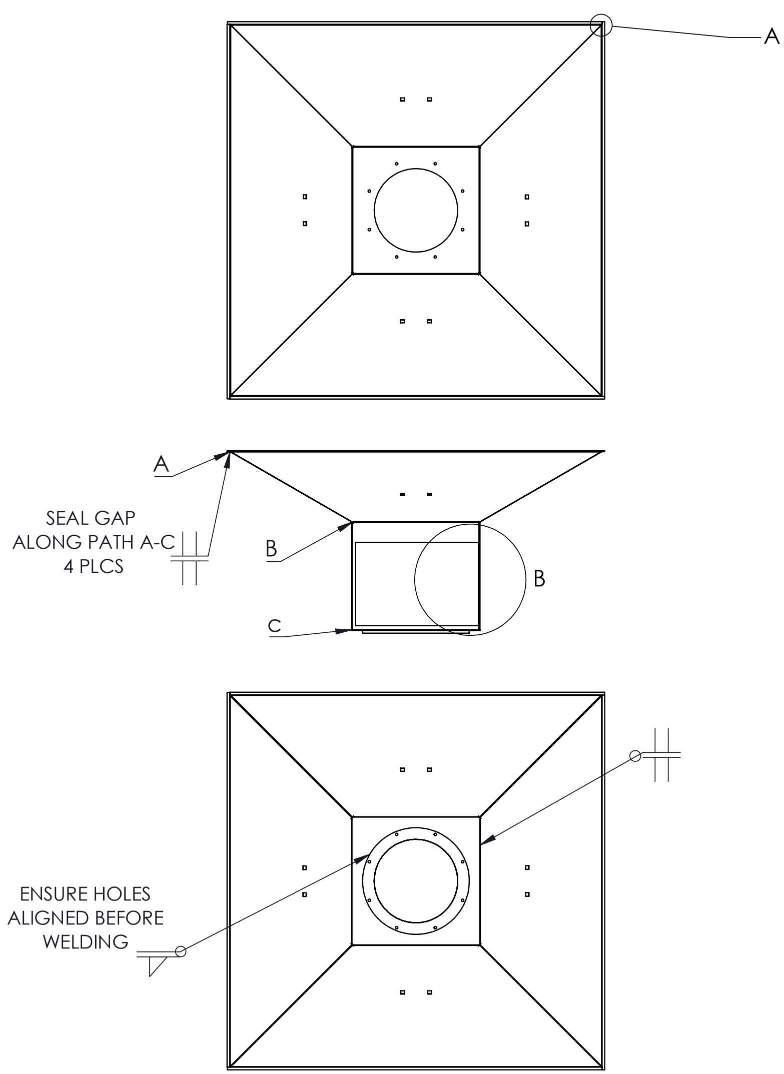
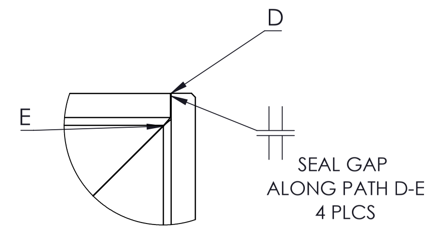
Proj.No. S-4???

Dwg.No. ???-?-???

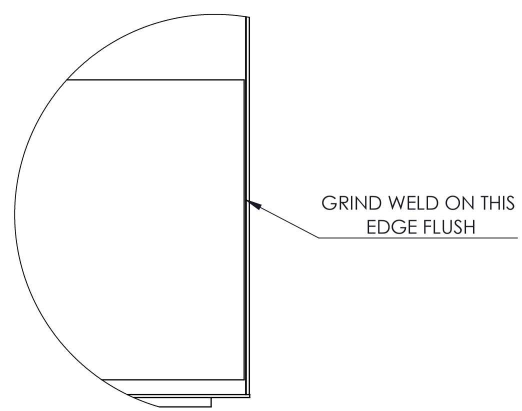
Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_P6	HOPPER HINGE SIDE	1
2	DSS_P7	HOPPER BOTTOM	1
3	DSS_P8	SLIDE DOOR SPACER	1
4	DSS_P15	HOPPER LATCH SIDE	1
5	DSS_P16	HOPPER SOLID WALL	1
6	DSS_P13	HOPPER DOOR SIDE	1

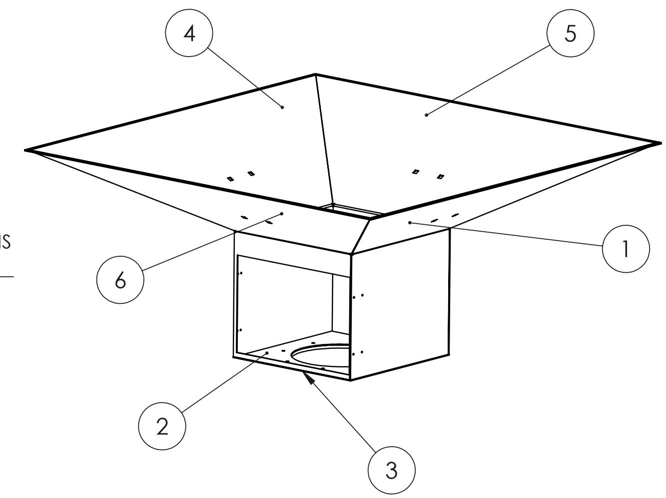




DETAIL A
SCALE 1 : 2



DETAIL B
SCALE 1 : 5



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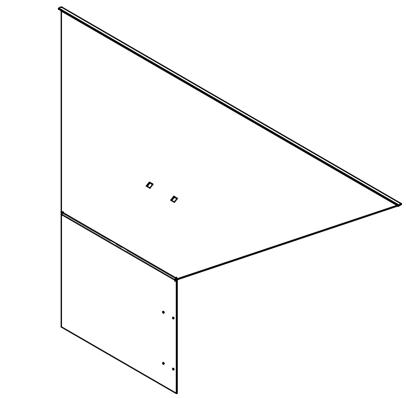
DSS_ASM_02_2

Proj.No. S-4???

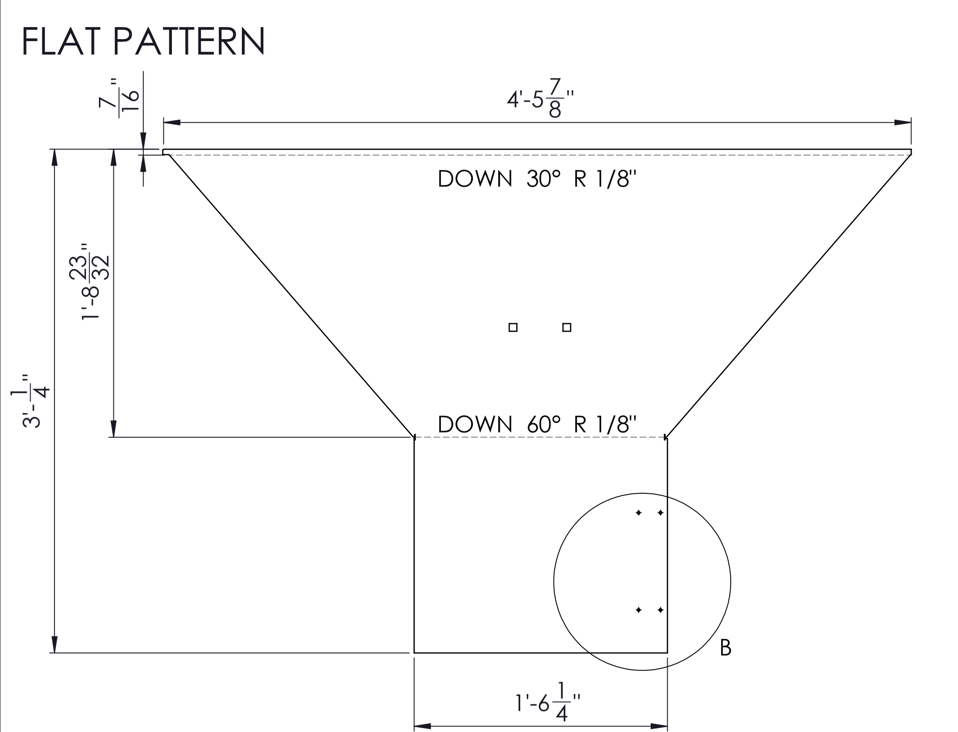
Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P6	HOPPER HINGE SIDE	AISI 316 Stainless Steel Sheet (SS)	1



FLAT PATTERN



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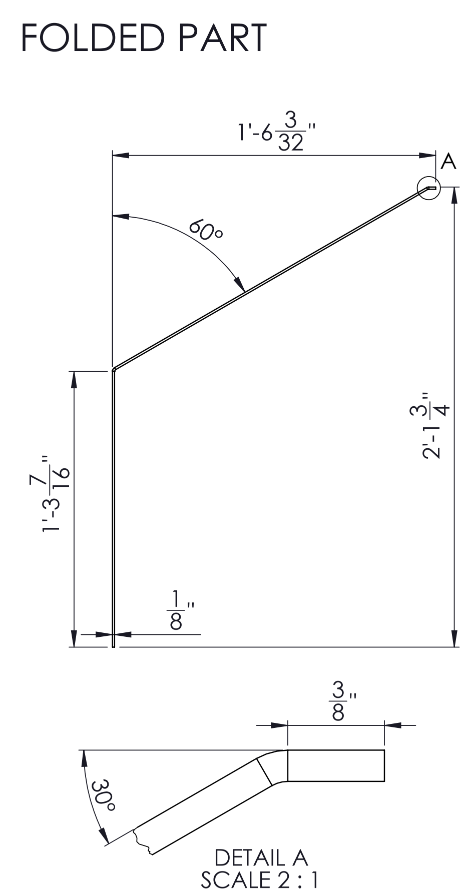

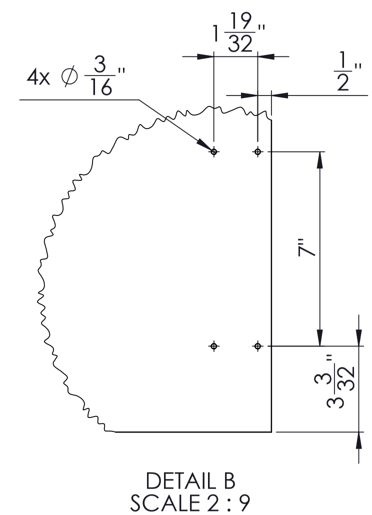

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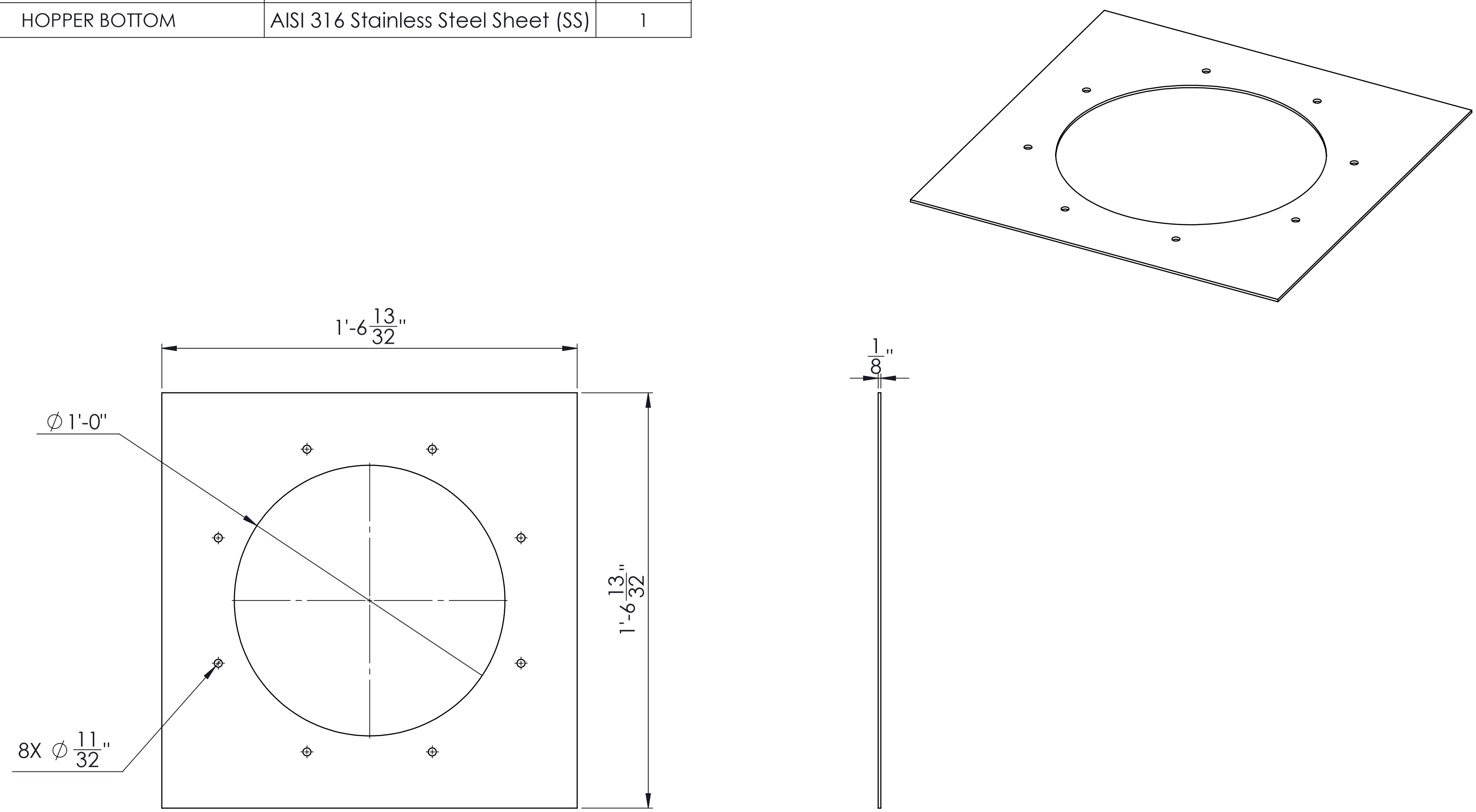
Designed:	A.D.	
Drawn:	L.M.K.	
Checked:		
Approved:		

HOPPER HINGE SIDE

Proj.No. S-4???
Dwg.No. ???-?-???
Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P7	HOPPER BOTTOM	AISI 316 Stainless Steel Sheet (SS)	1



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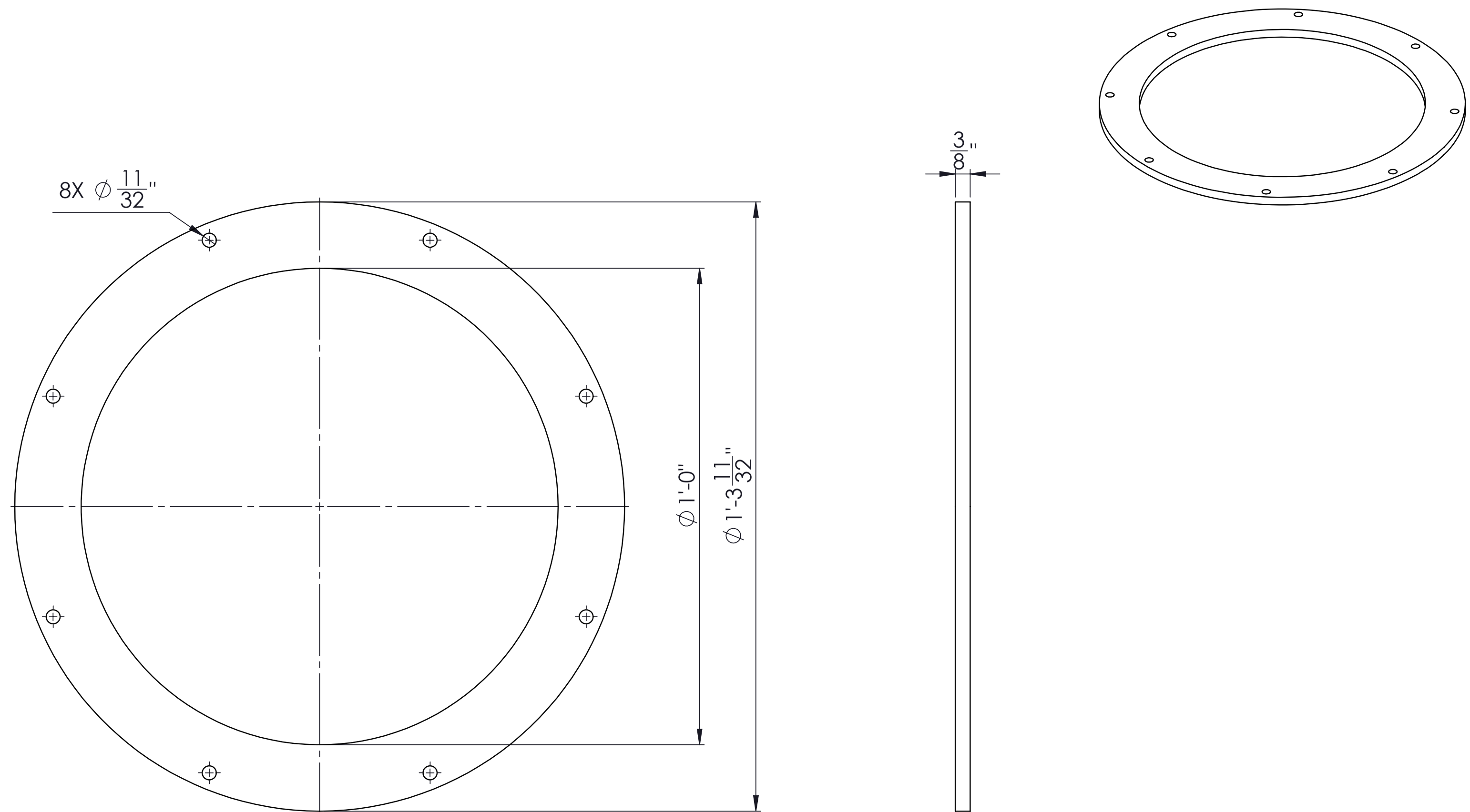
HOPPER BOTTOM

Proj.No. S-4???
Dwg.No. ???-?-???
Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P8	SLIDE DOOR SPACER	AISI 316 Stainless Steel Sheet (SS)	1



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Approved:		

SLIDE DOOR SPACER

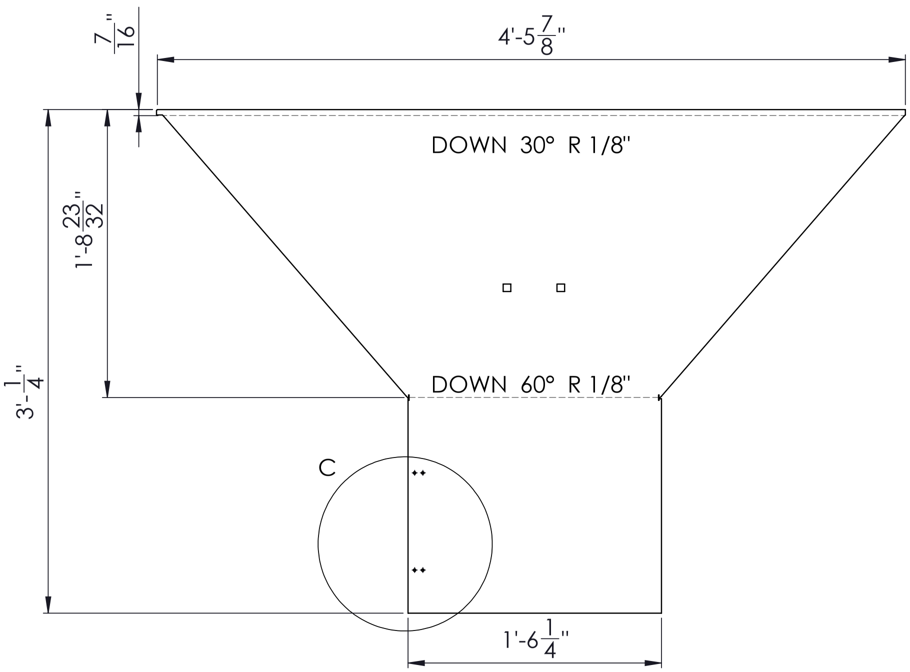
Proj.No. S-4???

Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P15	HOPPER LATCH SIDE	AISI 316 Stainless Steel Sheet (SS)	1

FLAT PATTERN



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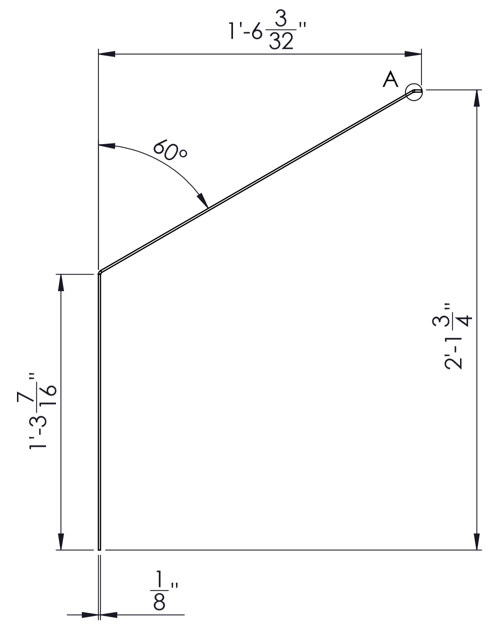
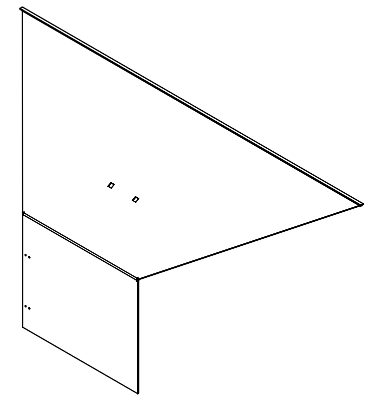
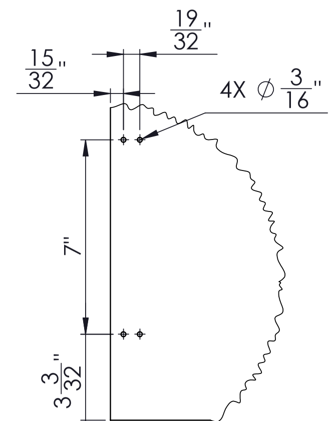
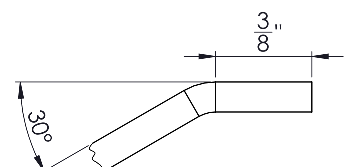






DETAIL C
SCALE 2 : 9



DETAIL A
SCALE 2 : 1

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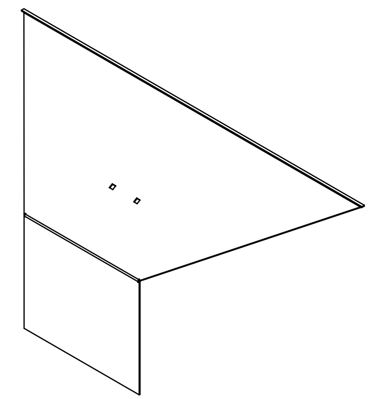
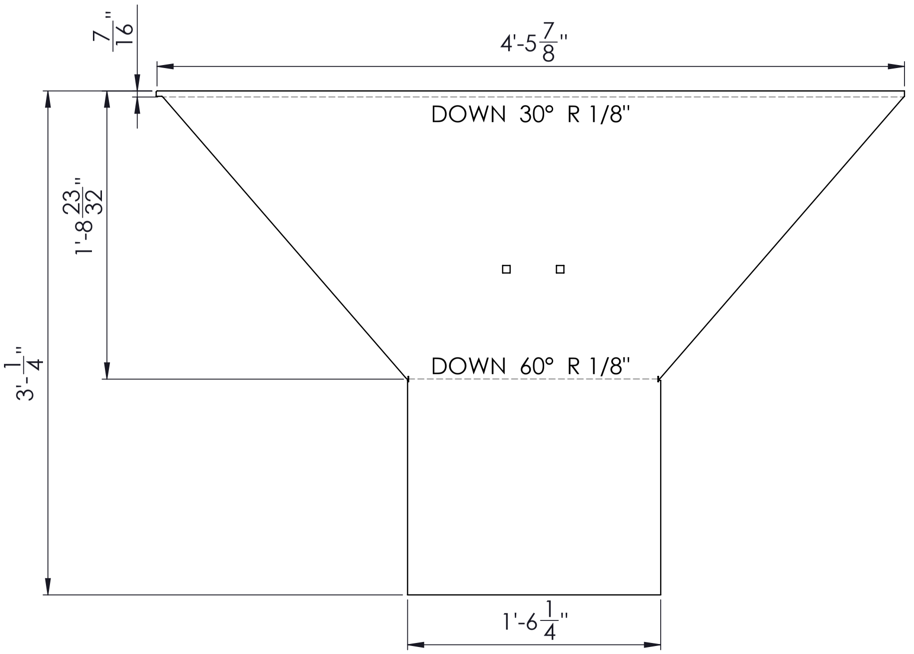
HOPPER LATCH SIDE

Proj.No. S-4???
Dwg.No. ???-?-???
Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P16	HOPPER SOLID WALL	AISI 316 Stainless Steel Sheet (SS)	1



FLAT PATTERN



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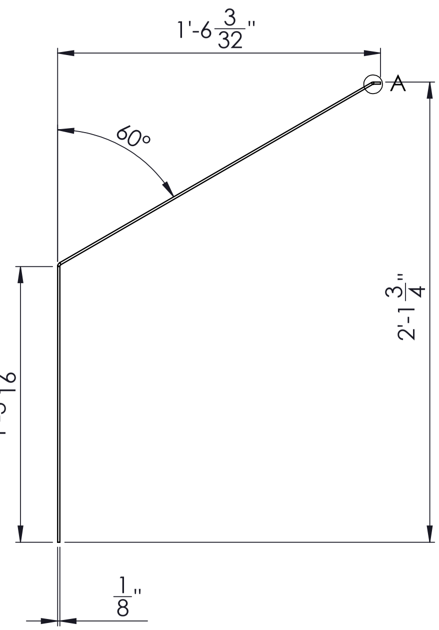

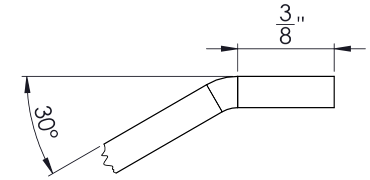

DETAIL A
SCALE 2 : 1

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HOPPER SOLID WALL

Proj.No. S-4???
Dwg.No. ???-?-???
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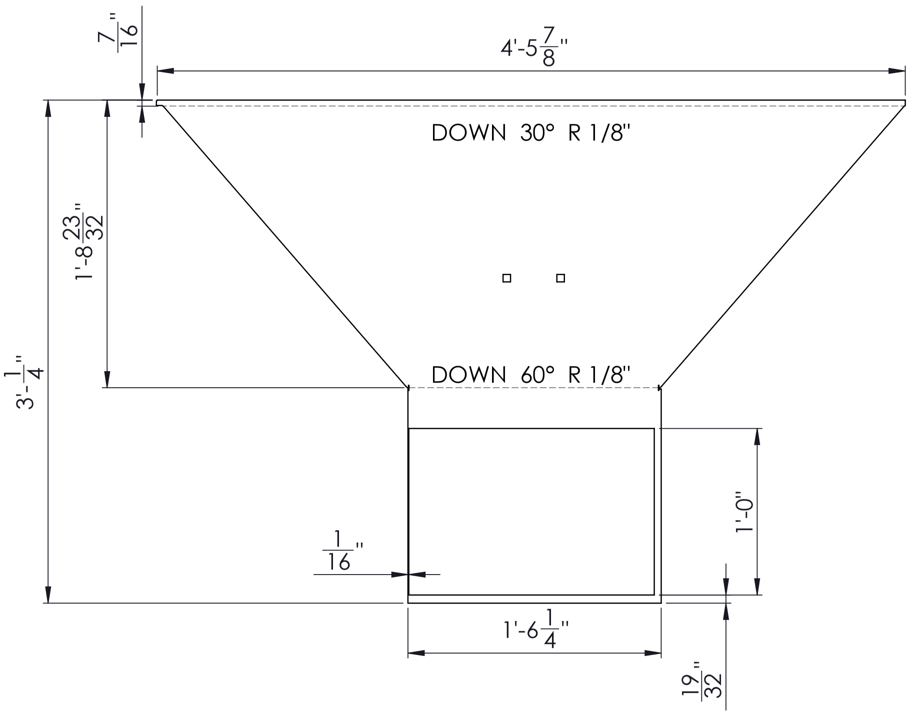
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P13	HOPPER DOOR SIDE	AISI 316 Stainless Steel Sheet (SS)	1

FLAT PATTERN



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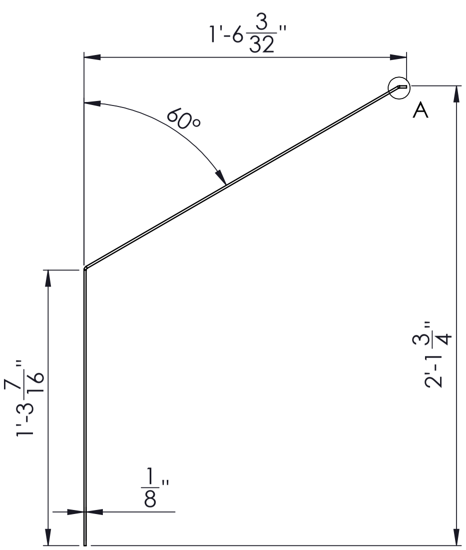

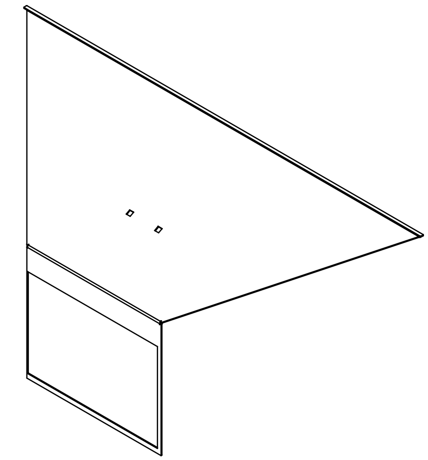

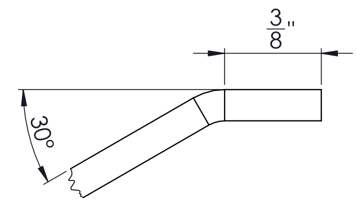

DETAIL A
SCALE 2 : 1

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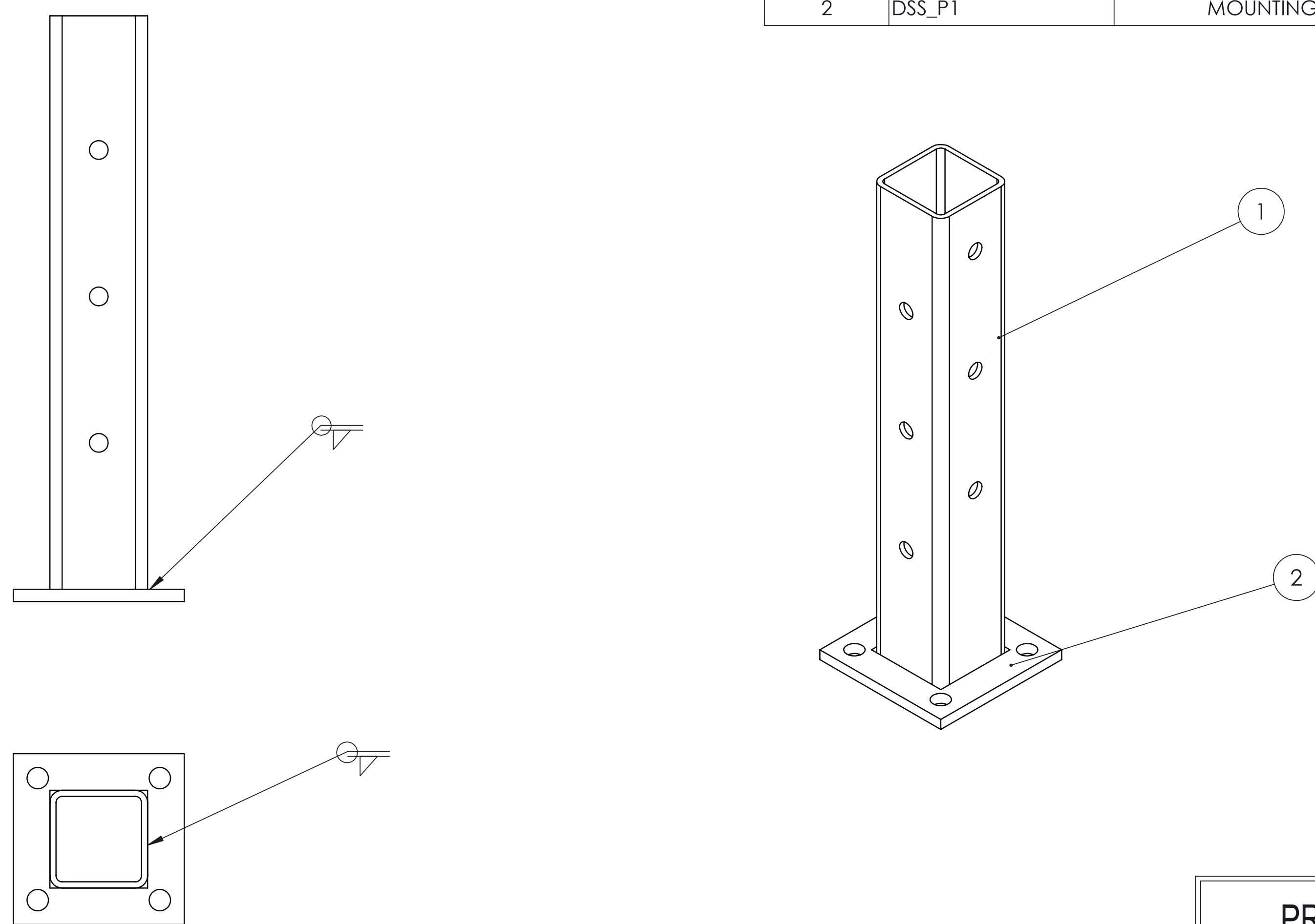
HOPPER DOOR SIDE

Proj.No. S-4???

Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_T1	HOPPER ADJSUTMENT OUTTER TUBE	1
2	DSS_P1	MOUNTING PLATE	1



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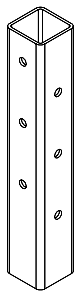
DSS_ASM_01

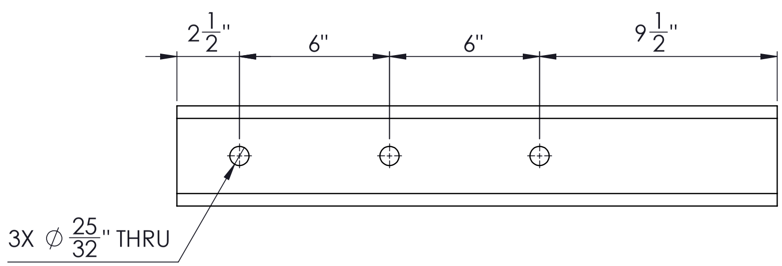
Proj.No. S-4???

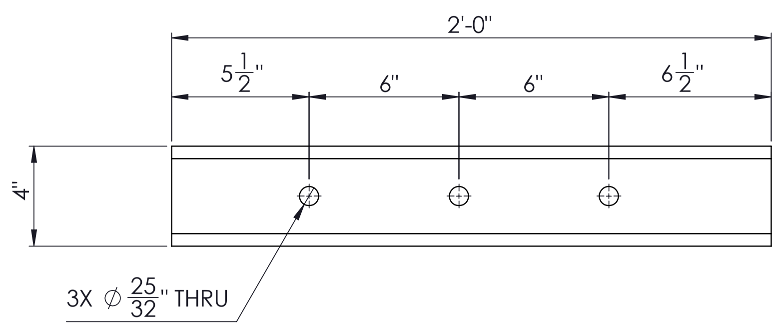
Dwg.No. ???-?-???

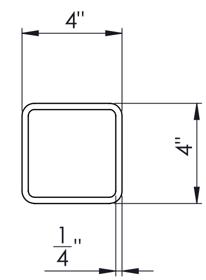
Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_T1	HOPPER ADJSUTMENT OUTTER TUBE	AISI 316 Stainless Steel Sheet (SS)	1









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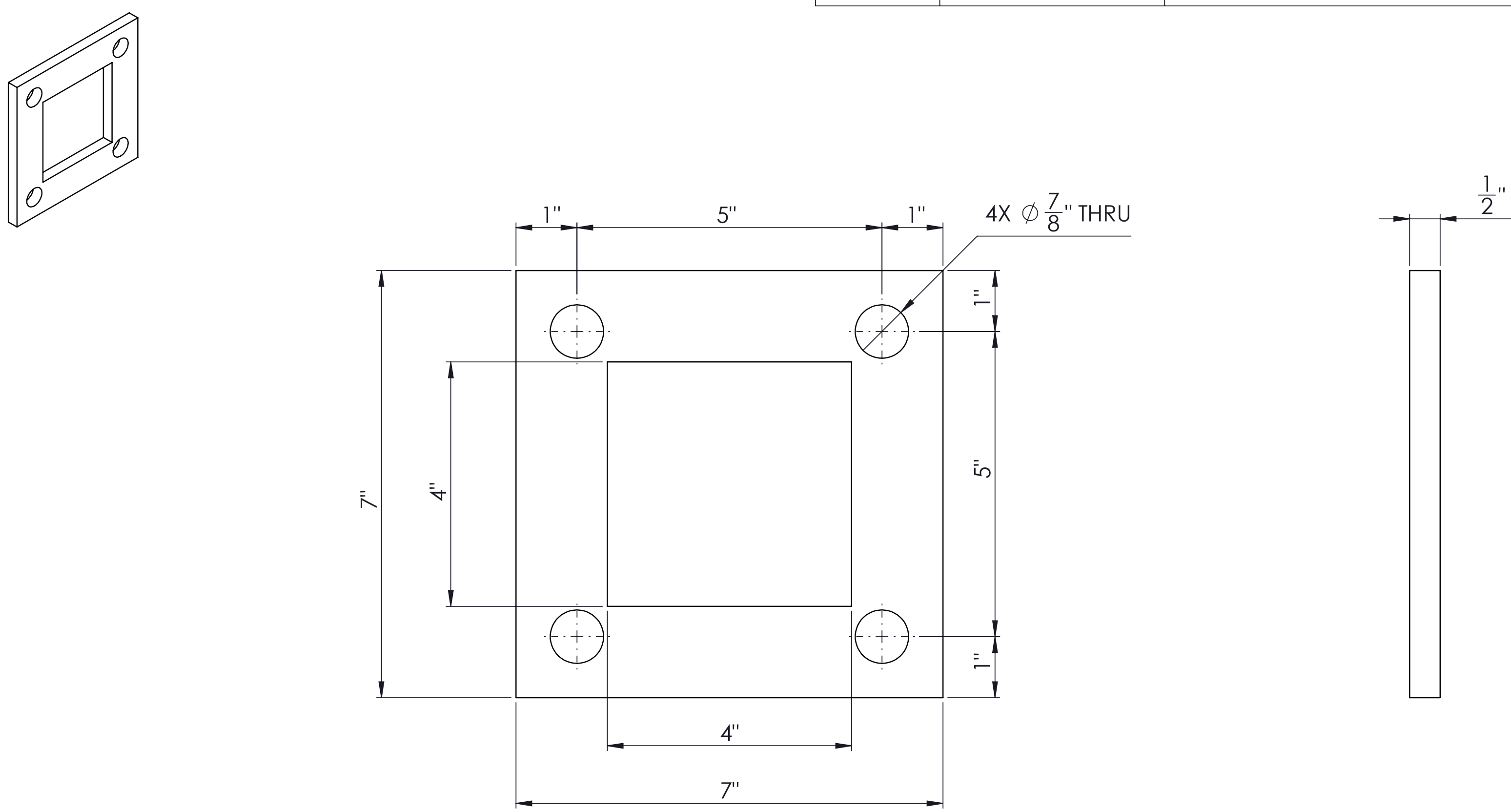
Proj.No. S-4???

Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P1	MOUNTING PLATE	AISI 316 Stainless Steel Sheet (SS)	1



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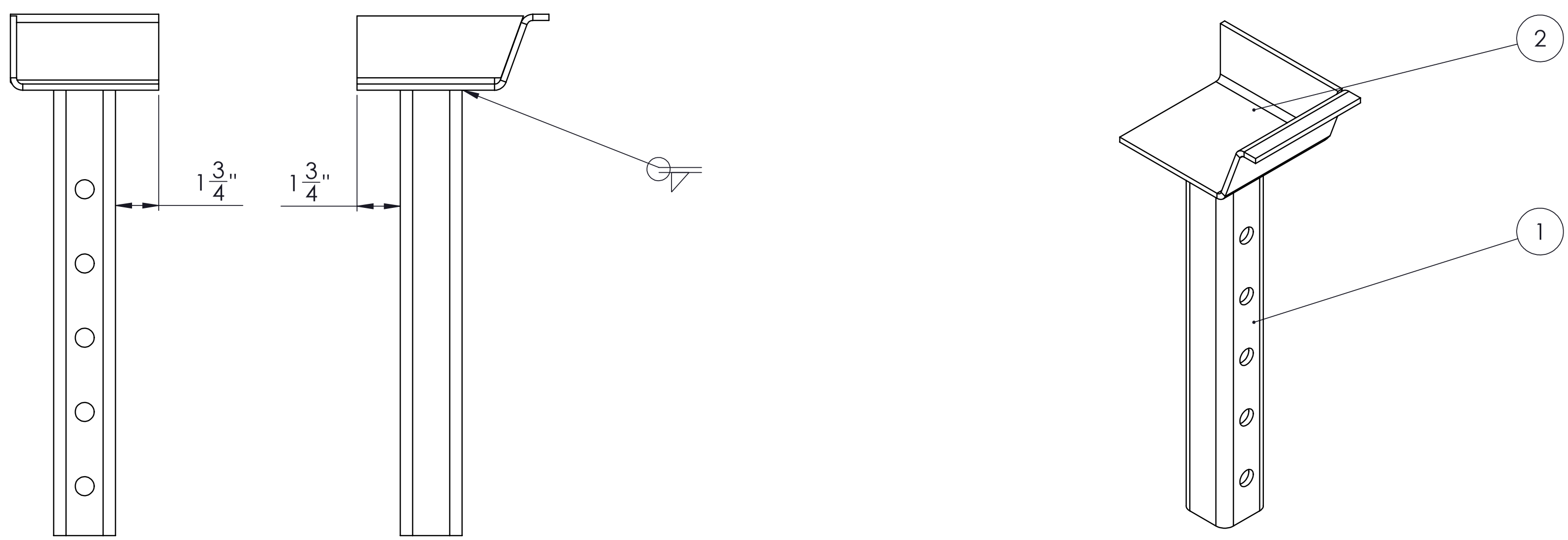
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_T5	BAG ADJUSTMENT TUBE	1
2	DSS_P4	JIG REST PLATE(1)	1



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ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
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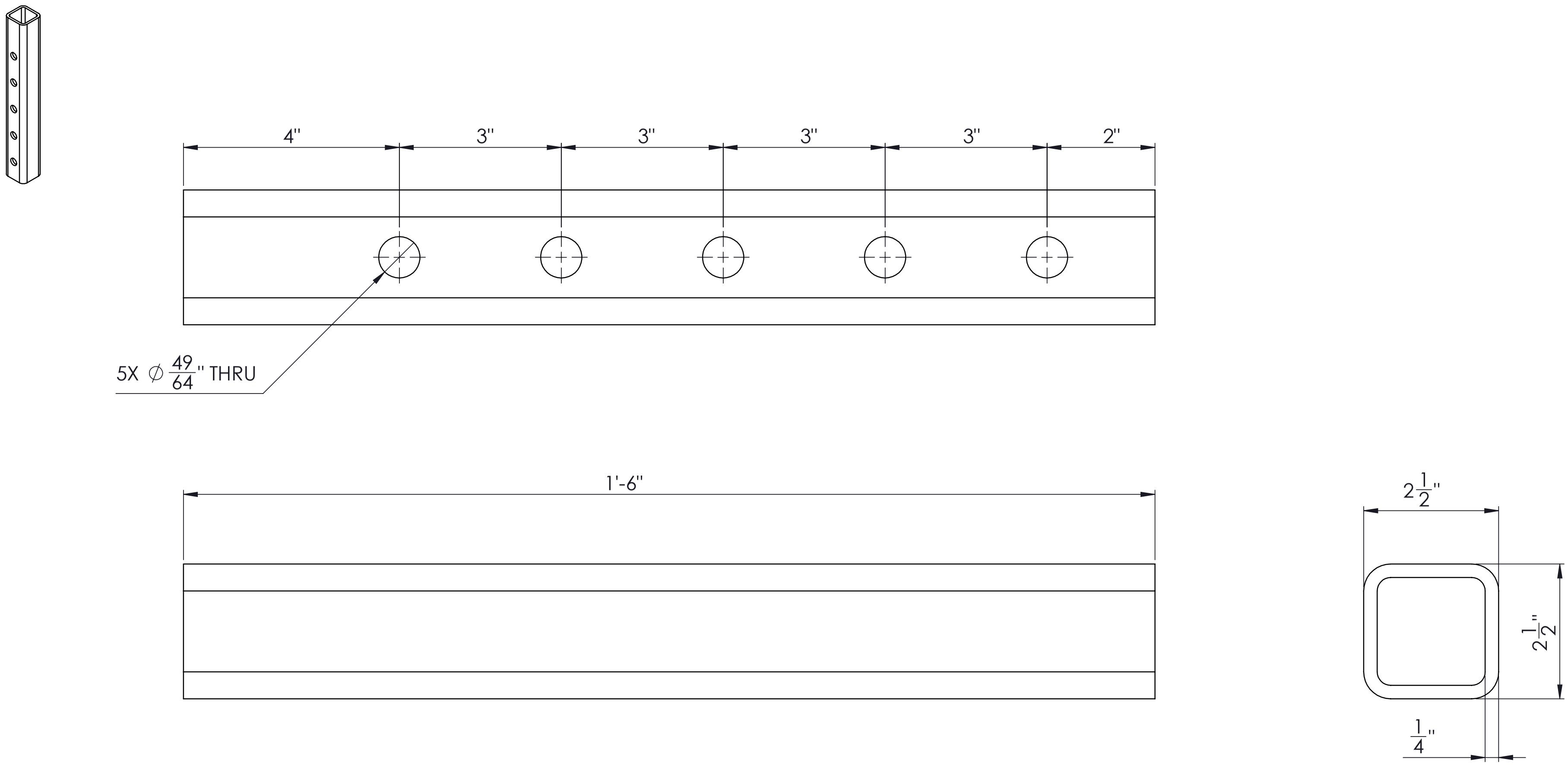

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ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
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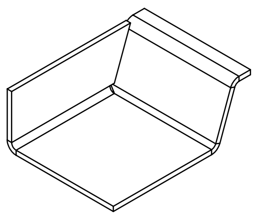

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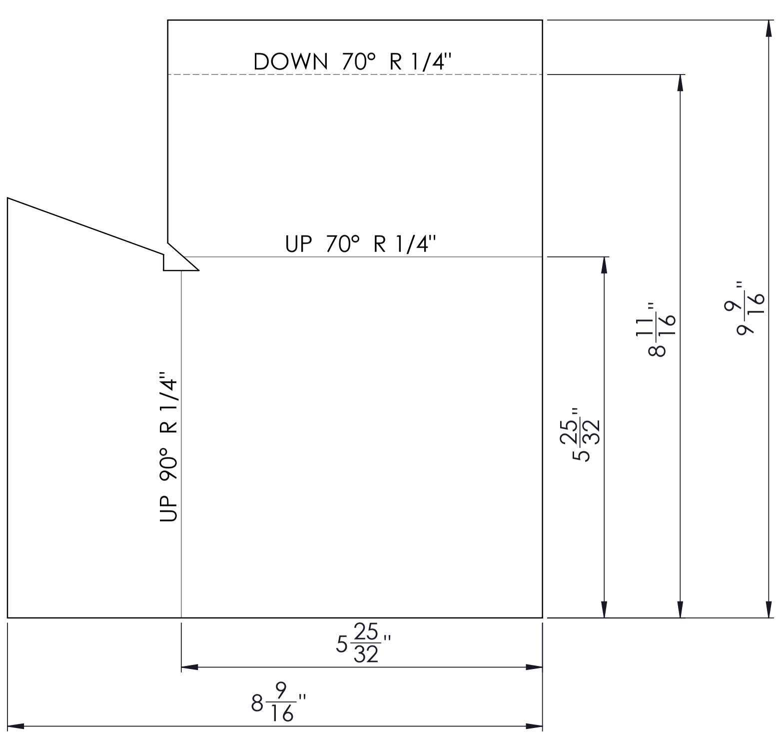

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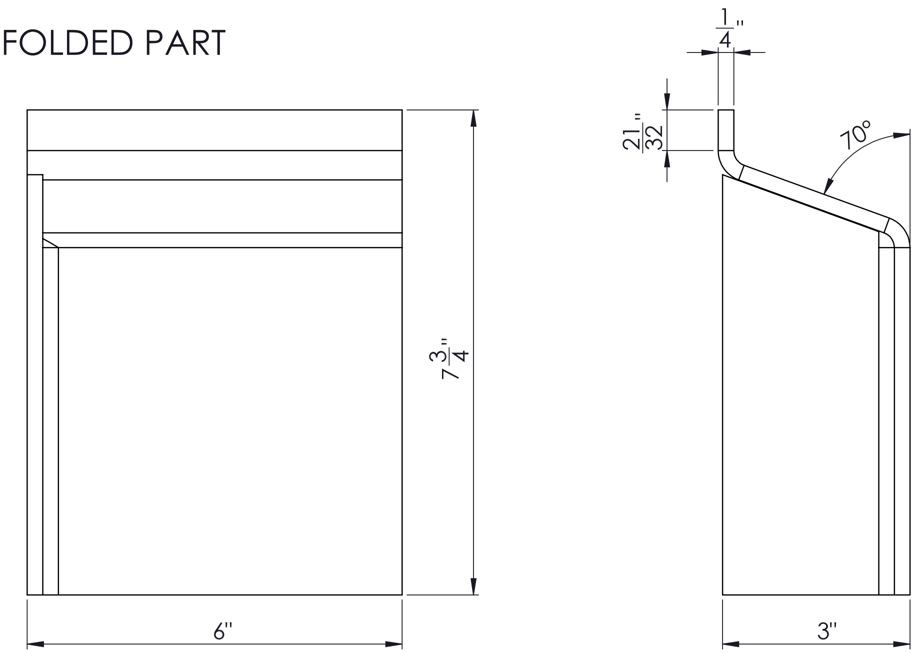

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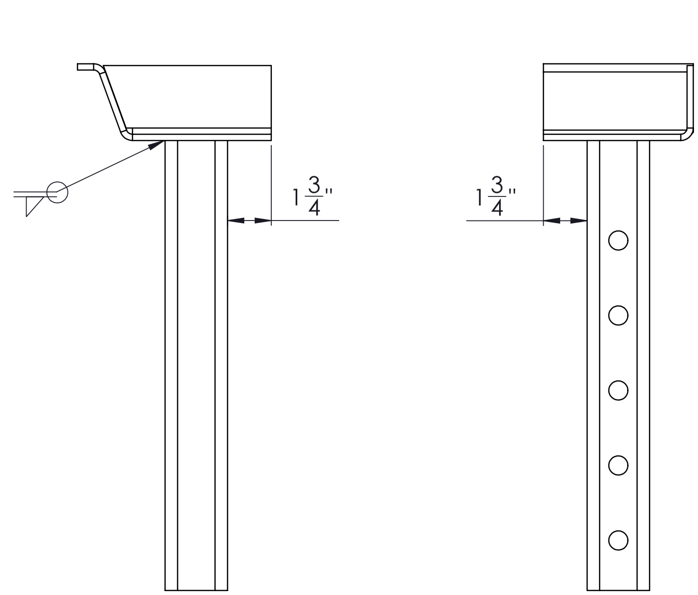
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_P5	JIG REST PLATE(2)	1
2	DSS_T5	BAG ADJUSTMENT TUBE	1



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DSS_ASM_07

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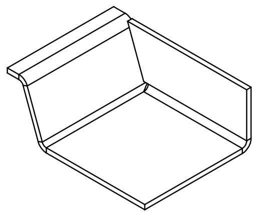
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P5	JIG REST PLATE(2)	AISI 316 Stainless Steel Sheet (SS)	1



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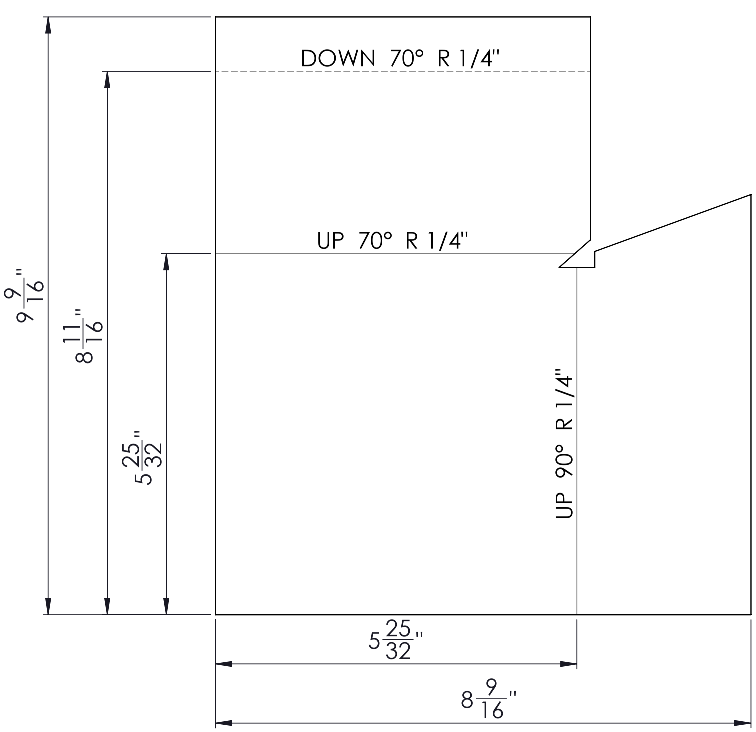

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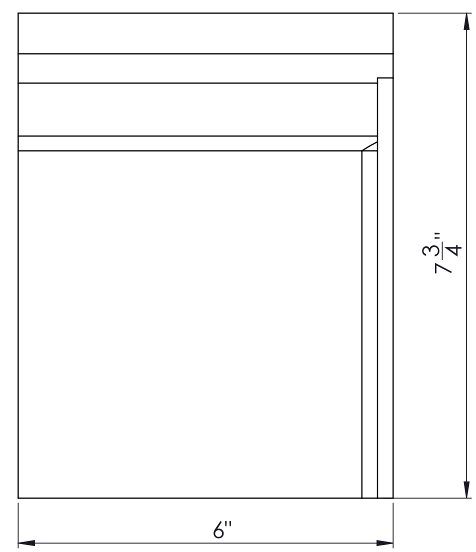

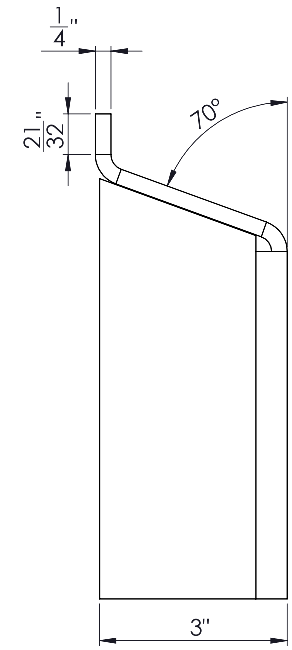

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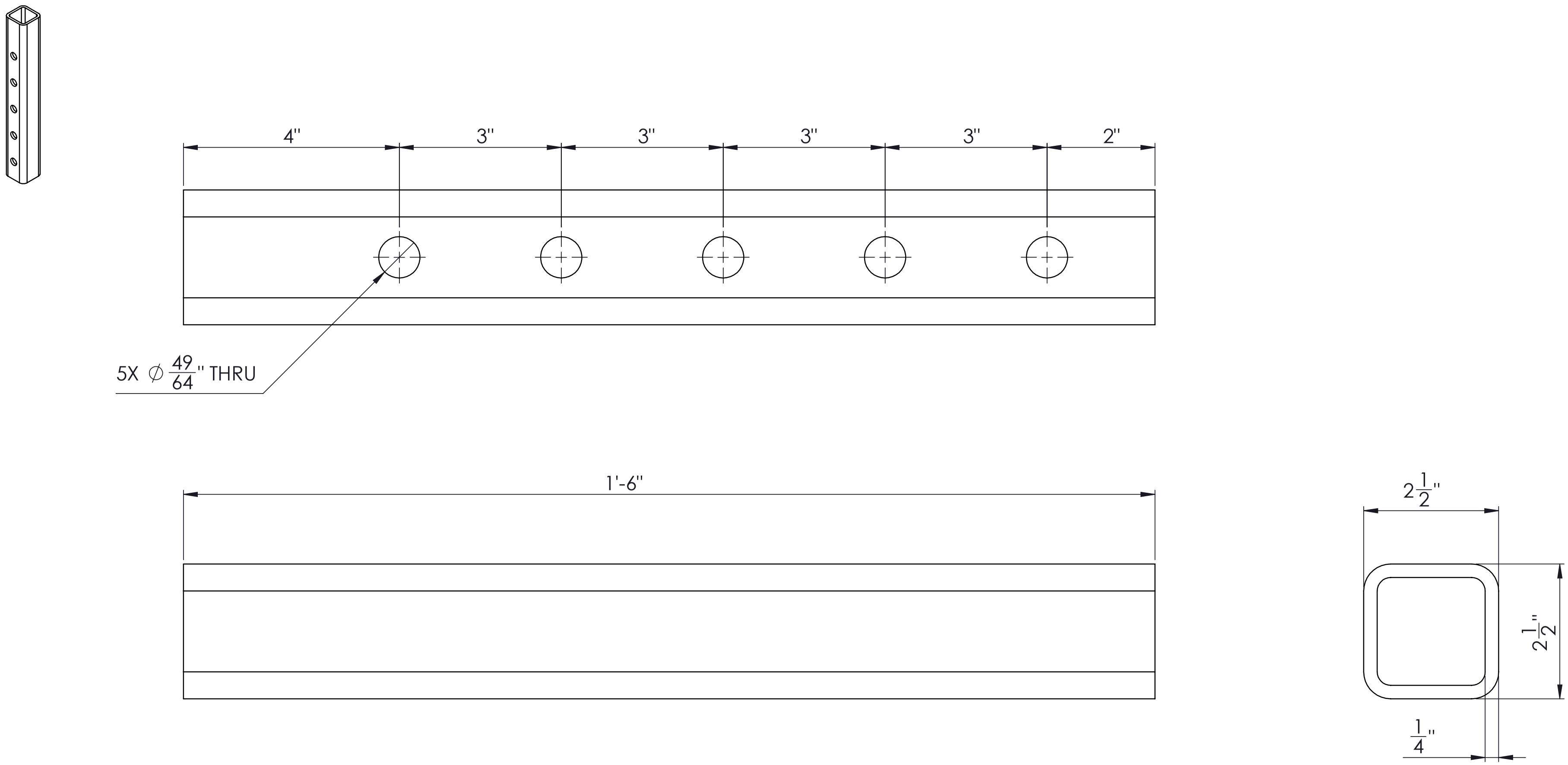
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_T5	BAG ADJUSTMENT TUBE	AISI 316 Stainless Steel Sheet (SS)	1



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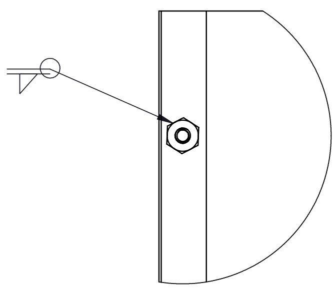
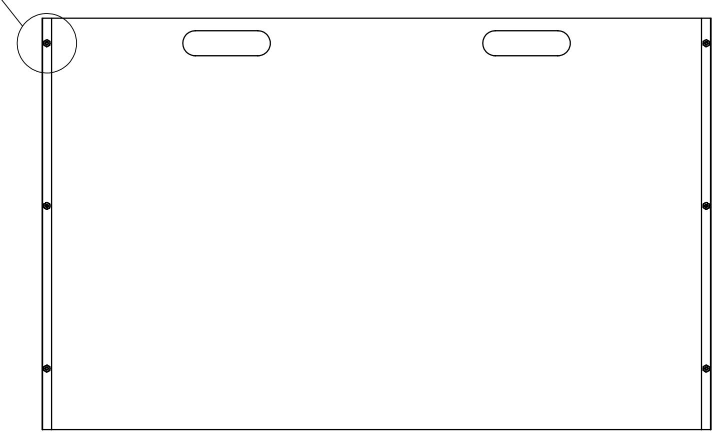
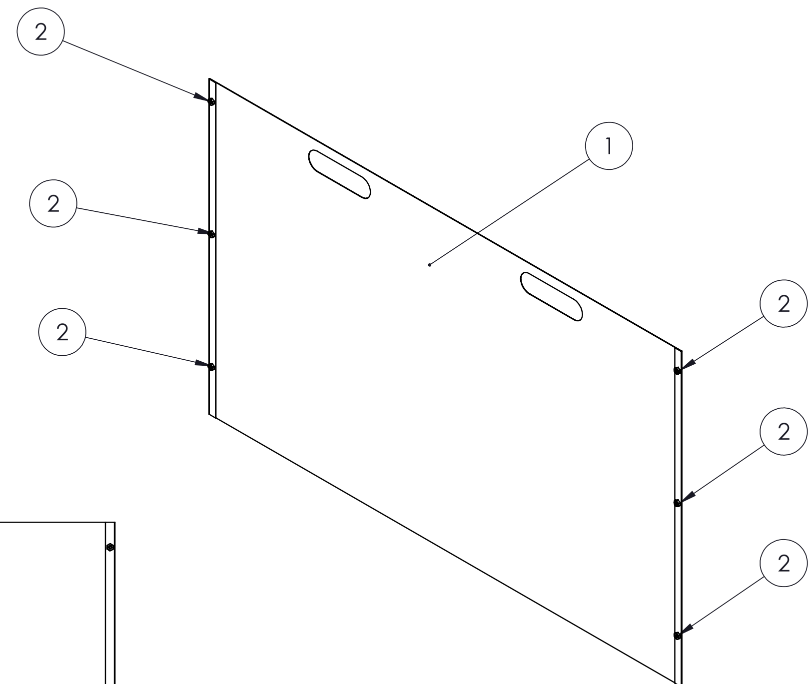
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_P3	SIDE WALL	1
2	93560A140	WELD NUT	6







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DSS_ASM_03

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Dwg.No. ???-?-???

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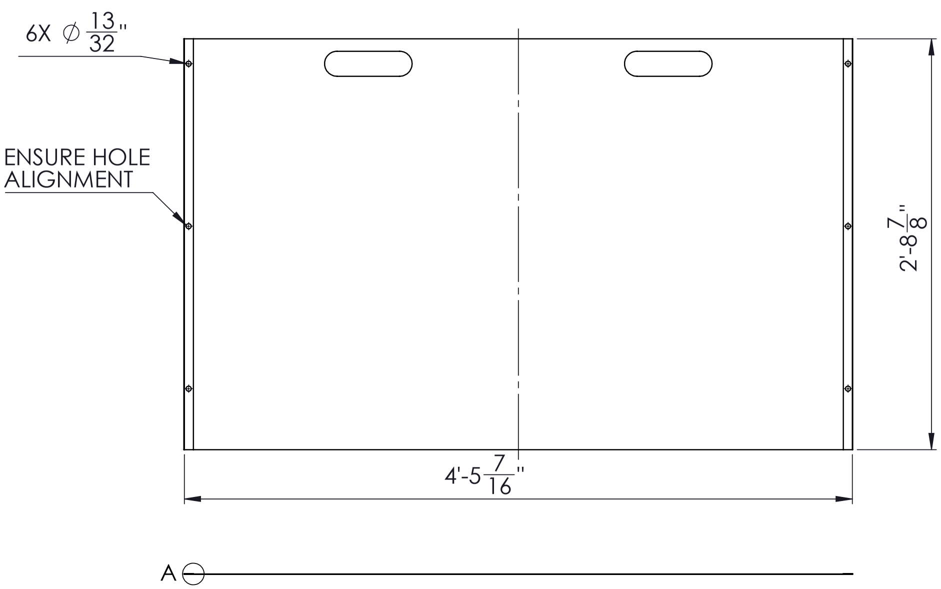
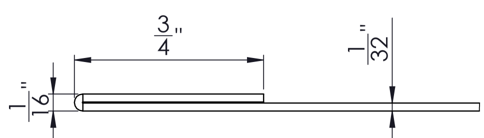
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P3	SIDE WALL	AISI 316 Stainless Steel Sheet (SS)	1

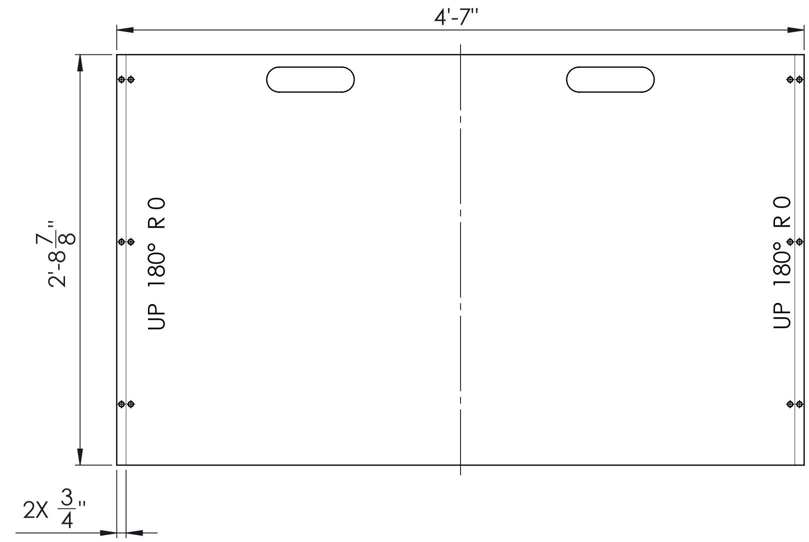
FOLDED PART





DETAIL A
SCALE 2 : 1

FLAT PATTERN



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Side Wall

Proj.No. S-4???

Dwg.No. ???-?-???

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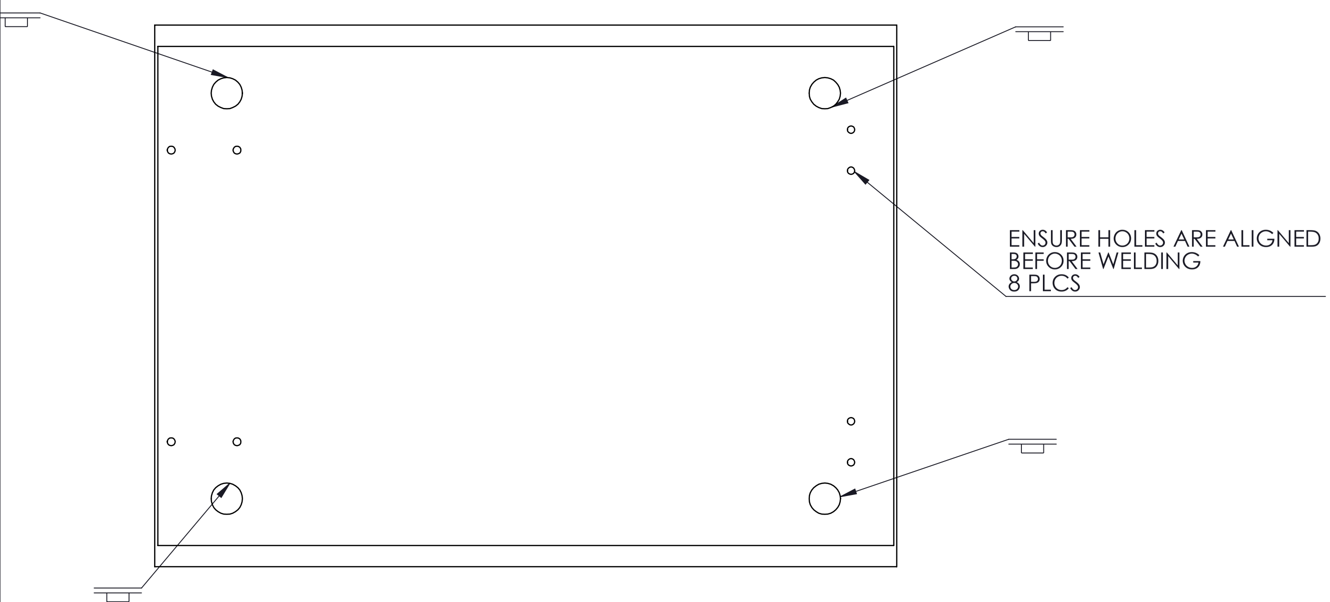
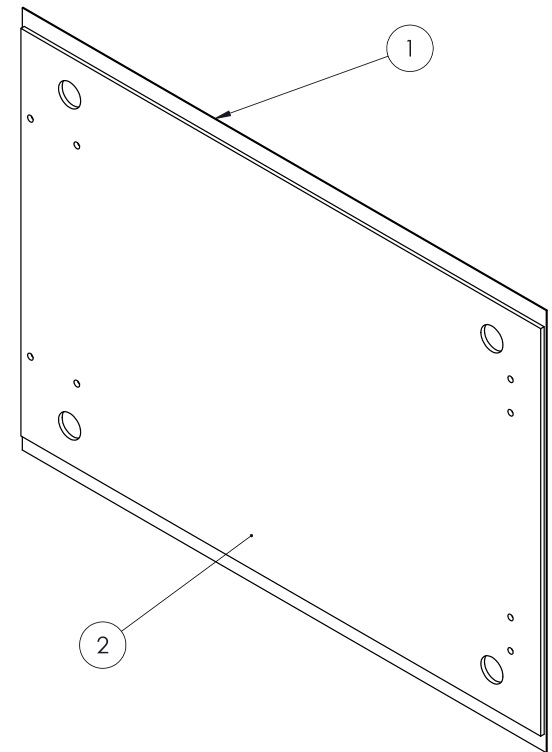
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DSS_P14	DOOR OUTER	1
2	DSS_P12	DOOR SEAL	1





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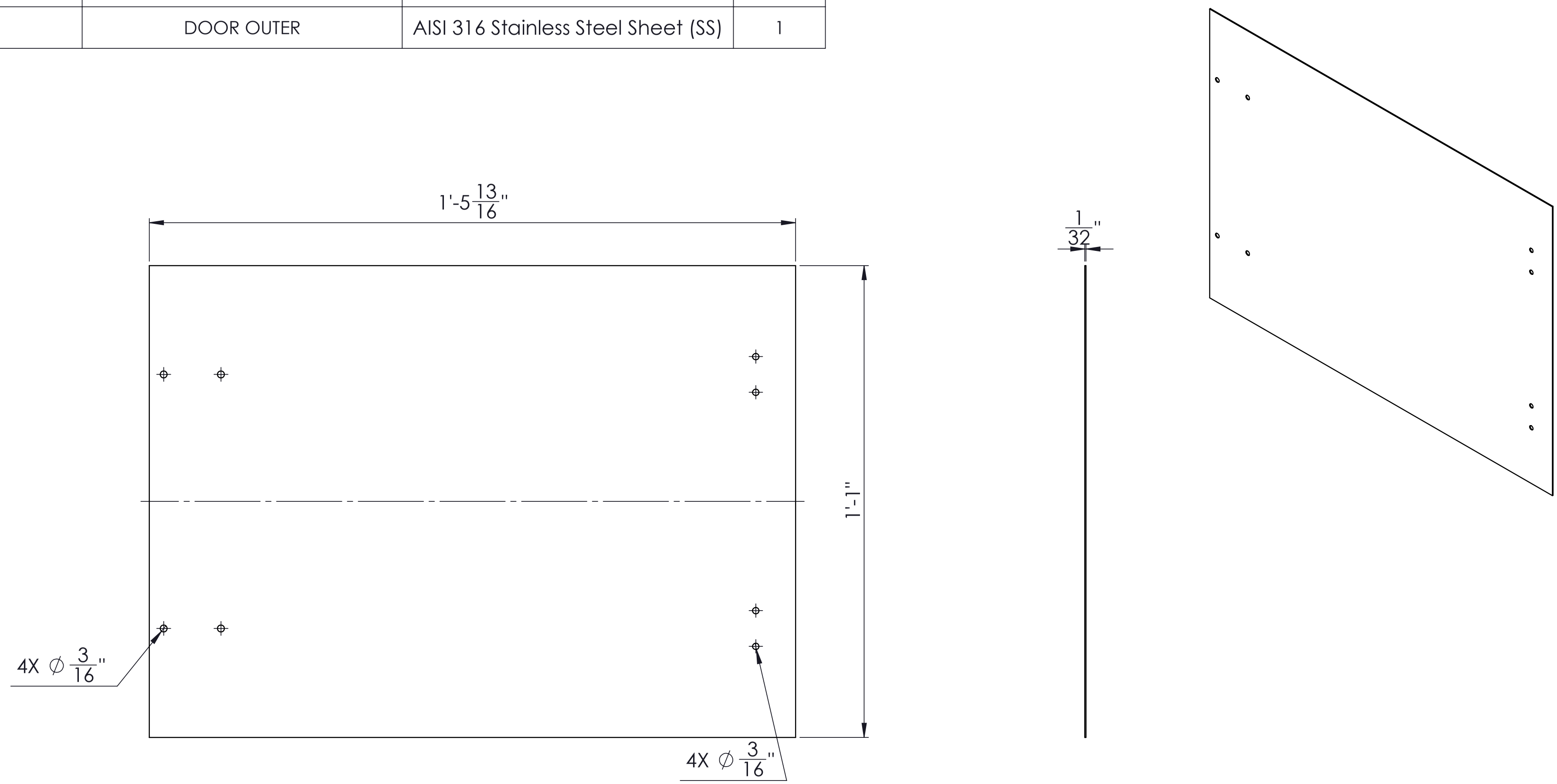
Proj.No. S-4???

Dwg.No. ???-?-???

Rev. 0

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P14	DOOR OUTER	AISI 316 Stainless Steel Sheet (SS)	1



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DOOR OUTER

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Dwg.No. ???-?-???

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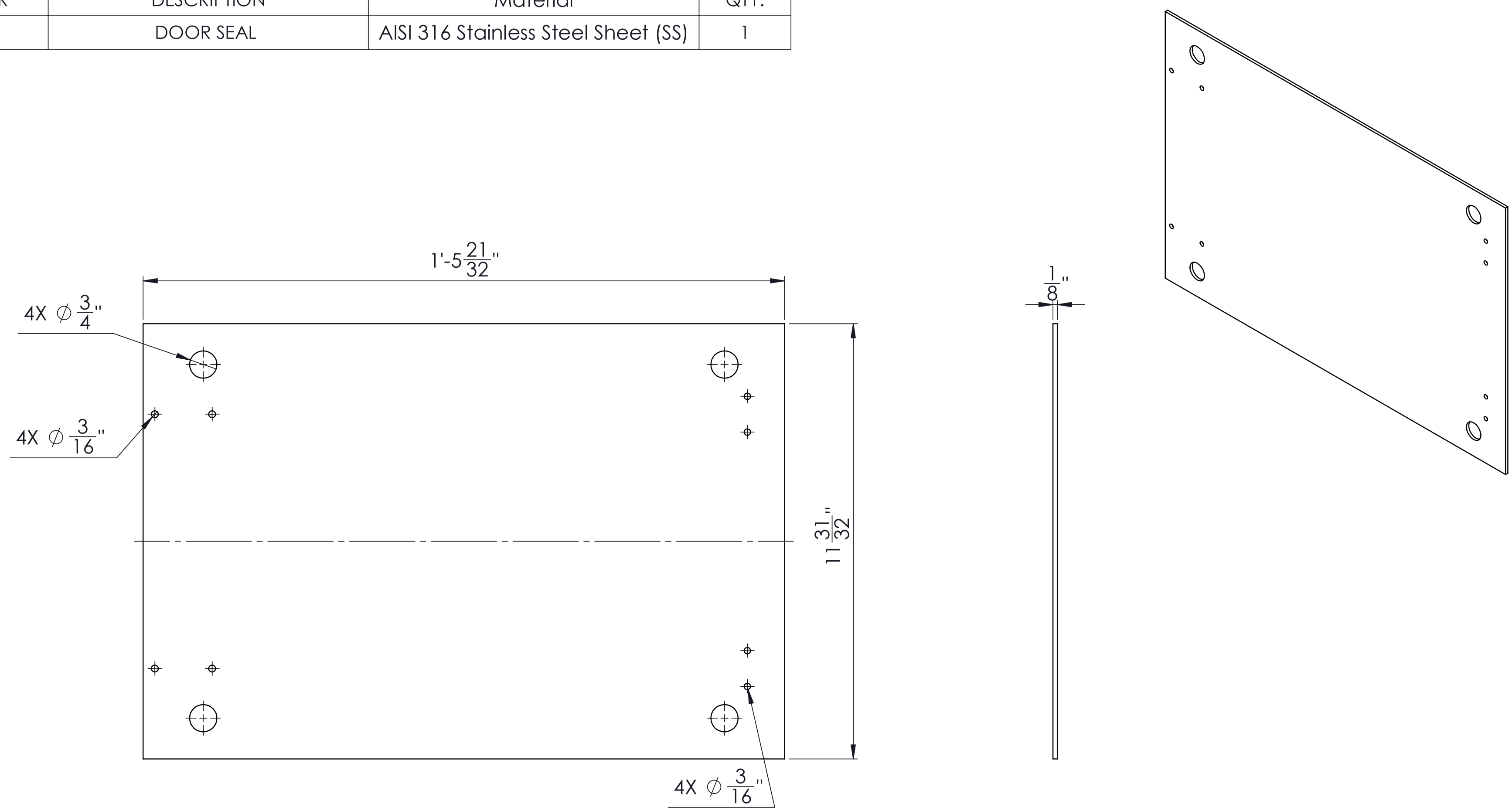
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	DSS_P12	DOOR SEAL	AISI 316 Stainless Steel Sheet (SS)	1



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DOOR SEAL

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J.8 QUOTES SUMMARY

The quotes received above from the respective suppliers and fabricators is summarized in, TABLE J.I, with the selected companies used for cost analysis bolded.

TABLE J.II: SUMMARIZED QUOTES

Company	Quoted	Cost [CAD]
Saskatoon Metal Manufacturing	**316 SS Material and Fabrication**	**$13,400**
Parkland Manufacturing LTD	316 SS Material and Fabrication	$18,496
Goodman Steel LTD	Material	$12,500
New West Metals Inc	Material	$10,492
Vibra Screw Inc.™	Complete Design	$90,000
Vibra Screw Inc.™	**Bag Splitter®**	**$5500**
Schenck Process	**Mucon™ DSV® 12 Slide Gate**	**$1100**
Superchute®	**Discharge Chute with Flange**	**$450**

Using Saskatoon Metal manufacturing, Vibra Screw Inc.™, Schenck Process and Superchute®, the total material cost estimate is $20,450 CAD, excluding taxes and shipping.

Adding labor rates provided by NRP ($85/hour) to install the design, it is estimated the design can be installed by two workers in an 8-hour shift, costing $1,360 CAD. Therefore, the total project cost including materials, fabrication and installation is estimated to be $21,810 CAD, excluding taxes and shipping. All parts have less than a 4-week lead time.

APPENDIX K – DRAWING PACKAGE

The engineering drawings for the final Bag Splitting Hopper design are attached below. Please note, NRP has final review and approval of these drawings prior to fabrication.

The max stress was found to be 3.256×10^8 [Pa] and the max displacement was found to be 3.298 [mm]. The distribution of the stress and the displacement can be seen in Figure H.6 and Figure H.7, respectively.

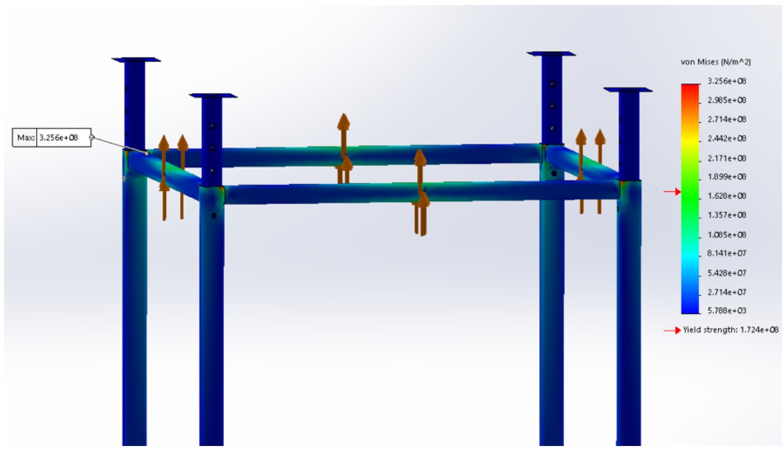

Figure H.6: Structure lift loading stress distribution

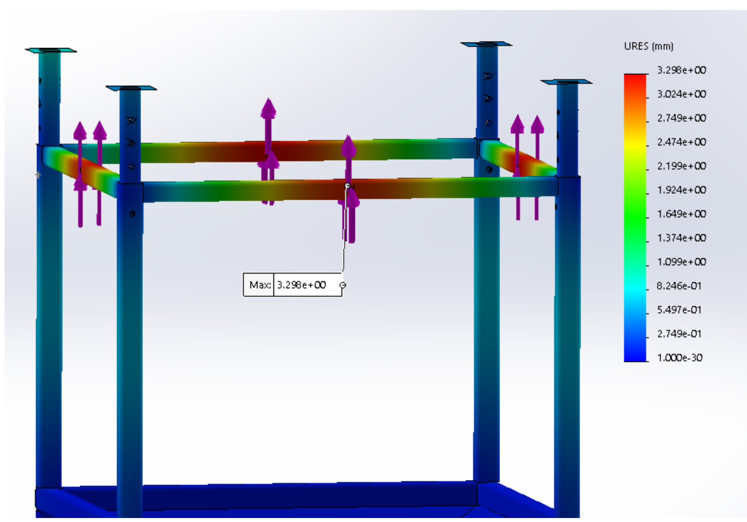

Figure H.7: Structure lift loading displacement distribution

Since the max stress concentration does not exceed meet the ultimate stress this design passed the load test. The deflection of 3 [mm] was also considered negligible as the stress in a majority of the bar is low enough to not cause permanent deformation.