# University of Manitoba IDEA Program:

# Design of an Automated Nozzle Sealing System

## Detailed Design Report

**Company:** Price Industries

**Course Code:** MECH 4860

**Professors:** Paul Labossiere, P.Eng & Sean O'Brien, P.Eng

**Team Advisor:** Meghan Guyot, P.Eng

**Team Number:** 20

**Team Members:**

Matthew Cann
Alex Czehryn
Davis McClarty
Brooke Giesbrecht

# Executive Summary

The objective of this project was to develop an automated nozzle sealing system to seal the six-inch nozzle in Price Industries’ air flow test chamber. The sealing system designed meets the client’s needs and is scalable for all five nozzle diameters. The sealing system saves Price time and labour costs by replacing manual input with an autonomous solution.

The customer needs and related technical specifications are reviewed. Next, the detailed design is split into subsections which are then explained. The customer needs are then revisited and the final design is compared to the marginal and ideal target specifications. Finally, a detailed cost analysis, as well as design recommendations and future work, are presented.

A seal against the nozzle is achieved using a self-aligning plate and a cellular urethane rubber foam sheet. A retractable mechanism moves this plate from the open position, at the wall, to the closed position, against the nozzle. The mechanism was designed to allow continuous air flow, when open, and have a minimal footprint, when closed. The mechanism is moved by an electric, rotary actuator.

The automated sealing system was designed for a 10-year lifespan. The project was allocated a budget of 5,000CAD and the total estimated project cost is 2,050CAD. A computer aided design model of the mechanism will be sent through private communication to the client as part of the final package.

# Contents

Executive Summary ....................ii

List of Figures ....................vi

List of Tables ....................vii

1. Introduction .................... 1

1.1 Project Definition .................... 1

1.1.1 Problem Statement .................... 2

1.1.2 Project Objectives .................... 3

1.1.3 Constraints and Limitations .................... 4

1.1.4 Customer Needs .................... 5

1.1.5 Technical Specifications .................... 6

1.1.6 Design Methodology .................... 8

2. Detailed Design .................... 9

2.1 Design Overview .................... 9

2.2 Spider Mechanism .................... 10

2.2.1 Geometry .................... 10

2.2.2 Linkage Dimensions .................... 12

2.2.3 Pin Configuration .................... 13

2.3 Sealing System .................... 14

2.3.1 Sealing Plate ........ 15

2.3.2 Hinges ........ 16

2.3.3 Sealing Material ........ 17

2.4 Support Structure ........ 17

2.4.1 Mounting Plate ........ 18

2.4.2 Wall Brackets ........ 19

2.4.3 Mechanism Mounts ........ 19

2.5 Actuator Assembly ........ 20

2.5.1 Actuator ........ 20

2.5.2 Mounting ........ 21

2.5.3 Coupling with Spider Mechanism ........ 22

2.6 Summary of Final Design ........ 23

3. Cost Analysis ........ 27

4. Final Recommendations and Future Work ........ 28

5. Conclusion ........ 30

6. References ........ 32

7. Appendix A – Customer Needs and Technical Specifications ........ A-1

8. Appendix B – Concept Development ........ B-1

9. Appendix C – Drawings ........ C-1

10. Appendix D – Solid Mechanics Analyses....................D-1

11. Appendix E – Material Selection.................... E-1

12. Appendix F – GMB(X)24-SR Technical Data Sheet.................... F-1

13. Appendix G – Detailed Assembly Instructions....................G-1

14. Appendix H – Detailed Cost....................H-1

# List of Figures

Figure 1.1. Depiction of the air flow test chamber ........ 2

Figure 1.2. Depiction of a nozzle from (a) the throat side and (b) the mouth side. ........ 3

Figure 2.1. Spider mechanism with subsections. ........ 9

Figure 2.2. Spider mechanism in the (a) open position and (b) closed position. ........ 11

Figure 2.3. Mechanism linkage dimensions for a 6 in diameter nozzle ........ 11

Figure 2.4. Mechanism linkage joints schematic from the (a) side and (b) front. ........ 14

Figure 2.5. Sealing system. ........ 15

Figure 2.6. Aluminum sealing plate. ........ 15

Figure 2.7. Hinge assembly. ........ 16

Figure 2.8. Design support structure against the nozzle wall. ........ 18

Figure 2.9. Mounting plate render. ........ 18

Figure 2.10. Wall bracket attachment to (a) support plate and (b) wall. ........ 19

Figure 2.11. Bracket to mount the mechanism to the mounting plate. ........ 20

Figure 2.12. Belimo's GMB24-SR actuator. ........ 21

Figure 2.13. Actuator mounting assembly. ........ 22

Figure 2.14. Custom actuator arm mounting the mechanism. ........ 23

Figure 2.15. Complete final design render of the spider mechanism. ........ 23

# List of Tables

TABLE I: PROJECT CONSTRAINTS AND LIMITATIONS ........ 5

TABLE II: LIST OF CUSTOMER NEEDS AND RELATIVE IMPORTANCE ........ 6

TABLE III: LIST OF METRICS AND CORRESPONDING MARGINAL AND IDEAL TARGETS ........ 7

TABLE IV: FINAL DIMENSIONS OF LINKAGES AND PIN HOLE DIAMETERS. ........ 13

TABLE V: FINAL DESIGN SPECIFICATIONS ........ 25

TABLE VI: COST ANALYSIS ........ 27

# 1. Introduction

Price Industries (Price) tests their air distribution products using an air flow test chamber. Within this test chamber there is a nozzle bank consisting of five nozzles. To reach distinct air flow rates, combinations of the nozzles must be sealed. Currently, Price's method to seal the nozzles is tedious and time consuming. Therefore, team 20 is tasked with designing an automated sealing system to reduce the time required to seal the nozzles.

An explanation of the problem, the customer needs and the technical specifications is provided before all components of the final design are explained. A cost analysis of the design is then provided before the final recommendations and the future work that can be complete on the design are discussed.

## 1.1 Project Definition

Since its inception, Price has become a market leader in the heating, ventilation, and air conditioning (HVAC) industry. Price invests heavily into research as they believe investment in product development creates effective products and solutions for their customers. As a testament to Price's commitment to innovation, the Price Research Center North was constructed in 1978. This research center allows for testing of real-time environments using their 16 specialized testing rooms, three fan rooms and two sound testing rooms [1].

Air flow performance is tested for various HVAC products, including fan powered terminals, fan coils and blower coils within one of the air moving testing rooms. A test chamber containing a nozzle bank, as shown in Figure 1.1, is used to acquire an accurate reading of the air flow rate for any given product.

Figure 1.1. Depiction of the air flow test chamber [2].

The nozzle bank consists of five nozzles varying in diameter and can generate volumetric flow rates between 100 CFM and 10,000 CFM [3]. A combination of sealed and opened nozzles is needed to achieve these specified volumetric flow rates.

### 1.1.1 Problem Statement

The current method of sealing a nozzle is a manual hand pump used to inflate ball pipe plugs to the desired diameter. This process is time consuming, as multiple tests are performed daily and the plugs must be deflated and inflated repeatedly. Therefore, to save time and labour, Price requires a scalable, automated device capable of sealing different sized nozzles. To ensure all air flow measurements are accurate, it is essential that the device creates a strong seal, allowing little amount of air to leak.

Previously, Price attempted to solve this sealing problem with an automatic pneumatic sealing system consisting of a metal plate and gasket that covered the throat of the nozzles. A depiction of a nozzle from the throat and mouth ends is shown in Figure 1.2.

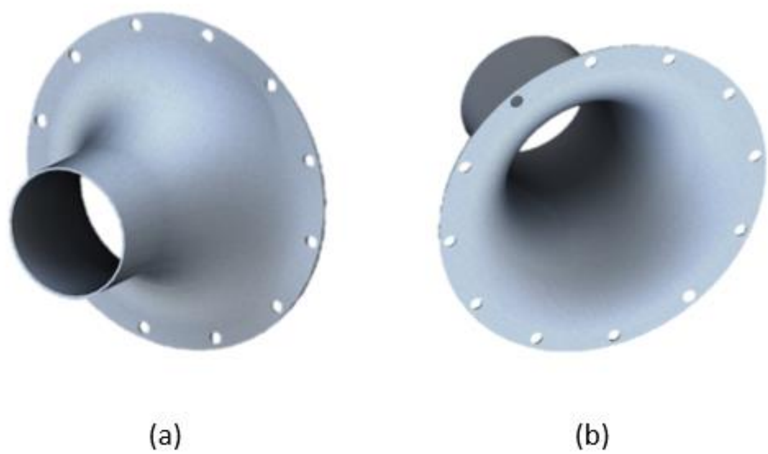



Figure 1.2. Depiction of a nozzle from (a) the throat side and (b) the mouth side [4].

The operation of Price's previous attempt was stopped because the metal plate and gasket could not withstand the pressure differential between the two sections of the test chamber. As a result, Price prefers a system that does not use pneumatics, but rather electric, linear actuators.

### 1.1.2 Project Objectives

The purpose of this project was to design an automated nozzle sealing system for Price's nozzle bank testing chamber. The design was modeled for the six-inch nozzle and was ensured a complete seal with respect to gauge pressures ranging from -3 to +3 inches of water at room temperature.  The system was designed to fit within the testing chamber, to avoid the pressure taps on the wall, and to ensure the flow through the nozzle is unimpeded when sealing is not required. The sealing system is a scalable design, allowing for size modifications to fit the various sized nozzles.

The final report package includes the following deliverables as requested by the client:

- Design report containing the following sections
    - Design methodology
    - Design justification
    - Cost analysis
- Complete design that allows implementation of automation
- Design life lasts approximately 10 years
- CAD model of the system
- Manufacturing and assembly instructions
- Bill of materials
- Preliminary list of vendors

**The project scope does not include the following:**

- Any electrical and signal aspects of the automation process
- Sensors to determine if the complete seal is lost

### 1.1.3 Constraints and Limitations

Restrictions caused by the engineering design course schedule and Price's needs, create constraints and limitations for the project. The constraints and limitations that impact the project are summarized in TABLE I.

TABLE I: PROJECT CONSTRAINTS AND LIMITATIONS

| | **Constraint or Limitation** | **Measurable Restriction** |
|---|---|---|
| **1** | Project deadline | December 5th, 2018 |
| **2** | Design space | 77 ¾ in X 27 ⅝ in |
| **3** | Interaction with nozzles | No damage |
| **4** | Location and size of nozzles | Fixed |
| **5** | Independence of nozzles | N/A |
| **6** | Analytical methodologies | N/A |
| **7** | Prototyping opportunity | N/A |
| **8** | Client availability | N/A |

A further description of all the above constraints and limitations is found in Appendix A.

### 1.1.4 Customer Needs

The team identified a list of project needs that the final design must satisfy from correspondence with Price. The needs are broken into six main sections: operational, environmental, automation, manufacturing and cost, lifecycle and aesthetic needs. Each need was analyzed and assigned an importance ranking of high, medium or low, denoted by ●, ○, ▽, respectively. The importance rating of each need was used to weigh and score the proposed designs. A detailed description of each need and the rationale for the importance rating is found in Appendix A. These needs are outlined in Table II and was confirmed with Price.

TABLE II: LIST OF CUSTOMER NEEDS AND RELATIVE IMPORTANCE

| Need # | Customer Needs | Imp* |
|---|---|---|
| | **Operational Needs** | |
| **1** | The sealing system's operational space allows continuous air flow | ● |
| **2** | The sealing system completely prevents any air from passing through | ● |
| **3** | The sealing system can be scaled to function on any nozzle size | ● |
| **4** | The sealing system adheres to space constraints | ● |
| | **Environmental Needs** | |
| **5** | The sealing system remains operational at room temperature | ● |
| **6** | The sealing system remains operational between two chambers of varying pressures | ● |
| | **Automation Needs** | |
| **7** | The sealing system for each nozzle can be operated independently | ● |
| **8** | The sealing systems for each nozzle are operational in tandem | ● |
| | **Manufacturing and Cost Needs** | |
| **9** | The sealing system is simple in design | ○ |
| **10** | The sealing system is easy to assemble | ∇ |
| **11** | The sealing system has detailed instructions to build | ∇ |
| **12** | The sealing system components can be sourced from Canadian vendors | ∇ |
| **13** | The sealing system is affordable to implement | ∇ |
| | **Lifecycle Needs** | |
| **14** | The sealing system components are durable | ○ |
| **15** | The sealing system is easily accessible for maintenance | ∇ |
| | **Aesthetic Needs** | |
| **16** | The sealing system is tidy | ∇ |

* ● = High, ○ = Medium, ∇ = Low

### 1.1.5 Technical Specifications

The team generated a list of technical specifications in the form of engineering metrics and corresponding marginal and ideal values. The metrics were created to evaluate Price's needs based on numerical values. Each need was correlated to one or more metrics; each metric was given a unit and an ideal value to verify the need(s). A detailed description of each specification and the corresponding values is found in Appendix A. In Table III, the metrics, linked needs, units and the marginal and ideal targets are outlined.

TABLE III: LIST OF METRICS AND CORRESPONDING MARGINAL AND IDEAL TARGETS

| **Metric #** | **Need #** | **Metric** | **Unit** | **Marginal value** | **Ideal Value** |
|---|---|---|---|---|---|
| **1** | 1 | Change in fan power | Watts | 1 | 0.5 |
| **2** | 2 | Air flow rate when sealed | Cubic Feet per Minute | 0.1 | 0.05 |
| **3** | 3 | Nozzle compatibility | # | 1 to 5 | 5 |
| **4** | 4 | Footprint | Feet and Inches | 4’ 10½” x 8’ 4¼” | 4’ 10½” x 8’ 4¼” |
| **5** | 5 | Operational temperature range | Fahrenheit | 68 to 72 | 50 to 150 |
| **6** | 6 | Operational pressure range | Inches of $H_2O$ | -3 to 3 | -6 to 6 |
| **7** | 7 | Each nozzle can be operated independently | Binary | 1 | 1 |
| **8** | 8 | Nozzle devices can operate in tandem | Binary | 1 | 1 |
| **9** | 9 | Number of parts | Number | < 35 | < 25 |
| **10** | 10,11 | Time to assemble design | Hours | < 3 | < 1 |
| **11** | 12 | Vendors | List | Majority Canadian | All Canadian |
| **12** | 13 | Unit manufacturing costs | Canadian Dollars | < 5000 | < 4000 |
| **13** | 14 | Lifespan | Years | > 10 | > 15 |
| **14** | 15 | Time to disassemble/assemble for maintenance | Minutes | < 30 | < 20 |
| **15** | 16 | Visually organized | Subjective | Pass | Pass |

### 1.1.6 Design Methodology

Preliminary concepts were generated by performing research on any relevant patents and competitor designs. The team also reached out to professors at the University of Manitoba who have experience with complex mechanisms. The design was divided into five categories: (1) sealing method, (2) mechanism, (3) seal material, (4) location and (5) side of chamber, each with multiple design concepts. Each category was analyzed separately, and a sensitivity analysis was performed on the sealing methods and mechanisms.

Further analyses consisted of scoring the designs based on six criteria: (1) manufacturability, (2) simplicity of mechanism, (3) footprint, (4) cost, (5) maintenance and (6) aesthetics. The criteria were inputted into a weighted decision matrix, one each for the sealing method and mechanism. The weighted decision matrix revealed the top sealing method and the top two mechanisms, which were combined with an appropriate seal material, location and side of chamber during the detailed design phase. A plate design was selected for the sealing method. Two designs were selected as potential sealing mechanisms, with the final design selected by Price. The concepts and selection for the sealing system and mechanism are found in Appendix B.

After the final design was selected, a detailed solid mechanics analysis was performed. From this analysis, the mechanism material and geometry were determined, and a CAD model was created. Finally, an actuator was selected, and a supporting plate was designed to facilitate the operation of the mechanism.

# 2. Detailed Design

A design was developed for an automated nozzle sealing system within Price's air flow testing chamber. The design was divided into four main subsections to elucidate the analysis and operation of the sealing system; the four subsections include: (1) spider mechanism, (2) sealing system, (3) support structure, and (4) actuator assembly. The combination of these subsections forms a design that meets all the customer's needs.

## 2.1 Design Overview

The integrated system with all subsections is shown in Figure 2.1; the spider mechanism is coloured blue, the sealing system yellow, the support structure red, and the actuator green.

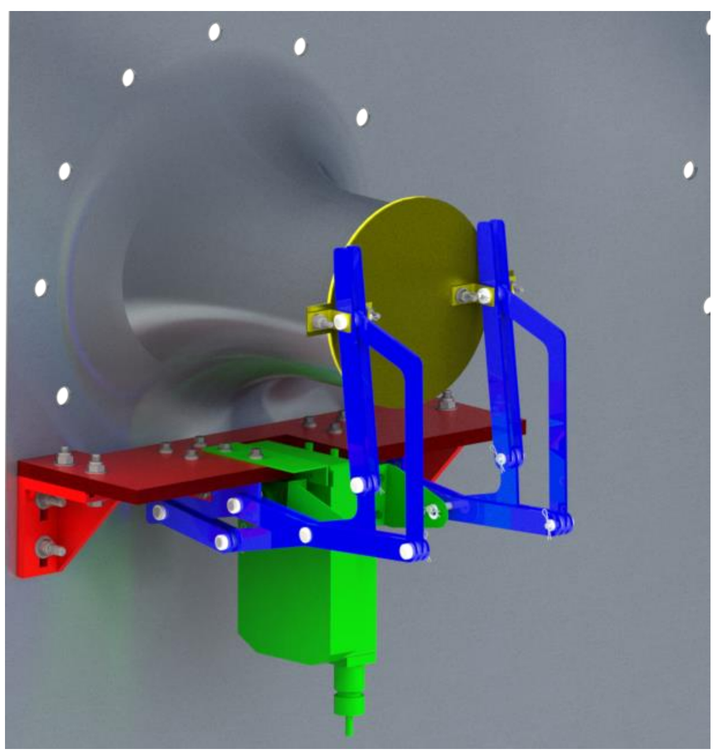


Figure 2.1. Spider mechanism with subsections [5].

The support structure is used to connect the entire system to the chamber wall whilst providing sufficient space for all components to attach. The spider mechanism is connected to the support structure and retracts out of the air flow, when open, while extending into an upright position against the nozzle, when closed. The sealing system is comprised of a metal plate and rubber material which is pushed against the nozzle to impede airflow when the spider mechanism is in the closed position. Finally, the actuator is connected to the support structure and is coupled with the spider mechanism through two actuator arms, transferring the required torque to the mechanism. Technical drawings for all components of each subsection are found in Appendix C.

## 2.2 Spider Mechanism

Throughout the design process of the spider mechanism, the customer's needs were considered. Specifically, the mechanism was designed to allow continuous air flow and maintain a small footprint. The spider mechanism is comprised of five linkages connected via clevis pins. The mechanism is bolted to the support plate and moves the sealing system to the nozzle throat.

### 2.2.1 Geometry

The mechanism's linkages dimensions were designed to allow the plate to actuate from the open to closed position. Iterations of the linkage geometry were conducted to maximize the horizontal force applied to the nozzle; the analysis is shown in Appendix D. The actuator rotates 85° between the open and closed positions; the open and closed positions are shown in Figure 2.2.

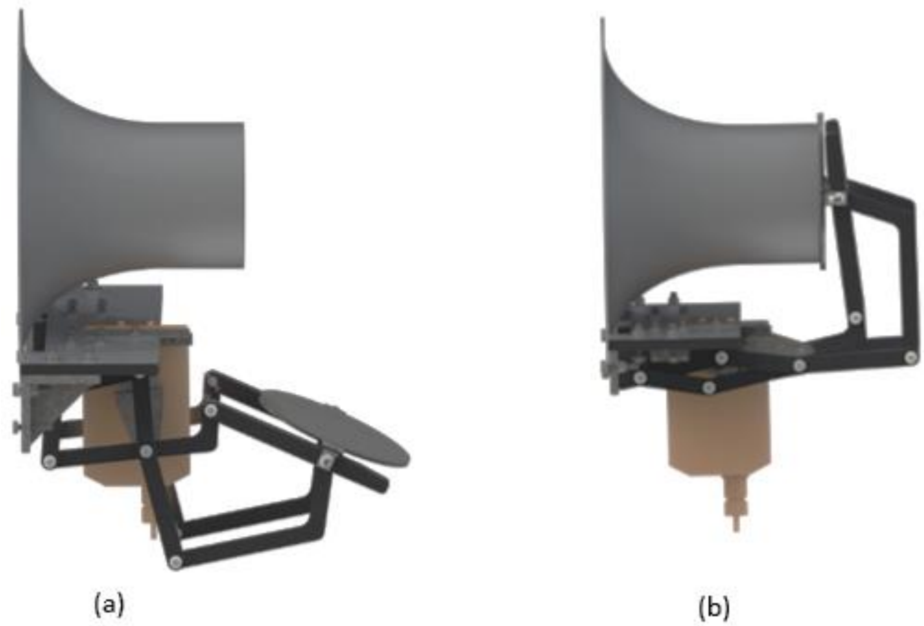



Figure 2.2. Spider mechanism in the (a) open position and (b) closed position [6].

A schematic of the linkage lengths is shown in Figure 2.3. Linkages AC, BDE, and FG are doubled up to evenly distribute force on the clevis pins.

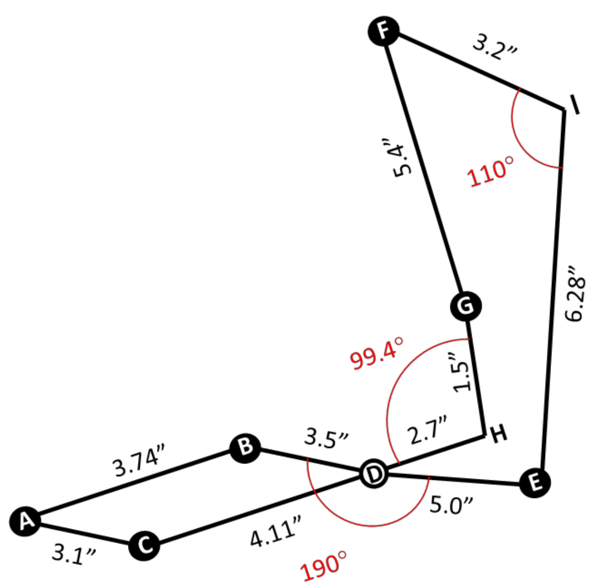



Figure 2.3. Mechanism linkage dimensions for a 6 in diameter nozzle

The lengths of each linkage can be linearly scaled for the varying nozzle diameters. This scalability satisfies the customer's need of the sealing device being functional for all nozzle sizes.

### 2.2.2 Linkage Dimensions

After the linkage lengths were set, a stress analysis was conducted on the mechanism to determine the thickness and width of all linkages. This stress analysis is overviewed in the following section; the complete analysis is found in Appendix D.

#### 2.2.2.1 Pin Hole Diameters

The pin with the largest internal force was analyzed to determine the minimum pin diameter. This diameter was then rounded up to the nearest standard size (3/16 [in]) which was then used for all clevis pins, with exception to the pin that couples the mechanism with the actuator. This pin's diameter was increased to 1/4 [in] for assembly purposes.

#### 2.2.2.2 Linkage Width

As per common practice, the width of the linkages was set to three times the largest pin hole diameter, resulting in 3/4 [in] wide linkages. The linkages in tension were then analyzed to ensure failure does not occur at the pin hole.

#### 2.2.2.3 Linkage Thickness

After a fatigue stress analysis, the thickness of the linkages was set to 1/8 [in]. The mechanism was assumed to be operated five times a day, five days a week, resulting in 12,000 load cycles for a 10-year life span. Using the fatigue strength of 6061-T6 aluminum, a minimum factor of safety of 4.41 was found for linkage CDG. Smaller thicknesses were also analyzed; however, 1/8 [in] was the smallest standard thickness that maintained a factor of safety of at least two.

To allow for the mechanism to be easily laser cut, all linkages have the same width and thickness. Table IV shows the widths and thicknesses of all linkages, as well as the pin hole diameters. Technical drawings of the linkages are found in Appendix C.

TABLE IV: FINAL DIMENSIONS OF LINKAGES AND PIN HOLE DIAMETERS.

| Part | Dimension |
|---|---|
| **Linkages Width** | 3/4 [in] |
| **Linkages Thickness** | 1/8 [in] |
| **Pins A,C,B,G,E,F Diameter** | 3/16 [in] |
| **Pins D Diameter** | 1/4 [in] |

### 2.2.3 Pin Configuration

Once the linkage dimensions and pin hole diameters were set, the pin configuration was designed. A configuration was created to secure the linkages and to ensure they do not contact each other, causing abrasion.

Nylon spacers and washers are used between linkages and the clevis pin to minimize friction and metal on metal contact. A hitch pin clip is slotted through the clevis pin to keep the pin from falling out during actuation. The pin configuration used is shown in Figure 2.4.

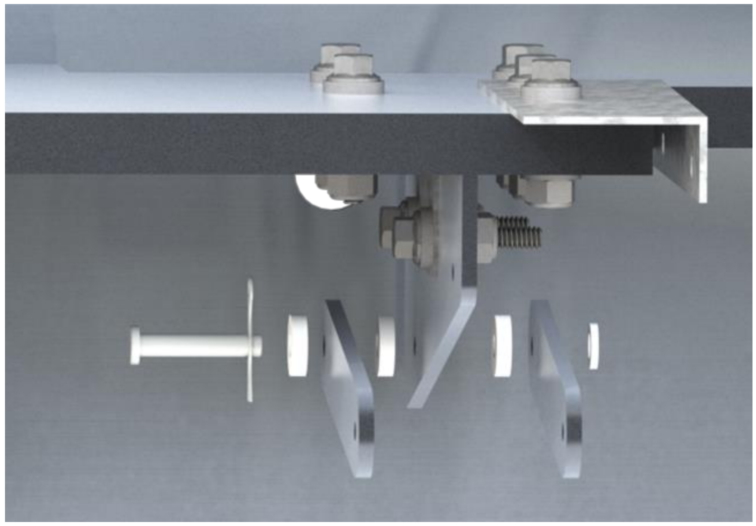


Figure 2.4. Mechanism linkage joints schematic from the (a) side and (b) front [7].

To reduce friction on the pins, each pin will be periodically lubricated with graphite powder. A sliding clearance fit is used between the pins and linkages, allowing the linkages to rotate freely while remaining secure. All information on tolerances for the system can be found in Appendix D.

## 2.3 Sealing System

The purpose of the sealing system is to meet Price's need of having a full seal. The sealing system consists of a circular metal plate, a rubber foam sheet and two hinges. The two hinges, made up of two L-brackets each, connect the metal plate to the spider mechanism, as shown in Figure 2.5.

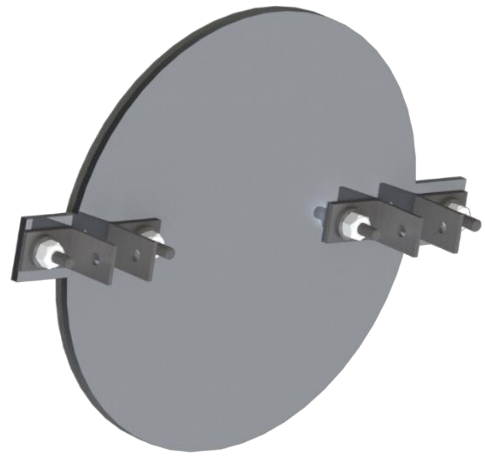


Figure 2.5. Sealing system [8].

### 2.3.1 Sealing Plate

The sealing plate for the six-inch nozzle is an aluminum circular plate with a seven-inch diameter and a thickness of 1/16 [in]. The plate has a one-inch by one-inch square tab on each side of the plate where an L-bracket is attached. The plate is depicted in Figure 2.6.

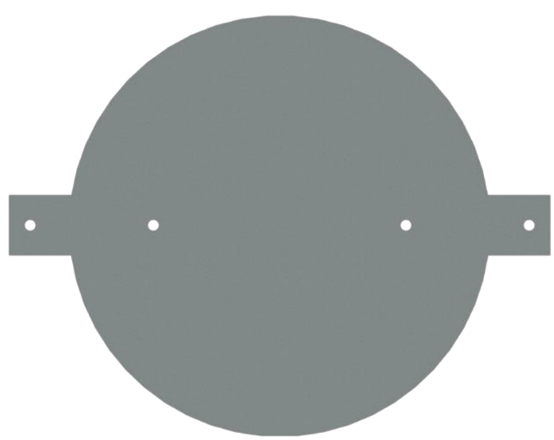


Figure 2.6. Aluminum sealing plate [9].

When the nozzle is sealed, the sealing plate it vertical. During the sealing process, the plate is capable of rotating about the hinges. Without the hinges, the plate would press on the lower lip of the nozzle as the plate was being lifted to create the seal. This contact might damage the nozzle or prematurely wear out the rubber foam sheet. 6061-T6 aluminum was chosen for the sealing plate because it is a relatively inexpensive and light metal that can be laser cut. 6061-T6 aluminum was also selected for the linkage materials and the rationale is found in Appendix E.

### 2.3.2 Hinges

There is a hinge on either side of the sealing plate. Each hinge is made up of two steel L-brackets facing away from each other and a 3/16 [in] pin. This pin is passed through the vertical flanges of the L-brackets and the linkages of the spider mechanism, as shown in Figure 2.7.

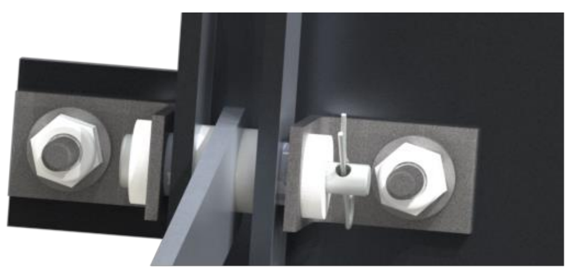


Figure 2.7. Hinge assembly [10].

One of the L-brackets is bolted to the tab of the plate, whereas, the other L-bracket is bolted onto the main body of the plate. The bolt keeping the L-bracket fixed to the body of the plate will be inside the throat of the nozzle; the bolt will be covered by the rubber foam sheet. All screws used for the brackets are pan head screws, have a nylon washer and use a lock nut to keep them secured. Sizing of these fasteners is found in Appendix C.

### 2.3.3 Sealing Material

Five rubber foams were acquired from Argus Industries and the materials were ranked based on cost, compressibility, quality of seal and hardness of the material. Cellular urethane 4701-30 was ranked highest and was selected as the rubber foam sheet; the process for this decision and the properties for cellular urethane 4701-30 are shown in Appendix E. The rubber foam has a thickness of 1/8 [in] and adheres to the aluminum sealing plate by an adhesive backing. The rubber foam is compressed 6% of its thickness to ensure a full seal, thereby meeting the customer's need. The lifespan of the sheet was not analyzed; however, the sheet is easily replaceable.

## 2.4 Support Structure

The support structure connects to the wall of the testing chamber and serves as a mounting surface for the mechanism and actuator. The structure has three main components including the mounting plate, the wall mounts and the mechanism mounts. All three components are shown in Figure 2.8.

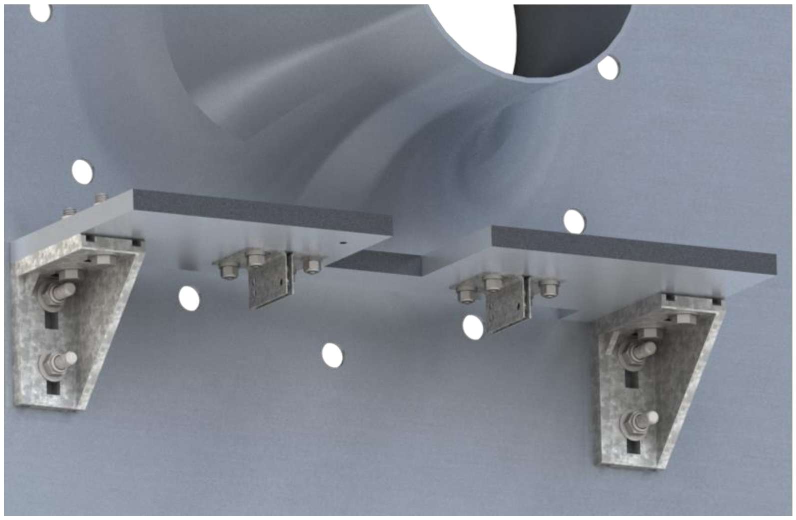


Figure 2.8. Design support structure against the nozzle wall [11].

### 2.4.1 Mounting Plate

The mounting plate is made up of 1/2 [in] 6061 T-6 aluminum and is positioned below the nozzle. There is a shallow rectangular cut out at the back of the plate for the base of the nozzle and a cut out in the middle of the plate allowing space for the actuator. The mounting plate is shown in Figure 2.9.

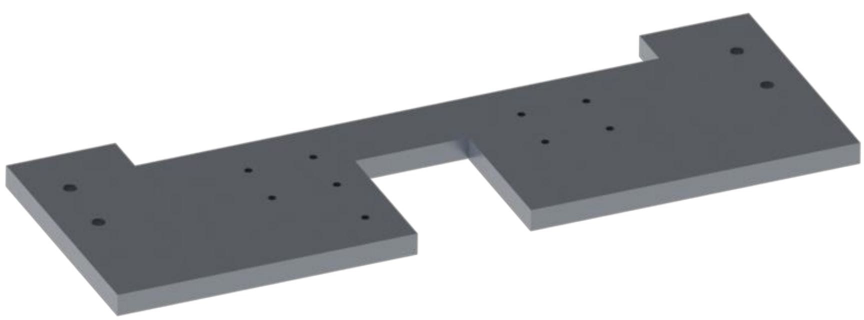
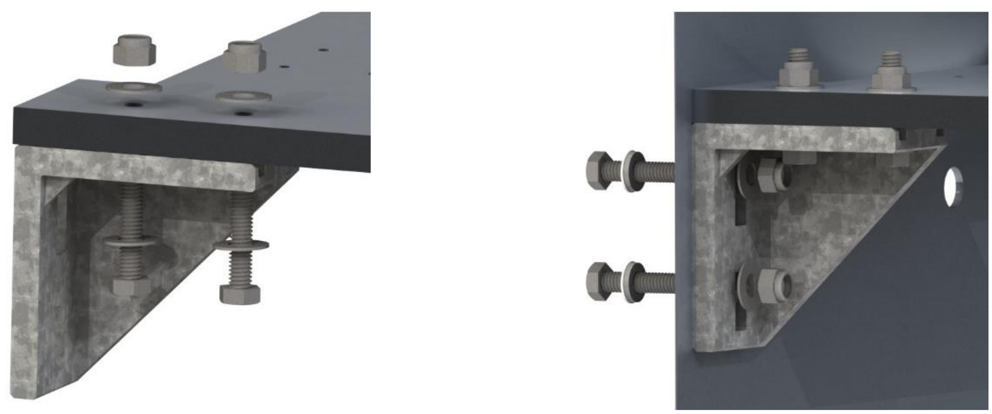


Figure 2.9. Mounting plate render [12].

There are also holes in the plate that serve as fastening points for the corner brackets, which make up the wall mounts, and the L-brackets, which make up the mechanism mounts.

### 2.4.2 Wall Brackets

The wall brackets are two corner brackets that support the mounting plate to the test chamber wall. Four hex bolts per bracket are used for attachment; sizing of the hex bolts is found in Appendix C. The wall brackets are shown in Figure 2.10.



(a) (b)

Figure 2.10. Wall bracket attachment to (a) support plate and (b) wall [13].

At the connection points between the chamber wall and the wall mounts, sealing washers are used to prevent air leakage.

### 2.4.3 Mechanism Mounts

Both mechanism mounts are made up of two L-brackets. A render of the mount used to connect the mechanism to the plate is shown in Figure 2.11.

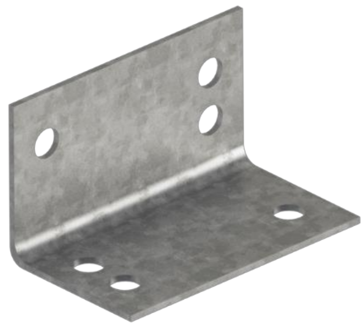


Figure 2.11. Bracket to mount the mechanism to the mounting plate [14].

Each bracket will be attached to the plate and mechanism using four bolts, metal washers, and locking nuts; sizing is found in Appendix C.

## 2.5 Actuator Assembly

The actuator is used to rotate the spider mechanism upwards, into the closed position. The actuation of the design is split into three main subsections: the actuator, the method of mounting, and how the actuator couples with the spider mechanism.

### 2.5.1 Actuator

The actuator selected for the final design was the GMB24-SR manufactured by Belimo, shown in Figure 2.12

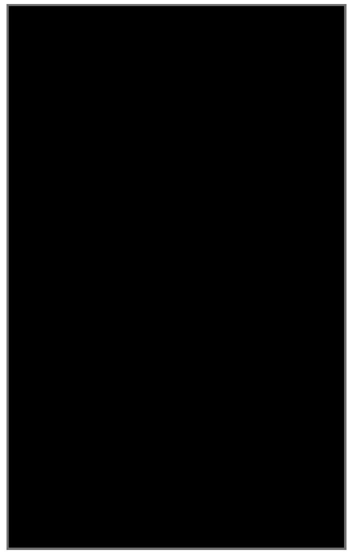


Figure 2.12. Belimo’s GMB24-SR actuator [15].

This actuator is capable of rotating 95°, exceeding the need of 85°, has a torque output of 360 [lbf in], exceeding the need of 340 [lbf in] and has a feedback output of 2-10 [VDC], as required by Price. A full analysis of the required torque, caused by the sealing force and the mass of the system, is shown in Appendix D. The Belimo GM actuators are also guaranteed to run 100,000 life cycles, surpassing the 10-year lifespan which requires 12,000 life cycles. The full technical data sheet for the actuator is shown in Appendix F.

### 2.5.2 Mounting

A mounting bracket assembly can be purchased for the GMB24-SR actuator; the mounting bracket screws into the actuator allowing the actuator to be attached to a custom steel bracket. This custom bracket is then attached to the aluminum mounting plate which connects the actuator to the wall of the test chamber. The mounting assembly is shown in Figure 2.13.

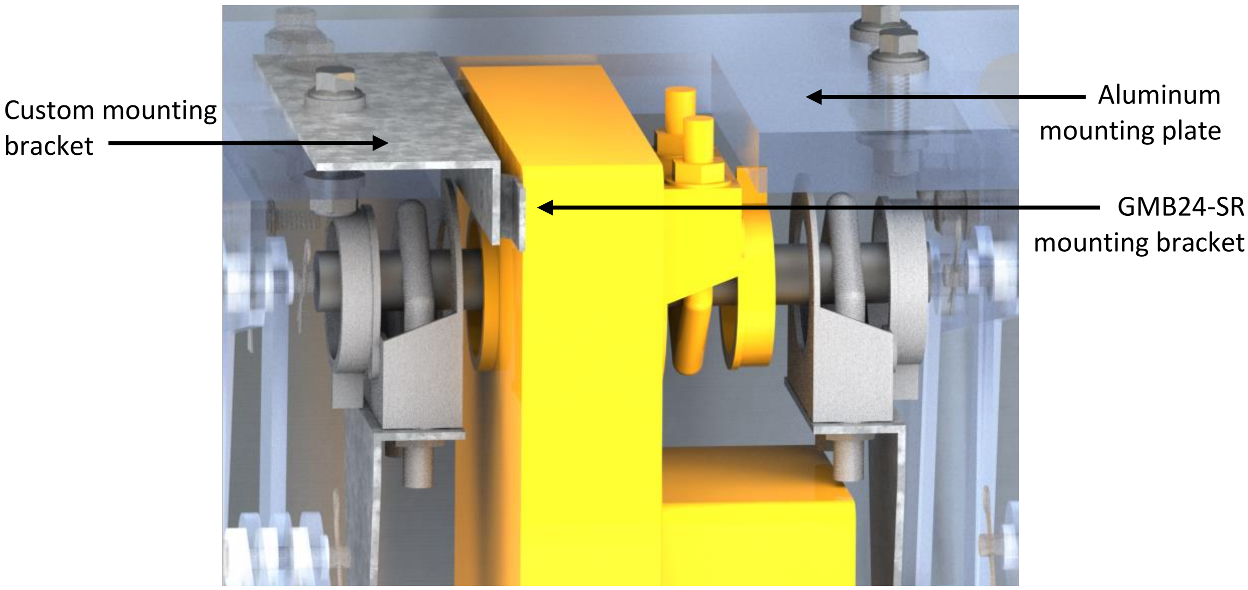



Figure 2.13. Actuator mounting assembly [16].

### 2.5.3 Coupling with Spider Mechanism

The actuator will be positioned between the two spider mechanisms, under the aluminum mounting plate. A 1/2 [in] diameter steel shaft runs through the actuator with a circular clamp on either side, which will rotate with the shaft. A custom crankarm is used to connect each circular clamp to the spider mechanism by means of a clevis pin. This pin has a 1/4 [in] diameter, which is larger than the other pins in the system to accommodate the required coupling with the actuator.  A nylon washer is friction fit into the custom crank arm to reduce friction and allow smooth actuation. The crankarm being used is shown in Figure 2.14.

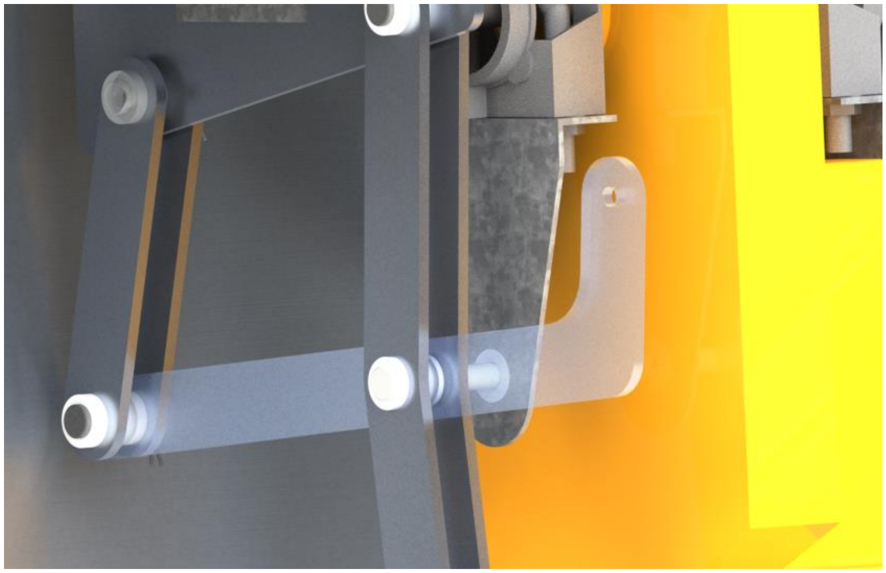


Figure 2.14. Custom actuator arm mounting the mechanism [17].

## 2.6 Summary of Final Design

The integration of the aforementioned subsections creates a solution that satisfies all of Price's needs. Figure 2.15 shows complete renders of the final design.

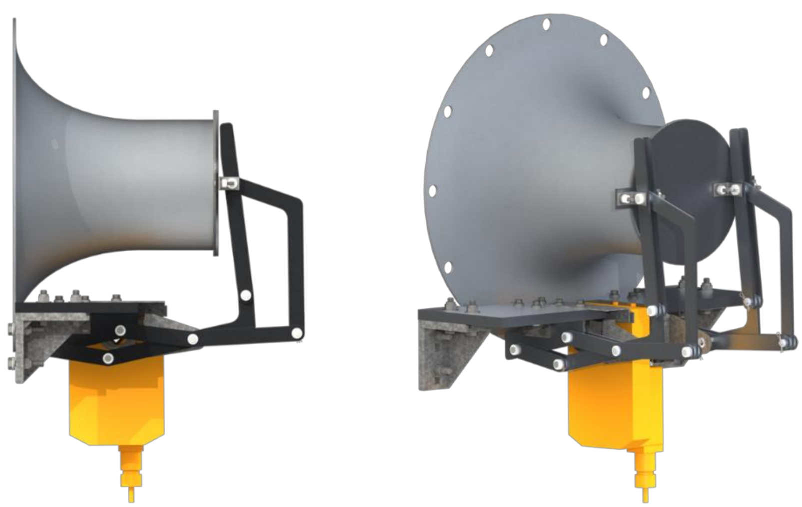


Figure 2.15. Complete final design render of the spider mechanism [18].

Each component of the automated nozzle sealing system was designed to meet the specified metrics and corresponding marginal or ideal values. A summary comparing the technical specifications and the design values for each metric is shown in Table V. Values highlighted in green correspond to ideal targets met, yellow corresponds to marginal targets met and red indicates failure to meet a marginal or ideal target.

TABLE V: FINAL DESIGN SPECIFICATIONS

| Metric # | Need # | Metric | Unit | Marginal Value | Ideal Value | Final Design |
|---|---|---|---|---|---|---|
| **1** | 1 | Change in fan power | Watts | 1 | 0.5 | - |
| **2** | 2 | Air flow rate when sealed | Cubic Feet per Minute | 0.1 | 0.05 | - |
| **3** | 3 | Nozzle compatibility | # | 1 to 5 | 5 | 5 |
| **4** | 4 | Footprint | Feet and Inches | 4' 10½" x 8' 4¼" | 4' 10½" x 8' 4¼" | 1' 5½"x 1' 5½" |
| **5** | 5 | Operational temperature range | Fahrenheit | 68 to 72 | 50 to 150 | 68 to 72 |
| **6** | 6 | Operational pressure range | Inches of $H_2O$ | -3 to 3 | -6 to 6 | -3 to 3 |
| **7** | 7 | Each nozzle can be operated independently | Binary | 1 | 1 | 1 |
| **8** | 8 | Nozzle devices can operate in tandem | Binary | 1 | 1 | 1 |
| **9** | 9 | Number of parts | Number | < 35 | < 25 | 208 |
| **10** | 10,11 | Time to assemble design | Hours | < 3 | < 1 | 1.4 |
| **11** | 12 | Vendors | List | Majority Canadian | All Canadian | All Canadian |
| **12** | 13 | Unit manufacturing costs | Canadian Dollars | < 5000 | < 4000 | 2021.07 |
| **13** | 14 | Lifespan | Years | > 10 | > 15 | 10 |
| **14** | 15 | Time to disassemble/assemble for maintenance | Minutes | < 30 | < 20 | - |
| **15** | 16 | Visually organized | Subjective | Pass | Pass | Pass |

Some final design values are missing because without testing the design, some metrics were unable to be measured.

The only technical specification not met was the number of parts; the final design contains 208 parts and the marginal target was 35 parts or less. This specification was not met due to an oversight on the number of fasteners required.

The sealing system met the marginal values of the operating temperature range, operating pressure range, time to assemble, and the lifespan of the design. Proper operation of the design at the ideal temperature range was not verified because material properties were only obtained for the marginal temperature range. Due to limited torque and size constraints of available actuators, only the marginal pressure range was satisfied. To estimate the target specification for the assembly time metric, a prototype was built. Two people built a simple prototype in a total of 1.4 hours, following the detailed instructions, found in Appendix G. Therefore, the assembly time metric met the marginal value; however, the actual assembly time will be longer, due to the complexity of the final design.  Fatigue analysis was only completed for a 10-year lifespan, therefore the operation at 15 years cannot be guaranteed.

The design met the ideal values for nozzle compatibility, footprint, ability to operate independently, ability to operate in tandem, material vendors, cost, and organization of the system. The sealing system was designed to be scalable for all five nozzle sizes, although a complete stress analysis needs to be complete. The footprint of the system meets the ideal target because the spider mechanism is capable of remaining tight to the wall and has a 17 1/2 [in] by 17 1/2 [in] footprint. Each automated sealing system contains its own actuator allowing the sealing system on each nozzle to operate independently and in tandem. The bill of materials contains vendors only in Canada, thus satisfying the ideal target. The total cost of the entire automated sealing system was 2,021.07CAD, therefore, meeting the ideal target. Finally, the system was concluded to be visually organized because all components are compact and self-contained.

# 3. Cost Analysis

A budget of 5,000CAD was allocated for the design of an automated nozzle sealing system. TABLE VI outlines a detailed budget summing to a total of 2,021.07CAD for the automated sealing system.

TABLE VI: COST ANALYSIS

| Item | Cost [CAD] |
|---|---|
| Hardware Costs | $106.25 |
| Actuator Costs | $906.78 |
| Manufacturing & Material Costs | $630.12 |
| Subtotal | $1,643.15 |
| Tax | 13% |
| Contingency | 10% |
| **Total Cost** | $2,021.07 |

A thorough cost breakdown of the automated sealing system is found in Appendix H. A 10% contingency was set to accommodate for shipping costs and any unexpected price changes. In the detailed cost breakdown, there are two Canadian vendors for most items; some manufacturing costs were not found for two vendors.

# 4. Final Recommendations and Future Work

The design for the six-inch nozzle meets all specified criteria; however, there are some additional optimizations that should be considered before implementation. These recommendations include: the use of springs to minimize the required moment supplied by the actuator, the number of actuators used, the use of nylon washers in between the linkages, location of the mechanism relative to the nozzle, and the scaling of the system.

Springs can be attached to the clevis pins at the middle of the nozzle and the point of rotation. This will aid the actuator in sealing the nozzle by pulling the sealing plate towards the wall. The spring force will also allow for the use of an actuator rated for a smaller torque, thereby creating a less expensive design. To ensure this implementation is beneficial, the displacement of the spring at all points of motion should be analyzed. If the force caused by the spring is too great for the actuators to overcome, the system will be stuck in the shut position.

It is also recommended to consider using two actuators for the design when scaled to other nozzle sizes. For smaller nozzle sizes, the actuator will be too big to fit in between the two sides of the spider mechanism; to remedy this problem, the actuator will need to be mounted beside the nozzle. If this solution is implemented, it is recommended that an actuator be added to both sides of the spider mechanism to ensure proper balance of the sealing system. Furthermore, for the six-inch nozzle, the actuator selected is nearing its maximum torque rating. The actuator with the next largest torque is too large to be implemented, therefore, the use of an actuator on either side of the design will ensure the system can prevent the maximum pressure with a factor of safety of two.

It is recommended to add nylon bushings on the inner diameters of the pin holes in the mechanism linkages. These nylon bushings will reduce the friction during actuation and will also reduce metal on metal contact between the linkages. The bushings will also eliminate the need for lubrication on the linkage pins and ensure smooth actuation. To ensure successful implementation of this solution, the bushings will require a tight tolerance between the linkage pins to avoid instability.

The detailed design consists of a mechanism located below the six-inch nozzle. Alternatively, the mechanism can be installed above or to the side of the nozzle, dependent on space limitations within the air flow test chamber. If the mechanism is located above the nozzle, a lower moment will be required to seal the nozzle because gravity will help pull the mechanism downward and the actuator will not need to support the weight of the structure when closed. For successful implementation, a weight analysis for the moment required to hold the actuator in the open position would be required.

Prior to implementing this design on the other nozzles, an equivalent analysis should be completed for each nozzle size to determine linkage forces and dimensions. The varying nozzle sizes will cause different sealing forces and linkage lengths resulting in different stresses and a different torque required by the actuator.

# 5. Conclusion

The objective of this project was to develop an automated nozzle sealing system to seal the six-inch nozzle in Price Industries' air flow test chamber. The sealing system designed meets the client's needs and is scalable for all five nozzle diameters.

The sealing system was broken down into four main categories: the spider mechanism, the sealing system, the support structure, and the actuator assembly. The spider mechanism is composed of six aluminum linkages which move the sealing system to the nozzle throat. The sealing system consists of a cellular urethane sheet adhered to a circular aluminum plate. The support structure is attached to the chamber wall by two steel brackets and is used as an attachment point for the spider mechanism and the actuator. The actuator is mounted underneath the support structure, is connected to the mechanism with two actuation arms, and delivers torque to the mechanism, allowing the nozzle to be sealed.

A seal against the nozzle is achieved using a self-aligning plate and a cellular urethane rubber foam sheet. A retractable mechanism moves the sealing system from the open position, at the wall, to the closed position, against the nozzle. The mechanism was designed to allow continuous air flow when open and have a minimal footprint when closed. The mechanism is moved by an electric, rotary actuator.

The sealing system was designed for a 10-year lifespan. The project was allocated a budget of 5,000CAD and the total estimated cost of the design is 2,021.07CAD. A computer aided design model of the mechanism will be sent through private communication to the client as part of the final package.

# 6. References


[1] Price Industies, *About Us*, 2018. [Online]. Available: https://www.priceindustries.com/corporate/about-us [Accessed 25 September 2018].

[2] B. Giesbrecht. *Air Flow Test Chamber*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 20, 2018.

[3] Price Industries, *Research Center North Brochure*, 2018. [Online]. Available: https://www.priceindustries.com/resources/assistants/permlink/1540 [Accessed 25 September 2018].

[4] B. Giesbrecht. *Nozzles*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 20, 2018.

[5] B. Giesbrecht. *Spider Mechanism with Subsections*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 30, 2018.

[6] B. Giesbrecht. *Open and Closed Positions*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 30, 2018.

[7] B. Giesbrecht. *Mechanism Linkage Joints*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 27, 2018.

[8] B. Giesbrecht. *Sealing System*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB,

Nov. 27, 2018.

[9] B. Giesbrecht. *Sealing Plate*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 28, 2018.

[10] B. Giesbrecht. *Hinge Assembly*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 27, 2018.

[11] B. Giesbrecht. *Support Structure*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 26, 2018.

[12] B. Giesbrecht. *Mounting Plate*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 27, 2018.

[13] B. Giesbrecht. *Wall Brackets*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 23, 2018.

[14] B. Giesbrecht. *Mounting Plate Bracket*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 27, 2018.

[15] Belimo, *Actuators*, 2018. [Online]. Available: https://www.belimo.ca/shop/en_US/Actuators/Non-Fail-Safe-Actuators/AMB24-SR/p?code=AMB24-SR [Accessed 24 November 2018].

[16] B. Giesbrecht. *Actuator Mounting Assembly*, Winnipeg: Design Eng., Univ Manitoba,

Winnipeg, MB, Nov. 26, 2018.

[17] B. Giesbrecht. *Custom Actuator Arm*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 29, 2018.

[18] B. Giesbrecht. *Final Render*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 30, 2018.

# University of Manitoba IDEA Program:

# Design of an Automated Nozzle Sealing System

## Detailed Design Report

# Appendix A
# Constraints, Customer Needs and Technical Specifications

# Contents

List of Figures ........ A-ii

A.1 Introduction ........ A-1

A.2 Constraints and Limitations ........ A-1

A.3 Customer Needs ........ A-4

A.4 Target Specifications ........ A-8

A.5 References ........ A-14

# List of Figures

Figure 1. Drawing of the nozzle bank with the nozzle throat diameters labeled. .......... A-2

Figure 2. Sealing chamber dimensions. ............................................................... A-9

# A.1 Introduction

The constraints and limitations of the problem are fully described. After, a detailed outline of Price's needs, technical specifications, and the relationship between them are presented. The target specifications section lists and ranks Price's needs by their importance. These needs are linked to quantified specifications including marginal and ideal targets.

# A.2 Constraints and Limitations

The eight constraints and limitations that impacted the project are outlined.

**Constraint #1 – Project deadline**

The project deadline, December 5th, 2018, was stated in the engineering design course schedule. At this point, all deliverables for the course and the client are due, excluding the final oral presentation and poster. To prepare for the project deadline, an internal schedule was created along with a Gantt chart to keep the project organized throughout the semester.

**Constraint #2 – Design space**

The final design must be able to fit within the chamber with each component of the design fitting in the 77 ¾ in X 27 ⅝ in door. There are also pressure taps halfway up the wall of the chamber which cannot be blocked by the design. Most importantly, the system cannot impede the flow of air; when a nozzle is not supposed to be sealed, no component can affect the airflow because the test conditions will not be met, causing inaccuracies in Price's measurements.

**Constraint #3 – Interaction with nozzles**

The sealing system cannot scratch, deform or change the integrity of the nozzle. The nozzles are made of aluminum, which is a relatively soft metal, meaning they can be damaged easily. This means that no part can be attached to the nozzle through permanent means, such as screwing a hole in the nozzle.

**Constraint #4 – Location and size of nozzles**

The placement of the nozzles cannot be changed, limiting the surfaces that the sealing system can be attached to. The nozzle test chamber is set up with five nozzles of varying sizes in different positions. The nozzles are 2.5, 3.5, 4.5, 6 and 10 inches in the middle, top left, bottom left, top right and bottom right positions, respectively, as seen in Figure 1**.**

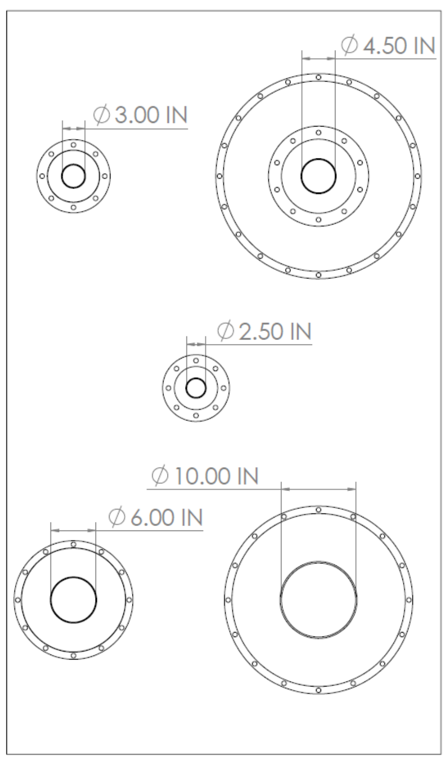



Figure 1. Drawing of the nozzle bank with the nozzle throat diameters labeled [1].

**Constraint #5 – Independence of nozzles**

The sealing system must be able to open and close a nozzle independently; the system must be able to have any combination of nozzles open or closed at any given time. This limits the ability to use a single actuator for two different nozzles as it cannot be assumed they will need to be opened and closed at the same time.

**Constraint #6 – Analytical Methodologies**

Theoretical calculations, such as computational fluid dynamics (CFD), will not be able to accurately represent the test scenario, meaning empirical analyses must be used. A large portion of the design relies on the power of the actuators and the elasticity of different materials to create an 100% seal. CFD would not be able to take these factors into account. Mating the device with the nozzle on a computational software will force the computation to predict zero air flow. This false positive will lead to inaccurate test results meaning the actual device may not create a perfect seal.

**Constraint #7 – Prototyping opportunity**

Building on Constraint #6, the best way to verify a 100% seal is to prototype the design and test it. A prototype of the seal will be created if time permits.

**Constraint #8 – Client availability**

The team is working with a large company that has many ongoing projects. The employees who are the communication points will have limited time to meet with the group.

This will reduce the amount of time available to work with the design space and limit the personal interactions between the team and company.

## A.3 Customer Needs

A short description of each need and a justification of the importance rating are described.

**Need #1 – The sealing system's operational space allows continuous air flow**

The test chamber is used to acquire an accurate reading of the air flow for any given product; the sealing system cannot obstruct the airflow through the nozzles. This was given a high importance because obstructed airflow will cause inconsistencies in the results.

**Need #2 – The sealing system completely prevents any air from passing through**

The sealing system must create a 100% seal preventing any air from passing through. This need was given a high importance because air that passes through the sealing system would corrupt test results.

**Need #3 – The sealing system can be scaled to function on any nozzle size**

The nozzle bank contains five nozzles of different diameters. To fully utilize the test chamber, all nozzles must be sealable. Therefore, it is of high importance that the sealing system can be scaled to all five nozzle sizes.

**Need #4 – The sealing system adheres to space constraints**

The sealing system must operate within the test chamber and not cover the pressure taps on the walls. This need is of high importance because the device must fit in, or be easily assembled within, the chamber to operate.

**Need #5 – The sealing system remains operational at room temperature**

The test chamber is operated at room temperature and, therefore, the sealing system must also be operational at room temperature. This need was given high importance because without this ability, the system is unusable by Price.

**Need #6 – The sealing system remains operational between two chambers of varying pressures**

The nozzles are positioned between two chambers of different pressure. The sealing system must be able to maintain a complete seal on the nozzle regardless of the forces exerted by this pressure differential. To ensure the seal holds, the components and connections between them must be able to withstand the pressure differential. This need was categorized as high importance because it affects the overall function of the device.

**Need #7 – The sealing system for each nozzle can be operated independently**

Various tests performed in the test chamber require different combinations of nozzles to be sealed and, therefore, the sealing systems must operate independently. This need was classified as a high importance because if the nozzles cannot be sealed independently, Price is unable to adjust the airflow.

**Need #8 – The sealing systems for each nozzle are operational in tandem**

The sealing systems must operate in tandem and not interfere with each other. This need was classified as high importance because if two of the sealing systems interfere with each other the correct combination of open and closed nozzles cannot be obtained.

**Need #9 – The sealing system is simple in design**

The system must have a limited number of actuators and components; if the system stops functioning, it will be easier to diagnose the problem with minimal parts. For this reason, this need was given medium importance.

**Need #10 – The sealing system is easy to assemble**

The system must be easily assembled to ensure a minimal amount of time is used by the employee. This does not impact the objectives, meaning this need was given a low importance value.

**Need #11 – The sealing system has detailed instructions to build**

Price will require detailed instructions to assemble the system. It is possible to successfully build the device without instructions, however, the amount of time and effort required will be much greater. This need was assigned a low importance because the integrity of the project does not rely on detailed build instructions.

**Need #12 – The sealing system components can be sourced from Canadian vendors**

To reduce shipping costs, components from the sealing system should be sourced from Canadian vendors. Although Canadian sourcing is preferred, it is not essential, thus, decreasing the importance of the need.

**Need #13 – The sealing system is affordable to implement**

The final design should be cost-effective, including purchasing of the components and installation of the hardware. This need was given a low importance rating because it does not directly impact the effectiveness of the design.

**Need #14 – The sealing system components are durable**

The sealing system must be able to withstand the chamber conditions and the required motions. If the components are not durable, the maintenance costs and down time will increase as the components are repaired or replaced more often. This need was given a medium importance rating because the performance of the testing chamber is not impacted by the durability of the design.

**Need #15 – The sealing system is easily accessible for maintenance**

The system should be designed to facilitate quick fixes and replacements of components as they wear out during use. This need was given a medium importance because, although repair and replacement of components is time consuming, it does not impact performance of the testing chamber.

**Need #16 – The sealing system is tidy**

The final design should be aesthetically pleasing with all wires grouped together properly. This will instill pride in the company, increasing confidence when tours of the facility are offered to potential clients. This need was given a low importance because it does not impact the performance of the testing chamber.

## A.4 Target Specifications

The team has generated a list of technical specifications in the form of engineering metrics and corresponding marginal and ideal values. The metrics were created to evaluate Price's needs based on numerical values. Each need was correlated to one or more metrics; each metric was given a unit and an ideal value to verify the need(s).

**Metric #1 - Change in fan power**

The change in fan power will be measured in watts and the marginal value of one watt and ideal target as 0.5 watt. If the system interrupts the air flow through the open nozzles, the air flow resistance will be increased, changing the measured fan power. This metric will be critical in evaluating Need #1 to ensure the sealing system allows continuous air flow.

**Metric #2 - Air flow rate when sealed**

The air flow rate when sealed will be evaluated by the volumetric flow rate of air passing through a sealed nozzle. The marginal target is set to 0.1 cubic feet per minute and ideal target is set to 0.05 cubic feet per minute for each seal. This metric is used to evaluate Need #2 to ensure the sealing system completely prevents air from passing through.

**Metric #3 - Nozzle compatibility**

The nozzle compatibility will be evaluated by the number of nozzles that the sealing system can operate on. Marginal acceptance requires the system to fit on a minimum of one nozzle, with an ideal acceptance requiring the system to work on all five nozzles. This metric will determine how many of the five nozzles the device can be scaled to and used for. This metric is necessary to evaluate if the nozzle is scalable to other sizes, as described in Need #3.

**Metric #4 - Footprint**

The footprint will be evaluated by measuring the dimensions of the system. These dimensions will ensure the system fits inside the test chamber, seen in Figure 2, and does not cover the pressure taps.

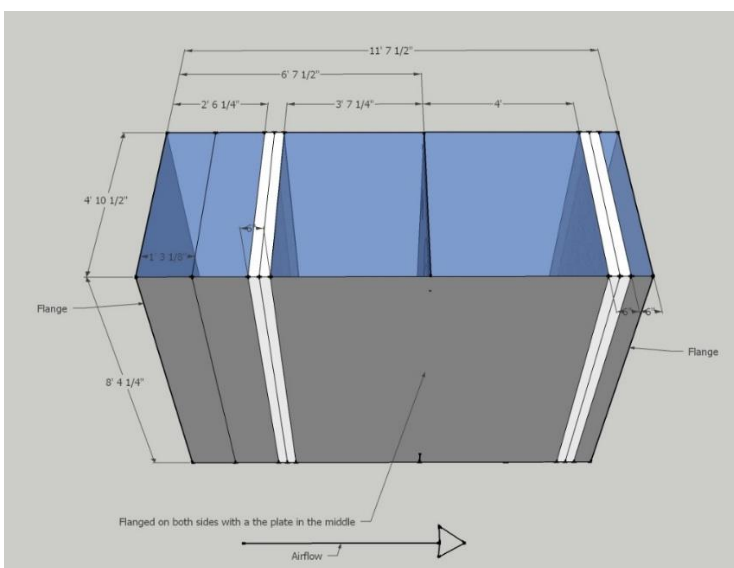



Figure 2. Sealing chamber dimensions [2].

This metric will be used to evaluate Need #4, the sealing system adheres to space constraints.

**Metric #5 - Operational temperature range**

The operational temperature range is evaluated by the temperature range at which the system operates. To determine if the system functions at the operational temperature range, the system must successfully operate between the minimum marginal value of 68°F, and the maximum marginal value of 72°F. The ideal value range of 50°F to 150°F is used in a similar test chamber that operates at more extreme conditions. This metric will be used to evaluate Need #5 to ensure the system can operate at ambient temperatures.

**Metric #6 - Operational pressure range**

The operational pressure range will be evaluated by the pressure range at which the system functions normally. The marginal value is -3 to +3 in$H_2O$, and the ideal value is -6 to +6 in$H_2O$. The actuators and moving parts must be able to function similarly at atmospheric pressure and the operational pressures of the chamber. The operational pressure range is used to evaluate Need #6 as it will be used to determine if the device can function in a pressurized chamber.

**Metric #7 - Each nozzle can be operated independently**

The nozzles' ability to work independently will be evaluated in binary units; if the devices can operate independently, the metric will be assigned a value of one. The nozzles must be able to function independently to ensure every combination of open and closed nozzle can be attained. This metric is used to assess Need #7 which states that the sealing device for each nozzle can be operated independently.

**Metric #8 - Nozzles devices can operate in tandem**

The nozzles' devices can operate in tandem metric will be evaluated in binary units, such that if the devices are operational in tandem, the metric will be assigned a value of one. With multiple nozzles inside the test chamber, the sealing devices must operate in tandem to ensure all nozzles can be used. The nozzle devices can operate in tandem metric is used to assess Need #8.

**Metric #9 - Number of parts**

The number of parts will be evaluated by the quantity of parts incorporated in the final design. The total number of parts in the final design should be less than ten but ideally fewer than five. If the final design has fewer parts, inherently it will be simpler to manufacture and maintain. This metric is used to evaluate Need #9.

**Metric #10 - Time to assemble design**

The time to assemble the sealing system is measured in hours to assemble. A marginal value capped at three hours was selected as it is assumed a simple device with thorough instructions can be assembled quickly. Similarly, an ideal value capped at one hour was selected. This metric is used to evaluate Need #10 and Need #11 as the assembly time is correlated to the difficulty of assembly and the thoroughness of instructions.

**Metric #11 – Vendors**

The vendors will be evaluated by compiling a list of all component vendor locations. Ideally, all vendor locations are Canadian. This metric is used to evaluate Price's request for all components of the sealing system to be sourced from Canadian vendors, Need #12.

**Metric #12 - Unit manufacturing costs**

The unit manufacturing cost will be evaluating the total implementation cost of the final design in Canadian dollars. The overall cost of implementing the design must be less than 5,000 CAD but will ideally be less than 4,000 CAD. This metric is used to evaluate Need #13, the sealing system is affordable to implement.

**Metric #13 – Lifespan**

The lifespan will be measured in years, with a marginal value of minimum 10 years and an ideal value of minimum 15 years. If the sealing system components are fragile, this will increase the maintenance cost and increase down time between tests. This metric will be used to determine if Need #14, the sealing system components are durable, is met.

**Metric #14 - Time to disassemble/assemble for maintenance**

The time to disassemble/assemble the device components for maintenance will be measured in minutes with a marginal value of 30 minutes and an ideal value of 20 minutes. When the device must be disassembled to perform maintenance, this process should be as efficient as possible to decrease down time between tests. The disassembly/assembly time will be used to determine if Need #15, the sealing system is easily accessible for maintenance, is met.

**Metric #15 - Visually organized**

The measurement units for visual organization of the design are subjective and will be assessed as a pass or fail. The overall system should be arranged in an organized manner, including the positioning of the wiring, positioning of the individual components, and linkages between the components. The visual organization of the system will be used to evaluate Need #16, the sealing system is tidy.

# A.5 References

[1] B. Giesbrecht. *Nozzle Bank*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 20, 2018.

[2] Price. *Test Flow Chamber*, Winnipeg: Price Industries, Winnipeg, MB, Sept. 13, 2018.

# University of Manitoba IDEA Program: Design of an Automated Nozzle Sealing System

## Detailed Design Report

# Appendix B
# Concept Development

# Contents


B.1 Introduction ........ B-4

B.2 Preliminary Design Concepts ........ B-4

B.2.1 Sealing Method ........ B-4

B.2.2 Mechanism ........ B-8

B.3 Concept Analysis ........ B-12

B.3.1 Sensitivity Analysis ........ B-12

B.3.2 Quantitative Discussion ........ B-15

B.3.2.1 Manufacturability ........ B-16

B.3.2.2 Simplicity ........ B-19

B.3.2.3 Footprint ........ B-21

B.3.2.4 Cost ........ B-24

B.3.2.5 Maintenance ........ B-27

B.3.2.6 Aesthetics ........ B-29

B.4 Final Concept Selection ........ B-31

B.5 References ........ B-34

# List of Figures

Figure 1. Push button sealing method example (a) open and (b) closed. ........................... B-7

Figure 2. Mint container sealing method example (a) open and (b) closed........................ B-7

Figure 3. Spider mechanism with the linkages labeled alphabetically. ............................. B-17

Figure 4. Slide pivot mechanism labeled alphabetically. .................................................. B-18

Figure 5. Labeled one pivot mechanism. ........................................................................ B-18

Figure 6. Preliminary design concept for (a) spider, (b) slide-pivot, and (c) one-pivot to compare footprint. ........................................................................................................ B-22

Figure 7. Mechanism securing location at either (a) one point or (b) two points. ............ B-23

Figure 8. Plate sealing methods with (a) spider and (b) one-pivot mechanisms .............. B-33

# List of Tables

TABLE I: PRELIMINARY SEALING METHOD CONCEPTS ........ B-5

TABLE II: PRELIMINARY MECHANISM CONCEPTS ........ B-9

TABLE III: SEAL METHOD SENSITIVITY ANALYSIS ........ B-13

TABLE IV: SENSITIVITY ANALYSIS FOR MECHANISM ........ B-15

TABLE V: SEALING METHOD MANUFACTURABILITY RANKING ........ B-17

TABLE VI: MECHANISM MANUFACTURABILITY RANKING ........ B-19

TABLE VII: SEALING METHOD SIMPLICITY RANKING ........ B-20

TABLE VIII: MECHANISM SIMPLICITY RANKING ........ B-21

TABLE IX: SEALING METHOD FOOTPRINT RANKING ........ B-22

TABLE X: MECHANISM FOOTPRINT RANKING ........ B-24

TABLE XI: SEALING METHOD COST RANKING ........ B-25

TABLE XII: MECHANISM COST RANKING ........ B-26

TABLE XIII: SEALING METHOD MAINTENANCE RANKING ........ B-28

TABLE XIV: MECHANISM MAINTENANCE RANKING ........ B-29

TABLE XV: SEALING METHOD AESTHETICS RANKING ........ B-29

TABLE XVI: MECHANISM AESTHETICS RANKING ........ B-30

TABLE XVII: CRITERIA DECISION MATRIX ........ B-31

TABLE XVIII: SEALING METHOD WEIGHTED DECISION MATRIX ........ B-32

TABLE XIX: MECHANISM WEIGHTED DECISION MATRIX ........ B-32

# B.1 Introduction

The methodology preformed to obtain the final design included generation of preliminary design concepts for the automated sealing system. To reach a final design concept, the number of preliminary designs was reduced by performing a sensitivity analysis. Finally, a weighted decision matrix was used to choose the top two designs and Price was consulted to determine the design to be developed.

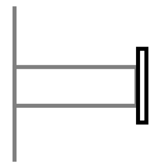
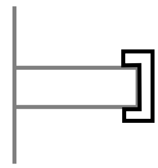
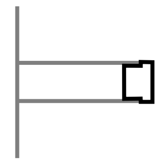
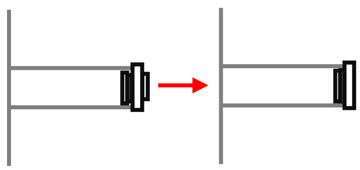
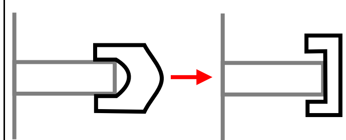
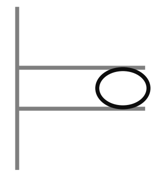
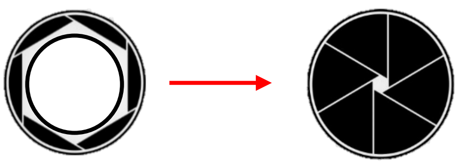
# B.2 Preliminary Design Concepts

The team first divided the design into five categories: (1) sealing method, (2) mechanism, (3) seal material, (4) location and (5) side of chamber. Design concepts were created for each category and further explanation is provided for the category of method, mechanism and seal material.

## B.2.1 Sealing Method

Seven sealing methods were created for the conceptual design as shown in Table I.

TABLE I: PRELIMINARY SEALING METHOD CONCEPTS

| 1. Plate | 2. Cap | 3. Plug |
|---|---|---|
|  |  |  |
| 4. Push button | 5. Mint container | 6. Balloon |
|  |  |  |
| 7. Aperture lens | | |
|  | | |

Each of these sealing methods can be used with a different mechanism, seal material, location and side of chamber.

## Method 1: Plate

The first sealing method is a flat plate which applies a seal to the entire face of the nozzle. The face in contact with the nozzle will be covered with a layer of rubber or foam for the seal.

Advantages

- Simple to manufacture
- Compact design
- Nozzle opening can contact at any point on the face of the plate
- Can be used on either side of the nozzle wall
- Does not require any additional actuation to seal

Limitations

- Nozzle may not be perfectly perpendicular to the wall
- Requires higher force to push plate against the nozzle because the quality of seal is dependent on the force asserted

## Method 2: Cap

The cap has a lip around a circular plate with an O-ring embedded in the notch of the lip. The O-ring creates a seal with the outer diameter of the throat.

Advantages

- Requires less force to complete the seal
- Does not require any additional actuation to seal

Limitations

- More complex geometry to manufacture
- Can only be used on nozzle throat because there is no lip on the nozzle mouth to encircle

## Method 3: Plug

The next method of sealing is a plug design, like a wine stopper. The plug has an O-ring embedded on the outside of the plug, which is in contact with the inside of the nozzle.

Advantages

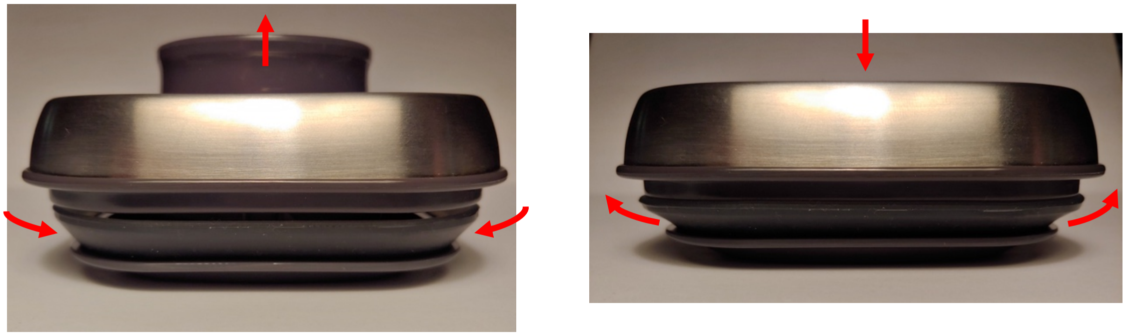
- Requires less force to complete the seal
- Can be used on either side of the nozzle wall
- Does not require any additional actuation to seal

Limitations

- More complex geometry to manufacture

## Method 4: Push Button

The push button uses a mechanism to expand a band made out of rubber when a button is compressed. When pushed, the band is in contact with the inner diameter of the nozzle. A sample push button lid in both the open and closed positions is shown in Figure 1



(a) (b)

Figure 1. Push button sealing method example (a) open and (b) closed.

Advantages

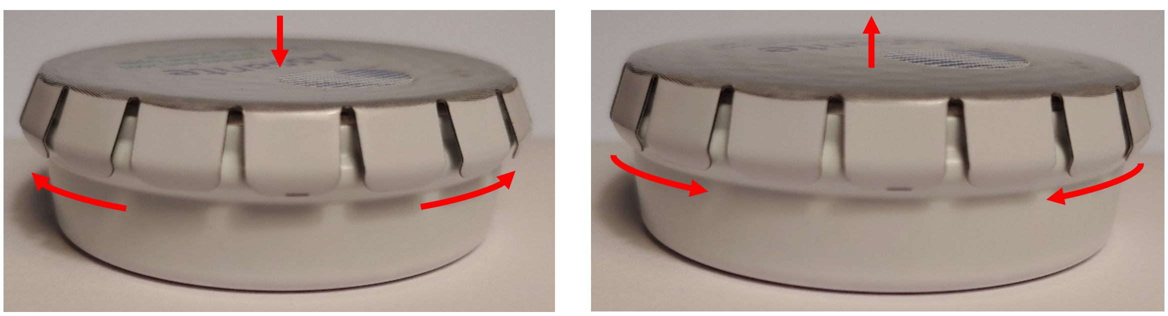
- Can be used on either side of the nozzle wall
- Requires less force to insert the seal into the nozzle

Limitations

- More complex geometry and more components to manufacture
- Additional actuation required to push the button

## Method 5: Mint Container

The mint container is like a cap; however, when the centre is pushed inward, the edges deflect outward as shown in Figure 2.



(a) (b)

Figure 2. Mint container sealing method example (a) open and (b) closed

The seal is formed between a band made of rubber, adhered to the inside lip of the cap, and the outer diameter of the nozzle. This rubber must be able to expand, as the edges deflect outward when opened.

Advantages

- Compact design
- Few parts required, making it easy to assemble

Limitations

- Requires two separate motions to open and close the lid, increasing complexity of the design
- Can only be used on the nozzle throat because it requires a lip to encircle

### Method 6: Balloon

The balloon is an inflatable rubber plug which is inserted into the nozzle. Price currently uses this method because it provides a full seal, but it is not currently automated.

Advantages

- Already proven to provide a complete seal
- Can purchase components, no manufacturing required

Limitations

- Requires an additional step to inflate and deflate the balloon
- Requires either a pump or an air supply tube

### Method 7: Aperture lens

The aperture lens is a circular mechanism that has triangular fins which rotate to meet in the center of the circle. When not in use, the lens is kept around the outside diameter of the nozzle with the fins retracted.

Advantages

- Can be used on either side of the nozzle wall
- Compact design with minimal footprint when not in use
- Stored completely outside of airflow

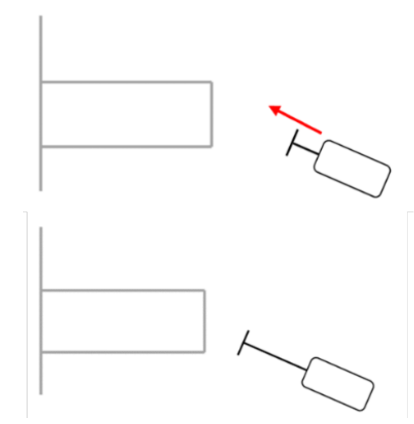
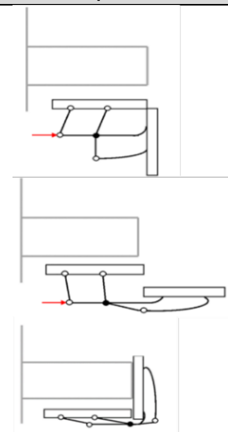
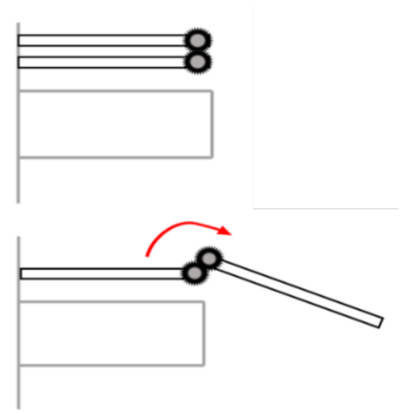
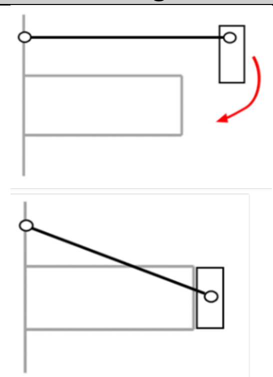
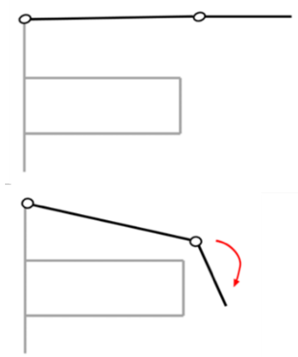
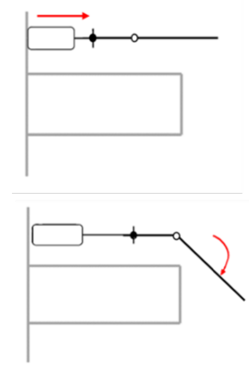
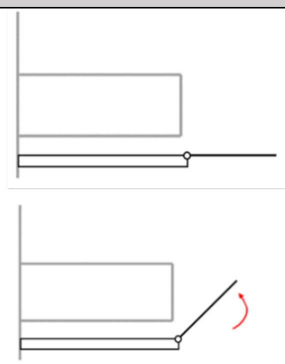
Limitations

- Requires additional actuation to open and close the lens
- May not provide a complete seal in the center of the nozzle opening

## B.2.2 Mechanism

Seven different mechanisms to actuate the sealing process were created for the design concepts as shown in Table II.

TABLE II: PRELIMINARY MECHANISM CONCEPTS

| 1. Linear | 2. Spider | 3. Gear |
|---|---|---|
|  |  |  |
| 4. Swing Arm | 5. Two-Pivot | 6. Slide-Pivot |
|  |  |  |
| 7. One-Pivot | | |
|  | | |

Each of these mechanisms can be used with a different sealing method, seal material, location and side of chamber.

## Mechanism 1: Linear

The linear mechanism uses either a pneumatic cylinder or a linear actuator to move the seal into position on the nozzle opening. This consists of either pushing a seal straight into the nozzle or sliding a hinged surface radially overtop of the nozzle.

Advantages

- Simple design with minimal footprint
- Requires only one actuator

Limitations

- May not provide enough force to keep the nozzle sealed

## Mechanism 2: Spider

The spider mechanism uses hinged linkages between two plates to radially move a vertical plate 180 degrees upwards to cover the nozzle opening. The linkages are secured at two locations on each plate for stability.

Advantages

- Ensures design is completely removed from the airflow
- Compact design when closed

Limitations

- Requires a large space to store the seal

## Mechanism 3: Gear

The gear mechanism consists of two plates that each have a gear attached to their end. When the gear on the stationary plate is turned, the second plate's gear will spin, causing the plate to rotate 180 degrees.

Advantages

- Compact design with minimal footprint

Limitations

- Difficult to actuate gears due to limited accessibility

## Mechanism 4: Swing Arm

The swing arm mechanism consists of a single arm that pivots about a hinge on the nozzle wall to move the seal in front of the nozzle opening. The arm uses a pin within a slot on the seal to pull the seal tight against the nozzle.

Advantages

- Compact design with a small footprint
- Simple operation

Limitations

- Complex interaction between seal and mechanism
- Potential force balance issue leading to leakage

## Mechanism 5: Two-Pivot

The two-pivot mechanism has one member which pivots about a hinge on the nozzle wall, with a second member pivoting about the free end of the first member.

Advantages

- Provides a uniform seal
- Second pivot reduces the length of the radial arm

Limitations

- Requires two actuators

## Mechanism 6: Slide-Pivot

The slide-pivot mechanism consists of a member perpendicular to the wall which slides outwards, after which, a seal rotates about the free end to cover the nozzle opening.

Advantages

- Seal is stored away from the airflow when not in use
- Compact design with small footprint
- Provides a uniform seal

Limitations

- Requires more than one actuator

Mechanism 7: One-Pivot

The one-pivot mechanism consists of an actuator that pushes a plate radially about a hinge in front of the nozzle. The actuator sits on a platform extruded from the nozzle wall to keep a short distance between the actuator and the plate pivot point.

Advantages
- Simple motion
- Requires only one actuator
- Provides a uniform seal

Limitations
- May slightly obstruct the airflow

## B.3 Concept Analysis

To reach a final design concept, the number of preliminary designs was reduced by performing a sensitivity analysis. After the sensitivity analysis, quantitative analyses were performed on each component of the remaining design concepts. The information from the sensitivity and quantitative analyses were then used to select two final design concepts using a weighted decision matrix.

### B.3.1 Sensitivity Analysis

A sensitivity analysis was performed for the sealing method and mechanism. The three top concepts from each category were combined to make nine complete design concepts.

The sealing methods were rated on eight criteria: (1) number of actuators, (2) quality of seal, (3) simplicity of operation, (4) compactness, (5) number of parts, (6) ease of insertion, (7) manufacturability and (8) aesthetic appeal. The number of actuators includes any linear or rotatory, electric or pneumatic actuators to close the seal. The quality of the seal defines how effective the seal will be when closed. The simplicity of operation includes ease of closure and how many steps are required to fully close the seal. The compactness considers how much space the seal will take up when stored. The number of parts will consider all components that make up the seal itself. The manufacturability will consider how the seal is manufactured and if parts are readily available. The aesthetic appeal will incorporate the overall look and organization of the seal.

For the sensitivity analysis of the sealing method, the plate method is used as a reference, and all other methods are ranked as either better or worse than the reference, as shown in Table III. The three methods with the highest net score will be chosen to pursue further quantitative discussion.

TABLE III: SEAL METHOD SENSITIVITY ANALYSIS

| | **Concept Variants (Seal Method)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Selection Criteria** | Plate (Reference) | Cap | Plug | Push Button | Mint Container | Balloon | Aperture Lens |
| Number of Actuators | 0 | 0 | 0 | - | - | - | 0 |
| Quality of Seal | 0 | + | + | + | - | + | - |
| Simplicity of Operation | 0 | 0 | 0 | - | - | - | - |
| Compactness | 0 | 0 | 0 | 0 | 0 | - | 0 |
| Number of Parts | 0 | 0 | 0 | - | 0 | 0 | - |
| Ease of Insertion | 0 | - | - | - | - | - | + |
| Manufacturability | 0 | - | 0 | - | - | 0 | - |
| Aesthetic Appeal | 0 | 0 | 0 | + | - | - | + |
| Sum of "+" | 0 | 1 | 1 | 2 | 0 | 1 | 2 |
| Sum of "-" | 0 | 2 | 1 | 5 | 6 | 5 | 4 |
| Net Score | 0 | -1 | 0 | -3 | -6 | -4 | -2 |
| Rank | 1 | 2 | 1 | 4 | 6 | 5 | 3 |
| **Continue with Design** | **Yes** | **Yes** | **Yes** | **No** | **No** | **No** | **No** |

The plate, cap and plug received the highest scores and were further quantitatively analyzed.

Next, the mechanisms were rated based off seven criteria, (1) number of Actuators, (2) simplicity of operation, (3) compactness, (4) number of parts, (5) manufacturability, (6) location adaptability and (7) aesthetic appeal. The number of actuators will define how many actuators are required, either linear, rotary, electric or pneumatic, are required to move the seal into place in front of the nozzle opening. The simplicity of operation considers the number of linkages and connections. The compactness considers how much space the mechanism takes up both when stored and when in use. The number of parts includes all linkages, fasteners and spacers required for operation. Manufacturability includes obtaining and assembling the individual components. Location adaptability considers if the mechanism can function from any side of the nozzle or if it is limited to one direction. The aesthetic appeal incorporates the overall look and device organization.

For the sensitivity analysis of the mechanism, the linear mechanism is used as a reference with all other mechanisms ranked either better or worse, shown in Table IV. The three highest scoring mechanisms were chosen for further quantitative discussion.

TABLE IV: SENSITIVITY ANALYSIS FOR MECHANISM

| Selection Criteria | Concept Variants (Mechanism) Linear (Reference) | Spider | Gear | Swing Arm | Two Pivot | Slide Pivot | One Pivot |
|---|---|---|---|---|---|---|---|
| Number of Actuators | 0 | 0 | 0 | 0 | - | - | 0 |
| Simplicity of Operation | 0 | 0 | - | + | + | + | + |
| Compactness | 0 | + | + | - | 0 | + | - |
| Number of Parts | 0 | - | - | - | - | - | 0 |
| Manufacturability | 0 | - | - | - | 0 | - | 0 |
| Location Adaptability | 0 | + | + | 0 | + | + | + |
| Aesthetic Appeal | 0 | + | - | + | - | + | + |
| Sum of "+" | 0 | 3 | 2 | 2 | 2 | 4 | 3 |
| Sum of "-" | 0 | 2 | 4 | 3 | 3 | 3 | 1 |
| Net Score | 0 | 1 | -2 | -1 | -1 | 1 | 2 |
| Rank | 3 | 2 | 6 | 4 | 5 | 2 | 1 |
| **Continue with Design** | **No** | **Yes** | **No** | **No** | **No** | **Yes** | **Yes** |

The spider, slide-pivot and one-pivot were ranked highest and were quantitatively analyzed.

Sensitivity analysis was not performed on the material, location or side of chamber because most designs are compatible with any combination of these. The material, location and side of chamber will be determined once the final design is chosen.

## B.3.2 Quantitative Discussion

A quantitative discussion is directed to the three mechanisms and the three sealing methods, with each design concept being ranked by six criteria: (1) manufacturability, (2) simplicity of mechanism, (3) footprint, (4) cost, (5) maintenance and (6) aesthetics. These criteria were chosen to determine the optimal design, assuming each design already meets the customer needs. The advantages and disadvantages of the preliminary designs were obtained from this discussion.

### B.3.2.1 Manufacturability

The manufacturability of each mechanism and sealing method was ranked by the difficulty of manufacturing, and number of components. The designs being considered are preliminary, thus, the ease of manufacturability will be estimated based on the general complexity of the design.

#### B.3.2.1.1 Sealing Method Manufacturability

The complexity of the sealing method shape corresponds to the difficulty of manufacturing. All rubber sealing materials will be waterjet cut to the required dimensions.

##### Sealing Method: Plate

The plate is simple to manufacture because it is a uniform flat plate. A rectangular or circular piece of rubber can be cut and attached to the metal plate using an adhesive.

##### Sealing Method: Cap

The cap is manufactured by machining a lip around the outer diameter of a circular plate. A notch is then machined on the inside of the lip and a rubber O-ring is inserted and fixed into the notch.

##### Sealing Method: Plug

To manufacture the plug, a notch is machined around the outer diameter of a circular plate. A rubber O-ring is then inserted and fixed into the notch and a rubber cushion is attached to the metal plate’s lip.

The three discussed sealing methods are ranked from best (1) to worst (3) with respect to manufacturability, as shown in Table V.

TABLE V: SEALING METHOD MANUFACTURABILITY RANKING

| **Sealing Method** | Plate | Cap | Plug |
|---|---|---|---|
| **Rank** | 1 | 2 | 2 |

B.3.2.1.2 Mechanism Manufacturability

The number and complexity of linkages and joints correspond to the difficulty of manufacturing. Possible techniques to fabricate these components are outlined.

Mechanism: Spider

The spider mechanism is difficult to manufacture as it consists of five linkages and four pivot points. Figure 3 shows the linkages labeled alphabetically.

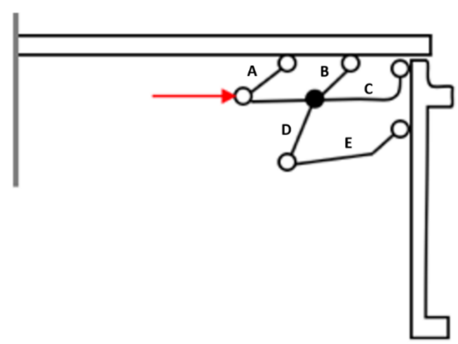



Figure 3. Spider mechanism with the linkages labeled alphabetically.

These five linkages can easily be machined; linkages C and E would be more difficult to manufacture because they are curved. A support structure must be fixed to the nozzle plate wall; this support contains a bracket accommodating the revolute joints of linkages A and B. Similarly, a bracket must be fixed onto the sealing device to connect the revolute joints of linkages C and E. All parts of this mechanism can be manufactured using standard machining processes, such as computer numerical control (CNC) milling.

## Mechanism: Slide-Pivot

The slide-pivot mechanism is easy to manufacture because it consists of two linkages, as shown in Figure 4.

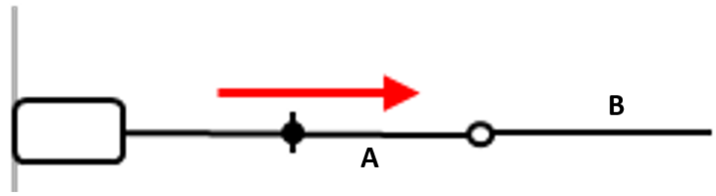



Figure 4. Slide pivot mechanism labeled alphabetically.

Linkage A has a bracket for the pivot point of linkage B and attaches to a linear actuator on the opposite end. Also, linkage A must support another actuator to rotate linkage B to the nozzle. Linkages A and B are easy to machine because they are linear and require few fastening holes. All components of the slide pivot mechanism can be fabricated using a CNC mill.

## Mechanism: One-Pivot

The one-pivot mechanism is easy to manufacture because it consists of one linkage and support, as shown in Figure 5.

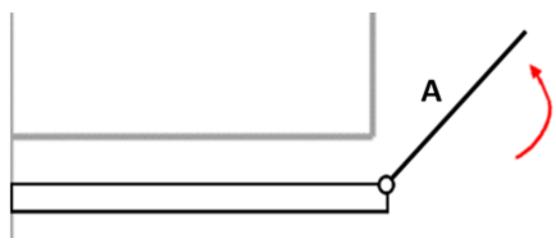



Figure 5. Labeled one pivot mechanism.

The support is simple to manufacture because it requires only one bracket to fasten to the nozzle wall and must support an actuator to rotate linkage A. All components of the one pivot mechanism can be fabricated using a CNC mill.

The three discussed mechanism are ranked from best (1) to worst (3) with respect to manufacturability, as shown in Table VI.

TABLE VI: MECHANISM MANUFACTURABILITY RANKING

| **Mechanism** | Spider | Slide-pivot | One-pivot |
|---|---|---|---|
| **Rank** | 3 | 2 | 1 |

### B.3.2.2 Simplicity

The simplicity of each mechanism and sealing method is analyzed to determine the most efficient design. The simplicity of the design is important because the simplest design is optimal for Price.

#### B.3.2.2.1 Simplicity of Sealing Method

The simplicity of the sealing method is evaluated by the ease of operation and the application of seals.

##### Sealing Method: Plate

The plate is the simplest sealing method because it is a flat metal plate with a sheet of sealing material attached. The plate is also simplest because the seal does not have to be inserted into the nozzle.

##### Sealing Method: Cap

The cap is relatively more complex than the plate because it requires an internal O-ring. The cap also must fully cover the nozzle which adds a level of complexity.

##### Sealing Method: Plug

The plug is relatively more complex to the cap because it has an external O-ring. Further, the plug must be inserted into the nozzle which is more difficult than covering the nozzle.

The three discussed sealing methods are ranked from best (1) to worst (3) with respect to simplicity, as shown in Table VII.

TABLE VII: SEALING METHOD SIMPLICITY RANKING

| **Sealing Method** | Plate | Cap | Plug |
|---|---|---|---|
| **Rank** | 1 | 2 | 3 |

#### B.3.2.2.2 Simplicity of Mechanism

The simplicity of the mechanism is analyzed by the ease of operation, number of parts and number of linkages.

##### Mechanism: Spider

The spider mechanism's operation is easy because only one linear input is required to seal the nozzle. The drawback of this design is the large number of linkages and pivot points; the design has five linkages and four pivot points which outnumbers any other design. Overall, the drawback of numerous parts outweighs the benefit of the simple operation.

##### Mechanism: Slide-Pivot

The slide-pivot's operation is complex because the mechanism requires a sliding member and a pivot point. The number of parts is minimal; this benefit outweighs the complexity of operation.

##### Mechanism: One-Pivot

The one-pivot mechanism's operation only requires rotation about one pivot point. The number of parts is minimal because the design is comprised of a free-standing support.

The three discussed mechanism are ranked from best (1) to worst (3) with respect to simplicity as shown in Table VIII.

TABLE VIII: MECHANISM SIMPLICITY RANKING

| **Mechanism** | Spider | Slide-pivot | One-pivot |
|---|---|---|---|
| **Rank** | 3 | 2 | 1 |

### B.3.2.3 Footprint

The footprint of each mechanism and sealing method is analyzed to determine the most compact design. The footprint of the design is important because of the space limitations within the airflow testing chamber. All devices must fit fully inside the chamber while not interfering with adjacent devices or nozzles.

#### B.3.2.3.1 Footprint of Sealing Method

Each of the various sealing methods will have two different footprints, a stored: and activated footprint. The three sealing methods which are analyzed further are the plate, cap and plug.

##### Sealing Method: Plate

The plate will be the thinnest sealing method because there are no raised edges. The plate can be either circular, to follow the outline of the nozzle, or square, which will be easier to manufacture but will take up more space. Overall, the plate will have the smallest footprint of all the sealing methods.

### Sealing Method: Cap

The cap will have a similar outline to the plate but will be thicker. This increased thickness is due to a lip which will run along the outside diameter of the nozzle.  Overall, the cap will have an larger footprint in comparison to the plate.

### Sealing Method: Plug

The outline of the plug will be similar to the cap and plate with a similar thickness to the cap. The plug will have a raised lip on the device, rather than the outside as shown with the cap. Overall, the plug will have a similar footprint to the cap method.

The three discussed sealing methods are ranked from best (1) to worst (3) with respect to footprint as shown in Table IX.

TABLE IX: SEALING METHOD FOOTPRINT RANKING

| **Sealing Method** | Plate | Cap | Plug |
|---|---|---|---|
| **Rank** | 1 | 2 | 2 |

#### B.3.2.3.2 Footprint of Mechanism

Each of the mechanisms will have different footprints when stored or fully actuated. Figure 6 shows possible configurations of the three mechanisms to be analyzed.

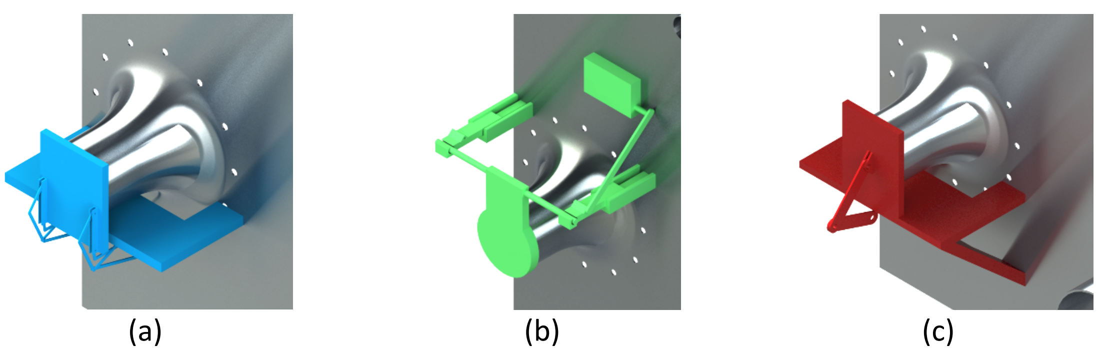


Figure 6. Preliminary design concept for (a) spider, (b) slide-pivot, and (c) one-pivot to compare footprint [1].

Figure 6 will be used to analyze the footprint of each mechanism. It should be noted that these are preliminary design concepts showing only one possible configuration for each mechanism.

## Mechanism: Spider

The spider mechanism is a compact design when the nozzle is sealed, but as the nozzle is opened, the linkages will move away from the nozzle, increasing the footprint. When stored, the seal will rest parallel to the nozzle throat face, outside of the airflow. There can be two spider mechanisms working in parallel on either side of the nozzle to reduce the thickness of the linkages. The actuator must be secured to the wall, and not the linkage mounting plate, because the actuator must be able to function with the smallest nozzle. This placement creates a larger footprint and is necessary because the smallest nozzle's mounting plate is not large enough to support the actuator.

## Mechanism: Slide-Pivot

The slide-pivot mechanism is a compact design, allowing the device to sit closer to the nozzle wall when stored. The device can use either one or two linear rails to secure to either one or two points, respectively, as shown in Figure 7.

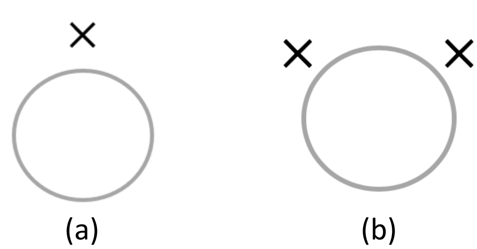



Figure 7. Mechanism securing location at either (a) one point or (b) two points.

With two linear rails, the mechanism and sealing device can be positioned closer to the nozzle throat without interfering with the base of the nozzle.

Two actuators are used side-by-side, one to move the rail and one to move the sealing device; this will increase the overall footprint. The slide-pivot mechanism will have a smaller footprint than the spider mechanism when stored, but a larger footprint when actuated.

#### Mechanism: One-Pivot

The one-pivot requires a platform or plate extending from the wall to locate a hinge in line with the nozzle throat. This can be achieved by a platform affixed to the wall at the base of the nozzle; however, the hinge will be farther away from the nozzle throat. The platform can be moved closer to the nozzle throat, which would require supports on either side of the nozzle base to avoid interference with the nozzle geometry. Both mounting locations are like those seen in Figure 7 for the slide-pivot mechanism which will result in either a narrow but tall footprint or wide but short footprint. The actuator can be mounted to either the platform or the wall directly. Overall, the one-pivot mechanism will have a similar footprint than the spider but a larger footprint than the slide-pivot, both when stored and when in use.

The three discussed mechanism are ranked from best (1) to worst (3) with respect to footprint as shown in Table X.

TABLE X: MECHANISM FOOTPRINT RANKING

| **Mechanism** | Spider | Slide-pivot | One-pivot |
|---|---|---|---|
| **Rank** | 2 | 1 | 2 |

### B.3.2.4 Cost

The cost of each mechanism and sealing method was analyzed to determine the most economical design. The cost of the design is important because the least expensive design saves Price money.

#### B.3.2.4.1 Cost of Sealing Method

The cost of the sealing method includes the material and manufacturing costs.

##### Sealing Method: Plate

The plate is the least expensive of the sealing methods because it has a simple geometry which requires minimal machining. Once the plate is machined, a rubber sealing material is cut and adhered to the plate.

##### Sealing Method: Cap

The cap will likely have additional manufacturing costs because either a piece of sheet metal must be bent, or a thicker plate must be machined down to form a lip around the outer diameter. The lip will also require an additional cutout to secure the O-ring. The cost of purchasing and cutting the rubber seal will be the same for the plate as for the cap.

##### Sealing Method: Plug

The cost of the plug will be similar to the cap because it requires a metal plate to be machined down to obtain the required shape, and an additional cutout to secure the O-ring. The cost of purchasing and cutting the rubber seal for the plug will be the same as for the plate and the cap.

The three discussed sealing methods are ranked from best (1) to worst (3) with respect to cost as shown in Table XI.

TABLE XI: SEALING METHOD COST RANKING

| **Sealing Method** | Plate | Cap | Plug |
|---|---|---|---|
| **Rank** | 1 | 2 | 2 |

B.3.2.4.2 Cost of Mechanism

The cost of the mechanism includes the number of linkages, attachment points and actuators as well as the cost of manufacturing.

Mechanism: Spider

The spider mechanism will be costly because there are numerous linkages of varying geometry that require machining. However, only one actuator is required, which will help keep the cost at a minimum.

Mechanism: Slide-Pivot

The slide-pivot does not have as many linkages as the spider, but requires separate actuators to first extend the linear rails, then rotate the seal onto the nozzle throat. Overall, the slide-pivot is more expensive than the spider because it requires two actuators.

Mechanism: One-Pivot

The one-pivot is the least expensive mechanism because it requires a minimal number of machined parts and only requires one actuator.

The three discussed mechanism are ranked from best (1) to worst (3) with respect to cost as shown in Table XII.

TABLE XII: MECHANISM COST RANKING

| **Mechanism** | Spider | Slide-pivot | One-pivot |
|---|---|---|---|
| **Rank** | 2 | 3 | 1 |

### B.3.2.5 Maintenance

The difficulty and frequency of required maintenance for each mechanism and sealing method was analyzed to determine lowest maintenance design.

#### B.3.2.5.1 Maintenance of Sealing Method

The maintenance of the sealing method will include replacement of the rubber seal or O-ring to maintain seal quality. To reduce the replacement frequency, the team will select a material with an appropriate lifespan.

##### Sealing Method: Plate

The plate will require minimal maintenance because there is only one rubber seal with a simple geometry. The rubber seal will need to be replaced periodically due to wear from repeated load cycles.

##### Sealing Method: Cap

The rubber cushion and O-ring inside the cap will need to be replaced periodically as they wear over repeated load cycles. Although the frequency of replacement for the cap is the same as for the plate, it will be rated lower due to an additional O-ring.

##### Sealing Method: Plug

The rubber cushion and O-ring along the outside diameter of the plug will need to be replaced periodically as they wear over repeated load cycles and lose their sealing qualities. This will require the same level of maintenance as the cap.

The three discussed sealing methods are ranked from best (1) to worst (3) with respect to maintenance as shown in Table XIII.

TABLE XIII: SEALING METHOD MAINTENANCE RANKING

| **Sealing Method** | Plate | Cap | Plug |
|---|---|---|---|
| **Rank** | 1 | 2 | 2 |

B.3.2.5.2 Maintenance of Mechanism

The spider, slide-pivot and one-pivot mechanisms need minimal maintenance because they do not experience large forces. Therefore, the maintenance of the mechanism will consider the frequency and difficulty of replacement of parts due to unexpected failures.

Mechanism: Spider

The probability of unexpected failures in the spider is higher than the slide-pivot and the one-pivot because of the increased number of joints and linkages. Outside of unexpected failures, the spider requires minimal maintenance because there are no parts that must be regularly replaced.

Mechanism: Slide-Pivot

The slide-pivot will be easier to maintain compared to the spider because it has fewer parts, and each individual part will be easier to replace. The only maintenance required is replacement of a linkage or joint due to unexpected failure.

Mechanism: One-Pivot

The one-pivot requires minimal maintenance because no parts need to be replaced on a regular basis, and it also has a low probability of unexpected failure because it has a fewer individual parts. However, the replacement of the individual parts will be more difficult.

The three discussed mechanism are ranked from best (1) to worst (3) with respect to maintenance as shown in Table XIV.

TABLE XIV: MECHANISM MAINTENANCE RANKING

| **Mechanism** | Spider | Slide-pivot | One-pivot |
|---|---|---|---|
| **Rank** | 1 | 2 | 1 |

### B.3.2.6 Aesthetics

The aesthetic appeal of each design considers the overall look and organization of the device and is important to instill pride in both the designer and the client.

#### B.3.2.6.1 Aesthetics of Sealing Method

The aesthetics of the sealing method relates solely to the overall shape of the sealing device.

Sealing Method: Plate

The plate offers a sleek aesthetic appeal without any bulky attachments.

Sealing Method: Cap

The cap will wrap around the nozzle, creating a look of completeness when the nozzle is sealed. However, with a bulky shape, it has less aesthetic appeal than the plate.

Sealing Method: Plug

The plug will look bulky when it is not in the nozzle, leading to a less desirable aesthetic compared to both the plate and cap.

The three discussed sealing methods are ranked from best (1) to worst (3) with respect to aesthetic as shown in Table XV.

TABLE XV: SEALING METHOD AESTHETICS RANKING

| **Sealing Method** | Plate | Cap | Plug |
|---|---|---|---|
| **Rank** | 1 | 2 | 3 |

#### B.3.2.6.2 Aesthetics of Mechanism

The aesthetic of the mechanism will focus on the linkages, attachment points and the overall shape.

Mechanism: Spider

The spider will have many linkages leading to a bulkier-looking design. The crossing linkages may help the aesthetic appeal by forming interesting patterns.

Mechanism: Slide-Pivot

The slide-pivot is a compact design and is packaged together when the nozzle is not sealed, leading to a neat and tidy appearance.

Mechanism: One-Pivot

The one-pivot mechanism looks similar both when the nozzle is sealed and open. The one-pivot mechanism appears bulky and in the way because it does not retract to the nozzle bank wall when stored.

The three discussed mechanism are ranked from best (1) to worst (3) with respect to aesthetic as shown in Table XVI.

TABLE XVI: MECHANISM AESTHETICS RANKING

| **Mechanism** | Spider | Slide-pivot | One-pivot |
|---|---|---|---|
| **Rank** | 2 | 1 | 3 |

## B.4 Final Concept Selection

A weighted decision matrix was used to choose the top two designs. To determine the weight of each criterion in the weighted decision matrix, each criterion was first compared to each other to decide which was most important. The more important criteria between each selection is shown in Table XVII with its corresponding letter. The total hits for each letter was used to determine a percentage which will weigh the rankings in the weighted decision matrix.

TABLE XVII: CRITERIA DECISION MATRIX

| | | Manufacturability | Simplicity of Mechanism | Footprint | Cost | Maintenance | Aesthetics | Placeholder |
|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | - |
| Manufacturability | A | | A | A | A | E | A | A |
| Simplicity of Mechanism | B | | | B | D | E | B | B |
| Footprint | C | | | | D | E | F | C |
| Cost | D | | | | | E | D | D |
| Maintenance | E | | | | | | E | E |
| Aesthetics | F | | | | | | | F |
| Total Hits | | 5 | 3 | 1 | 4 | 6 | 2 | |
| Weightings | | 23.8% | 14.3% | 4.8% | 19.0% | 28.6% | 9.5% | |

Maintenance received the highest percentage, which means it is the most important criteria, and will therefore have the greatest influence in the weighted decision matrix.

Table XVIII shows the weighted decision matrix for the sealing methods, where a higher score implies a more desirable design.

TABLE XVIII: SEALING METHOD WEIGHTED DECISION MATRIX

| Criteria | Weighting | Plate | | Cap | | Plug | |
|---|---|---|---|---|---|---|---|
| | | Score | Total | Score | Total | Score | Total |
| Manufacturability and assembly | 23.8 | 3 | 0.71 | 2 | 0.48 | 2 | 0.48 |
| Simplicity | 14.3 | 3 | 0.43 | 2 | 0.29 | 1 | 0.14 |
| Footprint | 4.8 | 3 | 0.14 | 2 | 0.10 | 2 | 0.10 |
| Cost | 19.0 | 3 | 0.57 | 2 | 0.38 | 2 | 0.38 |
| Maintenance (frequency & accessibility) | 28.6 | 3 | 0.86 | 2 | 0.57 | 2 | 0.57 |
| Aesthetics | 9.5 | 3 | 0.29 | 2 | 0.19 | 1 | 0.10 |
| | Total | | 3.00 | | 2.00 | | 1.76 |
| | Ranking | 1 | | 2 | | 3 | |
| | Continue with design | Yes | | No | | No | |

As determined from the sealing method weighted decision matrix, the team will continue with the plate sealing method as the best design.

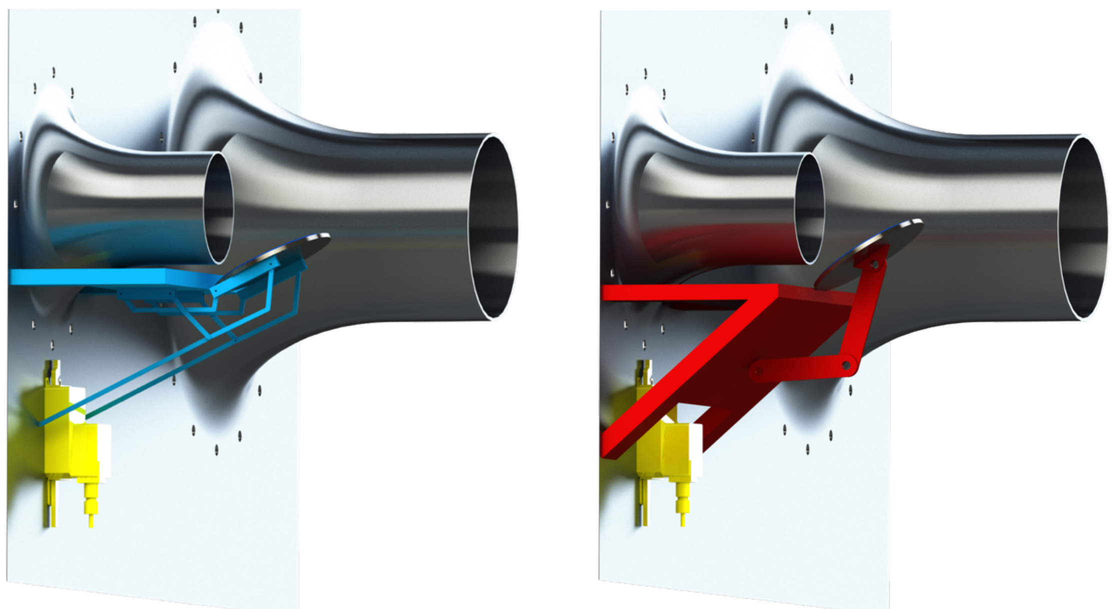
Table XIX shows the weighted decision matrix for the mechanisms, where a higher score implies a more desirable design.

TABLE XIX: MECHANISM WEIGHTED DECISION MATRIX

| Criteria | Weighting | Spider | | Slide-pivot | | One-pivot | |
|---|---|---|---|---|---|---|---|
| | | Score | Total | Score | Total | Score | Total |
| Manufacturability and assembly | 23.8 | 3 | 0.71 | 4 | 0.95 | 5 | 1.19 |
| Simplicity | 14.3 | 3 | 0.43 | 4 | 0.57 | 5 | 0.71 |
| Footprint | 4.8 | 3 | 0.14 | 4 | 0.19 | 3 | 0.14 |
| Cost | 19.0 | 3 | 0.57 | 1 | 0.19 | 4 | 0.76 |
| Maintenance (frequency & accessibility) | 28.6 | 3 | 0.86 | 2 | 0.57 | 3 | 0.86 |
| Aesthetics | 9.5 | 3 | 0.29 | 4 | 0.38 | 2 | 0.19 |
| | **Total** | | 3.00 | | 2.86 | | 3.86 |
| | **Ranking** | 2 | | 3 | | 1 | |
| | Continue with design | **Yes** | | **No** | | **Yes** | |

As determined from the mechanism weighted decision matrix, the team will move forward with both the spider and the one-pivot mechanisms. After input from Price, the final mechanism will be confirmed.

The two possible configurations for the final design concepts, the spider mechanism and the one-pivot mechanism, both with a plate as the sealing method, are shown in Figure 8.



(a) (b)

Figure 8. Plate sealing methods with (a) spider and (b) one-pivot mechanisms [2].

A Belimo linear actuator has been placed next to each design concept in yellow to show the average space required to actuate the mechanism.

After consulting Price, the spider mechanism was chosen as the design to develop.

## B.5 References


[1] B. Giesbrecht.*Preliminary design concepts*, Winnipeg: Design Eng.,Univ

Manitoba,Winnipeg,MB, Nov.15,2018.

[2] B. Giesbrecht.*Final plate sealing methods,*Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov.15,2018.

# University of Manitoba IDEA Program:
# Design of an Automated Nozzle Sealing System

## Detailed Design Report

## Appendix C
## Design Drawing

# Contents

List of Figures ........ C-ii

C.1 Detailed Design Drawings ........ C-1

C.2 References ........ C-5

# List of Figures

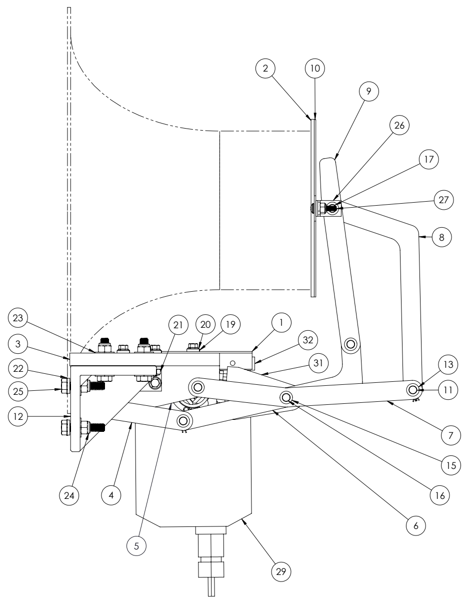
Figure 1. Spider mechanism detailed drawing sheet 1. .......... C-2

Figure 2. Spider mechanism detailed drawing sheet 2. .......... C-3

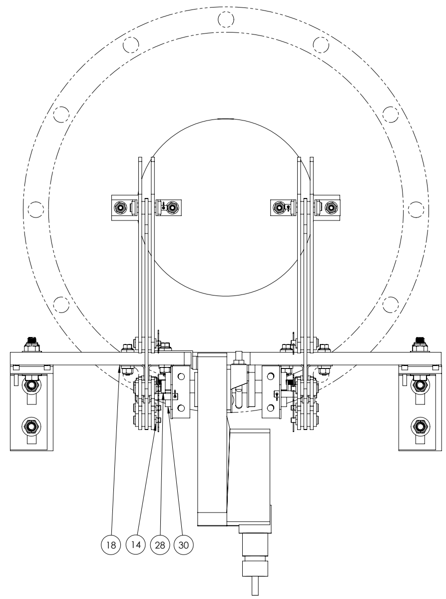
Figure 3. Spider mechanism detailed drawing sheet 3. .......... C-4

# C.1 Detailed Design Drawings

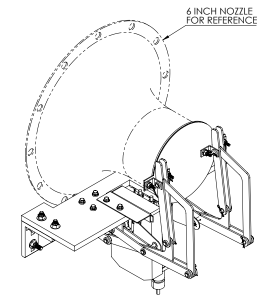
Detailed design drawings for the full spider mechanism with all dimensions for custom components are shown in Figure 1, Figure 2, and Figure 3.




ASSEMBLY VIEW
SCALE 1:2
FROM THE LEFT SIDE




ASSEMBLY VIEW
SCALE 1:2
FROM THE FRONT




ISOMETRIC
SCALE: NTS

| ITEM NO. | PART NUMBER | DESCRIPTION | VENDOR | QTY. |
|---|---|---|---|---|
| 1 | - | ACTUATOR MOUNTING BRACKET | - | 1 |
| 2 | - | RUBBER SEAL | ARGUS INDUSTRIES | 1 |
| 3 | - | SPIDER BOTTOM PLATE | - | 1 |
| 4 | - | SPIDER LINK AC | - | 2 |
| 5 | - | SPIDER LINK AB | - | 4 |
| 6 | - | SPIDER LINK CDG | - | 4 |
| 7 | - | SPIDER LINK BDE | - | 4 |
| 8 | - | SPIDER LINK EF | - | 2 |
| 9 | - | SPIDER LINK FG | - | 2 |
| 10 | - | SPIDER SEAL PLATE | - | 1 |
| 11 | 0156717 | 3/16 CLEVIS PIN | FASTENAL | 10 |
| 12 | 14086 | CORNER WALL BRACKET | ROCKY MOUNTAIN WESTMILL | 2 |
| 13 | 0145791 | 3/16 NYLON SPACER | FASTENAL | 38 |
| 14 | 76060 | 6/16 NYLON WASHER | FASTENAL | 14 |
| 15 | 76061 | 1/4 NYLON WASHER | FASTENAL | 8 |
| 16 | 0156731 | 1/4 X 1-3/4 CLEVIS PIN | FASTENAL | 2 |
| 17 | 97245A604 | 3/16 X 1-1/2 CLEVIS PIN | FASTENAL | 2 |
| 18 | 13998069 | 90 DEG BRACKET | RONA | 4 |
| 19 | 11128442 | #10 METAL WASHER | FASTENAL | 30 |
| 20 | 0148130 | #10-24 X 1 BOLT | FASTENAL | 13 |
| 21 | 37014 | #10-24 LOCKING NUT | FASTENAL | 17 |
| 22 | 0160877 | 5/16 RUBBER SEALING WASHER | FASTENAL | 4 |
| 23 | 71015 | 5/16 METAL WASHER | FASTENAL | 12 |
| 24 | 1170861 | 5/16-18 LOCKING NUT | FASTENAL | 8 |
| 25 | 0177394 | 5/16-18 X 1-1/2 BOLT | FASTENAL | 8 |
| 26 | 51053209 | 90 DEG BRACKET FOR PLATE | RONA | 4 |
| 27 | 28975 | #10-24 X 7/8 MACHINE SCREW | FASTENAL | 4 |
| 28 | - | 1/5 DIA. X 5 LENGTH SHAFT | - | 1 |
| 29 | GMX24-SR | 40 nm ROTARY ACTUATOR | BELIMO | 1 |
| 30 | K-LM12 | SHAFT CLAMP | BELIMO | 2 |
| 31 | - | ACTUATOR ARM | - | 2 |
| 32 | ZG-GMA | MOUNTING BRACKET ASSEMBLY FOR ACTUATOR | BELIMO | 1 |

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.001
ANGULAR ± 0.01
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL VARIOUS
FINISH N/A
DO NOT SCALE DRAWING

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

COMMENTS:

University of Manitoba
TITLE: Spider Mechanism
SIZE D DWG. NO. 001 REV 0
SCALE: 1:2 WEIGHT: 11.95 lbs SHEET 1 OF 3



Figure 1. Spider mechanism detailed drawing sheet 1 [1].

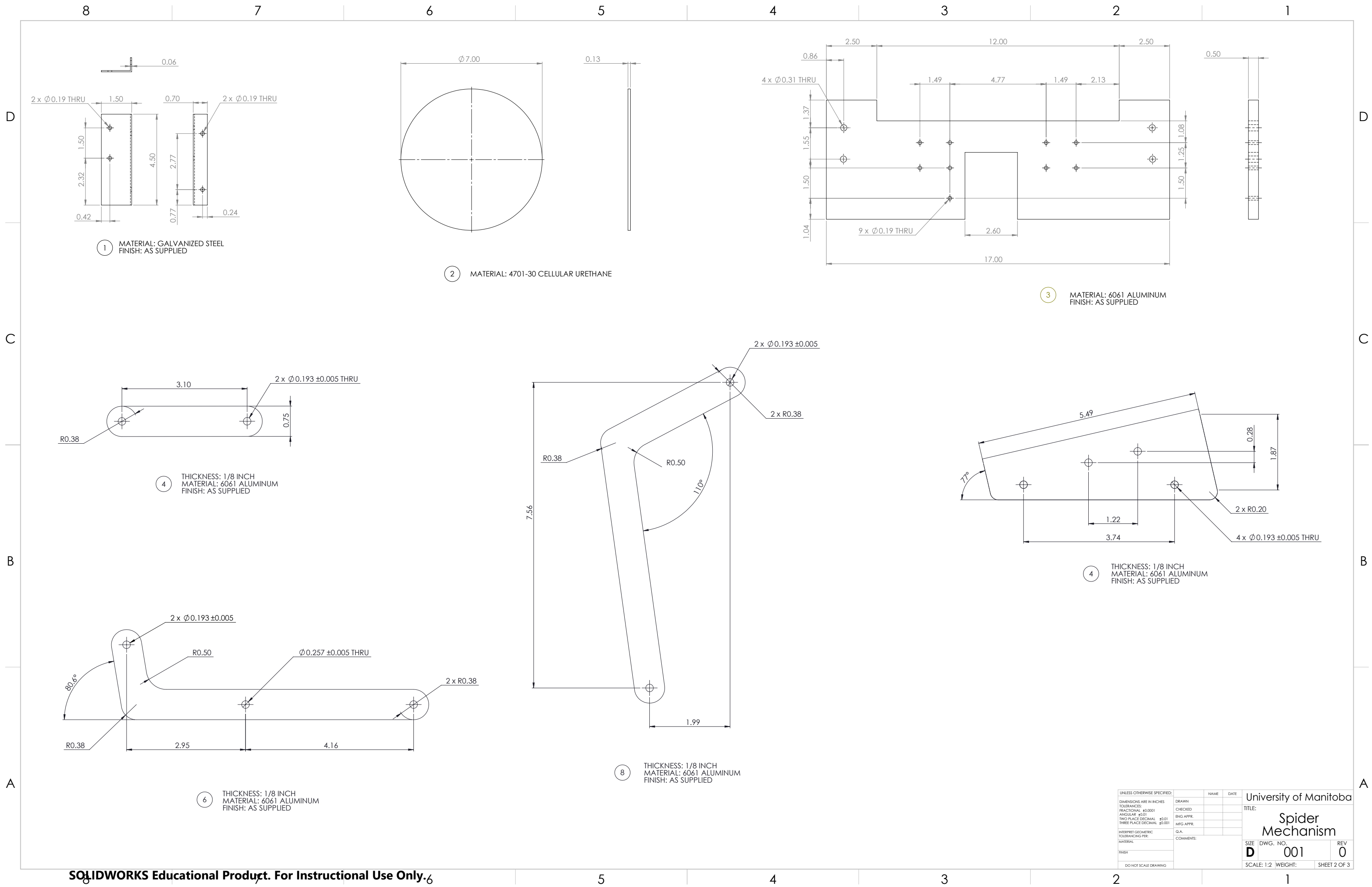



Figure 2. Spider mechanism detailed drawing sheet 2 [1].

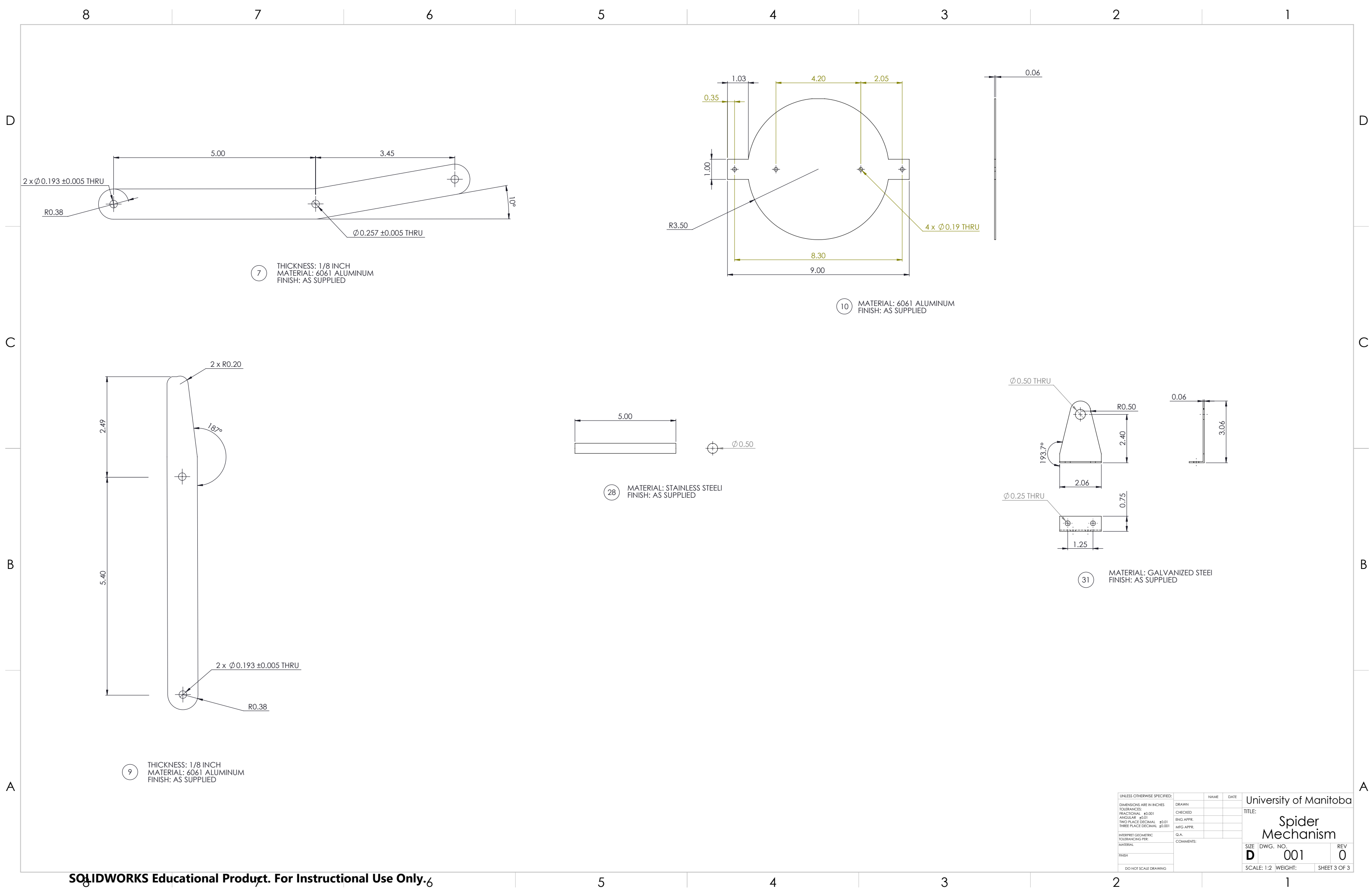



Figure 3. Spider mechanism detailed drawing sheet 3 [1].

## C.2 References

[1] B. Giesbrecht. *Spider mechanism detailed drawing*, Winnipeg: Design Eng., University of Manitoba, Winnipeg, MB, Dec. 2, 2018.

# University of Manitoba IDEA Program:
# Design of an Automated Nozzle Sealing System

Detailed Design Report

# APPENDIX D

## Solid Mechanics Analyses

# Contents


List of Figures ..................................................................................................D-iv

List of Tables ....................................................................................................D-1

D.1 Introduction ...................................................................................................D-2

D.2 Sealing Force ..................................................................................................D-2

D.3 Internal Linkage Forces ...................................................................................D-3

D.4 Linkage Lengths...............................................................................................D-5

D.5 Linkage Cross-Sectional Dimensions...............................................................D-6

D.5.1 Fatigue .........................................................................................................D-6

D.5.1.1 Surface Condition Factor, $\boldsymbol{ka}$ .....................................................D-7

D. 5.1.2 Size Factor, $\boldsymbol{kb}$ ..............................................................................D-7

D. 5.1.3 Loading Factor, $\boldsymbol{kc}$ ........................................................................D-8

D. 5.1.4 Temperature Factor, $\boldsymbol{kd}$ ...............................................................D-8

D. 5.1.5 Reliability Factor, $\boldsymbol{ke}$ ...................................................................D-8

D.5.1.6 Miscellaneous Modification Factor, $\boldsymbol{kf}$ .......................................D-9

D.5.1.7 Modifying Factor Results .............................................................................D-9

D.5.1.8 Lifetime ........................................................................................................D-9

D.5.1.9 Modified Fatigue Strength.........................................................................D-10

D.5.1.10 Fatigue Stress Analysis............................................................................D-10

D.5.2 Pin Shearing Analysis ....................................................................... D-12

D.5.3 Pin Hole Analysis ............................................................................. D-13

D.5.4 Pin Hole Tolerances .......................................................................... D-14

D.5.5 Inside Corner Stress .......................................................................... D-16

D.6 Weight Analysis ..................................................................................... D-17

D.7 MapleSoft Code ..................................................................................... D-19

D.8 References ............................................................................................ D-31

# List of Figures

Figure 1. Schematic of the forces and moment acting on each linkage. ........................D-4

Figure 2. Linkage lengths in the x and y-direction. ........................................................D-5

Figure 3. Equivalent diameter of noncircular cross sections. .........................................D-8

Figure 4. S-N diagram for aluminium T6-6061.............................................................D-10

Figure 5. Schematic of linkage dimensions. .................................................................D-13

Figure 6. Stress concentration graph. ..........................................................................D-14

Figure 7. Clearance fit. .................................................................................................D-15

Figure 8. Inner radius relationship on corner stress concentration factor. .................D-17

Figure 9. Location of the center of mass for both the open and closed positions. .......D-18

Figure 10. Notation for the forces in each linkage. .....................................................D-19

Figure 11. Notation for the lengths in the x and y direction of each linkage. ..............D-20

# List of Tables

TABLE I: LIST OF FORCE AND MOMENT MAGNITUDES. ................................................D-4

TABLE II: LINKAGE LENGTHS AND MOMENT ITERATIONS ..............................................D-6

TABLE III: PARAMETERS FOR MARIN SURFACE FACTOR ..................................................D-7

TABLE IV: REALIABILITY FACTORS FOR DESIRED RELIABILITY PERCENTAGE ....................D-9

TABLE V: MODIFYING FACTORS ..........................................................................D-9

TABLE VI: SUMMARY OF MODIFYING FATIGUE STRENGTH .........................................D-10

TABLE VII: FACTOR OF SAFETY FOR EACH LINKAGE ......................................................D-12

TABLE VIII: LISTING OF LINKAGE AND PIN DIMENSIONS ..............................................D-14

TABLE IX: TOLERANCES OF PIN SHAFT AND MEMBER HOLE ........................................D-16

TABLE X: ALL NECESSARY VALUES TO CALCULATE THE MOMENT DUE TO THE WEIGHT OF LINKAGE IN THE OPEN POSITION ......................................................................D-18

TABLE XI: ALL NECESSARY VALUES TO CALCULATE THE MOMENT DUE TO WEIGHT OF LINKAGE IN THE CLOSED POSITION ..................................................................D-18

## D.1 Introduction

An analysis was performed for each design component to ensure they would meet the lifespan requirements of 10 years. The analyses covered include: sealing forces, internal linkage forces, and determining linkage dimensions through stress analysis.

## D.2 Sealing Force

The sealing force required to create a full seal was calculated to determine the resulting internal forces within the system. This force is made up of two components: the force counteracting the pressure on the sealing device and the force used to compress the rubber. To create a full seal, the rubber pad must be compressed 5% of its thickness. This pressure force is a function of the open area of the nozzle and the pressure applied, shown in equation (1).

$$F_{pressure} = A_{nozzle} P_{chamber} \tag{1}$$

The compression force of the rubber is shown in equation (2), where the force is a function of the area of the nozzle in contact with the rubber, the percent deformation and Young's modulus of the rubber.

$$F_{compression} = A_{rim} \delta_{rubber} E_{rubber} \tag{2}$$

The entire force needed to seal the nozzle is then calculated by summing equations (1) and (2), as shown by equation (3).

$$F_{seal} = F_{pressure} + F_{compession} \tag{3}$$

## D.3 Internal Linkage Forces

To determine the internal forces in the linkages, a force analysis was conducted. The spider mechanism was broken down into its five linkages and analyzed in the closed position where the sealing force is applied. To determine the forces in the linkages, the following static equations were applied:

$$\Sigma F_x = 0 \tag{4}$$

$$\Sigma F_y = 0 \tag{5}$$

$$\Sigma M = 0 \tag{6}$$

Applying these equations to each linkage, a total of 11 equations and 11 unknowns were found for the entire mechanism. A MapleSoft program was written to solve for the internal forces and the required moment at node B, at the location of the actuator. The forces and moment are shown in Figure 1 with the solved magnitudes in Table I.

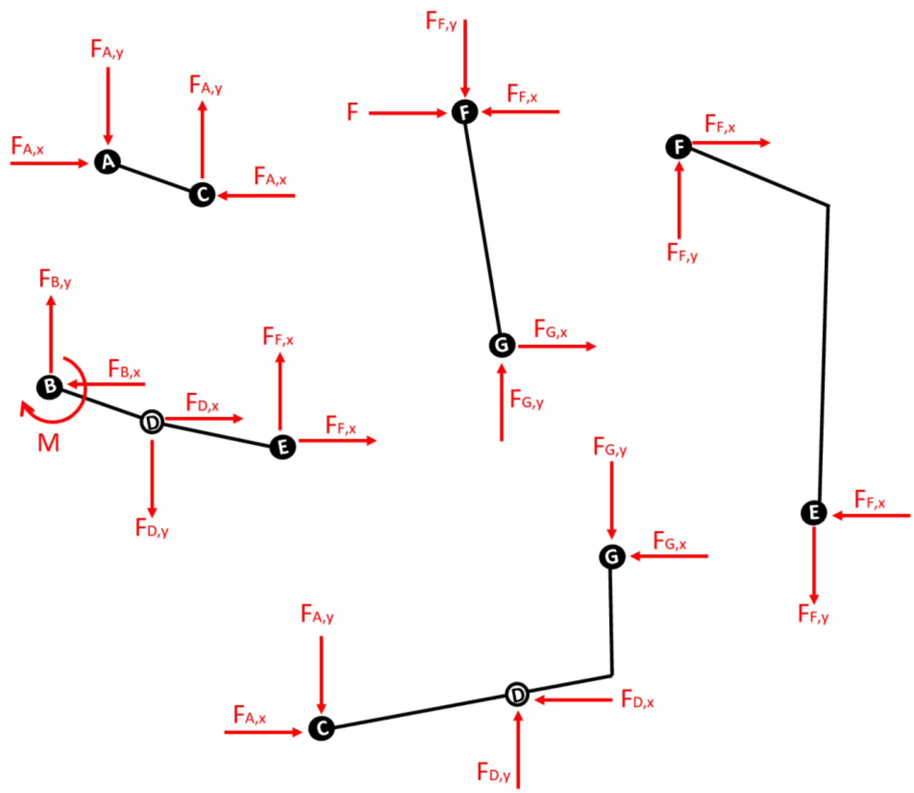



Figure 1. Schematic of the forces and moment acting on each linkage.

TABLE I: LIST OF FORCE AND MOMENT MAGNITUDES

| | Magnitude |
|---|---|
| $F$ | 8.98 [lbf] |
| $F_{A,x}$ | 69.44 [lbf] |
| $F_{A,y}$ | 12.63 [lbf] |
| $F_{B,x}$ | 57.85 [lbf] |
| $F_{B,y}$ | 8.89 [lbf] |
| $F_{D,x}$ | 45.42 [lbf] |
| $F_{D,y}$ | 39.63 [lbf] |
| $F_{F,x}$ | 12.43 [lbf] |
| $F_{F,y}$ | 30.74 [lbf] |
| $F_{G,x}$ | 3.45 [lbf] |
| $F_{G,y}$ | 30.74 [lbf] |
| $M$ | 156.96 [lbf in] |

## D.4 Linkage Lengths

Multiple linkage lengths were iterated through to minimize the moment at node B. The linkage lengths were first broken down into x and y components, as shown in Figure 2.

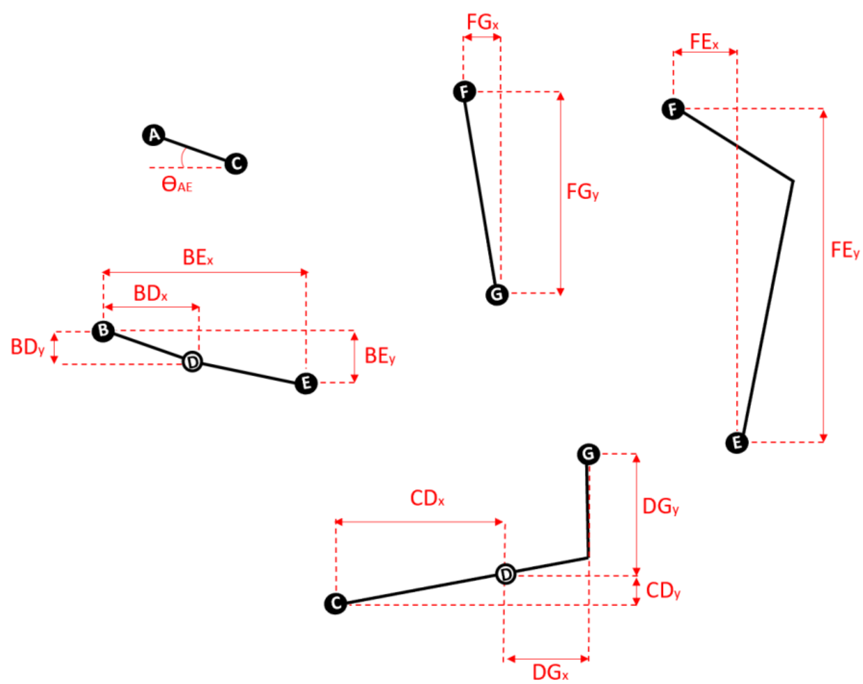



Figure 2. Linkage lengths in the x and y-direction.

After the third iteration, the moment was decreased by 67% of its original value. The main reason for this drastic moment decrease was the increase in the horizontal length of CG and FE. This increase of length allows the force applied to the nozzle to become more horizontal, causing the majority of the force to be used to counteract the pressure force. The results from all three iterations are shown in Table II.

TABLE II: LINKAGE LENGTHS AND MOMENT ITERATIONS

| | Iteration #1 | Iteration #2 | Iteration #3 |
|---|---|---|---|
| $\theta_{AC}[rad]$ | 0.4650 | 0.3171 | 0.1901 |
| $CD_x$[m] | 3.7432 | 3.6732 | 4.0360 |
| $CD_y$[m] | 0 | 0.6181 | 0.7700 |
| $DG_x$[m] | 2.9547 | 2.6654 | 2.6160 |
| $DG_y$[m] | 1.4866 | 1.9409 | 2.0060 |
| $BE_x$[m] | 6.5123 | 6.7953 | 8.4450 |
| $BE_y$[m] | 2.4994 | 1.5748 | 0.6310 |
| $BD_x$[m] | 2.6836 | 2.8386 | 3.4450 |
| $BD_y$[m] | 1.3520 | 0.9646 | 0.6170 |
| $FG_x$[m] | 0 | 0.6772 | 0.6020 |
| $FG_y$[m] | 5.4583 | 5.3583 | 5.3660 |
| $FE_x$[m] | 0.8992 | 1.9685 | 2.9860 |
| $FE_y$[m] | 8.0321 | 7.9094 | 7.3860 |
| **M @ Node B [lb in]** | 466.29 | 431.24 | 156.96 |

# D.5 Linkage Cross-Sectional Dimensions

The linkage thickness, width, and pin hole diameters were determined through a fatigue stress analysis for a 10-year life span. Furthermore, the necessary tolerancing of the pin holes and the corner stress of bent members was analyzed.

## D.5.1 Fatigue

The modified fatigue strength of 6061-T6 aluminum is determined from the pristine endurance limit and the applicable modifying factors, shown in equation (7).

$$S_e = k_a k_b k_c k_d k_e k_f S_e' \tag{7}$$

In this equation, $k_a$ is the surface modification factor, $k_b$ is the size modification factor, $k_c$ is the load modification factor, $k_d$ is the temperature modification factor, $k_e$ is the reliability factor, and $k_f$ is the miscellaneous-effects modification factor.

#### D.5.1.1 Surface Condition Factor, $\boldsymbol{k_a}$

The surface modifying factor takes into consideration the surface condition of the linkage and its effect on fatigue. The practical surface factor depends on the quality of the finish and the ultimate strength, $S_{ut}$, of the material.

$$k_a = aS_{ut}^b \tag{8}$$

The quality of the surface finish is determined from the coefficients found in Table III.

TABLE III: PARAMETERS FOR MARIN SURFACE FACTOR [1]

[redacted]

The sheets of aluminium are assumed to be hot-rolled to be conservative.

#### D.5.1.2 Size Factor, $\boldsymbol{k_b}$

The size modification factor considers the higher probability of fatigue failure in larger linkages. The equivalent diameter for rectangular linkages is shown in Figure 3.

Figure 3. Equivalent diameter of noncircular cross sections [1].

The size factor can be determined using equation (9).

$$k_b = 0.879 {d_e}^{-0.107} \tag{9}$$

### D.5.1.3 Loading Factor, $\boldsymbol{k_c}$

The linkages in the spider mechanism experience both axial and bending loading. To account for the axially loaded members, the loading factor is set to 0.85 [1].

### D.5.1.4 Temperature Factor, $\boldsymbol{k_d}$

The sealing system is operating at room temperature, so the temperature factor is set to one.

### D.5.1.5 Reliability Factor, $\boldsymbol{k_e}$

The reliability modification factor considers the statistical nature of fatigue strength and can be determined from the reliability percentage shown in Table IV.

TABLE IV: RELIABILITY FACTORS FOR DESIRED RELIABILITY PERCENTAGE [1]

[redacted]

A reliability of 99.99% will be used for the sealing mechanism meaning the reliability factor is set to 0.702.

#### D.5.1.6 Miscellaneous Modification Factor, $k_f$

The miscellaneous modification factor considers other variables that may accelerate fatigue such as corrosion, residual stresses, and changes in cyclic frequency. For our system, the factor us assumed to be one.

#### D.5.1.7 Modifying Factor Results

The summary of modifying factors is shown in Table V.

TABLE V: MODIFYING FACTORS

| $k_a$ | $k_b$ | $k_c$ | $k_d$ | $k_e$ | $k_f$ | **Resultant** |
|---|---|---|---|---|---|---|
| 0.936 | 0.984 | 0.850 | 1 | 0.702 | 1 | 0.549 |

#### D.5.1.8 Lifetime

The sealing system was assumed to be used five times per day, five days a week and assumed to operate year-round. The approximate number of cycles over the 10-year life of the system is 12,000 cycles. The corresponding pristine endurance limit, from the S-N curve of 6061-T6 aluminum, is determined to be 30.46 [kpsi] and is shown in Figure 4.

Figure 4. S-N diagram for aluminium T6-6061 [2].

### D.5.1.9 Modified Fatigue Strength

The pristine endurance limit determined from the S-N curve, the modifying factor, and the modified fatigue strength are shown in Table VI.

TABLE VI: SUMMARY OF MODIFYING FATIGUE STRENGTH

| **Pristine Fatigue Strength ($S_e{}'$)** | **Modifying Factor** | **Modified Fatigue strength ($S_e$)** |
|---|---|---|
| $30.46\ kpsi$ | $0.549$ | $15.75\ kpsi$ |

### D.5.1.10 Fatigue Stress Analysis

The DE-Soderberg fatigue failure criterion was used when analyzing fatigue because it is a conservative measure against yielding [1].

$$\frac{1}{n} = \frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{yld}} \tag{10}$$

In the DE-Soderberg equation, $n$ is the fatigue stress safety factor, $\sigma_a$ is the equivalent von Mises stress amplitude applied, $S_e$ is the modified fatigue strength, $\sigma_m$ is the mean equivalent von Mises stress and $S_{yld}$ is yield strength of the material. For the sealing application, there is only an equivalent von Mises stress amplitude, as the design only experiences force when the nozzle is sealed. Equation (11) shows the equivalent von Mises stress amplitude as a function of the normal stress, $\sigma$, and shear stress, $\tau$.

$$\sigma_a = \sqrt{\sigma^2 + 3\tau^2} \tag{11}$$

The normal and shear stresses were found using equations (12) and (13).

$$\sigma = \frac{Mc}{I} + \frac{F}{A} \tag{12}$$

$$\tau = \frac{VQ}{It} \tag{13}$$

The largest moment and shear force were found in each member by using MapleSoft. The shear force was calculated by summing the product of the force perpendicular to the linkage. The square of the magnitudes of the shear force caused by the vertical and horizontal forces was summed, and the square root of the result was calculated. The moment equation was then found by integrating the shear force equation.

As the spider mechanism has two sides, all the factors of safety were doubled. Similarly, linkages AC, BDE, and FG have two members per link and therefore their factors of safety were doubled again. All members were found to exceed a factor of safety of two at a 1/8 [in] thickness. To try and reduce weight, a stress analysis was conducted on the next smallest standard size thickness (1/16 [in]); however, it was found that some member's factor of safety was less than two. For manufacturing simplicity, all linkages were designed with the same thickness of 1/8 [in]. The factor of safety and stresses for each linkage is shown in Table VII. Sample calculations for the stresses and factors of safety can be found in Section C.6.

TABLE VII: FACTOR OF SAFETY FOR EACH LINKAGE

| Linkage | Number of Links | Maximum Shear Force [lbf] | Maximum Moment [lbf in] | Normal Stress [psi] | Shear Stress [psi] | Stress Amplitude [psi] | FOS |
|---|---|---|---|---|---|---|---|
| **AC** | 4 | 0 | 0 | 529.86 | 0 | 529.89 | 118.90 |
| **BDE** | 4 | 58.53 | 158.97 | 14189.46 | 936.50 | 14281.87 | 4.41 |
| **CDG** | 2 | 49.67 | 73.58 | 6808.49 | 794.77 | 6946.37 | 4.53 |
| **FG** | 4 | 0 | 0 | 329.99 | 0 | 329.99 | 190.91 |
| **EF** | 2 | 33.16 | 78.05 | 7014.38 | 530.58 | 7074.33 | 4.45 |

## D.5.2 Pin Shearing Analysis

To ensure the pins do not shear, the minimum diameter of the pin with the greatest internal forces was determined. The clevis pins sourced are made from general steel, therefore, AISI 4130 steel material properties were used for this analysis. As per common practice, the shear strength of the steel was assumed to be 60 percent of the tensile yield strength [1]. Using a tensile yield strength of 63,091 [psi], the minimum diameter of the pin was found using equations (14) and (15).

$$A_{pin} = \frac{FOS * F}{\tau_{steel}} \tag{14}$$

$$D_{pin} = \sqrt{\frac{4 * A_{pin}}{\pi}} \tag{15}$$

From these equations the minimum pin diameter was found to be 0.06 [in], however, the smallest standard size of clevis pin is 3/16 [in]. Therefore, all pinhole diameters were set to 3/16 [in] except for the pin connecting to the actuator which must be 1/4 [in] for coupling purposes.

## D.5.3 Pin Hole Analysis

The pin holes within members under tension create a stress concentration; to verify linkage failure does not occur at the pinhole, the linkage with the greatest tensile forces was analyzed. The largest pin size (1/4 [in]) was analyzed to guarantee that all linkages under tension do not fail. The width of the members was set to 3/4 [in] to follow the common practice of allowing 1.5-hole diameters on either side of the pinhole, as shown in Figure 5.

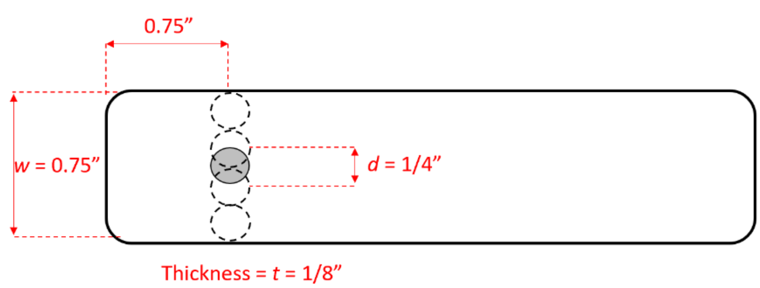



Figure 5. Schematic of linkage dimensions.

To determine the stress at the pinhole within the linkage equations (16) and (17) were used.

$$\sigma = \frac{k_t F}{A} \tag{16}$$

$$A = t \times (w - d) \tag{17}$$

In equation (16), $k_t$ is the stress concentration factor which was found using Figure 6.

Figure 6. Stress concentration graph [1].

It was found that the linkage with the largest tensile stresses has a factor of safety of 4.41 and therefore does not fail at the location at the pin; all calculations can be found in the Maple code. Linkage and pin dimensions are summarized in Table VIII.

TABLE VIII: LISTING OF LINKAGE AND PIN DIMENSIONS

| | **Dimension** |
|---|---|
| **Linkage Thickness** | 1/8 [in] |
| **Linkage Width** | 3/4 [in] |
| **Pin: A, B, C, E, G, F** | 3/16 [in] |
| **Pin: D** | 1/4 [in] |

## D.5.4 Pin Hole Tolerances

The pins and linkages are connected through a clearance fit, where the hole in the linkage will always be larger than the pin outer diameter when assembled. This clearance fit will allow the system to rotate while not being too loose. The pin and linkage connections are considered to be a shaft and hole connection type, which is shown in Figure 7.

Figure 7. Clearance fit [3].

The clevis pins have a diameter of 0.1835 ± 0.0025 [in] as determined from the product standard [4]. A tolerance of 0.0025 [in] corresponds to an h6 class for a shaft, as determined from the ISO tolerance system [5]. A sliding clearance fit was chosen to allow the pins to move and turn easily but are not intended to run freely. A sliding clearance fit requires the hole to meet the G7 class of the ISO system. The G7 class requires the hole dimensions to be 0.1931 ± 0.005 [in].

The allowance is the space between the shaft and pin at the tightest possible configuration, as shown in equation (18).

$$Allowance = Min\ diameter\ of\ hole - Max\ size\ of\ shaft \tag{18}$$

The clearance is the space between the shaft and pin at the loosest possible configuration, as shown in equation (19).

$$Clearance = Max\ diameter\ of\ hole - Min\ size\ of\ shaft \tag{19}$$

The summary of the tolerance analysis on the clevis pin and member hole is shown in Table IX.

TABLE IX: TOLERANCES OF PIN SHAFT AND MEMBER HOLE

| | Hole | Shaft |
|---|---|---|
| **Fit Type** | Clearance | |
| **Clearance Fit Subsection** | Close clearance | |
| **ISO Class** | G7 | h6 |
| **Dimension [in]** | $0.1931in \pm 0.005in$ | $0.1835in \pm 0.0025in$ |
| **Allowance [in]** | 0.0071 | |
| **Clearance [in]** | 0.00121 | |

These allowances and clearances are acceptable; however, it is necessary that the holes in the linkages are cut with a machine that has a tolerance of seven thou or less.

## D.5.5 Inside Corner Stress

Increased stress concentrations will occur at corners with sharp inner radii. The corner stress will trend to infinity for a theoretical perfectly sharp corner; to reduce these high stresses, sharp corners will be filleted.

The quotient of the allowable stress and the largest stress in the mechanism must be greater than the stress concentration factor caused by the corner, depicted in equation (20).

$$K_{max} < \frac{\sigma_a}{\sigma_{max}} \tag{20}$$

The greatest stress concentration factor in the linkages was determined to be 1.55. With the maximum allowable stress concentration factor, the ratio of inner corner radius and wall thickness can be determined from the relationship shown in Figure 8.

[redacted]

Figure 8. Inner radius relationship on corner stress concentration factor [6].

From Figure 8, the allowable ratio of inner radius to the wall thickness must greater than 0.45. From this, the inner radius was restricted to values of 0.34 [in] or greater. An inner radius of 0.5 [in] will be used for the members to ensure the concentration factor does not lead to failure at the corners.

## D.6 Weight Analysis

A weight analysis was performed to verify that the actuator can support the weight of the mechanism. The center of mass of the mechanism's linkages and the sealing plate were located using the SolidWorks model. The moment at node B due to the mass of the linkages and sealing plate was calculated using equation (21) and equation (22).

$$F_g = m * g \tag{21}$$

$$M_B = F_g * d \tag{22}$$

In this equation, $d$ is the perpendicular distance from the gravitational force to node B. Figure 9 shows the location of the center of mass for the mechanism in the open and closed positions.


Figure 9. Location of the center of mass for both the open and closed positions [7].

The moment at node B due to the weight of the linkages for both the open and closed positions, are found in Table X and Table XI, respectively.

TABLE X: ALL NECESSARY VALUES TO CALCULATE THE MOMENT DUE TO THE WEIGHT OF LINKAGES IN THE OPEN POSITION

| | |
|---|---|
| **Mass, $m$** | 1.314 [lb] |
| **Gravitational Constant, $g$** | 32.174 [lbm-ft/lbf-s$^2$] |
| **Gravitational Force, $F_g$** | 42.28 [lbf] |
| **Distance, $d$** | 6.88 [in] |
| **Moment, M** | 290.88 [lbf in] |

TABLE XI: ALL NECESSARY VALUES TO CALCULATE THE MOMENT DUE TO THE WEIGHT OF LINKAGES IN THE CLOSED POSITION

| | |
|---|---|
| **Mass, $m$** | 1.314 [lb] |
| **Gravitational Constant, $g$** | 32.174 [lbm-ft/lbf-s$^2$] |
| **Gravitational Force, $F_g$** | 42.28 [lbf] |
| **Distance, $d$** | 4.32 [in] |
| **Moment, M** | 182.85 [lbf in] |

For the closed position, the actuator must also resist the 156.96 [lbf in] produced by the sealing force. Therefore, the total moment at node B produced by the sealing force and the weight of the linkages is 340 [lbf in].

## D.7 MapleSoft Code

The following section outlines the Maplesoft program used to perform the stress analysis. Figure 10 and Figure 11 show the notation used for programming purposes.

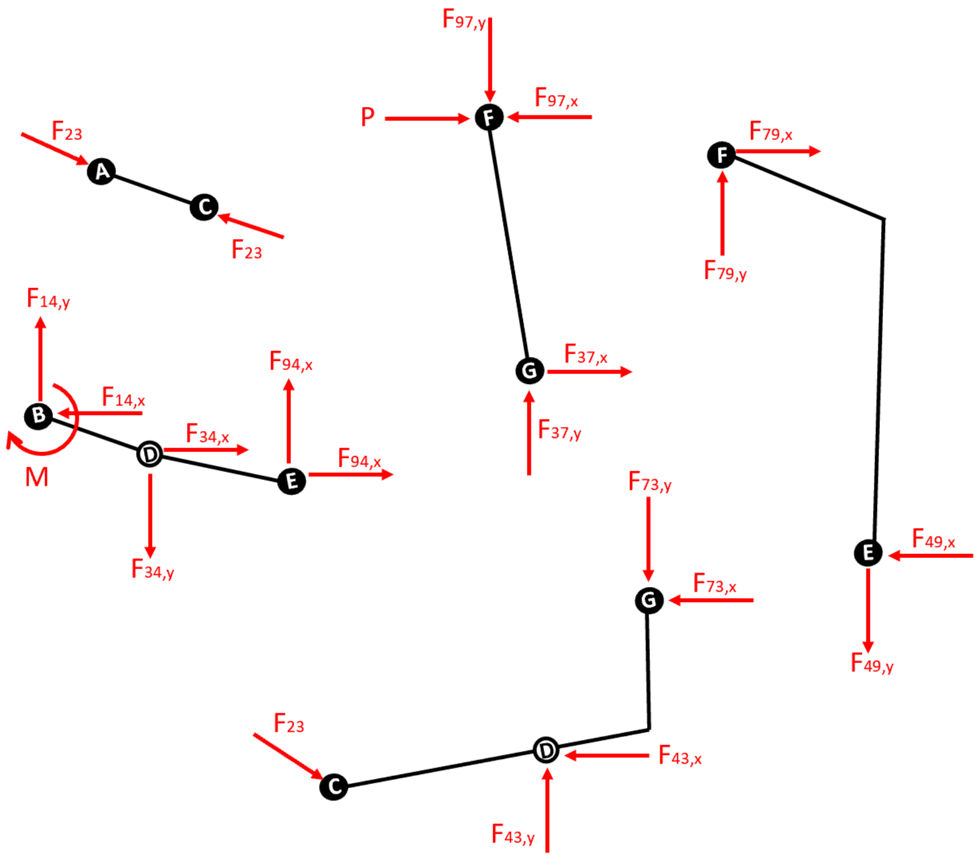



Figure 10. Notation for the forces in each linkage.

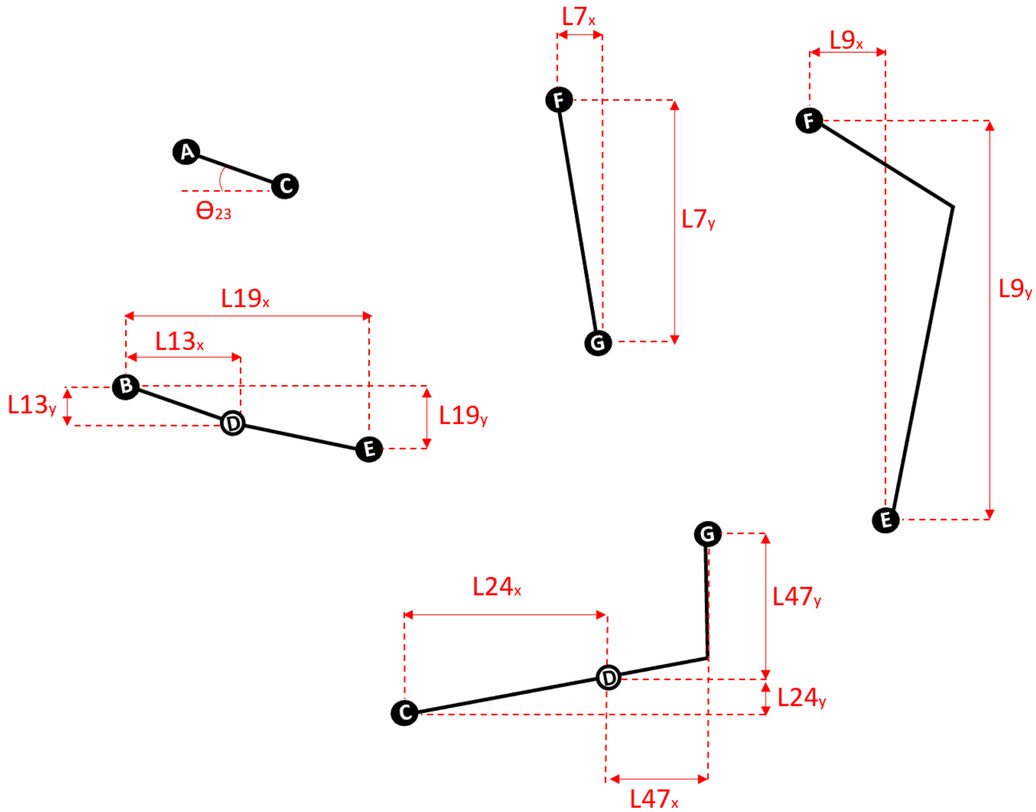



Figure 11. Notation for the lengths in the x and y direction of each linkage.

## Stress Analysis Program

Points are to find lengths of linkages from the Solidworks model.

```
restart;

Point1x := 4.336;
Point1y := -31.497;
Point2x := 7.338;
Point2y := -32.043 ;
Point3x := 11.374 ;
Point3y := -31.273 ;
Point4x := 7.929 ;
Point4y := -30.656;
Point6x := 13.990;
Point6y := -29.267 ;
Point7x := 16.374 ;
Point7y := -31.287 ;
Point9x := 13.388;
Point9y := -23.901;


L19x := abs(Point7x − Point4x);
L19y := abs(Point7y - Point4y);
L13x := abs(Point4x − Point3x);
L13y := abs(Point4y − Point3y);
L47x := abs(Point3x − Point6x);
L47y := abs(Point3y − Point6y);
L9x := abs(Point9x − Point7x);
L9y := abs(Point9y − Point7y);
L7x := abs(Point9x − Point6x);
L7y := abs(Point9y − Point6y);
L24x := abs(Point3x − Point2x);
L24y := abs(Point3y − Point2y);
```

$$\theta 23 := \arctan\left(\frac{\mathrm{abs}(Point2y - Point1y)}{\mathrm{abs}(Point2x - Point1x)}\right);$$

$$Point1x := 4.336$$

$$Point1y := -31.497$$

$$Point2x := 7.338$$

$$Point2y := -32.043$$

$$Point3x := 11.374$$

$$Point3y := -31.273$$

$$Point4x := 7.929$$
$$Point4y := -30.656$$
$$Point6x := 13.990$$
$$Point6y := -29.267$$
$$Point7x := 16.374$$
$$Point7y := -31.287$$
$$Point9x := 13.388$$
$$Point9y := -23.901$$
$$L19x := 8.445$$
$$L19y := 0.631$$
$$L13x := 3.445$$
$$L13y := 0.617$$
$$L47x := 2.616$$
$$L47y := 2.006$$
$$L9x := 2.986$$
$$L9y := 7.386$$
$$L7x := 0.602$$
$$L7y := 5.366$$
$$L24x := 4.036$$
$$L24y := 0.770$$
$$\theta 23 := 0.1799121267 \quad (1)$$

## Knowns

P is the applied force equal to the sum of the air pressure force and the sealing material force.

A is used to lineraly scale the linkages for different sized nozzle diameters. I.e. for the 10 inch nozle A = 10 in/ 6 in = 1.666.

$P := 8.98;$
$A := 1.0;$

$$P := 8.98$$

$$A := 1.0 \tag{2}$$

$L7x := L7x \cdot A;$
$L7y := L7y \cdot A;$
$L9x := L9x \cdot A;$
$L9y := L9y \cdot A;$
$L47x := L47x \cdot A;$
$L47y := L47y \cdot A;$
$L24x := L24x \cdot A;$
$L24y := L24y \cdot A;$
$L13x := L13x \cdot A;$
$L13y := L13y \cdot A;$
$L19x := L19x\, A;$
$L19y := L19y \cdot A;$

$$L7x := 0.6020$$
$$L7y := 5.3660$$
$$L9x := 2.9860$$
$$L9y := 7.3860$$
$$L47x := 2.6160$$
$$L47y := 2.0060$$
$$L24x := 4.0360$$
$$L24y := 0.7700$$
$$L13x := 3.4450$$
$$L13y := 0.6170$$
$$L19x := 8.4450$$
$$L19y := 0.6310 \tag{3}$$

## System of Equations

The following equations are the summation of the force in the x, force in the y and the moment for each linkage.

### *Linkage FGx:*

$eq1 := P + F97x - F37x = 0;$

$$eq1 := 8.98 + F97x - F37x = 0 \tag{4}$$

### *Linkage FGy:*

$eq2 := F97y - F37y = 0;$

$$eq2 := F97y - F37y = 0 \tag{5}$$

### *Linkage FGM:*

$eq3 := F37y \cdot (L7x) - F37x \cdot (L7y) = 0;$

$$eq3 := -5.3660\, F37x + 0.6020\, F37y = 0 \tag{6}$$

### *Linkage EFx:*

$eq4 := -F97x - F49x = 0;$

$$eq4 := -F97x - F49x = 0 \quad (7)$$

***Linkage EFy:***

$eq5 := -F97y - F49y = 0;$

$$eq5 := -F97y - F49y = 0 \quad (8)$$

***Linkage EFM:***

$eq6 := F97x \cdot (L9y) - F97y \cdot (L9x) = 0;$

$$eq6 := 7.3860\ F97x - 2.9860\ F97y = 0 \quad (9)$$

***Linkage CDGx:***

$eq7 := F37x + F34x + F23 \cdot \cos(\theta 23) = 0;$

***Linkage CDGy:***

$eq8 := F37y + F34y - F23 \cdot \sin(\theta 23) = 0;$

$$eq7 := F37x + F34x + 0.9838594209\ F23 = 0$$

$$eq8 := F37y + F34y - 0.1789431191\ F23 = 0 \quad (10)$$

***Linkage CDGM:***

$eq9 := F23 \cdot \sin(\theta 23) \cdot L24x + F37y \cdot L47x - F37x \cdot L47y + F23 \cdot \cos(\theta 23) \cdot L24y = 0;$

$$eq9 := 1.479786183\ F23 + 2.6160\ F37y - 2.0060\ F37x = 0 \quad (11)$$

***Linkage BDEx:***

$eq10 := F14x - F34x + F49x = 0;$

$$eq10 := F14x - F34x + F49x = 0 \quad (12)$$

***Linkage BDEy:***

$eq11 := F14y - F34y + F49y = 0;$

$$eq11 := F14y - F34y + F49y = 0 \quad (13)$$

***Linkage BDEM:***

$eq12 := M - F34x \cdot (L13y) - F34y \cdot (L13x) + F49y \cdot (L19x) + F49x \cdot L19y = 0;$

$$eq12 := -0.6170\ F34x - 3.4450\ F34y + 0.6310\ F49x + 8.4450\ F49y + M = 0 \quad (14)$$

$equations := \{eq1, eq2, eq3, eq4, eq4, eq5, eq6, eq7, eq8, eq9, eq10, eq11, eq12\}$

$$equations := \{-5.3660\ F37x + 0.6020\ F37y = 0,\ -F97x - F49x = 0,\ 7.3860\ F97x - 2.9860\ F97y = 0,\ -F97y - F49y = 0,\ F97y - F37y = 0,\ 8.98 + F97x - F37x = 0,\ F14x - F34x + F49x = 0,\ F14y - F34y + F49y = 0,\ 1.479786183\ F23 + 2.6160\ F37y - 2.0060\ F37x = 0,\ F37x + F34x + 0.9838594209\ F23 = 0,\ F37y + F34y - 0.1789431191\ F23 = 0,\ -0.6170\ F34x - 3.4450\ F34y + 0.6310\ F49x + 8.4450\ F49y + M = 0\} \quad (15)$$

$solutions := solve(equations, [F97x, F97y, F49x, F49y, F37x, F37y, F14x, F14y, F34x, F34y, F23, M])$

$$solutions := [[F97x = -12.42909141,\ F97y = -30.74389457,\ F49x = 12.42909141,\ F49y = 30.74389457,\ F37x = -3.449091415,\ F37y = -30.74389457,\ F14x = -57.85240040,\ F14y = 8.888850967,\ F34x \quad (16)$$

$= -45.42330898,\ F34y = 39.63274554,\ F23 = 49.67417027,\ M$
$= -158.9663196]]$

$assign(solutions);$

## Material Properties

$sig := 40000;$
$\text{tau} := 30000;$
$t := \frac{1}{8};$
$Sn := 15750;$
$E := 10000;$

$$sig := 40000$$
$$\tau := 30000$$
$$t := \frac{1}{8}$$
$$Sn := 15750$$
$$E := 10000 \tag{17}$$

# Normal/Shear Stresses

# Pin At Point D

$FOS := 2:$
$tau\_pin := 63091 \cdot 0.6:$
$F34 := \text{sqrt}(F34x^2 + F34y^2):$
$Area\_pin := \frac{FOS \cdot F34}{tau\_pin}:$
$D\_pin := \text{sqrt}\left(\frac{Area\_pin \cdot 4}{evalf(\pi)}\right);$

$$D\_pin := 0.06368071027 \tag{18}$$

# Link AC

$FOS := 2:$
$D\_pin := \frac{3}{16}:$
$Area := \frac{F23}{Sn}:$
$w2 := \frac{Area}{t}:$

$w := 0.75 :$
$Kt := 4 :$
$A := \frac{(w - D\_pin) \cdot 1}{8} :$
$F\_allowable := \frac{Sn \cdot A}{Kt};$

$$F\_allowable := 276.8554688 \qquad (19)$$

## Link BDE

$F23x := \mathrm{abs}(F23 \cdot \cos(\theta 23)) :$
$F23y := \mathrm{abs}(F23 \cdot \sin(\theta 23)) :$
$F14x := \mathrm{abs}(F14x) :$
$F14y := \mathrm{abs}(F14y) :$
$F34x := \mathrm{abs}(F34x) :$
$F34y := \mathrm{abs}(F34y) :$
$F49x := \mathrm{abs}(F49x) :$
$F49y := \mathrm{abs}(F49y) :$
$M := \mathrm{abs}(M) :$
$\theta DB := \frac{10.15}{180} \cdot evalf(\pi) :$
$\theta ED := \frac{1.60 \cdot evalf(\pi)}{180} :$

$F14x \cdot eval(y\_BD, x = 3.45) :$
$Vx\_BD := -F14x :$
$Vy\_BD := F14y :$
$M\_BD := -M - F14y \cdot x + F14x \cdot y\_BD :$
$y\_BD := piecewise(0 < x \textbf{ and } x \le 3.45, x \cdot \tan(\theta DB)) :$
$eval(M\_BD, x = 3.45) :$

$Vx\_DE := F34x + F49x :$
$Vy\_DE := -F34y + F49y :$
$M\_DE := eval(M\_BD, x = 3.45) + F34y \cdot (x - 3.45) - F34x \cdot (y\_DE - 0.62) - F14y \cdot (x - 4.45) + F14x \cdot (y\_DE - 0.62) :$
$y\_DE := piecewise(3.45 < x \textbf{ and } x \le 8.45, eval(y\_BD, x = 3.45) + x \cdot \tan(\theta ED)) :$
$eval(y\_DE, x = 8.45) :$
$eval(M\_BD, x = 3.45) :$
$eval\big(F34x \cdot (y\_DE - 0.62), x = 8.45\big) :$
$M\_BD := maximize(\mathrm{abs}(M\_BD), x = 0 .. 3.45) :$
$maximize(M\_DE, x = 3.45 .. 8.45) :$
$F14 := \mathrm{sqrt}(F14x^2 + F14y^2);$

$$sig\_mem := \frac{M\_BD \cdot \left(\frac{w}{2}\right)}{t \cdot \frac{(w)^3}{12}} + \frac{F14}{t \cdot w};$$

$$tau\_mem := \frac{F14 \cdot \left(\frac{w}{2}\right) \cdot t \cdot \left(\frac{w}{4}\right)}{\frac{t^2 \cdot w^3}{12}};$$

$$sig\_amp\_BDE := \text{sqrt}((sig\_mem^2 + 3 \cdot tau\_mem^2));$$

$$n\_BDE := \frac{Sn}{sig\_amp\_BDE}:$$

$$F14 := 58.53128996$$
$$sig\_mem := 14189.45972$$
$$tau\_mem := 936.5006397$$
$$sig\_amp\_BDE := 14281.87199 \quad (20)$$

$$n\_BDE := 4 \cdot n\_BDE;$$

$$n\_BDE := 4.411186436 \quad (21)$$

## Link CDG

$F23x := \text{abs}(F23 \cdot \cos(\theta 23)):$
$F23y := \text{abs}(F23 \cdot \sin(\theta 23)):$
$F34x := \text{abs}(F34x):$
$F34y := \text{abs}(F34y):$
$F37x := \text{abs}(F37x):$
$F37y := \text{abs}(F37y):$
$M := \text{abs}(M):$

$\theta CG := \frac{10.8}{180} \cdot evalf(\pi):$
$y\_CD := piecewise(0 < x \textbf{ and } x \le 4.04, x \cdot \tan(\theta CG)):$
$Vx\_CD := F23x:$
$Vy\_CD := -F23y:$
$M\_CD := F23y \cdot x + F23x \cdot y\_CD:$

$eval(M\_CD, x = 4.04):$

$Vx\_DH := F23x - F34x:$
$Vy\_DH := -F23y + F34y:$
$y\_DE := piecewise(4.04 < x \textbf{ and } x \leq 6.66,\ x \cdot \tan(\theta CG)):$

$M\_DH := eval(M\_CD, x = 4.04) + F23y \cdot (x - 4.04) + F23x \cdot (y\_DE - 0.77) - F34y \cdot (x - 4.04) - F34x \cdot (y\_DE - 0.77):$
$eval(M\_DH, x = 6.66):$
$M\_DH := maximize(M\_DH, x = 4.04..6.66);$

$$M\_DH := 73.57782536 \quad \textbf{(22)}$$

$$sig\_mem := \frac{M\_DH \cdot \left(\frac{w}{2}\right)}{t \cdot \frac{(w)^3}{12}} + \frac{F23}{t \cdot w};$$

$$tau\_mem := \frac{F23 \cdot \left(\frac{w}{2}\right) \cdot t \cdot \left(\frac{w}{4}\right)}{\frac{t^2 \cdot w^3}{12}};$$

$sig\_amp\_CDG := \text{sqrt}((sig\_mem^2 + 3 \cdot tau\_mem^2));$

$$n\_CDG := \frac{Sn}{sig\_amp\_CDG}:$$

$n\_CDG := 2 \cdot n\_CDG;$

$$sig\_mem := 6808.498916$$
$$tau\_mem := 794.7867245$$
$$sig\_amp\_CDG := 6946.273483$$
$$n\_CDG := 4.534805616 \quad \textbf{(23)}$$

$$n\_CDG := 4.534805616 \quad \textbf{(24)}$$

## Link FIE

$F97x := \text{abs}(F97x):$
$F97y := \text{abs}(F97y):$
$F49x := \text{abs}(F49x):$
$F49y := \text{abs}(F49y):$

$$\theta IF := \frac{70 \cdot evalf(\pi)}{180}:$$
$$Vx\_EI := -F49y:$$
$$Vy\_EI := -F49x:$$
$$M\_EI := F49x \cdot x:$$

$$Vx\_IF := -F97y:$$
$$Vy\_IF := -F97x:$$
$$y\_IF := piecewise(6.28 < x \textbf{ and } x \leq 7.39, (x - 6.28) \cdot \tan(\theta IF)):$$

$$M\_IF := (F97x \cdot x - F97y \cdot y\_IF):$$
$$M\_IF := maximize(M\_IF, x = 6.28..7.39);$$
$$F49 := \mathrm{sqrt}(F49x^2 + F49y^2):$$

$$sig\_mem := \frac{M\_IF \cdot \left(\frac{w}{2}\right)}{t \cdot \frac{(w)^3}{12}} + \frac{F49}{t \cdot w};$$
$$tau\_mem := \frac{F49 \cdot \left(\frac{w}{2}\right) \cdot t \cdot \left(\frac{w}{4}\right)}{\frac{t^2 \cdot w^3}{12}};$$
$$sig\_amp\_FIE := \mathrm{sqrt}((sig\_mem^2 + 3 \cdot tau\_mem^2));$$
$$n\_FIE := \frac{Sn}{sig\_amp\_FIE}:$$
$$n\_FIE := 2 \cdot n\_FIE;$$

$$M\_IF := 78.05469411$$
$$sig\_mem := 7014.387369$$
$$tau\_mem := 530.5802091$$
$$sig\_amp\_FIE := 7074.332211$$
$$n\_FIE := 4.452717100 \quad \textbf{(25)}$$

$$n\_FIE := 2.226358550$$
$$n\_FIE := 4.452717100 \quad \textbf{(26)}$$

## Link AC

$sig\_mem := \frac{F23}{w \cdot t};$
$sig\_amp\_AC := sig\_mem;$
$n\_AC := \frac{Sn}{sig\_amp\_AC};$
$n\_AC := 2 \cdot n\_AC \cdot 2;$

$$sig\_mem := 529.8578162$$
$$sig\_amp\_AC := 529.8578162$$
$$n\_AC := 29.72495549$$
$$n\_AC := 118.8998220 \quad (27)$$

## Link FG

$F37 := \mathrm{sqrt}(F37x^2 + F37y^2);$
$sig\_mem := \frac{F37}{t \cdot w};$

$$F37 := 30.93676268$$
$$sig\_mem := 329.9921352 \quad (28)$$

$sig\_amp\_FG := sig\_mem;$
$n\_FG := \frac{Sn}{sig\_amp\_FG};$

$$sig\_amp\_FG := 329.9921352$$
$$n\_FG := 47.72841023 \quad (29)$$

$n\_FG := 4 \cdot n\_FG;$

$$n\_FG := 190.9136409 \quad (30)$$

## D.8 References


[1] R. G. Budynas and K. J. Nisbett, Shigley's Mechanical Engineering Design 10th Edition, New York: McGraw-Hill Education, 2016.

[2] Open-i, *S-N curve of 6061-T6 aluminium alloy*, 2014. [Online]. Available: https://openi.nlm.nih.gov/detailedresult.php?img=PMC4003947_sensors-14-04364f8&req=4 [Accessed 26 November 2018].

[3] Misumi, *Shaft and Hole Tolerances and Fits*, 2015. [Online]. Available: http://blog.misumiusa.com/shaft-and-hole-tolerances-and-fits/ [Accessed 27 November 2018].

[4] Fastenal, *Product Standard*, 2017. [Online]. Available: https://www.fastenal.com/content/product_specifications/PIN.CLV.Z.pdf [Accessed 27 November 2018].

[5] Theoretical Machinist, *ISO tolerances*, 2015. [Online]. Available: http://theoreticalmachinist.com/IsoTolZoneCalc#radioHole [Accessed 27 November 2018].

[6] Christiani, *Inside Corner Stress*, 2016. [Online]. Available: http://www.christiani.eu/pdf/92903_probe.pdf [Accessed 24 November 2018].

[7] B. Giesbrecht. *Spider Mechanism*, Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Nov. 30, 2018.

# University of Manitoba IDEA Program:

# Design of an Automated Nozzle Sealing System

## Detailed Design Report

# Appendix E
# Material Selection

# Contents

List of Tables ........ E-ii

E.1 Material Selection ........ E-1

E.1.1 Linkage Material ........ E-1

E.1.2 Seal Material ........ E-3

E.2 Cellular Urethane Foam Specification Data Sheet ........ E-8

E.3 References ........ E-9

# List of Tables

TABLE I: LINKAGE MATERIAL CRITERIA DECISION MATRIX...................................... E-2

TABLE II: LINKAGE MATERIAL WEIGHTED DECISION MATRIX ................................. E-2

TABLE III: LINSTING OF 6061-T6 MATERIAL PROPERTIES ......................................... E-3

TABLE IV: MATERIAL DESCRIPTIONS........................................................................... E-3

TALBE V: SEALING MATERIAL CRITERIA DECISION MATRIX ..................................... E-5

TABLE VI: SEALING MATERIAL WEIGHTED DECISION MATRIX ................................ E-5

TABLE VII: CELLULAR URETHAN 4701-30 PROPERTIES ............................................ E-7

# E.1 Material Selection

The material used for the linkages and rubber foam were chosen following a selection process using two separate weighted decision matrices.

## E.1.1 Linkage Material

The materials for the linkages were ranked on five criteria: (1) cost, (2) strength, (3) density, (4) corrosion resistance, and (5) hardness. The cost of the material accounts for the purchase of the raw material, not the machining costs. The strength of the material considers the tensile yield strength and will be used to determine the overall size of the linkages. The density considers how heavy the material is. Corrosion resistance determines if the material requires extra maintenance to avoid corrosion, such as rust, over time. Finally, the hardness accounts for material scratching.

A weighted decision matrix was used to choose the top material for the linkages. To determine the weight of each criterion in the weighted decision matrix, each criterion was first compared to each other to decide which was most important. The more important criteria between each selection is shown in Table I with its corresponding letter. The total count for each letter was used to determine a percentage which will weigh the rankings in the weighted decision matrix. A placeholder column is used to ensure each criterion has some importance.

TABLE I: LINKAGE MATERIAL CRITERIA DECISION MATRIX

| | | A | B | C | D | E | Placeholder |
|---|---|---|---|---|---|---|---|
| Cost | A | | A | C | D | A | A |
| Strength | B | | | C | D | E | B |
| Density | C | | | | C | C | C |
| Corrosion Resistance | D | | | | | D | D |
| Hardness | E | | | | | | E |
| | Total Count | 3 | 1 | 5 | 4 | 2 | |
| | Total Weight | 0.20 | 0.07 | 0.33 | 0.27 | 0.13 | |

Table II shows the weighted decision matrix for the linkage material, where a higher score implies a more desirable material. Aluminum, stainless steel, and carbon steel were chosen as possible materials because they are accessible and commonly used in industry.

TABLE II: LINKAGE MATERIAL WEIGHTED DECISION MATRIX

| | | **Aluminum** | | **Stainless Steel** | | **Carbon Steel** | |
|---|---|---|---|---|---|---|---|
| **Criteria** | **Weight** | **Ranking** | **Score** | **Ranking** | **Score** | **Ranking** | **Score** |
| Cost | 0.20 | 2 | 0.40 | 1 | 0.20 | 3 | 0.60 |
| Strength | 0.07 | 1 | 0.07 | 3 | 0.21 | 2 | 0.14 |
| Density | 0.33 | 2 | 0.66 | 1 | 0.33 | 1 | 0.33 |
| Corrosion Resistance | 0.27 | 3 | 0.81 | 2 | 0.54 | 1 | 0.27 |
| Hardness | 0.13 | 1 | 0.13 | 3 | 0.39 | 2 | 0.26 |
| | | **Total Score** | **2.07** | | **1.67** | | **1.60** |

As determined from the linkage material weighted decision matrix, aluminum is used for the linkages. To ensure smooth actuation, the linkages will require lubrication anywhere with metal on metal contact, including pins. Specifically, powder graphite will be used as lubricant because liquid lubricants collect dust and can impact the systems actuation. 6061-T6 aluminum will be used because of its corrosion resistance properties and ease of accessibility. The properties of 6061-T1 aluminum are tabulated in Table III.

TABLE III: LISTING OF 6061-T6 MATERIAL PROPERTIES

| Property | Value |
|---|---|
| **Yield Strength $S_y$** | 40 [ksi] |
| **Ultimate Tensile Strength $S_{ut}$** | 45 [ksi] |
| **Elastic Modulus $E$** | 10,000 [ksi] |
| **Shear Strength $\tau_y$** | 30 [ksi] |

## E.1.2 Seal Material

Argus Industries was contacted to send samples of materials suitable for sealing the nozzle. Five foam samples were collected of differing density, thickness and polymer type.

The materials were tested with a 3D printed nozzle. The nozzle was filled with water to simulate the approximate pressures acting on the seal. Observations about the ease of compression, quality of seal and any water leakage was recorded for each material. The noted observations are summarized in Table IV.

TABLE IV: MATERIAL DESCRIPTIONS

| Foam Material | Observations |
|---|---|
| 4# Crosslinked Polyethylene | -Harder to compress<br>-Too thin to provide seal<br>-Leaked water |
| 2# Standard Polyethylene (White Thick) | -Required more force to seal<br>-Nozzle left a visible indent once removed |
| 2# Standard Polyethylene (Grey Thin) | -Too thin to provide seal<br>-Nozzle left a large visible indent once removed |
| SC 42 N | -Too thin to provide a seal<br>-Leaked water |
| 4701-30 Cellular Urethane | -Least amount of force required to keep seal<br>-Easily compressed by nozzle |

4# Crosslinked Polyethylene was observed to have the worst properties to provide a seal. The material was hardest to compress and required the largest force to keep a seal. Furthermore, the sample was too thin and difficult to compress, causing water leakage.

The difference in performance of varying thickness is exemplified by comparing the observations of white 2# Standard Polyethylene and grey 2# Standard Polyethylene. The material and grade of the foam are the same for both samples; however, the white polyethylene is thicker than the grey polyethylene. The indent left on the thinner grey sample was much deeper than the thicker white material. To prevent the possibility of the nozzle cutting into the material, a thicker material is recommended.

SC 42 N allowed water to leak around the nozzle because the material is too thin for the nozzle to compress the material enough to seal. Thicker samples would be needed to determine if it can provide a full seal and if an indentation would be formed.

The cellular urethane 4701-30 performed the best in the test as it was observed to rebound the best after the nozzle was removed, leaving no indent. The sample also required the least amount of force to keep the seal.

Based off the preliminary tests of the sealing materials, a weighted decision matrix was used to choose the best material. To determine the weight of each criterion, they were first compared to each other to decide which was most important. The more important criteria between each selection is shown in Table V with its corresponding letter. The total count for each letter was used to determine a percentage which will weigh the rankings in the weighted decision matrix. A placeholder column is used to ensure each criterion receives some weight.

TABLE V: SEALING MATERIAL CRITERIA DECISION MATRIX

| | | A | B | C | D | Placeholder |
|---|---|---|---|---|---|---|
| Cost | A | | B | C | A | A |
| Compressibility | B | | | C | B | B |
| Quality of Seal | C | | | | C | C |
| Hardness | D | | | | | D |
| | Total Count | 2 | 3 | 4 | 1 | |
| | Total Weight | 0.20 | 0.30 | 0.40 | 0.10 | |

Table VI shows the weighted decision matrix for the seal material, where a higher score implies a more desirable material. Cellular urethane, standard polyethylene and cross-linked polyethylene were chosen as possible materials because of the results of the preliminary tests.

TABLE VI: SEALING MATERIAL WEIGHTED DECISION MATRIX

| | | **4701-30 Cellular Urethane** | | **2# Standard Polyethylene (White Thick)** | | **4# Crosslinked Polyethylene** | |
|---|---|---|---|---|---|---|---|
| **Criteria** | **Weight** | **Ranking** | **Score** | **Ranking** | **Score** | **Ranking** | **Score** |
| Cost | 0.20 | 1 | 0.20 | 3 | 0.60 | 2 | 0.40 |
| Compressibility | 0.30 | 3 | 0.90 | 2 | 0.60 | 1 | 0.30 |
| Quality of Seal | 0.40 | 3 | 1.20 | 2 | 0.80 | 1 | 0.40 |
| Hardness | 0.10 | 3 | 0.30 | 2 | 0.20 | 1 | 0.10 |
| | | **Total Score** | **2.60** | | **2.20** | | **1.20** |

As determined from the seal material weighted decision matrix, 4701-30 cellular urethane was chosen for the sealing material. One side of the sealing material has an adhesive backing allowing for the connection of the material to the sealing plate. A limitation of the sealing material is that it may not have a 10-year life span but is easily replaceable.

Following the selection, the material properties of the cellular urethane were determined. The modulus of elasticity was determined from the hardness of the material from the relationship shown in equation (1) [1].

$$E = \frac{0.0981(56 + 7.62336S)}{0.137505(254 - 2.54S)} \tag{1}$$

Where $E$ is the Young's modulus in Mpa and $S$ is the ASTM D2240 type A hardness. The hardness of 4701-30 cell urethane was determined from the specification sheets of the material from Argus Industries, shown in Section D.2 on page D-7. The durometer measure, Shore "A," is determined to be 5 from the ASTM D 2240-97 test. The modulus of elasticity can be determined by substituting the hardness into equation (1).

$$E = \frac{0.0981(56 + 7.62336(5))}{0.137505(254 - 2.54(5))} = 0.2783\ Mpa$$

The other relevant properties of cellular urethane 4701-30 are summarized in Table VII.

TABLE VII: CELLULAR URETHANE 4701-30 PROPERTIES [2]

| **Property** | **Value** |
|---|---|
| Hardness, Durometer, Shore A | 5 |
| Modulus of Elasticity ($Mpa$) | 0.2783 |
| Density ($lb/ft^3$) | 20 |
| Tensile Strength ($psi$) | 50 |

## E.2 Cellular Urethane Foam Specification Data Sheet [2]

[redacted]

## E.3 References

[1] A. J. Giacomin and A. W. Mix, "Standardized Polymer Durometry," *Journal of Testing and Evaluation,* vol. 39, no. 4, pp. 1-10, 2011.

[2] J. Vechina. (2018, November 26). “RE: Price Industries Capstone U of M IDEA Program.” Personal e-mail.

# University of Manitoba IDEA Program:

# Design of an Automated Nozzle Sealing System

## Detailed Design Report

# Appendix F
# GMB(X)24-SR Technical Data Sheet

# Contents

F.1 GMB24-SR Technical Data Sheet .................................................................... F-1

F.2 References ........................................................................................................ F-3

## F.1 GMB24-SR Technical Data Sheet [1]

[redacted]

[redacted]

## F.2 References

[1] Belimo, *Non Fail-Safe Actuators*, 2018. [Online]. Available: https://www.belimo.us/shop/en_US/Actuators/Non-Fail-Safe-Actuators/GMB24-SR/p?code=GMB24-SR [Accessed 26 November 2018].

# University of Manitoba IDEA Program:

# Design of an Automated Nozzle Sealing System

## Detailed Design Report

# Appendix G
# Detailed Assembly Instructions

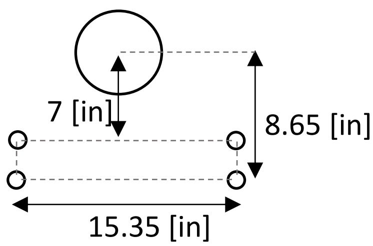
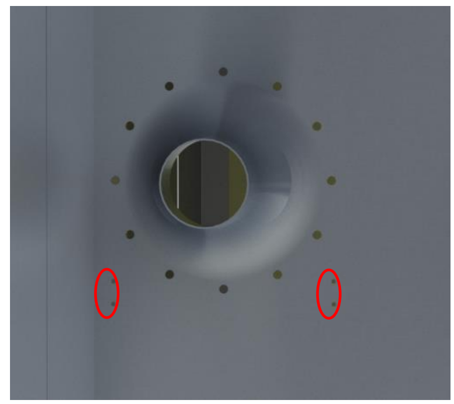
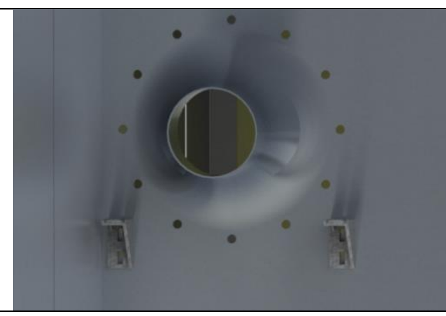
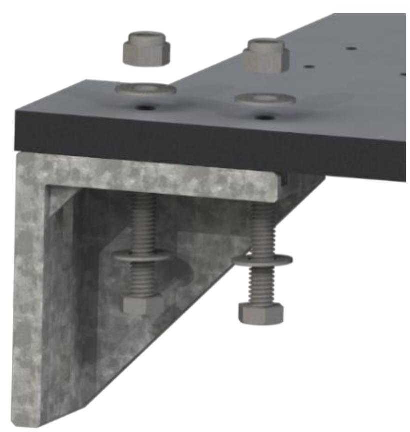
# Contents

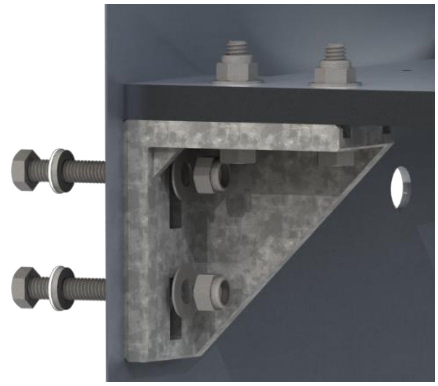
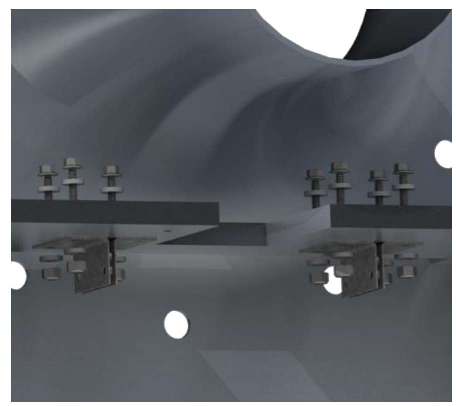
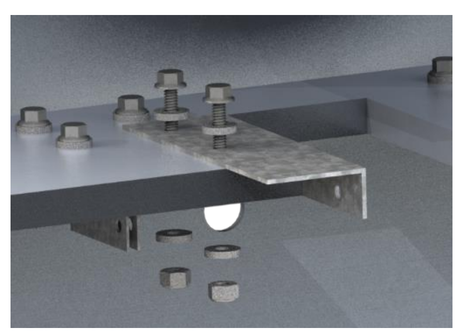
G.1 Mechanism Assembly Instructions ........................................................ G-1

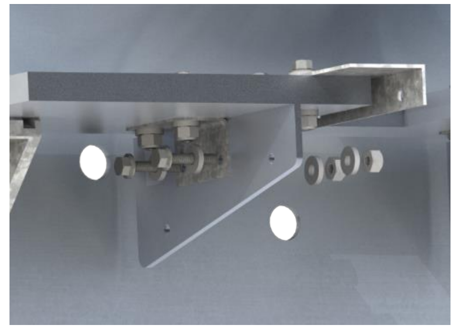
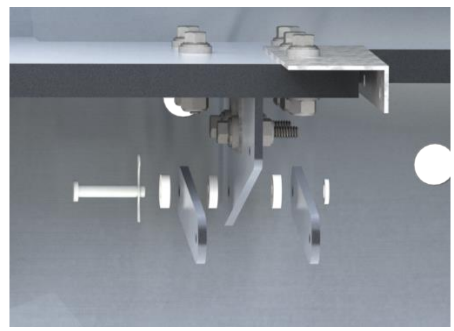
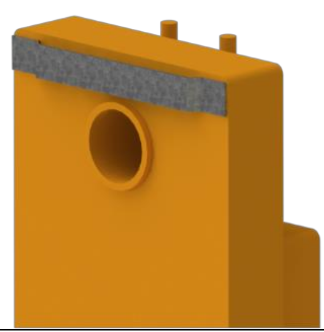
G.2 Adapting the Mechanism for Actuators Mounted on the Outside ............... G-9

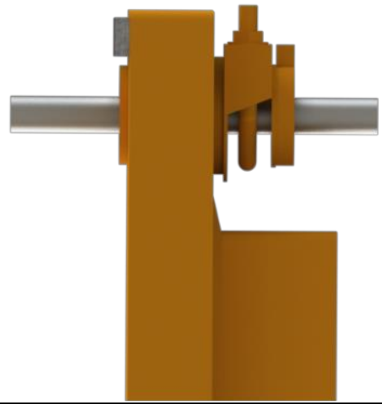
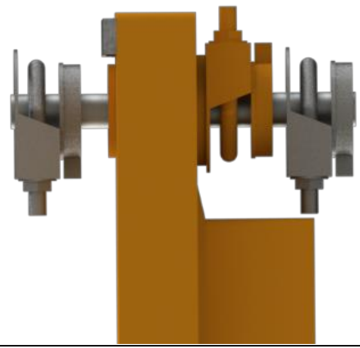
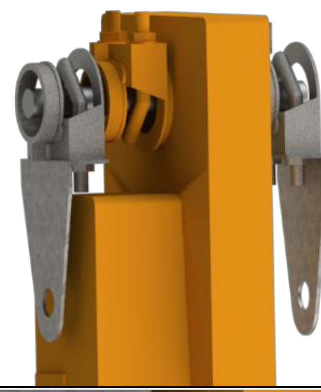
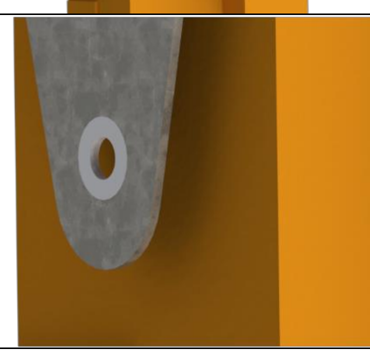
## G.1 Mechanism Assembly Instructions

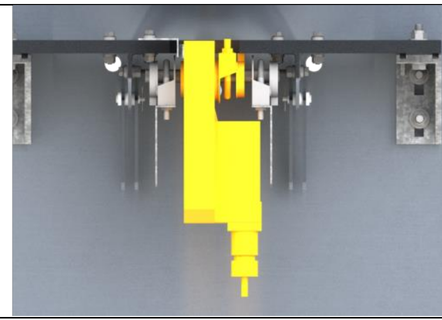
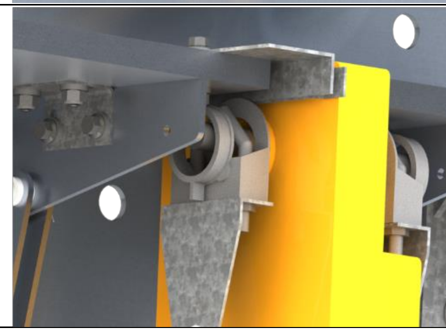
The following table will describe the step by step instructions for installing the spider mechanism into Price's air flow test chamber.

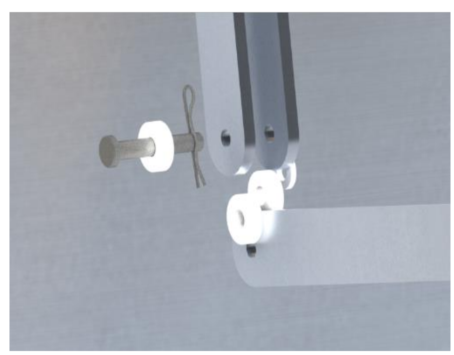
| | | |
|---|---|---|
| **Step 1** | **Necessary Items:**<br>None.<br>**Description:**<br>Drill four holes in the nozzle wall with 5/16 [in] diameters. The hole locations will follow the diagram below (center to center dimensions).<br><br> |  |
| **Step 2** | **Necessary Items:**<br>Corner wall bracket (qty 2)<br>**Description:**<br>Line up the holes in the corner brackets with the holes in the wall. These brackets will be used to install the aluminum support plate. |  |
| **Step 3** | **Necessary Items:**<br>5/16 metal washer (qty 8)<br>5/16-18 locking nut (qty 4)<br>5/16-18 x 1-1/2 bolt (qty 4)<br>**Description:**<br>Attach the aluminum support plate to the corner brackets. Insert a 5/16-18 bolt into the bottom of the bracket with a metal washer on either side of the plate and a locking nut at the end of the bolt.<br>NOTE: the bolt must be inserted upwards to allow for room of the bolts attaching the bracket to the wall. |  |

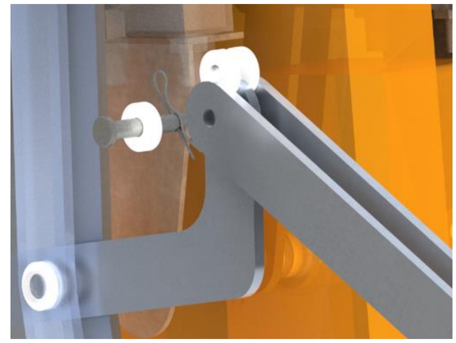
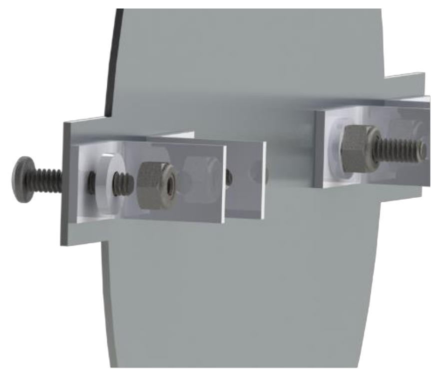
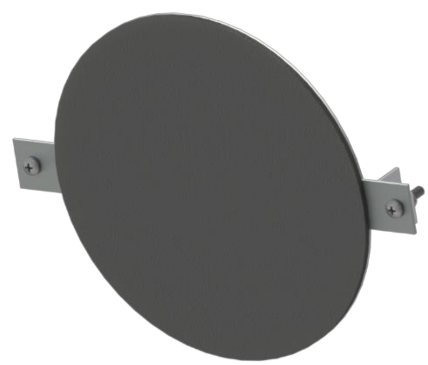
| | | |
|---|---|---|
| **Step 4** | **Necessary Items:**<br>5/16 metal washer (qty 4)<br>5/16-18 locking nut (qty 4)<br>5/16-18 x 1-1/2 bolt (qty 4)<br>5/6 rubber sealing washer (qty 4)<br>**Description:**<br>Attach the plate to the wall with two 5/16-18 bolts through each corner bracket. Install the bolts through the pre-drilled holes in the nozzle wall. Use a sealing washer on the backside of the wall and a metal washer and locking nut on the side of the wall with the bracket. |  |
| **Step 5** | **Necessary Items:**<br>90-degree bracket (qty 4)<br>#10-24 x 1 bolt (qty 7)<br>#10 locking nut (qty 7)<br>#10 metal washer (qty 14)<br>**Description:**<br>Attach the four 90-degree brackets to the bottom of the aluminum support plate with two #10-24 bolts per bracket through the pre-cut holes. Add a metal washer on top and below the plate before securing the bolt with a locking nut.<br>NOTE: the bracket closer to and on the left side of the nozzle will only have one bolt. The bolt closer to the chamber wall should be inserted. The second bolt will be added when installing the actuator mounting plate. |  |
| **Step 6** | **Necessary Items:**<br>Actuator mounting plate (qty 1)<br>#10-24 x 1 bolt (qty 2)<br>#10 locking nut (qty 2)<br>#10 metal washer (qty 4)<br>**Description:**<br>Install the actuator mounting plate on top of the aluminum support plate with two #10-24 bolts. Place a washer above and below the plate before securing the bolt with a locking nut. |  |

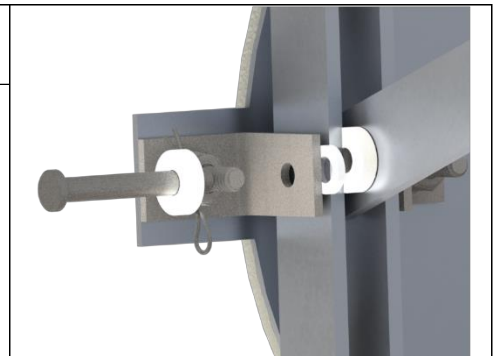
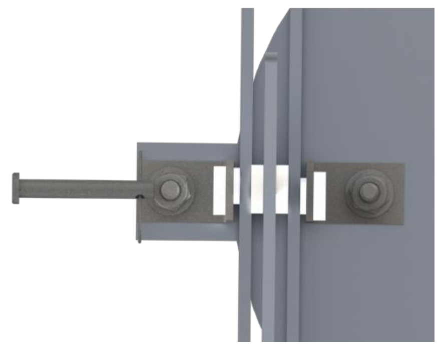
| | | |
|---|---|---|
| **Step 7** | **Necessary Items:**<br>Linkage AB (qty 2)<br>#10-24 x 1 bolt (qty 4)<br>#10 locking nut (qty 4)<br>#10 metal washer (qty 8) |  |
| | **Description:**<br>Install linkage AB in between the 90-degree brackets with two #10-24 bolts. Use a washer on either side of the bracket before securing the bolt with a locking nut.<br>Repeat this step for the mirrored mechanism on the other side of the plate. | |
| **Step 8** | **Necessary Items:**<br>Linkage AC (qty 4)<br>3/16 clevis pin (qty 2)<br>Hitch pin clip (qty 2)<br>3/16 nylon washer (qty 2)<br>3/16 nylon spacer (qty 6) |  |
| | **Description:**<br>Install linkage AC to linkage AB at pin A with a 3/16 clevis pin.<br>NOTE: there is a nylon spacer between each linkage and a nylon washer at the end of the clevis pin before installing the hitch pin clip.<br>Repeat this step for the mirrored mechanism on the other side of the plate. | |
| **Step 9** | **Necessary Items:**<br>GMX24-SR rotary actuator (qty 1)<br>Actuator mounting assembly (qty 1) |  |
| | **Description:**<br>Find the rotary actuator and mounting assembly. Attach the actuator mounting bracket to the back of the actuator with the supplied screws in the assembly. | |

| | | |
|---|---|---|
| **Step 10** | **Necessary Items:**<br>1/2 x 5 [in] steel shaft (qty 1)<br>**Description:**<br>Install the 1/2 [in] diameter steel shaft into the actuator and tighten the circular clamp. The end of the shaft should extend approximately 1.4 [in] from the back of the actuator.<br>NOTE: the back of the actuator is distinguished from the front by the absence of an electrical box. |  |
| **Step 11** | **Necessary Items:**<br>K-LM12 shaft clamp (qty 2)<br>**Description:**<br>Install two circular clamps on the 1/2 [in] steel shaft; one clamp should go on each side of the actuator. NOTE: the nut used to tighten the clamp should be facing downward. |  |
| **Step 12** | **Necessary Items:**<br>Custom actuator arm (qty 2)<br>**Description:**<br>Attach the custom actuating arms, one on each clamp, using the two tightening nuts at the bottom of clamp.<br>NOTE: the actuator will need to be zeroed in this position prior to use. |  |
| **Step 13** | **Necessary Items:**<br>1/4 nylon washer (qty 2)<br>**Description:**<br>Install a 1/4 [in] inner diameter nylon washer into the custom actuator arm with a clearance fit.<br>Repeat this step with the custom actuator arm on the other side of the actuator. |  |

| | | |
|---|---|---|
| **Step 14** | **Necessary Item:**<br>None.<br>**Description:**<br>Test to ensure the actuator assembly fits below the aluminum mounting plate and in between the spider linkages. Adjust the position of the circular clamps until satisfied. |  |
| **Step 15** | **Necessary Items:**<br>Actuator bracket assembly screws.<br>**Description:**<br>Attach the actuator to the actuator mounting bracket using the machine screws provided in the mounting assembly. Ensure the center of the shaft in concentric with the hole in linkage AB at pin B. |  |
| **Step 16** | **Necessary Items:**<br>Linkage BDE (qty 4)<br>3/16 clevis pin (qty 2)<br>3/16 nylon spacer (qty 6)<br>3/16 nylon washer (qty 2)<br>Hitch pin clip (qty 2)<br>**Description:**<br>Secure linkage BDE at pin B with a 3/16 clevis pin. NOTE: there are two linkages for BDE; nylon spacers should be on either side of linkage AB and a nylon washer should be at the end of the clevis pin before installing the hitch pin clip. Repeat this step for the mirrored mechanism on the other side of the actuator. |  |

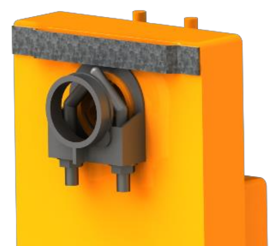
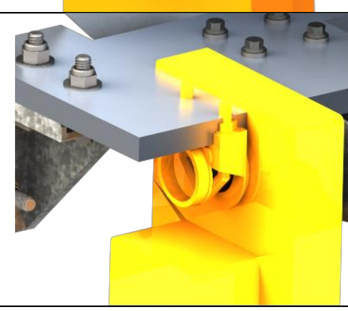
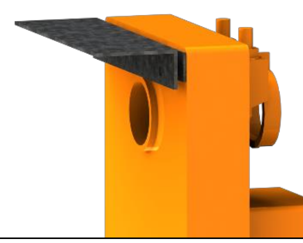
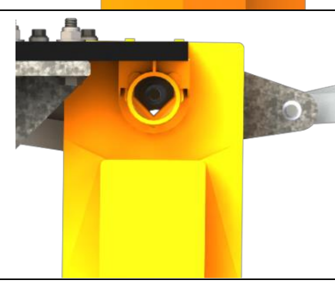
| | | |
|---|---|---|
| **Step 17** | **Necessary Items:**<br>Linkage CDG (qty 2)<br>1/4 clevis pin (qty 2)<br>1/4 nylon washer (qty 6)<br>Hitch pin clip (qty 2) |  |
| | **Description:**<br>Secure linkage CDG at pin D with a 1/4 clevis pin. Place a nylon washer on the clevis pin between each linkage. Continue to push the pin through the hole in the custom actuator arm and insert the hitch pin clip on the far side to prevent the pin from falling out.<br>Repeat this for the mirrored mechanism on the other side of the actuator. | |
| **Step 18** | **Necessary Items:**<br>1/16 clevis pin (qty 2)<br>3/16 nylon spacer (qty 6)<br>3/16 nylon washer (qty 2)<br>Hitch pin clip (qty 2) |  |
| | **Description:**<br>Install a clevis pin through linkages AC and CDG at pin C with a nylon spacer between each linkage. Place a nylon washer at the back of the pin before inserting the hitch pin clip.<br>Repeat this step for the mirrored mechanism on the other side of the actuator. | |
| **Step 19** | **Necessary Items:**<br>Linkage EF (qty 2)<br>1/16 clevis pin (qty 2)<br>3/16 nylon spacer (qty 6)<br>3/16 nylon washer (qty 2)<br>Hitch pin clip (qty 2) |  |
| | **Description:**<br>Secure linkage EF to linkage BDE at pin E with a clevis pin. Put a nylon spacer between each linkage and a nylon washer at the end of the pin before inserting the hitch pin clip.<br>Repeat this step for the mirrored mechanism on the other side of the actuator. | |

| | | |
|---|---|---|
| **Step 20** | **Necessary Items:**<br>Link FG (qty 4)<br>1/16 clevis pin (qty 2)<br>3/16 nylon spacer (qty 6)<br>3/16 nylon washer (qty 2)<br>Hitch pin clip (qty 2)<br>**Description:**<br>Secure linkage FG to CDG at pin G with a clevis pin. Use a nylon spacer between each linkage and nylon washer at the end of the clevis pin before installing the hitch pin clip.<br>Repeat this step for the mirrored mechanism on the other side of the actuator. |  |
| **Step 21** | **Necessary Items:**<br>1/8 thickness aluminum sealing plate (qty 1)<br>90-degree bracket for plate (qty 4)<br>#10-24 x 7/8 machine screw (qty 4)<br>#10-24 locking nut (qty 4)<br>#10 metal washer (qty 4)<br>**Description:**<br>Find the aluminum sealing plate. Install four L-brackets on the back of the plate at the locations of the pre-cut holes. Place a machine screw into each of the holes from the front and secure it with a metal washer and locking nut from the back.<br>NOTE: Shorter machine screws may be used if necessary. |  |
| **Step 22** | **Necessary Items:**<br>7 [in] diameter 4701-30 cellular urethane (qty 1)<br>**Description:**<br>Install the cellular urethane sealing material on the front of the sealing plate using the adhesive backing.<br>NOTE: this sealing material will cover up two of the machine screws used to secure the brackets on the back of the plate. These screws will not interfere with the nozzle sealing. |  |

| | | |
|---|---|---|
| **Step 23** | **Necessary Items:**<br>None.<br>**Description:**<br>Slide linkages EF and FG at pin F between the brackets on the sealing plate.<br>Repeat this step for the mirrored mechanism on the other side of the actuator. |  |
| **Step 24** | **Necessary Items:**<br>3/16 x 1-1/2 clevis pin (qty 2)<br>Hitch pin clip (qty 2)<br>3/16 nylon spacer (qty 8)<br>3/16 nylon washer (qty 4)<br>**Description:**<br>Secure the linkages at pin F using a 3/16 clevis pin through the hole in the brackets. Ensure there is a nylon spacer on the outside of each bracket and in between each linkage, and a nylon washer on the inside of each bracket.<br>Repeat this step for the mirrored mechanism on the other side of the actuator. |  |
| **Step 25** | **Necessary Items:**<br>None.<br>**Description:**<br>Check over the entire assembly and ensure all nuts and bolts are tight. Connect the actuator to a power source and perform a controls check. |  |

## G.2 Adapting the Mechanism for Actuators Mounted on the Outside

For nozzles with a smaller diameter, the actuator may not fit under the aluminum mounting plate and must be mounted on the outside of the spider mechanism. As well, for nozzles requiring a larger torque, two actuators may be required, one on each side of the spider mechanism. The steps below will outline how to mount the actuator on the outside of the spider mechanism.

| | | |
|---|---|---|
| **Step 1** | **Modify the Actuator.** Move the circular clamp on the front actuator to the back side of the actuator. |  |
| **Step 2** | **Modify the aluminum mounting plate.** A hole will need to be cut in the aluminum support plate where the actuator will be mounted so that the center of rotation of the actuator is concentric with pin B. NOTE: it is recommended to manufacture a new plate without the center cut out to increase plate structural strength. |  |
| **Step 3** | **Securing the actuator to the mounting plate.** Using the same mounting hardware as stated in step 9 of the assembly instructions above, the actuator can be mounted to the aluminum support plate with a custom bracket reaching over the top of the mounting plate. |  |
| **Step 4** | **Attaching the actuator to the mechanism.** Using the same method as stated above in step 17 of the assembly instructions, connect the custom actuator arm to the spider mechanism at pin D using a 1/4 [in] clevis pin. |  |

# University of Manitoba IDEA Program:
# Design of an Automated Nozzle Sealing System

## Detailed Design Report

## Appendix H
## Detailed Cost

# Contents

List of Tables ....................................................................................................H-ii

H.1 Detailed Cost.......................................................................................H-1

H.2 References ............................................................................................H-6

# List of Tables

TABLE I: MASTER LIST OF MANUFACTURERS ............................................................H-1

TABLE II: BREAKDOWN OF THE HARDWARE COSTS ................................................H-2

TABLE III: BREAKDOWN OF THE ACTUATOR COSTS ................................................H-3

TABLE IV: BREAKDOWN OF THE MANUFACTURING COSTS .....................................H-4

TABLE V: TOTAL COST BREAKDOWN OF THE SEALING SYSTEM ...............................H-5

# H.1 Detailed Cost

The detailed cost analysis consists of each component of the design listed with its corresponding quantity, price, and two Canadian vendors it can be purchased from. A master list of all the manufacturers used to source parts is shown in Table I.

TABLE I: MASTER LIST OF MANUFACTURERS

| **Manufacturer** | |
|---|---|
| Acklands Grainger | [1] |
| Lowes Canada | [2] |
| Rona Canada | [3] |
| Home Depot Canada | [4] |
| Siemens | [5] |
| Schneider Electric | [6] |
| Hi-Tec Profiles Inc. | [7] |
| Fastenal | [8] |
| Rocky Mountain Westmill | [9] |
| Belimo | [10] |
| Princess Auto | [11] |
| SCT Welding, Laser & Manufacturing Co. | [12] |
| Metal-Tech Industries | [13] |
| Metal Supermarket - Winnipeg | [14] |
| Argus Industries | [15] |

The detailed cost is broken down into the item name, quantity needed, unit cost, total cost, part number and manufacturer. The budget was split into three main components: hardware costs, actuator costs and manufacturing and material costs. A cost breakdown of these three components are found in Table II, Table III and Table IV.

TABLE II: BREAKDOWN OF THE HARDWARE COSTS

| Hardware Costs | | Option #1 | | | | Option #2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Purchased Components** | **Quantity** | **Unit Cost** | **Total Cost** | **Part Number** | **Vendor #1** | **Unit Cost** | **Total Cost** | **Part Number** | **Vendor #2** |
| **#10 Metal Washer** | 26 | $2.49 | $64.86 | 11128442 | Fastenal | $0.13 | $3.38 | 63868990 | Rona Canada |
| **#10-24 Locking Nut** | 17 | $0.11 | $1.80 | 37014 | Fastenal | $0.18 | $2.99 | 63868738 | Rona Canada |
| **#10-24 X 1" Bolt** | 13 | $0.51 | $6.61 | 148130 | Fastenal | $0.04 | $0.46 | 5111-793 | Home Depot Canada |
| **#10-24 X 7/8" Screws** | 4 | $0.09 | $0.35 | 28975 | Fastenal | $2.55 | $10.18 | EBP2BE42 | Acklands Grainger |
| **1/4 ID Nylon Washer** | 8 | $0.08 | $0.67 | 76061 | Fastenal | $0.70 | $5.57 | PPC5705-214 | Acklands Grainger |
| **1/4 X 1-3/4" Clevis Pin** | 2 | $0.57 | $1.15 | 156731 | Fastenal | $6.38 | $12.76 | EBP41MC60 | Acklands Grainger |
| **3/16 ID Nylon Washer** | 14 | $0.06 | $0.88 | 76060 | Fastenal | $0.39 | $5.51 | PPC5705-208 | Acklands Grainger |
| **3/16 X 1" Clevis Pins** | 10 | $0.63 | $6.34 | 156717 | Fastenal | $1.01 | $10.06 | EBP41MF22 | Acklands Grainger |
| **3/16 X 1-1/2" Clevis Pin** | 2 | $0.66 | $1.32 | 156719 | Fastenal | $5.09 | $10.18 | EBP41MC46 | Acklands Grainger |
| **3/16 X 5/8" Diameter Nylon Spacer** | 38 | $0.20 | $7.77 | 145791 | Fastenal | $0.06 | $2.29 | 139054 | Lowes Canada |
| **5/16 Metal Washer** | 12 | $0.14 | $1.69 | 71015 | Fastenal | $0.14 | $1.73 | EBP2DA57 | Acklands Grainger |
| **5/16 Rubber Sealing Washer** | 4 | $0.30 | $1.19 | 160877 | Fastenal | $1.88 | $7.53 | 163-143 | Home Depot Canada |
| **5/16-18 Locking Nut** | 8 | $0.41 | $3.27 | 1170861 | Fastenal | $0.54 | $4.28 | PFSLNNF516P | Acklands Grainger |
| **5/16-18 X 1-1/2" Bolt** | 8 | $0.41 | $3.28 | 177394 | Fastenal | $0.02 | $0.14 | 051147072 | Rona Canada |
| **90 Deg Bracket for Link AB** | 4 | $0.67 | $2.69 | 13998069 | Rona | $0.31 | $1.22 | 222-522 | Home Depot Canada |
| **90 Deg Bracket for Plate** | 4 | $0.59 | $2.36 | 51053209 | Rona | $0.31 | $1.22 | 222-522 | Home Depot Canada |
| **Total Hardware Cost [CAD]** | | | $106.25 | | | | | | |

TABLE III: BREAKDOWN OF THE ACTUATOR COSTS

| Actuator Costs | | Option #1 | | | | Option #2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Purchased Components** | **Quantity** | **Unit Cost** | **Total Cost** | **Part Number** | **Vendor #1** | **Unit Cost** | **Total Cost** | **Part Number** | **Vendor #2** |
| **Actuator** | 1 | $710.00 | $710.00 | GMX24-SR | Belimo | $325.00 | $325.00 | GIB163.1E | Siemens |
| **Clamp for Actuator Rod** | 2 | $23.00 | $46.00 | K-LM12 | Belimo | $28.50 | $57.00 | AM-710 | Schneider Electric |
| **Corner Angle Bracket** | 2 | $6.25 | $12.50 | 14086 | Rocky Mountain Westmill | $1.10 | $2.19 | 051052258 | Rona Canada |
| **Graphite Powder** | 1 | $7.89 | $7.89 | 960949 | Fastenal | $11.55 | $11.55 | 2988 | Acklands Grainger |
| **Hitch Pin Clip** | 14 | $0.17 | $2.39 | 156979 | Fastenal | $0.39 | $5.51 | 051038408 | Rona Canada |
| **Mounting Brackets and Screws for Actuator** | 1 | $128.00 | $128.00 | ZG-GMA | Belimo | $35.45 | $35.45 | ASK71.9 | Siemens |
| **Total Actuator Cost [CAD]** | | | $906.78 | | | | | | |

TABLE IV: BREAKDOWN OF THE MANUFACTURING COSTS

| Material & Manufacturing Costs | | Option #1 | | | | Option #2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Manufactured Components | | Unit Cost | Total Cost | Part Number | Vendor #1 | Unit Cost | Total Cost | Part Number | Vendor #2 |
| 1/2" Dia. Shaft for actuator | 1 | $5.00 | $5.00 | - | Metal Supermarkets - Winnipeg | $22.59 | $22.59 | 8257172 | Princess Auto |
| Actuator arm and mount material and machining | 1 | $49.00 | $ 49.00 | - | DB Stainless Products | | | | |
| Aluminum linkages and sealing plate | 1 | $300.00 | $ 300.00 | - | SCT Welding, Laser & Manufacturing Co. | $318.00 | $318.00 | - | Hi-Tec Profiles Inc. |
| Mounting Plate Material / Machining | 1 | $241.26 | $241.26 | - | DB Stainless Products | | | | |
| Sealing Material | 7 $ft^2$ | $4.98/$ft^2$ | $34.86 | - | Argus Industries | | | | |
| Total Manufacturing & Material Cost [CAD] | | | $630.12 | | | | | | |

The cost of each component was summed to reach the total cost of the automated sealing system. A contingency was set at 10% to accommodate for shipping costs and any unexpected price changes. An overview of the total cost for the automated sealing system is shown in Table V.

TABLE V: TOTAL COST BREAKDOWN OF THE AUTOMATED SEALING SYSTEM

| **Item** | **Cost [CAD]** |
|---|---|
| Hardware Costs | 106.25 |
| Actuator Costs | 906.78 |
| Manufacturing & Material Costs | 630.12 |
| Sub-total | $1643.15 |
| Tax | 13% |
| Contingency | 10% |
| **Total Cost** | $2021.07 |

Therefore, the total estimated cost for the automated sealing system is $2021.07.

## H.2 References


[1] Acklands-Grainger, *Industrial Supply, Safety Equipment and Fasteners,* 2018. [Online]. Available: https://www.acklandsgrainger.com/en [Accessed 27 November 2018].

[2] Lowe's Canada, *Home Improvement, Appliances, Tools, Bathroom, Kitchen*, 2018. [Online]. Available: https://www.lowes.ca/ [Accessed 28 November 2018].

[3] Rona Canada, *Home & Garden*, 2018. [Online]. Available: https://www.rona.ca/en [Accessed 28 November 2018].

[4] Home Depot Canada, *Hardware*, 2018. [Online]. Available: https://www.homedepot.ca/en/home/categories/building-materials/hardware.html [Accessed 27 November 2018].

[5] Siemens, *Actuators*, 2018. [Online]. Available: https://www.siemens.com/ca/en/home.html [Accessed 29 November 2018].

[6] Shneider Electric, *Energy Management and Automation*, 2018. [Online]. Available: https://www.schneider-electric.com/ww/en/ [Accessed 29 November 2018].

[7] H. Schlamp. (2018, November 26). “RE: Aluminum Laser Cutting – Quote Request.” Personal e-mail.

[8] Fastenal, *Industrial Supplies, OEM Fasteners, Safety Products & More*, 2018. [Online].

Available: https://www.fastenal.ca/ [Accessed 25 November 2018].

[9] Rocky Mountain Motion Control, *T-Slot Aluminum Extrusions*, 2018. [Online]. Available: http://rmmc.net/8020/ [Accessed 28 November 2018].

[10] Belimo, *Actuators*, 2018. [Online]. Available: https://www.belimo.com/ [Accessed 20 November 2018].

[11] Princess Auto, *Hardware*, 2018. [Online]. Available: https://www.princessauto.com/en/ [Accessed 28 November 2018].

[12] L. Kreviazuk. (2018, November 26). “RE: New Customer Message.” Personal e-mail.

[13] N. Sorin. (2018, November 30). “RE: Steel Laser Cut and Bending – Quote Request.” Personal e-mail.

[14] S. James. (2018, December 3). “RE: Quote Request.” Personal e-mail.

[15] J. Vechina. (20018, December 4). “RE: Price Industries Capstone U of M Program.” Personal e-mail.