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Recycling of Compressed Air Within an Industrial System

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ABSTRACT

Compressed air is used for a wide variety of manufacturing processes, including a thermoforming process at Berry Global which produces 30 ounce plastic cups. Currently, the machine used to produce these plastic cups uses a substantial amount of 80 psig air, roughly 1400 gal/min, which is being exhausted to the atmosphere. It was determined that the cost to provide the necessary air for this one machine is approximately $3.34 per hour. The objective of this project is to design a system that is capable of recycling some of the air that is currently being exhausted to the atmosphere. To begin the design process, previous solutions to this problem were researched. The three preliminary designs developed by the team were inspired by the previous solutions researched. The preliminary designs were all considered, and the final design was chosen. The design chosen for critical design captures a portion of the exhausted air and boosts the pressure back to 80 psig where it can be reused in the current system. This design was divided into three main subsystems, each of these subsystems was designed, and a model for the entire system was developed. The model was a key factor for determining the cost savings of the system and the specifications of the different system components. Next, the determined specifications were used to select the system components. These components, as well as the installation costs, were arranged into a budget. The final system cost was then divided by the cost savings to determine a Return on Investment period. Finally, future changes and improvements to the design were discussed.

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Variable	Variable Name
V_{Form}	Volume of the form air (gal)
$\dot{V}_{Form}$	Volumetric flow rate of form Air (cfm)
T_{cycle}	Thermoforming cycle time (s)
$\eta_{compressor}$	Efficiency of centrifugal compressor (kW/cfm)
P_{Form}	Power to compress form air (kW)
$C_{original}$	Cost of form air for thermoformer ($/hr)
C_{kWh}	Amount Berry pays for electricity ($/kWh)
k	Adiabatic expansion coefficient (unitless)
P_1	Initial air pressure (psi absolute)
P_2	Final pressure (psi absolute)
$\dot{V}_{40\ psig}$	Flow rate of 40 psig air (cfm)
$\dot{V}_{inline}$	Volumetric flow rate of the in-line compressor (cfm)
HP	Power required to compress the air (hp)
P_{actual}	Actual power required to compress air (kW)
$\eta_{40\ psig}$	Efficiency of assumed 40 psig compressor (unitless)
$C_{40\ psig}$	Cost per hour to produce 40 psig air ($/hr)
d	Smaller diameter (in)
D	Larger diameter (in)
K_L	Loss Coefficient (unitless)
P	Pressure (Pa)
t	Time (s)
m	Mass (kg)
ρ	Density of air (kg/m^3)

$\dot{m}$	Mass flow rate of air (kg/s)
$\bar{V}$	Volume (m^3)
n	Amount of substance (moles)
M	Molar mass (kg/mol)
R	Ideal gas constant (m^3*Pa/K*mol)
T	Temperature (K)
A	Cross Sectional Area of pipe (m^2)
V_{air}	Velocity of air leaving thermoformer (m/s)
L_{pipe}	Estimated length of pipe from bottom die to check valve (ft)
$T_{check\ valve}$	Time for air to reach check valve (s)
C_{inline}	Cost per hour for in-line compressor ($/hr)
Von Mises	Maximum stress undergone (ksi)
σ_m	Mean stress (ksi)
σ_a	Alternating stress (ksi)
S_e	Endurance limit at critical location of a machine part (ksi)
S_{ut}	Ultimate tensile stress (ksi)
k_a	Surface factor (unitless)
a	Surface finish factor (unitless)
b	Surface finish exponent (unitless)
k_b	Size factor (unitless)
k_c	Load factor (unitless)
k_d	Temperature factor (unitless)
k_e	Reliability factor (unitless)
k_f	Miscellaneous effects factor (unitless)
S_e'	Test specimen endurance limit (ksi)
η_f	Safety factor (unitless)

Recycling of Compressed Air Within an Industrial System

1 INTRODUCTION

Compressed air is utilized throughout many different industrial processes. Its rapid reaction time and relatively low cost of production has made it a staple for many manufacturing processes. However, with rising energy bills, the cost to produce this compressed air is increasing daily. Because of this, Berry Global approached the USI Engineering Department with the proposition of determining the possibility of reducing energy costs by capturing and reusing some or all of the compressed air from a thermoformer that is otherwise exhausted to the atmosphere.

Berry Global is a plastics company with its world headquarters in Evansville, Indiana. Berry Global produces a wide variety of plastic products including cups, tapes, straws, and many other products within a total of 22 portfolio groups. Berry's plant in Evansville makes a variety of these different products. One of the products made at this facility is plastic cups used at fast food chains. The machine used to make this product is known as a thermoformer and is the main focus of this entire project **[1]**. An image of the thermoformer being discussed is pictured below in Figure 1.

Figure 1. Thermoformer Line 18 ***[2]***

1.1 Objective

The objective for this project is:

Design a compressed air recycling system at Berry Global that will operate autonomously and concurrently with a thermoforming pneumatic process to reduce energy costs.

1.2 Deliverables

The deliverables determined for this project are the following:

- Air Recycling System design
- Complete engineering calculations relating to the air recycling system
- Cost savings analysis of the new system

2 BACKGROUND

2.1 Statement of the Problem

The cost of producing compressed air for use in an industrial setting is extremely high. In many cases, the production of compressed air can account for nearly one third of all the electricity being used within an industrial facility **[3]**. This sizeable draw of energy leads to a massive electricity bill for large industrial facilities. While much of the compressed air that is produced is put to good use, a significant portion of that air is lost via leaks in the piping or residual pressure that is exhausted to the atmosphere after it has completed its task.

While it may be possible to reduce losses in both of the situations previously described, repairing leaks could be very costly and nearly impossible in complex compressed air distribution systems. The amount of air lost from leaks is also much less than the amount air exhausted to the atmosphere after its use. For this reason, the project will focus on solving the second issue that involves using compressed air which is currently exhausted to atmosphere. For the specific system at Berry Global, there is a high pressure thermoformer which is allowing compressed air to be vented to the atmosphere without any restriction besides a muffler for sound deadening. While this current design is effective in keeping the machine in operation, the implementation of a compressed air recycling system would provide a way to recapture some of the energy that would otherwise be lost.

2.1.1 Thermoforming Process

The thermoforming process used at Berry Global in this specific application produces 30-ounce plastic Taco Bell cups. The machine we are examining in Figure 1 is known as Thermoforming Line 18. This line can produce 110 cups during each 4.7 second machine cycle. A cycle in this setting is defined as the amount of time between the first and final tasks that are performed by the thermoformer to produce one batch of cups. In Figure 2 below, the finished product from this machine is shown.

Figure 2. Picture of Taco Bell Cup

The machine being considered is capable of producing approximately 1,400 cups per minute. A generalized version of the thermoforming process is shown in Figure 3 below.

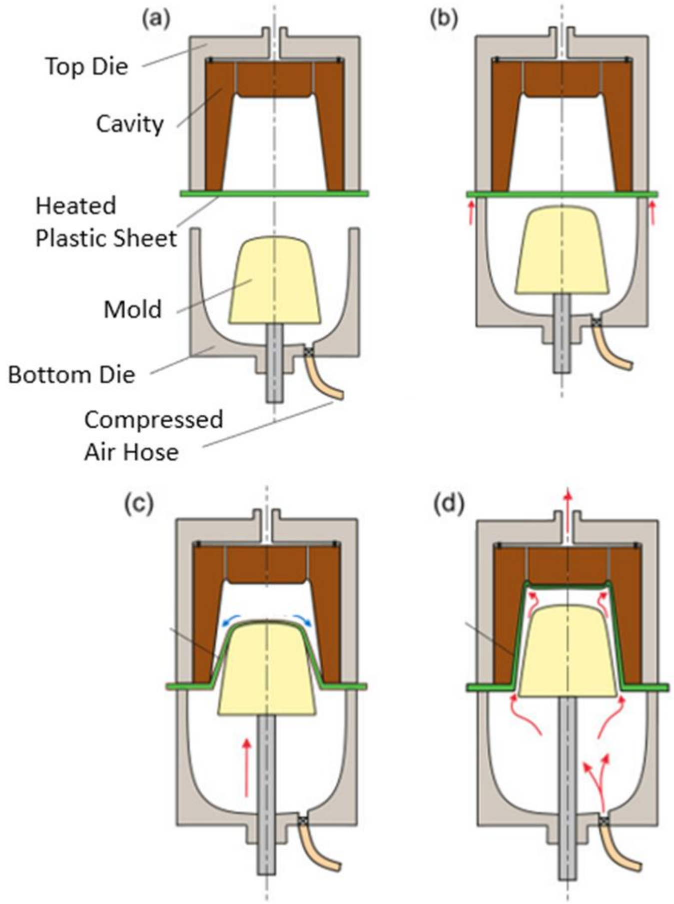


Figure 3. Thermoforming Process Diagram **[4]**

The thermoforming process used at Berry Global is represented in the diagram above. This process utilizes both mechanical molds as well as compressed air to form the cups. Starting from image (a), the heated plastic sheet, shown in green, slides into position in between the top and bottom dies. In image (b) the two dies close together creating an airtight seal between them. Image (c) shows where the yellow mold moves upward which stretches the heated plastic sheet and partially forms the shape of the cup. Finally, in image (d) compressed air is released into the bottom die which then forces the heated plastic sheet to hug the walls of the brown cavity, giving the cup its defined and final features. These steps are what constitutes the thermoforming process used in Thermoforming Line 18.

In order to analyze the potential energy and cost savings of recycling the compressed air of such a system, first the current system will need to be considered. The current system is a thermoformer which is used to mass produce plastic cups for fast food restaurants. Figure 4 shown below demonstrates the basic flow of compressed air through the current system.

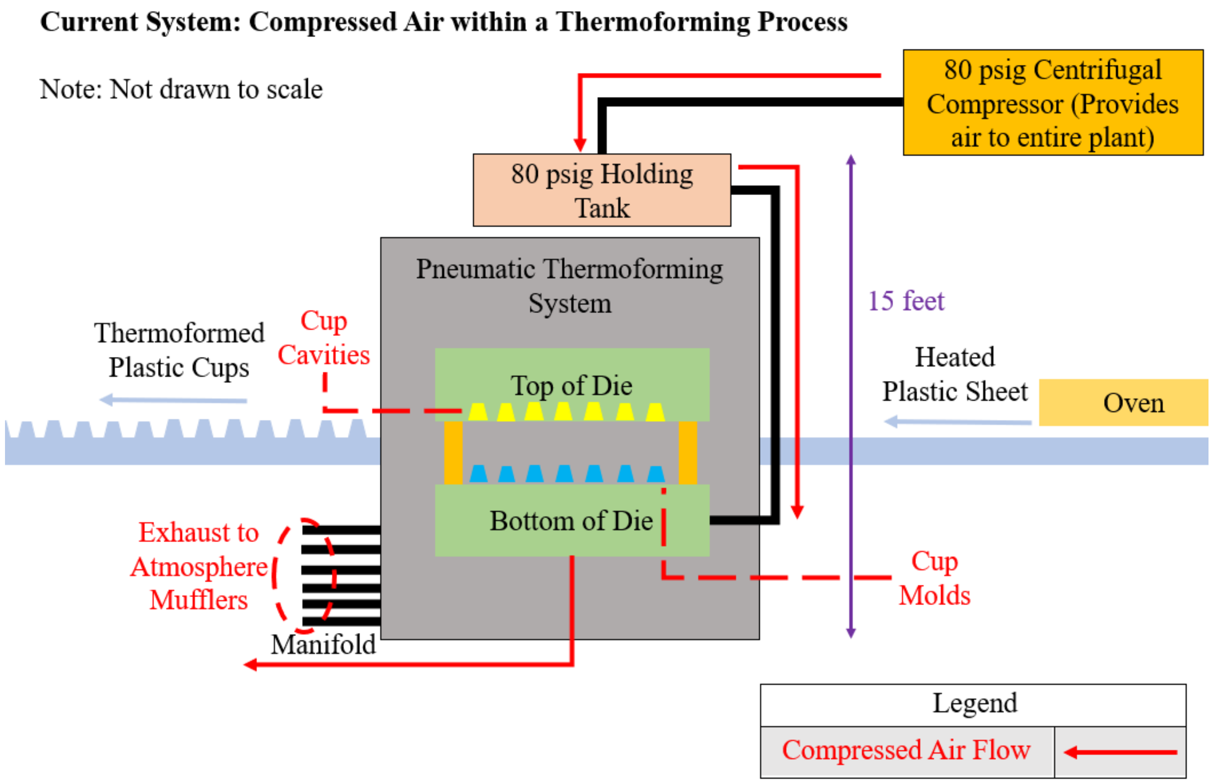


Figure 4. Current Thermoforming System Diagram (Die Mold in Open Position)

In *Figure **1***Figure ***4***4, the air begins at the centrifugal compressor which provides air to the entire plant. The air from this compressor is routed all around the facility to a variety of different machines that utilize compressed air. For this specific thermoformer, air from the centrifugal compressor is held in a 1,100 gallon holding tank shown on top of the thermoformer in Figure ***4***4. This holding tank stays at a constant pressure of 80 psig by drawing in the necessary amount of air from the centrifugal compressor when necessary. Air is released out of the holding tank and into the bottom die via an actuation valve where it is used to form the plastic cups inside the die cavities once the dies close. While it is not shown in the image above, 6 actuation valves located on the bottom of the bottom die then exhaust this air to the atmosphere. There is a separate actuation valve for each of the exhaust lines shown in Figure 4. The estimated cost to produce the air for this system can be seen in Appendix A.

The calculations show that there is a specific cost associated with the operation of the thermoformer's compressed air system. When determining the best method to recapture the energy that is currently being lost, it is important to consider all the factors within the system. All of the possible design options were analyzed thoroughly to see which one provided the greatest energy savings compared to the cost of installation.

2.2 SIMILAR PROJECTS

2.2.1 Technoplan Engineering Air Recycling System

The first similar solution considered for recapturing compressed air was developed by Technoplan Engineering SA from Geneva, Switzerland **[5]**. The system they designed is called ARS or Air Recycling System. This system has been predominantly implemented in facilities in Europe that do plastic blow molding. The system is designed to capture the high-pressure air which is then exhausted to a lower pressure instead of being released to the atmosphere. This lower pressure air is then repurposed to be used in other parts of the facility that operate on lower pressure systems. ARS is designed to be installed between the existing exhaust system and the low-pressure air system. It works by way of a regulator that lowers the pressure of the air exiting the exhaust to approximately 170 psig allowing it to be routed into the low-pressure air system. This solution has provided significant cost savings for companies that have implemented the design. While this design worked well for the plastic blow molding industry, it will be less effective for the application of this project since the pressures being captured are much lower, less than 80 psig. A diagram of the Air Recycling System can be seen in Figure 5.

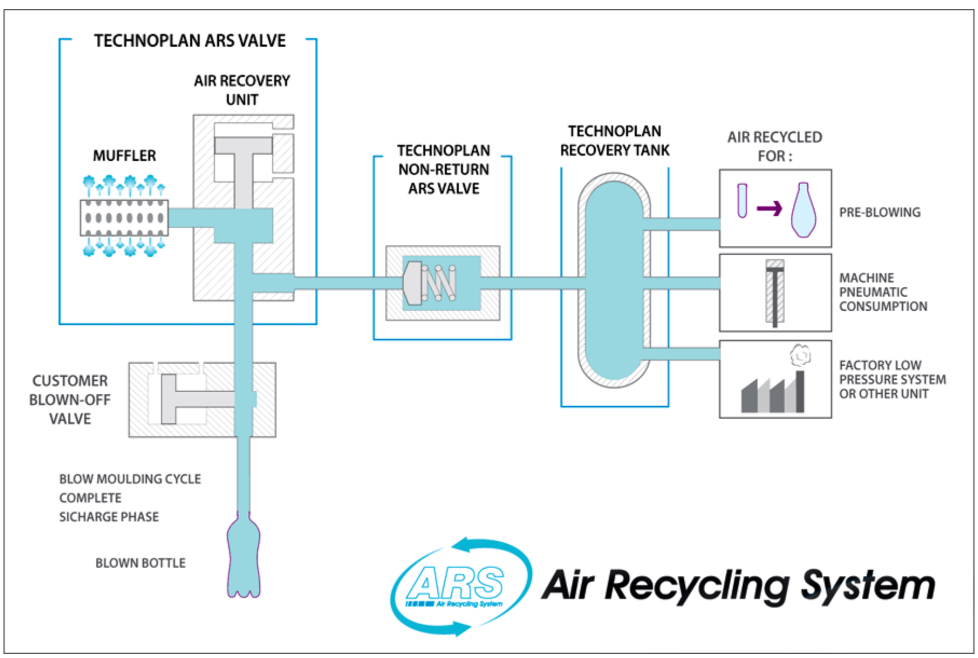


Figure 5. Technoplan Air Recycling System – System Diagram ***[5]***

2.2.2 Inner Mongolia University Pneumatic Actuating System

The second similar design for recapturing compressed air was established by a group of Chinese researchers **[6]**. This design acts in a similar way to the previous design by capturing the exhausted air. However, in this system, the air flow is controlled using solenoid valves, which are programmed to actuate once the pressure has reached a certain point. The solenoid first directs the compressed air into a storage tank where the pressure is measured with a pressure sensor. Once the pressure has been released almost completely, the cylinder will actuate, allowing the remaining air to be exhausted to the atmosphere. The system also has an extra solenoid valve in place to ensure that the pressure inside the storage tank doesn't get any higher than it should to prevent over pressurization within the tank **[6]**. This solution does go into much more detail on the design of the system and the actual testing of the system compared to other solutions. The system however does not account for the need to not affect the cycle time of the existing system. This is a critical consideration that must be accounted for in this design. An image of the experimental setup of the Pneumatic Actuating System can be seen in Figure 6 below.

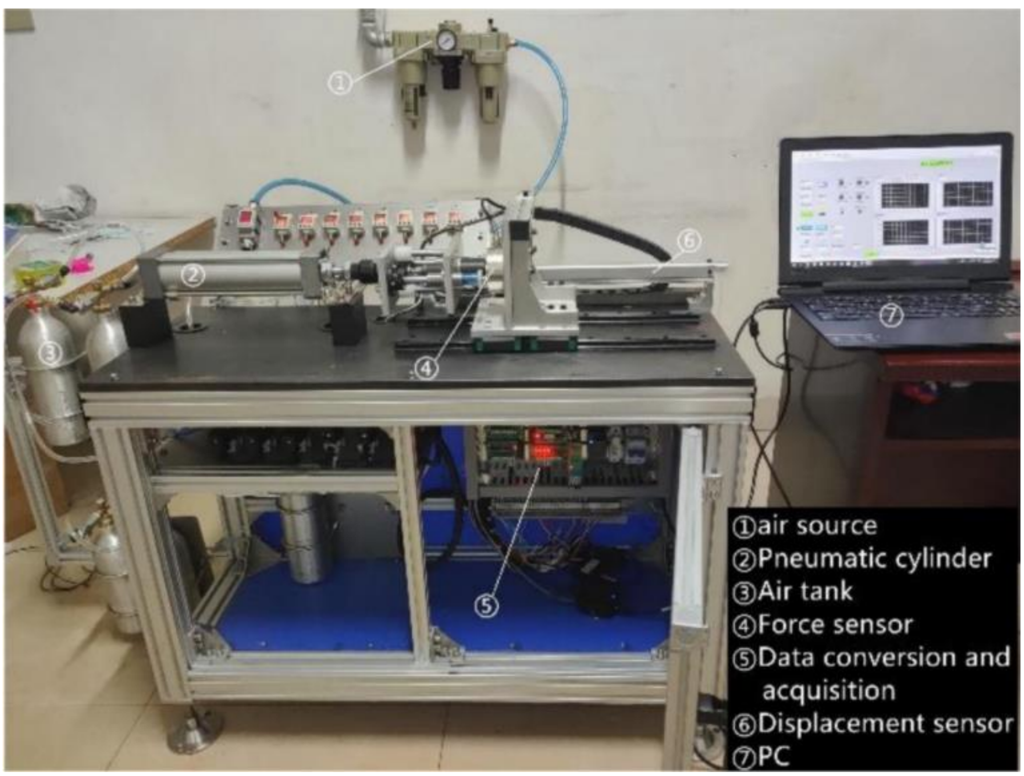


Figure 6. Experimental Setup of Pneumatic Actuating System ***[6]***

2.2.3 Michigan Pneumatic Tool Exhausted Air Recycling System

The third similar project was developed by an Australian man and distributed in the United States by Michigan Pneumatic Tooling, Inc. This device works similar to a hydraulic system, in the sense that the spent fluid, in this case air, is sent straight back into the tank, creating a closed-loop system **[7]**. A coupling and manifold are connected to the exhaust of a pneumatic tool, and into pneumatic tubing which connects into the compressor. This closed-loop system allows for the air typically exhausted to the atmosphere to be redirected into the compressor at a pressure higher than atmospheric. Because the pressure in the loop is greater than that of atmospheric pressure, the compressor requires less energy to recompress the air to the desired pressure. While this design is very effective, it is designed for common, small-scale retail compressors and air tools. It was not a design intended for a large-scale industrial setting. An illustration of the Exhausted Air Recycling System can be seen in Figure 7 below.

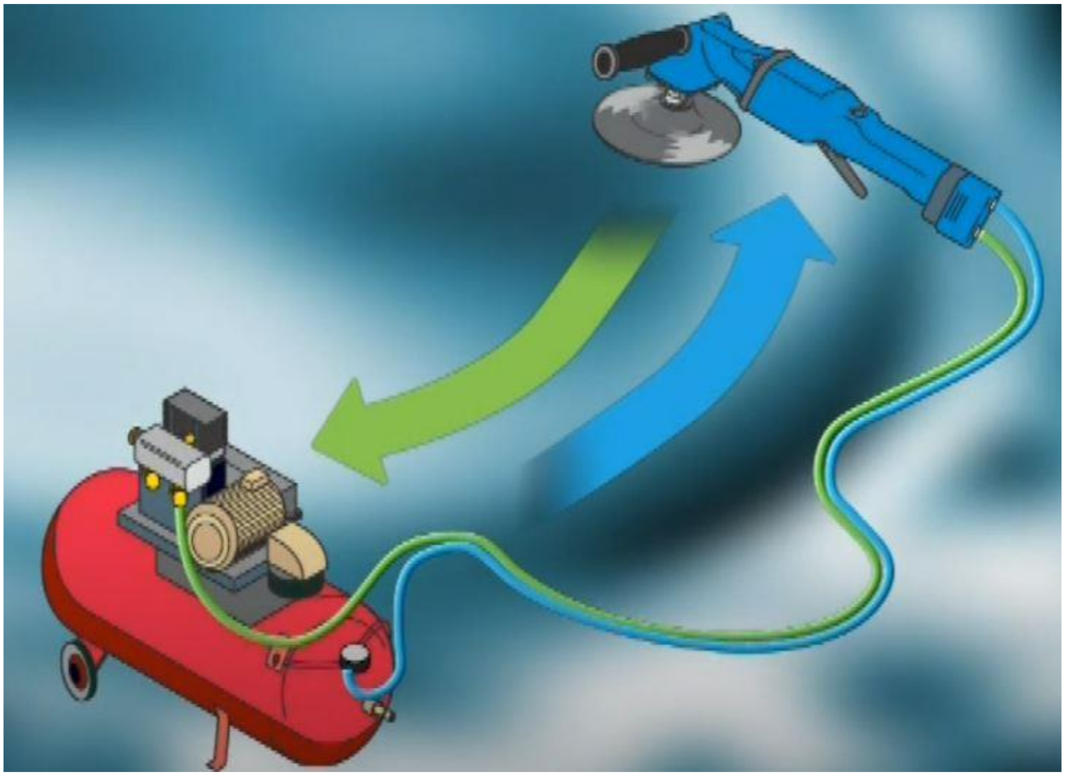


Figure 7. Exhausted Air Recycling System Illustration ***[7]***

2.3 APPLICABLE PROFESSIONAL STANDARDS

Through the literature review, the team discovered applicable standards for the system being designed. Some of the applicable standards found were OSHA and ISO safety standards. Some of these standards considered throughout the project include:

- OSHA noise exposure standard 1910.95. This states that when noise levels are over 85 dB for 8 or more hours, employees must wear hearing protection **[8]**.
- ISO8573-3:1999. This standard specifies the amount of humidity allowed in the compressed air **[9]**.

These standards as well as the factors and requirements described below guided the design and analysis of the system.

2.4 FACTORS THAT IMPACT DESIGN

Public Health, Safety, and Welfare

When designing the compressed air recycling system, public health, safety, and welfare factors were considered. Numerous safety features were added into this system to assure the protection of Berry employees from any potential danger. The team designated an isolation valve be installed which could serve as a key Lockout/Tagout component in the event that any maintenance was needed on the recycling system. Once manually actuated, this valve will assure that no exhausted air can enter the system from the thermoformer. This will keep employees safe during maintenance of the system. Additionally, the team called out a safety feature in the PLC programming that will assure that the system will not become over pressurized. If the system reads a pressure greater than anticipated, the system will revert to current operations, allowing all the air to exhaust to atmosphere until the pressure stabilizes again. The valve is discussed in detail in Section 5.3.1 and the programmed safety feature is covered in Section 4.3.3.

Environmental and Economic

The team concentrated on a key developmental goal of Berry Global while designing this system. The company is focused on minimizing their environmental footprint. Also, Berry strives to continually reduce their utility usage. The team designed the system so that the optimal amount of compressed air would be saved. This assures that the system will minimize the energy cost associated with compressing the air for this thermoformer line.

Additionally, economic factors such as energy resources were considered. The goal of this project was to design a system that would reduce energy costs by recycling compressed air. The team focused on designing a system that would optimize the cost savings associated with the system. The cost savings of this system is discussed in Section 8, Appendix A, and Appendix G.

2.5 REQUIREMENTS

Based on the constraints provided by Berry Global **[11]**, as well as industry standards, the following requirements for the Compressed Air Recycling System were determined.

Table 1. Table of Requirements

The Compressed Air Recycling System shall:

Not increase the current cycle time of 4.7 seconds.
Be able to exhaust all air to the atmosphere in an emergency situation.
Operate continuously and concurrently with the thermoformer.
Not induce backpressure.
Recompress the air to 80 psig prior to re-entering the existing 80 psig holding tank.

3 CONCEPT SELECTION

The team chose three initial concepts, described below. These three concepts were all considered, and the concept with the most promising results was carried into the critical design phase for the project.

3.1 80 PSIG TO 40 PSIG RECYCLING SYSTEM

How it Works

The first concept that was considered is shown below in Figure 8. This concept includes an exhaust manifold used to combine all the outlets from the thermoformer into a single pipe. Next the air is directed by the actuation valve mechanism which allows a portion of the air to flow into a 40 psig capacitor tank while the remaining air is exhausted to atmosphere. The captured air is then regulated to exactly 40 psig and routed into the 40 psig eject air system used on a different part of the thermoformer. The potential cost savings for this design is shown in Appendix B.

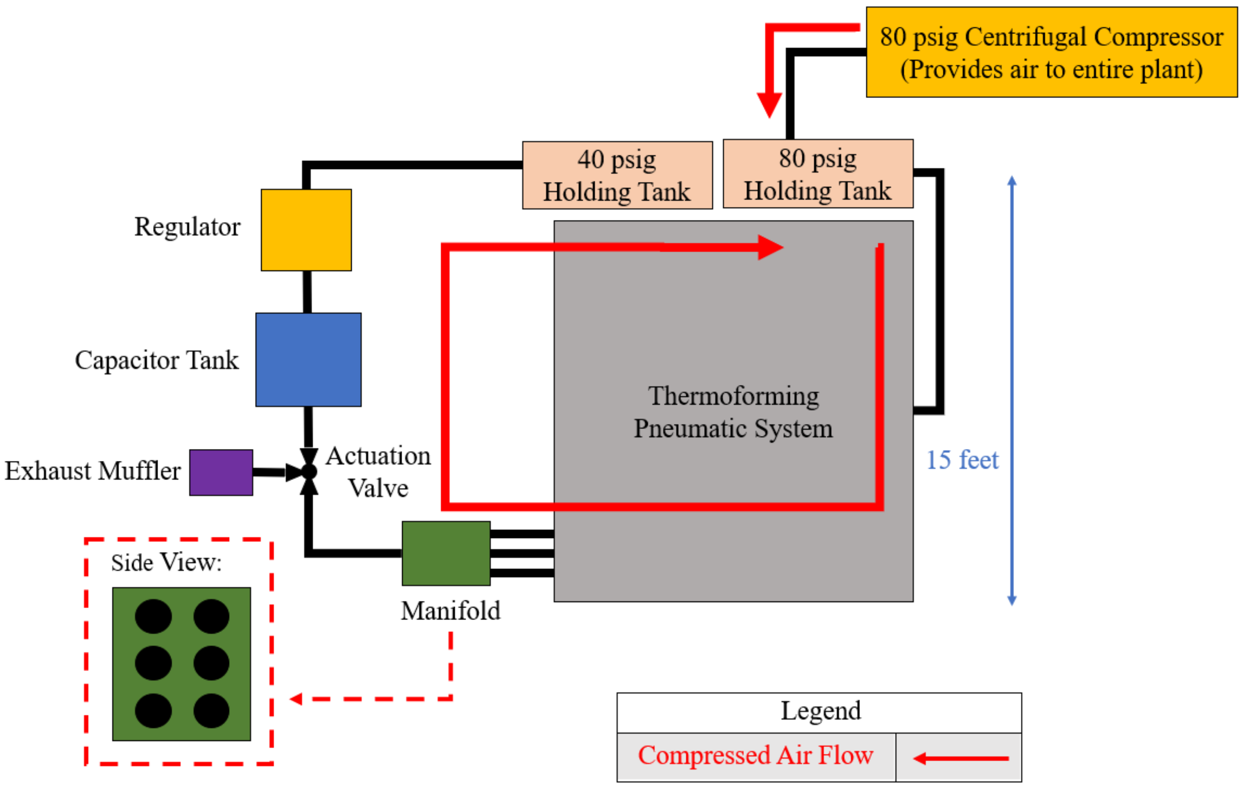


Figure 8. 80 psig to 40 psig Recycling System Diagram

Pros and Cons

When considering this design, there are several pros and cons to examine. The biggest pro to this system is that it would not require the addition of any air compressors in order to function properly. This would mean that the overall system would be simpler. The volume of 40 psig eject air used elsewhere on the thermoformer line was not provided by Berry Global; however, according to Berry Global, the size of the holding tank for this system is only 30 gallons **[11]**. This means that the air usage for the 40 psig air eject system is likely much less than the air usage for the 80 psig system. This would make it impossible to realize the entire cost savings for this system shown in Appendix B without integrating multiple lines together.

3.2 Electrical Generation System

How it Works

The second conceptual design was an electrical generation system. This system begins like the first concept, in the sense that the six thermoformer exhaust lines are combined into one line. However, this one line features a nozzle on the end of it. The 80 psig air travels through the nozzle and is exhausted out onto a turbine. The air will cause the turbine to spin, which when connected to a variable speed generator, will create electrical power that can be utilized by the facility **[12]**. A diagram of this concept can be seen in the Figure 9 below.

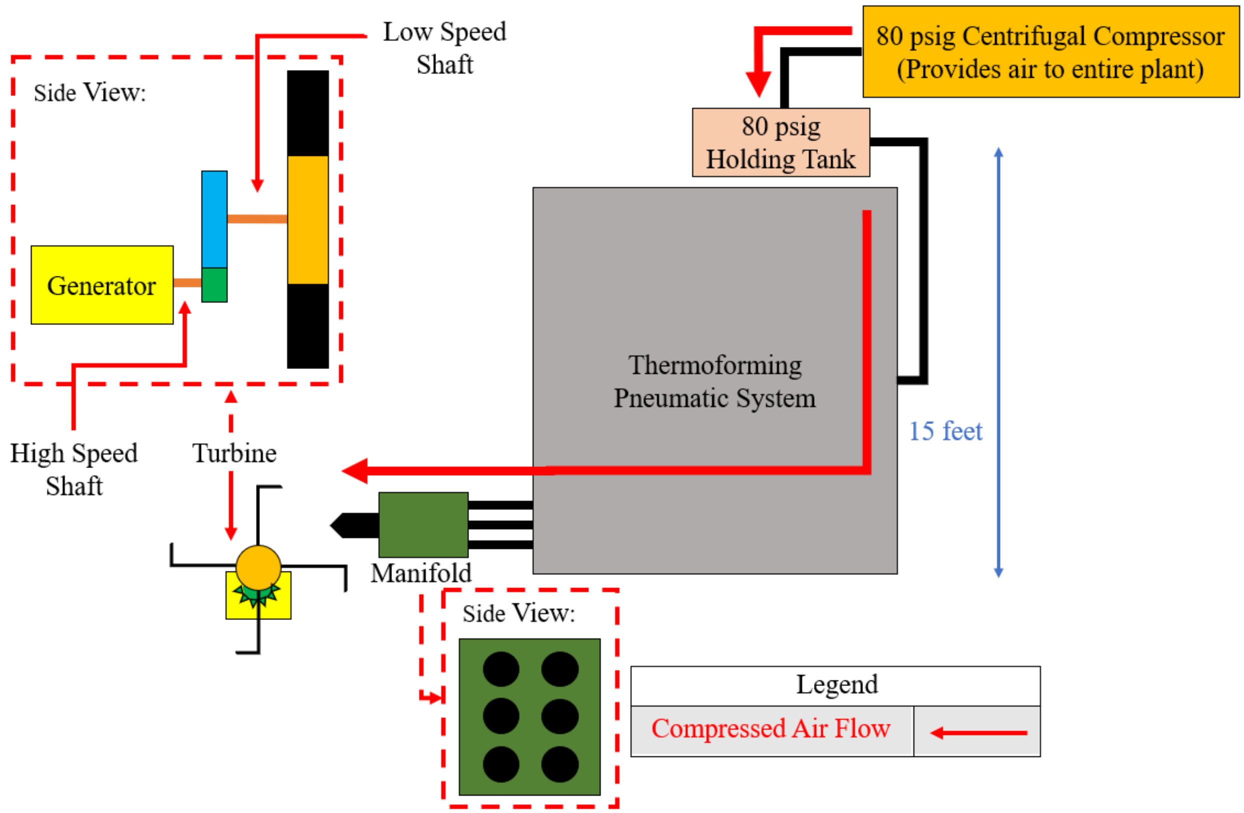


Figure 9. Electrical Generation System Diagram

Pros and Cons

Like the previous concept, this design also features several pros and cons. A positive feature with this design is that minimal modifications are needed to be made to the current system. The only change to the existing equipment is the removal of the mufflers, and the addition of a 6 to 1 manifold and a nozzle. A negative to this design is that electricity will not be produced continuously. This is because all the air is exhausted in 0.5 seconds, which would require that the turbine spins for an additional 4.2 seconds after the initial force from the exhausted air in order for the turbine to spin for the entirety of the 4.7 second thermoformer cycle time. Additionally, the noise level from the air exiting the turbine would be much higher than the current noise level. Since this concept was the least reasonable, it was not progressed any further.

3.3 80 PSIG TO 80 PSIG RECOMPRESSION SYSTEM

How it Works

The third concept that was considered is shown below in Figure 10. This concept includes an exhaust manifold used to combine all the outlets from the thermoformer into a single pipe. Next the air is directed by the actuation valve which allows a portion of the air to flow into a capacitor tank while the remaining air is exhausted to atmosphere. The captured air is then recompressed to 80 psig and routed back into the storage tank at the top of the thermoformer.

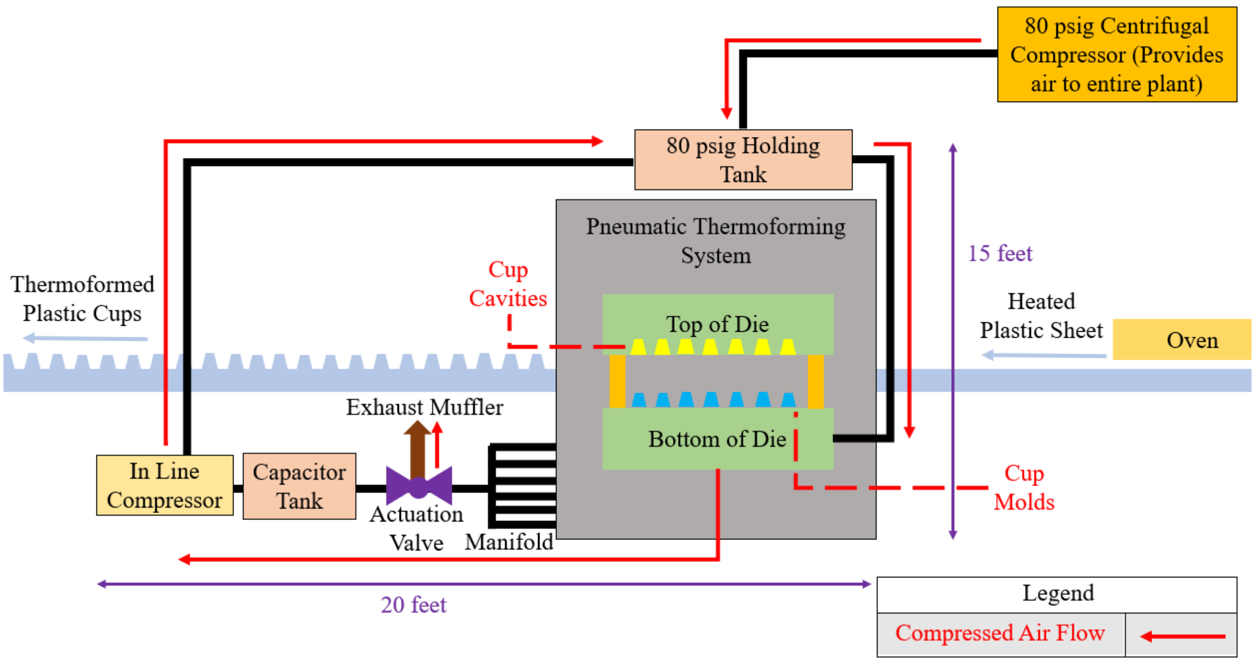


Figure 10. 80 psig to 80 psig Recompression System Diagram

Pros and Cons

The complexity of this design adds increased cost and potential problems in the design phase. Since this system requires the air to be recompressed, this will also add a cost of running the system, which will need to be considered. While it is more complex than the other options, it shows the greatest potential for cost savings if implemented. The potential for cost savings is greater than the others because this design allows the preservation of the higher-pressure, or higher-energy, air being captured.

3.4 JUSTIFICATION OF CHOSEN DESIGN

The team decided to choose the third conceptional design option to perform more detailed engineering analysis. Due to the greatest potential for cost savings obtained from the preliminary analysis of the conceptual designs, this design was chosen. While this concept is more complex than some of the others, the potential cost savings outweighed the potential problems that could arise in the system development. The design of the system and how it will function is detailed in Section 4 below.

4 FINAL DESIGN AND ANALYSIS

4.1 OVERVIEW OF OPERATIONS

As discussed previously, the third design choice was selected due to its potential for cost savings. The concept of operations is shown below in Figure 11.

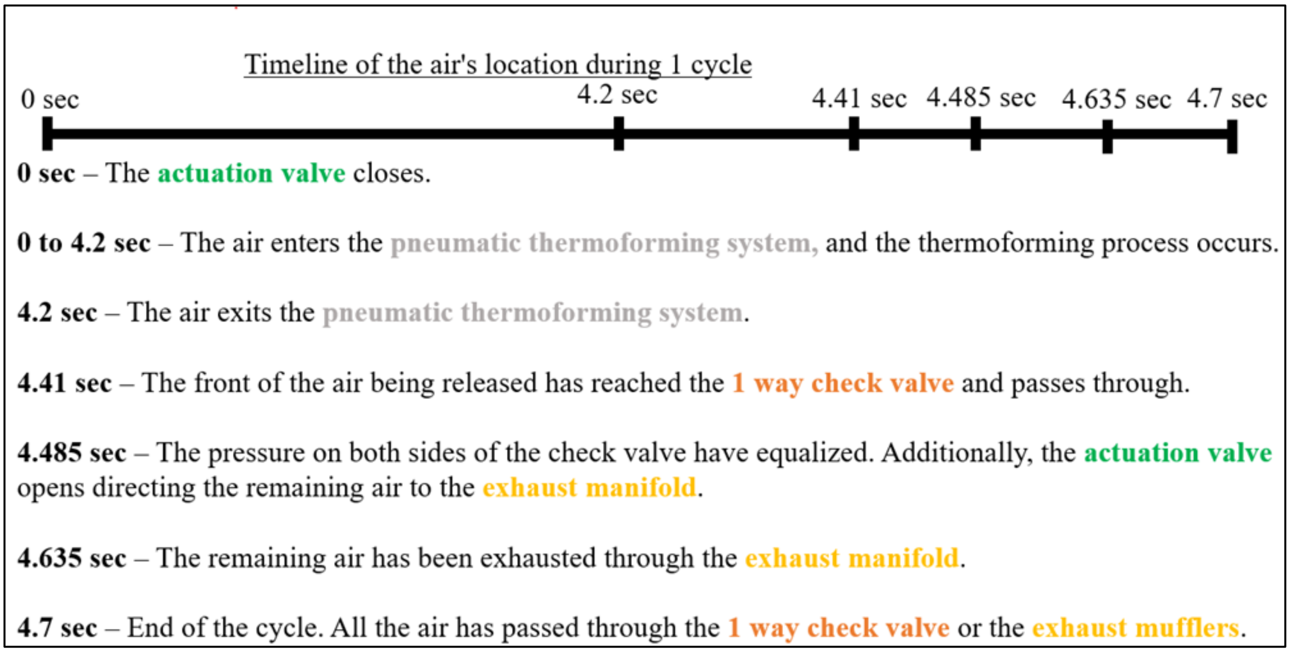


Figure 11. Concept of operations, See Figure 12

The timeline above represents how the compressed air recycling system operates along with the existing thermoforming system. The timeline begins at 0 seconds when the top and bottom dies have just opened, and the thermoforming cycle begins. The time between 0 and 4.2 seconds represents the amount of time that it takes to form the plastic cups. After these 4.2 seconds, the air is released, and the air recycling system begins to capture the compressed air.

4.2 SYSTEM OVERVIEW

The overall system is divided into three main subsystems in accordance with their function. The system hierarchy for the air recycling system can be seen in Appendix C. The mechanical block diagram for the overall compressed air recycling system is shown below in Figure 12. This diagram shows all the different subsystems and how they are connected to each other. The Exhaust Capturing subsystem is connected to the existing system via the 6 to 1 exhaust manifold. After the manifold, the air is split into two separate lines, one going up towards an actuation valve and the other going to the left through an isolation valve and a check valve. The direction of the air flow is determined by the pressure and timing of the system according to the concept of operations timeline shown above in Figure 11 and is described in more detail in Section 4.3.3.

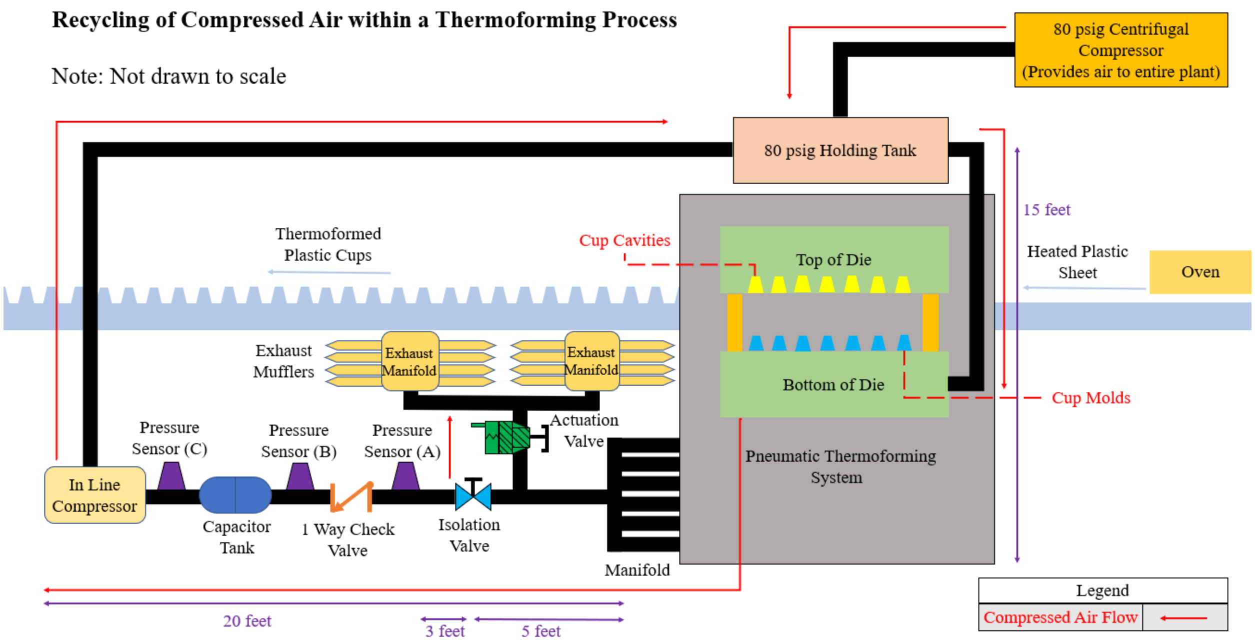


Figure 12. Air Recycling System- Mechanical Block Diagram, See Figure 20

4.2.1 Subsystem 1- Exhaust Capturing Subsystem

As previously mentioned, the first subsystem is the Exhaust Capturing subsystem, which includes the manifold and the pneumatic piping. This subsystem is circled in blue in Figure 13 below. During each 4.7 second thermoforming cycle, at 4.2 seconds the air inside the dies is released where it will then travel through the six exhaust lines and into the exhaust manifold. Once the air in the six lines has reached the manifold, the air will then be combined into a single 4-inch stainless steel exhaust line which continues on through the system.

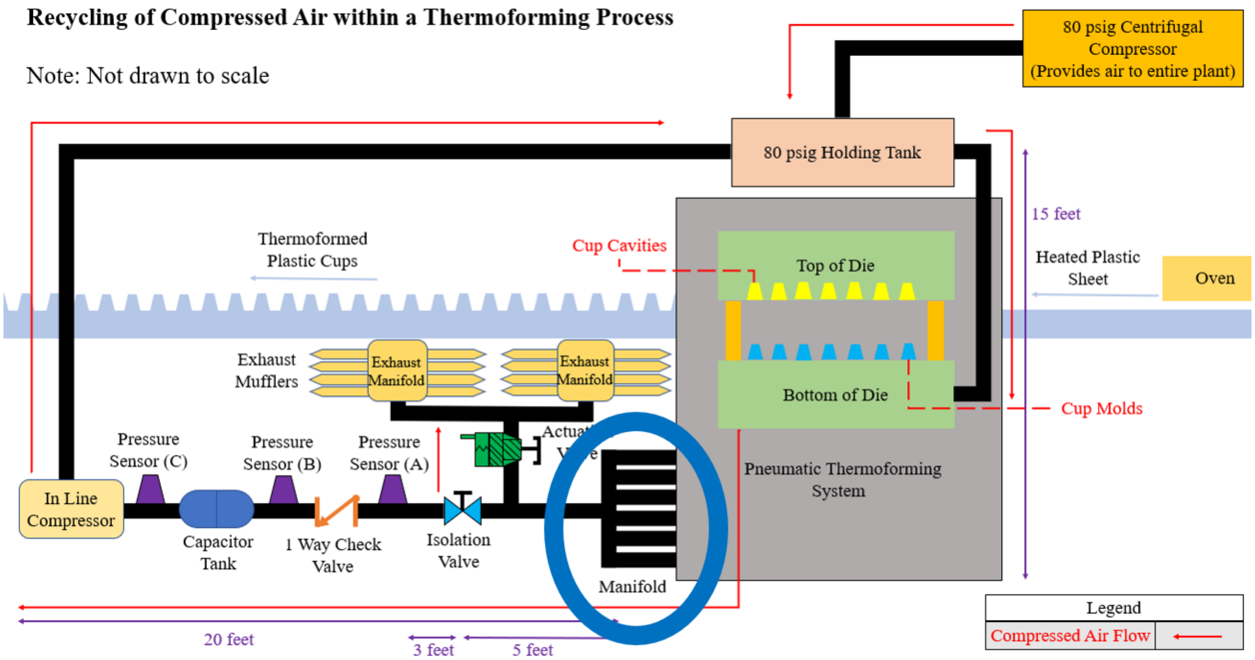


Figure 13. Exhaust Capturing Subsystem

Several different requirements influenced the design of the manifold. These requirements included containing a 6 to 1 reduction, being able to withstand 80 psig with a safety factor of 4, and being able to transfer 100% of the air through it. The final requirement is that there can be no back pressure traveling from the manifold and out through the dies upon reopening at 4.7 seconds. Several design considerations were taken into account when designing the exhaust manifold. These considerations are explained in greater detail in the section 5.2 of the report.

4.2.2 Subsystem 2- Air Transferring Subsystem

Following the Exhaust Capturing subsystem is the Air Transferring subsystem which determines how much air will be recycled and how much air will be exhausted to the atmosphere. This subsystem is circled in yellow in Figure 14.

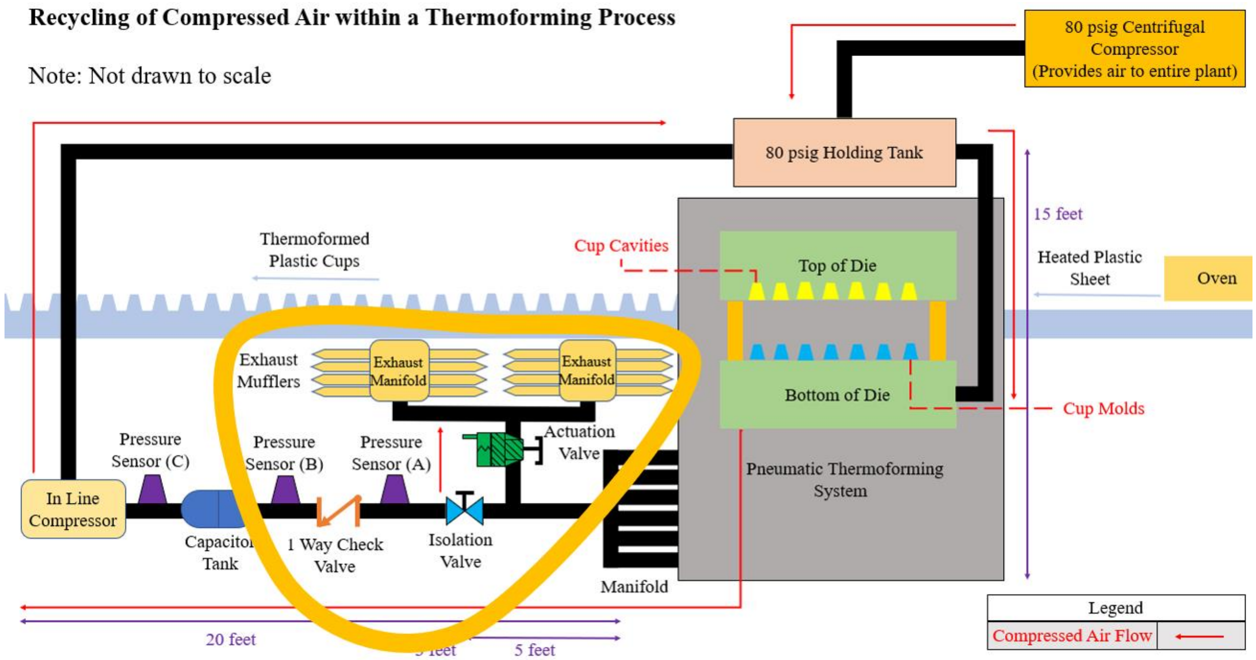


Figure 14. Air Transferring Subsystem

After the air has exited the manifold, it is divided into two sections, one portion moving to the left and the other moving in the vertical direction as shown in Figure 14. Initially, the actuation valve, shown in green, is closed which forces all the air through the isolation valve and the one-way check valve. This air then moves into the final subsystem, the Air Return subsystem. While a portion of the air is directed to the final subsystem, the remaining air is directed up through the actuation valve, approximately 4.5 seconds after the cycle begins, when pressure sensors A and B have read an equal pressure on either side of the check valve. A PLC controller will be utilized to interpret the incoming signals from the pressure sensors and will translate the signal to the actuation valve, ordering it to open. This air is then exhausted through the mufflers shown in Figure 14. The PLC logic is described in more detail in Section 4.3.3. The specifications and functions of each of the components of the subsystem are described in Section 5.

4.2.3 Subsystem 3- Air Return Subsystem

The final subsystem that will be discussed, is the Air Return subsystem. This subsystem is what recompresses the captured air and returns it to the holding tank located on top of the thermoformer. This subsystem is circled in red in Figure 15 below.

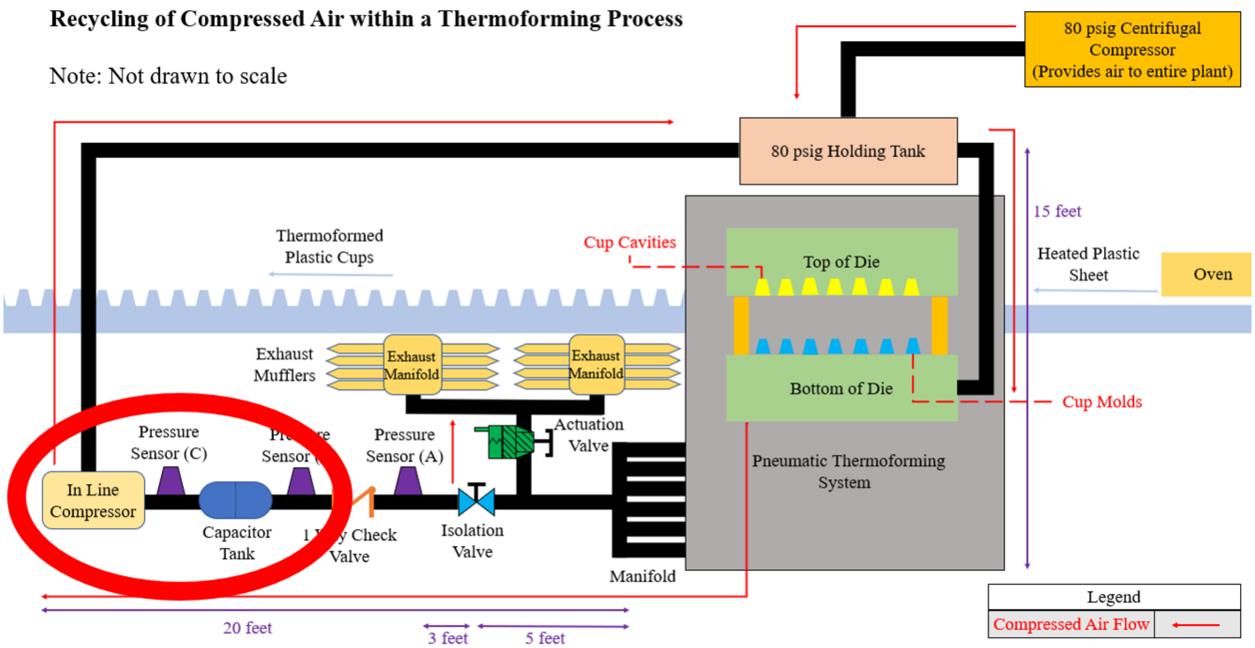


Figure 15. Air Return Subsystem

Once the air goes through the check valve, it then enters the capacitor tank. The purpose of this tank is to capture the air coming through the check valve and then provide a steady flow of air out the other side to the in-line compressor. The in-line compressor intakes the air from the capacitor tank then recompresses it back to 80 psig before it is routed back into the holding tank on top of the thermoformer. The specifications for the in-line compressor as well as the capacitor tank were determined through the model developed in Section 4.3.4.

4.3 System Model Development

4.3.1 Transient Air Transfer Model

In order to create a representative model of the air recycling system, relationships between pressure and mass were used as described below. The model developed helped determine the specifications for the in-line compressor as well as the capacitor tank. The following model was used to determine the amount of time necessary for the pressure of the air inside the thermoformer to equal the pressure of the air inside the capacitor tank as shown in the diagram below. The assumed volume of each container is also shown in Figure 16. The assumed volume comes from the volume of the form air provided by Berry Global **[10]** and was converted into cubic inches as shown below. Please note that this model utilizes the ideal gas law. Because the pressures in this system are relatively low, there is an insignificant change when the ideal gas law is assumed in this scenario. It was determined that there is approximately a 1% error associated with this assumption. The calculation to prove this percent error can be seen in the "Air_IGL" excel document on the flash drive.

$$V_{Form} = 115\ gal * \frac{231\ in^3}{1\ gal} = 26{,}550\ in^3$$

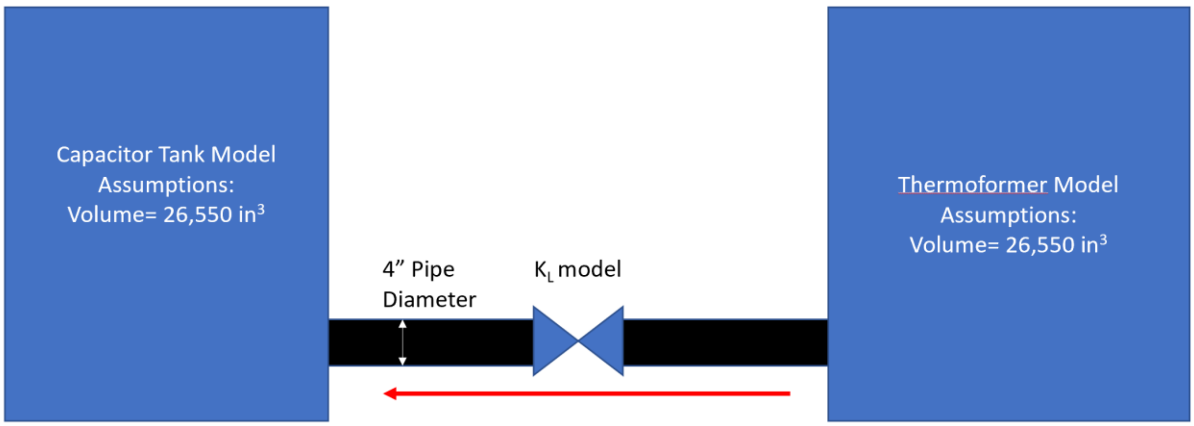


Figure 16. Transient Air Transfer Model

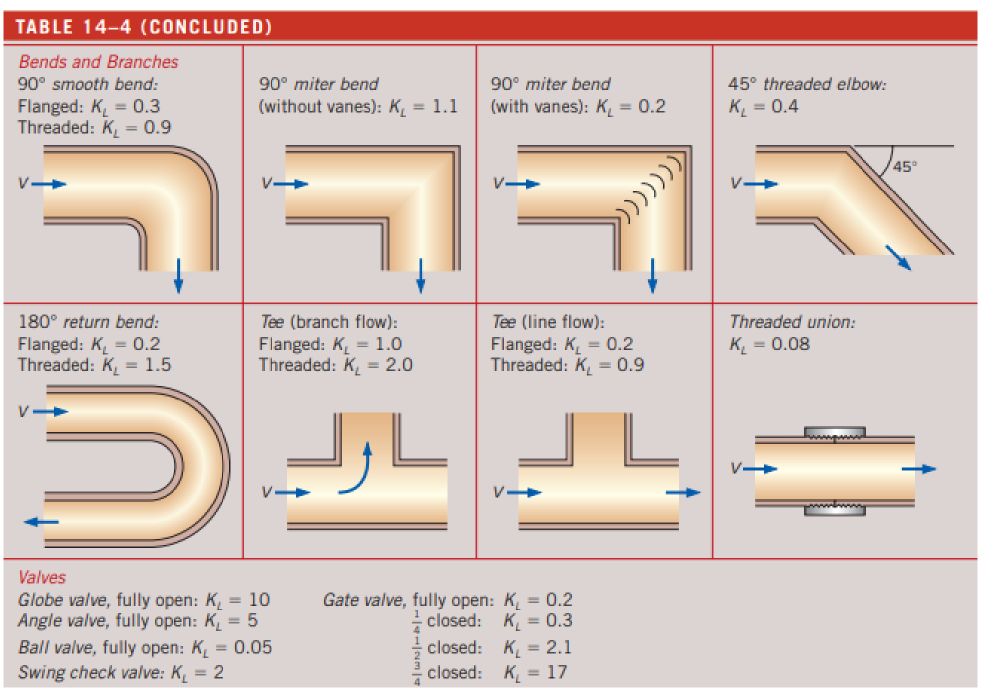
In the first iteration, the volume of the capacitor tank was assumed to be the same as the thermoformer form air volume. In this model, the pressure loss coefficient, or K_L value was determined by adding all the individual K_L values throughout the system as shown in the table below. The location of the different losses considered can be seen in Appendix D.

Table 2. K_L Values for Air Transfer Subsystem

Description	K_L Value
(3) 90 Degree Bends	3.3
Isolation Valve	0.2
Check Valve	2.0
2.5” Poppet Valve (Actuation Valve)	3.0
Tee Line Through	0.9
Contraction	0.3
Expansion	0.39
Total	**10.09**

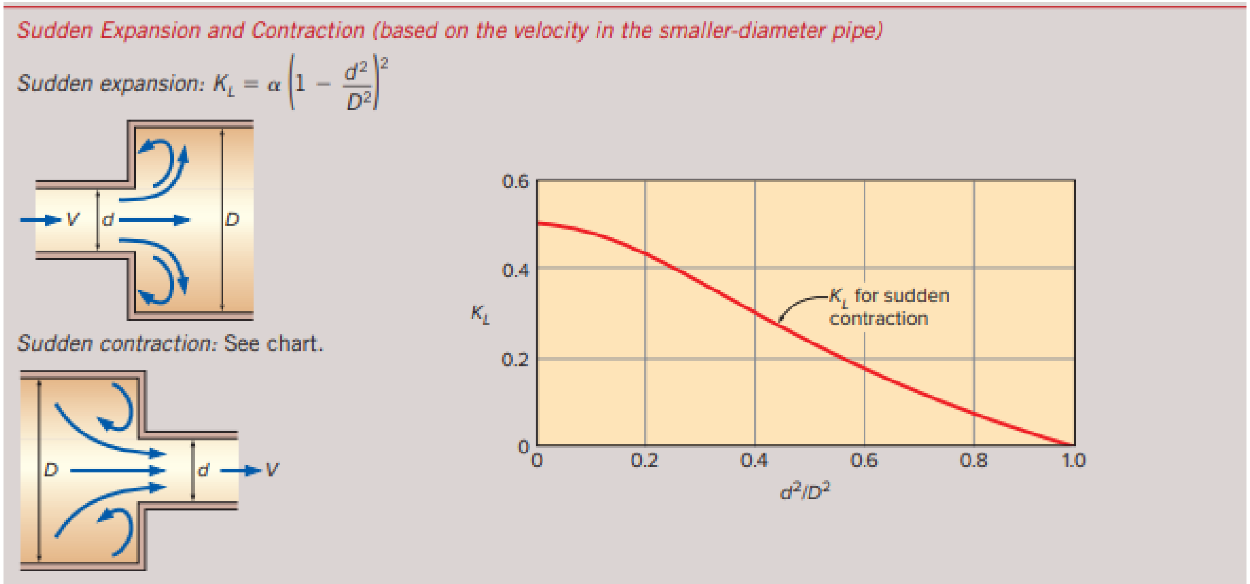
The K_L values for the 90-degree bends, isolation valve, check valve, and tee line flow were determined by referencing the following table. The K_L values shown in the following tables are applicable for any fluid **[13]**.

Table 3. Loss Coefficient Table ***[13]***



The K_L value for the poppet valve was determined from the specifications provided by the manufacturer, Ross Controls. Finally, the expansion and contraction K_L values were found using Table 4 below.

Table 4. Expansion and Contraction K_L Values ***[13]***



Contraction K_L Value:

$$d = 2.5\ in$$

$$D = 4\ in$$

$$\frac{\boldsymbol{d^2}}{\boldsymbol{D^2}} = \mathbf{0.39} \qquad \textbf{(1)}$$

Now the chart above in Table 4 can be used to determine the contraction K_L value.

$$K_L = 0.3$$

Expansion K_L Value:

$$d = 2.5\ in$$

$$D = 4\ in$$

$$\alpha = 1.05\ (turbulent\ flow\ assumed)$$

$$\boldsymbol{K_L = \alpha\left(1 - \frac{d^2}{D^2}\right)^2 = 0.39} \qquad \textbf{(2)}$$

In order to determine K_L value for the expansion, turbulent flow was assumed due to the velocity of the air discussed in Section 4.3.2 **[13]**.

Transient Air Transfer Model results:

The graph below shows the time required for the two tanks in the model to reach an equilibrium pressure. The equations used to develop this graph are shown in Appendix E. This equilibrium is reached at a pressure of 40 psig and takes approximately 0.115 seconds to complete. Once the equilibrium has been achieved, the actuation valve, or poppet valve, will be opened in order to evacuate the air remaining inside the system.

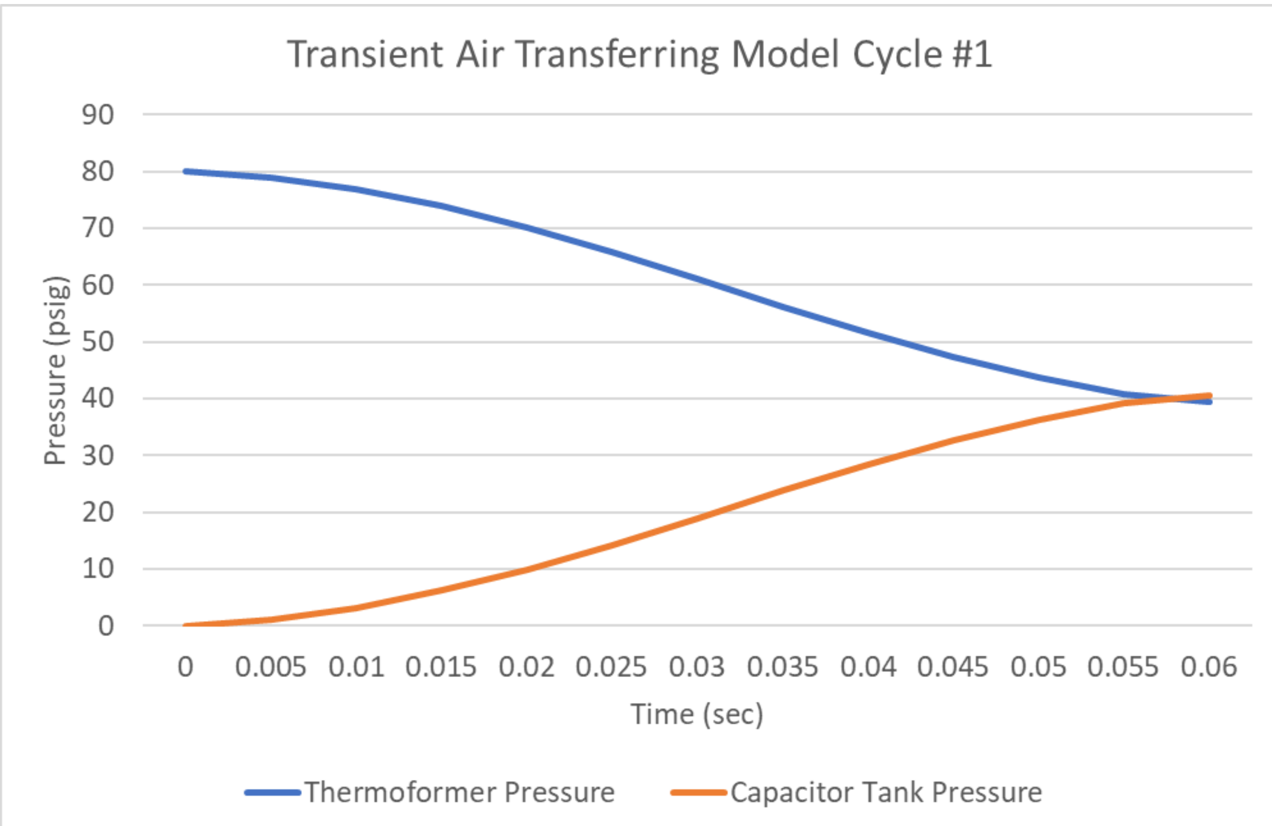


Figure 17. Transient Air Transferring Graph Cycle #1

Figure 17 shows what pressure the captured air will be stored in the capacitor tank during the first 4.7 second cycle. This first cycle will allow the pressure to build inside the capacitor tank before the in-line compressor is activated. After the first cycle, the pressure inside the capacitor tank will be at 40 psig as shown in Figure 17. Once the second cycle begins, the pressure inside the capacitor tank will begin to increase once the captured compressed air from the second overall cycle enters the capacitor tank. After this step, the compressor will run continuously, and the air pressure inside the capacitor tank will fluctuate from 60 psig to 40 psig, shown in Table 5, throughout each 4.7 second cycle. This fluctuation is due to the air being drawn out of the capacitor tank by the in-line compressor. The capacitor tank will provide a steady flow of air to the in-line compressor to eliminate the need for the compressor to continuously turn on and off when air is available. By considering the cost of recompression, it was determined that capturing the mass of air until the pressure drops to 60 psig would result in optimal cost savings as shown in Appendix G.

Table 5. Startup to Steady State

Cycle	Capacitor Tank (psig)	In-Line Compressor
0	0	Not Operating
1	40	Not Operating
2	40-60	Operating
∞	40-60	Operating

Table 5 shows how the delayed startup of the compressor will allow the pressure to reach the operating pressure before kicking on. A pressure sensor will provide readings between the capacitor tank and the in-line compressor that will transmit to a PLC controller to indicate when the in-line compressor can begin operation. This is discussed in more detail in Section 4.3.3. Figure 18 is the graph for the transient air transferring for the second cycle and all the cycles following.

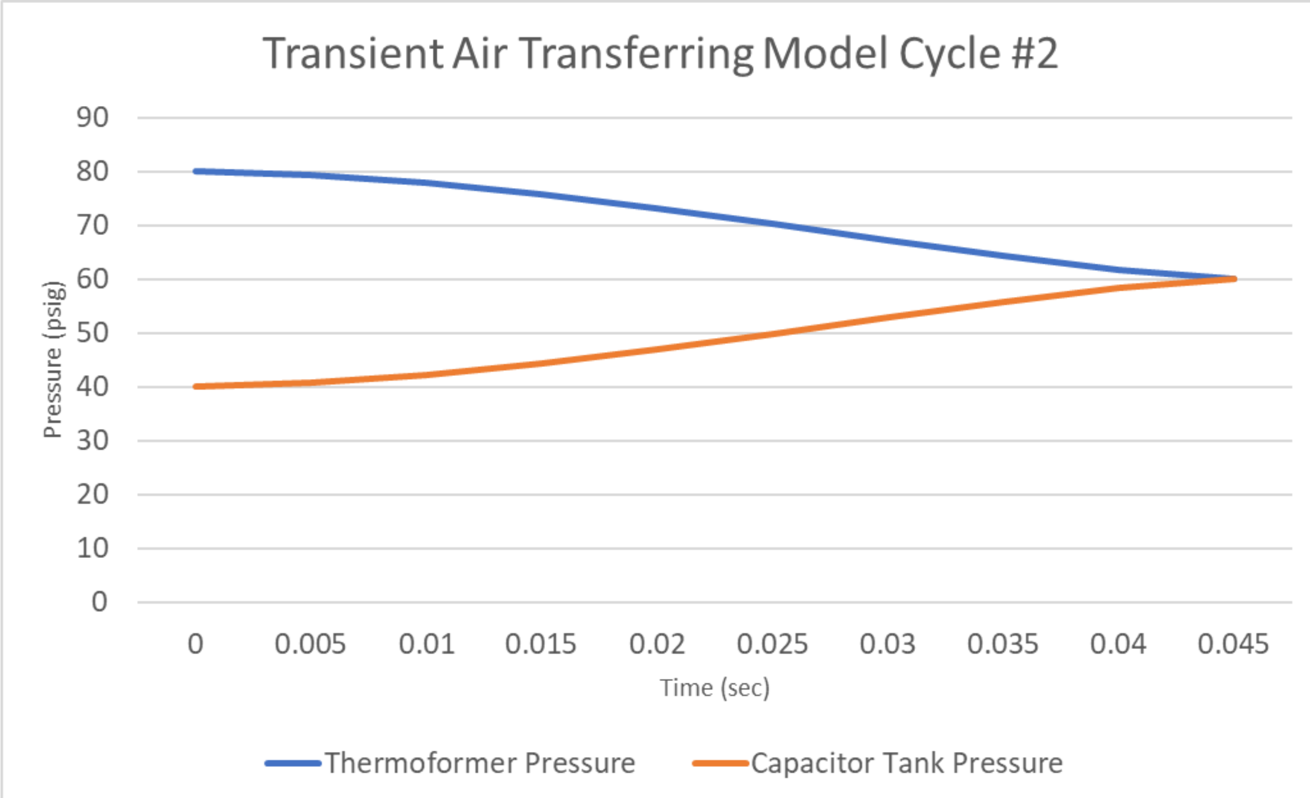


Figure 18: Transient Air Transferring Graph Cycle #2

After the air pressure has equalized, the remaining air will be exhausted to the atmosphere through the actuation valve. Table 6 below shows how the loss coefficient for the air exhausting system was determined. The location of all the loss coefficients shown in Table 6 can be seen in Appendix D. It is necessary to consider many of the same loss coefficients considered in the air transferring subsystem since the air will have to pass through this subsystem before it is exhausted.

Table 6. K_L Values for Air Exhaust Subsystem

Description	K_L Value
90 Degree Bends (3)	3.3
2.5” Poppet Valve (Actuation Valve) (2)	6.0
Tee Line Branch	2.0
Contraction (2)	0.6
Expansion (2)	0.78
Total	**12.68**

The overall loss coefficient was determined for the air exhausting subsystem in the same way as the air transferring subsystem.

Figure 19 shows the time necessary to exhaust the remaining air inside the thermoformer after the air capturing is complete.

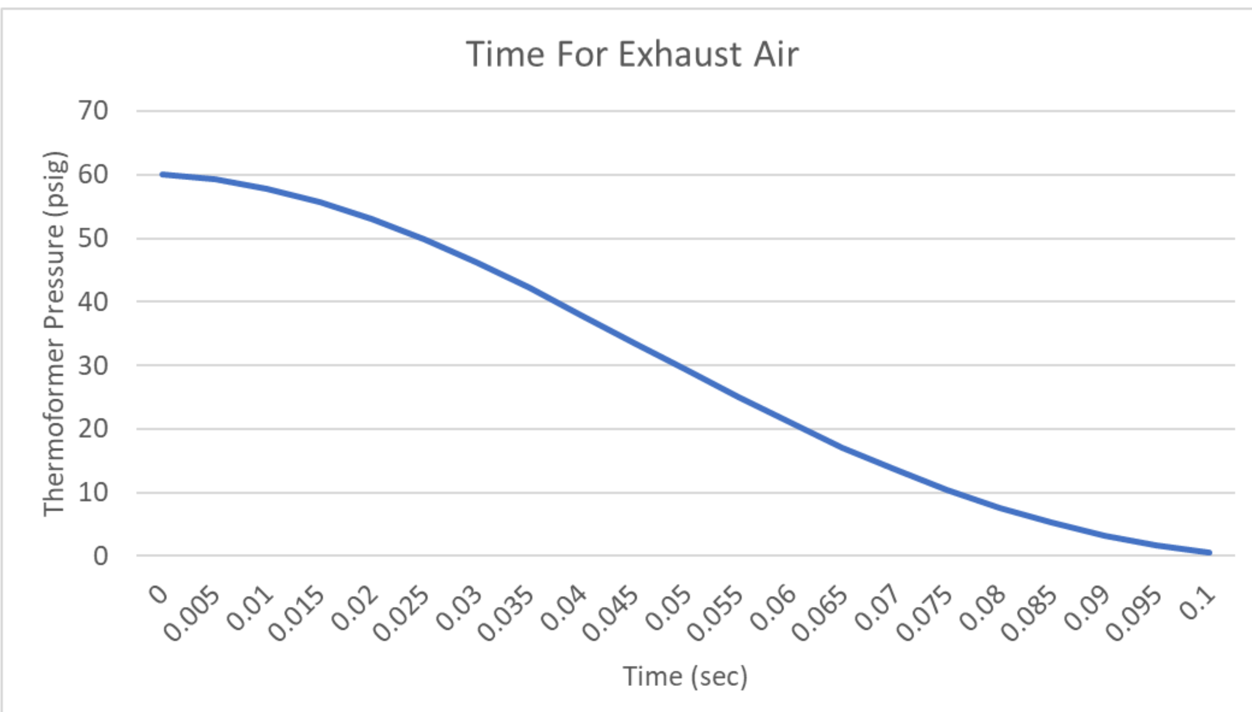


Figure 19. Transient Air Exhaust Time

It is important for the air pressure to be below 10 psig before the dies reopen at 4.7 seconds per the specifications provided by Berry Global **[11]**. Figure 19 shows that the necessary time to reach 10 psig is 0.08 seconds. By compiling all these times together, the timeline below was developed.

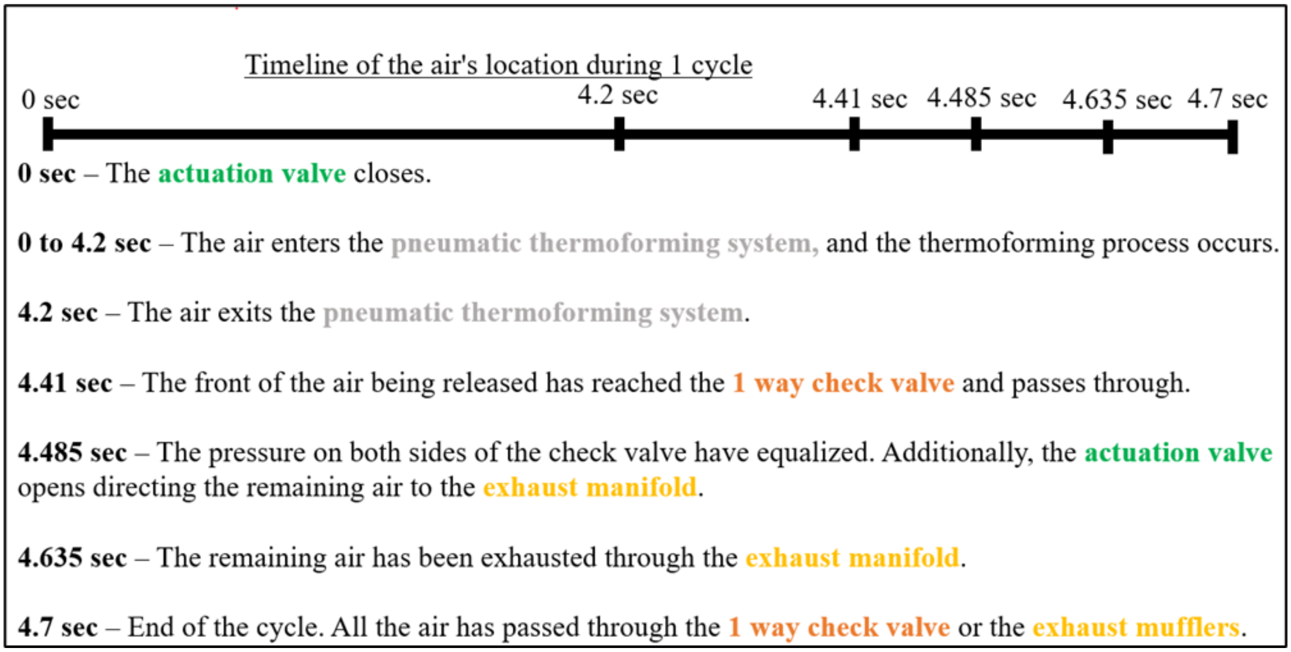


Figure 11. Concept of operations ***(Previously Shown)***

4.3.2 Front of Air Travel Time

In order to determine when the air will initially reach the check valve, the distance through the piping from the thermoformer to the check valve was estimated to be 20 feet as shown in the Figure 20 below. The exact distance is unknown as it was not provided by Berry Global.

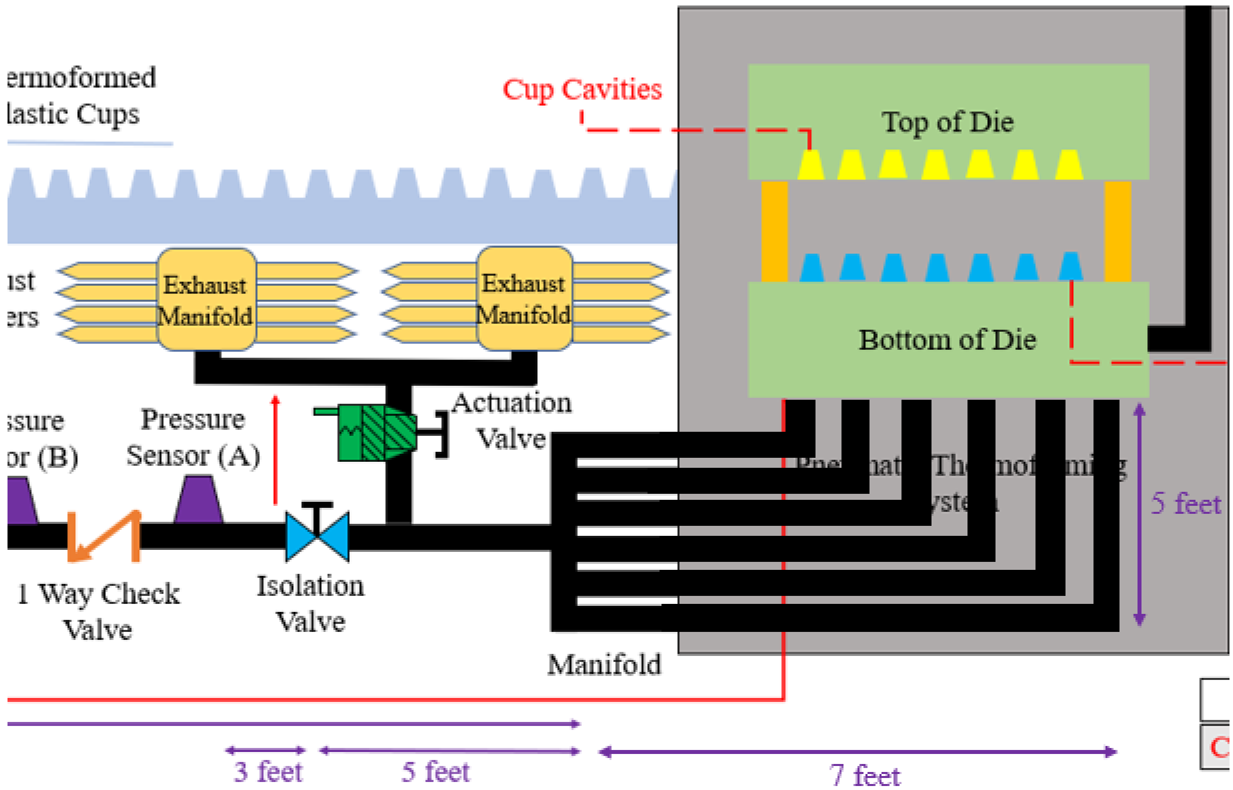


Figure 20. Piping Distance from Die Exit to Check Valve

Before the time for the air to reach the check valve could be calculated, the velocity of the air needed to be calculated. The equation below was derived and explained more thoroughly in Appendix E. This equation was used to calculate the velocity of the front of the air exiting the thermoformer. The worst case scenario was assumed, meaning the pressure differential value was considered to be 20 psig. This is due to the fact that this is the smallest potential pressure differential that could occur within the system. In the equation below, the density of dry air was considered at 80 psig and 70 degrees Fahrenheit.

$$V_{air} = \sqrt{\frac{2\Delta P}{\rho K_L}}$$

$$V_{air} = \sqrt{\frac{2 * 137900 \frac{N}{m^2}}{7.592 \frac{kg}{m^3} * 10.09}} = 57.71 \frac{m}{s} * \frac{3.281\ ft}{1\ m} = 189.3\ ft/s$$

By using the distance of 20 feet and the velocity of the air leaving the thermoformer calculated from the flow rate, the time necessary for the front of the air to reach the check valve was determined.

$$Velocity\ of\ air = V_{air} = 189.3\ ft/s$$

$$Length\ of\ piping = L_{pipe} = 20\ ft$$

$$\boldsymbol{Time\ for\ front\ of\ air\ to\ reach\ check\ valve = T_{check\ valve} = \frac{L_{pipe}}{V_{air}} = 0.105\ sec} \qquad \textbf{(3)}$$

This time was then doubled to account for any uncertainty in the length of piping, so the time used for the air to reach the check valve is 0.21 seconds.

4.3.3 Developing PLC & Pressure Sensor Performance

To create a system that will operate autonomously and concurrently with the thermoformer, one PLC controller will be added which will be responsible for transferring signals using three pressure sensors throughout the recycling system. In Figure 21, the PLC controllers are represented by PLC Controller A and PLC Controller B. PLC Controller A is already in use for the current thermoforming system and is responsible for signaling the thermoformer to open and close. In the recycling system, when PLC Controller A signals for the dies to close together, the signal will also be sent to the actuation valve to begin the programing logic at the start of each new cycle.

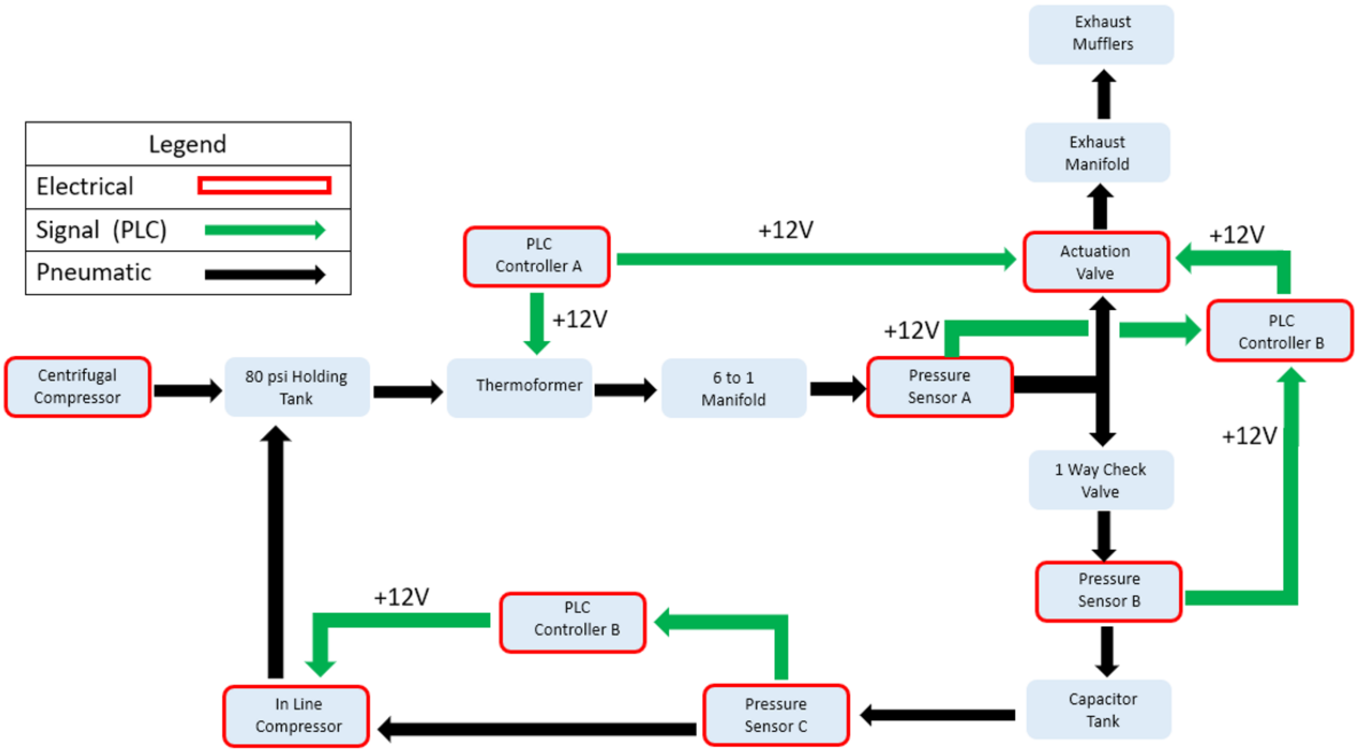


Figure 21. Functional Block Diagram

PLC Controller B will receive signals from Pressure Sensors A, B, and C. It will then analyze and translate the signals to command the actuation valve and in-line compressor. The pressure sensors can be referenced in Figure 22.

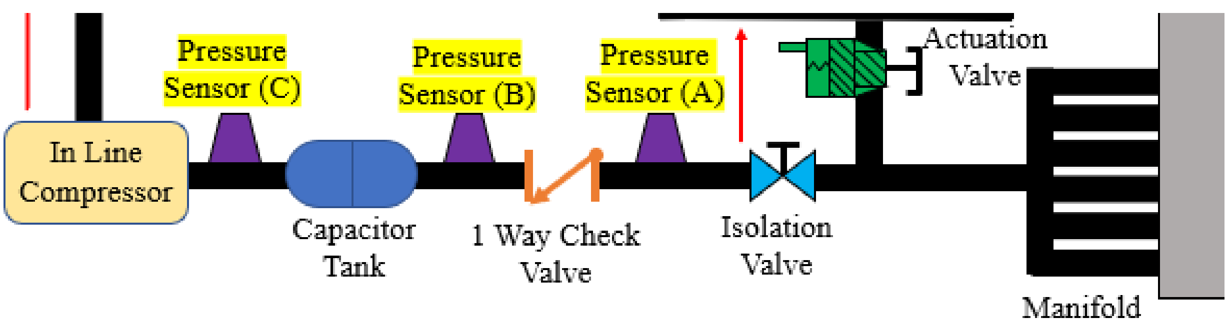


Figure 22. Pressure Sensors A, B, and C

The primary functions of each pressure sensor are detailed in Table 7. Pressure sensors A and B will work collectively to monitor the pressure on both sides of the check valve as compressed air is transferred through the system. When this pressure equalizes, PLC Controller B will then transfer the signal to the actuation valve which will open and release the residual air to the atmosphere. Additionally, pressure sensor B will act as a safety precaution to eliminate the issue of pressure building up in the recycling system. If the pressure were ever to exceed a set limit of 100 psig, PLC Controller B will signal the actuation valve to open. It will remain open to allow for the system to revert to what is currently being done by exhausting all the air to the atmosphere. To control the actuation valve throughout each cycle, a PLC programming flowchart was developed and can be seen in Appendix F along with a detailed explanation of the of the flowchart.

Table 7. Pressure Sensor Purposes

Pressure Sensor	**Purpose**
A	• When there is equalizing pressure
B	• Emergency release to atmosphere • When there is equalizing pressure
C	• When the in-line compressor can begin operating

To begin operation for the in-line compressor, pressure sensor C will transmit its pressure reading to PLC Controller B for the first two beginning cycles of operation. During this, the in-line compressor will remain in the non-operational state until the pressure reaches a level of 50 psig to realize maximum savings, which should happen during the second cycle. Once this point has been reached, the in-line compressor will now turn on and remain in the operational state for all the cycles following. Once the cycle has reached the steady state of operation, pressure sensors A and B now play a key role of sending pressure readings to the PLC Controller B which decide if the compressed air travels to the atmosphere or through the recycling system. Table 8 below can be referenced to understand this process.

Table 8. In-Line Compressor Operation & Sensors Reading

Cycle	Pressure Sensor	Capacitor Tank	In Line Compressor
0	C	0 psig	Not Operating
1	C	40 psig	Not Operating
2	C	40-60 psig	Operating
∞	A, B	40-60 psig	Operating

4.3.4 In-Line Compressor Power

In order to determine the required power to recompress the captured air, the equation below was used **[14]**.

$$k = adiabatic\ expansion\ coefficient, (1.41)$$

$$P_1 = Initial\ Abolute\ Pressure\ (64.7\ psi\ absolute)$$

$$P_2 = Desired\ Absolute\ Pressure\ (94.7\ psi\ absolute)$$

$$\dot{V}_{inline} = Volumetric\ Flow\ Rate\ (52.2\ cfm)$$

[14]
$$\boldsymbol{HP = \left(\frac{144 P_1 \dot{V}_{inline} k}{33000(k-1)}\right)\left(\left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} - 1\right)} \quad (4)$$

From this equation, the horsepower necessary to recompress the air back to 80 psig can be determined. Using this equation along with the current cost of producing compressed air, the graph below was created. The equations used to develop the graph in Figure 23 are shown in Appendix G.

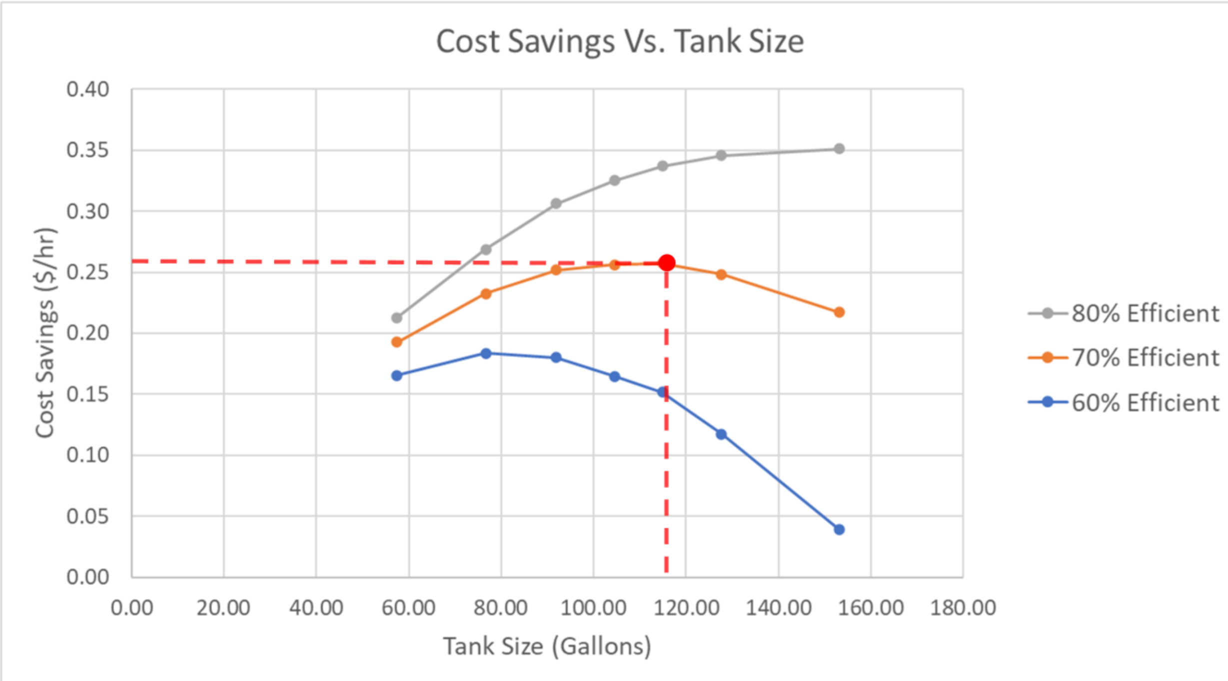


Figure 23. Cost Savings Vs. Capacitor Tank Size

The graph above shows the cost savings compared to the volume of the capacitor tank which is used to capture the air. Each separate curve on the graph represents a different efficiency value for the compressor. The compressor selected for this application has an efficiency of 0.7 so the orange curve was used to determine the tank size. Using this analysis, the optimal tank size was determined to be approximately 115 gallons.

4.4 System Model Functionality

The complete system design was animated using PowerPoint by considering the known air location at different time intervals to depict the compressed air movement throughout each subsystem. While the designed system will operate using pressure readings, the animation uses time to differentiate the air location at each critical step of the process. Snapshots of this animation can be seen in Appendix H.

5 COMPONENT SELECTION AND JUSTIFICATION

5.1 Pneumatic Lines

With the addition of the compressed air recycling system to the thermoformer, additional pneumatic lines would need to be installed to both the existing pieces and within the new system.

After discussion with Berry Global, it was decided that the specifications of the pneumatic lines would remain the same as what is currently in place on Thermoformer Line 18 **[11]**. Currently, the thermoformer features areas of hard pipe as well as sections of flexible tubing. The team determined the sections that would be best suited for both materials. Polyethylene flexible tubing would be used to connect the exhaust lines to the 6 to 1 manifold. This will allow the existing tubing to be easily run from the thermoformer to the manifold and not interfere with the dies opening and closing. Stainless steel hard piping would be utilized between the 6 to 1 manifold and the actuation and isolation valves. Additionally, hard pipe would be used to connect the exhaust manifolds, the check valve, and the capacitor tank. Finally, a hard pipe would connect the capacitor tank to the in-line compressor then the pipe would connect back to the holding tank on the top of the thermoformer.

5.2 6 TO 1 REDUCTION MANIFOLD

The first step in the manifold design was to determine the requirements for this component. It was decided that the manifold shall be able to withstand 80 psig internal pressure with a safety factor of 4. This factor of safety is common among pressure vessel designs. Inspiration was then pulled from common manifolds existing in various applications and SOLIDWORKS models were developed from them. The 3D CAD designs can be seen in the Figure 24 below. The name of each manifold, from left to right, is as follows; 3x3 manifold, combining manifold, and 6x1 manifold.

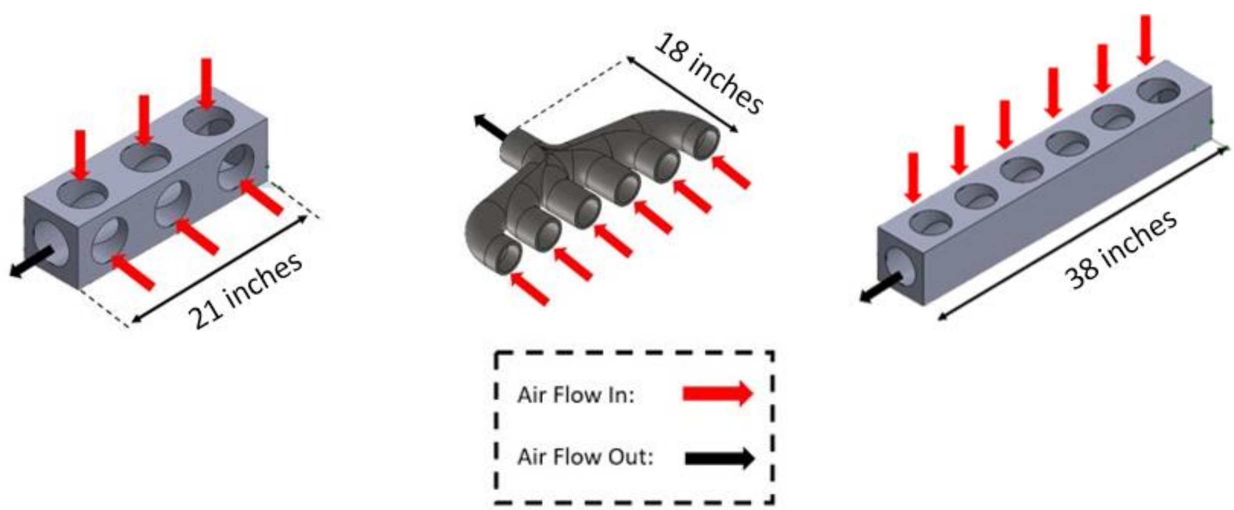


Figure 24. Manifold SolidWorks Designs

The design options were then analyzed using a computational fluid dynamics tool within SOLIDWORKS called “SOLIDWORKS Flow Simulation”. This software was utilized to observe any possible areas for concern with regards to the flow of the compressed air through the manifold, more specifically, recirculation zones. A recirculation zone is an area where fluid will separate from the main flow zone and move in a circular pattern instead of traveling through the pipe. This will be problematic when the top and bottom dies reopen, which eliminates the airtight seal and reintroduces the system to the atmosphere. The compressed air stuck in the recirculation zone would then travel back through the manifold and out of the bottom die, potentially damaging the seal on the thermoformer. It would also result in less compressed air capable of being recycled, therefore hindering the potential cost savings. The manifold design that contained a recirculation zone can be seen in the image below. Please note the flow trajectory arrows within the yellow circle indicating the recirculation zone. The flow simulation results for the other two manifold designs can be seen in Appendix I. Additionally, the flow simulation parameters for all of the manifold designs can be accessed in their respective SOLIDWORKS files on the flash drive.

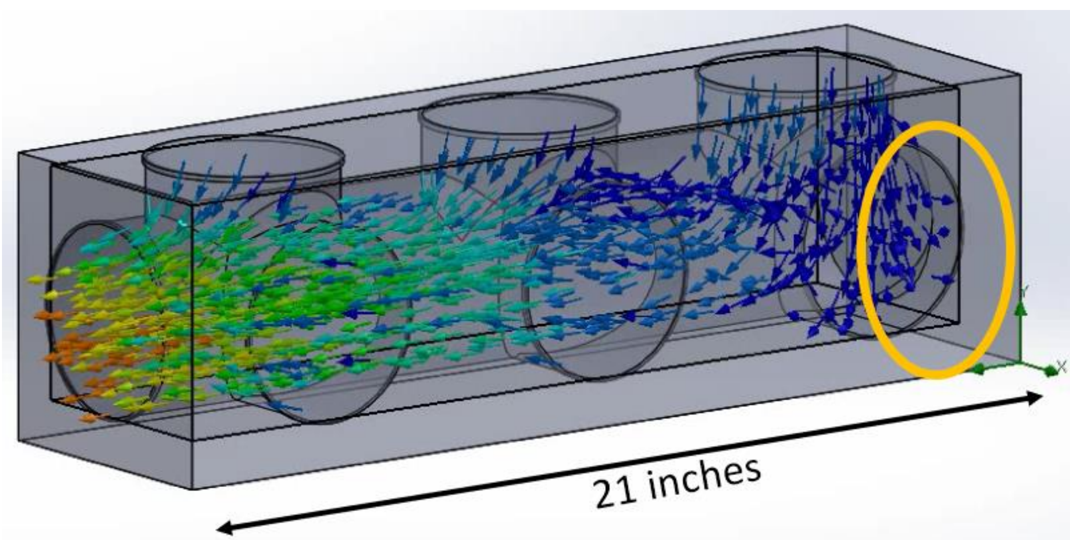


Figure 25. 3x3 Manifold Flow Simulation Result

The remaining two manifold designs were then compared by considering available space in the facility, overall manifold dimensions, total compressed air travel distance through each manifold, and manufacturability of the designs. It was determined that the combining manifold would be the design analyzed further, largely because it featured a shorter air travel distance. The combining manifold's travel distance was 30.7 inches, whereas the 6x1 manifold possessed a travel distance of 38 inches. This shorter distance resulted in a 20% faster air transfer time through the manifold. Considering the total exhaust time of 0.5 seconds, this 20% time savings is significant.

It was determined that 304 stainless steel would be the best material choice for the combining manifold, due to the need for high strength and corrosion resistance. The materials and their properties considered can be seen in the table below. Please note that all material properties were retrieved from MatWeb **[15]**.

Table 9. Manifold Material Considerations

Material	Density (lbm/in^3)	Yield Strength (kpsi)	Ultimate Strength (kpsi)	Cost ($ per lb)	Corrosion Resistance
Aluminum 6061	0.098	14.9	33.1	0.30	Low
Steel 1020	0.284	50.8	60.9	1.00	Low
Stainless 304	0.289	31.2	73.2	1.25	High
Stainless 316	0.289	60.2	89.9	1.45	High

While 6061 is corrosion resistant to some elements, the longevity of the material was concerning, considering the constant flow of water vapor within the compressed air traveling through the manifold. Additionally, the ultimate strength of the material was not sufficient to withstand the internal 80 psig pressure with a safety factor of 4. The 1020 steel contained a good ultimate strength, but would corrode over time from the water vapor within the compressed air. Both the 304 and 316 stainless steels possess sufficient ultimate strength to withstand the required internal pressure, and they both are highly corrosion resistant. However, 316 is more costly than 304, resulting in the final decision of 304 stainless steel.

Next, the minimum wall thickness of the manifold was determined using SOLIDWORKS Finite Element Analysis and common pipe schedule thickness. The pipe schedule table that was utilized can be seen in Table 10 below.

Table 10. Pipe Schedules ***[16]***

Nom.	O.D. Inches	PIPE SCHEDULES WALL THICKNESS (Inches)							
		5s	5	10s	10	20	30	40s & Std	40
4	4.500	.083	.083	.120	.120			.237	.237

Nom.	O.D. Inches	PIPE SCHEDULES WALL THICKNESS (Inches)							
		60	80s & E.H.	80	100	120	140	160	Dbl. E.H. (XXH)
4	4.500	.281	.337	.337		.437		.531	.674

The FEA was carried out beginning with the schedule 10 wall thickness and iterated until the manifold would not yield with an internal pressure of 320 psig, which is 80 psig multiplied by a safety factor of 4. Additionally, a 500 lb. vertical, downward force was added to the FEA as a precautionary measure to assure the manifold could withstand a large external force such as a heavy object falling on the component. The iterations showed a minimum of schedule 40 should be used for the manifold, as the material's yield strength of 30,000 psi was greater than the Von Mises stress of 20,630 psi. For a nominal diameter of 4 inches, this corresponds to a wall thickness of 0.237 inches. The FEA results can be seen in Figure 26. Please note the reversed vertical coordinate, which was a necessary step in order to view and analyze the stresses on the interior of the structure. Additionally, the FEA parameters can be accessed in the "Combining Manifold" file on the flash drive.

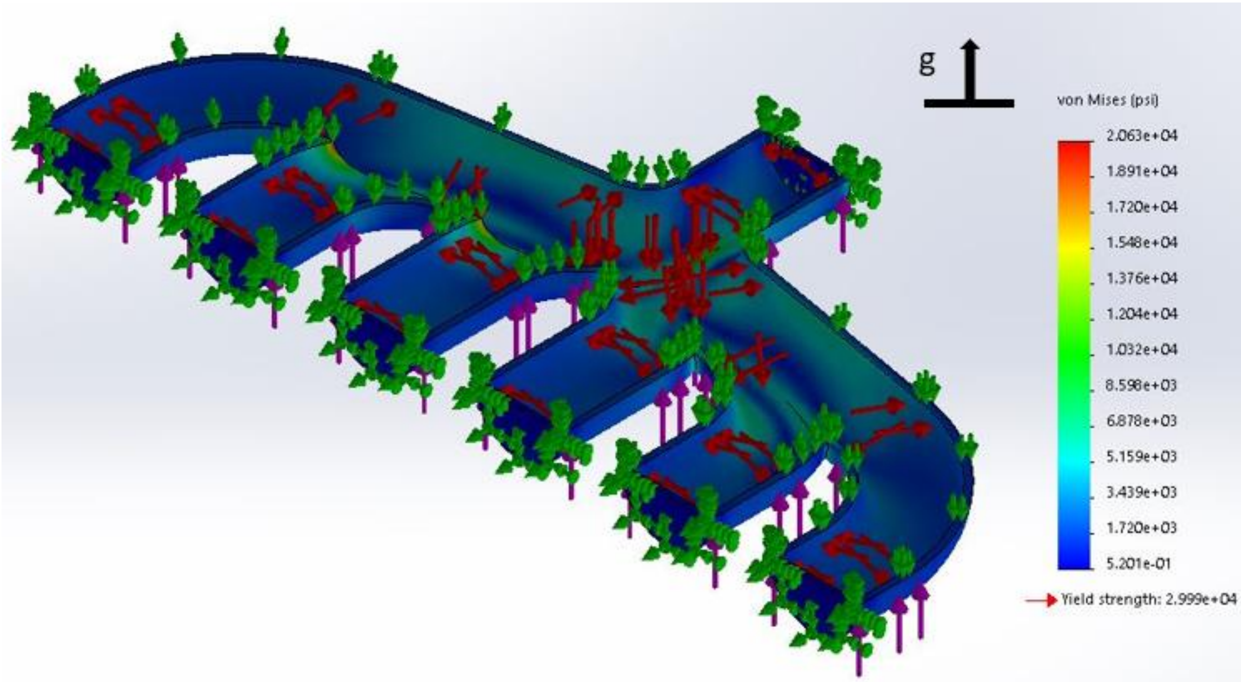


Figure 26. Manifold Yielding FEA Results

Lastly, a calculation was performed to assure the manifold would not fail in fatigue. Given that the 500 lb vertical force would only occur intermittently, if ever, the FEA was adjusted so that it was not accounted for. Because of this, the Von Mises stress was changed from 20,630 psi to 20,820 psi. From here, the fatigue calculation was carried out and can be seen in Appendix J. Because the safety factor, η_f, is greater than 1, it is known that the manifold will not fail in fatigue.

5.3 VALVES

5.3.1 Isolation Valve

It was decided that the system required a method to manually isolate the recycling system from the thermoformer. This will provide the thermoformer the capability of operating even if the recycling system was not running. After deliberation, it was determined that a manual shut off valve was the most effective way to achieve this. This valve will serve as the Lockout/Tagout component to allow maintenance to be performed on the compressed air recycling system without the need of shutting down the entire thermoforming line. A Lockout/Tagout component is the part of a system that allows for the control of hazardous energy. Because there is a large volume of air travelling through the system at high speeds, it poses a risk to anyone attempting to perform maintenance on components downstream. Installing a manual valve will allow a Lockout/Tagout procedure to be implemented which will assure that maintenance can be safely performed on the air recycling system. When the valve is closed, the exhaust system will function in the manner that it currently is, with all the compressed air being expelled to the atmosphere.

After much research, it was determined that a manual gate valve would be an effective method of isolating the recycling system. The valve, sourced from Grainger, features a maximum working pressure of 300 psig, which is well above the threshold of pressure that the valve will undergo. The valve also features a large hand wheel which allows for easy opening and closing of the valve when necessary. The sourced isolation valve can be seen in Figure 27.

Figure 27. Isolation Valve - Nibco Gate Valve

5.3.2 One-Way Check Valve

In order for the optimal amount of air to be autonomously recycled, the team determined that a one-way check valve would be appropriate. It was necessary for the check valve to feature a low cracking pressure and a durable seal to assure that it can withstand constant utilization. After discussion with Berry Global regarding check valves previously tested in similar applications within the facility, the team decided that durability and backpressure prevention were key requirements **[11]**.

Upon significant investigation, it was decided that a dual disc check valve would be the best option due to its resilience and backflow aversion ability. A dual disc wafer type check valve was sourced for this system. This valve features a carbon steel body, stainless steel disc, and a Viton seal, which all make the valve extremely durable. Additionally, the valve features a maximum operating pressure of 275 psig and a cracking pressure of only ¼ psi. The low cracking pressure will assist in maximizing the amount of compressed air that passes through the valve. Lastly, this valve features shock bumpers that reduce deterioration of the valve overtime. The selected one-way check valve can be seen in Figure 28.

Figure 28. One-Way Check Valve – Titan Flow Control Dual Disc Wafer Type Check Valve

5.3.3 Actuation Valve

Arguably the most critical component in the system, the actuation valve was also sourced. This valve plays a major role in eliminating backpressure by exhausting to the atmosphere the remaining air in the system before the dies reopen. Because of the quick exhaust time of only 0.5 seconds, a fast actuation time is critical for this valve. The team conferred with Berry Global to source a valve, as the facility currently uses actuation valves in various applications, including on Thermoformer Line 18. It was recommended that the actuation valve in the compressed air recycling system remain consistent with the ones already in use **[11]**. Because of this suggestion, a previously designed custom poppet valve was chosen.

The selected poppet valve features a maximum operating pressure of 145 psig, which is almost two times higher than the expected pressure of 80 psig. Additionally, the actuation time of the poppet valve is 20 milliseconds, or 0.02 seconds. This is an extremely quick actuation time and will be sufficient for the compressed air recycling system. This valve features inlet and outlet diameters of 2.5 inches, which will require a pipe reduction to and from the valve and was accounted for in all necessary calculations. The selected actuation valve can be seen in Figure 29.

Figure 29. Actuation Valve – Ross Controls 2.5" High Speed Poppet Valve

5.4 EXHAUST MANIFOLDS AND MUFFLERS

When designing the exhaust manifolds, several factors were considered. The current manifolds that Berry Global use are capable of exhausting 100% of the compressed air to the atmosphere. It is a requirement for the design of the exhaust manifolds to be able to exhaust 100% of the air if the recycling system were not in operation for any reason. An additional requirement for this component is to be able to maintain or reduce the compressed air to muffler ratio that is currently used. The term "compressed air to muffler ratio" refers to the volume of air being exhausted per muffler. This is directly related to the noise level, in decibels (dB), that the system produces in the plant. As the volume of air going through each muffler increases, the noise level would also increase. This is an important concept to note to reduce the risk of harm to operators or other workers that are in the vicinity. The current noise level of the compressed air being exhausted to the atmosphere is at 95 decibels, per Berry Global **[11]**. Appendix K references how a rise in noise level can quickly increase the possibility of irreversible harm on an individual.

The structural design has been modeled after the current manifolds that feature 3 inlets and 6 outlets and are used to exhaust the air in the system. The compressed air entering these manifolds will now be traveling through one line instead of three. In order to not increase the noise level, two additional exiting lines and mufflers were used. These additions result in the exhausting manifolds being 1 to 8 expansion manifolds. Because it is already a requirement to wear hearing protection within the facility and reducing the current compressed air to muffler ratio, the air recycling system will be in compliance with OSHA noise exposure standard 1910.95 **[8]**. To reduce the possibility of back pressure occurring, the velocity and time for the air to exit the manifold is an important characteristic to its proper functionality. To ensure the exhausting manifold can transfer and disperse the compressed air in the needed time, SOLIDWORKS Flow Simulation was utilized to represent the velocity of the medium. The flow simulation parameters for this manifold can be accessed in the SOLIDWORKS file "4x4 Pneumatic Manifold." This is represented in Figure 30. The maximum velocity recorded from the flow simulation entering the exhausting manifold was 133.75 ft/s which is a transient value that will decrease as the compressed air leaves the system. By the time the air reaches the 8 exiting locations, the velocity within the simulation reaches 0 ft/s. This occurs as the compressed air is introduced to the atmosphere through the exhaust mufflers. The manifold flow simulation without the mufflers can be seen in Figure 30. *Exhaust Manifold - SOLIDWORKS Flow Simulation for Air Velocity* below.

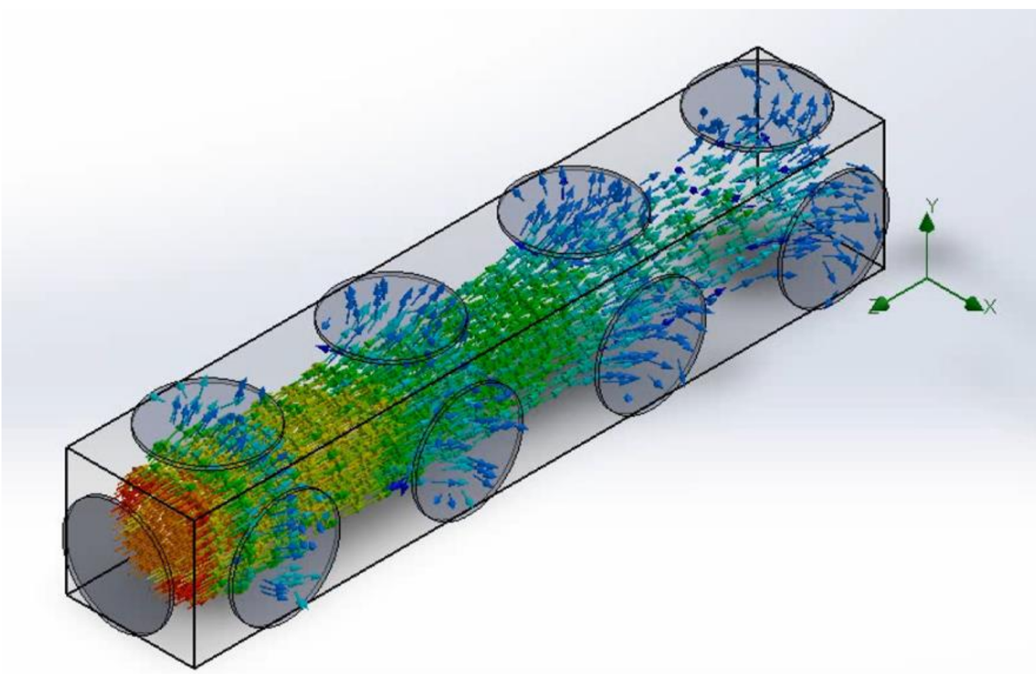


Figure 30. Exhaust Manifold - SOLIDWORKS Flow Simulation for Air Velocity

As a complete assembly, the exhausting manifold with the mufflers attached can be seen in Figure 31. The manifold was chosen to be manufactured out of 304 stainless steel to remain consistent with Berry Global's current manifolds. Additionally, 304 stainless steel was selected due to its high strength and corrosion resistance. The mufflers that are currently in use can be disassembled from the existing manifolds and reused for the exhausting manifolds in the new system. This will reduce installation costs and support a shorter return on investment time.

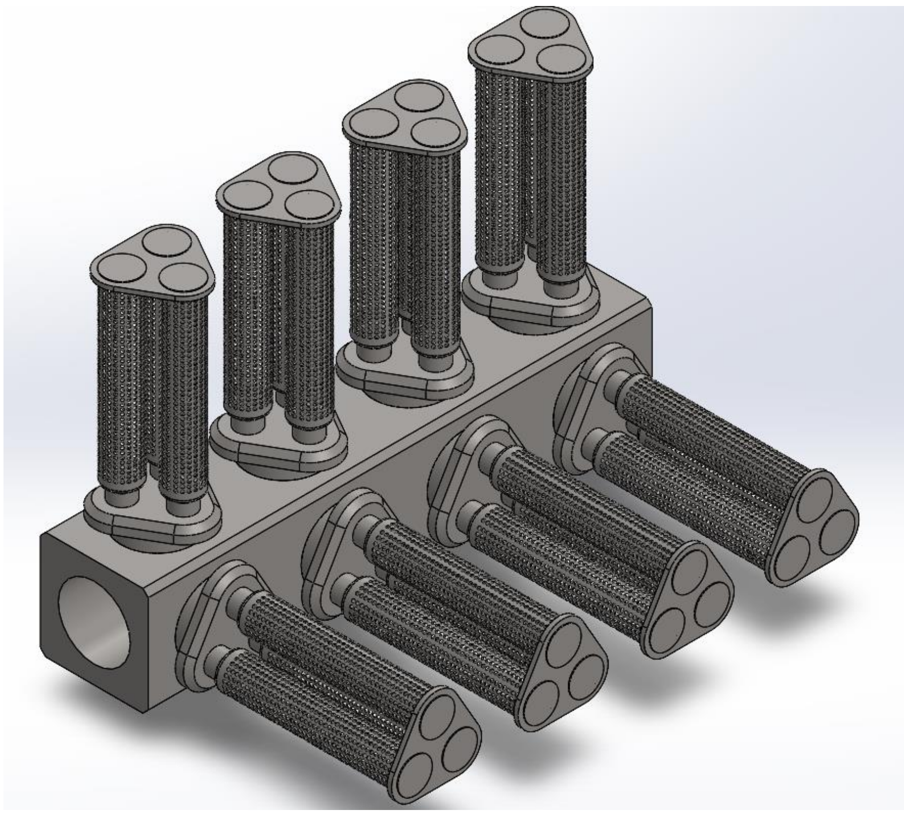


Figure 31. Exhaust Manifold and Mufflers – 1 to 8 Expansion

5.5 PRESSURE SENSORS & PLC CONTROLLER

In order for the system to operate autonomously, the team determined that installing pressure sensors would sufficiently perform the necessary functions. The pressure sensors would need to operate from atmospheric pressure to at least 100 psig. Additionally, given the rate of exhaust within the system of only 0.5 seconds, accuracy and response time of the sensors are critical.

After significant research, the team decided on a Honeywell pressure sensor. This device can operate from 0 to 750 psig, which covers the necessary pressure range for the system. Also, it features an accuracy of 0.25%, which correlates to a maximum pressure differential of +/- 0.2 psig and is insignificant. Lastly, the sensor yields a maximum response time of 2 milliseconds, or 0.002 seconds. This response time is extremely quick, assuring that there will be no delay in pressure readings within the system. The selected pressure sensor can be seen in Figure 32.

Figure 32. Honeywell PX2EN1XX750PSBGX Pressure Sensor

For the pressure sensors to communicate with the actuation valve and compressor, a PLC controller system was necessary. Ideally, the same model of PLC that is currently in place on the thermoformer line will be used for the air recycling system. However, Berry did not provide the exact make and model of the current PLC controller. Because of this, a new PLC controller was sourced for the air recycling system. The PLC controller required a minimum of three inputs for each of the pressure sensors being connected. Given the short exhaust time of 0.5 seconds, a fast data transfer rate was also very critical for the system. The team decided to select the Allen Bradley 5069-L306ERM PLC Controller for the compressed air recycling system. This PLC features 16 inputs and a data transfer rate of 128,000 packets per second. Both of these specifications will be sufficient for the requirements. The selected PLC can be seen in Figure 33.

Figure 33. Allen Bradley 5069-L306ERM PLC Controller System

5.6 CAPACITOR TANK

The process for determining the specifications for the capacitor tank are explained in detail in Section 4.3.4. The optimal size for the capacitor tank was determined to be approximately 115 gallons. The closest tank size that was commercially available had a volume of 120 gallons. The selected tank also has a maximum operating pressure of 200 psig which means that it would easily be able to withstand the pressures that it would experience under normal operation. This tank also has an inlet and an outlet diameter of 2 inches which would allow the connection of the pneumatic lines between the components. The capacitor tank chosen is made by Atlas Copco and is shown in Figure 34.

Figure 34. Atlas Copco LV120-200 Vertical Air Receiver

5.7 IN-LINE COMPRESSOR

The in-line compressor is responsible for boosting the pressure of the captured air back to 80 psig before it can be reused in the thermoforming process. It is crucial that this compressor is able to operate continuously so that it is constantly supplying a steady flow of pressurized air through the outlet. The methods used to determine compressor power and flow rate specifications were described in detail in section 4.3.4. The necessary power for the compressor was determined to be approximately 6 horsepower. The flow rate necessary to provide a steady flow of 80 psig air leaving the compressor was determined to be 53 cfm at 80 psig.

Figure 35. Atlas Copco GA7 Variable Speed Rotary Screw Air Compressor with Dryer

Taking all of the power, flow rate, and functional requirements into account, the compressor pictured in Figure 35 above was chosen. The selected compressor has 10 horsepower and is capable of producing 67.6 cfm of air flow at 80 psig. This compressor is also a variable speed compressor meaning that it can operate at different air flow rates. The variable speed function allows the compressor to have a greater efficiency at different flow rates. This will aid in assuring the stream of air leaving the compressor is consistent throughout the whole 4.7 second thermoforming cycle. This compressor also features a built in air dryer which will ensure that moisture does not get into the air being returned to the thermoformer. This compressor ensures that the system will comply with ISO8573-3:1999 **[9]**.

6 DISPOSAL PLAN

Once the thermoformer has reached the end of its useful life, Berry Global will look to dispose of the machine and all associated components. Additionally, the compressed air recycling system will need to be removed as well. The disposal plan for the major components within the compressed air recycling system can be seen in Table 11 below.

Table 11. Disposal Plan for Compressed Air Recycling System

Component	If in working condition	If obsolete	Recycle As:
6 to 1 manifold	Sell for Scrap	Sell for Scrap	N/A
Isolation Valve	Re-use within facility	Recycle	Metal
Actuation Valve	Re-use within facility or resell	Recycle	Electronics
1 Way Check Valve	Re-use within facility or resell	Recycle	Metal
Exhaust Manifolds & Mufflers	Re-use within facility	Sell for Scrap	N/A
Capacitor Tank	Re-use within facility or resell	Sell for Scrap	N/A
In-Line Compressor	Re-use within facility or resell	Sell for Scrap	N/A
Pressure Sensors	Re-use within facility	Recycle	Electronics

7 BUDGET

The team developed a budget for the project, shall Berry choose to proceed with the implementation of the compressed air recycling system. The spending limit was set at $75,000, which included parts, P.E. review, and installation costs. The budget can be seen in Table 12.

Table 12. Project Budget

Item	Price
6 to 1 Reduction Manifold	$6,500
4” Check Valve	$1,500
2.5” Poppet Valve	$2,000
4” Manual Gate Valve	$750
1 to 8 Exhaust Manifold (2)	$8,000
4” Pneumatic Tubing (50’)	$750
Rotary Screw Compressor	$15,000
120 Gallon Capacitor Tank	$2,000
Pressure Sensor (3)	$1,500
PLC Controller	$2,500
Couplers, Flanges, Hose Clamps	$500
P.E. Review	$10,000
Installation	$24,000
TOTAL:	**$75,000**

While sourcing components, a more detailed bill of materials was created. The total estimated costs of all the necessary components were determined to be $40,346.61. When factoring in the estimated P.E. review and installation costs, the total costs were found to be $74,346.61, which is just under the $75,000 budget. The complete Bill of Materials can be seen in Appendix L.

8 ECONOMIC ANALYSIS

The results are summarized below in Table 13.

Table 13: Results Summary

Total System Cost	$75,000
Cost Savings Per Year	$2,300
Return on Investment Period	33 Years

In order to determine the viability of this project, an extensive economic analysis was performed. This economic analysis considered the cost of all the components as well as the engineering approval and installation cost. The cost breakdown of the system is shown in detail in Section 7 of the report. A detailed Bill of Materials is also shown in Appendix L.

While the cost of implementation is vital in the economic analysis, another important aspect to consider is the potential cost savings of the system. The potential cost savings of the compressed air recycling system is explained extensively in From this equation, the horsepower necessary to recompress the air back to 80 psig can be determined. Using this equation along with the current cost of producing compressed air, the graph below was created. The equations used to develop the graph in Figure 23 are shown in Appendix G. The most important result from that section, however, is the final cost savings that is determined. The calculations performed show that if this system were implemented, it could save Berry Global approximately $0.26 per hour. When considering that this machine operates 24 hours per day year around, this equates to a yearly savings of nearly $2,300.

Finally, combining the system cost and the potential cost savings of the system, a return on investment period was determined. Using the total startup cost of roughly $75,000 and the yearly cost savings of approximately $2,300, the ROI period was determined to be 32.6 years. This means that the air recycling system is not cost effective to install independently. However, it might be worthwhile to consider implementing this system in the future.

If the cost of energy that Berry pays doubles from $0.10 per kwh to $0.20 per kwh, and there are plans to install a new thermoformer line, then the company may want to consider installing the compressed air recycling system. By installing the recycling system along with a new thermoformer, the P.E. review cost and installation costs can be eliminated, as these are fees that would have to be paid for the thermoformer installation. This would yield an ROI period for the recycling system of approximately 8 years, which would pay for itself within the useful life of a thermoformer at Berry Global of 15 years.

Additionally, Berry Global operates at least 9 other thermoforming lines similar to Thermoformer Line 18, which was investigated in this project **[11]**. It is conceivable that a similar system could be implemented on these other 9 thermoforming lines. Assuming that the air recycling systems for these lines were capable of producing a similar cost savings, this could multiply the cost savings of the system. By using Line TFE 18 as the standard cost savings across the other lines, this could equate to a yearly cost savings of nearly $20,700.

9 FUTURE WORK

The team determined multiple components of the system that could be designed further in order to develop a more complete compressed air recycling system. The recommendations are detailed below.

9.1 IN-LINE COMPRESSOR AIR INTAKE DESIGN

The in-line compressor that was selected for this project operates like most rotary screw compressors, in the sense that they are designed to intake atmospheric air through a large, grated area located on the top or the side of the compressor. Because this system will send partially compressed air into the compressor, the intake will need to be able to fit a 4-inch pneumatic line within an airtight seal. In order to do this, an intake attachment would need to be designed so that the large, grated area is secluded from the atmosphere with an airtight seal and reduces into a 4-inch diameter opening. The airtight seal, presumably comprised of rubber, will assure that the compressor will only intake the partially compressed air being sent to it by the system and will not draw in any atmospheric air. The 4-inch diameter opening on the opposite end will allow the 4-inch compressed air return line to be attached, sending the partially compressed air from the system directly into the in-line compressor air intake.

9.2 RECOMPRESSED AIR HOLDING SYSTEM

Currently, 80 psig compressed air from the centrifugal compressor is sent directly to the existing 80 psig holding tank with a constant flow. Recycling the exhausted air in the manner discussed in this report has the potential to reduce energy costs. A method of collecting the recycled air must be developed so that the centrifugal compressor is no longer providing a constant flow. The team took part in a few preliminary design discussions with Berry Global, but nothing was finalized.

One option to realize the potential energy savings is to install a pressure sensor within the 80 psig holding tank that would control a newly installed actuation valve placed between the tank and the centrifugal compressor. The sensor would determine the internal pressure of the 80 psig holding tank after the recompressed air has entered the tank. It would then signal the actuation valve to open, allowing the centrifugal compressor to complete the refill process of the 80 psig holding tank. Once the appropriate pressure is achieved, the sensor would then signal the actuation valve to close again, prohibiting any additional compressed air to be delivered from the centrifugal compressor. Doing this would assure that the centrifugal compressor would realize the potential energy savings created by the compressed air recycling system.

Another possibility would be to install an additional 80 psig holding tank that would supply compressed air to the thermoformer. Pressure sensors and actuation valves would have to be installed on both the new and existing 80 psig holding tank. The system would pull from the existing 80 psig holding tank until the new holding tank has reached the appropriate pressure and volume. From here, the actuation valve installed on the existing holding tank would close, and the actuation valve on the new tank would open. This actuation system would allow the air from the compressed air recycling system to be utilized at the appropriate times, again allowing the potential savings from the design to be realized.

9.3 Optimal In-Line Compressor Design

The air compressor selected for this project was chosen because it most closely met the required specifications. However, like all air compressors, it is designed to intake atmospheric air. This system requires that the in-line compressor intake partially compressed air and recompress it to 80 psig. While commercially available devices, such as pressure boosters exist, these are typically designed to intake a steady flow of compressed air at a constant pressure and recompress it to much higher pressures, up to 2,000 psig. Because standard air compressors are not typically used in the capacity that this project requires, in-depth consultation and design with the assistance of custom compressor manufacturers would be necessary in order to develop the most effective in-line compressor for this system. However, there is strong belief that air compressors can be used effectively in the manner required for this system because of the "Exhausted Air Recycling System" discussed in Section 2.2.3.

10 LESSONS LEARNED

10.1 Engineering Design

Throughout the design process, the team learned several important aspects of engineering design. From the beginning of the project, the group started with a variety of design options. These design ideas were inspired by previous solutions that sought to solve a similar problem to the one the team attempted to solve. This process of analyzing past projects taught the team that it is important to do preliminary research at the beginning of any project to gain a better understanding of where to start.

Secondly, the team learned that design is an iterative process. As made apparent throughout the report, there were many different iterations before the final design was decided upon. These changes were made incrementally, allowing their effects to be considered more thoroughly. As the system progressed through the design process, the team found missing pieces that needed to be added. While some of the design changes throughout the semester were due to factors that were overlooked, other design changes were out of the team's control.

Another lesson the team learned was that with any design, it is important to consider the level of uncertainty that is being dealt with. One specific example of this involves the volume of air used in 4.7 second thermoforming cycle. At the beginning of the design, the team was not provided with the volume of air used during each 4.7 second cycle. Since this information was not originally provided, the team estimated a value for the volume. After the actual volume was provided by Berry Global, the team discovered that it was around 10 times the assumed value. This taught the team that it is important to consider an amount of uncertainty during the design process.

10.2 TEAMWORK

During the development of the final design, the team had to work together to make sure different deadlines were met on time. The team also maintained a schedule in order to make sure that all the team members were on the same page. Originally, the system was divided into the three subsystems that were divided among the different group members. The group members worked together to ensure that the different subsystems interfaced with one another.

As the project progressed, the team also discussed different ideas to improve the design with each iteration. Disagreements between team members occurred several times when considering design changes. These disagreements were resolved by discussing the issues as a team and coming to a consensus on the best path forward. The team allowed every member to have an equal say in design changes making sure that all potential ideas were considered.

11 CONCLUSION

Compressed air is an important aspect of many manufacturing processes. In this specific instance, compressed air is utilized for a thermoforming process at Berry Global, which forms plastic fast food cups. In its current form, the machine used to produce these plastic cups uses a substantial amount of 80 psig air which is being exhausted to the atmosphere. It was determined that the cost to provide the necessary air for this one machine is $3.34 per hour.

The goal of this project was to design a system that is capable of capturing some of the air that is currently being exhausted to the atmosphere. In this design process, research was performed to find previous solutions to this problem. The previous solutions helped inspire the design process, where the group developed three preliminary designs. These designs were all considered, then the final design was chosen. The selected design captures the optimal portion of the exhausted air then boosts the pressure back to 80 psig.

This design was broken up into three main subsystems and each of these subsystems were designed and a model for the entire system was developed. This model was then utilized to determine the cost savings of the system and the specifications of the different system components. Next, these specifications were used to select the system components. These components, as well as the cost of installation were compiled into a budget. This budget was then combined with the cost savings to calculate a Return on Investment period. Finally, future changes and improvements were discussed.

REFERENCES

[1] *Plastic Packaging Manufacture & Product Innovation: Berry global*. Plastic Packaging Manufacture & Product Innovation | Berry Global. (n.d.). Retrieved April 6, 2022, from https://www.berryglobal.com/en/

[2] Eickhoff, J. (2021). Thermoforer Line 18. Berrry Global, Evansville, IN.

[3] Jones, Vanda. "Waste Not Want Not." TCE: The Chemical Engineer, no. 945, Mar. 2020, pp. 42-45. EBSCOhost, search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=a9h&AN=142073818&site=eds-live&scope=site.

[4] Thermoformed product. Thermoformed Product - an overview | ScienceDirect Topics. (n.d.). Retrieved April 6, 2022, from https://www.sciencedirect.com/topics/engineering/thermoformed-product

[5] Cornell Industries. "Recycled Compressed Air, the 'Low-Hanging Fruit' of Energy Conservation." *EETimes*, 27 July 2007, www.eetimes.com/recycled-compressed-air-the-low-hanging-fruit-of-energy-conservation/#

[6] Yu, Qihui, et al. "Experimental Study of a New Pneumatic Actuating System Using Exhaust Recycling." *Sustainability* 13.4 (2021): 1645.

[7] "Capturing Air No Longer an Exhausting Task." Hydraulics & Pneumatics, 12 Nov. 2010, www.hydraulicspneumatics.com/applications/machine-tools/article/21885273/capturing-air-no-longer-an-exhausting-task.

[8] OSHA (Ed.). (n.d.). *Department of Labor Logo United Statesdepartment of Labor*. 1910.95 - Occupational noise exposure. | Occupational Safety and Health Administration. Retrieved April 20, 2022, from https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95

[9] ISO (Ed.). (1999). ISO. Retrieved April 20, 2022, from https://www.iso.org/obp/ui#iso:std:iso:8573:-3:ed-1:v1:en

[10] Eickhoff, John. "Senior Design Overview TFE18 10.13.21" *Berry Global*, 13 October 2021

[11] Eickhoff, J. (2022, January). Personal communication [In-Person Conversation]

[12] Leszczynski, J. S., and D. Grybos. "Compensation for the Complexity and Over-Scaling in Industrial Pneumatic Systems by the Accumulation and Reuse of Exhaust Air." Applied Energy, vol. 239, Apr. 2019, pp. 1130–1141. EBSCOhost, doi:10.1016/j.apenergy.2019.02.024.

[13] Çengel Yunus A., et al. *Fundamentals of Thermal-Fluid Sciences*. McGraw-Hill, 2017.

[14] Horsepower required to compress air. Engineering ToolBox. (2008). Retrieved April 20, 2022, from https://www.engineeringtoolbox.com/horsepower-compressed-air-d_1363.html

[15] *Online materials information resource*. MatWeb. (n.d.). Retrieved April 6, 2022, from https://www.matweb.com/

[16] Engineers Edge, L. L. C. (n.d.). *Standard pipe schedules and sizes chart table data*. Engineers Edge - Engineering and Manufacturing Solutions. Retrieved April 6, 2022, from https://www.engineersedge.com/pipe_schedules.htm

[17] Budynas, R. G., Nisbett, J. K., & Shigley, J. E. (2020). *Shigley's Mechanical Engineering Design*. McGraw-Hill Education.

[18] Savchuk, A. (2021, October 14). How loud is a decibel: What is one decibel. Decibel Meter App | Best Digital Sound Level Meter For Your Smartphone. Retrieved April 7, 2022, from https://decibelpro.app/blog/how-loud-is-a-decibel/

APPENDIX

APPENDIX A

Current System Compressed Air Cost

The compressed air utilized in the thermoforming process at Berry Global requires an extensive amount of energy, resulting in large utility costs for the company every year. The equation below breaks down the cost required per hour to produce the portion of air that is consumed by Thermoformer Line 18.

First, the known volume of air per cycle was converted from gallons to cubic feet. Next, the volumetric flow rate was calculated by converting the cycle time of 4.7 seconds to minutes and dividing the volume by the time in minutes. The cycle time is the time it takes for the thermoformer to press one batch of cups. The dies close around over the heated plastic sheet, then the molds press the heated plastic into the cavities. From there, compressed air is sent into the dies to fill the remaining space not completed by the molds. An actuation valve located just under the bottom die then opens exhausting the air through mufflers to atmosphere. These steps complete one full cycle. The volume given below is the volume of the compressed form air used during each cycle which was provided by Berry Global **[10]**.

$$V_{Form} = 115\ gal * \frac{1\ ft^3}{7.48\ gal} = 15.37\ ft^3$$

$$T_{cycle} = 4.7\ seconds$$

$$\dot{\boldsymbol{V}}_{\boldsymbol{Form}} = \left(\frac{\boldsymbol{V}_{\boldsymbol{Form}}}{\boldsymbol{T}_{\boldsymbol{cycle}}}\right) \times \frac{\mathbf{60\ sec}}{\mathbf{1\ min}} \qquad \mathbf{(5)}$$

$$\dot{V}_{Form} = 196.21\ cfm$$

With the above values, the volumetric flow rate was able to be calculated as shown in equation (5). This value is important because the centrifugal compressor efficiency is given as the power used with respect to the flow rate. From here, the power used by the compressor each cycle was determined by multiplying the volumetric flow rate by the known compressor efficiency which was provided by Berry Global **[10]**. As shown below, the units cancel out to return the power in kW required to provide air for the thermoformer.

$$\eta_{compressor} = \frac{17\ kW}{100\ cfm}$$

$$\boldsymbol{P_{Form} = \dot{V}_{Form} * \eta_{compressor}} \qquad \textbf{(6)}$$

$$P_{Form} = 196.21 \frac{ft^3}{min} * \frac{17\ kW}{100 \frac{ft^3}{min}} = 33.36\ kW$$

Finally, the energy cost to provide compressed air to the thermoformer per hour was determined. The electricity cost per kilowatt-hour, provided by Berry Global **[10]**, was multiplied by the compressor power to get a final compression cost per hour of $3.34.

$$\boldsymbol{Cost\ Per\ Hour = C_{original} = C_{kWh} * P_{Form}} \qquad \textbf{(7)}$$

$$C_{kWh} = Cost\ per\ kWh = \$0.10/kWh$$

$$C_{original} = \$3.34/\text{hr}$$

APPENDIX B

Potential Cost Savings for 40 psig Capturing

The calculation below shows the amount of power required to produce 40 psig air. The %Captured shown below would be 26.8%, which is the percent of mass that has passed through the check valve when the pressure on either side of the valve equalize. This equalization is shown in more detail in Appendix E and Section 4.3.1. The equation shown below is explained in more detail in Appendix G.

$$k = adiabatic\ expansion\ coefficient, (1.41)$$

$$P_1 = Initial\ Abolute\ Pressure\ (14.7\ psi\ absolute)$$

$$P_2 = Desired\ Absolute\ Pressure\ (54.7\ psi\ absolute)$$

$$\dot{V} = Volumetric\ Flow\ Rate\ (52.5\ cfm)$$

$$\%Captured = 26.8\%$$

$$\dot{V}_{40\ psig} = \dot{V}_{Form} * \%Captured$$

$$\dot{V}_{Form} = 196\ ft^3/min$$

[14] $$HP = \left(\frac{144 P_1 \dot{V} k}{33000(k-1)}\right)\left(\left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} - 1\right) = 5.39\ horsepower$$

$$\boldsymbol{P_{Actual} = \frac{HP}{1.341 * \eta_{40\ psig}} = 5.74\ kW}$$

$$\eta_{40\ psig} = 0.7\ (assumed)$$

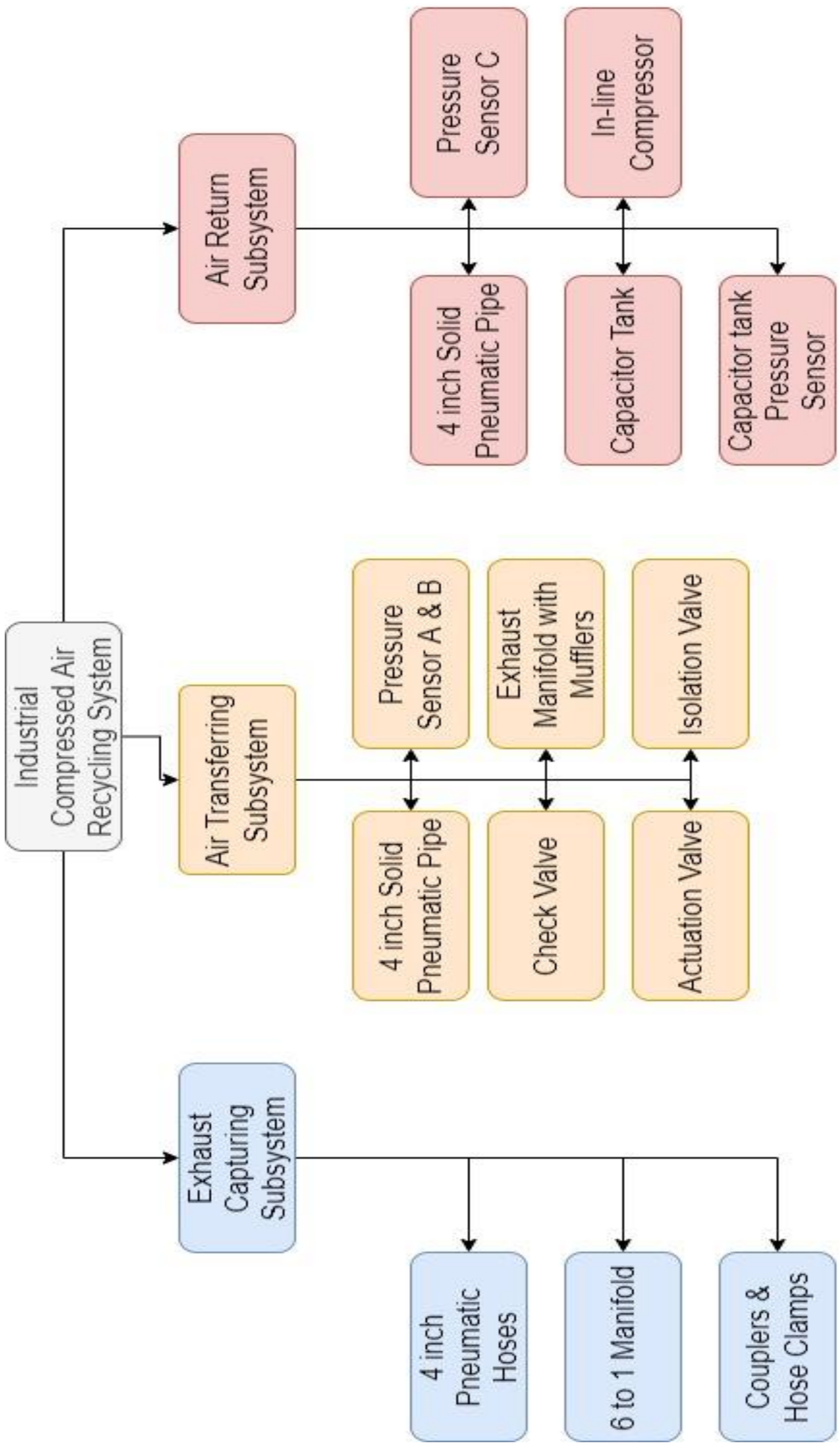
$$C_{40\ psig} = Cost\ per\ hour\ for\ producing\ 40\ psig\ air$$

$$\boldsymbol{C_{40\ psig} = P_{Actual} kW * 0.10 \frac{\$}{kWh} = \$0.57/hr}$$

While this is the theoretical maximum amount of energy that could be saved using this design option, the volume of air that would be captured each cycle would be much higher than the amount of air used each cycle in the 40 psig system. In order to use all the captured air each cycle, the line would need to be integrated with other lines. While this could be done, it would add more potential issues to the system, and would prevent the lines from running independently from one another. Also, per the request of Berry Global, the team was instructed to make sure the line remained independent of the other lines **[11]**.

APPENDIX C

System Hierarchy



APPENDIX D

Location of loss coefficients (K_L values) considered:

Air Transferring Subsystem:

Reference Table 2 from above to see the different loss coefficients determined for each component. Figure 36 below shows the location for the different loss coefficients throughout the system.

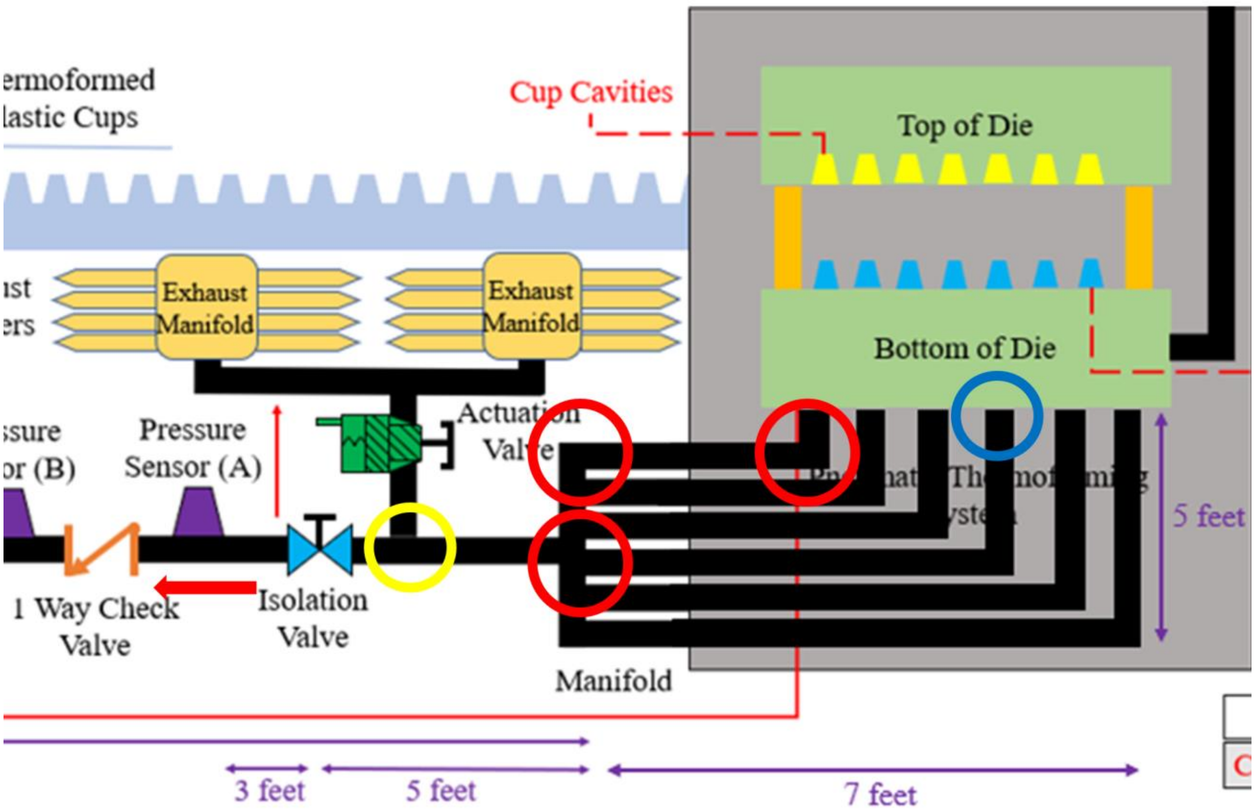


Figure 36. Location of K_L values in system for Air Transferring

Table 14 below shows the color that corresponds with each of the loss coefficient locations called out in Figure 36. The red arrow on the left of the isolation valve shows the direction the air is moving.

Table 14. Color Corresponding to K_L values Location (Air Transferring)

Description	Shown in
(3) 90 Degree Bends	Red
2.5" Poppet Valve (Actuation Valve)	Blue
Tee Line Through	Yellow

While there is a total of more than (3) 90 degree bends, all the lines end up flowing into one another. Because of this, the system was analyzed as if 100% of the air travelled through 1 exhaust line, when in reality, 1/6 of the air would travel through each of the 6 exhaust lines. As a result, the group analyzed the system by looking at only one of the 6 exhaust lines. Likewise, there are actually 6 actuation valves on the bottom of the die, one for each exhaust line circled in blue. Similar to the 90 degree bends, the team only considered one of these actuation valves for the K_L value calculation.

The expansion and contraction considered in the text accounted for the reduced diameter, d=2.5 inches, of the actuation valve. This expansion and contraction were once again only considered for one of the six exhaust lines.

Air Exhaust Subsystem:

Reference Table 6 from the text to see the different loss coefficients determined for each component. Figure 37 below shows the location for the different loss coefficients throughout the system.

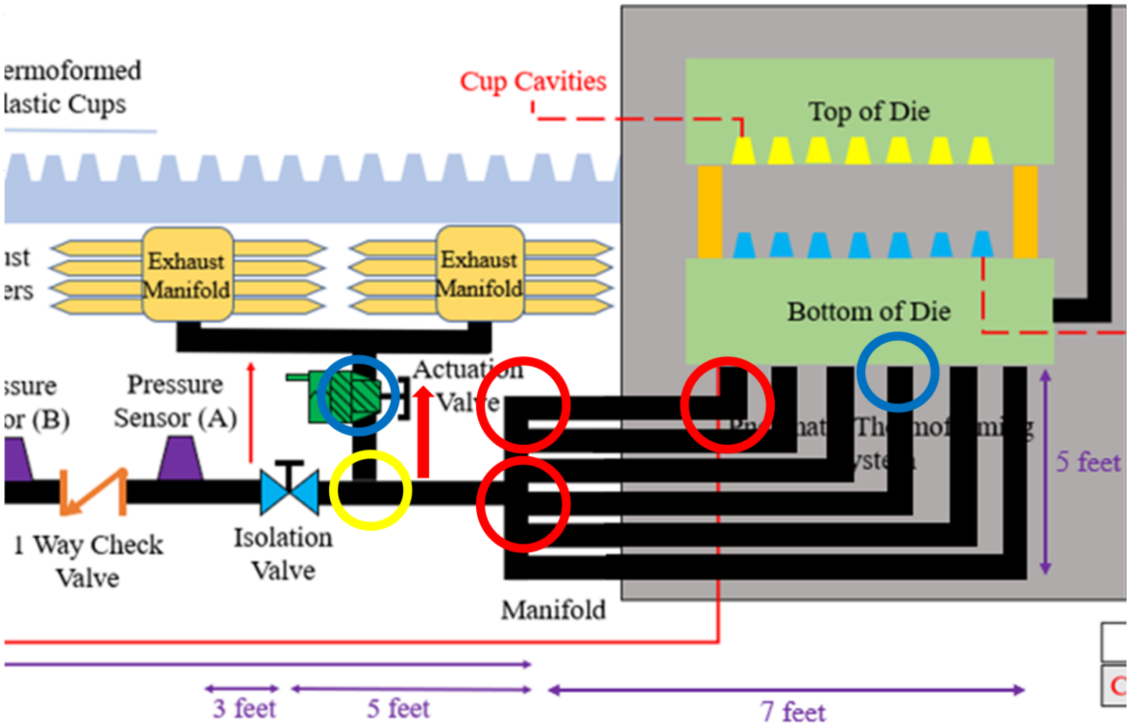


Figure 37. Location of K_L values in system for Air Exhaust

Table 15 below shows the color that corresponds with each of the loss coefficient locations called out in Figure 37. The red arrow next to the actuation valve shows the direction the air is moving.

Table 15. Color Corresponding to K_L values Location (Exhaust)

Description	Shown in
(3) 90 Degree Bends	Red
(2) 2.5" Poppet Valve (Actuation Valve)	Blue
Tee Line Branch	Yellow

The same amount of 90 degree bends are included in the air exhaust K_L values. While there are additional 90 degree bends shown on the diagram after the actuation valve, these 90 degree bends are not necessary for the actual operation of the system and would likely not be included in the actual design. The bends were shown in order to make the diagram more visually appealing. Due to this, the additional bends were not considered in the calculations. The addition of a new actuation valve was considered as well as the additional expansion and contraction that would be caused by the actuation valve. These K_L values as well as the others discussed in the text were used in the development of Appendix E.

APPENDIX E

Transient Air Transferring Model Development

The air transferring graphs were developed in excel using the following fluid mechanics equations. These equations were developed from the simplified figure of the system shown below.

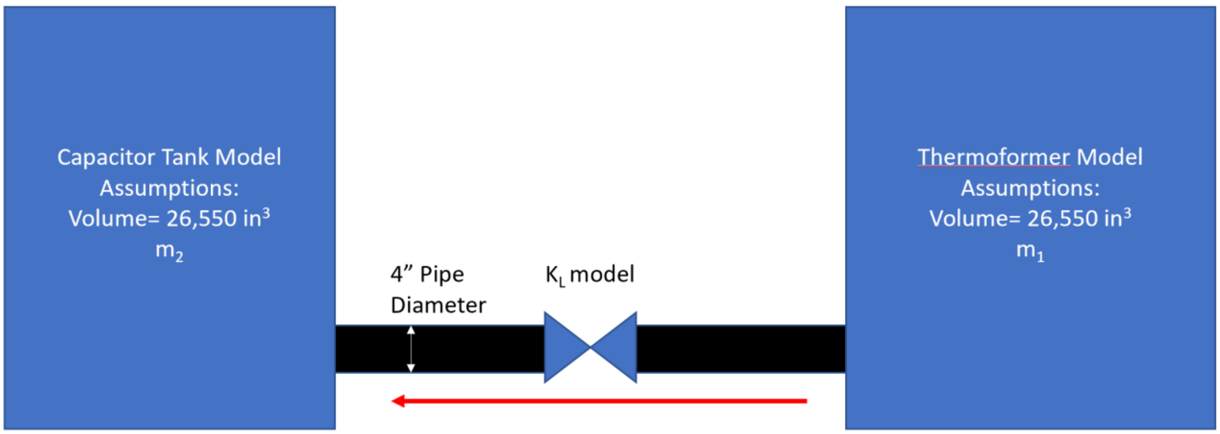


Figure 16. Transient Air Transfer Model

In order to correctly make the calculations for the air transfer model, the units had to be converted into metric units. This was done to simplify the conversions required for the equations shown below in Table 16.

Table 16. Variable Table

Variable	Variable Name
K_L	Loss Coefficient (unitless)
P	Pressure (Pa)
t	Time (s)
m	Mass (kg)
ρ	Density of air (kg/m^3)
$\dot{m}$	Mass flow rate of air (kg/s)
$\bar{V}$	Volume (m^3)
n	Amount of substance (moles)
M	Molar mass (kg/mol)
R	Ideal gas constant (m^3*Pa/K*mol)
T	Temperature (K)
V_{air}	Velocity of air leaving thermoformer (m/s)
A	Cross Sectional Area of pipe (m^2)

First, the minor loss equation for pressure drop was used as shown below. This equation and the other fluid mechanics equations assume a quasi-steady flow and were found in *Fundamentals of Thermal-Fluid Sciences* **[13]**.

[13] $$\Delta \boldsymbol{P} = \boldsymbol{K_L V_{air}}^{\boldsymbol{2}} \boldsymbol{\rho} \quad \text{(8)}$$

$$\Delta \boldsymbol{P(t)} = \boldsymbol{K_L V_{air}(t)^2 \rho(t)}$$

In the second line, the pressure, velocity, and density are made time dependent since all of these will change as time progresses. The loss coefficient, K_L will not change with respect to time. In the excel file "Pressure Energy Calculations" included on the flash drive, a time step for each row is 0.005 seconds. The equation above was manipulated to isolate the velocity and can be seen in the equation below.

$$V_{air}(t) = \sqrt{\frac{2\Delta P(t)}{\rho(t) K_L}}$$

As shown in the equation above, the minor loss equation can be manipulated to solve for the velocity at each time step. As previously mentioned, the density changes with respect to the pressure. This change in density was accounted for using a variation of the ideal gas law as shown below.

$$[13] \quad \boldsymbol{P\overline{V} = nRT} \quad (9)$$

$$P * \frac{m}{\rho} = nRT$$

$$\rho = \frac{P * \frac{m}{n}}{RT}$$

$$M = \frac{m}{n}$$

$$\rho(t) = \frac{P(t)M}{RT}$$

From this equation, the density of the air given at each time step was able to be determined which is shown in the excel sheet included on the flash drive. Next, the mass flow rate was determined at each time step as shown below.

$$[13] \quad \boldsymbol{\dot{m}(t) = \rho(t)V_{air}(t)A} \quad (10)$$

The mass flow rate of the air is also time dependent as shown above. By determining the mass flow rate of the air moving out of the thermoformer at each time step, the mass in each tank in the model can be determined at each time step as shown below.

$$[13] \quad \boldsymbol{m_1(t_{i+1}) = m_1(t_i) - \dot{m}(t_i)\Delta t} \quad (11)$$

$$m_2(t_{i+1}) = m_2(t_i) + \dot{m}(t_i)\Delta t$$

The steps above show that the mass going out of the thermoformer (m_1) must be transferred to into the capacitor tank (m_2) during each time step. By using these new masses in each tank, the pressure in each tank can be determined as shown below.

$$[13] \quad \boldsymbol{P_1(t_{i+1}) = \left(\frac{m_1(t_i)}{m_1(t_{i+1})}(P_1(t_i) + 14.7)\right) - 14.7} \quad (12)$$

$$P_2(t_{i+1}) = \left(\frac{m_2(t_i)}{m_2(t_{i+1})}(P_2(t_i) + 14.7)\right) - 14.7$$

The equations above show how the pressure in each tank was determined at each time step. This process was repeated in the excel spreadsheet until P_1 and P_2 equalized.

APPENDIX F

PLC B Logic - Flowchart Diagram

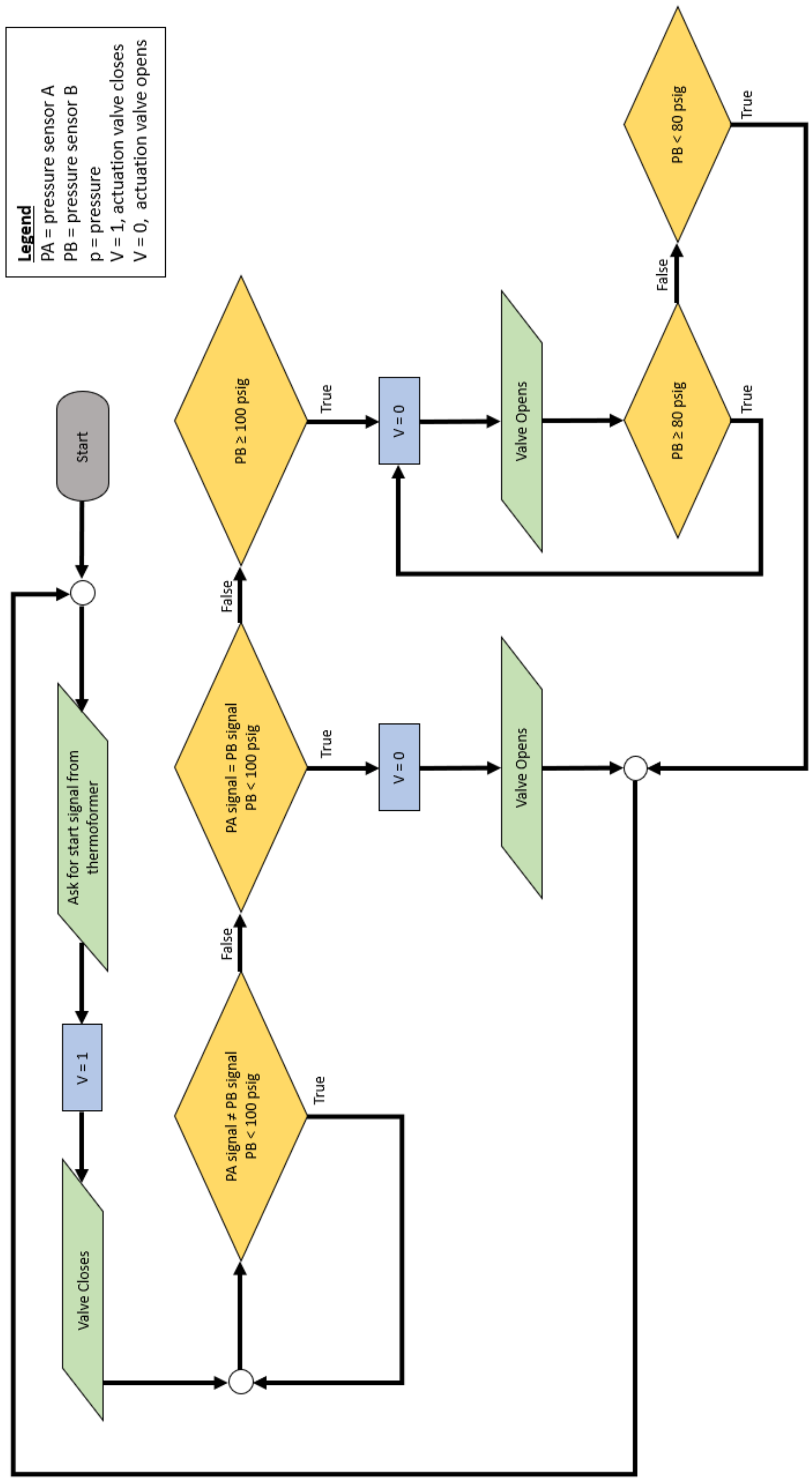


Figure 38. PLC Programming Logic for the Actuation Valve

This flowchart operates primarily from pressure readings because the thermoformer's cycle time can change based upon the desired production rate. By having pressure readings, the actuation valve can adjust for the changing cycle times autonomously.

To begin the flowchart, the start signal that PLC Controller A sends to the thermoformer to close the dies will also be sent to the actuation valve. This signal will initially set the actuation valve in the closed position. Throughout each cycle, sensors A and B, which are located on each side of the check valve, will provide constant readings of pressure to PLC Controller B. The duration of time that these two pressure readings stay unequal, the actuation valve will remain closed. This is because compressed air is travelling into the recycling system through the check valve. Once the pressure has equalized on both sides of the check valve, the compressed air downstream of the valve will force the valve to remain in the closed position. The actuation valve will now open and introduce the system to the atmosphere which will divert the remaining compressed air to travel through the actuation valve and leave the system through the exhaust manifolds and mufflers. The PLC logic will now reset to the initial start position and wait for the next signal from PLC Controller A. This signal will occur at the beginning of the next cycle.

If there is an instance where pressure sensor B has a pressure reading over 100 psig, the PLC flowchart will fail to satisfy the pressure being less than 100 psig and immediately open the actuation valve to direct 100% of the compressed air to the atmosphere. The reason that pressure sensor B was chosen for this task is because it is the first location that a pressure reading can be taken past the check valve. Opening the actuation valve will allow the recycling system enough time to reduce the pressure level without having more compressed air being introduced. Once the pressure level readings from pressure sensor B have decreased to equal or less than 80 psig, the PLC program will now return to the start position and wait for the next signal from PLC Controller A.

APPENDIX G

Cost Savings Vs Tank Size Development

In order to determine the cost savings for the air recycling system, the cost of recompressing the air was determined given different tank sizes and compressor efficiencies. Table 17 below shows the cost savings per hour at different tank sizes for an efficiency of 0.7.

Table 17. Savings Per Hour With 70% In-Line Compressor Efficiency

70% Efficiency				
V1/V2	**V2 (Gallons)**	**% Mass Captured**	**Average Air Pressure (psig)**	**Savings ($/hr)**
2.00	0.03	10.6%	62.00	0.19
1.50	0.04	15.7%	57.50	0.23
1.25	0.05	20.5%	54.00	0.25
1.10	0.06	24.2%	51.50	0.26
1.00	0.07	26.8%	50.00	0.26
0.90	0.07	30.9%	47.50	0.25
0.75	0.09	38.6%	43.50	0.22
0.50	0.13	60.8%	35.25	0.08

The V1/V2 column refers to the ratio between the volume of air in the thermoformer and the volume of the capacitor tank. The volume V1 is the volume of air in the thermoformer, which is constant (114.9 Gallons). The volume V2 is the volume of the capacitor tank which is varied in the table above. In order to determine the percent captured each cycle, the mass of the air that is captured was determined using the air transferring model previously described in Section 4.3.1 and Appendix E. This mass is then divided by the total mass of the air in the thermoformer which returns the percentage of the air mass that is captured.

Next, the average air pressure inside the capacitor tank is determined for each different capacitor tank size. This is done by looking at Figure 18 shown below.

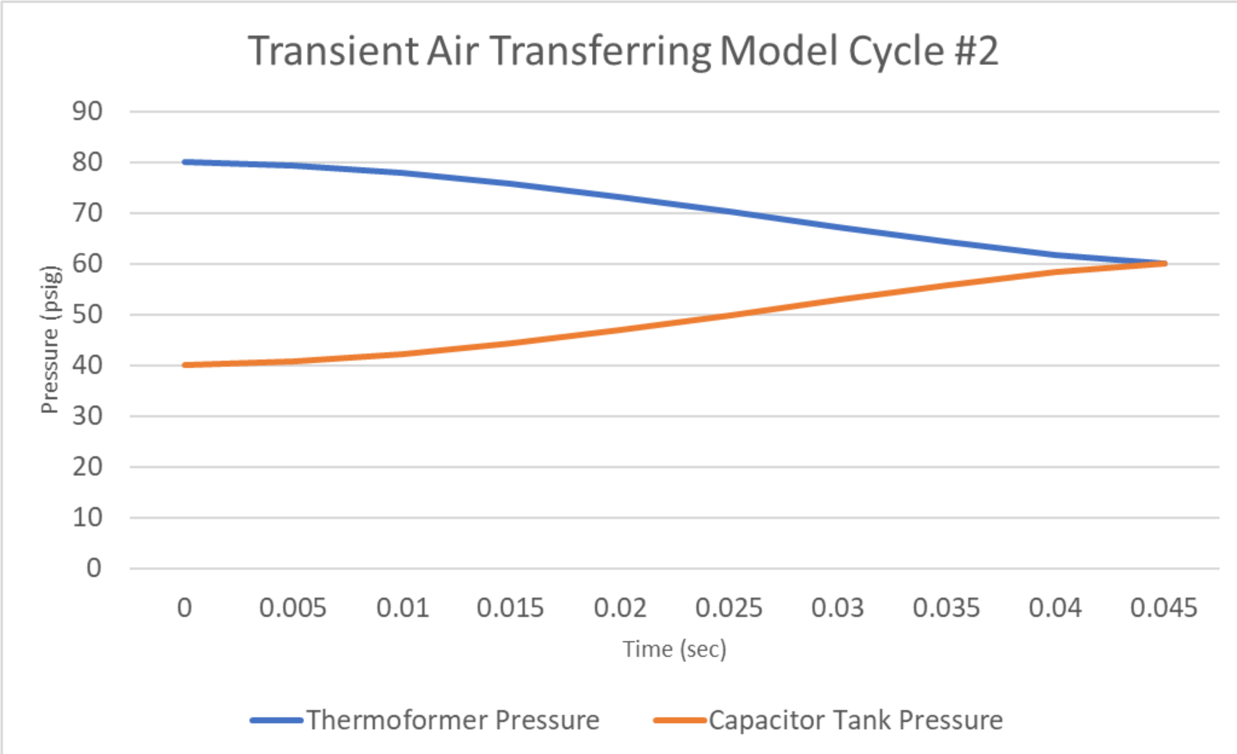


Figure 18: Transient Air Transferring Graph Cycle #2, V1=V2 ***(Previously Shown)***

This graph is specifically for the V1=V2 due to the maximum cost savings being associated with this ratio. However, a similar graph was developed for each row shown in the table above. By examining the chart above, the following can be determined.

$$Inital\ Capacitor\ Tank\ Pressure = 40\ psig$$

$$Final\ Capacitor\ Tank\ Pressure = 60\ psig$$

$$Average\ Capacitor\ Tank\ Pressure = \frac{40\ psig + 60\ psig}{2} = 50\ psig$$

At the beginning of each cycle, the pressure inside the capacitor tank would be approximately 40 psig. After the 0.045 seconds necessary for the air pressure from the thermoformer to equalize with the air pressure in the capacitor tank, the capacitor tank will be at approximately 60 psig. During the entire 4.7 second cycle, the capacitor tank will be providing a steady flow of air to the in-line compressor which lowers the pressure in the capacitor tank back to 40 psig before the next shot of air is captured. This approach was used at each different capacitor tank size in order to determine the percentage of air captured as well as the average air pressure in the capacitor tank.

After determining these parameters for each given capacitor tank size, they were used in the in-line compressor power requirement equation shown below.

$$k = adiabatic\ expansion\ coefficient, (1.41)$$

$$P_1 = Initial\ Abolute\ Pressure\ (64.7\ psi)$$

$$P_2 = Desired\ Absolute\ Pressure\ (94.7\ psi)$$

$$\dot{V}_{inline} = Volumetric\ Flow\ Rate\ (Calculation\ Below)$$

[14] $$HP = \left(\frac{144 P_1 \dot{V}_{inline} k}{33000(k-1)}\right)\left(\left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} - 1\right)$$ **(4)**

The values shown in parenthesis are once again for the situation where V1=V2. The volumetric flow rate was determined as shown below.

$$\dot{V}_{Form} = 196\ ft^3/min$$

$$\dot{V}_{inline} = \dot{V}_{Form} * \%Captured = 196\frac{ft^3}{min} * 26.8\% = 52.5\frac{ft^3}{min}$$

$$HP = \left(\frac{144\frac{in^2}{ft^2} * 64.7\frac{lb}{in^2} * 52.5\frac{ft^3}{min} * 1.41}{33000\frac{\frac{lb*ft}{min}}{hp}(1.41-1)}\right)\left(\left(\frac{94.7\frac{lb}{in^2}}{64.7\frac{lb}{in^2}}\right)^{\frac{(1.41-1)}{1.41}} - 1\right) = 5.97\ hp$$

The horsepower determined to raise the pressure from P_1 to P_2 was then converted to kW and the efficiency of the compressor was applied to the value. This value is then used to find the cost per hour to run the in-line compressor.

$$\boldsymbol{P_{Actual} = \frac{HP}{1.341 * \eta_{inline}} = 6.38\ kW} \qquad (13)$$

$$\eta_{inline} = 0.7$$

$$C_{inline} = Cost\ per\ hour\ for\ in\ line\ Compressor$$

$$\boldsymbol{C_{inline} = P_{Actual} kW * 0.10\frac{\$}{kWh} = \$0.64/hr} \quad \textbf{(14)}$$

$$C_{original} = Original\ Cost\ of\ producing\ air = \$3.34/hr$$

$$\boldsymbol{Cost\ Savings} = \left(\%\boldsymbol{Captured} * \boldsymbol{C_{original}}\right) - \boldsymbol{C_{inline}} = (\mathbf{26.8}\% * \mathbf{3.34}) - \mathbf{0.64} \quad \textbf{(15)}$$

$$Cost\ Savings = \$0.26/hr$$

The cost savings calculation shown above was done for each of the different capacitor tank sizes. This calculation was done using a compressor efficiency of 0.7, while the actual compressor chosen has an efficiency of 0.6982. The calculation was also performed using the exact efficiency, however the change in cost saving was less than $0.01 per hour. This calculation was performed with compressor efficiencies of 0.6, 0.7, 0.8. All these calculations were compiled to produce Figure 23 Cost Savings Vs. Tank Size chart.

APPENDIX H

System Model Functionality

Figure 39 below depicts the compressed air recycling system in its initial state. Here, the actuation valve will be closed, and no compressed air will be within the system. The system will remain in this state until it receives a signal from the thermoformer that a cycle has begun. Please note that compressed air will be animated by sections of the system turning red.

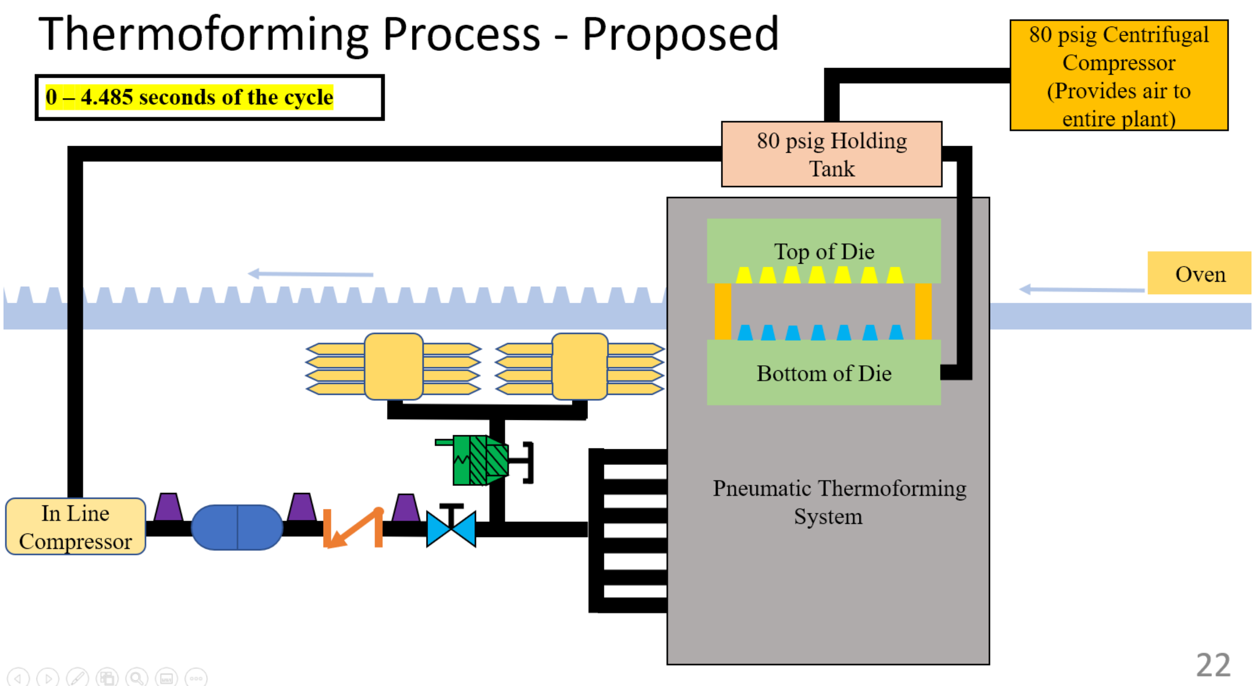


Figure 39. Initial State of Compressed Air Recycling System

The next step in the recycling system process can be visualized in Figure 40. In this image the cycle has started, and compressed air has now been sent from the 80 psig centrifugal compressor, through the 80 psig holding tank, and into the bottom die. The dies will be closed before the air is sent into the bottom die and then the compressed air will be used along with the cup molds to create the 30 ounce plastic cups.

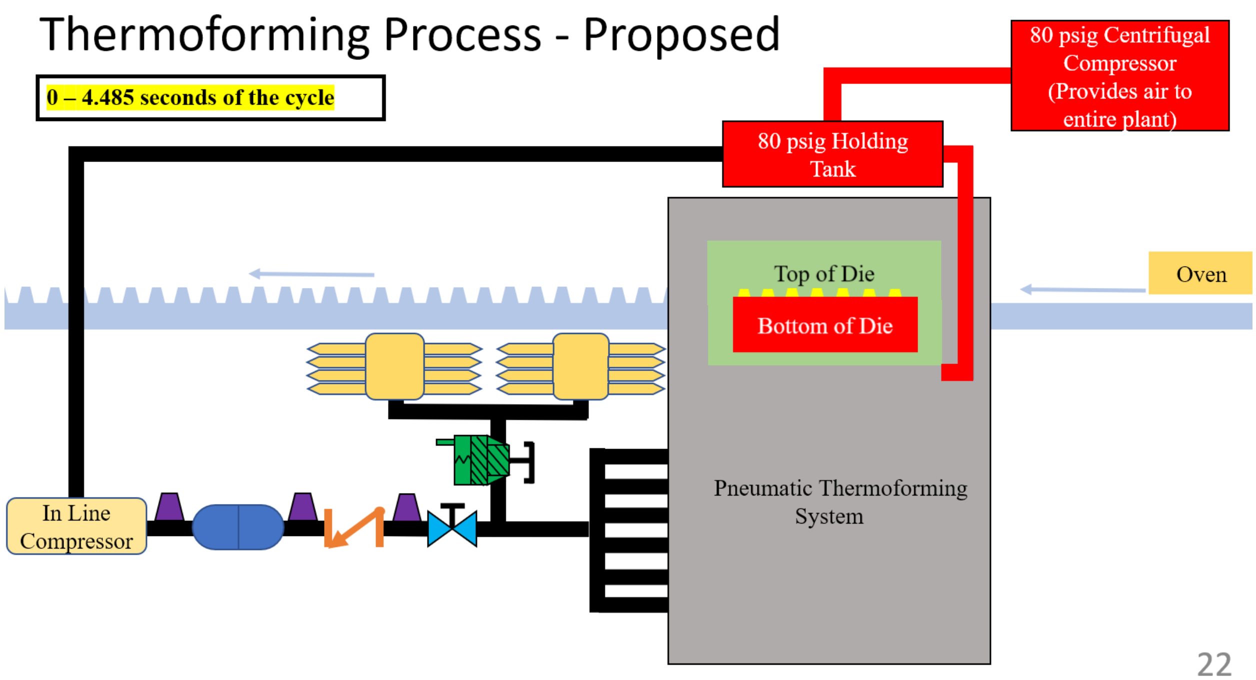


Figure 40. Bottom Die Filled with Compressed Air

Once the molds and compressed air have been utilized to form the cups, the air will be released from the bottom die through the existing six exhaust lines. From here, the exhaust lines will be combined through a manifold and reduced into one return line. The air will travel through the manifold and into the return line where it will reach an actuation valve in the closed position, a manual isolation valve in the open position, and a one-way check valve. Some of the compressed air will proceed through the check valve and into a capacitor tank. This tank will slow the velocity of the air down, which will allow it to be fed into the in-line compressor at a constant rate throughout the entire 4.7 second cycle. Note that as the air travels through the manifold, valves, and capacitor tank, it will undergo a pressure loss. The in-line compressor will then account for the pressure loss and recompress the air to the appropriate pressure of 80 psig before recycling it into the 80 psig holding tank. This step is shown in Figure 41.

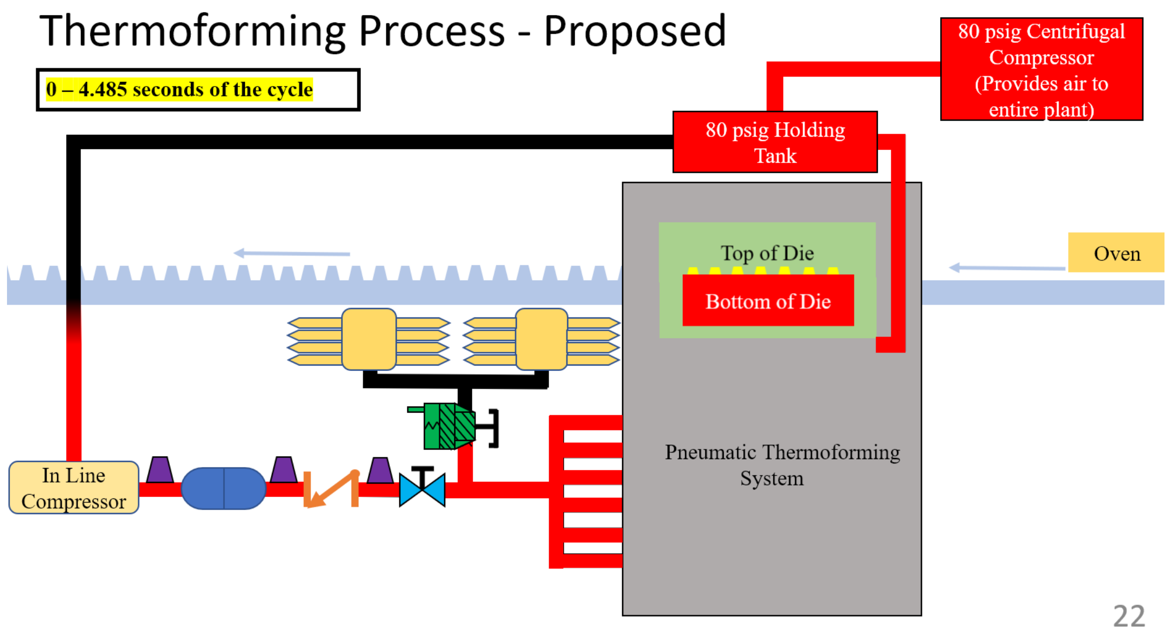


Figure 41. Compressed Air being Recycled through System

Figure 42 shows the next phase of the cycle. Here, the pressure sensors on either side of the check valve have read an equal pressure and have signaled for the actuation valve to open. Once the actuation valve opens, all the air on the back side (right side in the image) of the check valve will be exposed to the atmosphere.

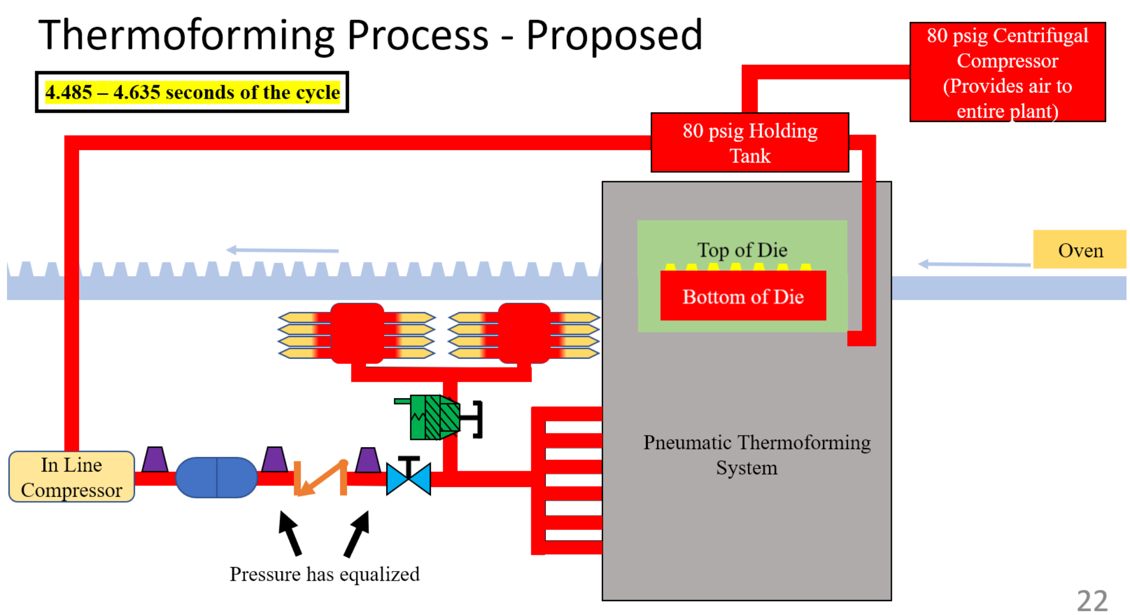


Figure 42. Remaining Compressed Air leaving through Actuation Valve

Next, the compressed air will exit the bottom die and travel through the manifold, actuation valve, and out of the exhaust mufflers to atmosphere as shown in Figure 43. The compressed air on the front side (left side in the image) of the check valve will continue to travel through the recycling system. As previously mentioned, this portion of system will recompress and return the compressed air to the 80 psig holding tank.

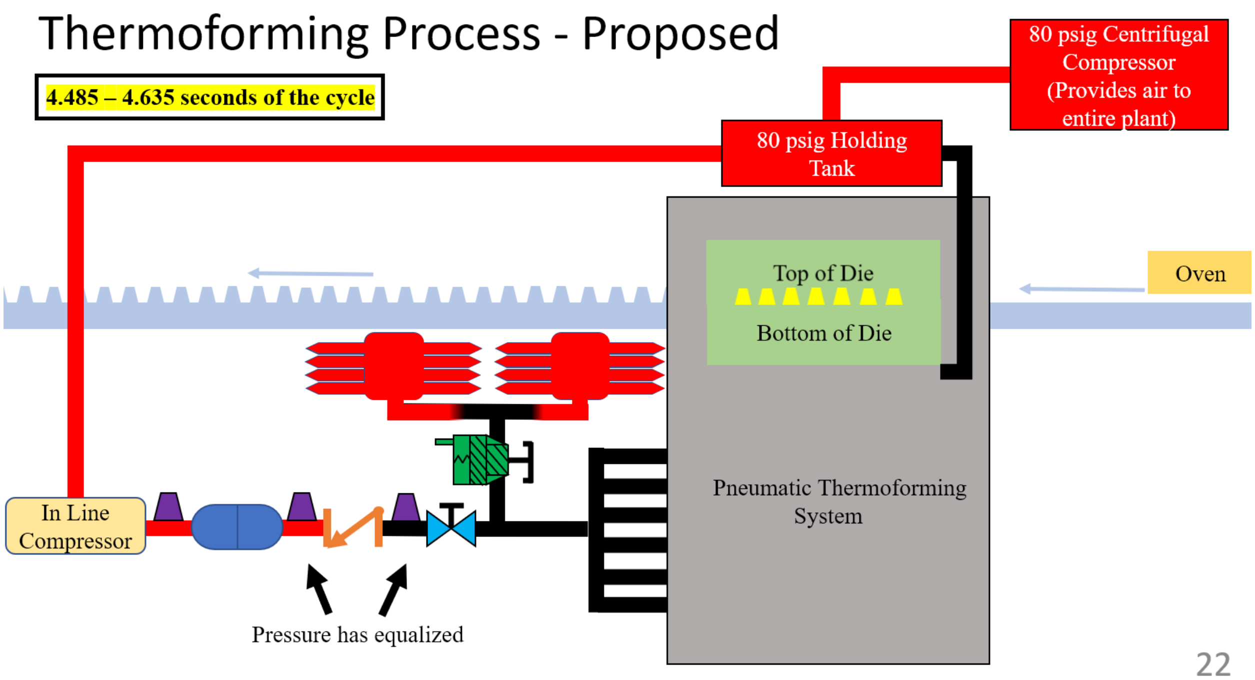


Figure 43. Remaining Compressed Air being Exhausted to Atmosphere

The last phase in the cycle will consist of all of the compressed air not being recycled to be exhausted to the atmosphere through the exhaust mufflers. The dies will then reopen, and the cycle will reset. Removing all residual compressed air from the system is critical in assuring that there will be no backpressure, which could damage the thermoformer. The final step is shown in Figure 44.

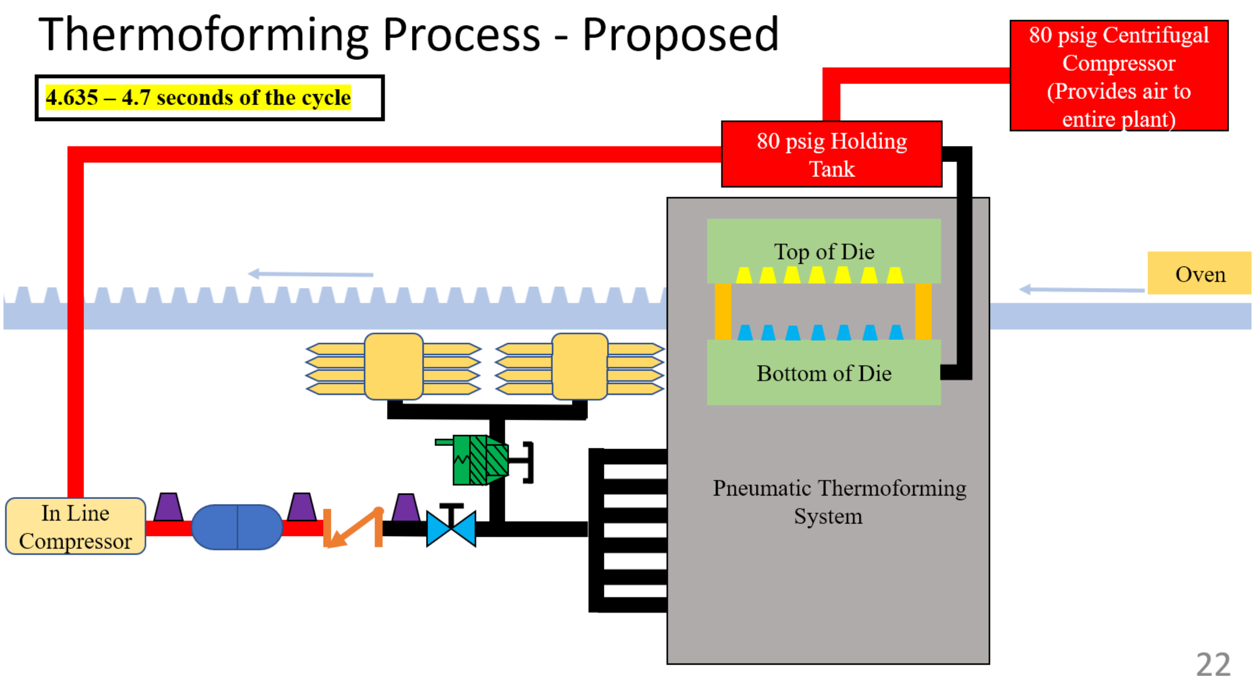


Figure 44. Steady State Recycling System Awaiting Next Cycle

APPENDIX I

6 to 1 Manifold Flow Simulation Results

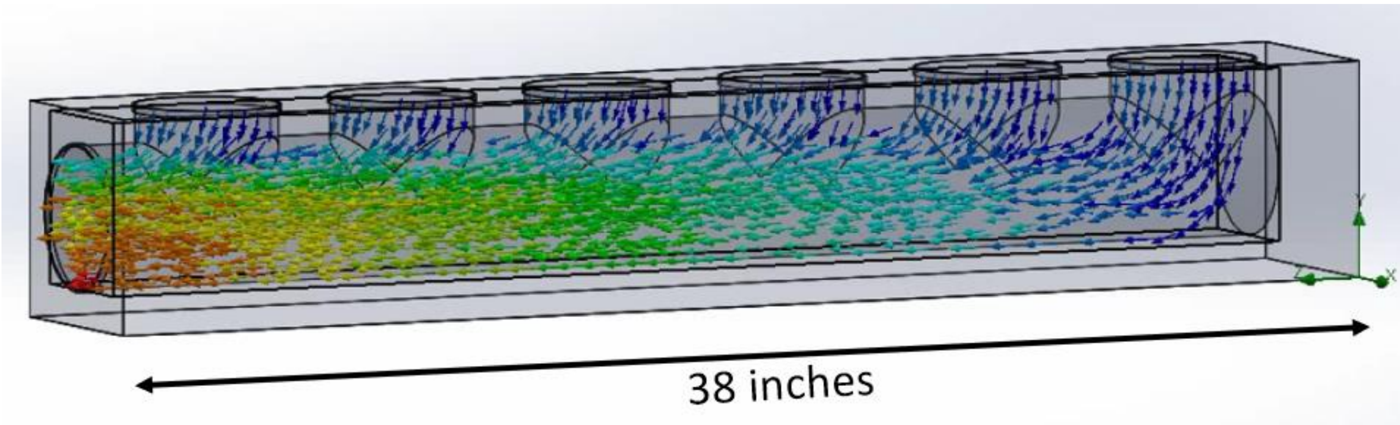


Figure 45. 6x1 Manifold Flow Simulation Result

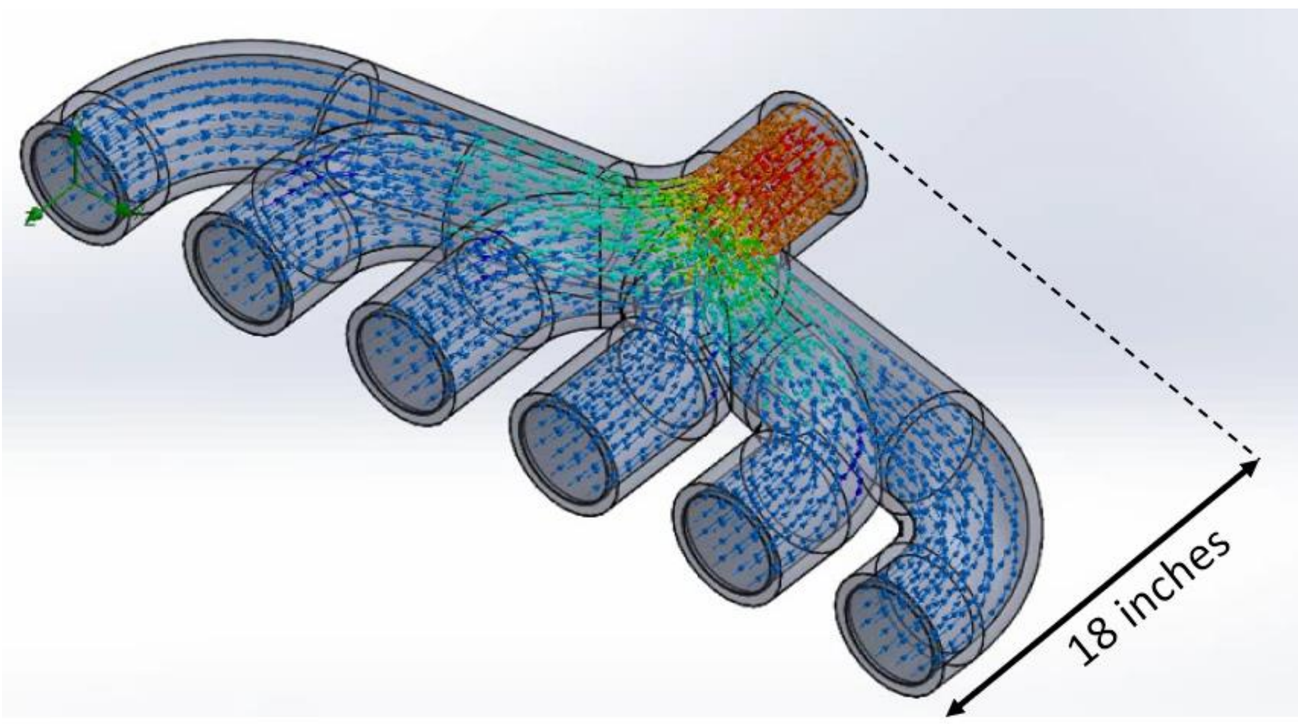


Figure 46. Combining Manifold Flow Simulation Result

APPENDIX J

6 to 1 Manifold Fatigue Calculation [17]

$$Von\ Mises = 20.82\ ksi$$

$$\sigma_m = \sigma_a = 10.41\ ksi$$

$$\boldsymbol{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{\eta_f}} \quad \textbf{(16)}$$

$$\boldsymbol{S_e = k_a k_b k_c k_d k_e k_f S'_e} \quad \textbf{(17)}$$

$$S'_e = 0.5 * S_{ut}$$

$$S_{ut} = 73.2\ ksi$$

$$S'_e = 0.5 * 73.2$$

$$S'_e = 36.6\ ksi$$

$$k_a = aS_{ut}{}^{b}$$

$$a = 2$$

$$b = -0.217$$

$$k_a = 0.788$$

$$k_b = k_d = k_f = 1$$

$$k_c = 0.85$$

$$k_e = 0.814$$

$$S_e = (0.788)(0.85)(0.814)(36.6)$$

$$S_e = 19.75\ ksi$$

$$\frac{10.41}{19.75} + \frac{10.41}{73.2} = \frac{1}{\eta_f}$$

$$\eta_f = 1.49$$

Please see *Shigley's Mechanical Engineering Design – Fatigue Calculation Equations* document on the flash drive for all tables and variables utilized to complete the equations.

APPENDIX K

Decibel Chart

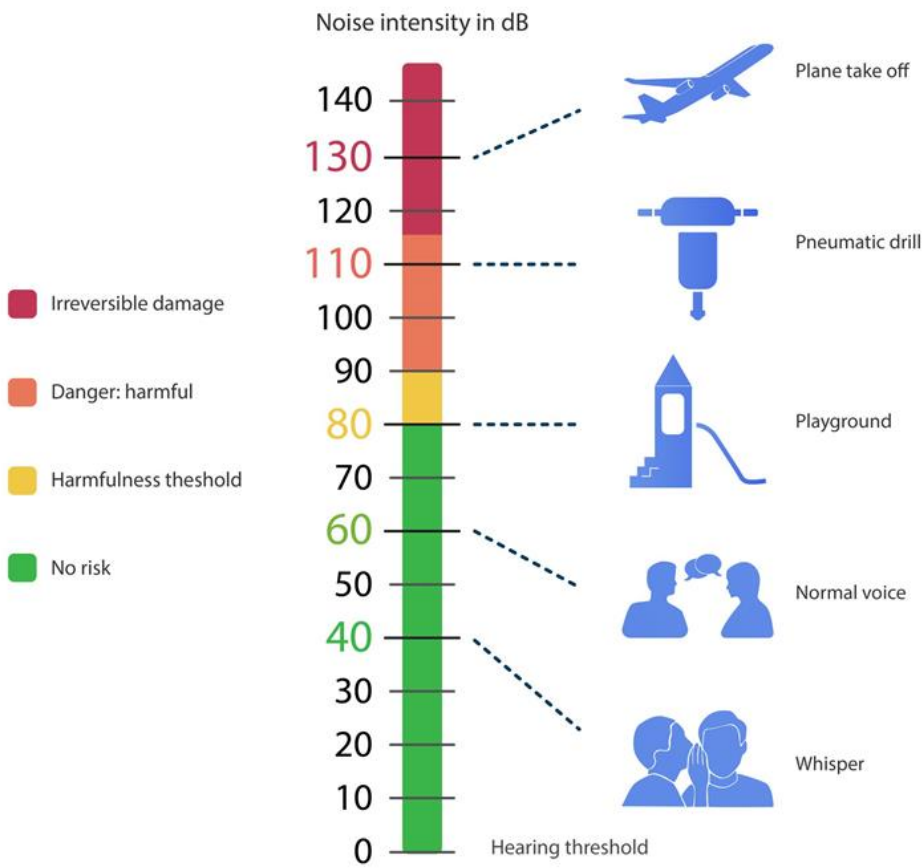


Figure 47. Decibel (dB) Noise Level Overview ***[18]***

APPENDIX L

Bill of Materials

Item Description	Source	Part #	Quantity	Unit Price	Total Price
Titan Flow Control CV 42-SS Stainless Steel Dual Disc Wafer Type Check Valve w/Viton Seat & SS Disc – ASME Class 150	JME Sales	TFCCV42SSV0400	1	$812.00	$812.00
2.5 Inch Poppet Valve	Ross Controls	P13900A1258	1	$1,788.00	$1,788.00
4 Inch Pneumatic Tubing (12')	Direct Industry	1210	1	$186.25	$186.25
4 Inch Pneumatic Pipe (18' 8")	Aluminum Air Pipe	2811800000	2	$243.38	$486.76
Atlas Copco LV120-200 120-Gallon Vertical Air Receiver	Air Compressors Direct	1310072051	1	$1,160.00	$1,160.00
Atlas Copco GA7 VSD 10-HP Variable Speed Rotary Screw Air Compressor w/Dryer	Air Compressors Direct	8153038206	1	$16,708.00	$16,708.00
Honeywell Industrial Pressure Sensor	Mouser Electronics	PX2EN1XX750PSBGX	3	$504.16	$1,512.48
4 Inch Manual Gate Valve	Grainger	F-619-RWS	1	$681.68	$681.68
Allen Bradley PLC System	Williams Automation	5069-L306ERM	1	$2,200.00	$2,200.00
6 to 1 Reduction Manifold	N/A	Custom	1	$6,500.00	$6,500.00
1 to 8 Exhaust Manifold	N/A	Custom	2	$4,000.00	$8,000.00
4" Coupler	PRM Filtration	CLAL400MAMTX	8	$14.99	$119.92
4" Flange	Pipe Fittings Direct	KFSO4	4	$32.98	$131.92
4" Hose Clamp	Lowe's	120906	20	$2.98	$59.60
				Total:	**$40,346.61**

APPENDIX M

ABET Outcome 2, Design Factor Considerations

ABET Outcome 2 states "*An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health safety, and welfare, as well as global, cultural, social, environmental, and economic factors.*"

Table 18. Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	Section 2.4, pg. 9
Global	N/A due to the project focusing on a single thermoformer line located in Evansville, IN.
Cultural	N/A due to the thermoformer having no cultural impacts.
Social	N/A due to the thermoformer having no social impacts.
Environmental	Section 2.4, pg. 9
Economic	Section 2.4, pg. 10
Professional Standards	Section 2.3, pg. 9