SMART SILO FOR THE SAFE STORAGE OF COMBUSTIBLE MATERIALS

BY

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Abstract:

The goal of the project was to develop an automated smart system that would be capable of reducing the risk of ignition of most materials stored within silos. Specifically, the initial focus was on carbonaceous material like silage, wood pellets, or coal. For the smart silo system, the design consists of the silo to store the material, a computer connected to valves and thermocouples regulating the system, a centrifugal air compressor with varying air flows, an air dryer to reduce moisture that can lead to clumping, and nitrogen tanks for an emergency purge of the whole system if temperatures get too high. The smart system will do several calculations by using the temperature from the thermocouples and the chemical properties of the material stored within the silo. With this information heat generation and heat dissipation curves can be simulated with different air flows to find the optimal air flow needed from the compressor. This way the silo's temperature can not rise above the unsteady state point in which the heat generated will be too large leading to a runway reaction causing a fire or an explosion. The total capital investment for the design was $90,000 including the silo meaning it could still be affordable to implement.

Smart Silo for the Safe Storage of Combustible Materials

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Summary:

To reduce the risk of silo fires or explosions, an automated temperature control system was explored and simulated for a model silo and material. Heat generation and dissipation were simulated with varying flow rates of air used as a purge gas. A design was formulated to allow air to be used as a purge gas and allow measurement and control of the temperature inside the silo. This design consists of the silo, a computer, a compressor, and an air dryer. Equations were derived to determine whether temperature would increase or decrease at any given temperature and air flow rate. The computer can solve for a safe temperature using these equations and can then control the air flow rate to bring the current temperature to a safe temperature. A nitrogen tank was added to the design for the case in which temperature is raised rapidly by an unexpected source and air purge gas becomes counterproductive and nitrogen purge gas becomes necessary. Because no harmful substances were used in this design, electricity usage is the only major factor in environmental impact. When operating continuously the yearly carbon dioxide emissions is 13,680 lb./MWh. The operating cost of this process is minimal because the compressor will only run when temperatures exceed safe levels. The total capital investment needed for this design is approximately $90,000. This design will prevent combustion inside silos and will prevent costly and potentially fatal disasters in the future as well as providing peace of mind to investors and the public.

Overview of Contributions:

Each member of the team contributed equally to this project and contributed to the following specific areas. Special thanks also to our mentor Dr. Farhang Shadman for his support and insights throughout the project.

Andy Kamrowski:

Focused on the heat transfer equations specifically on the heat generation and heat dissipation equations used in modeling the silo. Then worked on developing the computer logic and controls system that will use the heat transfer equations to change air flow and sound an alarm. Wrote the equipment description of the computer system, the conclusion of the repot, and the summary. Also did model parameters and calculations portions of the report.

Ghassan Flimban:

Focused on the air dryer dehumidification unit in terms of the sizing, costing, and equipment description. Wrote the process description for the air dryer and created the equipment and stream tables. Focused on the rational portion of the process description and the hazard operations section of the report.

Francisco Martinez:

Focused on the sizing and costing of the centrifugal air compressor. Also did the equipment description of the air compressor in the report. Wrote the introduction, social impact, and the environmental impact sections of the report. For the environmental impact did the life cycle assessment calculations. Typed the references up to follow MLA format and aided in the objective of the report.

Abdul Alqahtani:

Focused on the nitrogen tank emergency purge system portion of the project in terms of sizing and costing. Also wrote the equipment description for that portion of the report. Wrote a large portion of the objective of the report. Developed the process diagrams and majority of the figures used. Calculated the utilities and operating costs of the report. Wrote the safety issues section of the report.

Introduction:

Combustible materials are commonly used in agricultural and industrial processes requiring them to be stored in large quantities. When the necessary precautions are not taken or when an accident occurs tragic fires and explosions can occur. Accidents like the recent tragic event of the Beirut, Lebanon explosion that occurred August 4, 2020. In this case the explosion was a result of the ignition of 2750 tons of ammonium nitrate stored in a warehouse. Ammonium nitrate is a combustible material often used for fertilizers or as an explosive for mining. This explosion resulted in 220 dead and over 7000 wounded (Shakoor 2020). This has led to the need to look at how the storage of combustible materials is handled. Materials like ammonium nitrate are stored in silos designed with features to handle explosive materials. However worst-case scenarios where the materials stored start to form hotspots because of an accidental fire or runaway reactions can still occur leading to combustion. A smart silo design that is capable of real time monitoring of temperatures and able to initiate a cooling protocol to prevent the growth of hotspots can prevent tragic accidents like the Beirut explosion from happening again.

The importance of this smart silo design is further highlighted by looking at previous accidents. These previous accidents were the result of the worst-case scenario happening to improperly stored combustible materials. Taking a deeper look at the recent Beirut explosion there was an apparent lack of safety features in place. The ammonium nitrate was stored in a warehouse for several years. Over this time the ammonium nitrate was stored with no ventilation resulting in moisture buildup (Shakoor 2020). When ammonium nitrate is exposed to moisture, clumping occurs leading to more extreme reactions. Ventilation is also a source of aeration that helps keep the material cool preventing the formation of hotspots. Investigative reports also suggest that the explosion was caused by sparks from welding that was performed near the warehouse.

In designing a safety feature for silos, it is first important to look at the current designs of silos. Silos usually come in three different configurations: bagged, tower, and bunker (Elebia). For this project, the focus will be on tower silos which are used to store materials such as grains, silage, fertilizers, and wood pellets which are all combustible. Tower silos are designed in a cylindrical shape often made of steel or concrete slabs. The bottoms of the silos can have a conical or flat bottom depending on the material and purpose of the silo. Conical bottoms are preferred for fertilizers as they are used to store materials temporally and provide easier access to unloading the material. To get the material in the silo a loader is used to move the material through the top of the silo. An example of a loader is a blower which is often used for lighter materials like grain or silage. These lighter materials are blown through a chute to be evenly distributed. For heavier materials conveyor belts are used instead. These loading methods do provide sources of ignition either through friction of moving parts (conveyer belt) or static charges (from the blower) (Abbasi et. al 2007). Unloaders or hoppers are used to remove the contents from the silo when they need to be transported or used (Hanson Silo Company). Hoppers are automated while traditional unloaders are manually adjusted. Hoppers however can cause weight distribution problems leading to uneven material distribution. If the materials are not evenly distributed hotspots are more likely to occur leading to combustion.

Additional features can be added to a silo design to improve the safety of storing combustible materials. Current features include aeration which can reduce moisture and prevent heat buildup within the silo. Moisture results in clumping of the material making hotspots more capable of happening. Other gases other than air can also be used to decrease reaction rates occurring within the silo (Prather 1988). Gases like nitrogen or argon which are inert can be passed through the silo. Slabs or wedges can also be incorporated to help evenly distribute the material within the silo. Even distribution can help lower combustion rates by providing buffers of air that can act as insulation lowering the temperature in the silo. These features all focus on preventing the formation of hotspots that can lead to runaway reactions within silos. Combustion is an exothermic reaction that occurs at high temperatures. But once the reaction occurs heat will be generated increasing the temperature in the silo. This runaway reaction leads to the rest of the material in the silo in combusting resulting in a big fire or explosion.

This is where a smart silo design for any carbonaceous or combustible material can come into place. Such a system should be able to be applicable to materials like silage, wood pellets, fertilizers, coal, etc. by considering the chemical properties. This can be done through the computer system being able to receive material property inputs to calculate the unstable temperature point. Thermocouples will be incorporated to monitor the silo temperature to check for the formation of hotspots. Once temperatures increase towards the unstable point a cooling system using a centrifugal compressor will pass air through the silo’s piping to cool the material down. An emergency protocol is also implemented that will use an inert gas, in this case nitrogen, to completely halt any reactions if temperature does go above the unstable point or ignition occurs.

Objectives:

A serious problem in stockpiling combustible materials is the combustion of material either by run-away reactions or an accidental sudden increase in temperature. Therefore, the objective of the project is to design a smart silo for the safe storage of combustible materials. A smart silo differs from regular silos by measuring internal temperature and implementing safety measures autonomously, by providing an adequate amount of air flow into the silo which acts as a heat sink. The goal is to regulate temperature inside it to avoid reaching any critical limit and prevent combustion and explosions from occurring.

The scope of the project for this semester includes methods of monitoring the temperature within the silo and reducing the temperature when it exceeds a certain value. The design is based on an analysis of the rate of heat diffusion away from a hot spot compared against the heat generated. The design is considered successful if the temperature of the silo does not reach above the unsteady state point were heat generation will grow out of control.

Process Description, Rationale and Optimization:

Block Flow Diagram:

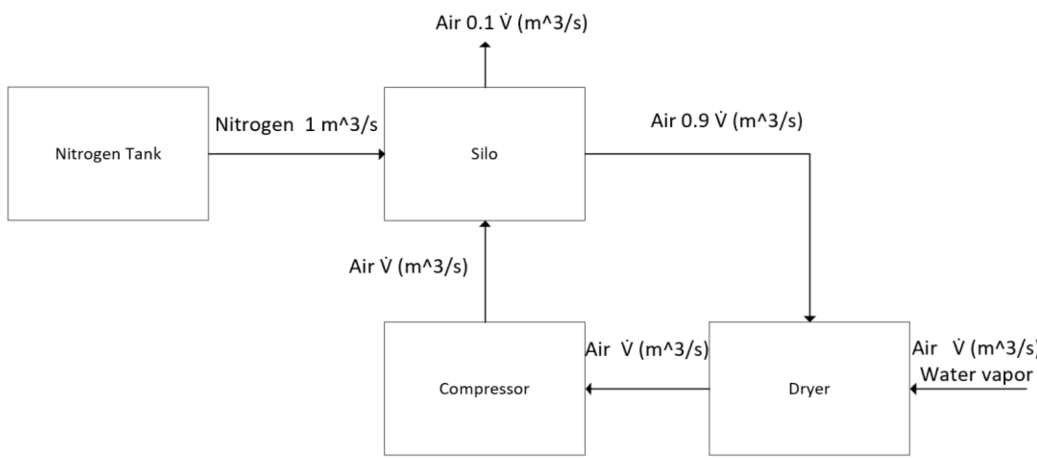


Figure 1. *Block Flow Diagram for "Smart Silo"*

Process Flow Diagram:

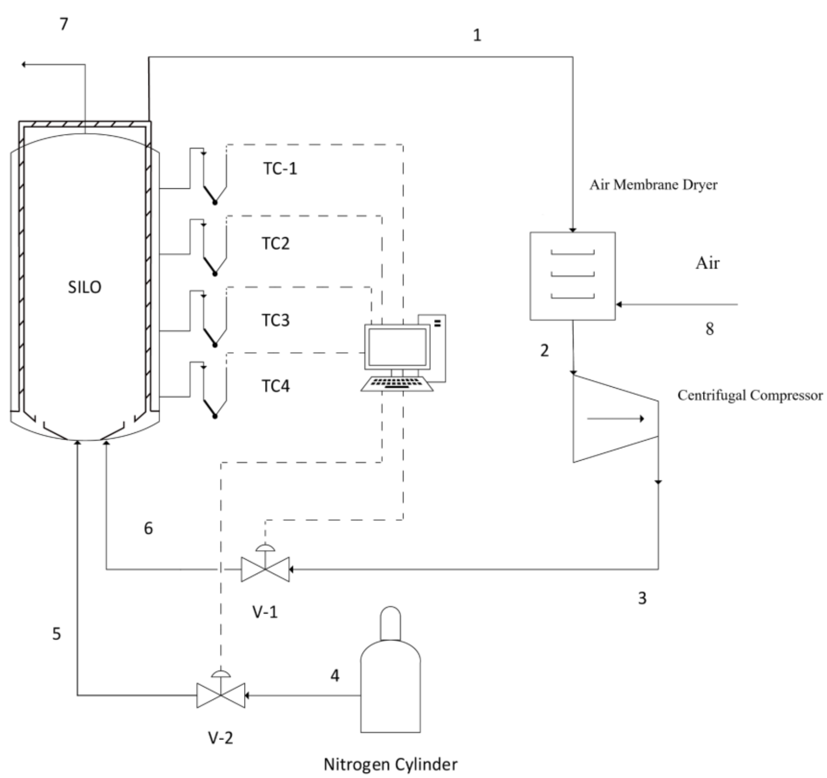


Figure 2. *Process Flow Diagram for "Smart Silo"*

Equipment Table:

Verticle Silo	
Temp (C)	< Tmax
Pressure (atm)	1
Height (m)	8
Diameter (m)	4
Volume (m^3)	100.5
Internals	Silage/Combustible Material
Centrifugal Compressor	
Sizing (hp)	7.5
Capacity (acfm)	51.2
Max P (psi)	175
Type	3-phase
Membrane Air Dryer	
Moisture Content	20% rel. humidity
Duty Size (cfm)	10
Emergency Nitrogen Tank	
Size (L)	50
Contents	Nitrogen Gas

Table 1: *Equipment Table for a Generic Silo Design*

Table 1 represents the equipment specifications used for a relatively small generic silo. For the purposes of implementing our design, the stored material used as a basis for the design is wood pellets, a carbon-based silage material. The size of the silo will vary depending on the amount of material wanted to be stored. The duty and size of the compressor also depends on the amount of material/volume of the silo. Moreover, the maximum operating temperature depends on the nature of the storage material. Operating temperature is further discussed in the Process Description section and a sample calculation for the operating temperature for wood pellets is presented in Appendix A3.

Stream Table:

The following table represents the volumetric flow rates of the purge gas in the streams of system, in terms of the volumetric flow rate ($\dot{V}$) produced by the centrifugal compressor:

Stream Number	Volumetric Flow rate ($\dot{V}$)
1	**0.909Vdot (format in Word)**
2	$\dot{V}$
3	$\dot{V}$
4	**0 (V2 closed), 1 m^3/s (V2 open)**
5	**0 (V2 closed), 1 m^3/s (V2 open)**
6	$\dot{V}$
7	**0.091**$\dot{V}$
8	**0.091**$\dot{V}$

Table 2*: Stream Table for the Silo Design*

Since our system operates variably depending on the volumetric flow rate required to moderate the system temperature (Appendix A1), our streams are in terms of the volume. Air is drawn into the system through stream 8 at a volumetric flow rate that is 0.909 the magnitude of the flowrate produced by the compressor. This is due to the separation of our purge gas when fed into the silo; the separation ratio is 10:1 of the gas going into the silo cooling pipes and directly into the silo body, respectively. The portion of the gas that is directly fed into the silo is then vented out into the environment through stream 7, whereas the remainder of the gas is compressed into the silo cooling pipes and recycled back to the membrane air dryer through stream 1. Table 3 shows sample flow rate values for all system streams, including molar flow rate of Oxygen, for an operation volumetric flow rate of 0.50 m^3/s.

Stream Number	Volumetric Flow rate	Molar Flow rate of Oxygen
1	**0.45 m^3/s**	**4.26 mol/s**
2	**0.50 m^3/s**	**4.69 mol/s**
3	**0.50 m^3/s**	**4.69 mol/s**
4	**0 (closed) 1.00 m^3/s (open)**	**0 - 9.375 mol/s**
5	**0 (closed) 1.00 m^3/s (open)**	**0 - 9.375 mol/s**
6	**0.50 m^3/s**	**4.69 mol/s**
7	**0.05 m^3/s**	**0.43 mol/s**
8	**0.05 m^3/s**	**0.43 mol/s**

Table 3*: Sample flow rate values for all system Streams*

Utility Table:

Electricity is our energy source to power equipment including the computer and the compressor. Compressor will be used 12 hours per day which brings it up to a total of 4320 hours per year. The energy required to run it for that period is 53650.108 megajoules. The computer, on the other hand, will run for 24/7 which gives a total of 1296 hours per year. The energy required to run it for that period is 4665.227 megajoules. Overall, the energy consumed to run this process for a year is 58315.335 megajoules.

Utility	Annual Usage
Electricity	58,315.335 MJ

Table 4: *Utility table for annual electricity usage*

Process & Design Description:

Process Rationale:

The process initially starts by drawing air from the surrounding environment into the system dehumidification unit, a membrane air dryer (see figure 2). For the purposes of our design, the environments where the design is implemented will be relatively hot and dry, like Beirut (Aljazeera S.), Tucson (Climatemps) etc. For that, the air being drawn into the system is taken to be at 20% relative humidity on average, and the atmospheric pressures of these hot and dry desert environments are almost equal to 1 atm on average (Tucson Weather) &

(WeatherWX). Ideally, we would want the air to be 100% dry before purging into the silo; otherwise, humidity would cause clumping of the stored material in the silo which would result in increased heat of generation over time, opposite of the goal of the project. Therefore, the first step of the process is dehumidifying the drawn air through a membrane air dryer. The dry air then flows into our centrifugal compressor where it is stored in the compressor's gas storage tank until a critical discrepancy in temperature is detected by the thermocouples in the silo and the air is needed for purging to reduce that temperature back to a safe level.

Knowing when to release the stored dry air into the silo is based on the design's heat transfer model. Two equations are used to model heat generation and dissipation inside the silo which provides input data for the computer system to determine temperature conditions safe conditions, including the maximum temperature (T_{max}) in the silo before run-away combustion occurs and the safe storage temperature range (see Appendix A1.). The heat generation equation accounts for mass transfer of oxygen to the surface of the combustible material. It also accounts for the reaction rate which is dependent on temperature and oxygen concentration. The heat dissipation equation accounts for the loss of heat by convection to the purge air. These two equations contain many constants determined by the material, silo dimensions, surrounding temperature, and purge gas. The two main variables in these equations are solid material temperature and purge gas flow rate. By setting the equations equal and choosing a flow rate, we can determine the unstable point when temperature will either increase or decrease. By choosing a flow rate which returns an unstable point higher than the current temperature, it is ensured that the temperature is always decreasing when the temperature is too high. The computer system allows us to measure the current temperature, calculate the unstable points in the heat of generation versus dissipation curves, and adjust purge flow rate accordingly.

When the system thermocouples TC-1, TC-2, TC-3, and TC-4 (see figure 2) detect a 10°C discrepancy between local silo temperature and T_{max}, a signal is sent to the central computer system which calculates the flow rate required for the purge gas that will reduce the silo contents' temperature to a safer temperature, where it is beneath the median of the safe operating temperature range. The exact reduction in temperature the system aims to achieve is optimized to what is most cost effective, in terms of utility usage of the compressor, and the lowest temperature it can reach below the median. When the 10-degree-discrepancy is detected at any point in the silo, and after calculating the necessary flow rate for optimized temperature reduction, the computer sends a signal to valve 1 (V-1) to open and the compressor [reference PFD] to release the stored dry air at the required flow rate. The purge gas flows through stream 6 into the silo, where it is then split at a 10:1 ratio (90.1% and 9.1%) a sparger-like gas splitter; most of the gas going through the silo cooling pipes, which is a collection of 32 pipes (6 cm diameter) spread in the center and around towards the wall of the silo, and the rest flows directly into the silo, contacting encountering the stored material. Depending on the nature of the stored combustible material, contact with Oxygen in air will minutely increase the rate of heat generation in the silo by fueling the combustion reaction through mass transfer. Therefore, including pipes in the design was essential to minimizing heat of generation and maximizing dissipation into the pipes. Although the 9.1% fraction of the purge gas that flows directly into contact with the combustible material slightly feeds the combustion reaction/increases heat of generation, it is important to reduce any already-existing moisture in the silo, which might have been introduced when loading the silo with the material or accumulated in the material before loading. The dry air purged through the cooling pipes is recycled back to the air dryer through stream 1 and the portion of the gas purged directly into the silo is vented out into the environment through stream 7 (see figure 2). The reason for venting out the air which encountered the material is to eliminate any existing moisture out of the system and not recycle it back into the membrane air dryer. Over several cycles of recycling the air, the system is guaranteed to be fully dry; this is important not only to minimize the amount of moisture introduced in the silo, but to also minimize corrosion over the entirety of the design, which makes the design more cost effective.

Moreover, the thermocouples monitor the rate of increase of the temperature in the silo, calculated using the heat of generation vs dissipation model (see appendix A1). When the rate of temperature increase reaches a point where dissipation by purging air is not sufficient to compensate for the rate of heat generation, the system operates under emergency mode. This could be caused by excessive internal temperature increase due to malfunctions in the compressor or valves, or it could be due to extraneous factors like on-site fires or major heat waves in the environment etc. When in emergency, pressurized Nitrogen gas is purged into the silo through stream 5; the computer sends a signal to turn off the compressor and closes V-1, then opens V-2 where the pressurized Nitrogen gas is released. Due to Nitrogen having no effect on feeding combustion reactions, it is fed directly into the silo to suffocate the combustion reaction and then vented out into the environment. When the temperature of the silo reaches a safe level, the system closes V-2 and operates normally thereafter. Ideally, the system will always operate normally and will not go into emergency mode unless extraneous factors present themselves. Appendix # shows example calculations for the process given a carbon-based silage material, like wood pellets. Given the versatile nature of the design, heat transfer and process control parameters are adjustable according to different environmental conditions such as temperature, pressure, and humidity, which vary depending on location. For the purposes of the design, Tucson climate will be used as a basis for our modeling and calculations (see Appendix A1.).

Purge Gas Decision Matrix:

The decision for which type of purge gas used was based on 4 criteria: the temperature component, cost effectiveness, environmental impact, and safety of the gas. Each category with its own grading scale according to their importance towards the design. The decision matrix section of Appendix # provides detailed scoring of each alternative.

Temperature:

Divided into two components, temperature control and combustion prevention. Temperature control primarily depends on the extent of heat retention of the gas from the stored material. The basis for this was their individual heat capacities (Table VI), where the higher the heat capacity, the more heat the gas could hold per mole. In terms of combustion prevention, scoring was based on whether a gas would increase the temperature of the silo due to feeding material ignition, based on their properties; ignition occurs when reaching a certain combustion ignition temperature, and oxygen is a key contributor to raising the temperature and fueling the combustion reaction. Air and Nitrogen have relatively higher heat capacities, therefore a higher 'capacity' to retain and remove heat. Due to Air being the only alternative containing oxygen, which fuels combustion, its score for combustion prevention was much lower than that of Argon and Nitrogen; see Table II in Appendix A for criterion values.

Costing:

Divided into the cost of the purge gas and cost of pump used to force the gas through the silo. Gas costs were based on dollar amount per unified unit volume (cubic meters). Gas costing ratios are Nitrogen is 4 times the cost of dry Air, while Argon is 24 times that of dry Air (Vac Aero), and the quantitative costs of the gases depends on the volume and density required for the process, which will be further analyzed in the second stage of the project. The gases would be purchased in tanks by volume and infused in the design where it is continually recycled. Pump cost was based on the power required to pump the gases through the materials in the silo. Because Air and Nitrogen have higher heat capacities, the extent of their heat capacity properties would be maximized if the gas had a higher residence time in the silo. In contrast, Argon has a lower heat capacity. Flowing Argon at the same rate as the other gases would introduce higher temperature gradients between the gas and other locations in the silo, which would defeat the purpose of using a purge gas. The solution would be flowing Argon at a higher rate such that temperature gradients between the gas and the stored material are lower, decreasing the amount of rejected heat transferred back into the material from the gas. On this basis, Argon has a lower score compared to Air and Nitrogen.

Environmental Impact:

Scoring was based on the negative impacts of the gases on the environment. None of the gases pose any intrinsic negative effects on the environment; however, the energy used to produce and process these gases usually come from sources that produce carbon footprint. Air, not requiring any processing to obtain, scores higher while the other two alternatives score similarly and slightly lower, in comparison.

Safety:

Specifically, safety of the workers maintaining the silos that are potentially exposed to the gases due to sudden leaks or when handling the gases. This could occur when filling or changing the existing gases during maintenance, like in the event of silo start-up. Nitrogen and Argon are not harmful unless high concentrations are inhaled at once or lower concentration periodically for an extended period. Scoring was based on asphyxiation limits of each of the gases.

The decision matrix is designed such that a company or an individual customer would use it to form a decision over which gas they should use that best fits their silo stored system, for a given certain combustible material. For the purposes of our design, our aim is to make the silo system the most cost effective. The following table is a summary of how the three alternatives' scores compared to one another in the four categories:

Category	**Alternative 1 (Air)**	**Alternative 2 (Nitrogen)**	**Alternative 3 (Argon)**
Temperature	120	180	180
Safety	20	18	18
Cost	103.4	66.5	35.1
Environment	80	72	72
Total Score	**323.4**	**336.5**	**305.1**

Table 5: *Decision Matrix Summary*

According to table 5, alternative 1 is the cheapest, safest, and the most environmentally friendly alternative; however, it does have the downside of fueling combustion. Alternative 1 would be used in silos storing materials that have low potential for combustion or are not combustible at all. Otherwise, the other two options would be preferred. Moreover, both Nitrogen and Argon have similar scorings in all categories besides cost, where Nitrogen scores higher (cheaper in cost). Tables in appendix E. display the effectiveness of each alternative when cost is not a major factor in the decision and the effectiveness of preventing combustion is prioritized. Argon has a higher combustion prevention score compared to Nitrogen (Table 5). For silos storing mild to high combustible materials, Nitrogen would be a suitable purge gas to use at a lower cost. In the event where marginal cost compared to Nitrogen is not a big deal and combustibility prevention is highly crucial, as for the case of storing extremely combustible materials, Argon is the safer and more effective alternative.

Equipment Description:

<u>Centrifugal Air Compressor:</u>

A centrifugal air compressor is used in the system to provide air for cooling. The centrifugal compressor can provide the necessary output pressure to propel the air through the piping of the silo. Benefits of a centrifugal compressor include providing a smooth air flow and it can handle large flow rates. Centrifugal compressors can also take up less space by having small foundations. The best characteristic of a centrifugal air compressor is the low maintenance needed which will reduce the overall operation costs (Seider et. al 460).

For the system, a two-stage air compressor with 3-phase compatibility is used. A 3-phase was chosen as it provides a steady moving power to the compressor which helps improve the lifespan of the compressor (Lavaa). Specifically, the motor does not have to be constantly turned on and off. The tank also has a tank capacity of 120 gallons allowing some initial loading so that when air flow is needed it can be immediate. Specifically, the Champion Advantage air compressor has a 7.5 hp engine which can provide a max ACFM 51.2 which would be the maxing velocity we would be using for the system. A max outlet pressure of 175 psi is also more than enough to circulate the air through the system.

Computer Control System:

This system is central to the silo design (SEE FIGURE E1). The computer control system will receive 8 inputs. These inputs include temperature inputs from each of 4 thermocouples, on/off signal from the compressor, flow rate data from the compressor, and finally open/close signals from the emergency tank and compressor valves. Using these inputs which are continuously measured, the following loop will run continuously. This system will first record the highest of the thermocouple inputs as a variable T-High. The air flow rate input will then be used in coordination with heat generation and dissipation equations which have been derived for the silo. Using these two equations, the temperature at which they are equal will be recorded as a variable T-max. The variable T-High will then be compared to the T-max. If T-High exceeds T-max minus 10 degrees Celsius then unsafe conditions are assumed, and compressor flow rate will be increased. If the compressor is at its maximum flow rate and unsafe conditions are determined, then the emergency mode will be activated. In emergency mode, the compressor will be shut off, compressor valve closed, and nitrogen valve opened to flow entirely into the silo.

Emergency Nitrogen Tank:

For the purposes of our design, given a carbon-based silage material, air will be used as a purge gas for dissipation, whereas Nitrogen is the emergency backup purge gas, for reasons discussed in the process description section. Nitrogen in the tank is compressed at a known pressure, and when emergency conditions are in operation, V-2 opens the tank to stream 5 to purge Nitrogen into the silo (see figure 2). The amount of Nitrogen is further discussed in Appendix E.

Membrane Air Dryer Dehumidification Unit:

The dehumidification unit in the design ensures that the gas purged into the silo is as dry as possible to prevent introducing moisture in silo; otherwise, moisture would result in the clumping of the stored material, leading to an increase in the heat of generation. Two alternatives for dehumidification were considered: a heat exchanger, used to cool down the gas and precipitate and separating the moisture out, and a membrane dryer, which filters out water molecules from the gas as the method of dehumidification. In terms of the dehumidification process, both methods would result in the same level of efficiency, dehumidifying the gas at a level above 90%, which is the optimum level for the system (Appendix A). However, the alternatives differ in terms of costing. Heat exchangers require electrical input in the form of compressors and thermal monitoring whereas membrane air dryers do not. Additionally, heat exchanger maintenance is almost 15 times more expensive than that pertaining to membrane dryers [costing Appendix]. For these reasons, the membrane dry was more favorable for the design, and given our choice of air as a purge gas for the system, using a membrane air dryer was the choice for dehumidification method. For the carbon-based combustible material used as a basis for calculation in appendix B, the required membrane filter size according to maximum volumetric flow rate is 10 cfm membrane dryer. According to manufacturers, dehumidification efficiency is almost 98%, and given that the purge gas is recycled continuously when the system is operating, the dehumidification process is compounded such that it further dehumidifies the gas.

Safety Issues:

The main goal of our project is to prevent any explosion that might happen when storing large quantities of combustible materials for a long time. To do that, the silo was provided with a set of thermocouples that read temperature inside it and when a sudden increase in temperature happens, a signal will then be sent to a compressor that will compress dried/dehumidified air to the silo to force heat loss which then reduce the temperature. An emergency nitrogen tank is also available and ready to go when air becomes impractical or impossible to reduce the temperature inside the silo. The nitrogen will smother and suffocate the reaction so even if it is hot the temperature will go down. Hazards and operability review was done on each equipment to avoid any explosion and a detailed chart describing this effort can be found in Appendix D.

Compressor

Flow

A compressor works through the output of air measured in volume per unit time. Therefore, any change in the flow of air may cause an explosion. For instance, lack of power to the compressor causes an effect to the compressor where there is a challenge of reducing the heat in the silo. As a result, the material in the silo is combusted. It is crucial to have an indicator light for power flow to the compressor to control this. This will enable easier checking to ensure that the hazard of destroying the materials in the silo is mitigated effectively.

Additionally, the compressor might fail because of the flow of air that can lead to an increase in temperature that may cause combustion. To avoid this, there should be regular maintenance on the equipment. Furthermore, it is vital to ensure that the dehumidifier is in good condition to reduce the effect of erosion.

Reverse compressor installation affects the operation of the pump, thus affecting its ability to lower suction pressure that enables it to have a higher discharge. This may lead to the creation of a vacuum within the silo that can cause an implosion, which leads to clogging of the compressor and the system. Therefore, a start check must be performed during the installation of the compressor to ensure that it is installed in the right direction for optimum operation.

Air is vital for cooling the materials inside the silo. Partial blockage in the compressor may result in less flow of air, thus, low cooling efficiency. This can cause the combustion of the material. To avoid this, it is advised to install it on a perforated floor that can allow easier flow of air through the silo. Additionally, the material should be larger than the size of the perforation.

The computer must always engage with the compressor to ensure a sufficient flow of air. An increase in temperature cannot compensate by increasing the flow rate; hence, this may lead to combustion. To avoid this, there must be a computer indicator that shows the connection to the compressor.

Pressure

Low-pressure compression causes the flow rate not to be high enough. This causes a low dissipation that can lead to combustion. For easier monitoring of this hazard, it is crucial to have performance maps that help in finding the efficient pressure ratio for the desired range of flow rates. On the other hand, high-pressure compression increases the pressure ratio above the standard rating, which can cause severe damages to the compressor. Eventually, this may lead to total failure of the equipment. However, it is possible to avoid this scenario by monitoring the pressure ratio of the compressor. This ensures that it is running at the standard recommended rating.

Temperature

High temperature in a compressor because of low pressure leads to inefficient cooling. This will require a higher flow rate for compensation, thus making it hard for the equipment to perform well. As a safety measure, simulation should be used where equations are modelled, and software used in finding a compression ratio that can achieve the desired temperature output.

Additionally, poor air dehumidification can lead to the formation of condensed water, thus leading to corrosion. Consequently, internal parts such as blades and rings are damaged, thus causing pump failure to control this hazard; it is advised to monitor the air that enters the compressor to probe humidity. Additionally, the efficiency of the dehumidifier should be checked regularly to ensure that it is in good working condition.

Air membrane Dryer

Since a dehumidifier works by drawing air and passing it across cold coils, a low flow of the air makes water condensation difficult, thus affects the whole process. Additionally, purge gas is introduced in the stream, resulting in a steric inability of purge gas to flow freely. This leads to insufficient gas that is present in the silo that plays a critical role in driving the rate of heat dissipation below the rate of heat generation. Therefore, safety measures must be taken in ensuring that the compressors are feeding the air membrane dryer with the correct flow of purge gas.

High pressure caused by the introduction of purge gas to the stream or having a high gas input from the compressor can lead to damage to the membrane. Consequently, the system that regulates temperature in the silo is destroyed and eventually, combustion can occur. As a safety measure, proper monitoring of the compressor should be observed.

Nitrogen Tank

Flow

A Nitrogen cylinder works through the output of nitrogen measured in volume per unit time. Therefore, any change in the flow of nitrogen may not prevent us from explosion. For instance, improper nitrogen flow will result in temperature increasing, which then leads to combustion. Therefore, it is critical to maintain the tank regularly. This helps to ensure that the cylinder valve is working properly.

The computer must always engage with the nitrogen cylinder to ensure a sufficient flow of nitrogen. Hence, an increase in temperature affects the ability of the nitrogen cylinder to compensate by increasing the flow rate, which might cause combustion. As a safety measure, a computer indicator that can conform the connection to the nitrogen cylinder should be put in place.

Computerized Control System

Power

When there is a loss of facility power, there is a disconnection from the source; thus, monitoring of temperature does not take place. This leads to the inability to monitor the temperature inside the silo, posing a high risk of combustion in case the temperature rises beyond the optimum level. A battery-powered alert should be installed to enable reliability since the facility power sources might have outages.

Temperature Data Input

Lack of an input interface for temperature may lead to lose connections and even breaking wires. Thus, the temperature will not be monitored, causing a risk for combustion. It is recommended that there should be data lights that indicate input to avoid such scenarios that can cause severe damage.

Compressor Flow Set by Data Out

Extremely high rates lead to incorrect data of temperature, thus causing inefficient power usage. The system should be designed in a way that prolonged high flow causes an alert that enables intervention measures to correct the fault. On the other hand, extremely low rates can lead to lose connections hence broken wires. This may cause a possible rise in temperature, which can lead to combustion. Having data lights in place can help to indicate the input on the compressor as a safety measure that can be used.

Environmental Impact Statement:

The smart silo design has very few aspects that will impact the environment during its operation. Specifically in this case the only utility consumed will be electricity which the yearly consumption will be 16200 kwh. This translates to a yearly carbon dioxide emission of 13,680 lb./MWh. The two components of the system consuming electricity are the computer which is on for 24 hours along with the centrifugal compressor which will turn on when needed.

Normal operation of the silo will lead to a discharge of air and in cases of emergencies nitrogen gas. Both gases are not hurtful to the environment. There could be some number of solid particles discharging from the silo through the air used to ventilate the stored material, but this should be at a minimum. If hazardous materials are stored it will be important to follow Environmental Protection Agency (EPA) protocols. For the construction of the smart silo system there are no environmental regulations.

Life Cycle Assessment

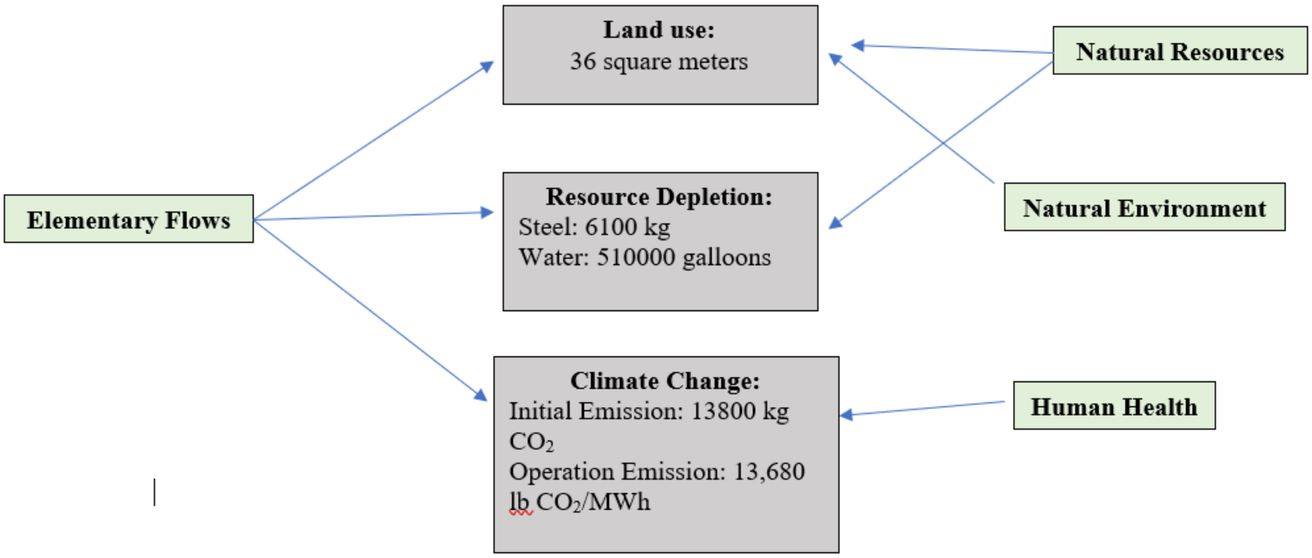


Figure 3. LCA Diagram

Land use for the construction of the smart silo will be the area needed for the foundation of the silo and the area needed for all the equipment. This comes out to be about 36 square meters of land meaning it will be a small impact project when it comes to land use. It also means it will not have an impact on the surrounding environment.

The smart silo system is mostly made up of steel which means large portions of the silo are recyclable. Specifically for this smart silo system 6100 kg of steel will be used. Iron, which is what steel is made from, is not a scarce resource as it is the fourth most abundant element in the Earth's crust (Frey and Reed 1477). At the end of the life cycle of the system most of it can be recycled meaning the impact on landfills will be very low. The only element of concern would be the lead present in the computer system that will have to be disposed of carefully at the end of its life. Raw extraction of steel and its manufacturing does use a lot of water leaving a big water footprint for the creation of the system. For the smart silo system 510000 gallons of water will be used to create the equipment needed.

Greenhouse gases are also created in the process of producing the equipment. This system mostly consists of steel and using "the average GHG emissions based on comprehensive energy consumption form four stainless steel manufacturers in Mainland China" a conversion of 1.76 kg CO_2-e/kg stainless steel was found (Jing et al. 47). The silo itself for being the largest piece of equipment has a CO_2 emission of 9700 kg from its creation followed by the computer system which will emit 3020 kg of CO_2 when created. Including the compressor's 1044 kg of CO_2 and the dehumidifier's 85 kg of CO_2 sums up to a total of 13850 kg CO_2. This is the total amount of CO_2 associated with the system initially.

Economic Analysis (including economic Hazards)

In our system we found the bare module cost of each piece of equipment using purchase cost and a bare module factor for each. These values are listed below in table 5. These values were determined for our model silo equipment. They may need to be adjusted depending on the material being stored and volume required for the silo because equipment may need to be scaled.

	Cp(purchase cost)	Fbm(bare module factor)	CBM	
Silo	15000	1.8	27000	
Compressor	9065	2.15	19489.75	
Air Dryer	2740	2.06	5644.4	
Nitrogen Tank	140	3.05	427	
TOTAL CBM				52561.15

Table 6. *Purchase cost and Bare module cost*

Total Capital investment was also calculated using total bare module cost and other values seen below in table 6. Most of these values were estimated as percentages of total bare module cost, direct permanent investment, or Total permanent investment. These calculations can be found in APPENDIX C.

C_{site}	2628.058
$C_{offsite}$	2628.058
C_{DPI}	57817.27
C_{cont}	8672.59
C_{TDC}	66489.85
C_{land}	0
$C_{royalty}$	0
$C_{startup}$	6648.985
C_{TPI}	81811.43
C_{WC}	8181.143
C_{TCI}	89992.57

Table 7. *Total Capital Investment*

While no profitable product is produced, this process is profitable because it prevents future disasters, damages, and loss of life. To determine average yearly rent for this silo a NPV of approximately 0 at a 20% interest rate was assumed as shown in the table below in TABLE 8.

	Investment						Cash	Cum PV	
Year	fCTDC	CWC	D	C excl D	S	Net Earn	Flow	0	IRR
1	-66,500	-8,000			0		-74,500	-66,500	-66,500
2			3,200	1,400	21,500	12,675	15,875	-53,271	-53,271
3			3,200	1,400	21,500	12,675	15,875	-42,247	-42,247
4			3,200	1,400	21,500	12,675	15,875	-33,060	-33,060
5			3,200	1,400	21,500	12,675	15,875	-25,404	-25,404
6			3,200	1,400	21,500	12,675	15,875	-19,024	-19,024
7			3,200	1,400	21,500	12,675	15,875	-13,708	-13,708
8			3,200	1,400	21,500	12,675	15,875	-9,277	-9,277
9			3,200	1,400	21,500	12,675	15,875	-5,585	-5,585
10			3,200	1,400	21,500	12,675	15,875	-2,508	-2,508
11			3,200	1,400	21,500	12,675	15,875	55	55

Table 8: *NPV calculations*

The required yearly rent was determined to be $21,500. This is a high estimate, and this value can be reduced assuming the compressor is not run continuously, but only when temperatures are too high. Because this system only has an annual cost of electricity it is resistant to economic uncertainty as there are no supply issues to be considered. Rising electricity costs could also be dealt with easily by operating the silo at the minimum flow rate which in most cases would be 0.

Social Impact:

The West Texas fertilizer explosion left a lasting impact on the surrounding community with many bringing up questions about current regulations. Specifically, questions focused on the proximity of such industries to schools and homes (Henry). Living near plants or storages of combustible materials can make community members feel uncomfortable. Some might even question their relative safety especially when an incident of an explosion occurs.

A web application for example called “Ammonium Nitrate in Texas” was developed so that residents can learn if they live near a storage facility with more than 10,000 pounds of ammonium nitrate (Tarrant). This smart silo design can help make communities that are near combustible material storages feel a lot more secure and give members a peace of mind. This can also be a way of improving the relationship of plants that store ammonium nitrate or wood pellets or coal with the surrounding community by indicating a strong desire of keeping everyone safe.

Another important impact is the security that the smart silo system can bring farmers and their crop investments. Silage and crop storage are investments to reduce the cost of purchasing outside feeds in the future. However, if a silo fire does occur it will be an expensive and unexpected purchase for the farmers (Hill). The smart silo design can help mitigate or even prevent the losses of silage because of a fire. This system can give farmers a sense of security and confidence that their investments will be safe for when they need them.

Conclusions and Recommendations:

In our smart silo temperature can be measured and used in heat generation and heat dissipation equations to determine whether temperature will continue to rise or decrease. By using a compressor and air dryer purge air can be introduced into the silo to increase heat dissipation and to prevent clumping or moisture accumulation. The computer system will ensure the silo is kept in a safe temperature range with a target temperature 10 degrees Celsius less than the calculated temperature when dissipation is equal to generation. This accounts for any uncertainty in our calculations. The nitrogen tank accounts for extreme temperatures or unexpected external heat sources by smothering the combustion reaction if air purge gas is calculated to be insufficient. This tank will be properly stored and secured to prevent accidents. No harmful substances are used in this process and the major environmental impact comes from electricity used to power the compressor with a maximum carbon footprint of 13,680 lb. CO_2 per year when run continuously. To reduce cost and environmental impact the compressor will run only when needed. After economic analysis, the total capital investment for the silo and equipment is equal to approximately $90,000 for 100 m^3 of storage space. Equipment specifications were designed for our model silo dimensions and model material properties. For an application of this analysis in a different system these values must be replaced with actual dimensions and properties. Equipment specifications may need to be scaled up or down. This system is most efficient in high temperature areas with low humidity. Higher humidity locations may require more air dryer modules. This system will allow an industry to safely store their materials and show commitment to providing a safe working environment.

Appendices:

Appendix A: Heat Generation & Dissipation Calculations:

The Heat Transfer model compares the heat of generation and heat of dissipation in silo, to then determine the required flow rate of air to purge into the silo and reduce the temperature to a level that is optimum.

A.1: Rationale for Calculations:

A.1.1: *Calculations: Generation*

Heat Generation: Finding the total reaction rate:

Reaction rate $r_a = KC_s$ (accounting for reaction rate coefficient)

Mass rate: $r_M = Km\ (C_b - C_s)$

Total rate: $r_T = \frac{KKm}{K+Km} C_b$

$$Q_g = -\Delta H \text{ (total rate)}$$

Heat generation rate = Total rate x ΔH

$K = Ae^{\frac{-E}{RTs}}$ (Source Arrhenius Equations)

$$Q_g = \frac{(-\Delta H)Km\ e^{\frac{-E}{RTs}}}{\frac{Km}{A} + e^{\frac{-E}{RTs}}} C_b$$

Now, K_m is calculated, which we can use the Sherwood number for spheres to obtain ($Sh_x = 2 \times 0.69\ Re^{1/2} Sc^{1/3}$ for $Re = 0 \sim 200$ and $Sc = 0 \sim 250$) . [5]

To account for counter diffusion:

$$Sh = \frac{Sh_x}{(1+y)_{logm}}$$

where $(1+y)_{logm} = \frac{(1+y_b)-(1+y_s)}{\ln(1+y_b)-\ln(1+y_s)}$ and y_s = mass fraction at the surface, and y_b = mass fraction in bulk:

$$Km = Sh\frac{D_{12}}{D_L}$$

Now Q_g is calculated using the following:

Km = Calculated

ΔH= found for reaction

E = Activation energy found for reaction.

C_b = 9.375 in air

A= pre-exponential factor found for reaction

R = ideal gas constant

Next, we calculate dissipation.

A.1.2: *Calculations: Dissipation*

Heat loss by convection:

$$Q_d = \text{h}(T_s - T_b)$$

For the silo, the convective heat transfer coefficient, ‘h’, can be calculated as f(v) [2]

$\text{h} = 12.12 - 1.16\text{v} + 11.6\sqrt{v}\ \frac{W}{m^2K}$ (for $v = 2 - 20$ m/s)

For the pipes in turbulent flow h can be calculated using Nusselt number [9]:

$$h = \frac{k\ Nu}{D}$$

$$Nu = 2 + \left(0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right)Pr^{0.4}\ \frac{\mu}{\mu s}^{\frac{1}{4}},\ \ where\ \frac{\mu}{\mu s}^{\frac{1}{4}} = 1\ for\ air$$

$$Re > 10000$$

$$0.7 < P_r < 16700$$

$$\frac{\text{L}}{\text{D}} > 10$$

We can now calculate h for the pipes and silo. We now have Q_g [Energy/ (area x time)], $Q_{d\text{-}pipe}$ [Energy/ (area x time)], $Q_{d\text{-}silo}$ [Energy/ (area x time)]. Because the surface area of the pipes is not equal to solid surface, we need to multiply both heat of generation and heats of dissipation terms by area for them to be comparable:

$Q_{g,total} = Q_g A_{silo}$ in Units of Energy/time

$Q_{d,total} = Q_{d,pipe}A_{pipe} + Q_{d,silo}A_{silo}$

A.2: Design & Model Dimensions:

The silo design and heat transfer model are versatile, such that it can be implemented using different dimension parameters based on the kind of combustible material, the size of each particle, and the amount of material stored at one time. The following dimensions were assumed to base the model:

- Silo is vertical and cylindrical in shape, with height = 8 m, Diameter = 4 m, Radius = 2m
- Cross-sectional Area = A_s = ($2m^2$) π = 12.566 m^2. Volume = (12.566 m^2)(8) = 100.53m^3.
- Solid material assumed as spherical pellets, with 1 cm diameters.
- Pipes connecting equipment used are 6 cm in diameter.
- 32 cooling pipes in silo, running through solid material, 6 cm in diameter.

Silo Cooling Pipes, the Second Source of Dissipation (32 pipes):

Total volume occupied by the pipes inside silo = 32(0.0028m^2)(8m) = 0.724 m^3

Cross-sectional area = $(0.03m)^2\pi$ = 0.0028 m^2

Diameter = 0.06 m

Circumference (0.06m) π = 0.1885 m

Radius = 0.03 m

Length = 8 m

Surface Area = (0.1885m) (8m) (32) = 48.255 m^2

Area (A_P) Air flows through = 4(0.0028m^2) = 0.0113 m^2 [Pipes connected in sets of 8]

Solid Material: (1cm sphere) with 0.7 packing density [3]

Material Volume = (0.7)(V_{silo} – V_{pipes}) = 0.7(100.53 m^3 – 0.724 m^3) = 69.865 m^3

Diameter = 0.01 m

Radius = 0.005 m

Volume (particle) = $\frac{4}{3}\pi(0.005m)^3 = 5.236\ x\ 10^{-7}m^3$

Number of particles = $\frac{V_{material}}{V_{particle}} = 1.33\ x\ 10^8$

Surface Area of particle = $4\pi(0.005)^2 = 3.1416\ x\ 10^{-4}m^2$

Total solid surface = (3.1416×10^{-4} m^2)(1.33×10^8) = 41919 m^2

Effective area for air flow (A_e) = $A_p + \left(A_s - \frac{V_{material}}{height}\right)$

A_e = ($0.0113 m^2$) + ($12.566 m^2 - 8.733 m^2$) = $3.845 m^2$

A_{pipes} :

Surface area of the 32 pipes = $48.255 m^2$

Effective area for flow = $3.845 m^2$

Solid material surface area = $41919 m^2$

(Using 1% interfacial Area) Solid-gas interfacial area = $419.19 m^2$

Now,

$Q_{g,total}$ [Energy/time] = $Q_{g,total}$ [Energy/time] x A_{s-gi}[Area]

$Q_{d,total}$ [Energy/time] = $Q_{d,silo}A_{s-gi} + Q_{d,pipe}A_{pipes}$

Using Excel solver for $Q_{d,total} = Q_{g,total}$, we find the maximum operating temperature for a given flowrate by simultaneously solving for temperature.

A.2.1: *Compressor Calculation:*

Ratio of pipe air flow to silo air flow = 10:1

Velocity of air in pipes = $V_{pipe} = \frac{10}{11}\frac{V}{A_p} = \frac{10}{11(0.0113)}V = 80.38V$

Velocity of air in silo = $V_{silo} = \frac{1}{11}\frac{V}{A_s - A_{solid}} = 0.0237\, V$

$$V_{silo} = \frac{1}{3389}\, V_{pipe}$$

Total volumetric air flow rate = $V = 42.19\, V_{silo}$

For power needed in a compressor [6]

$$Pb = 0.00436\left(\frac{k_{air}}{k_{air}-1}\right)\left(\frac{Q_I P_I}{n_B}\right)\left[\left(\frac{Po}{Pi}\right)^{\frac{k_{air}-1}{k_{air}}} - 1\right]$$

k_{air} = 1.4 (air), n_B = 0.7 (efficiency), $\frac{Po}{Pi} = 2$ [7]

Q_I = V (35.3147 ft^3/m^3)(60 s/min)

$P_B = 0.32046 Q_I$ [0.219] = 148.71 V

Power in H_p is 148.71 x Flowrate in m3/s

Using required V_{pipe} as a reference

Power = 1.84 V_{pipe}

Membrane Air Dryer Calculations:

System recycles pipe air and vents silo air.

$\frac{1}{11}V = Flowrate\ to\ be\ dried\ (V_{dry})$

Using required V_{pipe} for reference

[m3/s] V_{dry} = 0.00113 V_{pipe}

[f3/min] V_{dry} = 2.396 V_{pipe}

Emergency Tank Specifications:

When purged, the volumetric flow rate is 1 m^3/s.

Computer logic:

- Read thermocouples 1-4
- Solve for T_{max} when $Q_{g,total} = Q_{d\text{-}total}$ for current V
- If any thermocouple (T) > T_{max} (v) then increase V until T_{max} >1,1 (highest T)
- If any thermocouple (T) > $T_{system,max}$ then open valve for nitrogen tank and shutdown compressor

<u>A.3: Sample Calculations:</u>

These values were obtained by verbal communication from our project mentor, Dr. Shadman:

Using a generic carbon-based material, like wood pellets, the following is a sample calculation for heat transfer:

For different stored materials, actual values can be used in place of the following:

(ΔH=-4145 Kj/mol , A=10,000 , E = 60Kj/mol R = .00831 Kj/mol*K)

Molar concentration O2 in air = 9.375 mol/m^3

Assume Volumetric flowrate , V =0.5m^3/s

V_{pipe} = (80.38m^2 *V)= 40.19 m/s

V_{silo} = (V_{pipe}/3389) = 0.01186 m/s

h(pipe)= (12.12-1.16v_{pipe} +11.6($v_{pipe}^{1/2}$))=0.020 KW/m^2 *K

h(silo)= (12.12-1.16v_{silo} +11.6($v_{silo}^{1/2}$))=0.012 KW/m^2 *K

Km = Sh(D/L) = 0.0035 m/s

Heat of generation equation:

$$Q_g = \frac{(-\Delta H)Km\, e^{\frac{-E}{RTs}}}{\frac{Km}{A} + e^{\frac{-E}{RTs}}} C_b$$

$$Q_g = \frac{(4145)(0.0035)\exp\left(\frac{-60}{(0.00831)T}\right)}{\frac{(0.0035)}{(10000)} + \exp\left(\frac{-60}{(0.00831)T}\right)}$$

$$Q_g = \frac{(14.5)\exp\left(\frac{-7220}{T}\right)}{3.5E^{-7} + \exp\left(\frac{-7220}{T}\right)}$$

$$Q_{g,total} = 48.225\mathrm{Q}_g$$

Heat of dissipation:

$$\mathrm{Q}_d = \mathrm{h}(T_s - T_b)$$

Through pipe:

$$Q_{d,pipe} = \mathrm{h}(T_s - T_b)$$

$$h_{pipe} = (12.12 - 1.16v_{pipe} + 11.6\left(v_{pipe}{}^{0.5}\right) = 0.020\ kW/m^2$$

$$Q_{d,pipe} = 0.020(\mathrm{T} - 298)$$

Through silo:

$$Q_{d,silo} = \mathrm{h}(T_s - T_b)$$

$$h_{pipe} = (12.12 - 1.16v_{pipe} + 11.6\left(v_{pipe}{}^{0.5}\right) = 0.012\ kW/m^2$$

$$Q_{d,silo} = 0.012(\mathrm{T} - 298)$$

<u>Total dissipation:</u>

$$Q_{d,total} = A_{pipe}\left(Q_{d,pipe}\right) + A_{silo}\left(Q_{d,silo}\right) = 6.09(T - 298)$$

Simultaneously solving for T (using Excel Solver):

$$Q_{g,total} = Q_{d,total}$$

$$\frac{(48.225)(14.5)\exp\left(\frac{-7220}{T}\right)}{3.5E^{-7} + \exp\left(\frac{-7220}{T}\right)} = 6.09(T - 298)$$

Solving for T, the maximum safe operating temperature (T_{max})= **364.3 K @ 0.5 m^3/s** volumetric flowrate.

Figure A.1: Heat Generation vs Dissipation

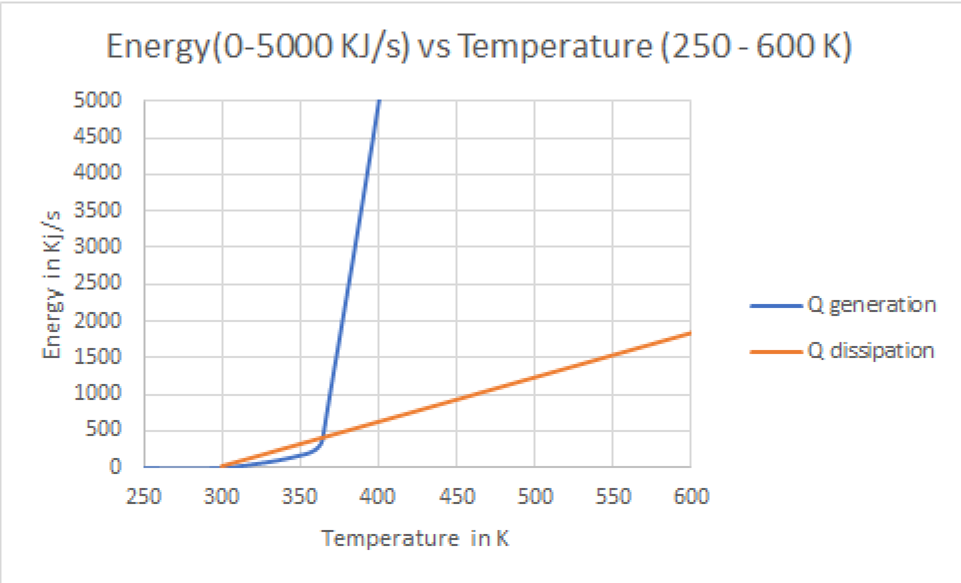
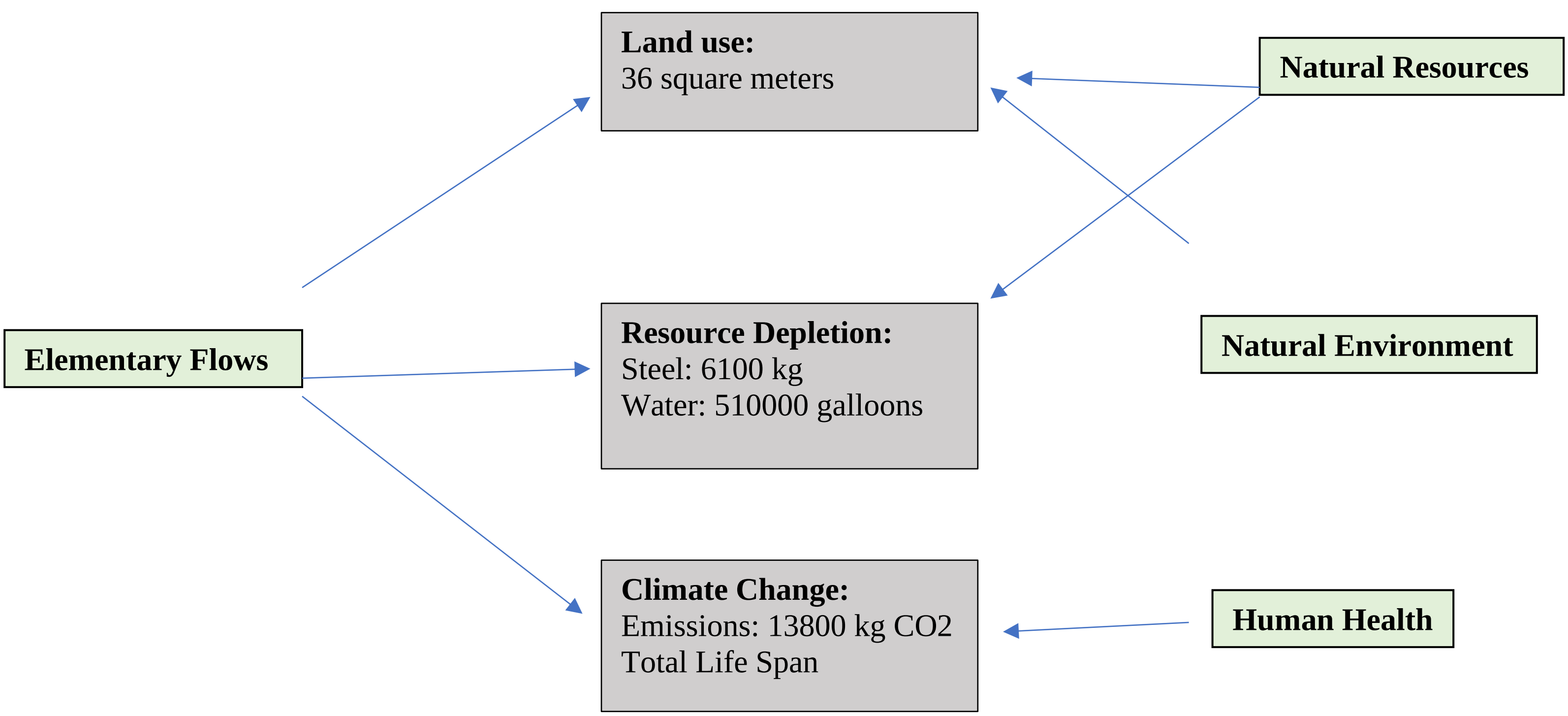


Table A.1: Sample Stream Table for Wood Pellets

Stream Number	Volumetric Flowrate	Molar Flowrate of Oxygen
1	0.45 m^3/s	4.26 mol/s
2	0.5 m^3/s	4.69 mol/s
3	0.5 m^3/s	4.69 mol/s
4	0(closed) 1 m^3/s (open)	0 to 9.375 mol/s
5	0(closed) 1 m^3/s (open)	0 to 9.375 mol/s
6	0.5 m^3/s	4.69 mol/s
7	0.05 m^3/s	0.43 mol/s
8	0.05 m^3/s	0.43 mol/s

Appendix B: Environmental Calculations:

Figure B.1: Life Cycle Analysis



LCA Calculations:

Silo dimensions: 8 m by 4 m

Area of Circle: πr^2

Cross-Sectional Area Silo: $\pi(\frac{4\ m}{2})^2 = 12.57$ m^2

Foundation Dimensions (square): $\sqrt{12.57\ m^2} = 3.55\ m\ \approx 4\ m$

Area for Equipment: $4\ m\ \times 4\ m = 16\ m^2$

Total area: $A_E + A_F = 16\ m^2 + (4\ m)^2 = 36\ m^2$

Compressor Impact:

- Weight: 1305 lbs. *Assumption:* Majority Steel (Champion Advantage Duplex)
- 1.76 kg CO2/kg steel (Jing et al. 47)

CO_2: $\frac{1305\ lbs.}{1} \times \frac{1\ kg}{2.2\ lbs.} \times \frac{1.76\ kg\ CO2}{kg\ stainless\ steel} = 1044\ kg\ CO_2$

Energy and Environmental Profile (Margolis, Nancy, and Sousa)

- 75,000 gal. water per ton of steel
- 6.6 lbs SOx/ton steel
- 2.5 lbs NOx/ton steel
- 0.8 lbs CO/ton steel

SO_x: $\frac{1305\ lbs.}{1} \times \frac{1\ ton}{2000\ lbs.} \times \frac{6.6\ lbs\ SOx}{ton\ steel} \times \frac{1\ kg}{2.2\ lb} = 1.96\ kg\ SO_x$

NOx: $\frac{1305\ lbs.}{1} \times \frac{1\ ton}{2000\ lbs.} \times \frac{2.5\ \ lbs\ SOx}{ton\ steel} \times \frac{1\ kg}{2.2\ lb} = 0.74\ kg\ NO_x$

CO: $\frac{1305\ lbs.}{1} \times \frac{1\ ton}{2000\ lbs.} \times \frac{0.8\ \ lbs\ SOx}{ton\ steel} \times \frac{1\ kg}{2.2\ lb} = 0.24\ kg\ CO$

H_2O: $\frac{1305\ lbs.}{1} \times \frac{1\ ton}{2000\ lbs.} \times \frac{75000\ \ gal.\ \ H_2O}{ton\ steel} = 48938\ gals\ H_2O$

For recycling about 90% can be while the remaining 10% landfill

Silo Impact:

- Shell steel thickness: 7 mm (Selvam, Grace, and Muthiralan 2273)
- Density of steel: 7850 kg/m^3 (EngineeringToolBox.com, Metals and Alloys – Densities)

Volume of steel used in Silo: $V = \ \pi h(r_1^2 - r_2^2)$

- h = 8 m, r1 = 2 m, r2 = 2-0.007 = 1.993 m

V_{silo}: $\pi \times 8\,m\,((2\,m)^2 - (1.993\,m)^2) = 0.702\,m^3$

M_{silo}: $7850\,\frac{kg}{m^3} \times 0.702\,m^3 = 5511\,kg$

CO_2: $5511\,kg \times \frac{1.76\,kg\,CO2}{kg\,steel} = 9699\,kg\,CO_2$

SO_x: $\frac{5511\,kg}{1} \times \frac{1\,ton}{907.185\,kg} \times \frac{6.6\,lbs\,SOx}{ton\,steel} \times \frac{1\,kg}{2.2\,lb} = 18.22\,kg\,SO_x$

NOx: $\frac{5511\,kg}{1} \times \frac{1\,ton}{907.185\,kg} \times \frac{2.5\,\,lbs\,SOx}{ton\,steel} \times \frac{1\,kg}{2.2\,lb} = 6.9\,kg\,NO_x$

CO: $\frac{5511\,kg}{1} \times \frac{1\,ton}{907.185\,\,kg} \times \frac{0.8\,\,lbs\,SOx}{ton\,steel} \times \frac{1\,kg}{2.2\,lb} = 2.21\,kg\,CO$

H_2O: $\frac{5511\,kg}{1} \times \frac{1\,ton}{907.185\,kg} \times \frac{75000\,\,gal.\,\,H_2O}{ton\,steel} = 455613\,gals\,H_2O$

For recycling the majority can be recycled

Computer Impact:

Table B.1: Embodied Energy of Life Cycle of the PC

Life cycle of PC	Embodied Energy (MJ)	Carbon Factor (KgCO2eq)
Raw material Extraction	4534 (21.8 %)	829.85 (27.5 %)
Manufacturing	7889 (38.1 %)	975.6 (32.33 %)
Transportation	45 (0.22 %)	2.82 (0.09 %)
Use	8237 (39.7 %)	1207.32 (40 %)
EoL	37 (0.18 %)	2.16 (0.07 %)

(Sirait, Biswas, Boswell 279)

Raw material: Focus on Major Components (Sirait, Biswas, and Boswell 278)

- Steel: 8.97 kg, 32.47%
- ABS: 3.87 kg, 14.01%
- Silica: 5.18 kg, 18.77%
- Copper: 1.09 kg, 3.98%
- Lead: 1.08 kg, 3.93%
- Aluminum: 1.04 kg, 3.77%

- Barium: 0.49 kg, 1.79%
- Strontium: 0.49 kg, 1.76%
- Silicon: 0.42 kg, 1.53%
- Epoxy: 0.31 kg, 1.12%
- Iron: 0.28 kg, 1.02 %

Total CO_2: 3017.75 kg CO_2

H_2O: Footprint = 6.247 m^3 (Product Water Footprint Report of Computer. Lenovo)

$$6.247\ m^3 \times \frac{264.172\ gal}{1\ m^3} = 1650.28\ gallon\ H_2O$$

<u>Dehumidifier Impact:</u>

Stainless steel made with weight of 38 kg: (50 hp compressed air dryer)

CO_2: $48\ kg \times \frac{1.76\ kg\ CO2}{kg\ steel} = 84.48\ kg\ CO_2$

SO_x: $\frac{48\ kg}{1} \times \frac{1\ ton}{907.185\ kg} \times \frac{6.6\ lbs\ SOx}{ton\ steel} \times \frac{1\ kg}{2.2\ lb} = 0.16\ kg\ SO_x$

NOx: $\frac{48\ kg}{1} \times \frac{1\ ton}{907.185\ kg} \times \frac{2.5\ \ lbs\ SOx}{ton\ steel} \times \frac{1\ kg}{2.2\ lb} = 0.06\ kg\ NO_x$

CO: $\frac{48\ kg}{1} \times \frac{1\ ton}{907.185\ \ kg} \times \frac{0.8\ \ lbs\ SOx}{ton\ steel} \times \frac{1\ kg}{2.2\ lb} = 0.02\ kg\ CO$

H_2O: $\frac{48\ kg}{1} \times \frac{1\ ton}{907.185\ kg} \times \frac{75000\ \ gal.\ \ H_2O}{ton\ steel} = 3968.32\ gals\ H_2O$

<u>Total System Impact:</u>

- Total CO_2: $84.48\ kg\ CO_2 + 3017.75\ kg\ CO_2 + 9699\ kg\ CO_2 + 1044\ kg\ CO_2 = 13845.2\ kg\ CO_2 \rightarrow 13800\ kg\ CO_2$
- Total H_2O: $3968.32\ gals\ H_2O + 1650.28\ gallon\ H_2O + 455613\ gals\ H_2O + 48938\ gals\ H_2O = 510170\ gals\ H_2O \rightarrow 510000\ gals\ H_2O$
- Total Steel: $8.97\ kg + 1305\ lbs \times \frac{1\ kg}{2.2\ lbs} + 5511\ kg = 6113.15\ kg \rightarrow 6100\ kg\ of\ steel$

Appendix C: Economic Calculations:

Economic Calculations:

Purchase cost:

Centrifugal Compressor:

Eqn. 16.30:

$$Pb = 0.00436\left(\frac{k_{air}}{k_{air}-1}\right)\left(\frac{Q_I P_I}{n_B}\right)\left[\left(\frac{Po}{Pi}\right)^{\frac{k_{air}-1}{k_{air}}} - 1\right]$$

- Assumptions:
  - k_{air} (air,standard) = 1.4
  - n_B = 0.7
  - P_I = 14.7 psi
  - Compression ratio 2 so P_O = 29.4 psi
  - Q_I [ft^3/min]
- Q_I= (0.5 m/s)*(60 s/min)*(π*(0.25 m)^2/4)*(35.3147 ft^3/m^3) = 52.01 ft^3/min
- P_B = 0.070185*52.01 ft^3/min = 3.65 bhp => 4 bhp
- Our centrifugal compressor specifications:
  - 7.5 hp, two stage, 51.2 ACFM, maximum pressure of 175 psi, with 3-phase compatibility. For our required specifications for the system, the fixed cost of our compressor is $9065. [1]

C_P = $9065

Membrane Air Dryer:

We are assuming a maximum 20% relative humidity of the air in the environment, which will be drawn directly into the dryer. Also, given our 8-meter higher, 4 meters in diameter silo body, a maximum of two 10 cfm duty would be needed in accordance with our compressor:

- Median cost is $1370/unit, taken from the manufacturer SPX Hankison (Total fixed cost = $2740).[4]
- At our production rate, membrane filter change is required at most twice/year (Total variable cost = $100/year).

- No electrical input required for operation.
- First year of installation of the dryer is $2840, and $100 for filter changing thereafter. Given the rate of duty towards the dryer, we assume it will need to be fully replaced every 8-10 years. Possibly, if more units are used at the same time, this would extend their lifetime. However, optimizing the number of units, to increase longevity of the equipment and minimize the number of times it needs to be replaced, is relative to the size of the silo, exact humidity of the environment (our design could be implemented in environments where it is more than 20% in relative humidity). For our silo size and humidity of the environment, two units are the optimum number.

C_P = $2740

Emergency Nitrogen Tank:

- Nitrogen Cylinders are commercially available in 40ft^3 size from New 40 cuft Steel Nitrogen Cylinder | Gas Cylinder Source
- Cost per cylinder approximately $70
- Giving a total one-time cost of nitrogen to be 2 x $70 = $140
- This is one extreme where we are buying new cylinders filled with nitrogen gas. The other extreme would be renting them and signing with a third-party firm where they come to site and fill our nitrogen tanks for us. Our estimated cost is 65% of the costs we calculated, based on filling pricings we found online.

C_P = $140

Silo:

- **Approximate silo cost of $15,000 for stainless steel**

C_P = $15000

Bare module cost

Bare module factors found (Seider, et. al, 441) give bare module cost.

BMF (silo= 1.8 , compressor= 2.15 , Dryer= 2.06 ,Horizontal pressure vessel= 3.05)

C_{TBM} = sum((Bare module factor * Purchase cost))

C_{TBM} = (1.8*15000)+(2.15*9065)+(2.06*2740)+(3.05*140) = $52,560

Direct permanent investment

C_{DPI}= $C_{TBM} + C_{site} + C_{offsite}$ (Seider, et. al, Chapter 17)

C_{site}= 0.05C_{TBM}

$C_{offsite}$= 0.05C_{TBM}

C_{DPI}= $58,000

Total Depreciable Capital

C_{TDC}= C_{DPI}+ C_{cont}

$C_{cont} = 0.15 C_{DPI}$

C_{TDC}= $66,500

Total permanent investment

C_{TPI}= $C_{TDC} + C_{land} + C_{Royal} + C_{Startup}$

$C_{land} = C_{Royal} = 0$

$C_{Startup} = 0.1 C_{TDC}$

C_{TPI}= 82,000

Total capital investment

C_{TCI}= $C_{WC} + C_{TPI}$

C_{WC} = 0.1C_{TPI}

C_{TCI}= $90,000

Appendix D: Hazardous Operations Tables:

Hazards and Operability Review					
Study Node	**Process Parameter**	**Deviations (Guide words)**	**Possible Causes Comment on L,M,H likelihood**	**Possible Consequences Include info on process immediately downstream**	**Action Required**
Compressor	Flow	No	No power to compressors (L)	Heat within silo cannot be reduced leading to combustion of material.	Power indicator light.
		No	Compressor failure (L)	Improper air flow resulting in temperature increasing to combustion.	Regular maintenance and ensuring the dehumidifier is working properly to reduce erosion.

		Reverse	Installed the wrong direction (M)	Can create vacuum within silo causing implosion, causing material to clog compressor and system.	Performing a start check when installing compressor to make sure it is in the right direction.
		Less	Partial blockage of compressor (M)	Improper flow rate of air leading to insufficient cooling resulting in combustion of material.	Install a full perforated floor allowing air to flow through silo, ensure material is larger than perforation size.
		Less	Computer not engaging with compressor (M)	When temperature spikes compressor will not compensate by increasing flowrate leading to combustion.	Computer indicator conforming connection to compressor.

		Less	Pressure compression too low (M)	Flow rate will not get high enough resulting in low dissipation which causes combustion.	Performance maps to find the most efficient pressure ratio for the desired range of flow rates.
	Pressure	High	Pressure compression too high (L)	Pressure ratio above rating can result in damages to compressor components leading to failure.	Monitor pressure ratio of the compressor to make sure it is running at or below rating.
		More	Compressio-n pressure too low to reduce temperature enough at the outlet (M)	Cooling less efficient which will require a higher flow rate to compensate leading to a harder working compressor.	Modeling equations and software to find compression ratio to get desired outlet temperature. Temperature probe at outlet flow.

	T	Corrosion	Air not dehumidifier -d completely resulting in condensed water (H)	Damaged internal parts like blades and rings leading to pump failure.	Humidity probe monitoring air entering compressor. Checking dehumidifier efficiency
Air Dryer	Flow	Less	Low flow from compressors or inert gas introduced in stream resulting in steric inability of purge gas to flow through freely.	Not enough gas will be present in silo to drive rate of Qd below rate of Qg adequately.	Monitor/make sure compressors are feeding air membrane dryer with correct flow of purge gas.

	Pressure	High	Due to having inert gas introduced to the stream or high gas input from compressor.	Disorientating/damaging membrane, ruining temperature regulation system in silo, eventual combustion of silo.	Properly monitor compressors.
Nitrogen Tank	Flow	No Less	Nitrogen Cylinder failure (L) Computer not engaging with Nitrogen Cylinder (M)	Improper Nitrogen flow resulting in temperature increasing which then lead to combustion. When temperature increases, the Nitrogen Cylinder will not be able to compensate by increasing flow rate, which then leads to combustion.	Regular maintenance to make sure the cylinder valve is working properly. Computer indicator conforming connection to Nitrogen Cylinder.

Computer Control System	Power	No	Loss of facility power, disconnected from source.	No temperature monitoring. Combustion possible.	Battery powered alert.
	Temperatur-e Data Input	No	Loose Connections/broken wires	No temperature monitoring. Combustion is possible.	Data lights to indicate input.
	Compresso-r flow set by data out	Too high	Incorrect T data.	Inefficient power usage.	Prolonged high flow causes an alert.
		Too low	Loose connections/ broken wire.	Possible temperature rises and combustion.	Data lights to indicate input on the compressor.

Appendix E: Other Figures and Diagrams:

Figure E.1: Computer System Logic

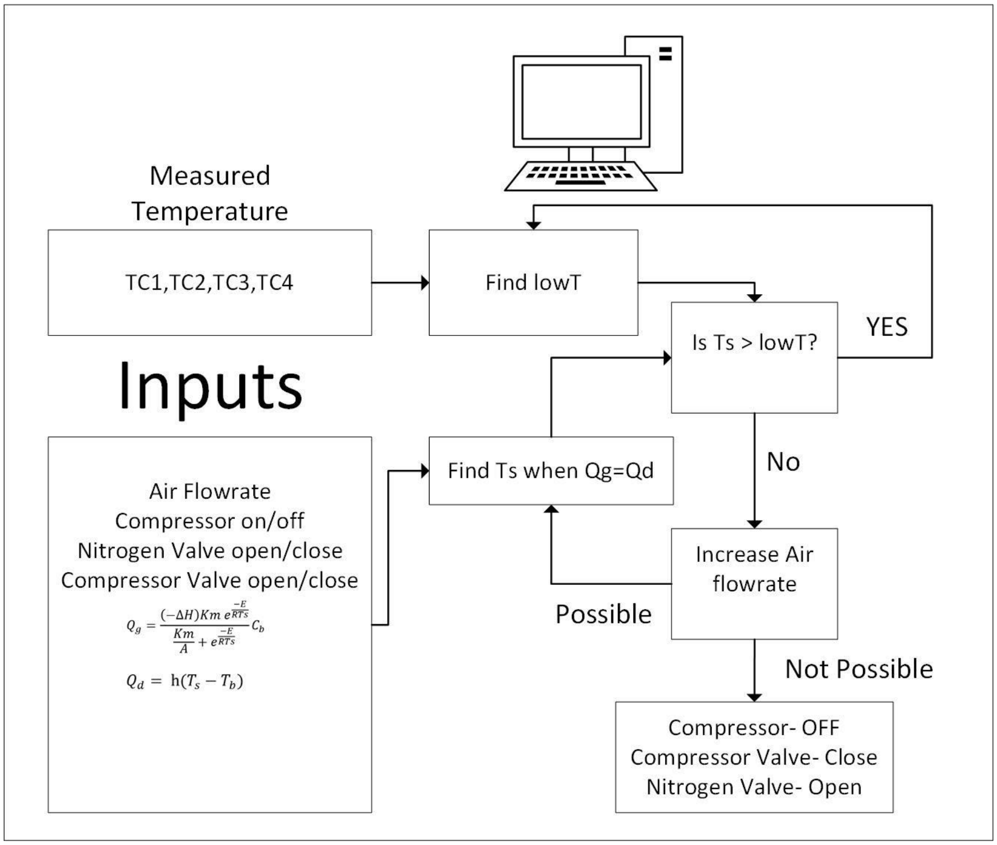


Table E2: Decision Matrix Without Cost Category

Category	**Alternative 1 (Air)**	**Alternative 2 (Nitrogen)**	**Alternative 3 (Argon)**
Temperature	120	180	180
Safety	20	18	18
Environmental	80	72	72
Total	**220**	**270**	**270**

Table E3: Detailed Decision Matrix (Alternative 1)

Category	Criterion	Category Weight	Criteria Weight	Alternative Score
Temp.	Temperature control	20	10	120
	Combustion Prevention		10	
Safety	Safety	2	2	20
Cost	Gas Cost	12	8	103.4
	Pump Cost		5	
Environment	Impact	8	8	80
			Total	**323.4**

Table E4: Detailed Decision Matrix (Alternative 2)

Category	Criterion	Category Weight	Criteria Weight	Alternative Score
Temp.	Temperature control	20	10	80
	Combustion Prevention		10	
Safety	Safety	2	2	18
Cost	Gas Cost	12	8	66.5
	Pump Cost		5	
Environment	Impact	8	8	72
			Total	**336.5**

Table E5: Detailed Decision Matrix (Alternative 3)

Category	Criterion	Category Weight	Criteria Weight	Alternative Score
Temp.	Temperature control	20	10	180
	Combustion Prevention		10	
Safety	Safety	2	2	18
Cost	Gas Cost	12	8	35.1
	Pump Cost		5	
Environment	Impact	8	8	72
			Total	**305.1**

Table E6: Heat Capacities for Alternative

Alternatives	**Air (1)**	**Nitrogen (2)**	**Argon (3)**
Heat Capacities (J/mol K)	29.19	29.11	20.78

Appendix F: Nomenclature and Variables:

A: Pre-exponential factor for Arrhenius equation.

Ae: Total effective area for air flow.

A_p: Total cross-sectional area of the pipes.

A_{pipe}: Combined surface area of pipes.

A_s: Cross-sectional area of the silo.

$A_{s\text{-}gi}$: Area of the solid-gas interface.

A_{silo}: Internal surface area of the silo.

A_{solid}: Total surface area of the solid material within the silo.

BMF: Bare module factor

C_b: Concentration of O2 in bulk gas.

C_P: Purchase cost

C_{TBM}: Total bare module cost

C_{DPI}: Direct permanent investment

C_{site}: cost of site preparations

$C_{offsite}$: cost of service facilities

C_{TDC}: Total depreciable capital

C_{cont}: Cost of contingencies and contractor fees

C_{TPI}: Total permanent investment

C_{land}: Cost of land

C_{royal}: Cost of royalties

$C_{startup}$: Cost of startup

C_{TCI}: Total capital investment

C_{WC}: Working capital

C_s: Concentration of O2 at surface of the stored combustible material.

D: The diameter of the pipes.

D_{12}: Diffusivity of air into solid

D_L: Characteristic length (diameter of particles)

E: The activation energy for the combustion reaction within the silo.

h: Heat transfer coefficient.

ΔH: Change in enthalpy of combustion reaction.

k: Reaction rate coefficient.

k_{air}: The standard specific heat ratio of air.

Km: Mass transfer coefficient.

L: The length of the pipes.

n_B: The air compressor efficiency.

Nu: Nusselt number.

P_B: The brake horsepower of the air compressor in hp.

P_I: The pressure of the air entering the air compressor in pounds per square inch (psi).

P_O: The pressure of the air exiting the air compressor in pounds per square inch (psi).

Pr: Prandtl number.

Q_d: The heat dissipation term.

$Q_{d,\ pipe}$: Heat dissipation through the pipes after applying the surface area of the pipes.

$Q_{d,\ silo}$: Heat dissipation through the silo after applying the surface area of the silo.

$Q_{d,\ total}$: Total heat dissipation of the system.

Q_g: The heat generation term.

$Q_{g,\ total}$: Total heat generation of the system after applying the surface area of the solids.

Q_I: Volumetric flowrate going through the air compressor in cubic feet per minute (CFM).

R: The molar gas constant [kJ/mol K].

r_a: reaction rate of the solid material.

Re: Reynolds number.

Sh: Sherwood number.

Sc: Schmidt number.

T_b: Temperature of the bulk fluid which is our purge gas.

T_{max}: Maximum temperature that the silo can operate at which is when the heat of generation is equal to the heat of dissipation at different air velocities.

T_s: Temperature of the solid material within the silo.

$T_{system\ max}$: It is the maximum temperature that the silo can operate at which is when the heat of generation is equal to the heat of dissipation at the maximum air velocity.

V: The total volumetric flowrate going through the system.

V_{dry}: Volumetric flowrate of air entering the dryer system.

v: The velocity of air.

$v_{material}$: Total volume of the materials within the silo.

$v_{particle}$: The volume of a single particle that is within the silo.

V_{pipe}: Volumetric flowrate of air going through the pipes.

V_{silo}: Volumetric flowrate of air going through the silo.

y_b: mass fraction in bulk.

y_s: mass fraction in source.

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