Portland State University
Maseeh College of Engineering and Computer Science

HUMIDIFYING A SEALANT CURE OVEN

PROGRESS REPORT

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Executive Summary

Boeing is the world's leading aerospace company and the largest manufacturer of commercial and military aircrafts. With an ever-increasing product line, more efficient manufacturing and design process is required in order to meet customer needs. As a result, the proper application of sealant to the aircraft parts is essential in achieving the required quality and reliability. The application of sealant on the aircraft parts prevents it from corrosion which jeopardizes the load carrying capability of the aircrafts. The sealant curing process requires controlled temperature and relative humidity conditions in order to avoid extensive and costly maintenance. Boeing's current sealant curing method is inconvenient and inefficient. It is for this reason Boeing has sought to improve upon the current curing methods.

Rory Olson, a research and development engineer at Boeing approached the MCECS in order to improve the current curing method. The Boeing's senior design team is doing exactly that by designing humidity controlled curing oven which will be retrofitted to Boeing's current ovens. A prototype will be delivered by June 2012.

The following document will familiarize the reader with this project by providing background information. It will then provide detail on the project progress up to date, solution selection, and finally propose a detailed design plan. Research methods and an updated version of the product design specifications are provided to support design analysis and evaluation.

Table of Contents

Introduction and Background

Boeing designs aircrafts that resist corrosion through the use of proprietary corrosion inhibiting sealants. The sealant curing process is essential in order to guarantee the quality and reliability of the aircraft and control corrosion to avoid jeopardizing the intended load carrying capability of the airplane [3]. The sealant curing process requires controlled temperature and relative humidity conditions in order to avoid extensive and costly maintenance.

Boeing uses a two-component polysulfide sealant containing corrosion inhibiting chromate to effectively eliminate corrosion. The two current approaches of curing the sealant are the “traditional” and “lean” methods.

The traditional method utilizes large curing ovens (Figure 1). Although the ovens allow for humidity control (accelerating the curing process) they are not equipped with corrosionresistant materials and are therfore heavily corroded. These ovens are large monuments (big enough to drive a car into) that require dedicated wiring and plumbing

Figure 1: Boeing’s Traditional oven

Figure 2: Boeing’s Lean oven

which makes them costly to move. Their large size also contributes to poor flow conditions and temperature stability. The more recent "lean" method utilizes smaller ovens offering better flow control and temperature stability (Figure 2). The small dimensions (3' wide x 6' long x 4' deep) and power requirements (120 Volts at 60 Hz) allow the machine to be moved with relative ease and located wherever a typical wall outlet can be found. However, these ovens are not equipped with humidity control and also require fixed plumbing.

Table 1: *List of current methods, their advantages and disadvantages.*

Method	Advantages	Disadvantages
Lean	• Proper Flow • Not Hardwired	• No Humidity Control • Plumbed
Traditional	• Humidity Control	• Large Size • Hardwired/ Plumbed

Mission Statement

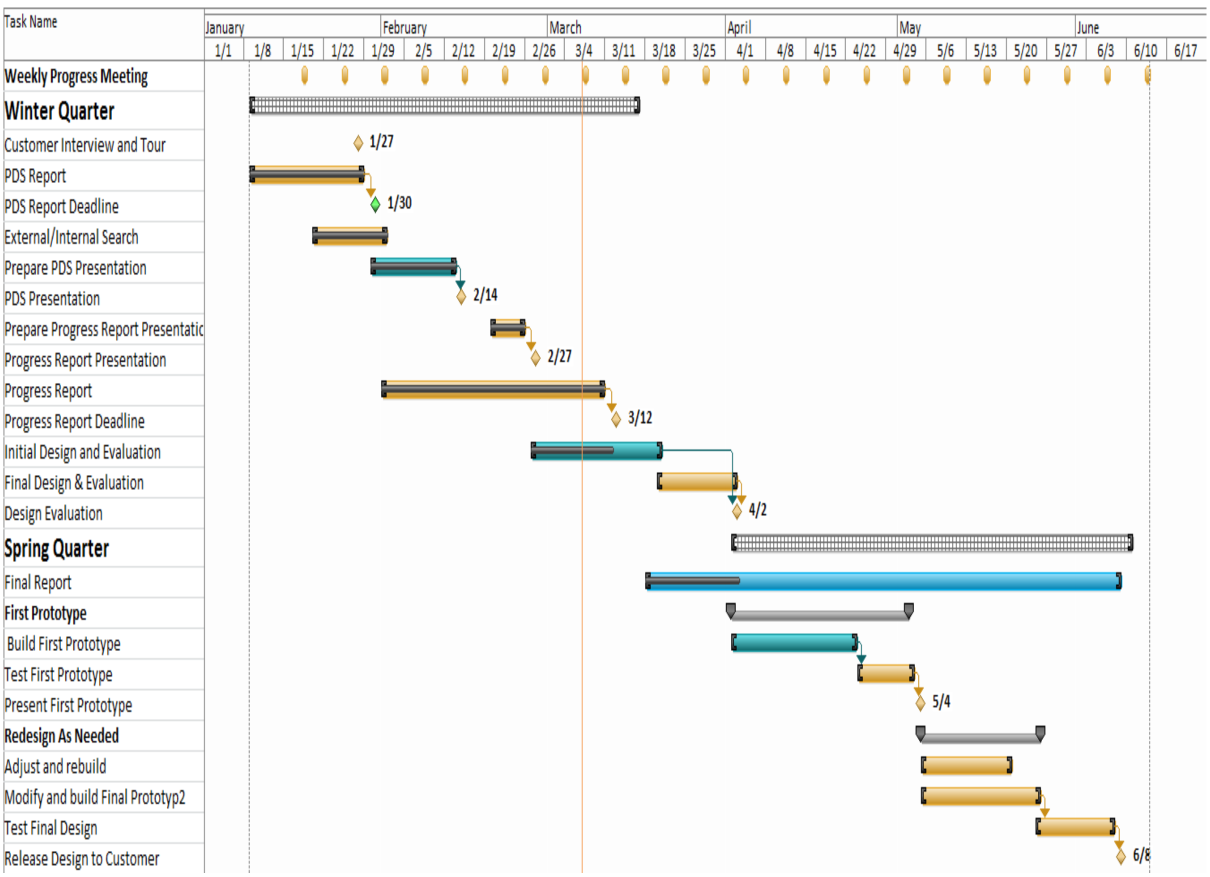
The main purpose of this project is to design a highly efficient curing oven that can embrace the advantages of each of the current methods known as "lean" and "traditional". The capstone team's design must be retrofit-table to Boeing's existing lean ovens with dimensions of 3'wide x 3' long x 4' deep with possible application important enhancements. These enchantments include a non- corrosive, humidity and temperature controlled environment that maintains the required lightweight design (< 250 lbs.). The capstone team is working on a concept which will meet those criteria.

This project involves research, development and implementation. The design team is expected to contribute time and energy in researching for potential solutions as well as building an operational prototype by the end of May 2012 in order to meet the deadline.

Latest Project Planning Document

Gantt chart is used to indicate a rough outline of the project progress up to date and further future plans. The chart indicates some design goals and shows the reference date of its completion. It will keep changing and evolving according to the deadlines. The Grant chart below shows the most current updates of this project.

Gantt chart:



Final Product Design Specification Summary

The Product Design Specification (PDS) is a document used to define the criteria and requirements for the design project. In the document, a list of engineering metrics and targets has been developed based on customer needs as well as the requirement of the sponsor. The PDS is also used as a verification of the team's progress. Once the PDS has been developed, any changes or improvements in the design must be correlated to the PDS to ensure the project is developing as planned. The main performance criteria of the project are listed below. A more detailed PDS is shown in Appendix B.

- Humidity inside the oven must be controlled at 50±5% RH.
- Temperature inside the oven needs to be maintained at 130±5^{o}F.
- The designed oven is expected to last for at least 5 years.
- No silicone products can be used in the fabrication or assembly of the oven.
- The size of the oven for this project will be 3'wide x 3'tall x 4'deep chamber that opens on both ends.
- There should be minimum maintenance required once the oven is deployed.
- Power source for operating the oven must be 120v AC at 60Hz.
- The designed oven should not be plumbed; it must have an onboard water supply with a 35lb weight limit.
- Efficient flow controls are expected in the prototype and final design of the oven.

Research Summary

External Search Summary

There are several ways to control the humidity within an oven. Three of the most common methods include water atomizing, steam injection, and water bath evaporation. Each of these processes has its strengths and weaknesses. The design team researched products that utilize each of these methods, however only steam injection systems are discussed below since this method fits best with the PDS requirements.

Portland State's Green Building Research Laboratory is currently using the steam injection process in order to simulate natural and manmade environments. By controlling the temperature and humidity of air flow through two separate ducts a simulated indoor and outdoor environment is created. Two relative humidity sensors and a thermocouple send data to the controls systems allowing for both temperature and humidity control. Heat flux sensors mounted between the ducts at different temperatures measure the heat transfer rate and allows for the calculation of an effective resistance value.

The steam injection system was purchased by the department from DRI-STEEM and included a steam generator, humidity controls system, and steam injection nozzles (Figure 3). The unit supplies from 5 to 200 lbs/hr and is easy to maintain since it contains a replaceable steam cylinder and replacement prompting system [1]. Benefits of this system include a proportional controls system that holds the relative humidity at an accuracy of ± 1% RH, an internal water pump with automatic flow control, and a variety of anti-drip dispersion nozzles. However, the system is plumbed, requires 240 VAC to run, and is costly (estimated at $2,000). Although the system does not meet the requirements detailed by the PDS, it provides a model to work from.

Figure 3: DRI-STEEM XT steam generation system with automatic water control, and vapor logic humidity control system (image courtesy of DRI-STEEM)

DRI-STEEM'S high pressure atomizing system uses high pressure forces typically between one and two thousand psi, to push fluid through a small nozzle with a diameter on the scale of seven thousandths of an inch [1]. The water hits an impact pin which breaks it up into super fine droplets (micron sized). The space requirements for a high pressure device is minimal and the upfront cost is less than steam systems, however this type of system is generally only cost effective for installations requiring 200 lbs/hr. Below this level the installation costs are high as the pump needed for such a small application is not proportional with size. Atomizers in general have a longer evaporative distance than steam meaning that moisture becomes a concern. Also, as the water uses the heat of the oven to evaporate the temperature in the oven will dip (latent heat of evaporation).

Figure 4: DRI-STEEM high pressure atomizing system (image courtesy of DRI-STEEM)

Internal Search Summary

Based on the requirements in the PDS and the information from the external search, the technical issues included thermal uniformity inside the chamber, air and water flow requirements, as well as control systems. The internal search focused on the three processes of adding humidity discussed above, steam injection, water atomizing, and evaporative baths. Each of these ideas was discussed among the design team and the results were evaluated by the team. Eventually, after several comparisons, the lack of humidity control in the evaporative bath method the design team made the decision to limit the design evaluation to the two remaining designs. The designs' advantages and disadvantages are summarized in Table 2.

Table 2: *Summary of advantages and disadvantages of two chosen designs*

Design Name	Advantage	Disadvantage
Atomizing water	• Inexpensive • Suitable for lower temperatures • Small space requirement	• Latent heat of evaporation (oven cooling) • Transition time (moisture problems) • Pressure control (high pressure required)
Steam Injection	• Dry process • Little effect on oven temperature	• More complex design • Expensive (steam generator)

Top-Level Final Design Evaluation and Selection

After reviewing the PDS and the internal/ external search on possible solutions for the project, a list of the most important criteria was developed as a basis for the concept evaluation. The criteria and their descriptions are shown below.

- Cost: depends on the humidification method. A steam generator will be purchased if the steam injection process is decided as a final concept. Cost for water supply systems will also be considered.
- Mobility: the size and weight of the water supply must be portable and less than 35 lbs. The steam generator needs to be capable of fitting in footprint of the oven.
- Performance:
  - ✓ Humidity Control
  - ✓ Temperature Uniformity
  - ✓ Moisture Prevention

The listed criteria were carefully selected to compare the advantages of the two possible solutions- steam injection and atomization of water. A concept scoring matrix was constructed to make the selection more precise (Table 3). Each design was given a score corresponding to the PDS criteria. The scores from each category were given from 1 to 5, 1 being the lowest. The scores then being multiplied by the weight factor assigned to each criterion based on their importance in the PDS. The total score of each design was then calculated.

Table 3: *Concept Scoring Matrix*

	Weight	**Atomizing Water**	**Steam Injection**
Performance			
Humidity Control	3	9	15
Temperature Uniformity	1	2	4
Moisture Prevention	2	2	8
Cost	3	12	3
Mobility	1	3	2
Total	10	28	32

The result from the decision matrix were reviewed carefully and compared to the requirements of the PDS Document. The “Steam Injection” was selected to be the final concept and a more detailed design of this concept will be further explained in the next section.

Progress on Detailed Design

Based on the chosen steam injection method, a design concept has been developed (Figure 6). At this point the system is being broken down into its fundamental pieces and measurements / calculations are being completed in order to size the necessary components and determine the mass and heat transfer rates of the system. Figure 5 shows one possible design solution. On-board water supply (blue tank), pump system (checkered box) and steam generator (steel casing) or shown along with the existing oven shell, door assembly and controls devices.

Figure 5: Solid Modeling of Boeing's current oven, the water tank, steam generator, controls mechanism and oven shell are detailed

Operation of the sealant oven is characterized into three modes:

I. Heating mode: The heating element is turned on and the temperature is brought up 130 $\pm$ 5 ^{o}F. During this time the part may be inserted into the oven to reach equilibrium, preventing condensation from forming on the part.

II. Constant temperature and humidity mode: Once the oven has reached operating temperature the steam injection system will bring the humidity up to 50 $\pm$ 10 % RH. The RH and temperature controllers will maintain the operating conditions throughout the curing process

III. Cooling mode: The system will be switched off and the oven doors opened to allow for a rapid cool down process.

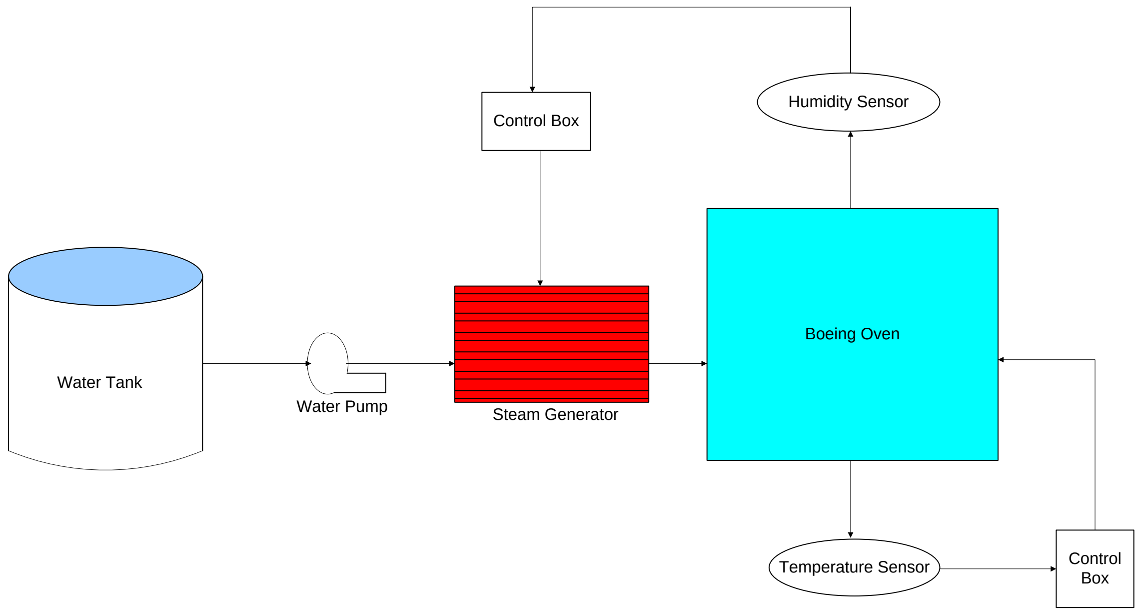


Figure 6: Flow analysis chart of detailed design

The basic components for the chamber can be obtained as off-the-shelf components or from Boeing. These components include relative humidity sensors, thermocouples, circulating fans and other miscellaneous components such as wire and plumbing materials.

- Thermal sensor: Thermocouples have been chosen as a temperature sensor as recommended by our industrial advisor and provided by Boeing.
- Relative humidity sensor: Vaisala Humidity Module has been chosen due to its accuracy (± 2% RH) and ease of calibration.

Major mechanical / electrical components of the chamber include the steam generator, water containment system, pump system, and controller.

- Steam Generator: a particular generator has not yet been determined. The capacity must be able to provide approximately 1 lb/hr (exact amount still to be determined).

- Pump system: the pump system has yet to be determined as it depends on whether or not the selected generator contains a pump.
- Controller: the Vapor-logic microprocessor is being researched. PID controller allows for tuning of the system for max performance. A web interface provides the capability to set up, view and adjust system functions. Auxiliary temperature sensor allows air temperature monitoring and enables temperature compensation.
- Water containment system: the water supply will be mounted on board and will therefore need to be sized appropriately. This will depend on the size of steam generator. Therefore, design of the water supply will be put on hold and an external water supply will be used in the testing procedures temporarily.

Conclusion

With the internal and external research complete a final design concept has been selected based upon the design evaluation (Table 3) and a system level design is almost completed. The PDS, external and internal search, as well as the final conceptual design have all been completed. With the conclusion of spring break, the team aims to complete all calculations and prototype design and finalize the system level design to present it to the sponsors. The feedback will be evaluated and updates to the design will be implemented based upon the outcome of this evaluation. The Boeing project team is currently on schedule for the expected completion date (June 2012). Although slow out of the gate the progress rate has improved as of late and the design is quickly coming together. The completion of necessary measurements and calculations has been marked as a major milestone in the progress of the project and substantial work has been done to reach this milestone. Further testing is currently underway which will provide an accurate mass flow rate needed to maintain the necessary humidity level.

The design may change at any given time to resolve problems that may occur. The most concerning issue would be the lack of potential parts that would delay the project's completion. Contacting suppliers, discussing with the sponsors and advisors is one way to remedy these potential problems.

Appendix A: Project Proposal

Project description:

A device is to be designed to control the humidity in sealant curing oven for Boeing. The temperature must be maintained at 130 $\pm$ 5 degrees Fahrenheit and the humidity maintained at 50%$\pm$ 10%. The project specification requires no use of silicon products.

To be delivered on June 2012:

A full functioning prototype will be designed and fabricated as well as demonstrated at the Capstone End of Year Poster and Display show.

Design Activity Opportunities:

The team will design a device that will be retro-fitted to Boeing's current curing ovens to control the humidity while maintaining an acceptable temperature. The team is completely free to select any suitable concept deemed acceptable. Rory Olson has agreed to provide the design specifications while allowing the team to explore any methods to achieve the requirements. This will give the team a chance to be more creative in solving the problem.

Analysis Activity Opportunities:

This project requires many decisions supported by analytical methods necessary to determine heat transfer mechanisms, stresses (strength of materials), machine design (welds, piping, valves, heating elements), fluid flow (fluid mechanics), material selection, engineering economics, manufacturing processes, electrical circuits and a controls mechanism.

Validation activity:

The task of the design team is to build a humidity controlled oven that maintains a level of humidity and temperature that allows for a more efficient oven. The team intends to build a full-scale prototype that will be fitted to a 3' x 3' x 4' chamber that may also be adapted to retro-fit to larger or smaller ovens. The prototype will be designed such that it will be able to be tested and put to work by the beginning of June, 2012. Given a successful product, Boeing will take control of future design and implementation of the product.

Appendix B: Detailed PDS Criteria

Table 4 shows a list of the criteria used to define the design requirements. The design requirements are arranged in the order of higher priority to lower priority. The criteria that are not applicable to this project are also labeled as (N/A).

Table 4: *PDS Criteria List*

Product Design Specification	
Criteria	**Priority**
Performance	High
Quality and Reliability	High
Life in service	High
Materials	Medium
Dimensions	Medium
Testing	Medium
Documentation	Medium
Timelines	Medium
Environment	Low
Maintenance	Low
Weight	Low
Ergonomics	Low
Cost of production per part (material and labor)	N/A
Competition Products	N/A
Shipping	N/A
Packaging	N/A
Aesthetics	N/A
Legal (Related patents)	N/A
Disposal	N/A

High Priority

Performance					
Primary Customer	**Requirements**	**Metrics**	**Targets**	**Basis**	**Verification**
Boeing	Humidity	Relative Humidity	50%RH±5%	Customer Feedback	Testing of Prototype
Boeing	Temperature	Degrees ^{o}F	130±5°F	Customer Feedback	Testing of Prototype

Quality and Reliability					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	Part Failure	-	1 per 1000	Customer Feedback	Testing

Life in Service					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	5 years continued operation	Years	5 years	Customer Feedback	Prototyping

Medium Priority

Materials					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	No part interaction with Silicon or water	-	No interaction	Group Decision with Customer's Input and Requirement	Design
Boeing	Corrosion Resistance	-	Corrosion resistant metals	Customer Feedback	Design

Dimensions					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	Must be 3'×3'×4' chamber with one opened-end	Varied with different parts	Variable Size	Customer Feedback	Design

Testing					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Project Team	Testing	+/-	Works as intended	Group Decision	Study of Testing Analysis

Documentation					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing/PSU	PDS, Progress, Final Reports	Deadline	Meet the deadline	Department of ME	Grade

Timelines					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
ME 492	PDS/Progress Reports	Submitted Reports	2 reports	Course Requirement	Grade
ME 493	Design Report	Submitted Reports	1 report	Course Requirement	Grade
Boeing	Completed design and prototype	Fully functional	Meet the Deadline	Customer Feedback and Course Requirement	Grade and Experience

Low Priority

Environment					
Requirement	**Metrics**		**Target**	**Basics**	**Verification**
Boeing	Operating process with clean, purified oven	Contamination of surroundings	No detectable contamination to the environment	Customer Feedback	Material and Process Record

Maintenance					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	Minimum maintenance	Maintenance Interval	1 week	Customer Feedback	Similar System Comparison

Weight					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	Light Weight	Pounds	< 250 lbs	Group Decision with Customer's Input	Measurement

Ergonomics					
Primary Customer	**Requirement**	**Metrics**	**Target**	**Basics**	**Verification**
Boeing	Weight Limit of Water Supply	Pounds	< 35 lbs	Customer Feedback	Measured

Not Applicable

Criteria	**Reasons**
Cost of production per part (material and labor)	Boeing's responsibility
Competition Products	Not applicable
Shipping	The part is installed and operated at Boeing facility.
Packaging	None required
Aesthetics	None required
Legal (Related patents)	Legal constrains and patents controlled by Boeing
Disposal	None required
Applicable Codes and Standards	Not applicable

Appendix C: Internal Search Document

C1. Temperature Sensor's:

Temperature sensors consist of two basic physical types:

- *Contact Temperature Sensor Types:* These types of temperature sensor are required to be in physical contact with the object being sensed and use conduction to monitor changes in temperature. They can be used to detect solids, liquids or gases over a wide range of temperatures.
- *Non-contact Temperature Sensor Types*: These types of temperature sensor use convection and radiation to monitor changes in temperature. They can be used to detect liquids and gases that emit radiant energy as heat rises and cold settles to the bottom in convection currents or detect the radiant energy being transmitted from an object in the form of infra-red radiation (the sun).

There are two types of temperature sensor that team intended to use: the thermocouple and resistance temperature detector [5].

Thermostat Off/On

Thermistor

RTD

Thermocouples

Table 5: *Summary temperature sensors*

Product	Temperature (F)	Description
Thermostat	N/A	Extensively control hot water heating elements
Thermistor	-75 to 500	Highly sensitive to small changes in temperature, fairly accurate over a limited temperature range.
Thermocouple	Up to 3100	Small size/fast response with extremely high temperature.
RTD	-328 to 1200	Accurate, repeatable and interchangeable over a wide operating range.

C2. Valve's Actuator:

Common Actuator types:

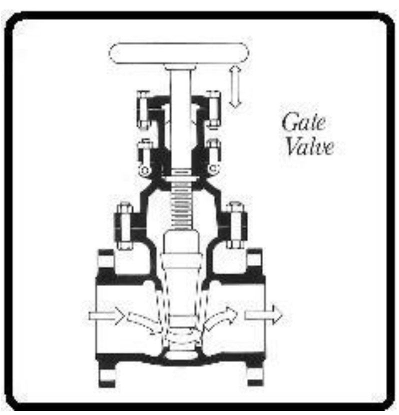
- **Manual Actuators:** A manual actuator employs levers, gears, or wheels to facilitate movement while an automatic actuator has an external power source to provide the force and motion to operate a valve remotely or automatically [5].
- **Hydraulic and Pneumatic Actuators:** Hydraulic and pneumatic actuators are usually simple devices with a minimum of mechanical parts, used on linear or quarter-turn valves. Sufficient air or fluid pressure acts on a piston to provide thrust in a linear motion for gate or globe valves [5].
- **Electric Actuators:** The electric actuator has a motor drive that provides torque to operate a valve. Electric actuators are often used on multi-turn valves such as gate or globe valves [5].

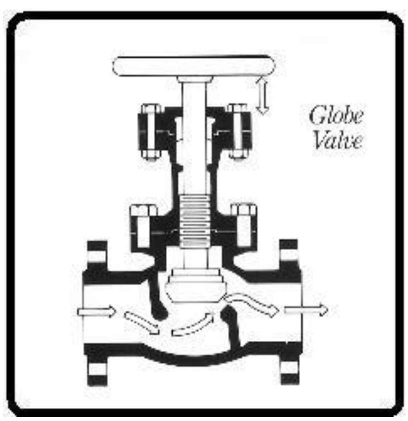
In this experiment the electrical actuator will be used. There are two types of electrical actuator for control valve:

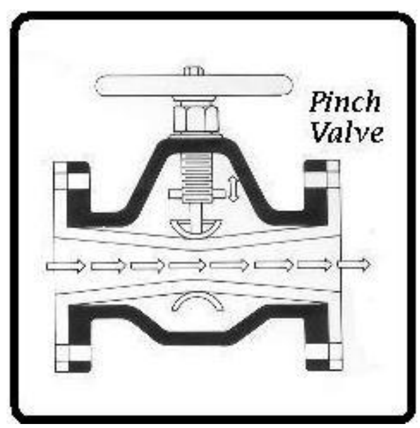
- **Valve Motor Drive**: used mostly for on/off application.
- **Modulating Actuator**: used mostly for regulating flow.

For our application, we need Modulating Actuator with multi-turn to be able to control the valve in response to the flow requirements. Here is some of the multi-turn valves that the team intends to use.

- **The Gate Valve:** The gate valve is a general service valve used primarily for on - off, non-throttling service. The valve is closed by a flat face, vertical disc, or gate that slides down through the valve to block the flow [5].
- **The Globe Valve:** The globe valve effects closure by a plug with a flat or convex bottom lowered onto a matching horizontal seat located in the center of the valve. Raising the plug opens the valve, allowing fluid flow. The globe valve is used for on - off service and handles throttling applications [5].
- **The Pinch Valve:** The pinch valve is particularly suited for applications of slurries or liquids with large amounts of suspended solids. It seals by means of one or more flexible elements, such as a rubber tube, that can be pinched to shut off flow [5].







<u>C3. Insulation for the Oven (RockWool Board):</u>

- Easy to insulate it.
- Excellent performance of insulation and fire proof.

- Applicable to insulation and sound of boiler, oven, industrial furnace, heat treatment equipment etc.
- Specifications:
    - Density: 50 -120 kg/m3
    - Thickness: 30-100 mm
    - Size: 5000 mm long * 600 mm width
- Physical properties:
    - Thermal Conductivity is about 0.035 W/m.K
    - Fire proof inflammable of grade A
    - Applicable Temperature 240-650 degree.

Appendix D: External Search Document

In this appendix, the full document of the external search is reported. This is a list of existing steam generators and atomizing systems in the market. [1]

1. Electrode steam generator

XT humidifier

Easy installation and maintenance

The XT electrode steam humidifier provides humidification for a wide range of buildings and applications. Low up-front cost and minimal maintenance make XT one of the most affordable humidification systems to purchase and install.

- Vapor-logic4 controller.
- Easy to maintain- just replace the affordable steam cylinder when prompted.
- Automatic drain and fill events optimize humidifier performance.

  Capacity range: 5-200 lbs/hr (2.3-91 kg/h); stage up to four humidifiers together for maximum system capacity of 800 lbs/hr (360 kg/h)

Figure D.1: XT electrode steam humidifier

2. High- Pressure Atomizing Systems

Versatility and energy efficiency

DRI-STEEM High-Pressure Atomizing Systems provide high-quality humidification solutions suitable for a wide variety of applications. Each system's high-pressure pump propels treated, unheated water past a small turbine insides each dispersion nozzle. This fragments water droplets into ultra-fine particles that quickly evaporate in airstreams or open spaces.

- <u>Guaranteed system performance:</u> Over 45 years of humidification experience allows DRI-STEEM to confidently guarantee system performance. DRI-STEEM's comprehensive system design charts ensure a properly designed system by addressing all relevant psychrometric parameters.

- Most energy-efficient humidification system when cooling year-round: As atomized water droplets evaporate, air temperature can drop 20^{o}F (11^{o}C) or more. Every pound of atomized humidification added to air removes approximately 1000 Btu of heat. Twelve pounds of atomized humidification replaces about one ton of cooling. (15 kg of atomized humidification replaces about 10kW of cooling.)
- Adaptable to all building types: DRI-STEEM High-Pressure Atomizing Systems humidity via air handlers, ducts, or in open spaces. One system can control multiple zones with multiple set points. A broad capacity range further enhances application versatility.
- Maximum uptime; systems can operate up to five seasons without interruption. Robust stainless steel construction, available reverse-osmosis water treatment, and automatic membrane back-flushing ensure maintenance-free operation, maximizing uptime.

  Capacity range: 250-8500 lbs/hr (114-3859 kg/h)

Figure D.2: Installed closed area

Figure D.3: Installed in open area

Appendix E: References

1. *DRI-STEEM*. 1 Jan. 2012. 7 Mar. 2012 <http://www.dristeem.com/home>.
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