Control Systems for Thermal Vacuum Chambers

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INTRODUCTION

The Jet Propulsion Laboratory (JPL) is a research facility managed by Caltech for NASA that constructs and operates robotic spacecraft for space exploration and scientific research. Prior to launch, all spacecraft hardware needs to be tested in a simulated space environment. These tests are conducted at several locations at JPL, including at the Reliability Assurance Technology Test Laboratory (RATT Lab). To increase the margin of safety when conducting thermal vacuum tests, automated control systems and fail-safes are required to ensure that the sometimes fragile and expensive instruments will not be harmed during testing. A spike in temperature or a loss of vacuum could fatally damage a critical piece of equipment and put the mission behind schedule.

OBJECTIVES

Controllers and their associated fail-safes that regulate temperature already exist; however, its sensors and actuators need to be installed. A vacuum fail-safe system is to be implemented for one of the vacuum chambers in use in the RATT Lab, shown in Figure 1. Since there are currently no vacuum fail-safe mechanisms installed, the chamber is not yet capable of being “flight” certified. Thus, the chamber is not suited for testing equipment that will one day be used in space. Instead, the chamber is currently used to test non-flight instruments during their development. The addition of the fail-safe will satisfy several of the requirements imposed on chambers prior to flight certification.

BACKGROUND

Vacuum Systems

To simulate a space environment, thermal vacuum chambers are used to mimic the vacuum and temperature environment found in space. Air is pumped out of a sealed chamber to achieve a vacuum. The transition from a viscous fluid to particles in a pipe is defined by the ratio of the mean free path of the molecules to the radius of the pipe, which is a dimensionless number called the Knudsen Number (Kn). In the region where Kn is less than 0.01, the properties of the air are similar to a laminar fluid with viscous effects. In this environment, air is able to be pulled using a simple pump that uses a spinning rotor to induce a pressure difference. A rotary "roughing" pump first evacuates the chamber to a "rough" vacuum which can reach up to 10^{-3} Torr (mm Hg). At higher vacuums, however, the air behaves less like a fluid and more like individual particles. When Kn is greater than 1, the molecules interact with the walls of the pipe more than with each other. To reach vacuums as high as 10^{-10} Torr or "high" vacuum required for lab use, a second pump is required, the turbomolecular pump. The turbo pump operates like a turbine and uses momentum transfer to move particles of air. These pumps stall in high pressure viscous flow. Therefore, the turbo pump is used in conjunction with the "roughing" pump connected in series [1].

Heat Exchanger Systems

Temperature control is accomplished by using a combination of heaters and liquid nitrogen (LN_2) in conjunction with a heat exchanger plate. To lower the temperature of the chamber, the thermal control unit will activate one of the solenoid valves on the LN_2 lines. This causes cool gases and eventually liquid to flow through the heat exchanger plate, which cools the plate through convection. To raise the temperature of the chamber, a voltage will be applied to the resistance heaters, which will transfer heat to the heat exchanger plates by conduction.

Vacuum and Temperature Sensors

To maintain a constant temperature environment in the thermal vacuum chamber involves the constant monitoring of the temperature inside the chamber with sensors. Thermocouples are used to monitor the temperature in the chamber. Thermocouple gauges measure the vacuum up to "rough" vacuum levels of approximately 10^{-3} Torr and Bayard-Alpert ionization gauges measure vacuums up to 10^{-10} Torr. A Varian vacuum gauge controller is used to measure the output of both types of gauges and translate it into a vacuum level.

Temperature Control and Fail-safe System

The overall control system that maintains the vacuum and temperature environment in the chamber consists of three components: the temperature controller, the temperature fail-safe, and the vacuum fail-safe. There is no vacuum controller because the pumps will try to increase the vacuum at all times. During normal operation, the temperature controller will attempt to maintain a preset temperature in the vacuum chamber. Once the temperature at the control point reaches the set temperature, the temperature controller will cycle the heaters and LN_2 valves to keep the temperature steady. If the system fails and exceeds the temperature presets, the temperature fail-safe will come into effect to prevent the system from reaching extreme temperature levels. In the case of excessively high temperatures, power to the heating elements will be cut. For excessively cold situations, a backup solenoid valve will shut off the flow of liquid nitrogen to the cooling system.

Vacuum Fail-safe System

The vacuum fail-safe will interact with the multi-gauge controller, which includes a set point board to initiate action in case of vacuum loss. Actions to be taken include: isolating the chamber from the turbo pump, and sealing the foreline between the turbo pump and the rough pump. Sealing the foreline prevents vacuum oil from the rough pump to travel upstream and damage the turbo pump. Isolating the chamber with the closure of the gate valve prevents oil from entering the chamber. Both actions serve to protect both the test article inside the chamber and the pumping system itself from accidental pressurization. Figure 2 shows the location of the foreline valve. To implement the existing temperature controller and fail-safe device, temperature sensors and actuators need to be installed. The vacuum fail-safe system needs to be implemented, so an interface box needs to be constructed to interact with the sensor readings from the vacuum gauge controller.

APPROACH

Vacuum Fail-safe Construction

A fail-safe control box for the vacuum system was constructed. Solid state relays (SSR) are used to control the flow of electricity to the solenoid valves and to provide a level of protection between the vacuum gauge controller switches and the potentially high currents called for when operating the valves. When the relay in the vacuum gauge controller switches, or when a manual switch is flipped, the SSR connects household line voltage (120 VAC) to the solenoid valves via a standard household duplex plug mounted in the rear of the interface box. A commercial AC adapter was installed in the interface box to step down the AC line voltage to 12 VDC to operate the solid state relays. Fuses were installed in the interface box as a safety precaution for surge protection. Figure 3 displays the contents of the fail-safe box, with the SSR and transformer shown.

The control box has a serial connector to interface with the Varian vacuum multi-gauge controller, which acquires real-time vacuum measurements from a Bayard-Alpert ionization gauge. The fail-safe system allows for the selection of automatic or manual control through a switch. Automatic control is provided by a set-point board on the Varian multi-gauge controller. When the system detects an unsafe vacuum level, it activates a switch which closes a pair of vacuum valves and places the system into a ‘safe’ mode. When manual control is active, these valves are controlled individually by flipping switches. This mode is of particular use during the process of bringing the chamber to vacuum. Figures 4 and 5 display the front and rear views of the fail-safe box, respectively, with the switches and outlets labeled.

The vacuum fail-safe box has control over two electro-pneumatic solenoid valves. One controls the gate valve placed in between the high vacuum turbo pump and the chamber, and the other controls the foreline valve between the turbo pump and the rough pump. For safety reasons, the vacuum valves are closed when no electric current is applied. When a voltage is applied, the valves open and a vacuum can be established inside the chamber. After construction, the switches and electrical sockets were labeled for ease of use. Currently, the system is designed such that other engineers can reset the threshold vacuum value that activates the fail safe mechanism through interaction with the multi-gauge controller.

Implementation of Temperature Actuators

Solenoid valves that supply liquid nitrogen (LN_2) to the temperature exchange plates inside the vacuum chamber were mounted in the back of the vacuum chamber stand. The design consists of mounting the solenoid valves using Unistrut channels and their associated clamps. Specialized Delrin insulators were machined on a lathe so that the copper tubes used to transport the LN_2 may be securely mounted while still remaining thermally insulated from the room temperature mounting brackets. A pressure relief valve was installed between the two valves to prevent the dangerous buildup of pressure in the tubing in the case that both solenoid valves are closed. Polyethylene foam insulation, designed specifically for low temperature applications was installed to insulate the pipes that deliver the liquid nitrogen to the thermal vacuum chamber cooling system. This prevents frost from building up on the lines, which can drip water on to electrical wires. Hoses that supply LN_2 were attached to the chamber. One of the solenoid valves will be used by the primary temperature controller, while the other will be used by the temperature fail-safe unit. Figures 6 and 7 show the solenoid valve setup.

Three copper heating elements were installed in the chamber. The heating elements are operated by the temperature controller. Several thermocouple sensors were installed on one of the thermal exchange plates in the vacuum chamber to measure temperature. These thermocouples were connected to the temperature controller and fail-safe boxes. The LN_2 solenoid valves and heater set up were integrated with the existing temperature controller and temperature fail-safe. Figure 8 displays the overall control and fail-safe setup.

RESULTS

After construction, the vacuum fail-safe was tested. Nitrogen gas was leaked into the chamber to simulate a loss of the vacuum. When the vacuum threshold was reached, as measured by the Bayard-Alpert ion gauge, both the gate valve and foreline valve closed indicating that the fail-safe units are working. Since the decrease in vacuum was sufficient to turn off the ion gauge, the system effectively latched in the ‘safe’ position. Manual override by an operator was required to reopen the valves and restart vacuum operations.

The temperature controller and fail-safe system were also tested. To test if the temperature fail-safe is working, thermocouples were connected to a data acquisition unit to record the temperature fluctuations over time. The temperature fail-safe was set to a low temperature limit of -20°C and a high temperature limit of 40°C. To test the fail-safe, the control temperature was first set to a temperature lower than the low temperature limit (-20°C) to engage the fail-safe. The temperature in the chamber began to fall after the solenoids opened, allowing LN_2 to cool the chamber. Once the lower temperature limit was reached, the flow of LN_2 was halted and the decrease in temperature began to level off. Once cold temperature failure was simulated and the fail-safe system shown to be working, the system was tested for another temperature situation.

In the next test, the temperature controller was set to a temperature above the high temperature limit of the fail-safe (40°C). Given that command, the temperature controller supplied power to the heaters mounted to the thermal control plate, causing the temperatures to rise. When the temperature reached the fail-safe set point at 40°C, all power to the thermal control unit was cut off by the fail-safe unit, shutting off the heaters. The data from this test is displayed in Figure 9.

DISCUSSION

The temperature data record in Figure 9 clearly shows when the fail-safe closed the flow of LN_2. The initial cooling shows a rapid decrease in temperature with time. When the temperature reached the -20°C fail-safe set point, the temperature flattens drastically. For the hot temperature fail-safe situation, the temperature plot shows that the temperature continues to increase slightly above the set point, but the rapid change in temperature was clearly halted. There is some temperature overshoot after shutting off the temperature actuators. After shutting down the heaters, the large thermal inertia of the copper plate causes a slight increase in temperature. Since the thermocouple sensors were attached on the heat exchanger plate, they are sensitive any residual heat in the heating elements.

Even with a temperature overshoot, the temperature change is small for both heating and cooling situations and should not pose a problem. To conclude the project, the existing operating procedure for the thermal vacuum chamber was improved with instructions on how to operate the fail-safe box so that JPL engineers in the lab will be able to use the system in the future.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "Vacuum Basics," 2008. [Online]. Available: http://www.belljar.net/basics.htm. [Accessed: Jun. 26, 2009]

FIGURES

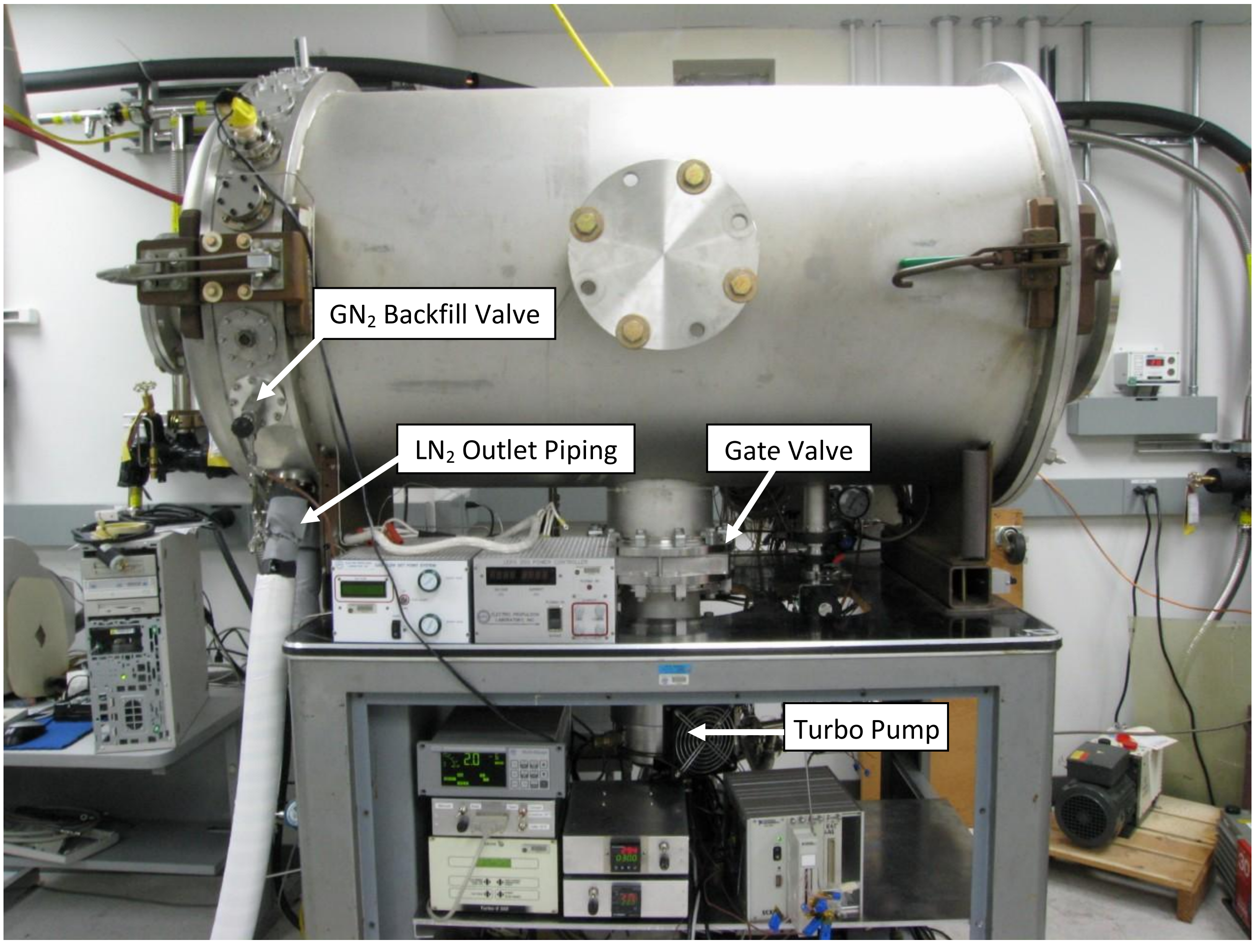

Figure 1: Photograph of the test chamber with parts labeled.

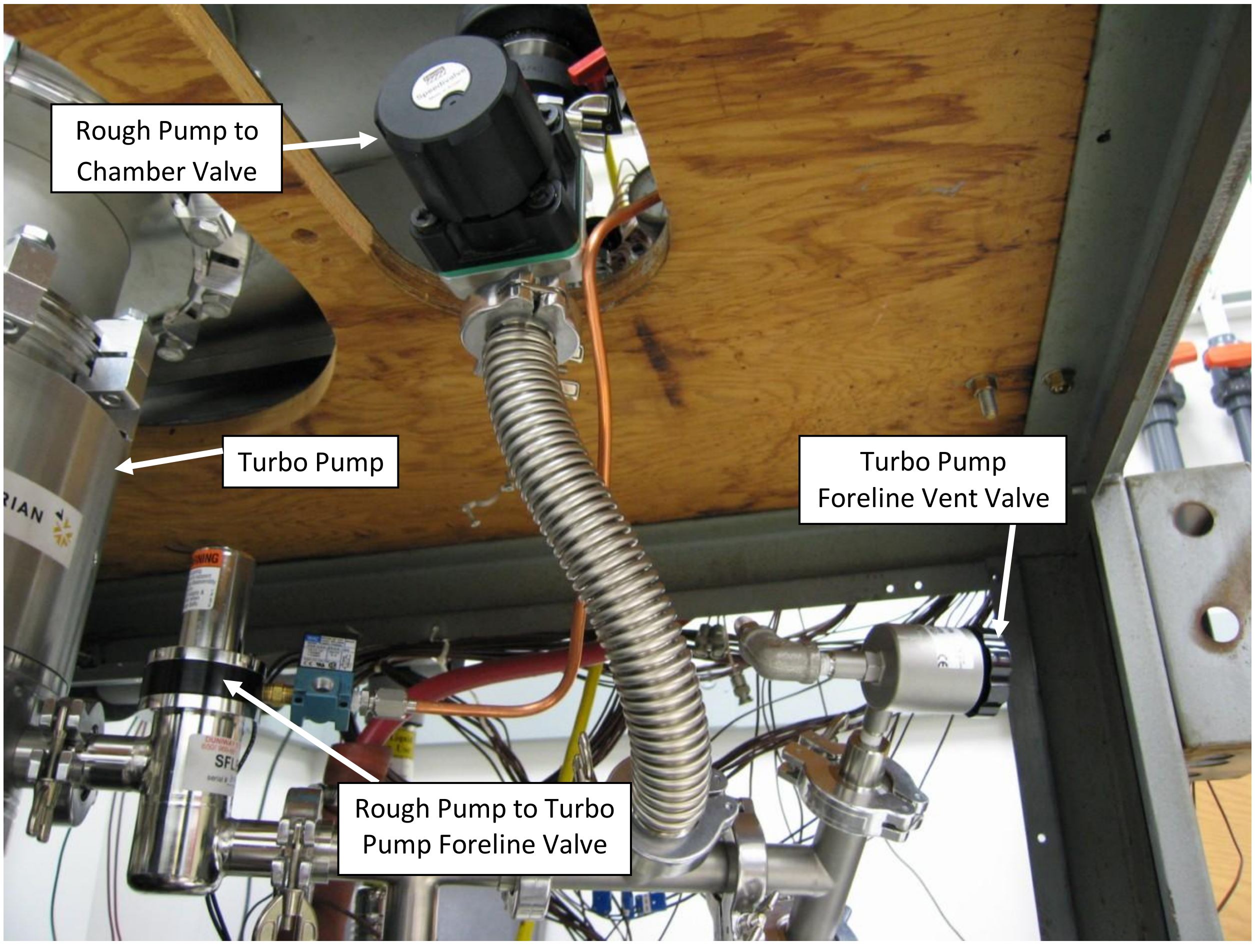

Figure 2: Detail on the valves and the turbo pump.

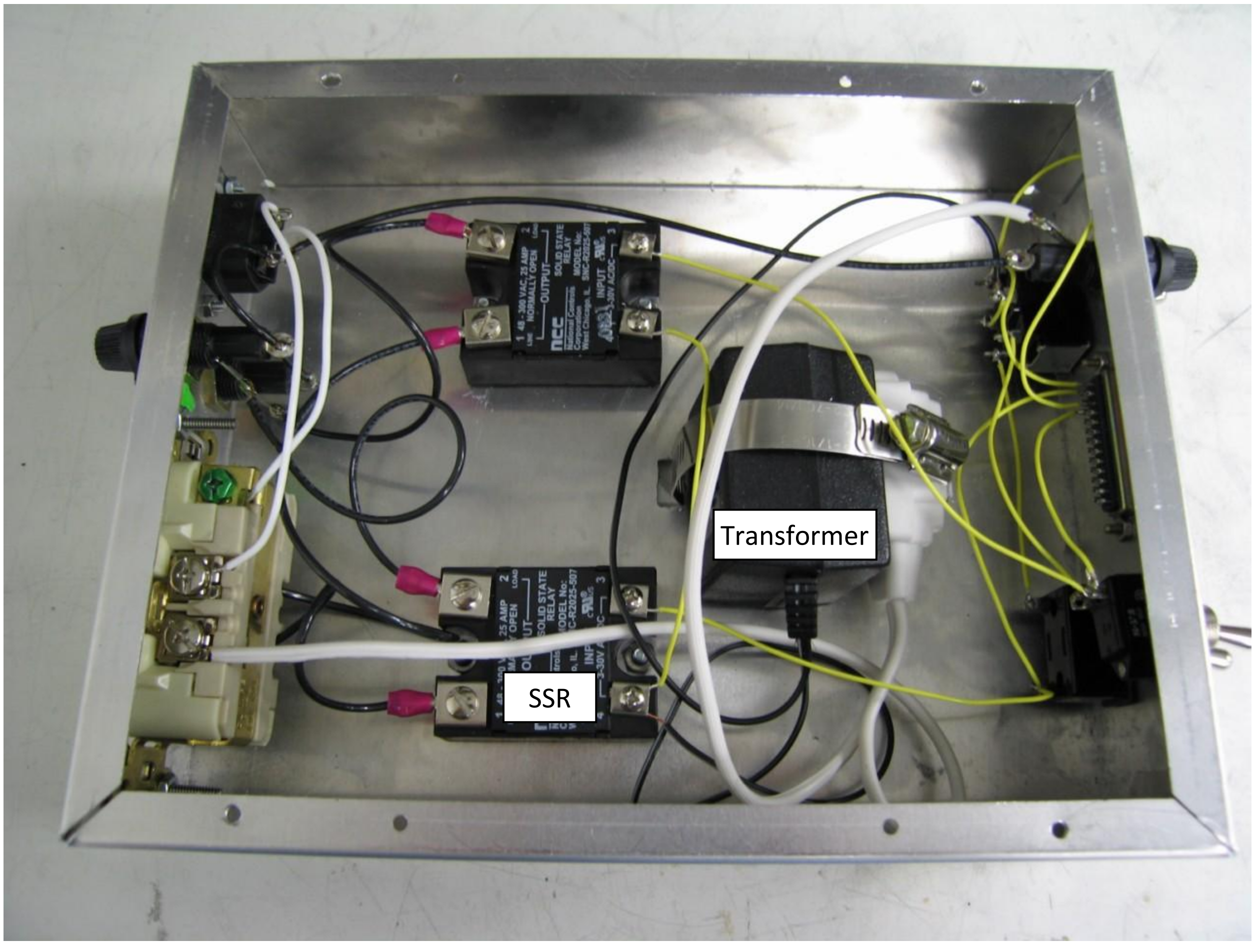

Figure 3: The inside of the fail-safe box. The solid state relays (SSR) are displayed, along with the transformer.

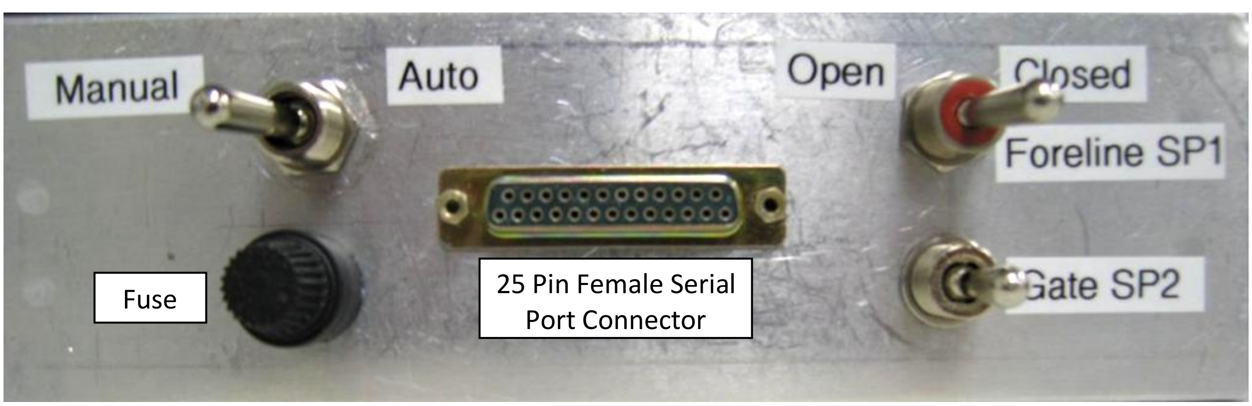

Figure 4: The front view of the vacuum fail-safe box. The left switch controls whether the unit is in manual mode or automatic mode. The switches on the right are labeled with the correct valve that the switch controls and its corresponding setpoint number when using the multi-gauge controller.

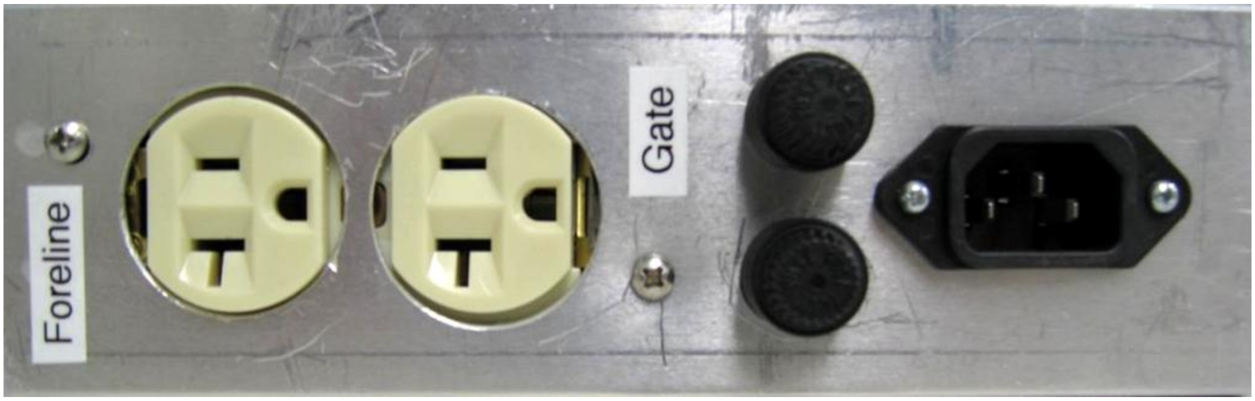

Figure 5: The back view of the fail-safe box. The electrical sockets are properly labeled to correspond the either the foreline valve or the gate valve.

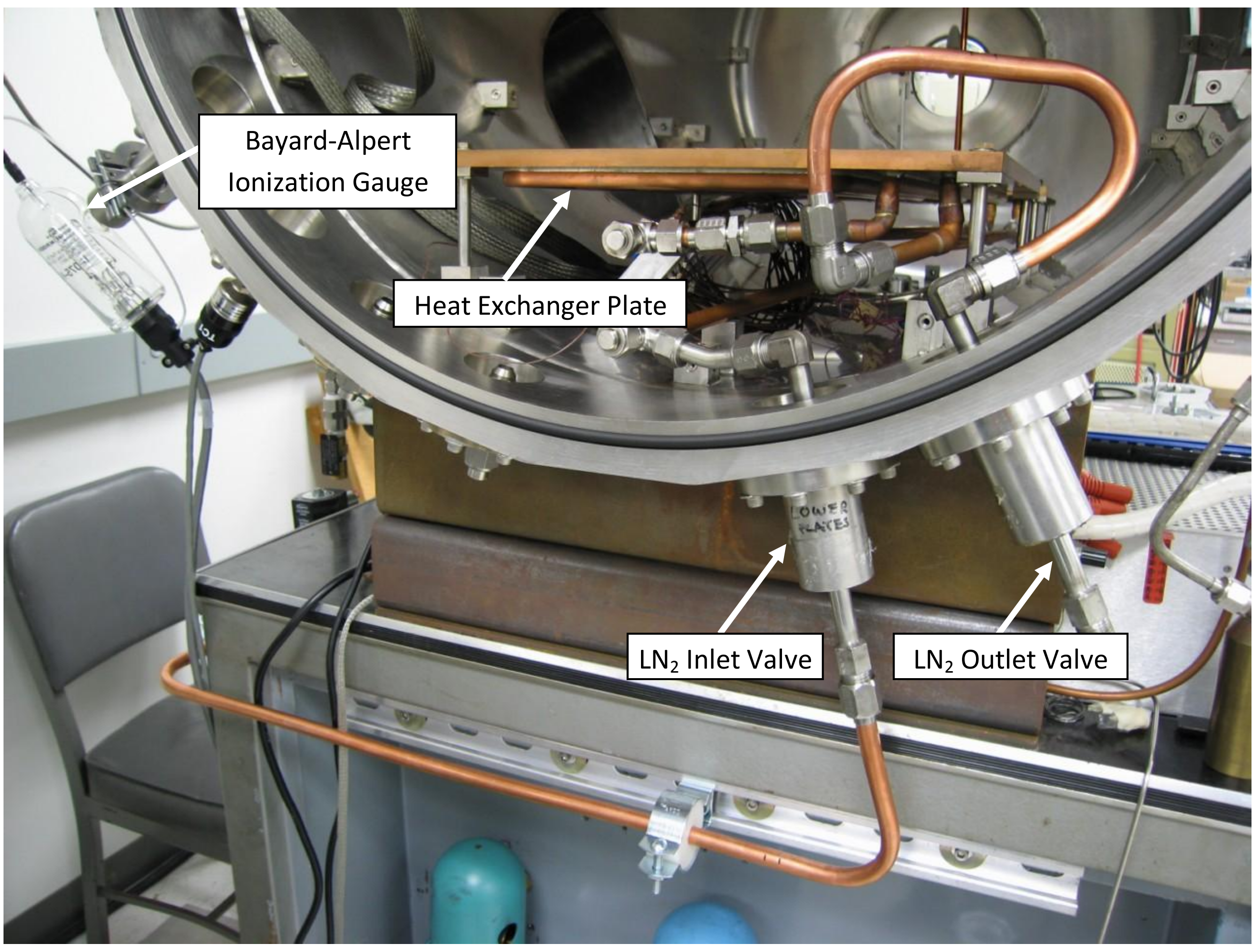

Figure 6: The inside of the chamber is visible, showing where the pipe connects to the heat exchanger. This photograph was taken before the LN_2 outlet piping and insulation was installed.

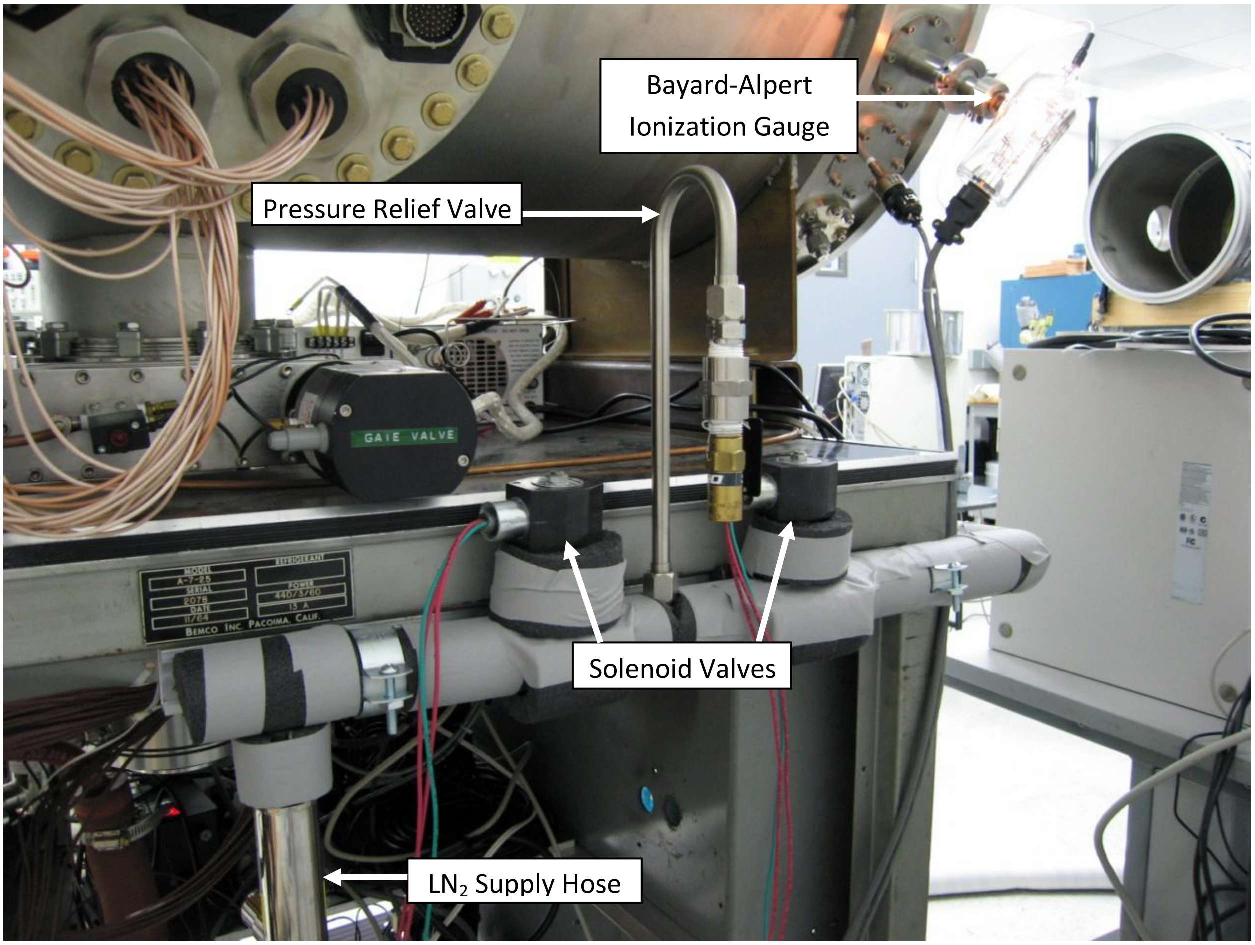

Figure 7: A Unistrut channel was mounted behind the vacuum chamber to mount the solenoid valves.

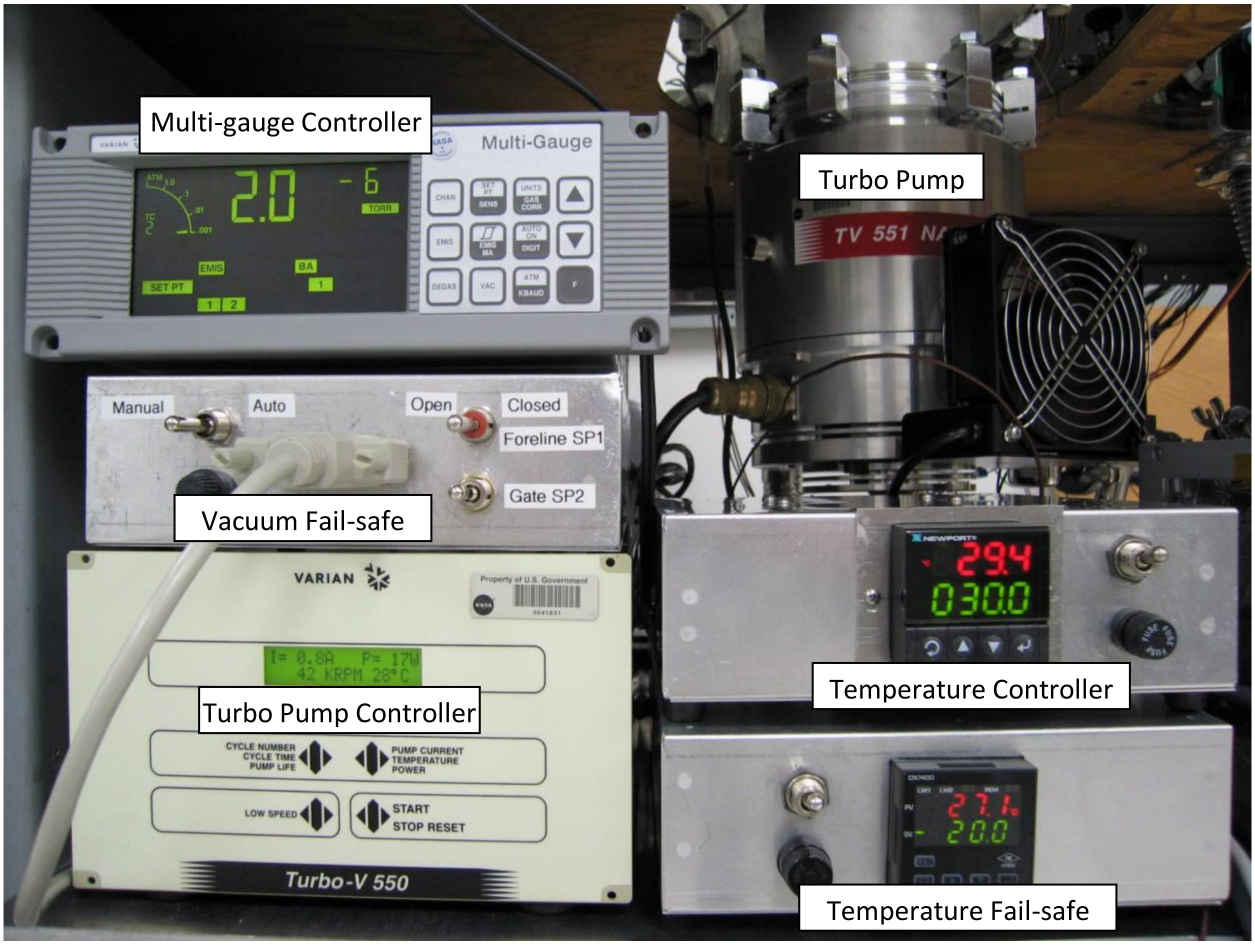

Figure 8: The controller and fail-safe setup.

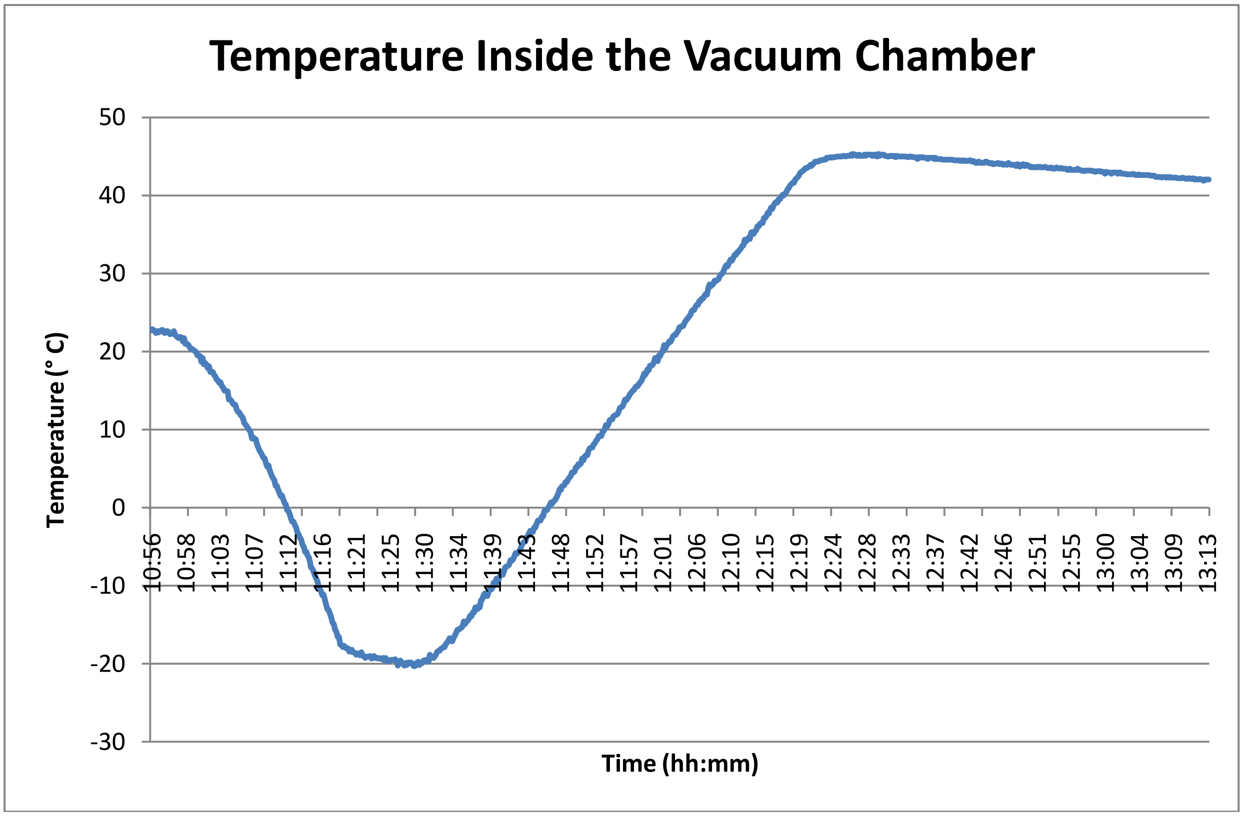

Figure 9: Temperature inside the vacuum chamber as a function of time.