Students Learn Problem Solving
with the Mars Electrostatics Chamber Project

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Abstract

The Mars Electrostatics Chamber is a recently developed vacuum chamber located at Kennedy Space Center (KSC) in Florida, and has been designed to provide for research and testing relative to future missions to Mars. Under the direction of one faculty member, nine students participated in the implementation and automation process for the chamber over the course of a summer. The students were tasked with designing a temperature control system for the chamber under established guidelines. After extensive testing and analysis, the students developed a successful working model that obtained and maintained stable temperatures for extended periods. The process proved to be an outstanding method of teaching problem solving concepts associated with design to students.

Background

The Mars Electrostatics Chamber (MEC) enables Kennedy Space Center personnel to perform not only electrostatics research, but also many diverse Mars-related environmental experimentation and simulation processes. The chamber has been designed to provide for research and testing relative to future missions to Mars.

The chamber (Fig. 1) measures 7 feet in length, nearly 4 feet in diameter, and has a volume of 52 cubic feet. Access ports were provided for component and peripheral device feed-through. In addition, several ports are used for pressure measurement, temperature signal lines, and gas feed-throughs. Access ports were also provided for monitoring payloads. The inside of the chamber is fitted with a cooling shroud that surrounds the back, sides, and top of the chamber. Located in the bottom of the chamber is a solid aluminum deck on which experiments are placed. [ref. 1]

Student Involvement

Nine students assisted one faculty over the course of a summer. The students functioned as interns for a NASA-contracted company and played an active role in the implementation and automation of the MEC. The summer effort was predicated by delegated research, presentations, and testing. Preparation included the mandatory review of documentation related to the project.
All students were assigned to research topics related to the project and then, throughout the course of the spring semester, the students conducted formal presentations to the selected group who would be participating in the summer project. They also assisted in the development work leading up to the project including the creation of a tentative implementation plan.

The MEC required painstaking integration procedures, in part due to the complexity of interfacing several independently controlled systems. For instance, the temperature control system operated independently from the pressure and atmospheric systems. Since the pre-existing structure was limited to manual operation only, there was a great deal of work to be accomplished to transform it into a fully functional automated process. The complexity resulted in many problems that required solving before the project could be successful.

Once on site, students were required to address project planning, implementation concerns, and organizational issues; engage in teamwork; and implement solutions to problems encountered on a daily basis. Various tasks and project components were delegated to the students, primarily on a daily basis. For the most part, each student was in charge of one major component of the project. Students were assigned project responsibilities according to the following major components: procurement, hardware installation, controller installation, controller programming, graphical user interface programming, program code generation, mechanical system, cooling system, heating system, atmospheric system, electrical system, gas analyzer system, testing, and documentation. Although each student was primarily responsible for at least one aspect of the project, all were provided with the opportunity to participate in all of the other project areas.

Primary to the accomplishment of the project was the successful design and implementation of the cryogenic cooling system. A range of temperatures, as experienced on Mars, was required to be replicated by the temperature control system. Due to the high thermal transfer characteristics of cryogenic nitrogen, achieving temperature control required extensive testing and chamber characterization, and was a major design task. Students were tasked with designing a cooling system that used a liquid nitrogen (LN\textsubscript{2}) supply, brought about effective cooling in the span of desired temperatures, and incorporated a previously existing cooling shroud and related hardware.

**Problem Solving Process**

Upon arrival at KSC, students were introduced to a manually controlled system for which an automated cryogenic cooling system was to be designed. The design criteria were established by KSC personnel and the faculty provided guidance throughout the process. After the initial system characterization was completed, many different design configurations were implemented and tested. Solutions were then derived for the problems encountered. Ultimately, a design was achieved that met the mandatory criteria and that design was validated.

**Pre-Existing System**

Previous work by NASA personnel and other various contractors had created an assemblage of hardware that was in place before the arrival of the student/faculty team. The pre-existing system consisted of a rudimentary temperature control system and a manually operated vacuum
chamber. The configuration employed both heating and cooling for temperature control, but the concept had not been fully tested (Fig. 2). The heating portion consisted of a series of shell tape heaters placed around the chamber. A standalone controller determined the operation of each heater. The intended use of the heaters was for trimming the temperature at a desired level and to assist the nitrogen in obtaining a stable temperature. The heat exchanger consists of a capillary system that incorporates the door, deck, and interior shroud of the chamber. The shroud is composed of two sheets of stainless steel welded together in such a fashion that it creates passageways for flow.

The cooling portion of the temperature system was designed to use gaseous nitrogen (GN₂) vented from the top of a liquid nitrogen dewar (cylindrical container), although the concept was never tested. The only existing method of controlling the amount of coolant into the system was to manually adjust the valve on the top of the dewar.

There were no existing means for measuring the temperature of the cooling system lines or any area inside the chamber, except for the use of standalone temperature measurement devices. Data cables had to be routed through access ports to accomplish temperature measurement. The achievement of desired temperature was based upon manual measurement, observation, and manual corrective action. During one initial cooling test, the students discovered that some temperatures measured within the chamber dropped to nearly –300°F (-184.4°C), while other zones remained at room temperature (Fig. 3). It was determined that this differential was caused by the extremely low temperature of the nitrogen, the lack of flow control, and the less than ideal design of the cooling shroud. This poor design hindered the thermal transfer characteristics of the cooling shroud. At this time, it became clear that an innovative means of controlling the cooling system would need to be implemented. All the information gathered to this point was used to develop the following design problem presented to the students.
**Problem**

The students were tasked with designing a temperature control system as a team, with the faculty advisor providing oversight and direction. The design specification included the following criteria and constraints:

1. Utilize all existing hardware when possible, including the cooling shroud.
2. Create a stable operating range and control of temperature from ambient temperature to as cold as possible without creating dry ice inside the chamber, considering the realm of operating pressures.
3. Establish automated operation utilizing a programmable controller with appropriate programming.
4. Incorporate existing chamber shell heaters, if possible.
5. Include existing external inline LN$_2$ heater, if possible.
6. Consume as little cryogenic LN$_2$ as possible.
7. Minimize the effects of temperature differentials within the chamber.

**Methodology**

In order to validate design concepts to show that they met the stated criteria and constraints, each approved design had to be implemented into the system and proper operating tests conducted. The students used the results from each test to improve upon the existing design until all of the objectives had been satisfied. This forced the team to convene, make decisions, and find solutions based upon existing circumstances and resources, during each step of the design process.

Before the cooling system for the MEC could be specified, the chamber and the cooling system needed to be characterized. Many cooling tests were performed using different hardware configurations to determine the cooling characteristics of the chamber.

Cooling tests performed by the students demonstrated the ineffectiveness of the existing cooling shroud to serve as a consistent cooling mechanism. It was found that multiple zones connected in series, combined with undesirable flow patterns, gave the chamber high temperature gradients and less than ideal heat transfer. Therefore, in addition to developing an appropriate control strategy, it was deemed necessary to employ numerous temperature measurements.

It was considered prudent to verify the coldest practical temperature obtainable from an LN$_2$ dewar before beginning the cooling system tests (Fig. 4). The coldest consistent temperature obtained was -320°F (-195.6°C), as anticipated. It was therefore concluded that the dewars would be able to provide cooling fluid at a temperature that was low enough to serve as the cooling means for the MEC. Additionally, it was apparent that the control system would have to be cognizant of the extremely low temperature of the medium it would be manipulating, in order to avoid ice and dry ice accumulation.

Figure 4. Cryogenic Testing
Calculations were performed to determine the freezing temperature of CO₂ at the lowest pressure at which the chamber would be operated. Due to CO₂ solidification temperatures of around –192°F (-123.3°C) at 7 torr pressure, minimum interior temperatures were chosen to be limited to –190°F (-124.4°C).

After analyzing the problem and reviewing the known variables, the students concluded that some portion of the design would result from the analysis of empirical data derived from experimentation. Many of the beginning design scenarios were not intended to accomplish all goals at once. Rather, the approach to solve one problem at a time was used. With each iteration of the design, students analyzed the results and the problems associated with that particular configuration. Based on that analysis, a subsequent design was implemented in an attempt to accomplish the next goal.

**Solution**

After extensive testing, numerous iterations of hardware configurations, and the application of several control strategies, a working model was developed that proved to operate within the established criteria (Fig. 5). The final configuration consists of two dewars of LN₂ connected in tandem to the system. Gaseous nitrogen is drawn from the top of the dewars to supply the cooling medium. Two solenoid valves are used to select which dewar is to be used at a given time, providing for continuous flow even when one dewar is being changed or serviced. The cryo fluid is mixed with warm GN₂ from the building supply in order supplement the flow rate of coolant through the cooling shroud, thus minimizing the use of LN₂. In addition, the warm GN₂ is used to assure that all nitrogen entering the chamber has been evaporated into a gaseous state. The GN₂ flow is measured with a turbine flow meter and controlled with an analog cryogenic control valve.

In order to heat the chamber, a combination of ambient temperature GN₂ routed through the warm GN₂ heater and the chamber shell heaters is used. The sixteen shell tape heaters, located in four zones throughout the length of the chamber, were intended to be used to help maintain the desired temperature throughout the chamber. Following testing, their use was limited to returning the chamber to ambient temperature. Ambient temperature GN₂ flows from an existing supply line in the room and through an adjustable regulator flow control. An inline heater is used to heat the ambient temperature GN₂ in order to decrease the time it takes to return the chamber to room temperature and to provide enhanced control of the chamber temperature. The cold GN₂ is combined with the warm GN₂. The combined flow is throttled by a variable-control analog cryogenic control valve and the resulting flow rate is measured by a cryogenic flowmeter before entering the chamber.

In order to obtain an accurate indication of the cooling system temperature and its effect on the chamber, it is necessary to acquire numerous temperature readings. Forty-eight thermocouples are used for temperature measurement. Twenty of these are located in heater zones near the shell heaters, and are connected in parallel such that they are averaged into four temperature measurements (one per zone). Twenty-eight additional thermocouples were permanently installed. Of these twenty-eight thermocouples, eight are located in the cooling lines outside the
chamber, sixteen are located on the input and output connections of each zone of the cooling shroud, and four are probes located near the proximity of the experiment.

The eight thermocouples located external to the chamber are used for nitrogen temperature monitoring. Two thermocouples are located in the GN2 input line to the chamber, and another in the exhaust line. There are three thermocouples associated with the warm GN2 heater, which are located at its input, on its heating element, and at its output. Two additional thermocouples are located in the cryo GN2 line to monitor the temperature of the GN2 source.

The sixteen thermocouples inside the chamber are attached to the inlet and outlet of each shroud zone. These thermocouples are used to monitor the temperature differential of each zone to determine the real-time cooling rate and to assure the low temperature limits are not violated. Four flexible thermocouple probes are mounted inside the chamber so they can be arranged to monitor the atmospheric temperature near an experiment. These thermocouples monitor the temperature of the atmosphere that the payload is actually exposed to, and indicate thermal transfer from the cooling and heating components to the chamber’s atmosphere.

At the core of the successful temperature control system is a programmable logic controller (PLC). Programming precise control of the system proved to be challenging, due to the erratic flow rate and unreliable temperature of the dewar’s output. However, the PLC was programmed to cool the chamber to a user-specified setpoint within the range of allowable temperatures from ambient to $-190^\circ$ F (-124.4$^\circ$ C). Proportional integral derivative (PID) programming functions, within the PLC software, are utilized to achieve this goal. The PID function essentially tracks the temperature measurements from the thermocouples and, using this data, determines the position of the cryogenic control valve. The valve throttles the flow of cryogenic GN2 from the dewar in an effort to achieve the desired temperature. This technique is a complete closed-loop process.

Figure 5. Final System Configuration
The combination of full variable control of the cryogenic supply, in conjunction with adequate temperature measurement appeared to provide suitable temperature control. Likewise, the use of heaters and heated house-supply nitrogen proved to be a satisfactory method of heating the chamber. To assure the cooling system would provide stable temperature control within the range of desired temperature, a validation of the cooling system was performed.

**Validation of Solution**

Many tests were performed to assure the system created would operate satisfactorily and predictably under all reasonable operating conditions. The system was tested using methods that emulated a wide range of circumstances. Representative of the overall process, and of notable interest, are a short duration test and a long duration test conducted at different temperatures.

**Brief Duration Test**

With an acceptable hardware configuration and control strategy established, the cooling system was tested at various setpoints for its ability to achieve and maintain a constant temperature. A short duration test of approximately 9 minutes was performed. The output response for the setpoint of -150°F (-101.1°C) is shown in Figure 6. As can be seen from the graph, the temperature of the cryo supply and the cooling input fluctuate (lower two responses). However, the temperature of the coldest zone (third plot from bottom) is relatively stable as it approaches the setpoint. The chamber atmospheric temperature, shown by the top line, gradually declines during the test. Subsequently, many additional short duration tests, ranging from 10 to 60...
minutes and from ambient temperature to -190°F (-124.4°C), were performed. Stable, predictable, and repeatable temperature control was confirmed in all cases.

**Extended Duration Test**

An extended duration test for the setpoint of -190°F (-124.4°C) was performed for approximately 5 hours (Fig. 7). The plotted response line at the bottom of the graph indicates severe fluctuations in the temperature of the cryogenic output from the dewar. Above that, similar fluctuations may be noted in the temperature of the cooling line input to the chamber, after the cryo is mixed with warm GN2. However, the next graphed line above, which represents the lowest surface temperature within the chamber, is held constant once recovering from initial cryo shock. More importantly, the top graphed line response of atmospheric temperature maintains a steady approach to the desired setpoint, despite the substantial cryogenic temperature fluctuations.

Simulation of the realm of atmospheric temperatures and pressures on Mars was proven obtainable by the newly implemented temperature control system, without the formation of dry ice. Chamber shell heaters, ambient temperature nitrogen, and an inline GN2 heater were used to compliment the liquid/gaseous nitrogen cooling supply. All pre-existing hardware was utilized in

![Figure 7. Long Duration Cooling Test](image-url)
some fashion, including the cooling shroud. By combining variable flow of LN$_2$ with ambient temperature nitrogen, LN$_2$ consumption was greatly minimized compared to manual control.

**Conclusions**

Students were vital participants in a faculty/student project team that ultimately automated KSC’s first working Mars simulation chamber. Although many aspects of the previously existing system impeded the project, their presence also proved to create a valuable platform for students to learn and develop problem-solving skills.

Once provided with the design problem, students were quick to realize that there were many variables that were yet undetermined. Moreover, they would have to perform much testing – and collect and analyze the subsequent experimental data – before a successful design could be realized. It was acknowledged from this process that the chamber had to be characterized, a reasonable cooling configuration had to be designed, adequate temperature measurements had to be made, and the proper control actions had to be established. Each of these steps in the process proved to be a valuable lesson not easily obtainable from a typical classroom.

Students were enthralled throughout the duration of the project in spite of its difficulty. The final system validation tests were perhaps some of their greatest moments. For most, it was the first time seeing a process implemented from beginning to end. They were able to witness successful results that they were credited with producing. Most of the students were so excited about the project that they performed many of the validation tests begun during the day throughout the night without cessation.

The students may have been at a disadvantage, as much of the work was not entirely within their field of study. For instance, no student involved in the project had any experience with cryogenic substances and handling the LN$_2$ safely was a learning experience in itself. However, students were involved in the various stages of cooling system development and they helped solve many problems related to controlling the cryogenic fluid. With appropriate guidance and an established learning process, they helped to successfully develop a working model that obtains and maintains stable temperatures for extended periods without developing dry ice within the chamber.

The automation process proved an outstanding method of helping substantiate concepts associated with design through actual testing. Students were challenged to apply their knowledge toward the problems associated with the design. This learning process was ongoing throughout the duration of the project, and problem solving was foremost to the success of the mission. The experience ultimately demonstrated that implementing real life projects such as the Mars Electrostatics Chamber provides an invaluable learning experience for students.

**References**

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Randy Buchanan is an Assistant Professor and Coordinator of Electronics Engineering Technology at the University of Southern Mississippi. Previously, he was a faculty member at Kansas State University and Pittsburg State University in Kansas. His undergraduate degrees were in the areas of Industrial Electronics and Electronics Engineering Technology. He completed his graduate study in Physics, specializing in the area of electron spectroscopy.

He has conducted applied research projects at several NASA centers, as both a fellow and a contractor. He has experience and expertise in the areas of instrumentation, automation, material science, control systems, and planetary/space simulation. He recently served as a representative for the IEEE Control Systems Delegation to China.