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# Cavity Environmental Control System Upgrade for NASA's Stratospheric Observatory for Infrared Astronomy

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# CAVITY ENVIRONMENTAL CONTROL SYSTEM UPGRADE FOR NASA’s STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

by

Ashraf Al-Hajjeh

A Thesis Submitted in

Partial Fulfillment of the

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# ABSTRACT

## CAVITY ENVIRONMENTAL CONTROL SYSTEM UPGRADE FOR NASA's STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

by

Ashraf Al-Hajjeh

The University of Wisconsin-Milwaukee, 2019
Under the Supervision of Professor Chiu Law

The main goal of this project is to fulfill the need of a controller upgrade for the Cavity Environmental Control System (CECS) on NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) aircraft. The preceding controller had multiple disadvantages including operating in an unpressurized region, incomplete functionality implementation, limited fault and status monitoring capability, and reduced maintainability and reliability. The new controller will go through the NASA design process to fulfill all the requirements of CECS operation including complete functionality of all devices currently installed on the aircraft, added devices to improve fault and health monitoring, and overall improvement in maintainability and reliability.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| NASA | National Aeronautics and Space Administration |
| SOFIA | Stratospheric Observatory for Infrared Astronomy |
| CECS | Cavity Environmental Control System |
| DSS | Desiccant Supply System |
| TAHS | Telescope Assembly Heating System |
| TA | Telescope Assembly |
| CONOPS | Concept of Operations |
| PRL | Primary Recirculation Loop |
| PD | Proportional-Derivative |
| RTOS | Real-Time Operating System |
| GUI | Graphical User Interface |
| API | Application Program Interface |
| I/O | Input / Output |
| CPU | Central Processing Unit |
| SBC | Single Board Computer |
| HIL | Hardware in the Loop |

# ACKNOWLEDGEMENTS

I would like to acknowledge NASA’s SOFIA program for the opportunity of working on this project and for their support in making the completion of this project possible. As with most significant projects at NASA, this was a team effort with contributions from many, not all are mentioned by name. I would also like to acknowledge Dr. Chiu Law for his guidance and support through the completion of my master’s degree and thesis.

Since this is an upgrade of an existing and operational system, the discussion of the subsystems, their components, and their control encapsulates both the pre-upgrade and post-upgrade components and operations. I would like to recognize all the SOFIA personnel that have worked on and made available the original pre-upgrade system. I would also like to recognize the team that performed their part in this upgrade successfully. This project was a collaboration between NASA Ames Research Center and NASA Armstrong Flight Research Center. I would like to congratulate the SOFIA management, technicians, and all other personnel for their diligent effort in making this upgrade a huge success.

# CHAPTER 1. INTRODUCTION

## 1.1 General Description

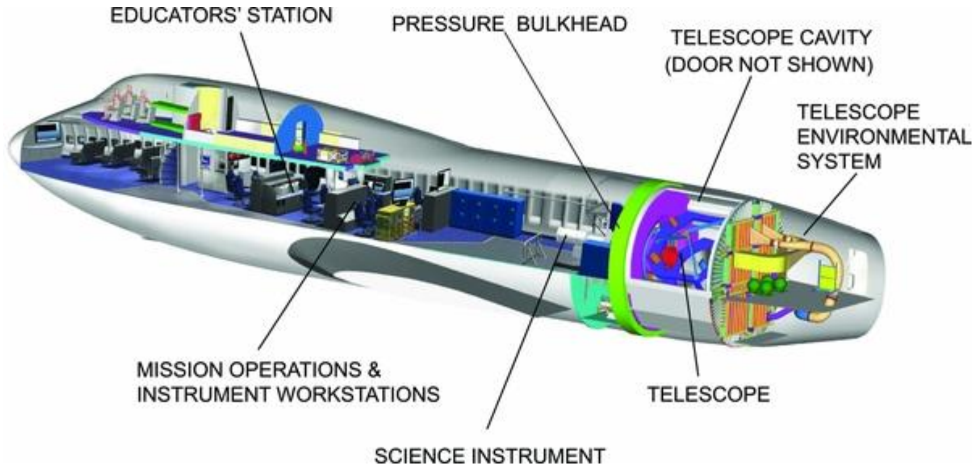


Figure 1. Breakdown of NASA's SOFIA (Image from [1])

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a modified Boeing 747SP aircraft that functions as a flying observatory by carrying a 2.7-meter telescope that was built in order to enable infrared astronomy above 99.8% of the water vapor, which obscures infrared observations made from the ground [1]. One of the biggest challenges with operating the telescope in the air is maintaining the integrity of the telescope cavity. During descent and landing, the CECS is used to protect the optical equipment from dust contamination and prevent condensation from forming on the cold soaked optics and electronics by providing the cavity with clean and dry air using the Desiccant Supply System (DSS) shown to the left of the Telescope Assembly (TA) Cavity in Figure 2. After descent, the CECS is also used to warm the cavity using the Telescope Assembly Heating System (TAHS), shown to the right of the TA cavity in Figure

2, in order to protect the mirror from condensation due to the mirror temperature being below the ambient dew point.

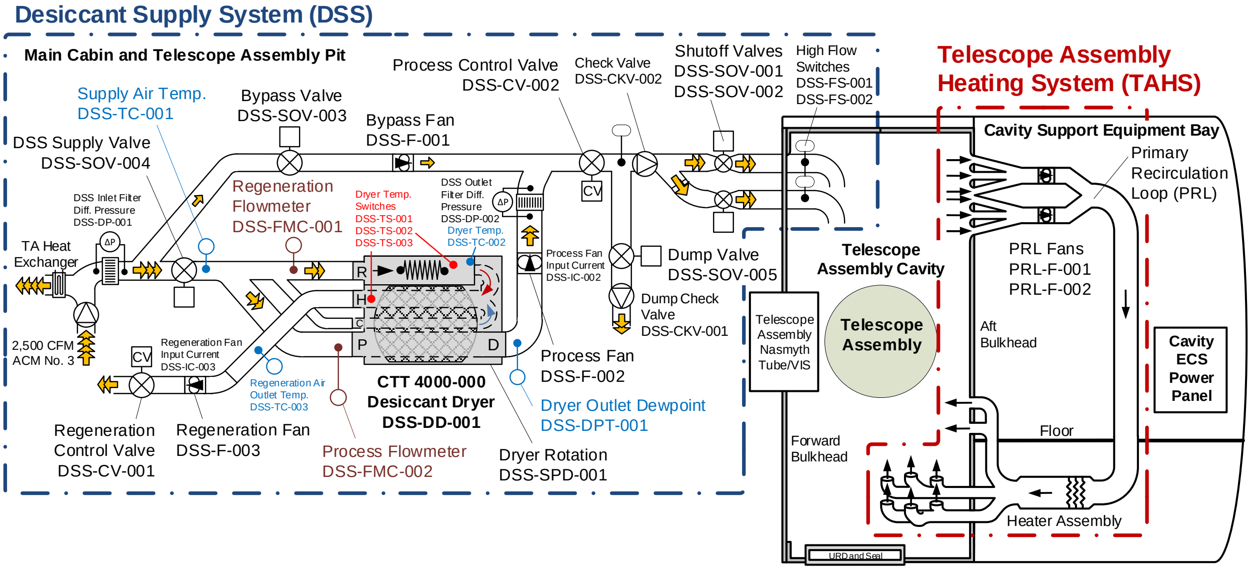


Figure 2. Breakdown of SOFIA’s Cavity Environmental Control System (CECS)
(Drawn by Andrew Gee)

The original CECS controller was in the aft of the aircraft, which is unpressurized and was putting the controller through a harsher operating environment compared with the pressurized main cabin. The original controller also had limited functionality and did not use all the available sensors and devices that were installed in the original system. A new controller has been designed and built after going through the NASA design process to utilize all existing and new devices. New devices were added such as current sensors for every fan, which provide feedback to verify that fans are running when they are commanded.

The main challenge of this project was the coordination of integration work done on the aircraft. On average, SOFIA flies four flights a week making any lengthy integration work difficult and small windows of aircraft downtime must be carefully planned with the program’s support staff months in advance. Another challenge is accurately modelling aircraft devices in the software.

Since the software was developed and initially tested off-aircraft, and a CECS system cannot be easily assembled off-aircraft, a HIL simulator made up of switches, potentiometers and lights with the help of device datasheets was used to simulate the CECS system as close as possible. The software must also be flexible in allowing configuration files to be updated for calibrations and reconfiguration quickly without the need of changing the software executable.

The new controller integration was divided into two phases with each phase being comprised of multiple integration steps. Phase one included moving the original controller to the pressurized main cabin with a new power distribution box that replaced the original power relays in the aft of the aircraft. The second phase was made up of replacing the original controller with the newly assembled controller, which was developed with completely new software. The integration design was implemented and executed in a way that divided the integration into smaller incremental steps that can be tested and verified in very little time and always leave the system in a working state after verification. The integration steps were also designed to leave the capability of easily reverting, at any stage of the integration, to a working configuration within half a day's shift. This phased approach was chosen in order to minimize rework and risk of the project.

For phase one, the following tasks were executed in sequential order:

1) A new power distribution box was designed, built and tested both functionally and environmentally.
2) Adapter harnesses to re-route signals to the main cabin were designed, built and installed.
3) The original controller was moved to the main cabin after the installation of the new power distribution box and harnesses.

4) The functionality of the original controller and software was tested and verified to be unaffected.

For phase two, the following tasks were executed in sequential order:

1) The new controller was designed, built, and tested both functionally and environmentally.
2) The new software was developed and tested off-aircraft with a hardware in the loop (HIL) simulator.
3) The installation and wiring of new devices was done on the aircraft.
4) The new CECS controller was swapped with the original one on the aircraft and the new software was tested to function according to the new design.
5) Once the new controller was installed on the aircraft and passed integration testing, a SOFIA check flight was flown to verify functionality while airborne.

This CECS upgrade added multiple capabilities that greatly improved the reliability and maintainability of the system. Some of these capabilities, which will be discussed in detail in later chapters, include:

1. An upgraded desiccant dryer with two separate command signals driving the regeneration heater and rotating drum independently. The first version of the dryer had only one command signal for both signals, which made turning off the heater separately not possible.
2. Power monitoring of fans with current sensors. The original controller did not have a feedback setup for the fans to indicate that they have been turned on successfully without any faults. Current sensors were added to phase A of each fan’s three-phase power as an indication of the fan running normally.

3. Temperature monitoring of dryer and regeneration temperatures so that the heater is turned off if either temperature rises above nominal conditions. The original controller always maintained the heater on which makes running the system above a certain altitude or during days with low dew point impossible.
4. TAHS Primary Recirculation Loop (PRL) automatic control was added. The original system operated the PRL fans in a manual mode. The PRL heaters were also not utilized with only the heat generated from the fans used for heating the air.
5. Control valves are now modulated with software proportional-derivative (PD) controllers to increase their responsiveness and reduce the relay switching needed to reach position and air flow targets.
6. Multiple temperature sensors, pressure sensors, and temperature switches were deployed for improved reliability.
7. Abnormal conditions of devices are now being monitored and specific error messages are reported to indicate failures which streamlines the troubleshooting of malfunctioning components. These errors also include an identification number that can be used to trace the originating source code in the software.

## 1.2 Cost-Benefit Overview

SOFIA is a unique aircraft, which flies approximately four flights a week. Each flight is carefully planned, months in advance, by scientists and flight planners for acquiring scientific data that can lead to astounding breakthroughs in astronomy. It is highly desirable to avoid a flight cancellation since the cost will be incurred for the flight setup and planning without any scientific achievement. In addition, some observation events such as occultations cannot be rescheduled and the opportunity is lost if the flight is cancelled. Hence, all systems on the aircraft must be as robust as possible with failures and anomalies easily detected and addressed as swiftly as possible.

The legacy CECS system has, over the years, presented the program with difficulties in its operation and fault diagnostics. This was the main driving force behind this upgrade as the potential for reducing operation costs and increasing reliability was very high. CECS is a mission critical system that must remain in optimal working condition to protect the optics of the telescope assembly (valued in the order of millions of dollars) during the descent of the aircraft. The main costs of the upgrade were that of personnel and new hardware that needed to be acquired which was deemed minor in comparison with the savings in operational and maintenance costs.

## 1.3 Project Responsibilities

My responsibilities on this project consisted of the following:

- Participated in design meetings and reviews with the team and SOFIA management, which included electrical design, software design, integration design, mechanical design, testing, and overall system control.
- Designed, implemented, and oversaw the wiring for aircraft integration, new devices, new sensors, the control hardware, and test harnesses.
- Developed the user interface software, written in C# using Visual Studio, which is used for control and monitoring of the CECS controller.
- Configured and utilized the APIs of controller software developed by Russell Franz, which handled data management using a shared table service, communication with the user interface, data collection and output setup for the I/O boards, and file storage to the SATA drive.

- Developed the PD control, system state and transition control, fault monitoring, and device drivers software portion of the controller software, written in C.
- Performed all stages of formal engineering testing including environmental, off-aircraft controller testing, and both aircraft integration phases.
- Performed post flight data analysis of the upgraded system to analyze meeting design requirements.

## 1.4 Thesis Layout

This thesis is broken up into seven chapters as follows. In this chapter (Chapter 1), an overview of the project is presented. Next chapter (Chapter 2) will reveal the system integration plan. Then the upgrade for each subsystem will be described including the CECS controller, user interface laptop, and power box hardware in Chapter 3. Next the Desiccant Supply System (DSS) and its operation control is described in Chapter 4 followed by the Telescope Assembly Heating System (TAHS) and its operational control in Chapter 5. After the Analysis of the final system's operation given in Chapter 6, Chapter 7 will present the conclusion and discussion of findings.

# CHAPTER 2. SYSTEM INTEGRATION

## 2.1 Phase 1 Integration

### *2.1.1 General Description*

Phase 1 integration involved moving the original controller from the unpressurized aft section of the aircraft to the pressurized main cabin. This involved rerouting all CECS signals to the new location and the buildup of a power box to replace, with some improvements, all the legacy power connections of the aft that are necessary for the CECS controller operation. The design principles of signal rerouting involved minimization of the amount of work on the aircraft, the impact on other subsystems, and the effort required for reverting to the original configuration with the original controller operating in the aft section of the aircraft. The design of the new power box was required to be backward compatible with the original CECS controller, and functional for both the new and the original controllers.

The final phase 1 integration plan involved plugging in four harnesses onto the aircraft, installation of the new power box, relocation of the original controller to the main cabin, and finally testing the controller in the new configuration. The integration plan involved unplugging and plugging connectors with no de-pinning of connectors for switching between the aft and the main cabin configuration, which minimized the work required by technicians to switch back and forth between the two configurations. Tasks performed off the aircraft included the fabrication of the four harnesses, and the assembly and testing of the power box. On the aircraft, the routing of about one hundred and fifty wires and the termination of roughly four hundred connections for new plugs going into the new controller and power box was carried out. In this chapter, the integration of harnesses and reversion plan will be discussed. The power box will be discussed in a later chapter.

### 2.1.2 Integration Harnesses

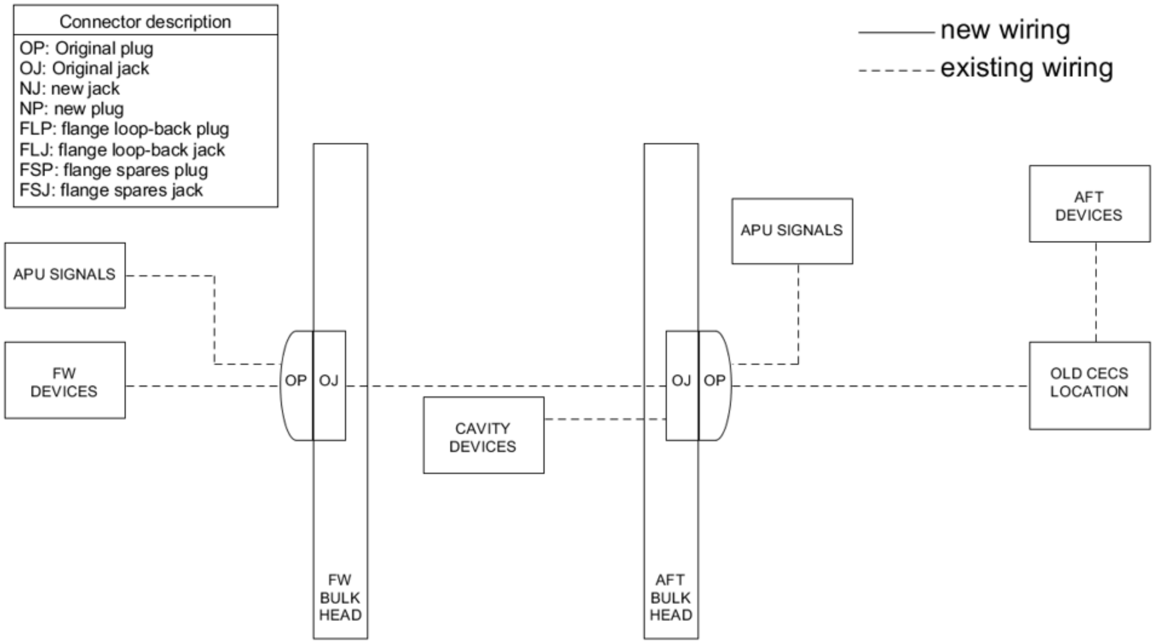


Figure 3. Original CECS configuration

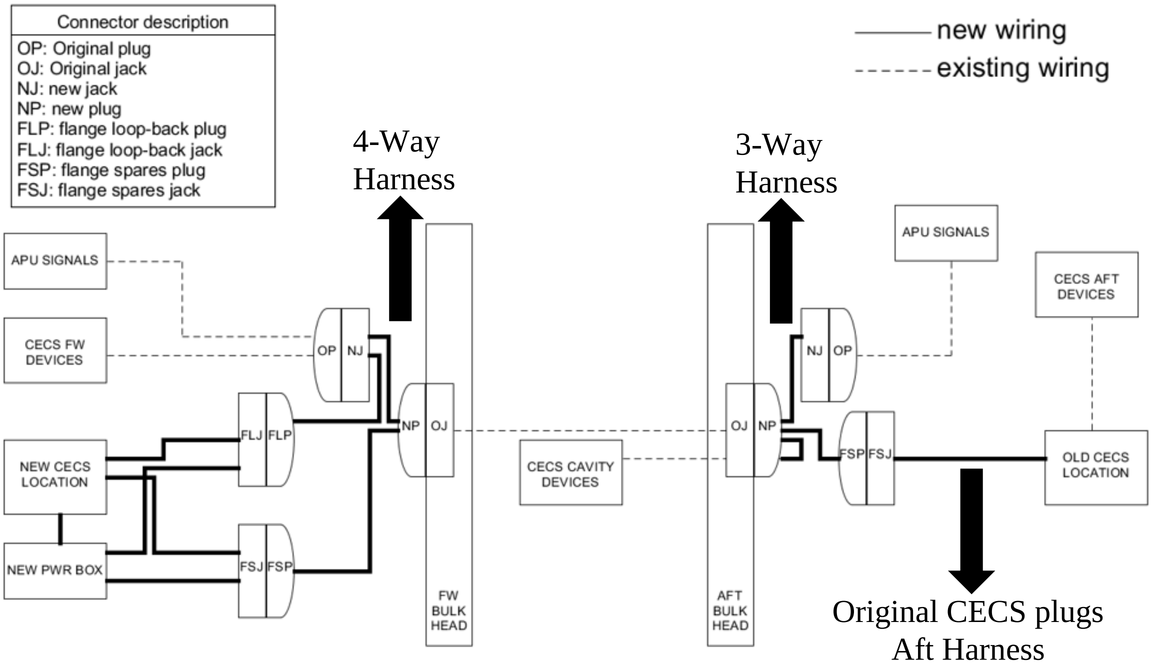


Figure 4. Phase 1 and 2 CECS configurations

The rerouting of CECS signals is summarized in Figures 3 and 4. Figure 3 shows the original CECS configuration with the controller in the unpressurized aft section of the aircraft while Figure 4 shows the new configuration with the controller in the pressurized main cabin. The configuration shown in Figure 4 is the configuration used for both post phase 1 and post phase 2 with the difference only being the CECS controller residing in the new CECS location. The harnesses required for this integration are the 4-Way harness at the forward bulkhead, the 3-Way harness at the aft bulkhead, the original CECS plugs aft harness, and an adapter harness for the original CECS controller, which has different style connectors, to work in the new configuration, which was wired to the new controller's plugs.

The 4-Way harness serves two purposes, the first is to reroute signals for devices in the main cabin to the new location of the CECS controller. The second purpose is to reuse cavity pass-through wiring in order to access devices in the cavity and the aft sections of the aircraft without the need of routing wires in the cavity and minimizing routing wires in the aft. The 3-Way harness is used to route the freed-up cavity pass-through connections to an easily accessible connector and access devices in the cavity by using jumper wires within the new aft bulkhead plug in the 3-Way harness. Both the 4-Way and 3-Way harnesses also maintain seven Auxiliary Power Unit (APU) signals that originally were going through the cavity with the same bulkhead connectors. The original CECS plugs aft harness is used to connect the cavity pass-through connections to devices in the aft without running new wires within the aft section. Finally, a temporary adapter harness is required for the original CECS controller to operate with the new configuration such that, when the new controller is installed, this adapter is no longer needed.

### *2.1.3 Integration and Reversion Plan*

The integration plan was comprised of installing the new power box, relocating the controller to the new location at the main cabin, plugging in all four integration harnesses, and verifying the testing checkout procedure for the original controller. In order to revert to the original configuration in Figure 3, if needed, the original controller is moved back to its aft location, the four harnesses are disconnected, the original connection configuration is performed, and finally the testing checkout procedure is done to verify that the original controller operation was not tampered with.

## **2.2 Phase 2 Integration**

### *2.2.1 General Description*

This phase of integration involved the installation and wiring of new devices that provided additional capabilities to the CECS system and replaced the controller with a newly designed and improved one. The new controller utilizes both new and old devices with many enhancements to the control algorithms.

### *2.2.2 Integration and Reversion plan*

After the phase 1 integration was completed, the new controller integration, and reversion if necessary, only involved swapping the controllers in the main cabin. Since newly installed devices did not have their signals routed to the original controller with the adapter harness, there was no issues in operating the original controller simultaneously with the new devices.

# CHAPTER 3. CECS CONTROL HARDWARE

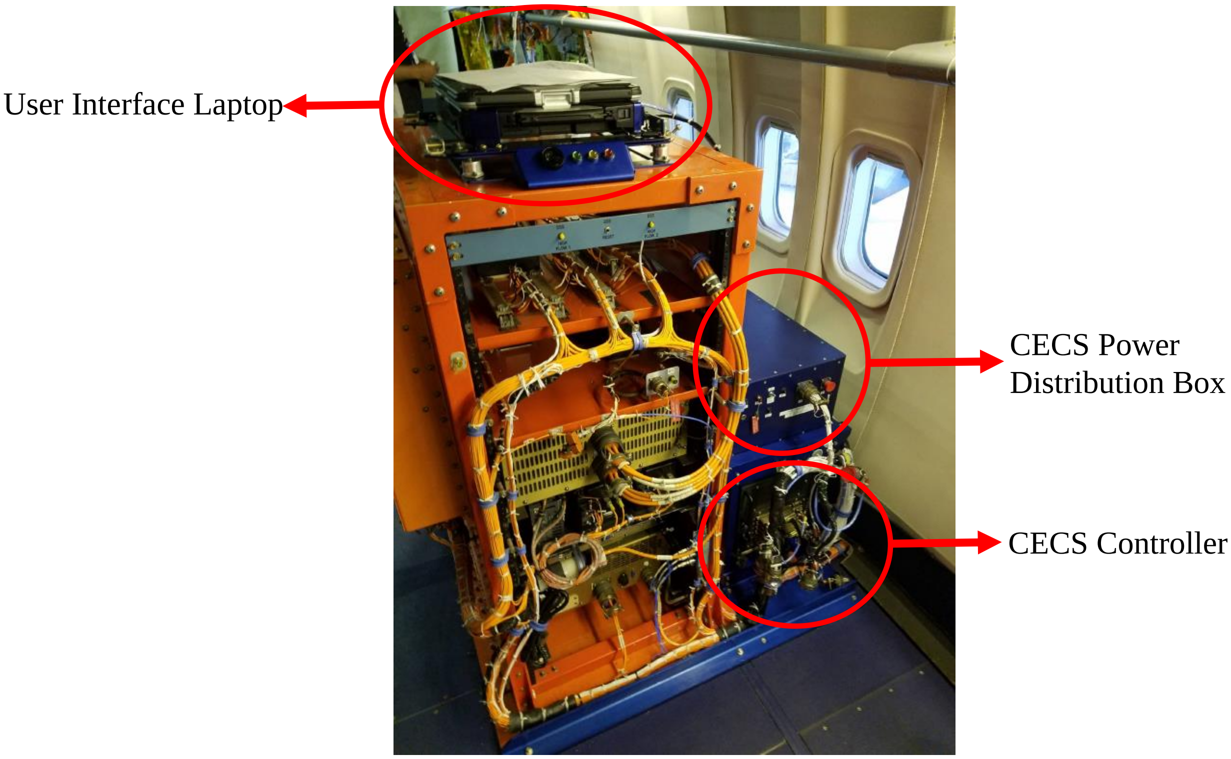


Figure 5. The new CECS control hardware after aircraft integration

The CECS control hardware is made up of the CECS controller, the power distribution box, and the user interface laptop, which are shown in Figure 5. The CECS controller includes the single board computer that monitors and drives the CECS system components. The power distribution box is used to provide any signal conditioning and protection needed for the CECS controller to operate the CECS devices. Finally, the CECS laptop is used to command and monitor the CECS controller.

## 3.1 Controller Hardware

### *3.1.1 General Description*

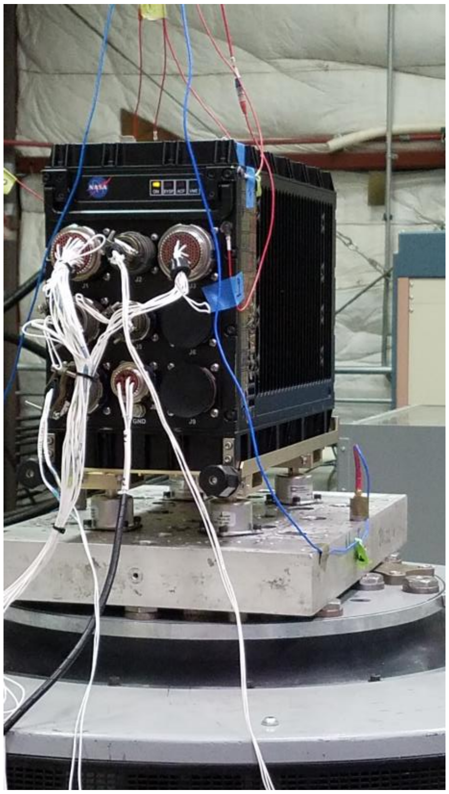


Figure 6. The new CECS controller during vibration testing

The new CECS controller, shown in Figure 6, is made up of a CPU board, three 64C2 Input/Output (I/O) boards [2], and one RRT-6UVME-SATA-R drive board [3]. The CPU is programmed to interface with the I/O boards to set up outputs and monitor inputs for the CECS system. It also uses the SATA drive for storage of non-volatile system parameters, configuration files, and log files. VMEBus is the computer bus standard used for communication between the CPU and the I/O boards. All five boards are mounted in a military grade VME ATR CHASSIS with a custom nine circular connectors front panel for interfacing with external signals. The chassis is wired internally between the VME backplane, which the boards connect to, and the nine circular connectors for the boards to have access to external signals.

### *3.1.2 CPU Board*

The CPU board supports the VxWorks Real-Time Operation System (RTOS), which is used in the implementation of this CECS controller. In addition to core functionality, the CPU board is programmed with four control-specific tasks, one for operating the system transitions and modes including periodic health monitoring, one for controlling the regeneration airflow, one for controlling the process airflow, and one for detecting the dryer drum rotation using a Hall Effect sensor.

### *3.1.3 64C2 I/O Boards*

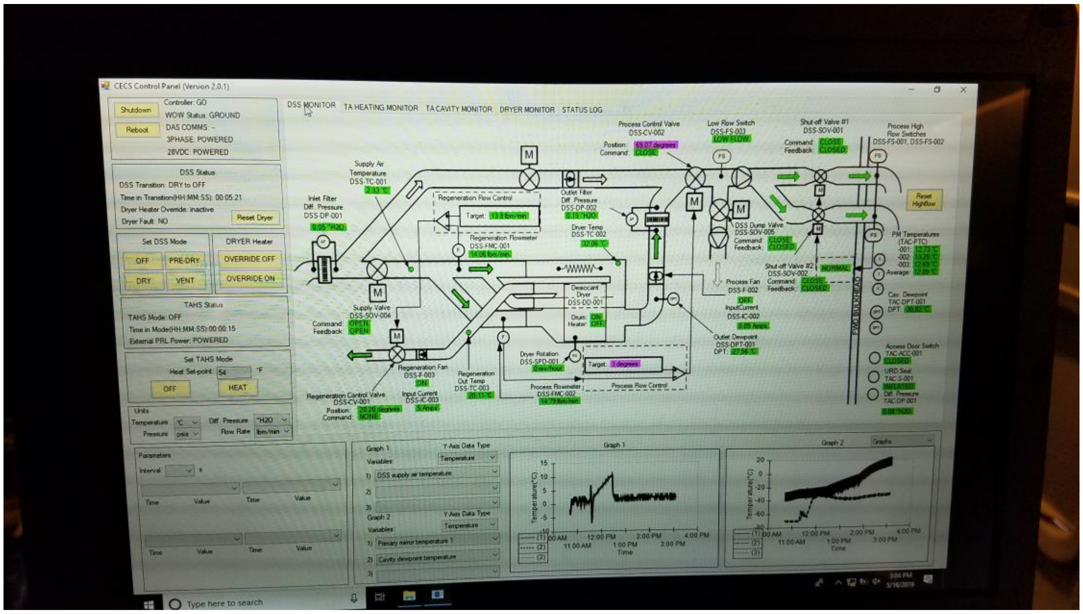
Each of the 64C2 I/O boards contain six I/O modules each of which are selected to provide enough I/O of each type necessary for the CECS system. The part numbers of the I/O boards are 64C2-C2C3K6D7D7D70FH20, 64C2-G4F1D7D7K6K60FH20, and 64C2-C2C2C2G4G4K60FH20.

The I/O modules used in the I/O cards are:

- C2: An analog voltage input module with ten differential non-isolated analog to digital (A/D) channels. Each channel uses a 16-bit A/D converter with programmable sampling rates up to 200 KHz. The input ranges are also programmable. The 0-5V and 0-10V ranges are used for this system.
- C3: An Analog current input module with ten differential non-isolated 16-bit A/D channels with programmable sampling rates up to 200 KHz. The input range is 0-25mA.
- K6: A discrete I/O module with sixteen programmable channels. This module is utilized for 0/28VDC discrete inputs and outputs, and contact closure inputs.

- D7: A digital TTL/CMOS I/O module with sixteen individual channels. This module is used for discrete commands with only the output capability being utilized in this system.
- G4: A resistance temperature detector (RTD) module with six channels. This module is used in both the 2-wire and 4-wire modes. This module has six programmable full-scale ranges designed around the three most common RTD devices. This module is used for RTD temperature readings of different temperature sensors.
- F1: An analog output module with ten digital to analog (D/A) channels. In the CECS system, this module is only used to provide two constant 5VDC signals necessary for the control valves, discussed in a later chapter. Future features, not included in this upgrade, will utilize this D/A module for control of a valve command signal of 0 to 5VDC signal.

## 3.2 User Interface



CECS Control Panel (Version 2.0.1)

Controller: GO
WOW Status: GROUND
DAS COMMS: –
3PHASE: POWERED
28VDC: POWERED

DSS Status
DSS Transition: DRY to OFF
Time in Transition(HH:MM:SS): 00:05:21
Dryer Heater Override: inactive
Dryer Fault: NO

TAHS Status
TAHS Mode: OFF
Time in Mode(HH:MM:SS):00:00:15
External PRL Power: POWERED

Set TAHS Mode
Heat Set-point: 54 °F

Units
Temperature: °C
Pressure: psia
Diff. Pressure: "H2O
Flow Rate: lbm/min

Supply Air Temperature DSS-TC-001: 2.33 °C
Inlet Filter Diff. Pressure DSS-DP-001: 0.05 "H2O
Supply Valve DSS-SOV-004 Command: OPEN Feedback: OPEN
Regeneration Flow Control Target: 13.8 lbm/min
Regeneration Flowmeter DSS-FMC-001: 14.06 lbm/min
Outlet Filter Diff. Pressure DSS-DP-002: 0.15 "H2O
Dryer Temp DSS-TC-002: 32.06 °C
Desiccant Dryer DSS-DD-001 Drum: ON Heater: OFF
Regeneration Fan DSS-F-003: ON
Input Current DSS-IC-003: 5 Amps
Regeneration Out Temp DSS-TC-003: 20.11 °C
Regeneration Control Valve DSS-CV-001 Position: 28.28 degrees Command: NONE
Dryer Rotation DSS-SPD-001: 0 rev/hour
Process Flow Control Target: 1 degrees
Process Flowmeter DSS-FMC-002: 14.79 lbm/min
Process Control Valve DSS-CV-002 Position: 69.07 degrees Command: CLOSE
Low Flow Switch DSS-FS-003: LOW FLOW
Shut-off Valve #1 DSS-SOV-001 Command: CLOSE Feedback: CLOSED
Process High Flow Switches DSS-FS-001, DSS-FS-002
DSS Dump Valve DSS-SOV-005 Command: CLOSE Feedback: CLOSED
Shut-off Valve #2 DSS-SOV-002: NORMAL Command: CLOSE Feedback: CLOSED
Process Fan DSS-F-002: OFF
InputCurrent DSS-IC-002: 0.05 Amps
Outlet Dewpoint DSS-DPT-001 DPT: -27.56 °C
PM Temperatures (TAC-PTC)
-001: 12.73 °C
-002: 13.25 °C
-003: 12.69 °C
Average: 12.89 °C
Cav. Dewpoint TAC-DPT-001 DPT: -30.02 °C
Access Door Switch TAC-ACC-001: CLOSED
URD Seal TAC-S-001: INFLATED
Diff. Pressure TAC-DP-001: 0.08 "H2O

Graph 1 Y-Axis Data Type: Temperature
Variables:
1) DSS supply air temperature

Graph 2 Y-Axis Data Type: Temperature
Variables:
1) Primary mirror temperature 1
2) Cavity dewpoint temperature

Figure 7. The CECS Graphical User Interface

A Windows 10 rugged laptop running a C# developed Graphical User Interface (GUI) software, shown in Figure 7, was used to command and monitor the CECS controller. The user interface enables system operators to transition the system into different states, display system health status, display all sensors and devices' feedback signals, report any detected errors and abnormalities, and provide different utilities that help in diagnostics and examination of the system.

## 3.3 Power Distribution Box

### 3.3.1 General Description

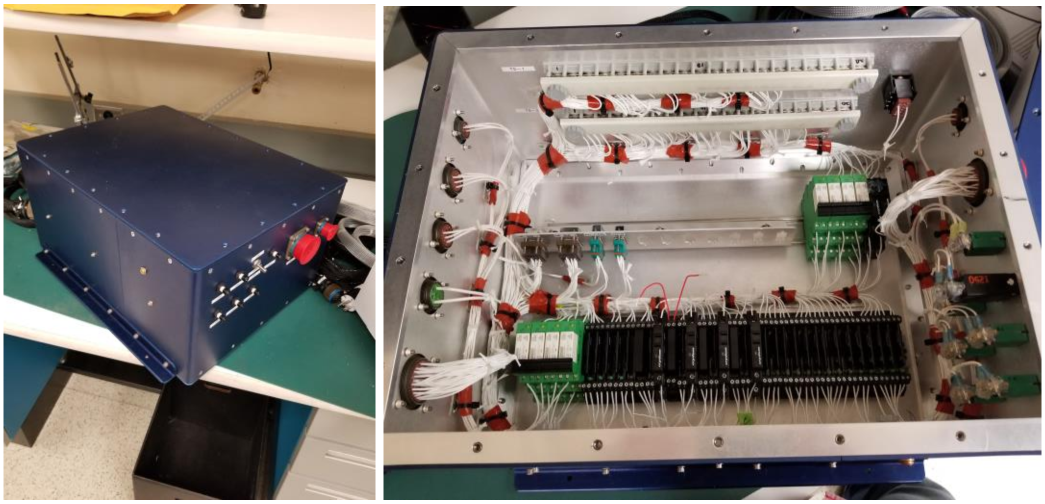

(a) (b)

Figure 8. External and internal pictures of the CECS power distribution box

The power distribution box is used to serve two purposes; the first is to enable the TTL command signals coming from the CECS controller to drive devices that require a relatively large amount of current and different voltage levels. The second purpose is to protect devices of the system that are not covered by the internal hardware protection of the CECS controller. The components utilized within the power box consist of different solid-state and electromechanical relays, diode blocks, terminal blocks and circuit breakers.

### *3.3.2 Command Relays*

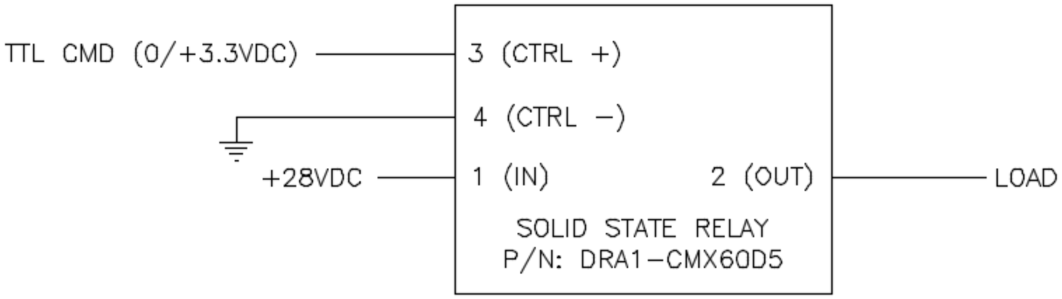


Figure 9. TTL controlled +28VDC signal

The CECS controller commands are TTL outputs, which are 0/3.3VDC discrete signals with a current output of 24mA. A Single-Pole Single Throw Solid State Relay (SSR), part number DRA1-CMX60D5 [4] shown in Figure 9, was selected as the relay controlled by the TTL signals. Its input characteristics are 3-10VDC control voltage with a typical input current of 15mA at 5VDC, a 1ms turn-on time, and a 300µs turn-off time. Its output characteristics are 1-60VDC with 5A of current. This relay allows the TTL commands to control the loads without putting the current burden on the controller.

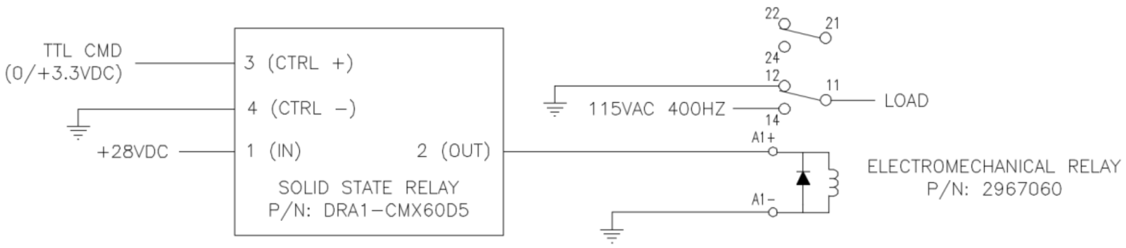


Figure 10. TTL controlled 0/115VAC 400Hz signal

The controller TTL commands are also required to drive some signals that must be switched between Neutral and 115VAC 400Hz. For those signals, the SSR output of 28VDC is used to drive a Double-Pole Double-Throw Electro-Mechanical (EM) relay, part number 2967060 [5] shown in Figure 10. The input characteristics of the EM relay are 24VDC nominal coil voltage with 28VDC being an acceptable input, 18mA nominal input current, and an 8ms response time. The output characteristics are 0-250VAC with 6A current. When the TTL command is in the low state of 0VDC, the load is connected to Neutral and when the command is in the high state of 3.3VDC, the load is connected to 115VAC 400Hz.

Similarly, EM relay 2967060 was also used to switch between 0VDC and 28VDC for some signals that required a double throw between ground and 28VDC instead of a single throw between an open state and 28VDC (Figure 9). The circuit for this is the same as Figure 10 but with 28VDC connected instead of the 115VAC 400Hz signal. Since the EM relay 2967060 can be used to switch both AC and DC voltages, there are no problems in using it this way.

### *3.3.3 Shutoff Valve Open/Close Limit Protection*

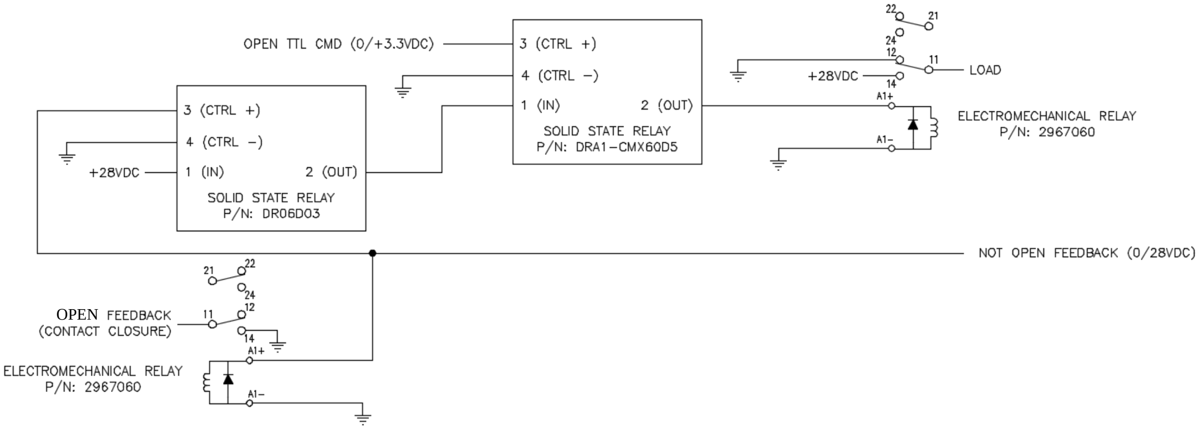


Figure 11. Valve command limit protection

While most valves have protective measures that cuts off the open/close command when the open/close limit is reached, there are two valves in the DSS that lack such protection. They do however have feedback signals that indicate their status and can be used with a few relays to implement valve limit protection externally, as shown in Figure 11. SSR DR06D03 [6] is used to cutoff the command signal in order to protect the valve from being overdriven. When the valve's feedback indicates "not open" the controller's open command can pass through and command the valve to open. When it indicates "open" the 28VDC supply is cutoff from the input of the TTL controlled relay rendering the command ineffective. An EM relay is also added to produce a contact closure (open/ground) signal as a feedback signal indicating the status of the valve. Contact closure for this signal was required to maintain compatibility with the original controller. The same circuit is also used for the close command utilizing the "not closed" feedback signal from the valve and produces a "closed" feedback signal.

### *3.3.4 High Flow Switches Protection*

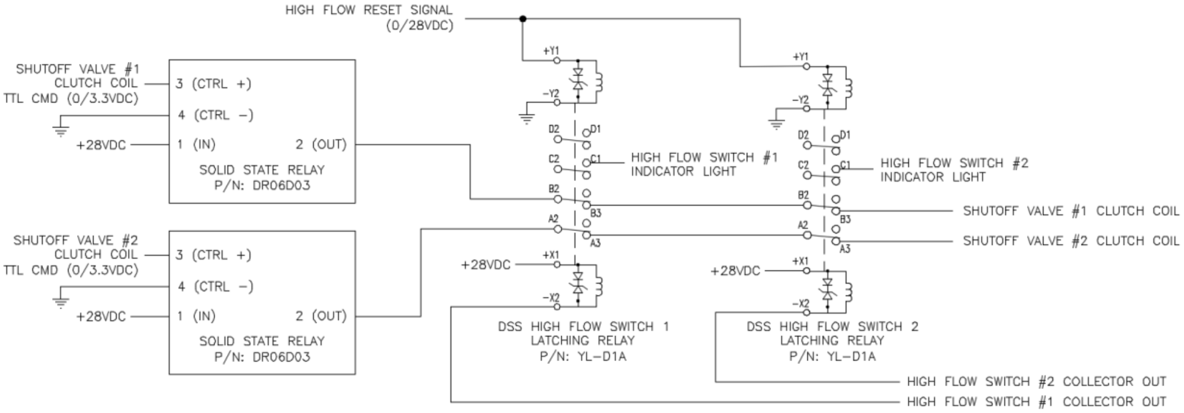


Figure 12. High flow switches protection circuit

Another safety concern that must be dealt with is the possibility of overflowing the cavity. In order to prevent overflow, two high flow switches are used with two latching relays to cut off the clutch coil command signals to the shutoff valves at the cavity, as shown in Figure 12. When the clutch coils of the shutoff valves are energized, the valve can be commanded to open/close freely. If the clutch coils are de-energized, the valves snap shut with the valve commands forced to become ineffective. The high flow switches’ collector output is used to disconnect the clutch coil signals if a high flow occurs. Two indicator lights show the occurrence of a high flow and identify the triggered high flow switch. A reset signal can be used to reset the latching relays to their normal operating state allowing the shutoff valve commands to pass through and command the valves freely.

# CHAPTER 4. DESICCANT SUPPLY SYSTEM (DSS)

## 4.1 General Description

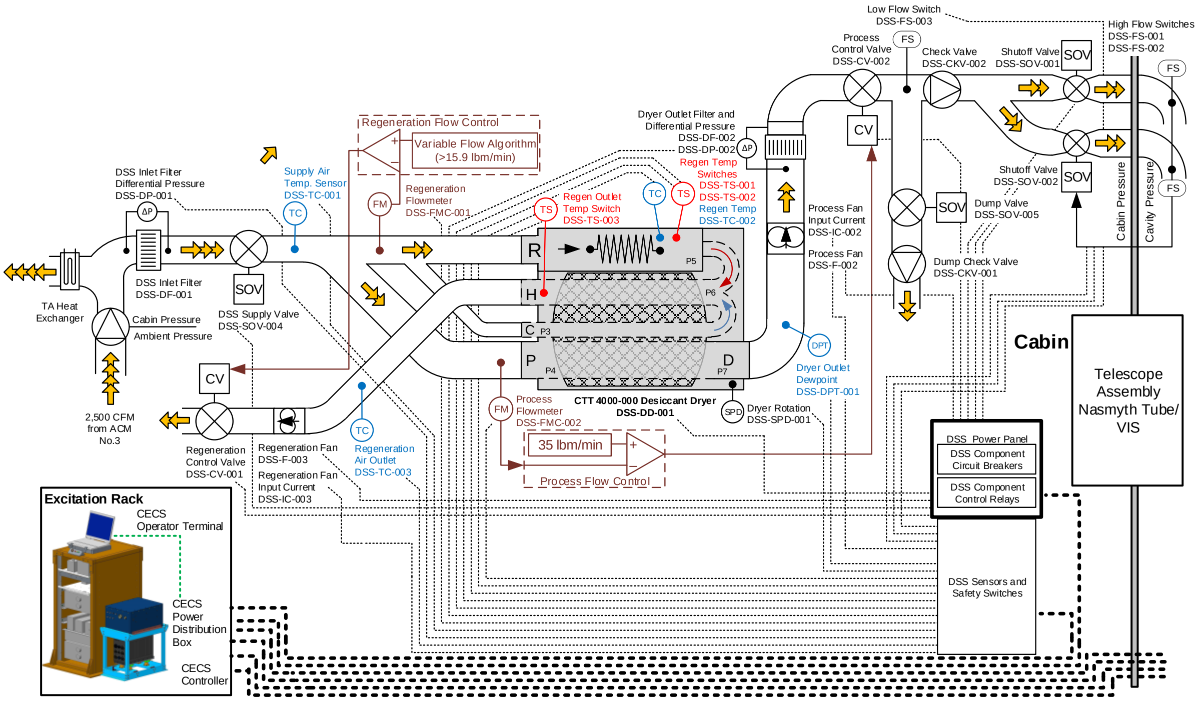


Figure 13. Desiccant Supply System
(Drawn by Andrew Gee)

The main purpose of the DSS is to provide the telescope cavity with clean and dry air. This system is operated with three possible modes: DRY. PREDRY, and VENT. The main function of DRY mode is to provide the cavity with clean and dry air. PREDRY is used to precondition the desiccant dryer in the DSS before using DRY mode and is the same as DRY mode apart from having the air dumped out into the main cabin at the end of the DSS instead of going into the cavity. VENT mode provides the capability of ventilating the cavity without the use of the desiccant dryer. VENT is used to cool the cavity since the air at the inlet of the DSS system is cooler than the cavity but is only allowed to be used while the aircraft is on the ground due to the pressure difference between the cavity and the DSS inlet while the aircraft is in the air.

The DSS devices are made up of a custom-made Desiccant Dryer (DSS-DD-001), two filters at the inlet and outlet of the DSS (DSS-DF-001, DSS-DF-002), three fans (DSS-F-001, DSS-F-002, DSS-F-003), five shutoff valves (DSS-SOV-001, DSS-SOV-002, DSS-SOV-003, DSS-SOV-004, DSS-SOV-005), two control valves (DSS-CV-001, DSS-CV-002), and two check valves (DSS-CKV-001, DSS-CKV-002). The DSS also incorporates multiple sensors (such as temperature sensors (DSS-TC-001, DSS-TC-002, DSS-TC-003), a dryer rotation speed sensor (DSS-SPD-001), two dew point sensors (DSS-DPT-001, TAC-DPT-002), filter differential pressure sensors (DSS-DP-001, DSS-DP-002), and flow meters (DSS-FMC-001, DSS-FMC-002)) for monitoring and control. Temperature (DSS-TS-001, DSS-TS-002, DSS-TS-003) and flow (DSS-FS-001, DSS-FS-002) safety switches are also used for protection against unsafe conditions.

## 4.2 Component Details

### *4.2.1 Desiccant Dryer (DSS-DD-001)*

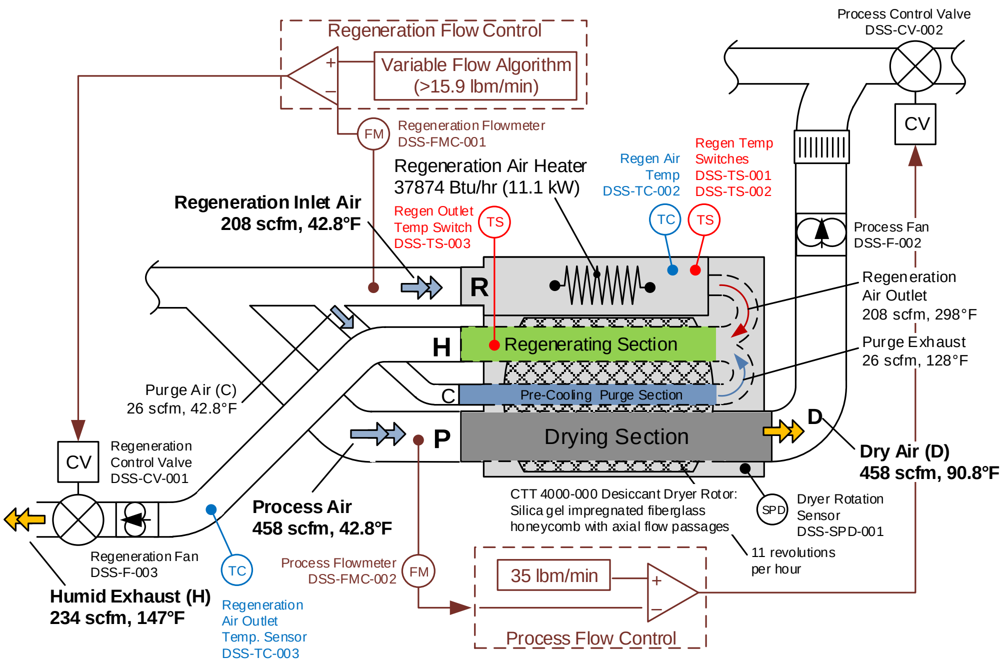


Figure 14. Desiccant dryer operation
(Drawn by Andrew Gee)

The Desiccant Dryer, shown in Figure 14, used in the CECS is a custom-made dryer designed and built by CTT Systems based on requirements from NASA. The dryer is comprised of a silica gel impregnated fiberglass honeycomb as the desiccant material inside a rotating drum with axial flow passages for process, regeneration, and purge flows. The process flow is the air that is dried by going through the desiccant inside the drum as it rotates. The regeneration flow is heated before entering the top of the dryer to regenerate the desiccant material to be reused in the drying cycle. The purge flow is combined with the regeneration flow after going through the dryer to reduce the temperature of the regeneration air to a safer temperature.

Desiccant dryers absorb the moisture, using a desiccant material, from the humid air supplied to the dryer and output dry air [7]. After the material absorbs the moisture, regeneration flow is used to revitalize the material and make it usable again for drying the process air. The material is rotated using a drum connected to a motor allowing the incoming air to go through a cycle of dehumidifying from the process air and refreshment of the desiccant material with the regeneration airflow. This cycle is continuously repeated to keep providing dry air to the outlet of the system.

For safety considerations of the cavity, the dryer process flow was targeted to be 35 lbm/min. The rotation of the drum and the target regeneration flow was picked to provide the process flow with regenerated material for reuse at the start of every drying cycle. The regeneration flow is varied from the minimum target of 13.8 lbm/min and increased slightly with the temperature at the inlet of the dryer. If the inlet temperature increases higher than a chosen limit, then the regeneration flow increases to cool down the regeneration flow to approximately the same desired safe temperature.

### *4.2.2 Regeneration and Process Control Valves (DSS-CV-001, -002)*

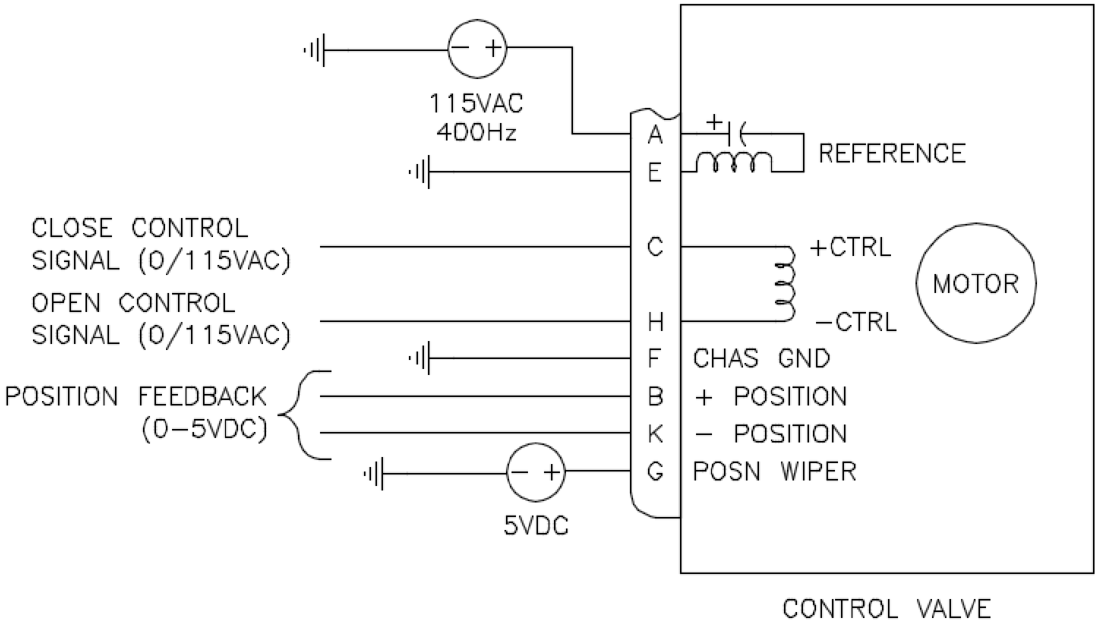


Figure 15. Control valve operation

The process and regeneration control valves are used to control the airflow and maintain them at the desired targets. The control valves used are 4.5-inch butterfly valves, part number BYLB 50495-1, made by Barber-Colman [8]. These valves are actuated using 115VAC 400Hz applied to their CTRL+ and CTRL- on pins C and H respectively as shown in Figure 15. By applying the AC voltage to the valve's CTRL+ and neutral to CTRL-, the valve begins to close. In the same way, by applying AC voltage to the valve's CTRL- and neutral to CTRL+, the valve begins to open. The valve requires a 115VAC 400Hz reference signal that is in phase with the CTRL voltage on pins A and E as shown in the figure. The valve also provides a 0-5VDC feedback signal across pins B and K if a 5VDC supply is provided on pin G. When the feedback is at 5VDC, the valve is fully open; when it is at 0VDC it is fully closed.

### *4.2.3 Regeneration and Process Flow Meters (DSS-FMC-001, -002)*

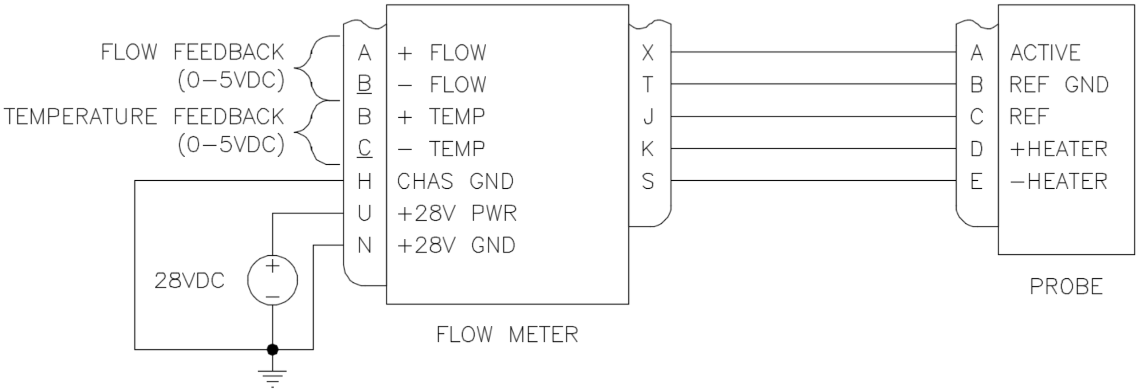


Figure 16. Flow meter wiring

The flow meters used are custom made by FCI Aerospace [9] and provide airflow feedback to be used with the control valves to establish the target flows for the DSS system. The flow meter, shown in Figure 16, provides a 0-5V analog signal that represents the airflow measured in 0.25-600 feet per second. The meter also provides a temperature measurement, which was not used in the control of the DSS system. The mass flow is calculated by the following equation:

$$\begin{aligned} mass\ flow\ \left[\frac{lbm}{minute}\right] \\ &= \left(measured\ flow\left[\frac{feet}{minute}\right]\right) \\ &\times (Pipe\ cross\ sectional\ area\ [feet^2]) \times \left(air\ density\left[\frac{lbm}{feet^3}\right]\right) \end{aligned} \quad (1)$$

The company provided the regeneration and process flow meters' 0-5V feedback signal, shown in Table 1, which were curve fitted with a linear equation and used for airflow feedback.

| Regeneration Flow Meter | | Process Flow Meter | |
|---|---|---|---|
| Voltage (V) | Flow (lbm/min) | Voltage (V) | Flow (lbm/min) |
| 0.73 | 8.975 | 0.838 | 17.95 |
| 1.434 | 11.97 | 1.521 | 23.93 |
| 2.842 | 17.95 | 2.889 | 35.9 |
| 4.249 | 23.93 | 4.257 | 47.86 |

Table 1. Flow meters feedback signals

The following equations that calculate airflow from voltage (V), in volts, were the result of the linear curve fit:

$$Regeneration\ Flow\left[\frac{lbm}{minute}\right] = 4.2494 \times V + 5.8743 \tag{2}$$

$$Process\ Flow\left[\frac{lbm}{minute}\right] = 8.7481 \times V + 10.622 \tag{3}$$

### *4.2.4 Filter Differential Pressure Sensors (DSS-DP-001, -002)*

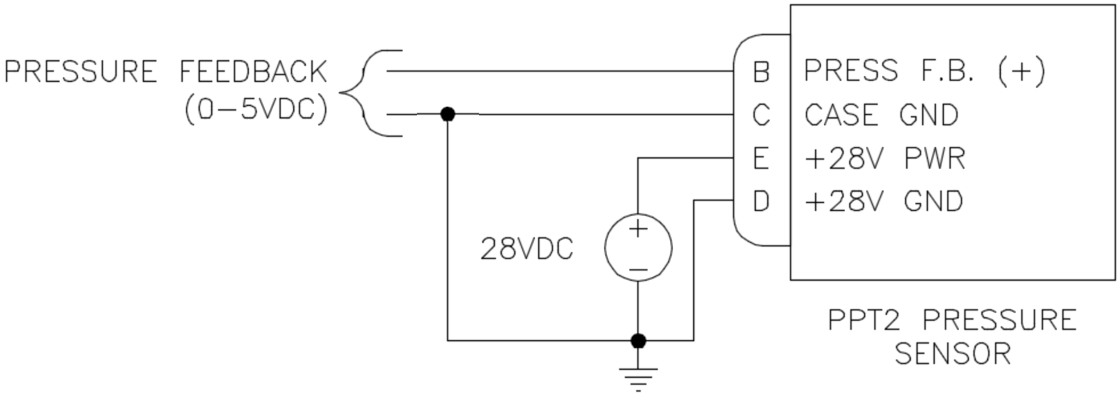


Figure 17. Pressure sensor wiring

Two differential pressure sensors are used to provide a feedback signal representing the differential pressure across the HEPA filters used in the DSS. The part number of these sensors is PPT20002DWW2VSBEF [10] with their wiring shown in Figure 17. The sensors used provide a linear 0-5V analog feedback signal with 0V representing -2 psi and 5V representing 2 psi. The feedback from these sensors will be monitored to detect if the HEPA filters must be replaced. If the pressure differential across either of the two filters is observed to be above 5 inches of water then the filter must be replaced.

### *4.2.5 Cavity Inlet Clutched Shutoff Valves (DSS-SOV-001, -002)*

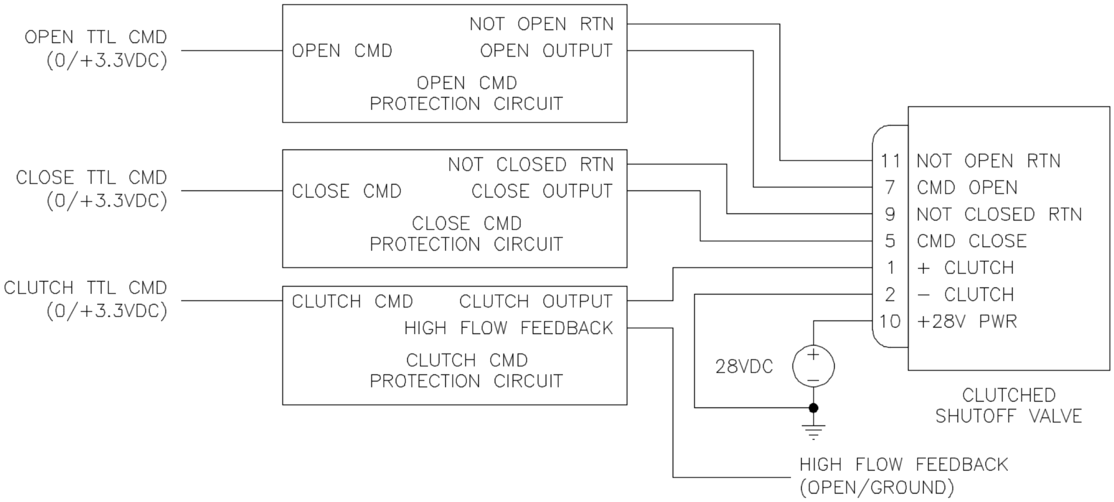


Figure 18. Clutched shutoff valve wiring

The clutched shutoff valves are used to control if the air exiting the DSS system enters the telescope cavity. Their part number is BYLB 52902-3 [11] and their wiring is shown in Figure 18. The open and close command protection circuits are the ones shown in Figure 11 while the clutch command protection circuit is shown in Figure 12.

These valves operate by first energizing the clutch coil on pin 1 with 28VDC and then applying the open/close command on pins 7 and 5 depending on which direction the valve is desired to be moved. If the valve reaches either limit (open/closed) then the corresponding feedback command is set to ground as compared to 28V when it is not at that limit. The protection circuits cut off the open/close commands if the valve is at the corresponding limit. Finally, if a high flow condition has occurred then the clutch 28V output is cut off from the valve forcing the valve to shut off to prevent the air from flowing into the telescope cavity.

### *4.2.6 Bypass, Supply, and Dump Valves (DSS-SOV-003, -004, -005)*

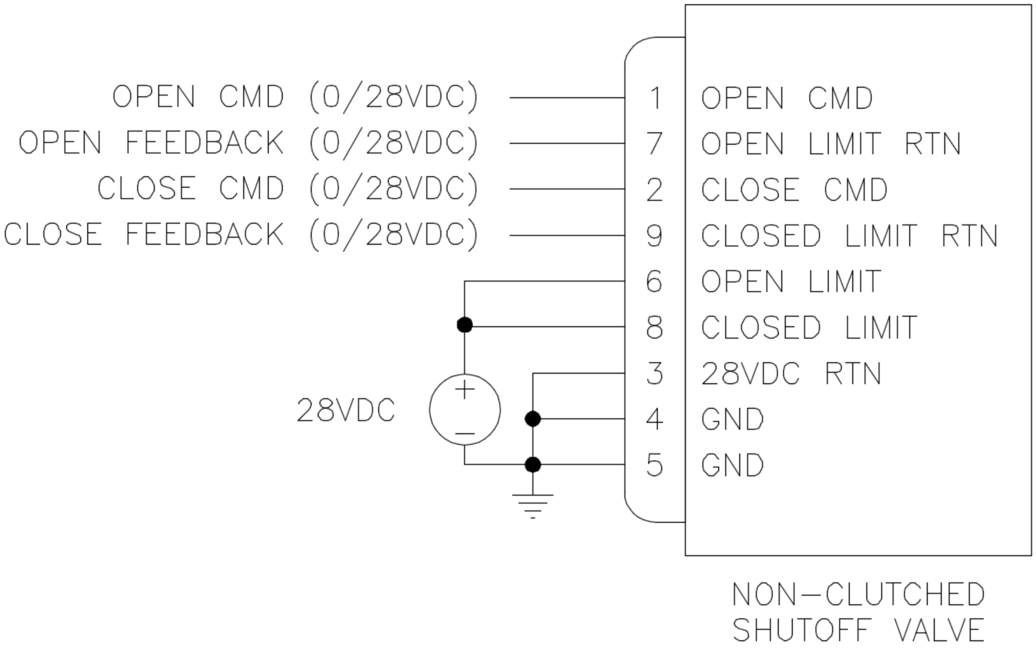


Figure 19. Bypass, supply, and dump shutoff valves wiring

These types of shutoff valves are used to control different flows in the DSS system. They are not clutched shutoff valves since they do not pose a safety risk as compared to DSS-SOV-001 and DSS-SOV-002. The part number for these valves is 60B40048-1 [12] and their wiring is shown in Figure 19.

These valves can be commanded to open by applying 28VDC to pin 1 and commanded to close by applying 28VDC to pin 2 as shown in Figure 19. The open and closed feedbacks are also shown and can assume a 0 or 28VDC signal level representing whether the valve is at the limit or not. These valves provide internal limit protection and therefore no external hardware protection is needed to cutoff the commands.

### *4.2.7 Bypass, Process, and Regen Fans (DSS-F-001, -002, -003)*

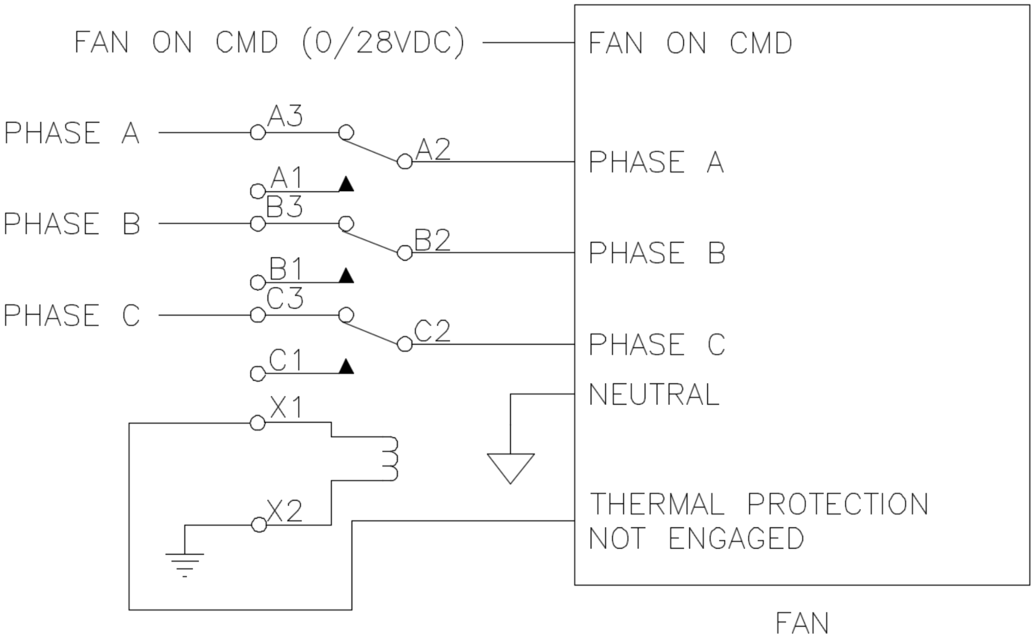


Figure 20. Flow fan wiring

The fans in the system are used to pull the airstream at the inlet of a pipe through the pipe. The part numbers for the bypass, process and regeneration fans used are 2780206-1, 645920-3-1, and 645995-1 respectively [13 — 15]. These three fans have different pinouts but are wired in a very similar fashion as shown in Figure 20.

The fan is powered with 3-phase 120VAC 400Hz power and can be commanded to turn on by providing a 28VDC control signal as shown in Figure 20. The fan also provides an internal thermal protection not engaged switch which passes the 28VDC command, if the thermal protection is engaged, to a 3-phase relay to disconnect the power to the fan. This ensures that the fan is not damaged from overheating.

### *4.2.8 DSS Air Temperature Sensors (DSS-TC-001, -002, -003)*

2-Wire RTD temperature sensors are used in the DSS. These sensors provide a resistance feedback signal proportional to the measured temperature. Different types of RTDs were used in the system and their resistance to temperature conversion equations were found by curve fitting polynomials of up to the 5th degree. These sensors are used to monitor different temperatures for the safe operation of the system.

The supply air temperature sensor, DSS-TC-001, is a probe sensor installed in the duct after the supply valve. This sensor is made by Norwich and follows the MIL-T-7990 Table I standard for the resistance to temperature relationship [16]. After curve fitting a 2nd order polynomial to the temperature standard data and making corrections for wire lengths, the following relationship will be used:

$$T_{DSS-TC-001}(°\mathrm{F}) = -0.01044 \times R^2 + 7.01784 \times R - 582.494 \tag{4}$$

Where R is resistance in ohms.

The dryer air and regeneration air temperature sensors, DSS-TC-002 and DSS-TC-003, are also probe sensors installed at the heater inside the dryer and the regeneration outlet of the dryer. These sensors are made by Thermometrics Corporation and follow the International Temperature Scale of 1990 (ITS-90) standard [17]. The temperature to resistance relationship can be approximated linearly with very little variation, less than 1 degree Celsius, for the operating range of this sensor. Its temperature to resistance relationship is:

$$T_{DSS-TC-002}(°\mathrm{F}) = 4.605588 \times R - 492.55826 \tag{5}$$

### *4.2.9 Cavity High Flow and DSS Low Flow Switches (DSS-FS-001, -002, -003)*

A flow switch is either open or closed when the high or low flow condition is met, depending on which type is used. These flow switches can be wired as indication with either a contact closure to ground or a 28VDC supply, or they can be wired in line with the power or command of a device to halt its operation. In the case of the DSS system, the two high flow switches, DSS-FS-001 and DSS-FS-002, were wired to be able to cut off the clutch coil command of the two shutoff valves before the cavity, DSS-SOV-001 and DSS-SOV-002, which forces the valves to close. The low flow switch, DSS-FS-003, was wired as a 28VDC indication only feedback signal for the controller to detect abnormal flow due to unforeseen behaviour in components.

The low flow switch used is made by FCI [18] with the flow set point being 364 standard feet per minute below which the feedback signal will be 28VDC. The high flow switches used are also made by FCI [18] with their set point being 3758 standard feet per minute above which the clutch coil command of the two shutoff valves will be disconnected and the valves forced to be closed shut.

### *4.2.10 DSS Fans Current Sensors (DSS-IC-001, -002, -003)*

Electrical current sensors were added to phase A of every fan in the system as a feedback signal showing that the fans are operating normally. These sensors are made by Seneca [19] and can be configured to different current ranges with three dipswitches on the sensor. The current ranges used for the DSS are 5A, 10A, and 10A for the bypass fan, DSS-IC-001, the process fan, DSS-IC-002, and the regeneration fan, DSS-IC-003, respectively. The feedback signal applies a 4-20mA signal to the analog current input (C3) module of the controller.

### *4.2.11 DSS Dew point Controllers (DSS-DPT-001, TAC-DPT-001)*

The main purpose of the DSS system is to provide dry air and reduce the moisture in the telescope cavity. Dew point controllers measure how well the DSS system performed after a flight. There are two dew point controllers, one at the outlet of the DSS system showing the dew point of the DSS output air and another in the cavity showing the resulting dew point that is being controlled. These controllers are used for post-flight analysis and are not part of the control loops. The controllers used are DMT347 made by VAISALA [20] and provide a 0-10VDC analog signal representing the dew point between -112$^{o}$F and 68$^{o}$F.

### *4.2.12 Dryer Rotation Sensor (DSS-SPD-001)*

A Hall Effect sensor is used to detect the drum rotation of the dryer. This sensor is made by PST [21] and is used for monitoring the proper drum rotation by providing an open collector signal that can be detected by the controller to measure a period between magnets placed on the drum surface, which indicates how fast the drum is rotating. An independent task keeps track of the drum rotation speed by detecting pulses and calculating the time between two consecutively detected pulses with the time between pulses being nominally around 26 seconds. A timeout period of 40 seconds was set to discard a detected pulse if a second pulse was not detected within that time. With the number of equally spaced magnets being 12, the nominal calculated drum rotation speed is around 11.5 rev/hour.

## 4.3 System Operation Control

### 4.3.1 DSS System Modes

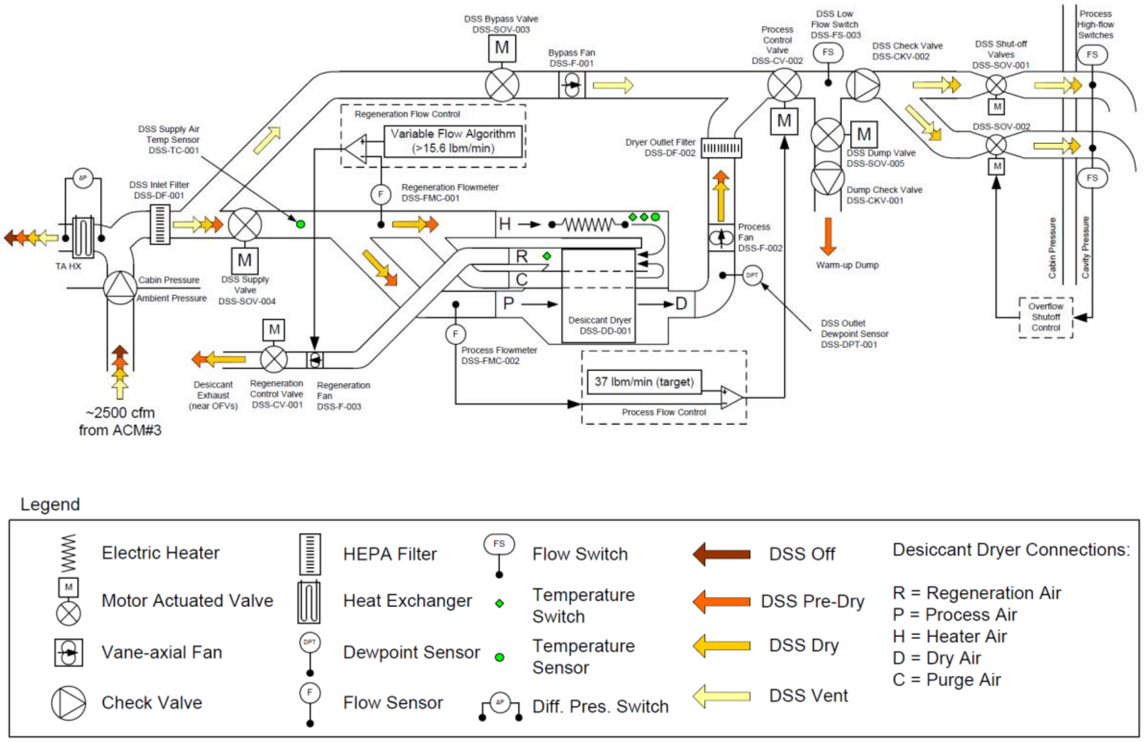


Figure 21. Desiccant Supply System operation

The DSS system can assume four different modes, which are:

1. OFF: All shutoff valves are closed, all fans and the dryer are turned off, the process control valve is completely closed, and the regeneration control valve is completely open.
2. VENT: Originally, this mode was designed to utilize the bypass valve and fan but was changed to utilize the DSS assembly due to safety concerns. The supply valve and shutoff valves 1 and 2 are open, all other shutoff valves and the regeneration valve are closed, the dryer is off, the process fan is on, the bypass and regeneration fans are off, the process control valve is regulating the flow.

3. PREDRY: The supply valve and the dump valves are open, all other shutoff valves are closed, the dryer and the process and regeneration fans are on, the bypass fan is off, the regeneration and process control valves are regulating the flow.
4. DRY: The supply valve and shutoff valves 1 and 2 are open, all other shutoff valves are closed, the dryer and the process and the regeneration fans are on, the bypass fan is off, the regeneration and process control valves are regulating the flow.

While in these modes, all the sensors and switches are continuously checked for abnormal conditions to ensure the proper operation of the system. If any sensor in the system indicates an abnormal condition, then the operator is alerted with an error to help diagnose the problem.

### *4.3.2 DSS System Transitions*

The available DSS transitions are summarized as follows:

1. OFF to VENT:
    a. Check if the aircraft is on the ground, cancel the transition otherwise.
    b. Open the supply valve (DSS-SOV-004).
    c. Move the process valve (DSS-CV-002) to throttle position (10 degrees open).
    d. Open shutoff valves 1 and 2 (DSS-SOV-001 and DSS-SOV-002).
    e. Close the regeneration control valve (DSS-CV-001).
    f. Turn on the process fan (DSS-F-002).
    g. Start the process flow regulation.
2. OFF to PREDRY:
    a. Open the supply valve (DSS-SOV-004).
    b. Open the dump valve (DSS-SOV-005).

    c. Turn on the regeneration fan (DSS-F-003).
    d. Start the regeneration flow regulation.
    e. Turn on the process fan (DSS-F-002).
    f. Start the process flow regulation.
    g. Begin the drum rotation of the dryer.
    h. Turn on the dryer heater.

3. OFF to DRY:
    a. Open the supply valve (DSS-SOV-004).
    b. Turn on the regeneration fan (DSS-F-003).
    c. Start the regeneration flow regulation.
    d. Move the process valve (DSS-CV-002) to throttle position (10 degrees open).
    e. Open shutoff valves 1 and 2 (DSS-SOV-001 and DSS-SOV-002).
    f. Turn on the process fan (DSS-F-002).
    g. Start the process flow regulation.
    h. Begin the drum rotation of the dryer.
    i. Turn on the dryer heater.
4. PREDRY to DRY:
    a. Turn off the dryer heater.
    b. Move the process valve (DSS-CV-002) to throttle position (10 degrees open).
    c. Open shutoff valves 1 and 2 (DSS-SOV-001 and DSS-SOV-002).
    j. Close the dump valve (DSS-SOV-005).
    k. Start the process flow regulation.
    l. Turn on the dryer heater.

5. DRY to PREDRY:
    1. Turn off the dryer heater.
    2. Open the dump valve (DSS-SOV-005).
    3. Close shutoff valves 1 and 2 (DSS-SOV-001 and DSS-SOV-002).
    4. Turn on the dryer heater.
6. DSS to OFF:
    1. Turn off the dryer heater and drum rotation if on.
    2. Turn off all fans except the regeneration fan.
    3. Close all shutoff valves except the supply valve.
    4. Close the process control valve.
    5. Wait for the heater to cool down below 90°F.
    6. Turn off the regeneration fan.
    7. Open the regeneration control valve (DSS-CV-001).
    8. Close the supply valve (DSS-SOV-004).

During transitions, before moving to the next step, feedbacks are checked with a set timeout to make sure the components are behaving properly. If at any step in the transition, a component is not behaving properly throughout the timeout period, then the system will timeout and return to OFF after alerting the operator of which component is behaving abnormally. This helps the operator diagnose if a component malfunctioned and needs to be replaced.

### *4.3.3 Process and Regeneration Flow Control*

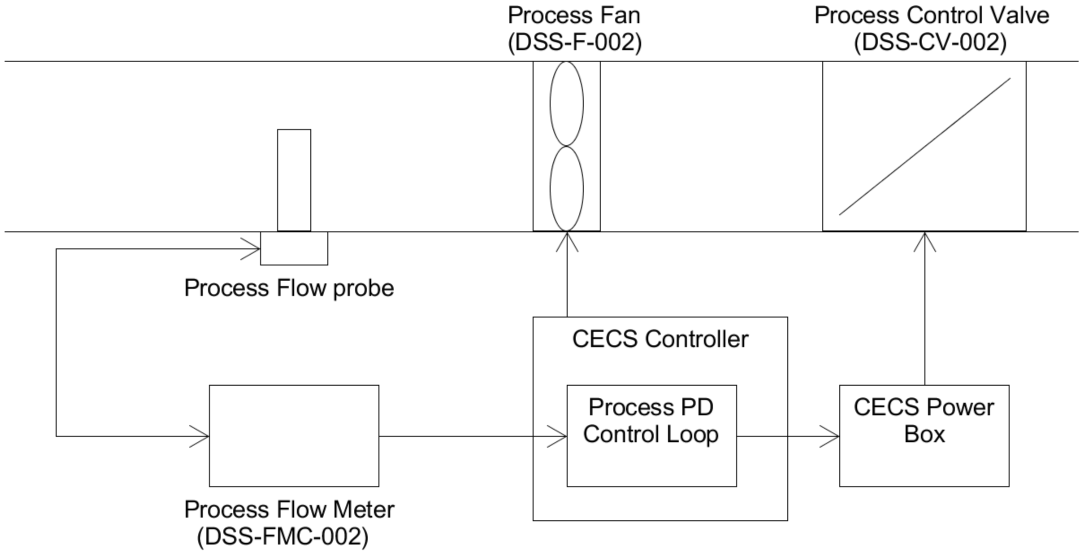


Figure 22. Process flow control loop

There are two sections of the DSS system where the airflow needs to be regulated as shown on Figures 14 and 22. The first section is the process flow, which needs to be regulated at a fixed flow rate of 35 lbm/min and is chosen based on the size of the telescope cavity. The second section is the regeneration flow which needs to be regulated at a flow rate higher or equal to 13.8 lbm/min and is determined by the supply air temperature (DSS-TC-001). The controller will utilize a software PD control loop that uses the flow meter signal as the feedback and the position of the control valve as the output of the control loop. By changing the position of the control valve, the flow rate can be set to the desired state.

When the DSS is in the OFF mode the process valve is commanded to be completely closed stopping any flow from going through. When the system is in the VENT, PREDRY or DRY modes, the process control loop is commanded to regulate the flow with the setup shown in Figure 18 and maintain the targeted rate of 35 lbm/min.

In order to begin process flow control, the path of the flow must first be opened. This means that on the inlet side of the DSS, the supply valve, DSS-SOV-004, must be opened. On the outlet side, if the mode is PREDRY, then the dump valve, DSS-SOV-005, must be opened. If the mode is VENT or DRY on the other hand, shutoff valves one and two, DSS-SOV-001 and DSS-SOV-002, must be opened. The process fan can be turned on once the valves at both sides of the DSS are open to start pushing processed airflow through the duct. When the DSS shutoff valves and the process fan are setup, then the controller can begin regulating the flow using the process flow meter and control valve.

The regulation of flow is performed with the pulse width modulation (PWM) of the open and close commands of the control valve. Using the flow meter signal as the feedback for controlling the flow to the targeted rate and the PD gains, the output of the controller is a 0-100% duty cycle PWM signal. The sign of the calculated error determines whether the open or the close command will be used to drive the valve. If the calculated duty cycle of the PWM signal is 100%, then the command is left on at the end of the control loop in order to avoid relay chatter. If the PWM signal has a duty cycle less than 100%, then the command is turned off at the end of the pulse.

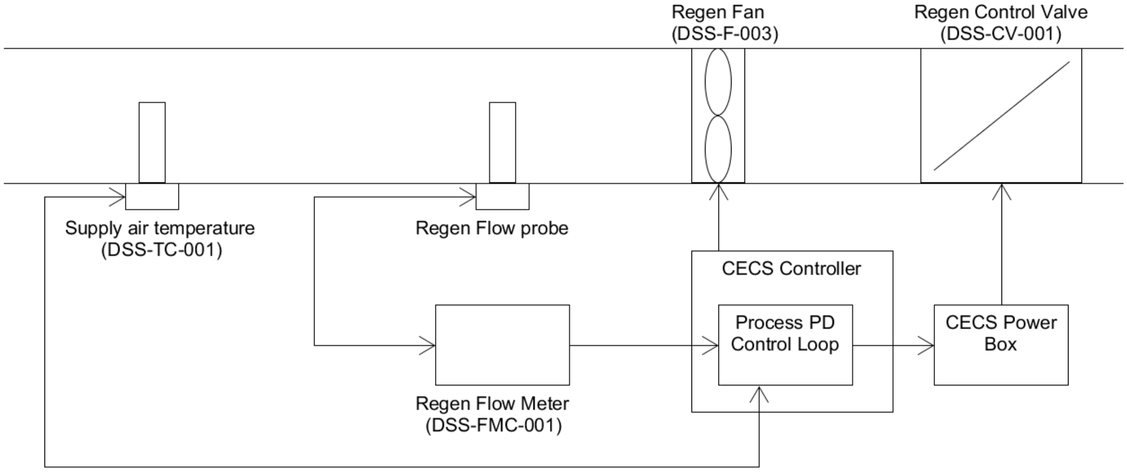


Figure 23. Regeneration flow control loop

When the DSS is in the OFF mode, the regeneration valve is commanded to be completely open. When the DSS is in VENT, PREDRY or DRY modes, the regeneration control loop is commanded to regulate the flow. The regeneration control loop can be initiated after the supply valve, DSS-SOV-004, is opened and the regeneration fan, DSS-F-003, is turned on to push the regeneration flow through the duct.

The Regeneration control loop regulates the flow in the same way as the process control loop regulates the flow with PWM. The only difference from the process control loop is that the targeted flow rate changes according to the temperature sensed by the supply air temperature sensor, DSS-TC-001. The main concept behind this is if the temperature is higher at the inlet of the DSS system, then more flow is pushed in the regeneration duct to cool down the heater in the dryer. The equation for the targeted regeneration flow is simply:

$$Regeneration\,Target\,Flow = 13.8\,lbm/min + C_m \times (T_{DSS-TC-001} - C_T) \qquad (6)$$

Where $C_m$ and $C_T$ are configurable constants.

### *4.3.4 DSS System Abnormal Condition Monitoring*

During each of the modes and transitions of the DSS system, the sensors in the system are checked for abnormalities in order to detect issues that arise from failing components, bad connections, and any unforeseen problems. Prior to checking for an abnormality, the sensors are first checked for sensor faults. This is done by checking if the sensor is reporting a value outside its normal operating range, which is an indication of sensor failure. If the sensor passes its sensor failure check, then the monitoring of abnormalities in the system is done. The DSS sensors are checked as follows:

1. **DSS-DP-001 and DSS-DP-002:** The filter differential pressure sensors are used to detect if the filter is clogged and needs to be changed. If differential pressure of more than 5 inches of water is detected across the filter, then the filter must be changed.
2. **DSS-TC-001:** The supply air temperature sensor is used to determine if the dryer heater can be turned on or not. If the temperature at the inlet of the DSS system is above 60$^o$F, then the dryer heater cannot be turned on for the safety of the system. This sensor is also used to determine the targeted regeneration flow for operating the dryer if the temperature is between 45$^o$F and 60$^o$F.
3. **DSS-TC-002 and DSS-TC-003:** These temperature sensors are used for the control of the heater, which should be turned off for temperatures above abnormal operating conditions and be turned on after the temperatures drop below safe cut-off temperatures. The heater turn-off temperatures are 365$^o$F and 158$^o$F for DSS-TC-002 and DSS-TC-003 respectively. The heater turn-on temperatures are 338$^o$F and 131$^o$F for DSS-TC-002 and DSS-TC-003 respectively.

4. **DSS-FMC-001 and DSS-FMC-002:** If the regeneration or the process flow meters detect flow in the OFF mode, then the system is operating abnormally. These sensors are also used as the feedback for the flow control algorithms.
5. **DSS fans current sensors:** Each fan has a current sensor for phase A which is checked to make sure the fan is in the correct state. No current must be detected when the fans should be off and current above a reasonable threshold must be detected when the fans are on.
6. **Shutoff and control valves feedback:** The valves' feedback signals are checked to ensure their proper status corresponding to the mode or the transition of the DSS system.
7. **DSS-SPD-001:** This sensor provides the feedback for detecting the proper rotation of the drum.

# CHAPTER 5. TELESCOPE ASSEMBLY HEATING SYSTEM (TAHS)

## 5.1 General Description

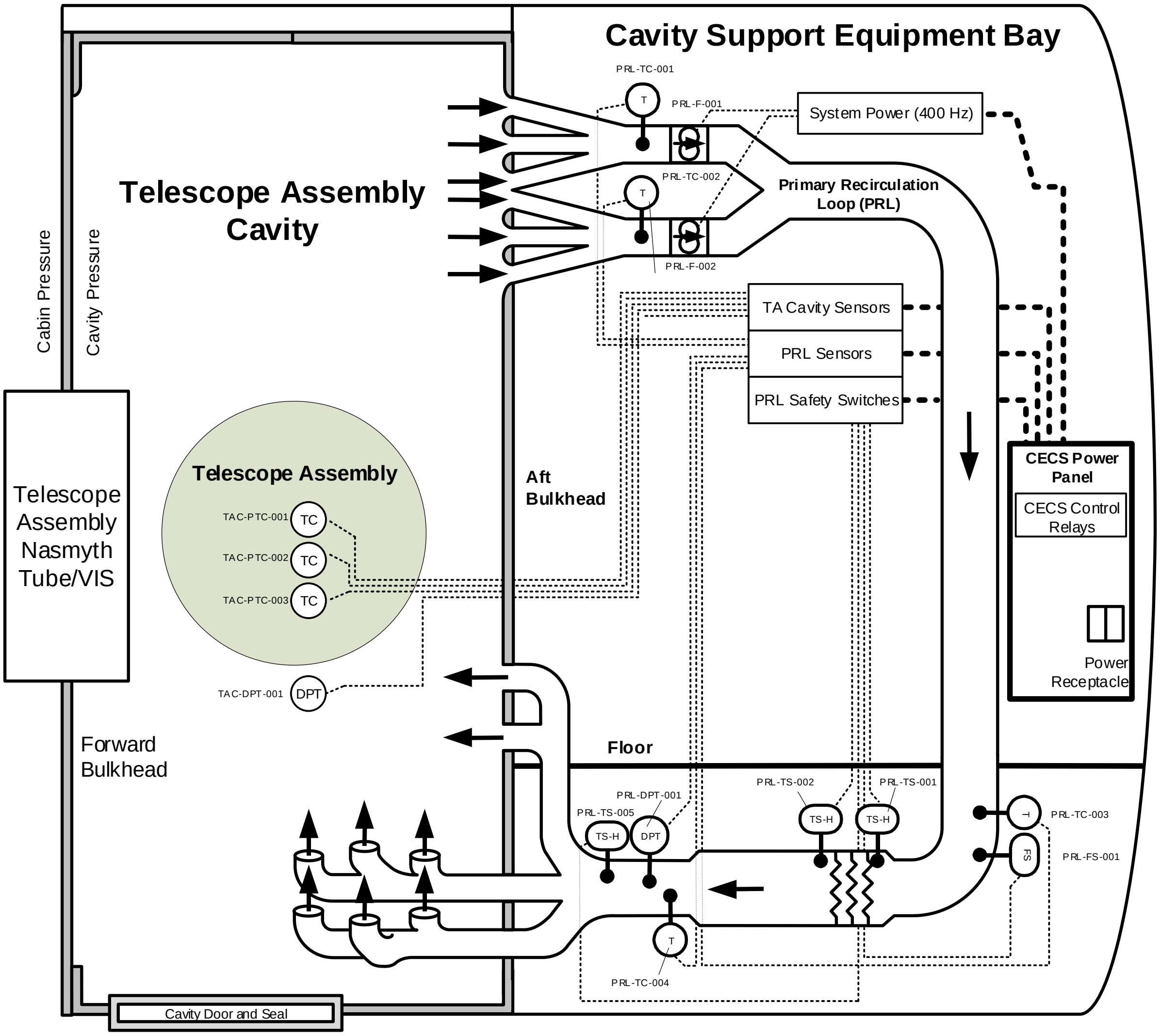


Figure 24. Telescope Assembly Heating System
(Drawn by Andrew Gee)

The purpose of the TAHS is to provide the operators with a way to heat up the telescope cavity by recirculating the air through a heater. This system is operated with two modes, which are OFF and HEAT. In HEAT mode, two fans pull air into the Primary Recirculation Loop (PRL) and push it through a heater assembly used to heat up the air.

The PRL is made up of two PRL fans (PRL-F-001, PRL-F-002), two fan current sensors (PRL-IC-001, PRL-IC-002), the heating assembly (PRL-HE-001), four PRL temperature sensors (PRL-TC-001, PRL-TC-002, PRL-TC-003, PRL-TC-004), three primary mirror temperature sensors (TAC-PTC-001, TAC-PTC-002, TAC-PTC-003), three high temperature switches (PRL-TS-001, PRL-TS-002, PRL-TS-005), and one low flow switch (PRL-FS-001).

## 5.2 Component Details

### *5.2.1 PRL Fans (PRL-F-001, -002)*

The PRL fans are more powerful than the DSS fans but have similar wiring and work the same way, as explained in section 4.2.7. The part number for the PRL fans is MIIF-9C [22]. These fans must be turned on within four seconds of each other in order to prevent one fan from pushing flow in the opposite direction of the other. These fans are also very powerful and have a large turn-on inrush current, which is why they are turned on one at a time with a two second time interval between the switching on time of each fan. Both fans provide a heat load to the air being pushed through of approximately 14kW.

### *5.2.2 PRL Heater Assembly (PRL-HE-001)*

The PRL Heater Assembly is made up of ten Heater rods with part number SWH28914/FBN161WH-X that are built by Watlow [23]. This assembly provides heating capability to the primary recirculation loop in order to increase the temperature of the cavity air to above the local dew point after the aircraft has landed. The heating power of this heater assembly is approximately 6.8kW.

### *5.2.3 PRL temperature sensors (PRL-TC-001, -002, -003, -004)*

The four PRL temperature sensors are the same part number as the DSS supply air temperature sensor (DSS-TC-001) which follows the MIL-T-7990 Table I standard for the resistance to temperature calibration [16].

### *5.2.4 Primary Mirror Temperature Sensors (TAC-PTC-001, -002, -003)*

The three temperature sensors installed on the primary mirror assembly of the telescope follow the RTD DIN EN 60751 specification with the following resistance to temperature equation:

$$Mirror\ Temperature\ (°\mathrm{F}) = 0.003888 \times R^2 + 7.43224 \times R - 759.8408 \qquad (7)$$

### *5.2.5 PRL Temperature switches (PRL-TS-001, -002, -005)*

Temperature switches PRL-TS-001 and PRL-TS-002 are both around the two sides of the PRL heater assembly. PRL-TS-005 is at the outlet of the PRL system for the air going back into the cavity. The three temperature switches are wired such that if any single switch detects a high temperature condition, the power to the heater is removed until the temperature drops down to a safe value again.

### *5.2.6 PRL fan current sensors (PRL-IC-001, -002)*

These electrical current sensors are the same ones used for the DSS current sensors as explained in section 4.2.10. These sensors are placed on phase A of each of the PRL fans. The current settings for these sensors are 25A to accommodate the two powerful PRL fan currents.

### *5.2.7 PRL Low Flow Switch (PRL-FS-001)*

The PRL low flow switch along with the temperature sensors are used to ensure the safe operation of the heating assembly in the PRL. The detection limit of this flow switch is approximately 5000 CFM.

## 5.3 System Operation Control

### *5.3.1 TAHS System Modes*

The TAHS system has two modes, which are:

1. OFF: The PRL fans and heating assembly are off. Monitoring of sensors is continuously done for abnormalities.
2. HEAT: The PRL fans are on, the heating assembly is on if there are no abnormalities. Temperature sensors, temperature switches, and the low flow switch are monitored, and the heaters are turned off if any of the sensors detect an abnormality.

### *5.3.2 TAHS System Transitions*

TAHS transitions cannot occur when the DSS system is in, or transitioning into, PREDRY or VENT. The TAHS system can transition into Heat and operate only if the DSS is in OFF, DRY or transitioning in between the two modes.

The available TAHS transitions are as follow:

1. OFF to HEAT:
    a. Turn on PRL fan #1 (PRL-F-001).
    b. After 2 seconds, turn on PRL fan #2 (PRL-F-002).

    c. Check PRL fan currents are nominal.

    d. Turn on the PRL heating assembly.

2. HEAT to OFF:

    a. Turn off the PRL heating assembly.

    b. Wait 5 minutes for the PRL heaters to cool down.

    c. Turn off both PRL fans.

# CHAPTER 6. OPERATIONAL ANALYSIS

## 6.1 Concept of Operations (CONOPS)

The desired operation of the CECS system on a flight is as follows:

1. Transition the DSS from OFF to PREDRY at least 30 minutes prior to the start of descent.
2. Maintain PREDRY until it is time to start descending.
3. Transition into DRY from PREDRY just before the start of descent.
4. After landing, transition the TAHS from OFF to HEAT with a targeted temperature of 3$^{o}$F above local dew point.
5. Maintain the combined DRY and HEAT modes until the targeted temperature is reached.

While the upgraded controller described in this thesis accomplishes this CONOPS, the original controller did not account for abnormalities and was not able to provide the required capabilities. An alternative, less ideal, CONOPS was used due to the limitations of this controller. This involved using PREDRY on the ground prior to takeoff for preconditioning, which was not as effective as doing it prior to transitioning into DRY. It also involved running DRY during descent at a lower altitude where the air is less thin. Finally, the controller was not able to automatically control the TAHS. The TA was warmed by running only the PRL Fans, without heaters, in a manual mode.

## 6.2 Nominal Operation

### *6.2.1 Flow Control*

After the shutoff valves and fans are setup during DSS transitions to DRY or PREDRY, the controller begins to regulate the process and regeneration flows as designed to accomplish the CECS's objective of providing the telescope cavity with dry air. This flow regulation is accomplished by tuned PD controllers with the response of which shown in Figures 25 and 26.

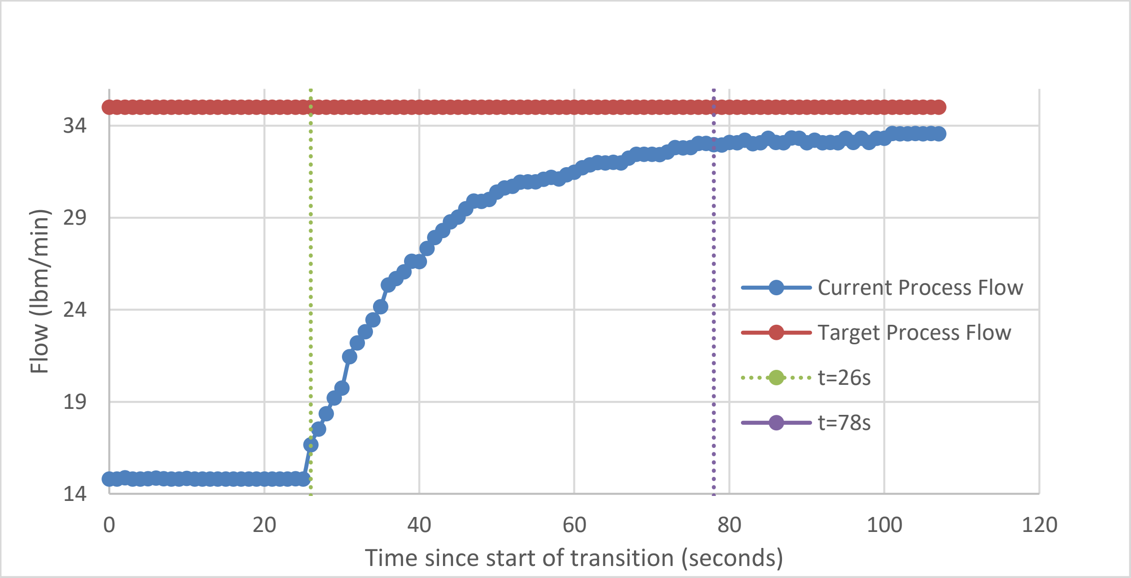


Figure 25. Process flow during OFF to PREDRY transition

In Figure 25, the process flow is plotted versus time for the target flow of 35 lbm/min. The first thing to note here is that a dead band of 1 lbm/min is used which is why the controller stops at 34 lbm/min instead as it acknowledges that the target flow has been met and no further control valve movement is needed. The 10% to 90% rise time of the process flow PID controller is 52 seconds.

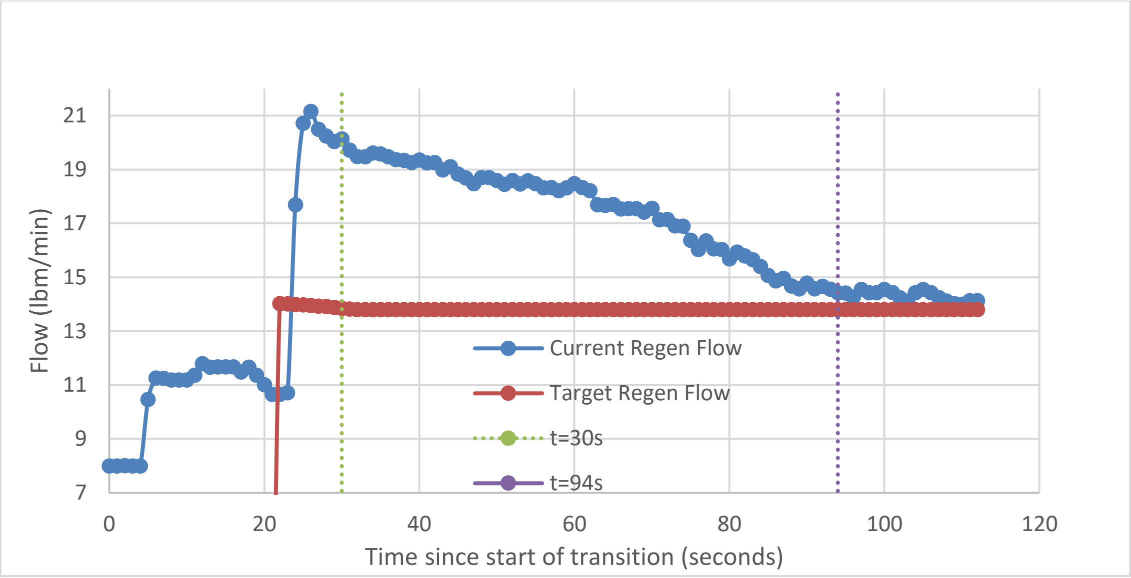


Figure 26. Regeneration flow during OFF to PREDRY transition

In Figure 26, the regeneration flow (labelled as Regen Flow) is plotted versus time with the target flow of 13.8 lbm/min (varies slightly due to DSS supply inlet temperature as designed). When the regeneration fan first turns on, the regeneration flow spikes to about 21 lbm/min since the regeneration control valve starts fully open, in contrast to the process control valve, which starts fully closed. This design choice was made since it is safer to have more regeneration flow than desired as compared with less flow. The 10% to 90% rise time of the regen flow PID controller is 64 seconds.

### 6.2.2 *Dryer Temperatures*

After all the valves, fans, and flows are set up in a DRY or PREDRY transition, the dryer drum rotation and heater are turned on. Figure 27 shows the dryer and regeneration temperatures (labelled as Dryer Temp and Regen Temp respectively) after the heaters have turned on. It takes the dryer temperature approximately 5.5 minutes after the heater turned on to rise to 300°F and finally settles around 320°F. The regeneration temperature rises to approximately 85°F after about 3.5 minutes. The regeneration temperature is very dependent on the dew point of the DSS supply inlet air and can increase depending on how dry the supply air is. The DSS outlet dew point decreases from 24°F when the heater was first turned on to about -25°F after approximately 12 minutes later. The outlet dew point can vary greatly depending on how preconditioned the dryer is. The CECS can even end up providing moist air and raise the dew point before it drops again if the operator is not careful.

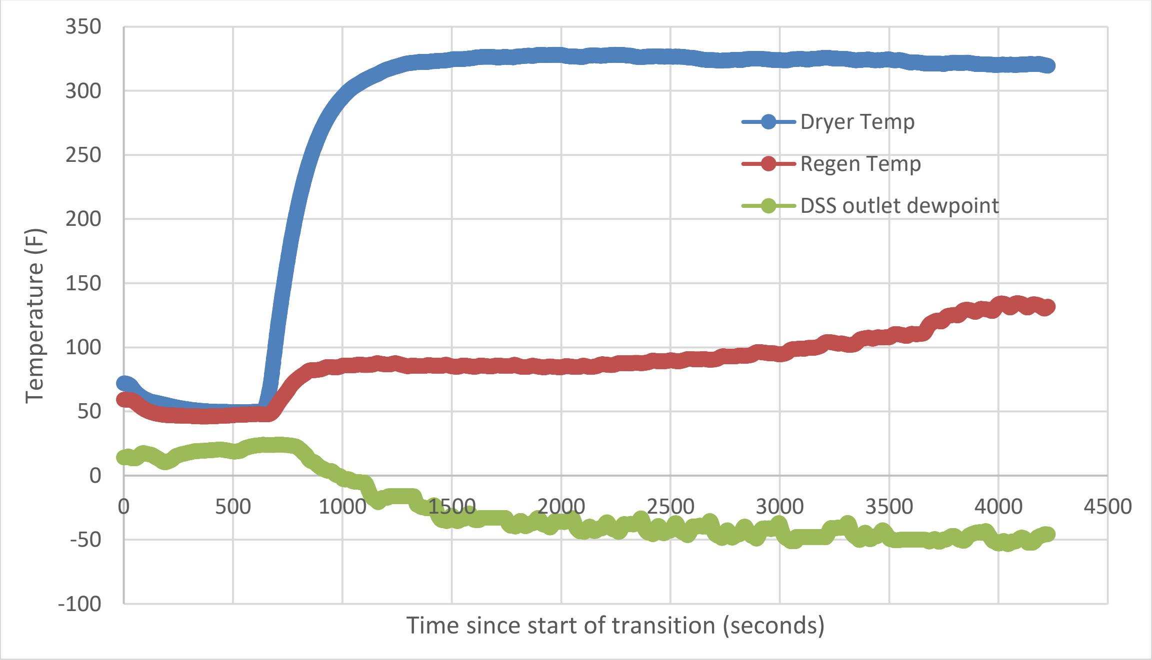


Figure 27. Dryer and regeneration temperatures during OFF to PREDRY

### *6.2.3 Flight Descent Operation*

Figure 28 shows the primary mirror temperature along with both the cavity dew point and the DSS outlet dew point during aircraft descent. As the aircraft lands, the cavity dew point begins to rise, and the system must continue to supply dry air into the cavity to hold down the cavity dew point while the mirror temperature is raised. Sometime after landing the TAHS is turned on, while dry air is still being supplied, which begins to circulate and heat up the air in the cavity to warm the TA primary mirror to a set point above the local dew point (In this case the target was 47°F). This guarantees that no condensation builds up on the mirror when the cavity is exposed to ambient conditions.

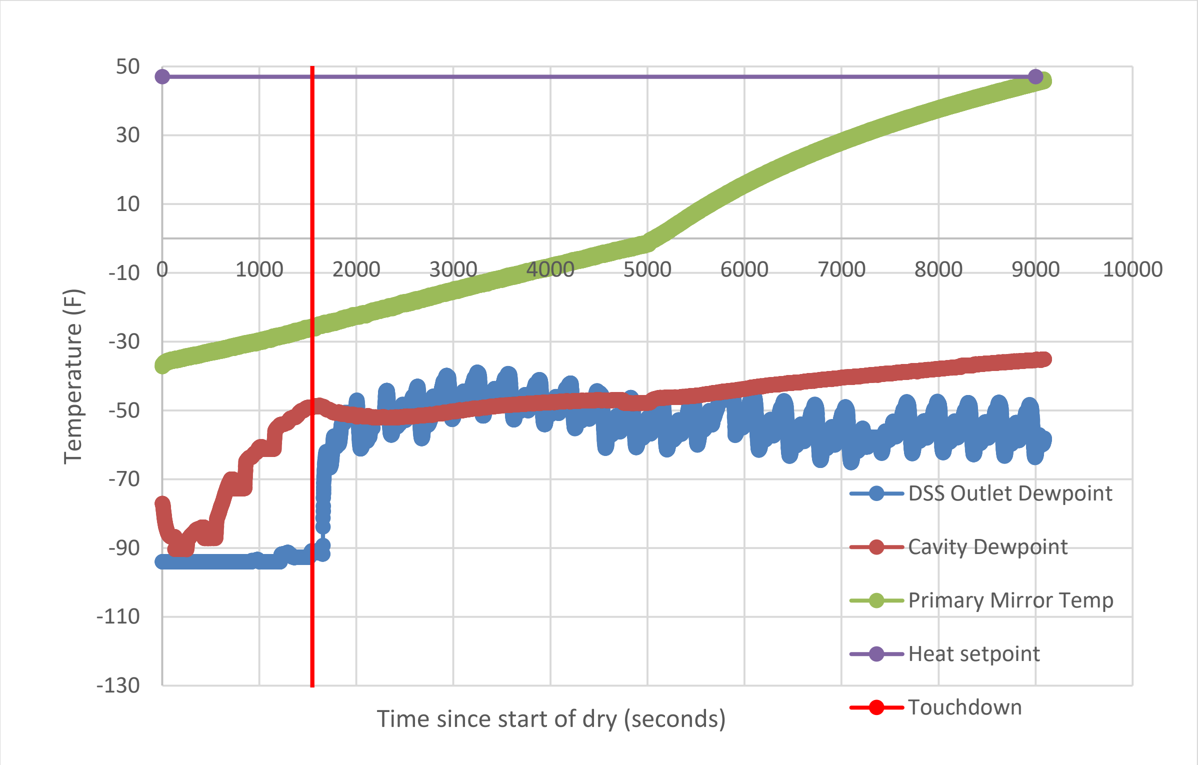


Figure 28. Mirror temperature during descent

## 6.3 Abnormal Operation

### *6.3.1 High Altitude*

Figure 29 shows the dryer and regeneration temperatures (labelled as Dryer Temp and Regen Temp respectively) from the start of the PREDRY pre-conditioning through descent and DRY and after landing. From the figure, the regeneration temperature is shown to increase to high temperatures above nominal due to the lower density air and low humidity levels at high altitudes. The controller senses a high temperature, above 158°F, and turns off the heater until the temperature drops down below a safe limit of 131°F. This continues until the aircraft descends to an altitude where the air is denser, and the regeneration temperature settles to a safe value.

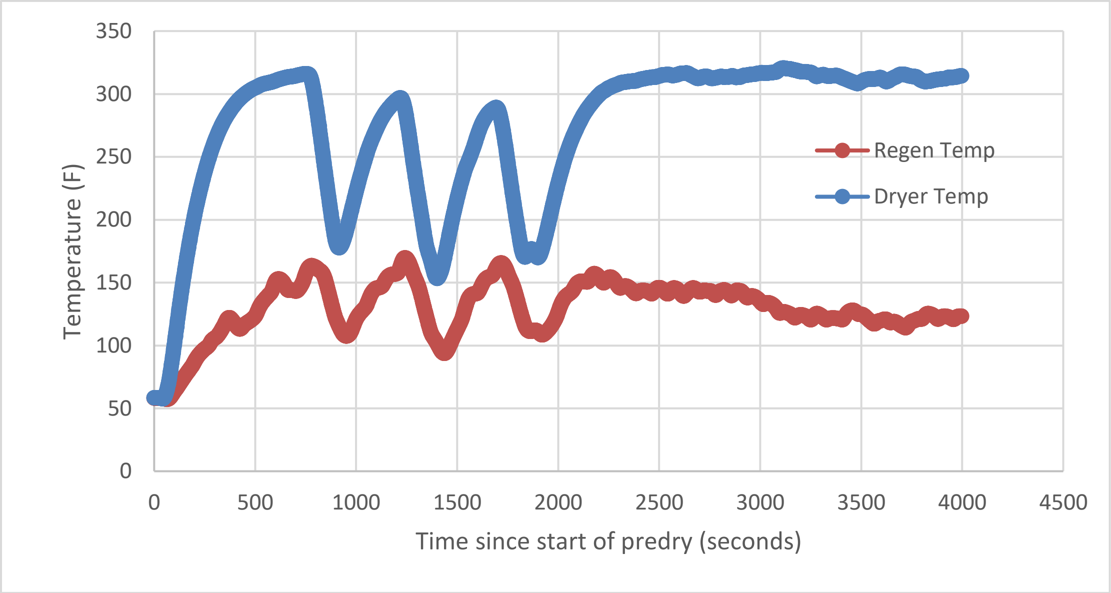


Figure 29. Dryer temperatures during descent

### 6.3.2 *Poor Pre-Conditioning*

Figure 30 shows an instance where the CECS entered DRY mode without proper preconditioning. At the beginning of DRY mode, the system ended up pushing moist air into the cavity and raising the cavity dew point to the primary mirror temperature. The dew point was eventually reduced to a safe value after the dryer was conditioned using DRY mode. This is highly undesirable as the telescope mirror can end up being damaged due to prolonged moisture exposure.

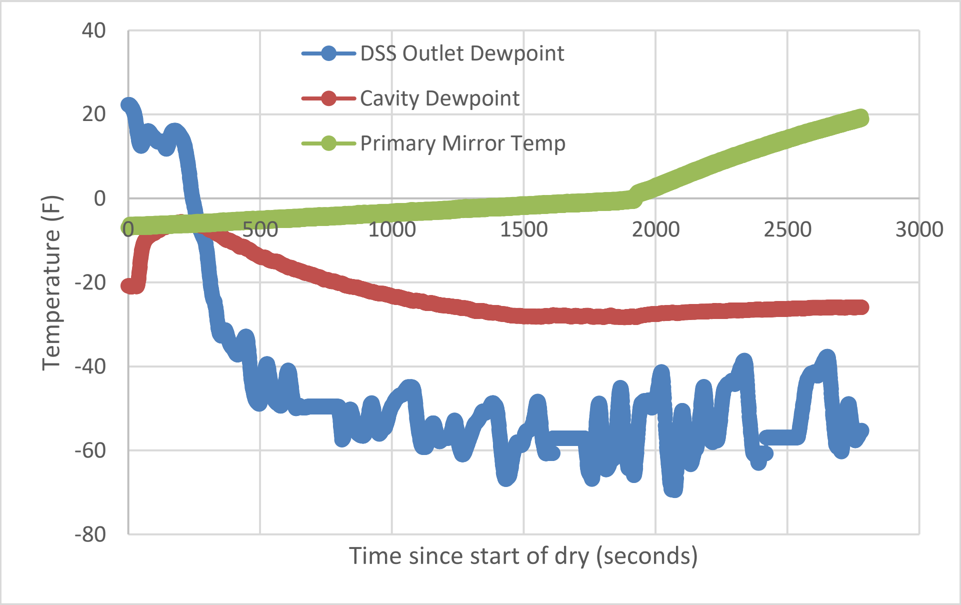


Figure 30. Cavity dewpoint behavior without preconditioning

### 6.3.3 *High Inlet Temperature*

Figure 31 shows the regeneration flow (labelled as Regen Flow) increase as a function of supply air temperature. As the supply air temperature increases above 43°F, the regeneration airflow is increased in order to increase the cooling of the dryer heater and remain in safe operating conditions. If the supply air temperature reaches 60°F then the heaters are turned off until the temperature cools down below 60°F.

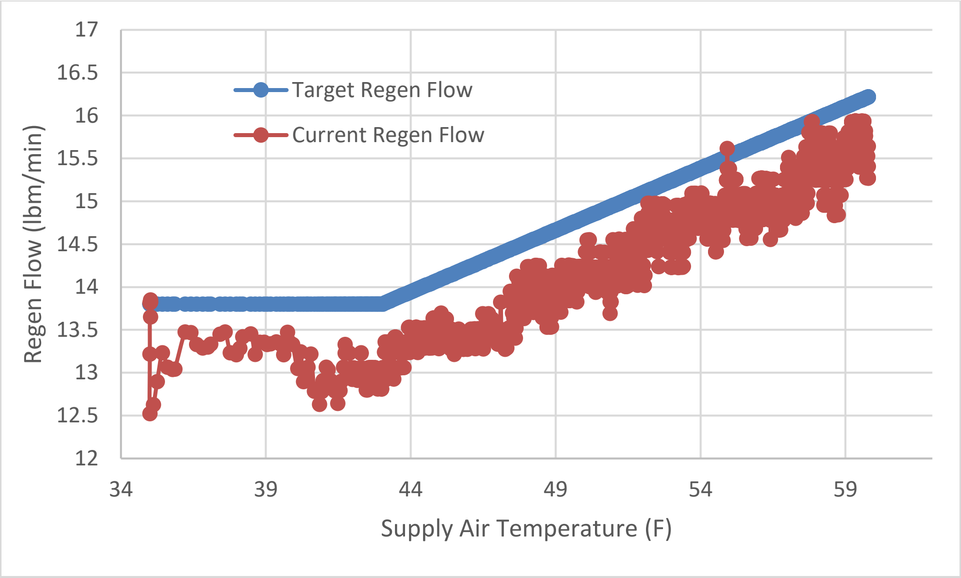


Figure 31. Regeneration flow adjustment for high supply temperature

# CHAPTER 7. CONCLUSION

The upgraded system has provided the SOFIA program with many benefits that the previous system lacked. The most important improvement is the additional protection to the system that enables safe operation at altitude by turning the heater off when the regeneration temperature rises too high due to lower density air and low humidity. By using the DSS in PREDRY mode right before descent, the dryer is preconditioned better, and the temperatures are already high enough to regenerate the desiccant material properly. Another benefit is the short transition time due to the introduction of PWM PD control of the process and regeneration control valves. This enhancement reduced the PREDRY and DRY transition times to less than 2 minutes as compared with the old system that utilized 100ms pulses with transition times that can go up to 5 minutes. The installation of multiple sensors for health monitoring will enable early prognosis and lead to easier maintainability of the system.

One improvement this system can greatly benefit from is the utilization of the dew points and the mirror temperature in controlling the system. It is imperative that this system provides dry air at descent and does not end up pushing moist air into the cavity. There are different things that can be done to help alleviate this issue, which can include one or all of the following strategies: 1) Automatically transition out of DRY mode if the heater is turned off or the DSS outlet dew point is too high for a sufficiently long duration. 2) Restricting the transition to DRY from PREDRY only if the DSS outlet dew point is sufficiently low. 3) Warning signal can be issued for the cavity dew point approaching the mirror temperature.

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