Final Report for the Dynamic Pressure Control System (DPCS)

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Revision History

Issue	Date	Changes	Prepared By
NC	4/24/08	First Draft	John Wertz

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1. Executive Summary

In the coming years, the private sector will begin to take a larger role in the development of space and space technologies. As the focus for these technologies shifts to commercial purposes, reliable and inexpensive methods of testing new hardware must be developed. To that aim, in August of 2007 Paragon Space Development Corporation requested that the Arcadia Innovations Design Group with the design, construction, and validation of a dynamic pressure control system for a pressure chamber antechamber.

With the task in mind, the Arcadian Innovations Design Group determined the technical requirements for the proposed system. These requirements led to the creation of several design concepts. Evaluation led to the acceptance of one of the design concepts. Once the final concept had been chosen, components for the system were identified and purchased. Finally, the system was built and tested.

2. Problem Statement

The Arcadia Innovations Design Team was tasked with the design of a dynamic pressure control system (DPCS) for a pressure chamber antechamber. This system was required to accept user-generated flight profiles which would be used to operate the system. Additionally, an interface was required to be developed for the user, allowing them to quickly, easily, and efficiently implement an altitude profile, operate the system and record data. Interaction with the system was to be performed through a graphical user interface (GUI) created through LabVIEW. Once designed, the system was to be built and validated for use.

The system developed by the Arcadia Innovations Design Team was required to utilize a sponsor-provided vacuum pump and software control platform. The remainder of the component selection was left to the team.

3. Technical Requirements

With the task defined, the Arcadia Innovations team investigated the technical requirements that would drive development of the design. The first of these technical requirements involved the interfaces of the system with the outside environment. These interfaces consisted of four separate domains: the mechanical interfaces, the electrical interfaces, the human interface, and the environmental interface. Concerning the mechanical interfaces, only one was identified: the connection from the pressure chamber antechamber to the larger, “crewed” chamber. This interface was determined to be a 13 ¼” CF flange connection. As for electrical interfaces, two were identified. The first was the power supply for the control software and hardware, which required 110 VAC, 15 amp power. This power was provided by the sponsor. The second electrical interface was the power to the vacuum pump supplied by the sponsor. The vacuum pump required 208 VAC - 3 phase, 30 amps per phase power, also provided by the sponsor. Regarding the human interface, only one was identified. This was the interface between the human operator and the computer control, which was required to be through the sponsor-provided LabVIEW software. Finally, although environmental interfaces were identified as interfaces to be investigated, they were determined to be non-critical to the design of the system. This is because the design was not expected to generate excessive amounts of noise or heat, or utilize harmful gases; thus, no requirement for mitigation of these possible sources of concern was produced.

With the interfaces identified, performance-oriented technical requirements were developed. The first of these is the requirement for the flight profile accuracy, which are summarized in Table 1.0 below.

Altitude Range	Required Accuracy	Goal
200 - 60,000 ft	±200ft	±20ft
60,000 – 110,000 ft	± 500ft	±50ft
> 110,000 ft	<20%	<2%

Table 1.0: Required Pressure Accuracies

These accuracies are relatively strict during the portion of flight below one-hundred-and-ten thousand (110,000) ft, although they become much more relaxed after this point. Next, as identified in the problem statement, the design was required to utilize the sponsor-provided LabVIEW software for hardware control and user-interface; additionally, it was required that this interface be flexible enough to allow a user to input a flight profile of their own design. The next technical requirement concerned the operational speed of the design, requiring a pump-down speed greater than 0.05 psi/second but dependent upon the requirements of the user-specified flight profile.

The requirements regarding design performance continued with a requirement for the leak rate recovery of the DPCS. The design was to be built to respond to the introduction of a leak to atmosphere at any point within the flight profile, and to recover from these new leak conditions in less than two seconds. To measure the internal pressures throughout the entire profile, the design was required to utilize at least one pressure transducer with a range of 760 torr to 0.001 torr. Finally, the DPCS was required to have a start-up time from software activation of less than five (5) minutes.

Concerning software, the DPCS was required to have three modes of operation, consisting of the initialization phase, the stand-by phase, and the operating phase. Initialization would occur when the program was launched; upon completion of initialization, the system would enter the stand-by phase. Here, the user would input their flight profile, and the computer would perform all necessary calculations required for the operation of the profile. Stand-by phase would end after the activation of testing. Finally, activation of testing would lead to the operating phase, within which the testing would be executed and data would be obtained.

The final technical requirements identified for the design of the system concern the safety of operation. The design was required to incorporate an emergency off-switch, allowing the user to quickly and safely power down the system, in the event of an emergency. Additionally, the design was required to utilize a safe method of repressurization of the pressure antechamber. Without this requirement, the return of the system from near-vacuum to atmospheric conditions would not occur in a controlled fashion.

The verification methods for each of the technical requirements outlined above can be found in Table 1.1 below.

The quality conformance inspection methods shall include:
A = Analysis (note 1)
D = Demonstration (note 2)
I = Inspection (note 3)
T = Test (note 4)
N/A = Not Applicable

Note 1: Analysis is defined as the verification that a specified requirement has been met through the technical evaluation of equations, charts, reduced data and/or representative data.

Note 2: Demonstration is defined as a non–instrumented test where success is determined by observation alone. Included in this category are the tests that require simple quantitative measurements such as dimensions and time to perform a task.

Note 3: Inspection is defined as a visual verification that the equipment, as manufactured, conforms to the requirements documentation to which it was designed.

Note 4: Test is defined as the verification that a specified requirement is met by a thorough exercising of the applicable element under appropriate conditions and using appropriate instrumentation in accordance with test procedures.

Number	**Paragraph**	**I**	**T**	**A**	**D**
1.	SCOPE				
1.1	Purpose				
2.	APPLICABLE DOCUMENTS				
2.1	Order of Precedence				
2.2	Specifications				
3.	REQUIREMENTS				
3.1	DPCS Description				
3.1.1	DPCS Interfaces				
3.1.1.1	Electrical Interfaces	X			
3.1.1.2	Mechanical Interfaces	X			
3.1.1.3	User-Computer Interface	X			
3.2	Performance Characteristics				
3.2.1	DPCS Pressure Profile Accuracy		X		
3.2.2	DPCS Vacuum Subsystem Control	X			

3.2.3	DPCS Vacuum Subsystem Flexibility	X			
3.2.4	DPCS Operational Speed		X		
3.2.5	DPCS Leak Rate and Recovery		X		
3.2.6	Pressure Transducer	X			
3.2.7	DPCS Conditions of Operation	X			
3.2.8	Startup Time				X
3.3	DPCS Safety				
3.3.1	On/Off Switch				X
3.3.2	Vacuum Release		X		
5.	PREPARATION FOR DELIVERY				
5.1	Preservation and Packaging				

Table 1.1: Requirements Verification Matrix

4. Concepts Considered

Several possible designs were developed for the DPCS based upon the technical requirements outlined above. These concepts can be separated into two groups, the hardware design concepts and the software design concepts.

Each of the following hardware concepts were analyzed as to their ability to physically implement the user-specified flight profile. The first of these concepts was known as the "manifold." In this concept, vacuum pipe of different lengths and diameter would be employed to control the flow into and out of the system. For slower depressurization, flow would be directed through the longer, smaller diameter pipe, while faster depressurization would require the shorter, larger diameter pipe. Repressurization would use the same logic, with flow moving in the reverse direction. Unfortunately, this concept was practically infeasible, as it would require both numerous lengths of vacuum pipe and multiple gate valves to control the flow, leading to a high expense. Additionally, this method would require an extremely advanced flow model to develop a system of equations that would even come close to properly matching the internal pressure with that specified by the flight profile. Finally, conductance losses through the vacuum pipe would be high, possibly hobbling the operation of the vacuum pump.

The second hardware concept was of the multi-valve system. In this design, the pressure within the antechamber would be regulated through one main length of vacuum tube. Pressure would be modulated through the utilization of several different types of valves, including gate valves, throttle valves, and mass flow controllers. The advantages of this type of system were its compact length and precise flow control. The only disadvantage was the sophistication of the system, as both mass flow controllers and throttle valves would require complex wiring and programming.

The final hardware concept was of the secondary vacuum reservoir system. Here, a secondary reservoir was to be kept at a constant, known pressure value. With the vacuum pump in operation, the second reservoir would be opened and closed on demand, allowing for quick, responsive depressurization of the main pressure chamber antechamber. However, this method had no provision for the repressurization of the chamber, and thus failed to satisfy the descent portion of the flight profile. Additionally, the cost of a secondary chamber would be prohibitive.

In addition to the three hardware concepts described above, three software concepts were also proposed. The first software concept was that of situational modification. In this approach, the system would be presented the proscribed flight profile and would utilize various control methods to modify its performance based not only on the input profile but also on the continuing response of the system. This approach afforded the greatest flexibility, as it allowed the program to recover from unexpected deviations from the profile (perhaps induced by a user-initiated leak). The downside of this approach was its complexity, as it would require the implementation of control loops within the system.

The second software concept was that of pure theoretical modeling. Here, the flight profile would be disassembled into various pressure regimes and modeled purely using theoretical equations. With the incorporation of equations describing conduction losses, heat transfer, and other deleterious effects, the theoretical modeling approach would provide relatively accurate pressure control. Additionally, this approach would not require the implementation of a feedback loop, reducing the system complexity. However, this approach would fail if any unexpected instability were induced in the system, whether through a user-initiated leak or losses unaccounted for in the theoretical equations. Also, this approach would require advanced flow modeling possibly beyond the current capability of the design team.

The final software concept used pure empirical modeling. In this approach, the system would be run for many flight cases. Data from these cases would be used to understand how the system operated under various conditions. With this knowledge, the system could approximate the actions required to successfully reproduce any given flight profile. This concept is possibly the simplest considered, although it suffers from a lack of accuracy and a failure to account for instabilities induced within the system due to a user-initiated leak.

One concept from each subset described above was chosen for implementation in the DPCS. For hardware, the multi-valve system was chosen due to its flexibility and precise flow control. For software, the situational modification scheme was chosen for its ability to adapt to unexpected system losses, including the introduction of a leak into the system. With these concepts chosen, five different configurations with different valve locations and combinations were explored. These can be seen below in Figure 1.0.

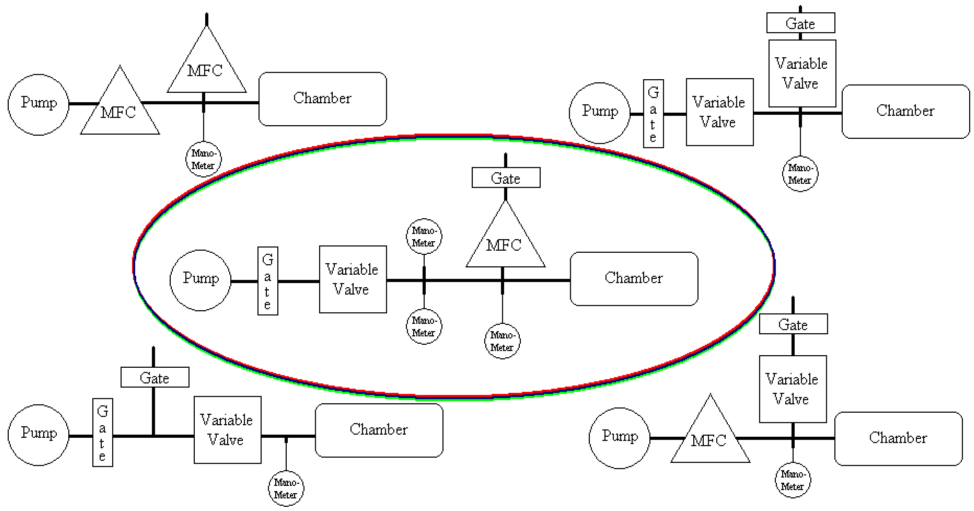

Figure 1.0: Possible Configurations

The final design of the DPCS was drawn from these configurations as discussed below

5. Final Design

Input from applications engineers from various vacuum technologies vendors led to the selection of the center configuration in Figure 1.0 as the primary design. This design incorporates a throttle valve to control vacuum flow out of the system and a mass flow controller to control flow from atmosphere into the system. The throttle valve for the pump-down phase controls the flow with acceptable precision and does not require a specified pressure delta to operate. This is critical, as the mass flow controller provides excellent flow control but will only operate with a certain pressure delta across its valves, precluding the use of the mass flow controller in the pump-down phase of the flight profile. However, the mass flow controller works well for the repressurization phase as it contains its own control system.

Images for a detailed final layout and the user-interface can be found below in Figures 1.1, 1.2 and 1.3 respectively.

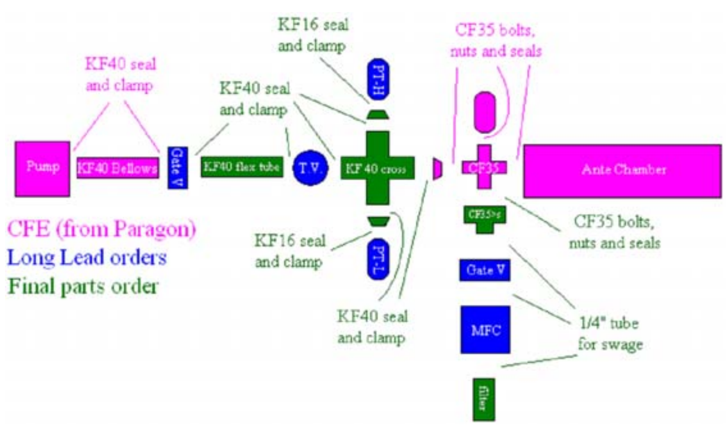

Figure 1.1: Detailed Final Layout

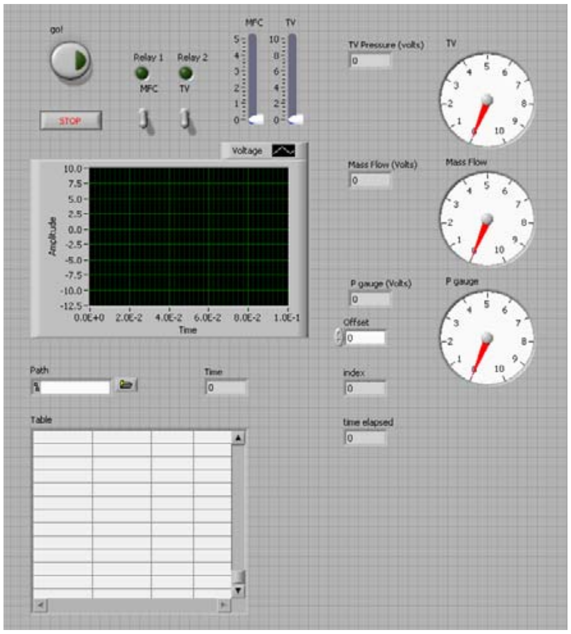

Figure 1.1: Test GUI

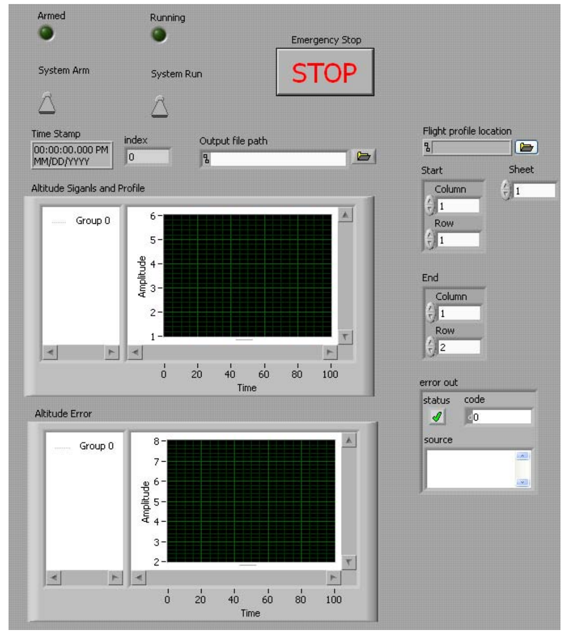

Figure 1.2: Profile GUI

The DPCS consists of twenty (20) key components. Nine (9) of these components are customer furnished equipment (CFE), including one (1) Sogevac SV200 pump, one (1) Dell Dimension desktop computer, one (1) LabVIEW v 8.2.1 package, one (1) Stanford Research Systems pressure transducer, four (4) components of a data acquisition (DAQ) unit (one (1) NI PCI-6221, two (2) NI SCC-AI13, and one (1) NI SC-2345), and one (1) Swagelok leak valve. The remaining eleven (11) components – one (1) T3BIA Throttle Valve, one (1) 163 Inline Pneumatic Isolation Valve with solenoid, one (1) type 99K0128 Inline Pneumatic Isolation Valve with solenoid, one (1) M100B Mass Flow Controller, one (1) 246C Single Channel Power Supply/Readout, two (2) 627B Absolute Manometers, two (2) NI SCC-AO10, and two (2) NI SCC-DO01 – were selected by the Arcadia Innovations team. These components were arranged into two functional subassemblies, the Pumping Subassembly (PS) and the Control Subassembly (CS). The PS consists of the vacuum pump, the variable valve, the mass flow controller, the two gate valves, the three pressure transducers, and the leak valve. The CS consists of the computer, the LabVIEW package, and the eight components of the DAQ unit.

Additional components (such as vacuum pipe, conversion connections, electrical wiring, etc.) were also required to provide connections for the major components.

6. Testing & Test Results

With the design complete, it was then required to develop tests for the system to validate the design. Four tests were developed, each driven by specific requirements from the verification matrix found above in Table 1.1. These tests are the safety readiness review (SRR), the operational speed test, the flight profile accuracy test, and the leak rate recovery test.

The SRR is a Paragon-mandated safety review. This review focuses on all possible safety hazards posed by the system. Once all possible hazards are identified, a safety mitigation plan is composed. This plan outlines the identified hazards and the methods to deal with each in case of an occurrence. With the safety mitigation plan in place, the system is operated for a sample flight profile to demonstrate the safety of the system in operation. Upon completion, Paragon representatives sign consent for full testing of the system. This test requires that all of the hardware be in place, along with the majority of the controlling software.

The second test is the operational speed test. This test is designed to validate the requirement for a pump-down speed greater than 0.05 psi/second contingent upon the demands of the flight profile. To perform this test, the vacuum pipe in front of the throttle valve gate valve would be pumped down to vacuum. Then, the throttle valve would be fully opened, allowing the vacuum to evacuate the rest of the system. Data would be recorded for pressure versus time. From this data, the maximum pump-down speed could be ascertained. Once again, this test requires that all of the hardware be in place, along with the majority of the controlling software.

The third test is the flight profile accuracy test. This is designed to validate two separate requirements. The first requirement is for the system accuracies as outlined in Table 1.0 above, while the second requirement is for the safe repressurization of the system. To perform this test, a sample flight profile would be loaded into the system. The system would operate the profile and data would be collected. The pressure data generated from the test would then be compared to the desired pressure data. Completion of this test would satisfy the second requirement of safe repressurization. This test requires that all of the hardware and software be in place and functional.

The final test is the leak rate recovery test. This test is designed to validate the leak rate recovery of the system. As mentioned above, the recovery of the system is required to be less than two (2) seconds. To clarify, this means the pressures may vary outside of the specified accuracies for two (2) seconds after the introduction of a leak: beyond these two (2) seconds, the pressures must return to within the accuracy range. To perform this test, a sample flight profile would be loaded into the system. The program would then be run, and at some point during operation the leak valve would be opened. After several minutes, the leak valve would be closed, and the program would run until completion. Analysis of the generated data would show the recovery time of the system with the introduction of the leak. This test requires all hardware and software to be in place and functional.

With the completion of these four tests, the dynamic pressure control system design will have been validated and made available for operation.

7. Deliverable Description

With permission from Paragon to proceed, the system components determined above were purchased. Once the parts had arrived construction of the system began. Components were added to the pre-installed pressure antechamber starting at the face of the pressure antechamber and moving outwards. With all of the parts installed, wiring the control components to the D.A.Q. proceeded. Once the wiring had been finished, the hardware was considered to be in a finalized state. A picture of the final hardware can be found below in Figure 1.3.

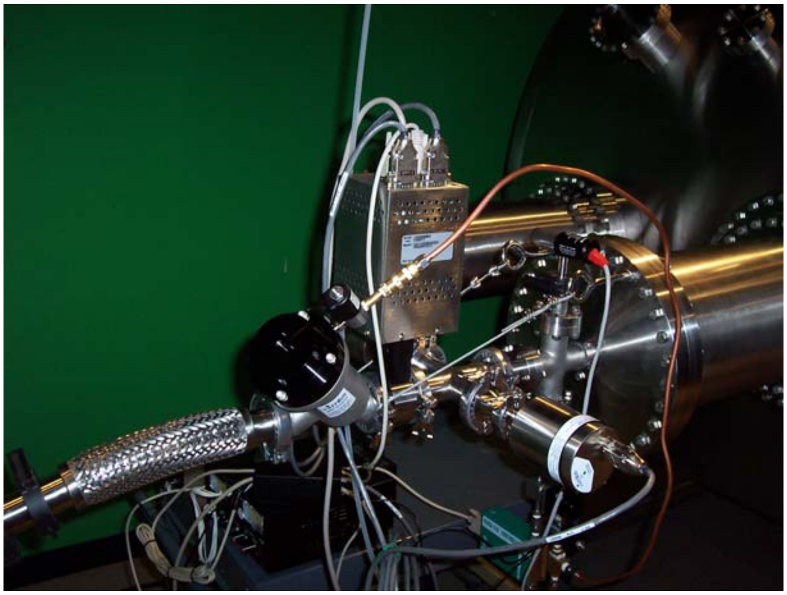

Figure 1.3: Final system

During the construction, work on the software control began. This software was finished with the completion of hardware construction. With this complete, testing of the system began.

Over the course of the safety testing, it was quickly ascertained that the throttle valve was not operating correctly. The throttle valve was able to attain the fully opened or fully closed position during manual operation. However, the computer was unable to actuate the valve to any position. Troubleshooting of the system failed to identify the problem. Thus, it was assumed that either the valve had been damaged in transit or suffered from a faulty internal connection. To rectify the situation, the valve in question was returned to MKS for inspection.

With the throttle valve out of action, only two of the four tests were performed. The safety readiness review was completed to the extent possible without the throttle valve in place. With this review complete, the operational speed test was performed. The results from this test can be found in Appendix G, *DPCS Test 2 Results*.

Analysis of the data across several regimes produces the following results; for the pump-down portion of the flight profile, the system is able to attain a 0.05 psi/second pump-down rate until approximately 0.2 psi, although this range may extend slightly farther. For repressurization, the maximum attainable rate for pressures between 10^{-2} and 3.77 is 0.145 psi/second; for pressures between 3.77 and 12.5 is 0.061 psi/second; and for pressures between 12.5 and 14.2 is 0.037 psi/second. Although the system does not meet the operational speed requirements for pressures below 0.2 psi during pump-down or 12.5 psi during repressurization, the system is still considered to have passed the test. This is due to the fact that, once certain regimes have been reached, it would be physically impossible to move more fluid through the system; additionally, the pump-down and repressurization speed possible through the system exceed those a user may wish to request.

8. Conclusions & Recommendations

At the end of the senior capstone period, the design of the system requested by Paragon Space Development Corporation had been completed. The system components have been ordered and the prototype constructed. Testing of the system had begun, but efforts were stalled due to the unexpected loss of the throttle valve for testing and/or repair at the MKS facilities. However, theoretical analysis has shown that the system should operate as designed. Despite the unforeseen setback, Paragon has concluded the contract with the Arcadia Innovations Design team.

Future work on the DPCS should focus on several items. The first is the completion of the validation testing, which may resume once the throttle valve has been returned. The second item is the streamlining of the software and its underlying control equations. By accounting for more complex variables (such as changes in temperature), the accuracy of the system could be increased. Finally, other options offered for the control of the throttle valve could be explored for use in the operation of the system.