Students for the Exploration and Development of Space
University of California, San Diego

Colossus
Liquid Rocket Engine Static Test Stand
Design Proposal

Submitted to:

NASA Marshall Space Flight Center
Program Office: Rocket Propulsion Testing

Revision E – November 1st, 2016

Abstract and Acknowledgement

The Colossus Static Fire System Project seeks to create a long-lasting hot fire capability for the SEDS UCSD program. The project will create a bi-propellant liquid rocket engine test stand, with the ability to be flexible and mobile in order to suit the needs of a team who is comprised entirely of undergraduate college students. Colossus is established as a technical development project utilizing proven designs and hardware, in order to create a foundation for performing future projects and test programs. The system will be used to attain performance parameters of liquid rocket engines, so that future iterations and designs of engines can progress armed with a critical mass of data and support.

The structure of this project will be built upon the foundation of knowledge provided by the first two static fire test systems created by SEDS@UCSD, which were used in tests in 2014 and April/May of 2015 for the Tri-D and Ignus engines. Colossus will be utilizing the same design and fabrication principles that keep development costs low. Cost management was instrumental in the fabrication of the earlier test stands, however, Colossus will come equipped with increased safety measures and fail-safes.

The University of California, San Diego Students for the Exploration and Development of Space would like to acknowledge and thank NASA's Rocket Propulsion Test (RPT) Program for their guidance and counseling. RPT, with engineering support from the Marshall Space Flight Center (MSFC) and Stennis Space Center (SSC), has been crucial in the design and development of Colossus. The NASA team has participated in design reviews and has provided critical recommendations and advice for the SEDS team in order to enhance the safety, reliability, operability, and performance of Colossus.

It is the SEDS team desire to incorporate NASA's recommendations into every facet of the Colossus design and future test operations. The SEDS team acknowledges NASA's focus on safety and are making every effort to incorporate NASA operating procedures into the design and our daily operations.

The SEDS team looks forward to continuing its relationship with NASA and to learn from the years of experience offered by NASA. It is the team's intent to invite NASA to future design reviews and Test Readiness Reviews in order to continue receiving the guidance and counseling that will transition the SEDS team and thier projects to the next level.

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1 Overview

The Colossus static test stand has been in the design phase for over 13 months, with the intention that SEDS at UCSD will be able to provide hot fire capability not only for ourselves, but other research entities as well. Although SEDS has demonstrated successes using 3-D printed technology (the static testing of Tri-D, Ignus, and the launch of the Vulcan-1 Rocket), it is time for the team to expand its limitations and contribute more heavily to industry. The SEDS at UCSD program designed the Colossus liquid rocket test stand from the ground up with the future and flexibility in mind for our ensuing projects.

The Colossus design team is confident that SEDS can provide a hot fire ready product by September 2nd, 2017. This timeline provides 11 months for SEDS to arrive at their fabrication workshop OSML and be ready to test. The goal of the summer and fall sessions is to secure as many sponsorships as possible and to order all critical hardware, to be delivered to OSML in anticipation of assembly in the winter quarter. The final product will be assembled, hydroed, cleaned, and cold flow tested during the spring quarter. There is a buffer in the timeline to allow for possible future setbacks (such as long hardware delivery times), with the first test occurring September 2nd, 2017 at the Friends of Amateur Rocketry site in Mojave, CA.

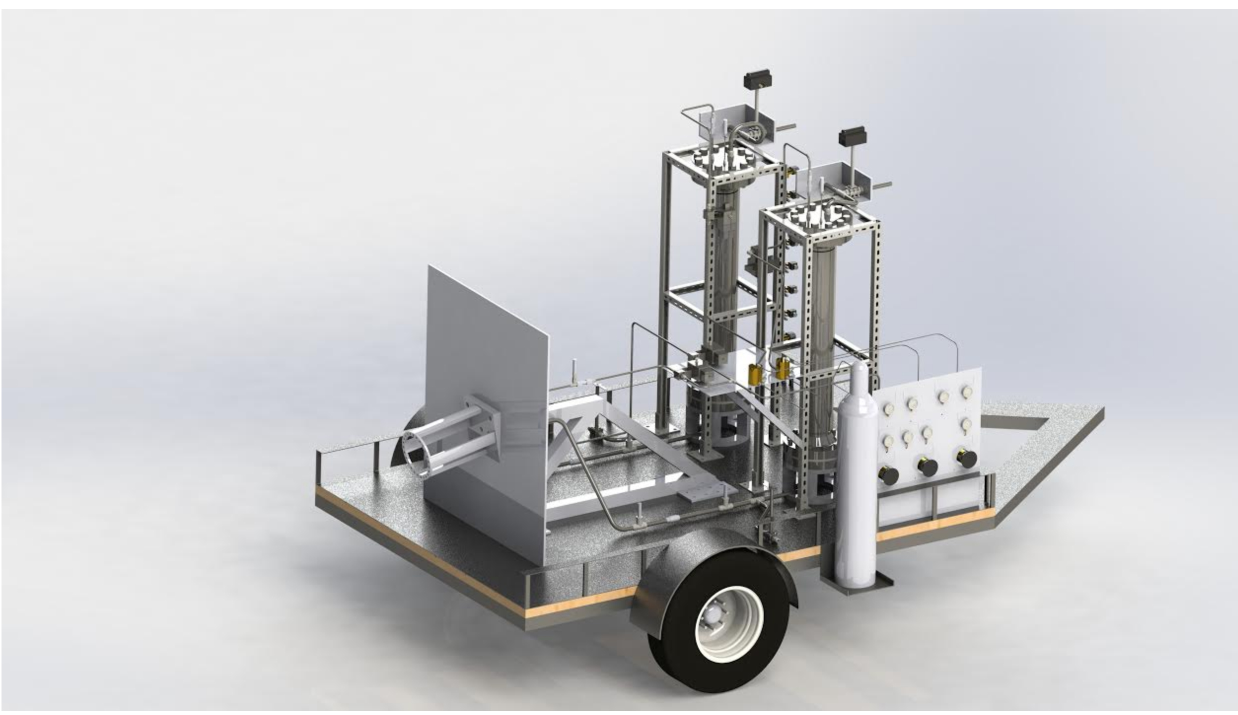


Figure 1: Overall System Rendering

The SEDS at UCSD team has a strong relationship with 3-D printing manufacturer Metal Technologies, Inc. of Albany and has secured a chamber and injector print set to be designed in the 2016-2017 academic year, and to be tested spring quarter of 2018. For the first test program Colossus undergoes, it will test the Vulcan-1 engine with three different injector configurations- Ignus, Bagaveev, and Couno. The details of these test programs will come from the propulsion team test requester with more specific requirements to characterize the injectors.

1.1 Technical Objectives

The main design factors of the system are as follows:

- Mobile- Colossus needs to be able to travel 150 miles to the test facility in the Mojave Desert, at the Friends of Amateur Rocketry Site outside of California City, CA.
- High throughput- Colossus needs to be capable of 6 tests in a weekend. Therefore the system must be able to be refueled quickly.
- Safe for personnel and equipment- Colossus will be utilizing an onboard controls system that constantly monitors system status in order to prevent over pressurization events and unintended disassembly of test articles.
- Data Acquisition- Colossus will utilize high fidelity data acquisition system through a National Instruments signal processor to send pressure, temperature, and load data via Ethernet back to the operator. High fidelity data provides critical information to analyze points of interest during a test, such as the start up or an event of a failure. The data will be processed live (through LabVIEW) in order to easily assess the system's status.
- Different size thrusters- By utilizing correctly pressure rated components, Colossus will be capable of exchanging different similar thrust class engines simply by exchanging a short length of tubing and two Cavitating Venturi flowmeters.

1.2 Advising Personnel

Dr. Kalyanasundaram Seshadri
Principal Investigator

Professor Seshadri received his BE degree from Coimbatore Institute of Technology (India) in 1970, his MS degree from the State University of New York at Stony Brook in 1973, and his PhD degree from the University of California, San Diego in 1977. After completing his PhD he became postdoctoral research staff member at Yale University, a member of the technical staff at TRW, and assistant professor of mechanical engineering at the University of Southern California. He joined the UCSD faculty in 1982.
(Cited from UCSD MAE Department)

Dan Hendricks
Manufacturing Adviser

Dan has over 30 years of experience in the Navy, with a bachelor of science degree in mathematics from the Naval Academy, and a master of science degree in computer science from the Naval Postgraduate School. After his certification as an engineering officer in the Navy Nuclear Propulsion Program, he qualified as an Engineering Duty Officer. Since leaving active duty, Dan has worked in both the private and public sectors, in roles of increasing responsibility in program management and budgeting, network architecture, systems engineering, and computer security. Dan is a registered Professional Engineer (Electrical) in the state of Washington, and is a Certified Information Systems Security Professional (CISSP). He is a member of IEEE, IEEE Computer Society, and IEEE Communications Society.

2 Systems Engineering

2.1 Project Timeline

A target timeframe schedule is presented in Tab. 1. This schedule will be tracked by the Chief Engineer and Lead Systems Engineer and will be adjusted as required by project progress and outside factors. Any severe adjustments to the schedule that impact the ability to perform a cold flow or hot fire test will be communicated by the Lead Engineer or Systems Engineer to each Sub-Team Lead.

Table 1: Projected Project Timeline

Test Series	Projected Date
Design update is turned in to NASA	August 1st
Discuss and negotiate potential grant details with NASA, while SEDS continues to look for sponsorship	August 1st-20th
Procurement Period	August 21th - September 30th
Construction Period	October 1st - February 28th
Validation Period	March 1st- April 15th
001-Ignus Injector	4/15/2017
002-Bagaveev Injector	10/7/2017
003-Couno Injector	10/21/2017
004-New Engine	1/6/2018

2.2 System Requirements

The system requirements are based on testing mid range thrusters from approximately 250 lbf to, optimistically, 3000 lbf. The feed system will be the limiting factor to the thrust range Colossus will be able to achieve. The system must be safe and all parts must be rated to the appropriate pressure and thermal ratings. Data acquisition is a necessity so accurate data can be measured and reviewed.

- Safe and Reliable- Automatic test sequencing, automatic shutdown procedures, ASME code pressure vessels
- Acquire Data- High fidelity pressure, temperature, and load measurements, high resolution transient data, failure analysis data

- Feed flexible mass flows- Allow up to 5lbs/s in feed system for larger class thrusters
- Double Cryogenic capable- Valves and seals are cryogenic capable for both oxidizer and fuel size Structurally secure: Rated to 5000 lbf with a dynamic safety factor of 2

2.3 Preliminary Budget

The Colossus design team has had a fairly difficult time sourcing a completely accurate budget analysis for the project, however the breakdown provided in Tab. 2 is what SEDS can guarantee a deliverable product at.

Table 2: Budget with a 10% flexibility built in

Propellant System	24000
Structure	6000
Electronics	12000
Spare Maintenance	4000
At-cost Engine Print	15000
Total	61000

For itemized budget, refer to Appendix D

Although a large part of the budget is reserved for an at-cost engine print, this is to guarantee a future test article for SEDS. We are still in the process of reaching out to different sponsors. Our sponsor MTI of Albany has agreed to provide a completely sponsored thruster in the next coming year, however if that sponsorship does not follow through it is critical that there is flexibility in the budget for another thruster to further the SEDS objective list.

2.4 Project Management Elements

Management of the project will consist of a three tiered system, in which sub-systems of Colossus will be divided to sub-system team leads, with engineering personnel reporting task progress to them. This structure will allow the team members to have ownership of a particular component of the system, but at the same time enable cohesiveness of final project fabrication. The three-tiered approach will allow the undergraduate students to continue their classwork while attending work-week meetings and weekend meetings. This system can be seen graphically in Fig. 2

2.4.1 Project Communications and Information Management

Integrated work activities of the team will be outlined and delegated through weekly Saturday morning meetings, discussing project performance and further project requirements. All meeting minutes and action item documentation will reside on the Google file management system for SEDS@UCSD, under Colossus-Weekly Agenda.

2.4.2 Project Reviews

Design review related to Colossus was held at the PDR (10% design) stage and CDR (90% design) levels at UC San Diego. The goal of the reviews was to assess system design to ensure they meet required propulsion team and safety standard. The design reviews solidified and ensured system design intent. Prior to the first cold-flow, there will be a ORR (Operation Readiness Report) presented to RPT in order to assure proper procedures and standards are exercised. Prior to every single hot fire test that SEDS@UCSD performs, a TRR will be presented to necessary interested parties so as to maintain proper operational safety. Items reviewed will include system status, goal of the test, status of detailed operating procedures and emergency response procedures. The TRRs should be presented no later than 10 business days prior to the test.

2.4.3 Project Recommissioning

After a Test Series is completed, necessary changes will need to be made to Colossus in order to accommodate the next test series. The most common changes that will need to be made are exchanging of the cavitating venturi flowmeters on board. The lead engineer will be tasked with ensuring the transition between Test Series is achieved.

The timeline for the actual Colossus system is indefinite at this time. The system will need to be stored in a safe, dry location and sealed from any debris at all times between tests. The system will not be maintained under positive pressure at all times.

2.5 Logistics

2.5.1 Test Location

All hot fire and engine testing of Colossus is performed at the Friends of Amateur Rocketry (FAR), located in the Mojave Desert North of Edwards Air Force Base. Cold flow testing is to be completed at the Open Source Makers Lab (OSML) located in Vista, California. OSML has sponsored SEDS UCSD with its facility for the year of 2016, but the availability past this point is undetermined. If the OSML facility is unavailable past the current sponsorship, SEDS UCSD must secure a location for cold flow testing. This would not be particularly difficut given the mobility of the

Colossus project. The alternate location must be suited for the safe operation of Colossus and all approval from the site must be obtained. SEDS UCSD must update the Test Report to include a new location. All other operation and maintenance of Colossus such as leak check, hardware exchanges, cleaning, etc. will be performed at OSML as well. Any cold flow or hot fire static testing will never be performed on the UC San Diego campus.

2.5.2 Test Procedure

All test procedures and system maintenance documentation are outlined and included in the Standard Operating Procedures Guide. Any personnel participating in the operation or maintenance of the Colossus system must have a thorough understanding of the system and its documentation. All of the necessary on-site safety equipment required is stated in section 5.1. of the SOP.

2.5.3 Cold Flows

Cold flow procedures are outlined in section 4.6. of the SOP. As stated earlier, the test will be executed at the OSML facility. Dan Hendricks of OSML should be notified prior of any intentions of testing on site at least a week in advance.

2.5.4 Hot Fires

The project engineering lead, systems engineering lead, all operators, and a sufficient amount of well-informed (in Colossus operation) SEDS personnel must be present to perform testing. The test site, FAR, is only available for testing during the first and third weekend of every month. For scheduling, the engineers at FAR must be contacted within a month preceding any intended hot fire testing as well as completing a Static Firing Request.

2.6 Liquid Oxygen Safety

The liquid form of Oxygen (LOX) is widely used in rocketry applications and most commonly serves as a cryogenic oxidizing propellant. LOX is very useful because it is safe to use relative to other oxidizers. Although technically a safer option, LOX is still an extremely dangerous and volatile component to handle. LOX is a powerful oxidizer and can be ignited when in contact with many materials in an oxygen-rich environment. Materials being used in combination with LOX must be assessed for compatibility, pressure, and temperature requirements. If the SEDS team incorporates new hardware into the system, the component must be assessed for oxygen compatibility and added to Section 2.7. Liquid Oxygen Material Safety Data Sheets are available in Appendix B. There are extreme hazards when utilizing LOX and proper safety handling must be implemented.

Personal Protective Equipment:
Cryogenic rated gloves, full-coverage face shields, and LOX-compatible coveralls.

Handling:
LOX should be stored away from any combustible or reactive materials. Ensure there is no grease or oil on any fittings, plumbing, or surface that comes into contact with LOX. Grease is made up of hydrocarbons and can create a combustion reaction when in contact with LOX. Do not walk or reach over LOX spills.

Dewar Handling:
Dewars should only be stored outdoors or in a well-ventilated area. Should only be opened when connected to the intended plumbing source. Keep upright and do not tilt or lean on its side.

2.7 Oxygen Ignition and Material Compatibility

Every piece of hardware in contact with liquid oxygen will be assessed for safe use and compatibility, according to American Society for Testing and Materials (ASTM) standards. The Oxygen Compatibility Assessment report is attached as Appendix C

2.8 Work Breakdown Structure

Colossus Position Descriptions
Sub-team Leads can also take on a technical position under their team. Program Manager and Chief Engineer may be the same person. The predicted overall project team size requires the involvement of approximately 30 SEDS members. Positions highlighted in green may see one responsible member with supporting teammates under their guidance.

Project Manager

- Lead personnel of Colossus project manages all teams
- Collect system requirements from Propulsion Team, and allocate to Systems Engineering
- Address fundamental design changes
- Maintain communication with NASA
- Ensures system design intent has been maintained

Systems Engineering Lead

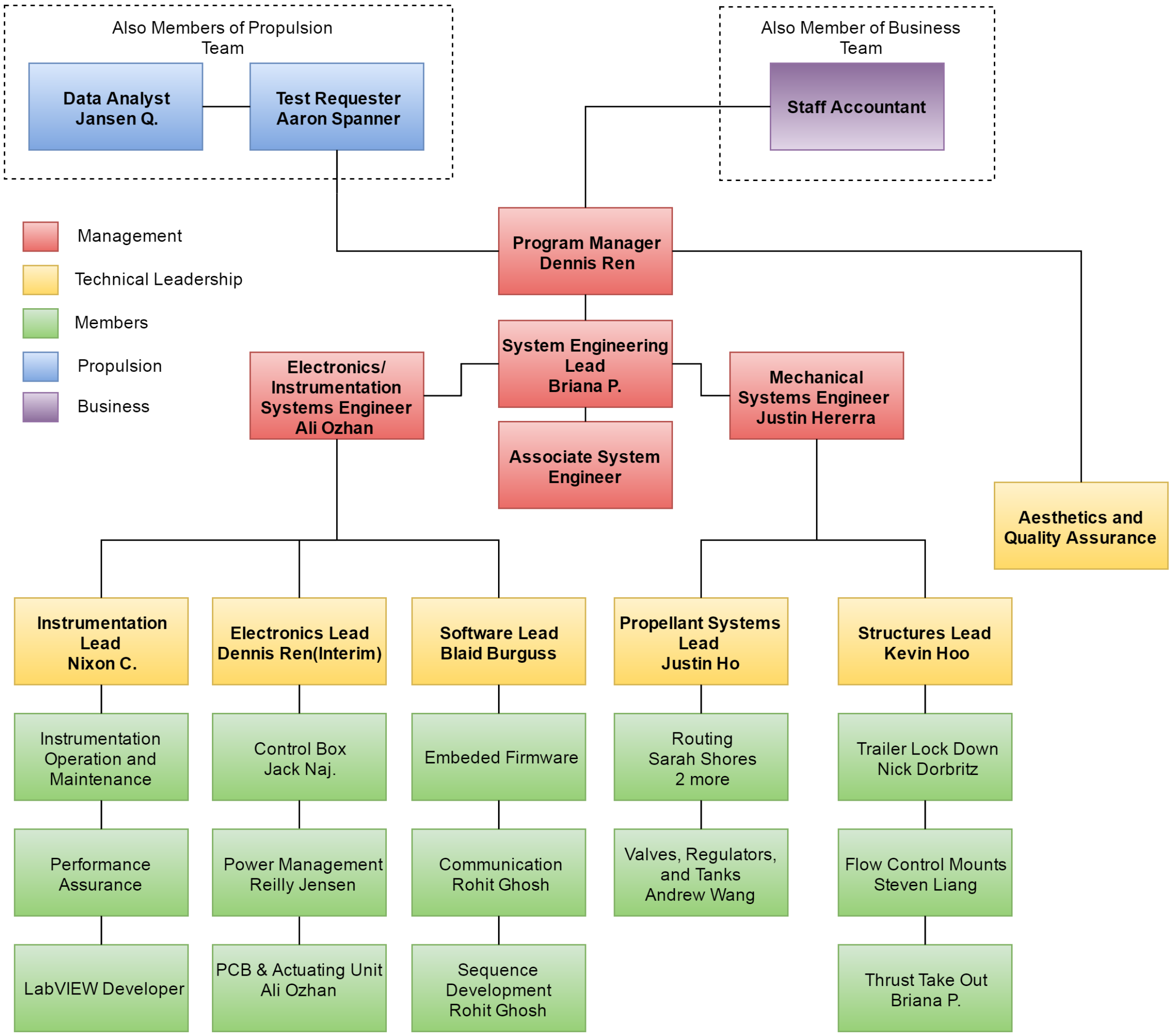


Figure 2: Work Break Down Diagram

- Communicate between systems engineers and program manager
- Oversees systems engineering team
- Maintains configuration control
- Maintain documentation procedures, responsible for updating documentation

Test Requester (Member of Propulsion Team)

- Pass system requirements from Propulsion team to Program Manager
- Monitor test requirements during system tests

- Communicate between propulsion team and Colossus team

Data Analysis (Member of Propulsion Team)

- Iterates through to calculate performance parameters
- In close communication with test requester

Staff Accountant (Member of Business Team)

- Manages budget
- Parts list
- Travel logistics
- Orders hardware/components (or communicates necessary purchases to treasurer)
- Keeps track of inventory

Electronics/Instrumentation Systems Engineer

- Ensures electronics/instrumentation system design intent
- Communicates project status to Lead Systems Engineer
- Responsible for putting together electronics/instrumentation documentation
- Responsible for updating said documentation

Mechanical Systems Engineer

- Oversees and manages Propellant systems/Structures Lead
- Ensures propellant system/structure system design intent
- Communicates project status to Lead Systems Engineer
- Responsible for putting together propellant system/structure documentation
- Responsible for updating said documentation

Aesthetics and Quality Assurance

- Oversees the quality of the product and correct installation of components
- Work in conjunction with Project Manager, ensure all design standards and codes are met

- Work with the visual design team from the Business Division to refine and polish the appearance of the system
- Routine checks on each team to examine the organization of the work environment

Instrumentation Lead (Technical Management)

- In charge of on-board instrumentation: DAQ and sensors
- Ensure the health of the system
- Oversees the installation and operation of the instruments on test day
- Ensure the retrieval of the Data after test

Instrumentation Operation and Maintenance

- Assembling the DAQ system
- Mechanical integration with the shelving
- Electrical interface to the sensors
- Perform regular maintenance procedures

Performance Assurance

- Ensure the physical operation environment of the DAQ
- Ensure the grounding scheme is effective
- Sensor calibration, linearization

LabVIEW Developer (Programming Intensive)

- Create LabVIEW program to interface with the instrument
- Assist in creating Propulsion Processing System to analyze the test data

Electronics Lead(Technical Management)

- Oversee the fabrication of PCBs
- Integrate the Control Box and the Actuation Unit
- Work in conjunction with the Instrumentation lead and the Software lead to ensure compatibility of components

Control Box

- Construct the control box(PCB and housing)
- Manage the User Interface

Power Management

- Construct the Power Management System on Colossus
- Maintain the health of the battery array

Actuating Unit

- Thermal management of the semiconductors
- PCB fabrication and assembly
- Housing assembly

Software Lead(Technical Management)

- Responsible for the software/hardware integration of the electronics system
- Integrates design changes from electrical systems engineer
- Oversees the overall development of the software package
- Manages the source version control, git, revisions

Embedded Firmware

- Create basic 8051 Kernel to bridge specific peripherals
- Verify the performance of the hardware interface
- Work closely with the Electronics Team

Sequence Development

- Translate testing sequence from the SOP to embedded programs
- Interpret real time system status and create failure detection mechanism

Communication

- Manage the RS-232 and the RS-485 communication scheme

- Create communication protocol with timing and verification mechanism in place
- Write interrupt service codes for the embedded firmware

Propellant Systems Lead

- Responsible for integration of plumbing/pneumatic system
- Maintains communication with other team leads to ensure proper installation
- Integrates design changes from mechanical systems engineer

Routing

- Responsible for routing of fluid lines (cutting, flaring, bending)
- Ensure proper seals in between fittings (secure connections, gaskets)
- Keep track of plumbing stock
- Checks connections and lines during leak check

Valves, Regulators, and Tanks (VRT Technician)

- Ensure correct regulator settings
- Perform regular maintenance on valves and regulators
- Checks connections and lines during leak
- Perform the cleaning of the tanks and valves
- Assist routing technician to complete connections to the Valves, Regulators, and Tanks

Structures Lead

- Oversees and manages structures team
- Responsible for integration of structures on entire system
- Integrates design changes from mechanical systems engineer
- Keep track of the inventory of the stock and fasteners

Trailer Lock Down

- Design and construct a mechanism to anchor the trailer to the concrete slab at the launch site

- Perform structural stress analysis on the anchors

Flow Control Mounts

- Responsible for mounting plumbing lines, valves, pressure gauges, and regulators to the structure
- Responsible for exchanging the K-bottles in accordance with VRT Technician

Thrust Take Out

- In charge of the design and the construction of the Engine mounting plate, as well as all load bearing structures that translates the thrust of the test subject to the body of the trailer
- Keep track of the stock inventory

2.9 Cleaning Components in Contact with Liquid Oxygen Systems

Any component/valve/tube/etc. that is in contact with liquid or gaseous oxygen must be LOX cleaned specifically the internal anatomy of the hardware. All fittings must be cleaned, especially the threads and internal components. Any cap or seal meant to protect the component from the ambient air must also be cleaned.

How to LOX clean:

LOX cleaning is completed through two procedures depending on the component: ultrasonic cleaning and manual cleaning (for tubing). Cleaning must be completed prefacing any and every test that utilizes oxygen systems. LOX cleaning must also be completed if any of the internal flow paths have been exposed to ambient air (i.e. if any components have been replaced or taken-off) for a long period of time. If any components are removed, ensure they are sealed with a cap or plug and avoid using tape that is not intended to seal without leaving residue. Isopropyl Alcohol (IPA) is used for all cleaning procedures.

Ultrasonic cleaning is required for all fittings/components that fit into the pan of the cleaner itself. Begin by cleaning off the exterior and interior of the component with IPA and kimwipes. Take off all Teflon and ensure that all Teflon particles are removed (you can use a razor blade and/or a brush). Fill the pan of the ultrasonic cleaner half-way (or as needed) with water. Fill another smaller container with IPA and place the fittings inside. Ensure that the small container filled with IPA is filled at a liquid level equal or more than the water inside the pan. The temperature of the ultrasonic cleaner depends on the device itself and if its already heated up from previous use (check ahead of time). Turn on the ultrasonic cleaner and allow to clean in the bath for 15 minutes. After the first bath, replace the IPA in the smaller container with fresh IPA (this is the clean bath). Ultrasonic clean the second bath for another 15 minutes. When the clean bath is completed, remove the fittings and dry them with an air compressor. Immediately reattach the fittings or cap them off to prevent dirt from ambient air to settle inside the component.

For tubing/extended cylindrical valves that dont fit in the ultrasonic cleaner, an alternate cleaning step is required. First, clean off the exterior of the tubing/component with IPA to avoid particulates entering the flow path after cleaning. Using Kimwipes, cut and create a small ball of tissue (depends on tubing inner diameter) and push it into one end of the tube. Make sure the tissue ball is small enough such that it wont clog the tub, but big enough to come into contact with the complete inner diameter of the component. Using a bottle of IPA in a lab squeeze bottle, completely wet the ball inside of the tube. Wearing safety glasses, use the air compressor to shoot the wet tissue ball out of the tube. Make sure the ball shoots off into a safe place. Repeat this step three times and then another three times for the opposite end of the tube (for a total of 6 times). Lastly, use the air compressor to completely dry the IPA inside (and outside) of the tube. Immediately reattach the tube to the system and/or cap off the open ends to prevent dirt from ambient air to settle inside.

3 Structures

The structure of Colossus is based around a 7×12 utility truck trailer. The following sections detail the necessary structural installments that need to be made in order to have a successful and durable system.

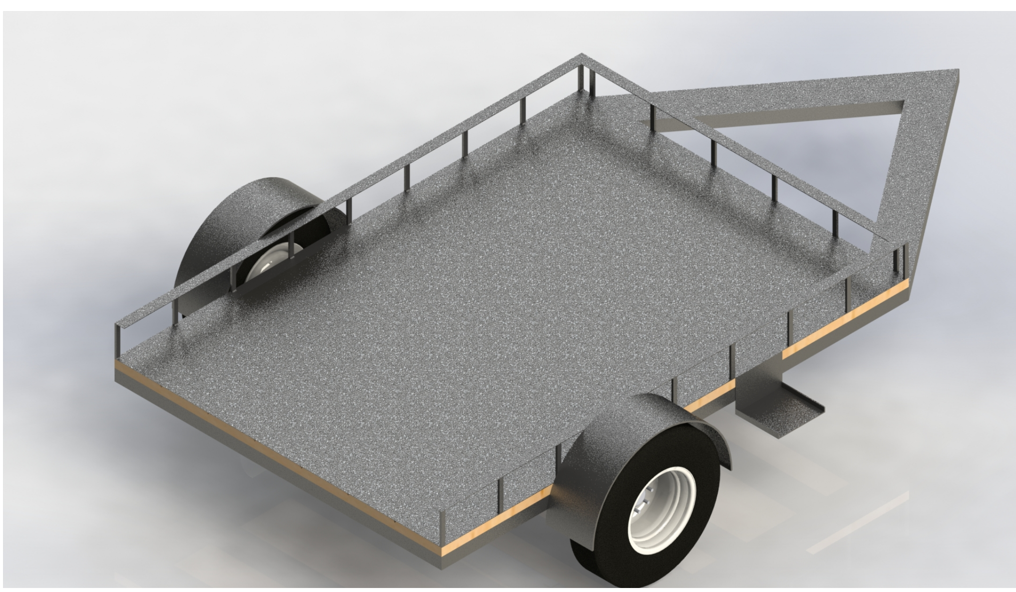


Figure 3: Utility trailer base to act as the foundation for the system

Figure 4: Utility truck trailer frame base support

3.1 Trailer Modifications

In Fig. 4 a base trailer frame is shown, which is the foundational structure for the entire test stand. Depending on the utility trailer obtained, the team will have to switch the layout schematic for the routing and other supporting structures in order to ensure that the proper mounts are bolted through the frame. The preferred option is to weld additional horizontal members along the base to act as further support and provide flexibility in mounting the components located above.

In Fig. 3 it can be seen that in addition to the traditional wooden base top that most utility trailers are manufactured with, there will be an additional 1/8″, 10 gauge, or 11 gauge steel sheet laid along the top so there is a square surface to mount along, as well as avoid bolt tear out for the mounted components.

3.2 Pressure Gauge Panel

The regulator and pressure gauge panel displayed in Fig. 5 will be used by the operator to calibrate the pressurizing legs of the propellant system. The structure of the panel will be 1/8" steel plate, supported through brackets mounted to the trailer. The panel will be waterjet cut, and measures 32" x 28". The larger holes are for the hand loaded regulators, and the smaller holes are for the 1/4" pressure gauge tube lines. There are mounting holes below the regulators to allow for easier installation. Above each pressure gauge there are slots available for lasercammed nameplates, so

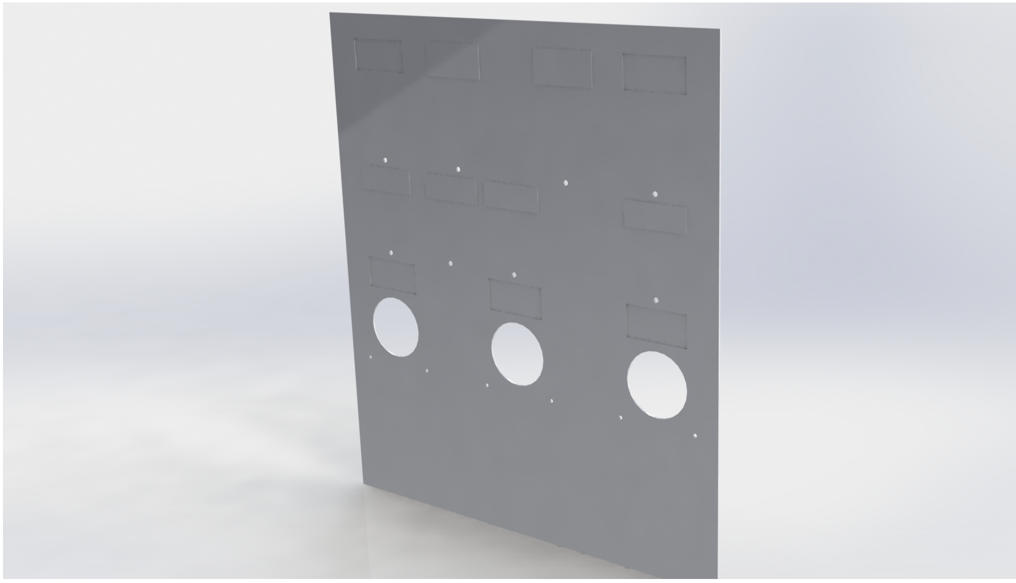


Figure 5: Regulator and pressure gauge panel plate

that each gauge is easily identifiable for the operator and the test conductor.

3.3 Tank Supports

Figure 6: 80/20 support frame to prevent movement of tanks and provide easy component mounting

The propellant pipe tanks will be supported laterally by the 80/20 assembly seen in Fig. 6. An added benefit of the frame is that it provides a rail for mounting components. The 80/20 will be purchased and cut to length by SEDS. Located at the top and middle of the frame are two shelves where the dome regulators and valves will be mounted to. The shelves will provide structural

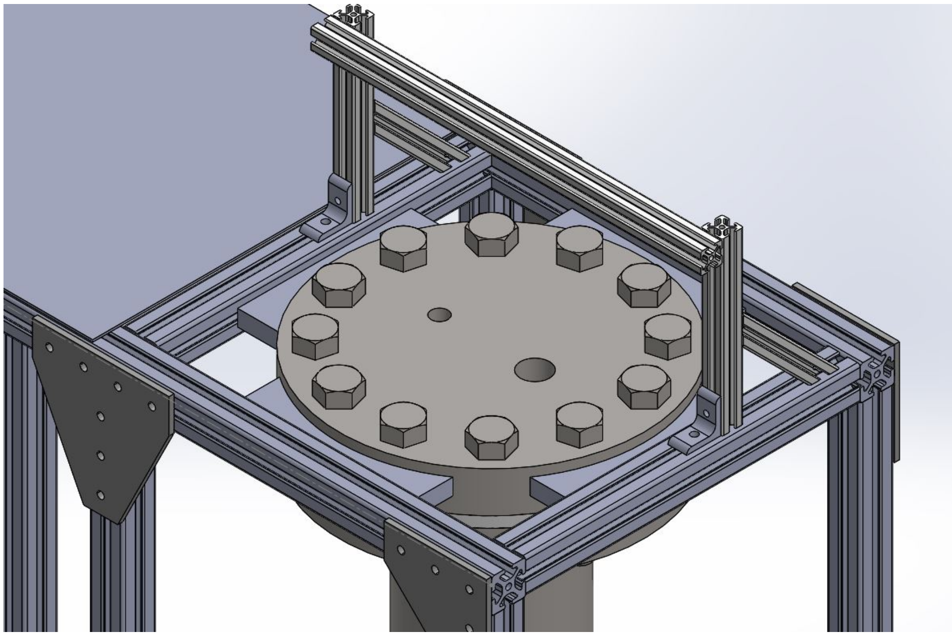


Figure 7: Cage Tank Support Assembly

supports to the plumbing and resulting thrust from the relief vents. Also located at the top of the frame are four machined blocks with radial cut outs that match the flanges of the tank as seen in Fig. 7. This will allow the flanges to rest tightly against the frame. The frame has a base of 20" x 20", and a height of 64".

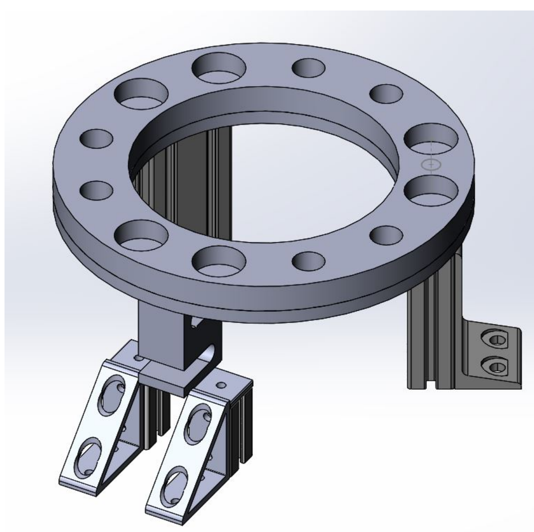


Figure 8: Tank boot support assembly

To support the weight of the tanks and lift them off the base of the trailer, the boot assembly seen in Fig. 8 will be used. The boot will secure the pipe tank down to the trailer as well as measure the mass flow rate of the propellant. A load cell is placed in one of the three vertical struts of the boot to measure the mass of the tank which can be used to estimate the mass flow rate of the tank propellant. The parts will be manufactured through water jet cutting the top ring and machining the tank boot struts to length. The entire assembly will be bolted together and to the frame of the utility trailer.

3.4 Trailer Lockdown

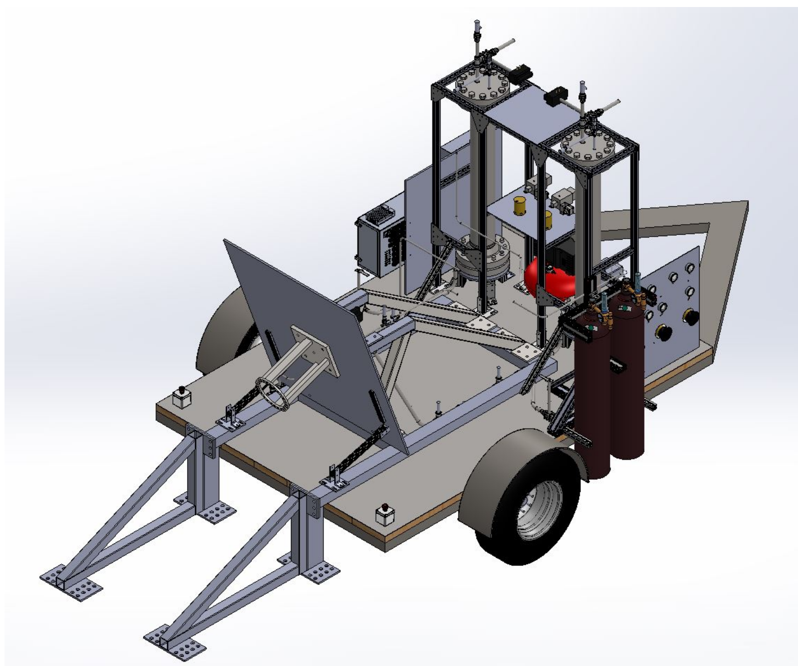


Figure 9: Trailer Lock Down Boots with truss support

The trailer will be secured through a lockdown boot truss system which ensures the stability of the TTO system during hot fire. As the structural integrity of the trailer cannot be ensured, this boot system lifts up the entire Colossus system off the ground and eliminates reliance on the trailers wheels and suspension.

SEDS will include 3 hydraulic car jacks that can be used to lift up the trailer at the test site. At this time, the trailer will be lifted up and the lockdown boots installed via the flange available at the end of the TTO Sled assembly. The system will then be lowered down into custom made concrete mounted bolts fabricated by FAR. The truss portion of the system will be manufactured from waterjet cut and welded 3 x 3 x 0.25 square steel tube. The steel baseplates will be waterjet cut to the proper size and bolt hole configuration. Using 0.5 bolts, the trailer lockdown will be secured to the concrete pad.

This system reduces the risk of catastrophic structural failure as all the thrust will be contained within SEDS manufactured parts, such as the TTO, Sled, and Lockdown Boot, as opposed to the trailer. This also eliminates the need to identify a suitable location on the trailer on where to wrap or mount the chain or other strap devices needed to constrain the thrust of the engine.

3.5 Thrust Take-Out

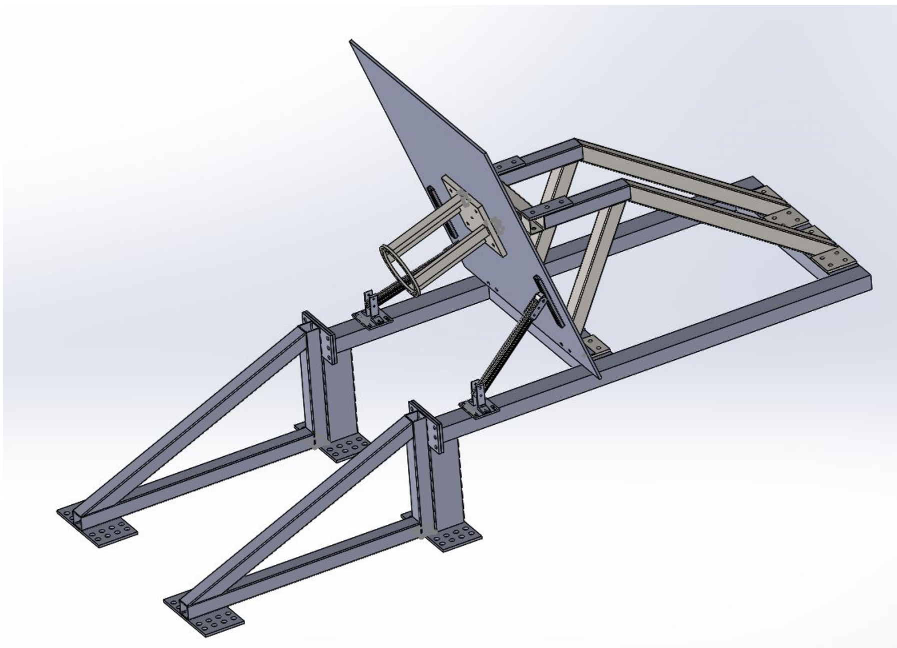


Figure 10: Engine interface mount block, canted at a 10° angle and bolted to the blast plate. A singular bolt is threaded into the truss

The engine thrust take-out (referred to as TTO) in Fig. 15 uses five main assemblies: the engine interface, the blast plate, and the dual-truss, and mounting beams. There will also be a load cell sandwiched between the blast plate and dual-truss to measure engine truss.

3.5.1 Engine Interface

The engine interface system shown in Fig. 11 and Fig. 12 allows the engine to be mounted to Colossus, while having space provided for tubing, pressure transducers on the engine injector, as well as instrumentation lines. The struts are 16" in length to provide adequate space and still satisfy the necessary load requirements. This ring and strut assembly will be welded to the canted blast plate interface block seen in **??**. The entire engine interface will bolt to the blast plate via four bolted holes with nuts at the corners, and one central bolt will be threaded into the truss frame. A single hole will be made offset from the plate's center to allow the oxidizer tubing to be routed through. The canted engine interface block will machined with a three-axis CNC in the campus shop.

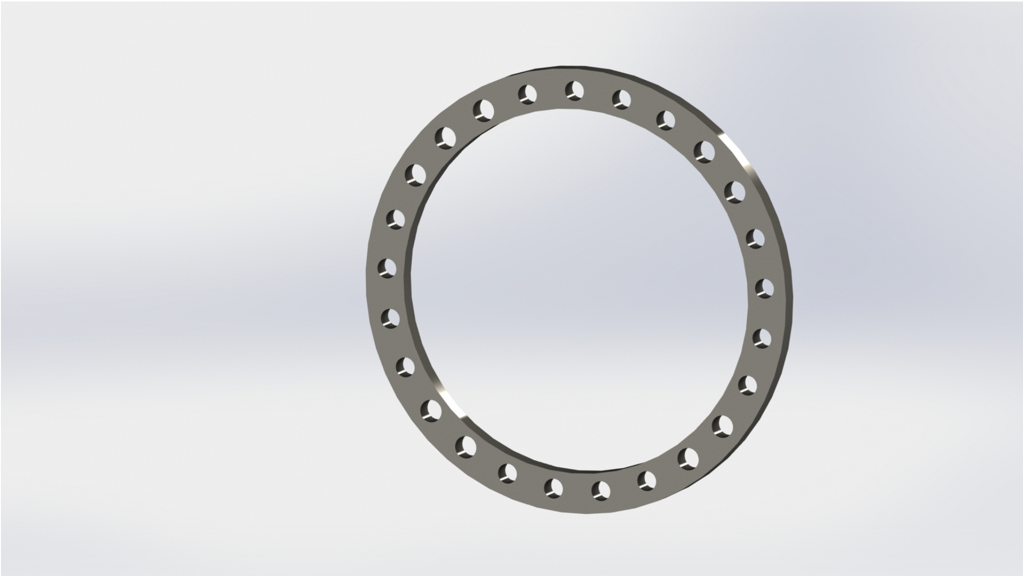


Figure 11: Waterjet ring to interface with engine bolt pattern

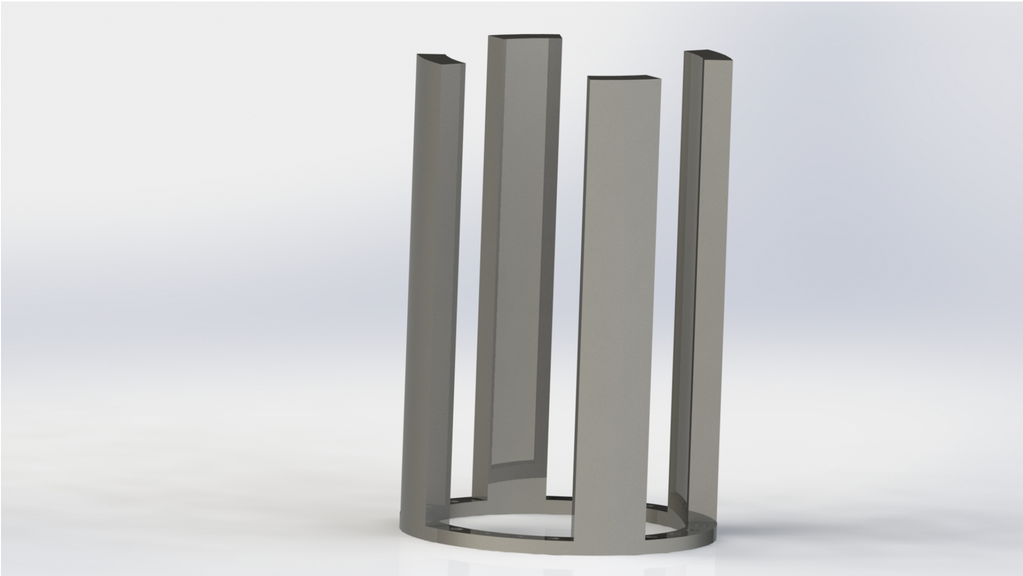


Figure 12: Thrust transmission mechanism, 4 radial struts allow for space for tubing and engine instrumentation

3.5.2 Blast Plate

The blast plate is a waterjet cut 54” x 48”. 1/2” thick steel plate, with the proper holes cut for the canted mounting block and a hole to allow the oxidizer tubing through.

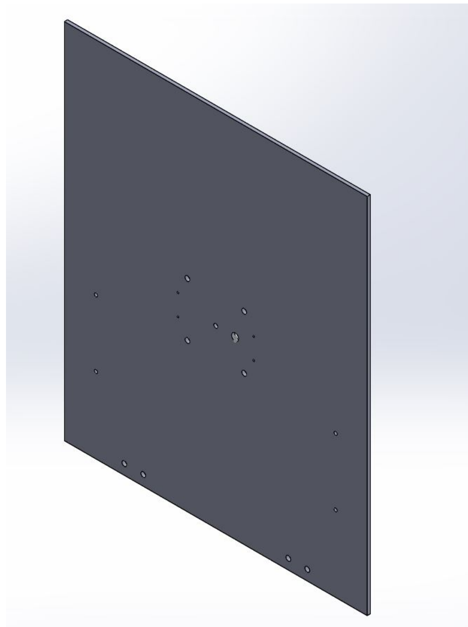


Figure 13: Waterjet cut 54” x 48”. 1/2” thick steel plate

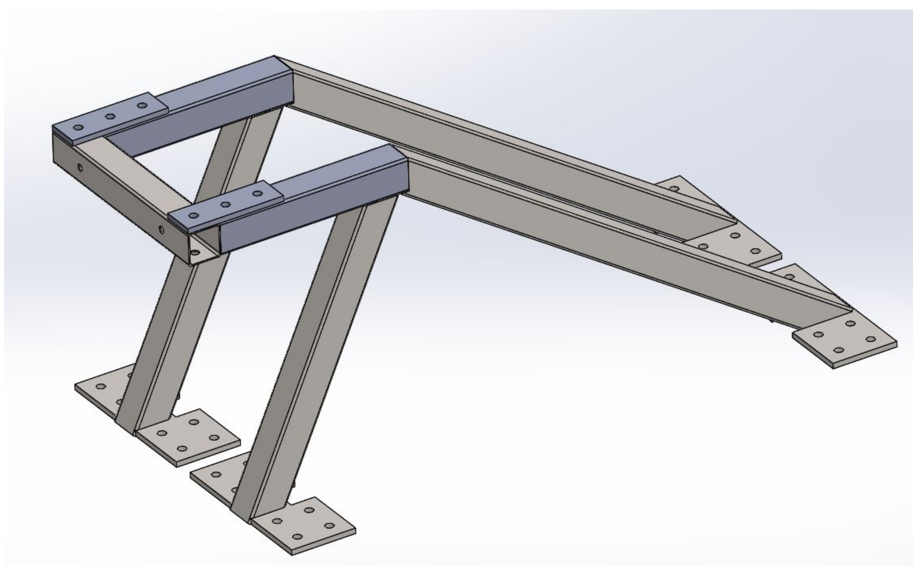


Figure 14: Truss thrust take out made of cut and welded steel members-bolted to the trailer frame

3.5.3 Truss Thrust Take Out

The bolts used to secure the truss to the trailer frame will be 3/4” and will be tightened with nuts on the underside of the trailer. The thickness of the plate that is being bolted through on the truss is 1/2” The truss frame is made of welded 3” steel square tube with a yield strength of 46000 *psi*. Two holes are ported into the truss that are threaded for the engine interface block and the blast plate. The ports are done into solid steel members that are welded to the square tube.

3.5.4 Thrust Take Out Lock-down bolts analysis

Objective:
The purpose of this analysis is to verify whether the current number of bolts in the present design is sufficient to resist the 2,700 lbf thrust load with a minimum safety factor of 2.

Method:
Using the reaction forces derived from the general TTO analysis to calculate the shear stress each bolt will experience.

Reference:
Reference to TTO Analysis with Thrust Vectoring the reaction force shearing the bolts is 5318 lbf in total (with an already accounted for S.F. of 2). The updated design for the TTO mounting plate has a total of 20 bolts each with a diameter of $0.75''$.

Solution:
Considering high strength grade 8 alloy steel bolts have a tensile yield strength of 150,000 psi, the number of bolts propose is more than sufficient to resist shear failure.

3.5.5 Allowable Thrust Deflection Analysis

Objective:
The purpose of this analysis is to verify that the current Thrust Take Out (TTO) design is capable of handling 15 degrees of thrust vectoring while still maintaining a Safety Factor of 2.

Method:
A static thrust of 5,400 lbf was loaded 15 degree horizontal to the engine interface ring, with fixed cylindrical supports applied to the base plates of the thrust take out beam. A frictional contact was applied between the blast shield canter and the blast shield with a friction coefficient of 0.8, and an assumed zero penetration between the contacting geometries. In addition, operating temperature was set to 22 degree Celsius, with an assumed 100 degree C constant thermal load applied to the interface ring. Thermal convection coefficient was assumed to be $5W/(m^2 * K)$ estimated for still air.

Results:
Maximum stress following the von Mises failure criteria is 38,211 psi. Material used in this analy-

sis is AISI 1025 Low Carbon Steel with a tensile yield strength of 45,000 psi. The minimum safety factor of the TTO under this loading condition is 2.356. Refer to the TTO Analysis with Thrust Vectoring for more information.

Solution:
The suggested material for the TTO should be a 3″ x 3″, 0.25″ thick AISI 1025 carbon steel from McMaster-Carr with part number: 6527K624.

3.6 Vent Thrust Take-Out

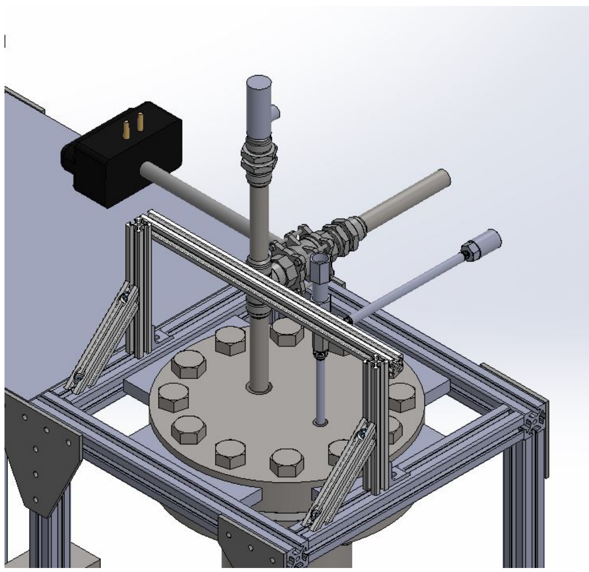
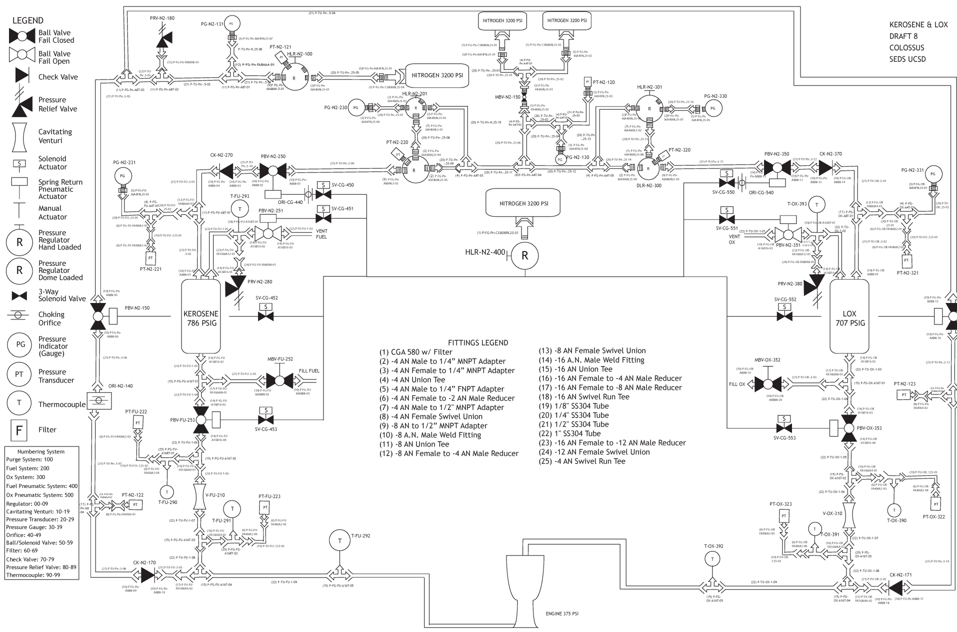


Figure 15: TTO to mitigate impulse in the event of an abort.

In a situation where the pressure in the tanks need to be purged through the vents, the vent TTO acts as a load bearing structure. The Vent TTO bears the split second impulse to avoid significant deformation of the vent line on top of the tanks.

The structure is made up of 80/20 and p-clamps to secure the pipe to the 80/20.

4 Propellant Systems



PS

Figure 16: Plumbing Diagram for Colossus

4.1 Regulators

The regulators on board the system provide the pressure feed control we need and will come from the supplier Aqua Environment. We will need 2 high flow dome regulators, 2 low flow hand regulators to provide the dome pilot pressure, and 1 high flow hand regulator. SEDS already owns the 2 dome regulators and 2 low flow hand regulators and will need to purchase the high flow hand regulator. The sizing for the required regulators can be seen in Tab. 20 and Tab. 21.

Figure 17: Aqua Environment 873-D Cv-0.8 High Flow Dome Loaded Reducing Regulator. Provides feed pressure to propellant tanks.

Figure 18: Aqua Environment 415 Reducing Regulator Cv-0.06 hand loaded regulator. Provides control pressure to dome regulators.

The hand regulators will be mounted to the gauge panel seen in Fig. 5. This is to provide easy access for the operator to change the regulators from the fully backed off state to the correct testing pressure. Upon preliminary calculations based on maximizing the mass flow rates in the feed system to the max allowable 20 ft/s, the Dome loaded regulators in Fig. 17 are the limiting factor. This implies that buying new tank feed regulators will be a required purchase if higher thrust engines are desired to be tested on this system.

Table 3: Dome Regulator Specifications

873-D Series Regulator	
Specifications	
Series Designation	873-D
Type	High Flow Dome Loaded Reducing Regulator
Loading Method	Dome Loaded
Maximum Rated Pressure	6000 psi
Outlet Pressure Setting Range	0-6000 psi
Outlet Pressure Rating	6000 psi
Maximum Control/Dome Pressure	6000 psi
Inlet Port Size	2 x 1/4" FNPT (One Inlet, One Gauge)
Outlet Port Size	1 x 1/4" FNPT (Gauge), 1 x 1/2" FNPT (Outlet)
Flow Coefficient	0.8 (Orifice = 0.23in)
Outlet Psi Variation with Inlet Psi Variation	3 psi rise/1000 psi inlet drop
Leakage	Bubble Tight
Control Port Size	1 x 1/4" FNPT
Weight	1200 g
Overall Length	4"
Round Diameter	3"
Minimum Temperature	-15 F
Body Material	Anodized Aluminum
Internal Materials	Anodized Aluminum
	Brass
	Stainless
Seal Materials	Kel-F
	Viton
Repair Kit/Service Items	979-D

Table 4: Hand Loaded Regulator Specifications

415-5000 Series Regulator	
Specifications	
Serie Designation	415 Series
Type	Reducing Regulator
PSI Out	0 to 5000 psi
Loading Method	Hand/Spring Loaded
Maximum Rated Pressure	6000 psi
Outlet Pressure Setting Range	50-5000 psi
Outlet Pressure Rating	6000 psi
Inlet Port Size	2 x 1/4" FNPT (One Gauge, One Inlet)
Outlet Port Size	2 x 1/4" FNPT (One Gauge, One Outlet)
Flow Coefficient	0.06 (Orifice = 0.07in)
Outlet Psi Variation with Inlet Psi Variation	70 psi rise/1000 psi inlet drop
Leakage	Bubble Tight
Weight	710 g
Overall Length	5.5"
Round Diameter	2.25"
Minimum Temperature	-15 F
Body Material	Anodized Aluminum
Internal Materials	Anodized Aluminum
	Brass
	Stainless
Seal Materials	Kel-F
	Viton
Repair Kit/Service Items	839-5000
Accessories	Mount Ring: P/N 657

Table 5: Purge Feed Regulator Specifications

873-1500 High Flow Reducing Regulators	
Specifications	
Series Designation	873 Series
Type	High Flow Reducing Regulator
Loading Method	Hand/Spring Loaded
Maximum Rated Pressure	6000 psi
Outlet Pressure Setting Range	0-1500 psi
Outlet Pressure Rating	6000 psi
Inlet Port Size	2 x 1/4" FNPT (One Inlet, One Gauge)
Outlet Port Size	1 x 1/4" FNPT (Gauge), 1 x 1/2" FNPT (Outlet)
Flow Coefficient (Cv)	0.8 (Orifice = 0.23in)
Outlet Psi Variation with Inlet Psi Variation	35 psi rise/1000 psi inlet drop
Leakage	Bubble Tight
Weight	1300 g
Overall Length	6.5"
Round Diameter	3"
Minimum Temperature	-15 F
Body Material	Anodized Aluminum
Internal Materials	Anodized Aluminum
	Brass
	Stainless
Seal Materials	Kel-F
	Viton
Repair Kit/Service Items	979-1500
Accessories	Mount Nuts: P/N 952 (Two Required)

Table 6: Dome Loaded Regulator Maximum Flow Rate

REGULATOR - TESCOM CALC	**26-1100**
Actual CV of Regulator	1.3
Inlet Pressure(Press of K-Bottle) (psia)	3214.7
Outlet Pressure (psia)	677.2
Specific Gravity of Gas	0.9669
Δ P	2537.5
Is P1 Greater than or equal to 2 x P2?	YES
IF YES QG (SCFM)	2125

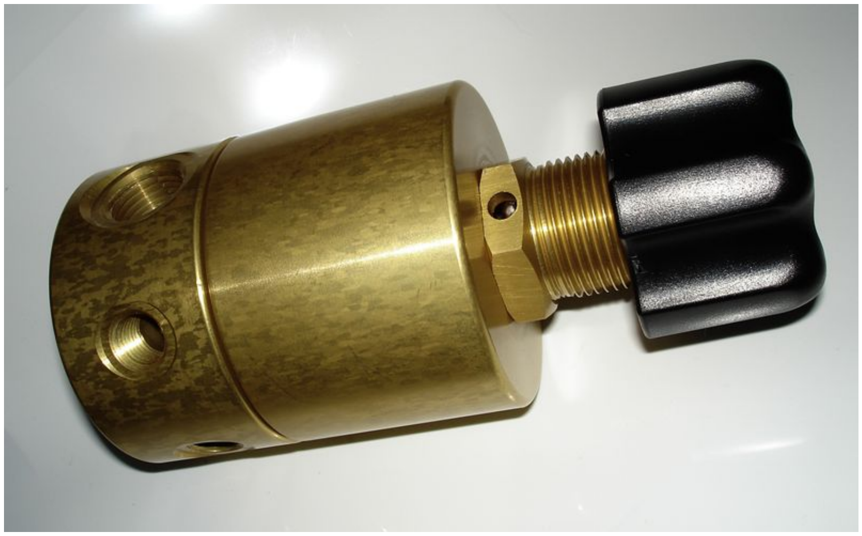


Figure 19: Aqua Environment 873 High Flow Reducing Regulator. Provides purge pressure.

4.2 Pressure Relief

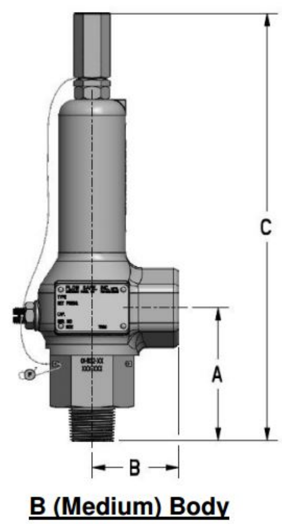


Figure 20: FlowSafe F84 -6 Pressure Relief Valve

The system pressure relief valves will be FlowSafe F84 Medium Body -4 Valves. The sizing for the relief valves were based on the maximum possible wide open flow of the Dome Regulators, which can be seen as 1438 $SCFM$ in Tab. 6. The end connections will be 3/4" in. female MS33649, which will be able to be directly connected to a -12 AN fitting, and will be attached to through a bulkhead fitting as seen in the mounted corner bulkhead in **??**. The relief valve sizing calculations can be seen in Tab. 7.

4.3 Valves

The valves on board will provide the necessary flow control for Colossus. The system will use pneumatically actuated ball valves for the pressurizing gas and propellants, while 3-Way solenoid valves will provide the pilot pressure for the pneumatic actuators.

4.3.1 Ball Valves

The ball valves that are going to be used are going to be Gosco Cryogenic (Full Port) Valves. The

Figure 21: Gosco C89 Cryogenic Ball Valve

fill valves located below the propellant tanks will be 1/2", the main propellant valves will be 1", and the vent valves will be 1", all with buttweld ends with AN weld-ons. We are pursuing acquisition of an at-cost sponsorship for the 6 cryogenic ball valves. Their only available size is Class 600, which would make them some of the pressure limiting components on board (1440 *PSIA*). With some short calculations and assuming kerosene as the fuel, SEDS can test approximately a maximum

Table 7: Relief valve sizing calculations based on tank set pressures.

RELIEF VALVE PARAMETERS FUEL	Flow Safe
Max Flow Capacity SCFM (V) (Max Reg Flow * 110%)	1438
Molecular Weight (M)	28
Inlet Temperature (F)	60
Inlet Temperature (Rankine)	520
Compressibility of Nitrogen (Z)	1
Gas Constant	356
Derated Valve Coefficient of Discharge (K)	0.878
Pressure at Valve Inlet During Flow (PSIA) (P1 * 110%)	881
Max System Pressure (psia)	1440
Set Pressure (psia)(Max Sys Pressure * 110%)	1584
A = (V*sqrt(M*T*Z))/(6.32*GasConst*K*P1*1.1)	
Calculated Required Valve Orifice Area (in^2)	0.04882
From Flow Safe: Orifice Area (in^2) -4	0.065

RELIEF VALVE PARAMETERS OX	Flow Safe
Max Flow Capacity SCFM (V) (Max Reg Flow * 110%)	1438
Molecular Weight (M)	28
Inlet Temperature (F)	60
Inlet Temperature (Rankine)	520
Compressibility of Nitrogen (Z)	1
Gas Constant	356
Derated Valve Coefficient of Discharge (K)	0.878
Pressure at Valve Inlet During Flow (PSIA) (P1 * 110%)	745
Max System Pressure (psia)	1440
Set Pressure (psia)(Max Sys Press * 110%)	1584
A = (V*sqrt(M*T*Z))/(6.32*GasConst*K*P1*1.1)	
Calculated Required Valve Orifice Area (in^2)	0.04882
From Flow Safe: Orifice Area (in^2) -4	0.065

*Note Max Reg Flow: 1438 SCFM; P1: corresponding tank pressure; Max Sys Press: 1440 psia
V: Max Flow Cap; M: Mol Weight; T: Temp; Z: Comp of N2; K: Coeff of Discharge

750 *psig* P_c thruster. SEDS was quoted 6500 USD for all of the propellant valves, limit switches, and actuators from a local San Diego supplier.

For the 1/2" pressurizing ball valves, SEDS already owns 2 pneumatically actuated ball valves from Swagelok, and will be purchasing two more identical valves (2200 *PSIG* maximum) for the purge lines.

The valves on board will be mounted along the 80/20 channels supporting the propellant tanks as seen in **??**, or they will be mounted along the steel sheet base. Every ball valve will have limit switches in order to communicate the status of the system back to the operator.

Table 8: Ball valve configuration example

Gosco C89	Class 600
Size (in.)	1
Body	316 SS
Ends	316 SS
Ball	316 SS
Stem	316 SS
Seat	PCTFE (Kel-F)
Body Seal	Teflon
Stem Packing	PTFE
Ends	Butt Weld

4.3.2 Solenoid Valves

The 3-way brass DC solenoid valves will be mounted along one of the 80/20 channels and come from the vendor ASCO. The pressure feed will come from a standard 125 *PSI* air compressor and be fed through flexible nylon tubing into the solenoid valves and then into the pneumatic actuators. Every port on the solenoid valves is 1/4 NPT, and the two solenoids that actuate the tank pressurizing ball valves will have machined orifices inserted in order to actuate the ball valves more slowly.

4.4 Tanks

The ASME code pressure vessels on board will be two identical pipe tanks, as seen in Fig. 22. The tank consists of a single 36 *in*. length, 8 *in*. diameter of seamless SS 304 40S pipe butt welded to two raised face (RF) weld-neck flanges, where those flanges are interfaced with ported RF blind flanges. These flanges, along with the Gosco cryogenic ball valves, are the pressure limiting components of the system (1440 psia). A PTFE CG gasket from ChemOilProducts will be used in between the two flanges. The bolts will be 1.13" A320 B8 Class 2 (SS 304) that are 7.5 *in*.

Figure 22: Pipe Propellant Tank

in length, the nuts will be A194 Grade 8, and the washers will be SS 304. These bolts will be torqued to 424 ft-lbs to ensure necessary tightness. The tank specifications are summarized in Tab. 9, Tab. 10, and Tab. 11.

Table 9: Tank Size Specifications

Tank Parameters (8 in. Seamless 40S, TP304 A312)	**ASME B36.19**
OD (in)	8.625
Wall Thickness (in)	0.322
ID (in)	7.981
radius (in)	3.9905
height (in)	36
Volume (in^3)	1800.97
Volume (gal)	7.80

The pipe lengths will be procured from a local San Diego supplier, while SEDS is still searching for a sponsor for the weld-neck flanges and blind flanges. SEDS is trying to find an at-cost sponsorship from Coastal Flange and Texas Flange. The welding will be done by a local ASME certified welder. Dye-penetrant and x-ray weld examination will be performed by the welding service provider as well.

Table 10: Required wall thickness calculation for a Class 600 allowable pressure rating

Wall Thickness Calculations	
ASME B31.3 2014-Equation 3a Pg 20	
P, Internal Design Pressure	1440
D, Outer Diameter (in)	8.625
S, Allowable Stress Value (psi)	20000
Ec, Quality Factor	1
Y, Coefficient	0.4
W, Weld joint strength reduction factor	1
t, Pressure Design Thickness Minimum	0.3018
Ratio of Wall Thickness Actual/Wall Thickness Minimum	1.06

Table 11: Weld-neck flange specifications

Weld Neck Flange (Butt Weld), Blind Flange (No Weld)	
ASME B16.5-2003 A182 F304 Class 600	
Bolt Classifcation	**ASTM A320 B8 CL 2 - 1-1/8 in.**
Nut Classifcation	**ASTM A194 Grade 8**
Washer Classifcation	**SS 304**
Gasket Classifcation	**ASME B16.20/Cryogenic/Raised Face/PTFE**

4.4.1 Port Thread Analysis

The bolts and nuts to be used to secure the tank flanges adhere to ASTM A320 B8 Class 2, and ASTM A194 Grade 8, respectively.

	Grade	Marking	Size	Tensile, ksi, min	Yield, ksi, min	Charpy Impact 20-ft-lbf @ temp	Elong, %, min	RA, %, min	Hardness max
Mechanical Properties	L7	L7	Up to 2 ½	125	105	-150° F	16	50	C35
	L43	L43	Up to 4	125	105	-150° F	16	50	C35
	B8 Cl 1	B8	All	75	30	N/A	30	50	B96
	B8M Cl 1	B8M	All	75	30	N/A	30	50	B90
	B8 Cl 2	B8	Up to ¾	125	100	N/A	12	35	C35
			7/8 to 1	115	80	N/A	15	35	C35
			1 1/8 to 1 ¼	105	65	N/A	20	35	C35
			1 3/8 to 1 ½	100	50	N/A	28	45	C35
	B8M Cl 2	B8M	Up to ¾	110	95	N/A	15	45	C35
			7/8 to 1	100	80	N/A	20	45	C35
			1 1/8 to 1 ¼	95	65	N/A	25	45	C35
			1 3/8 to 1 ½	90	50	N/A	30	45	C35

Figure 23: ASTM A320 Specifications: 1 in. B8 Class 2 bolt has a yield strength of 80ksi

According to the table, a 1 inch bolt should have a yield strength of 80,000 psi

	Specification	Marking	Nom. Size, In.	Tempering Temp. °F	Proof Load Stress, ksi	Hardness	
						Min	Max
Mechanical Properties	A194 Grd 2	2	1/4 - 4	1000	150	B159	B352
	A194 Grd 2H	2H	1/4 - 4	1000	175	C24	C38
	A194 Grd 2HM	2HM	1/4 - 4	1000	150	B159	B237
	A194 Grd 4	4	1/4 - 4	1100	175	C24	C38
	A194 Grd 7	7	1/4 - 4	1100	175	C24	C38
	A194 Grd 7M	7M	1/4 - 4	1100	150	B159	B237
	A194 Grd 8	8	1/4 - 4	-	80	B126	B300
	A194 Grd 8M	8M	1/4 - 4	-	80	B126	B300

Figure 24: ASTM A194 Specifications: Corresponding Class 8 Nut Specifications

This indicates that the recommended grade 8 nut for the above bolt also conforms to the 80,000 psi yield strength.

Given that the maximum pressure of our tank is expected to be no greater than 1440 psi, the selected nuts and bolts will have no issue handling the pressure, as long as the bolt is threaded in through the whole thickness of the nut.

4.5 Cavitating Venturis

The most critical component for the mass flow rate lock-down of the propellant system will be the usage of cavitating venturi flowmeters. These devices utilize a vapor bubble for specified liquids and pressures to ensure a precise mass flow rate is engaged throughout the propellant run lines. The venturi flowmeters will be sourced from Flow-Dyne for approximately 600 USD each. The sizing of the required throat diameters is displayed in Tab. 12. The calculations are based on the Ignus injector in conjunction with the Vulcan-1 combustion chamber/nozzle assembly. The values for the vapor pressure and density of the fluids were determined from a MATLAB plugin called CoolProp.

Table 12: Cavitating Venturi flowmeter throat sizing

LOX Venturi Sizing	
mdot=Cd*Athroat*(2*rho*(Pin-Pexit))$^{1/2}$	
Cd	0.94
Pventuri, inlet (psia)	667.2
Pvap (psia)	120.1884
Throat Area (in^2)	0.01657027665
Throat Diameter (in)	0.15
Line Size OD (in)	1.00
Material	SS 304
End Fittings	AN/37 deg flare
Uncalibrated	Machined, $\pm$ 3%
Kerosene Venturi Sizing	
mdot=Cd*Athroat*(2*rho*(Pin-Pexit))$^{1/2}$	
Cd	0.94
Pventuri, inlet (psia)	790.4
Pvap (psia)	0.0011435
Throat Area (in^2)	0.006394916938
Throat Diameter (in)	0.09
Line Size OD (in)	1.00
Material	SS 304
End Fittings	AN/37 deg flare
Uncalibrated	Machined, $\pm$ 3%

Table 13: Vulcan-1 Engine mass flow and pressure specifications with Ignus injector

General Flowrates	
Mass flowrate, LOX (lbm/s)	2.0567
Mass flowrate, Kerosene (lbm/s)	0.8034
Vol flowrate, LOX (ft^3/s)	0.028857864
Vol flowrate, Kerosene (ft^3/s)	0.0161002
Vol flowrate, LOX (gal/s)	0.215871832
Vol flowrate, Kerosene (gal/s)	0.120437871
Max Line Speed, LOX (ft/s)	20
Max Line Speed, Kerosene (ft/s)	20
LOX System Parameters	
Engine Inlet Mass Flow Rate (lbm/s)	2.0567
LOX Density (lbm/ft^3)	71.27
Chamber Pressure (psig)	375
Injector Head Loss (psig)	75
LOX Manifolding Head Loss (psig)	80
Engine Inlet Pressure (psig)	530
Venturi Pressure Drop (%)	25
Total Line Losses (psig)	2
LOX Tank Pressure (psig)	705
LOX Tank Pressure (psia)	719.7
Fuel System Parameters	
Engine Inlet Mass Flow Rate (lbm/s)	0.8034
Kerosene Density (lbm/ft^3)	49.9
Chamber Pressure (psig)	375
Injector Head Loss (psig)	75
Regen Cooling Head Loss (psig)	100
Engine Inlet Pressure (psig)	550
Venturi Pressure Drop (%)	30
Total Line Losses (psig)	1
Fuel Tank Pressure (psig)	785
Fuel Tank Pressure (psia)	799.7

4.6 Routing

4.6.1 Tubing

The tubing on Colossus will be entirely stainless steel 304, where the specific pressure ratings calculated by ASME code can be seen in Tab. 14. The propellant and vent lines utilize 1 *in*. tubing, the pressure feed and gauge lines run 1/4 *in*. tubing, the pressure feed after the main regulators is 1/2 *in*. tubing, and the pressure transducer lines coming off the tank and main propellant lines are 1/8 *in*. tubing. The calculations shown in Tab. 15 give Colossus room in the future to move higher

Table 14: Tubing wall thickness and pressure ratings

Stainless Steel Tubing ASME B31.3	2SEWt/(D-Yt)=P	
S, Allowable Stress Value (psi)	20000	
Ec, Quality Factor	1	
Y, Coefficient	0.4	
W, Weld joint strength reduction factor (Note (a))	1	
Tube Diameter	Wall Thickness	MAWP
0.25	0.028	4018
0.5	0.035	2599
1	0.049	1810

mass flow rates safely. The approximate maximum mass flow rate that the system can run for LOX is 5.407 lbm/s based on a 20 ft/s maximum propellant line speed. The system layout has made it clear that a priority for the last stages of the design process need to be making the routing as simple as possible to avoid bend configurations that may be too difficult to fabricate. The layout of the feed system will see many changes, however the propellant run system and vent lines will see no change.

In addition, some of the pressure transducers on Colossus will come into contact with the propellant. To prevent these pressure transducers from freezing due to the cryogenic temperatures of the system, a tube extension will be added between the pressure transducer and the rest of the system in order to separate the two entities. The tube extension will be made of stainless steel 304 and will have an outer diameter and an inner diameter of 0.125 *in* and 0.085 *in*, respectfully. This tubing will have a minimum length of 8.2 *in*. This length was calculated and took into account the lowest temperature at which they remain operational, -13 degrees Fahrenheit, and the ambient temperature, 100 degrees Fahrenheit.

Table 15: Line speed calculations based on Ignus Injector

LOX Tubing Below Tank	
Vol flowrate, LOX (ft^3/s)	0.0289
Minimum Area Allowed (ft^2) (Based on Max Line Speed, 20 ft/s)	0.00144
Minimum Area Allowed (in^2)	0.20778
Minimum Tube Inner Diameter Allowed (in)	0.514
Actual Tubing Inner Diameter	0.834
Actual Tubing Area (in^2)	0.546
Actual Tubing Area (ft^2)	0.0038
Line Speed, Actual (ft/s)	7.61
Fuel Tubing Below Tank	
Vol flowrate, Kerosene(ft^3/s)	0.0161
Minimum Area Allowed (ft^2) (Based on Max Line Speed, B13)	0.000805
Minimum Area Allowed (in^2)	0.1159
Minimum Tube Diameter Allowed (in)	0.384
Actual Tubing Inner Diameter	0.834
Actual Tubing Area (in^2)	0.546
Actual Tubing Area (ft^2)	0.0038
Line Speed, Actual (ft/s)	4.24

4.6.2 Fittings

The fittings on board will be a combination of buttweld, 37 degree flare, and NPT. We have decided to incorporate buttweld fittings due to the relatively low cost of valves with buttweld ends, as well as the difficulty of tapping a 37 flare into the ports of our tanks. A majority of our old hardware has NPT thread endings; however, it is preferable to avoid having any sort of Teflon tape on-board the system. We have decided to make a compromise between using 37 degree flare and NPT on the system. The purge line valves and the regulators will utilize NPT, as the regulators we currently have are NPT and will help us save cost. All fittings and valves will be 37 degree flare, with the valves having a 37 degree flare fitting buttwelded to the ends of the valves. We will be extra careful when wrapping our Teflon to minimize the chances of Teflon contaminating the lines. SEDS is looking to acquire fittings from Titan Fittings, Stainless Steel Fittings, and McMaster.

4.7 Fuel Purge Orifice

A choking orifice is added to the fuel purge line to further reduce its flow rate limit since the volumetric rate for LOX is generally higher than the fuel side. The output volumetric flow rate of the fuel side purge line should match up with the nominal flow rate of fuel through the main line to ensure proper mixture ratio at shut down. The size of the orifice is calculated on a engine to engine basis. For demonstration, the orifice size is calculated based on the combustion ratio of the Vulcan-1 injector.

Table 16: Fuel Purge Orifice Calculation

Inlet Pressure (psig)	100
Outlet Pressure (psig)	50
Molecular Weight of Gas	28
Temperature in oR	520
Orifice diameter (inch)	0.025
Inside diameter of upstream tubing(inch)	0.430
DP/P1	0.4359197908
Factor #3	0.966
Calculated volumetric flow rate (SCFM)	0.95
Nominal fuel line flow rate(SCFM)	0.97

* The Factor #3 values can be found using the Tab. 17

Table 17: Factor #3 Table

P/P1 VS. Factor # 3									
P/P1	Factor #3	P/P1	Factor # 3	P/P1	Factor # 3	P/P1	Factor # 3	P/P1	Factor #3
0.52	1	0.04	0.382	0.076	0.53	0.012	0.179	0.001	0.023
0.48	0.994	0.208	0.794	0.064	0.481	0.008	0.138	0.001	0.023
0.44	0.983	0.196	0.776	0.052	0.442	0.004	0.08	0.0009	0.0216
0.4	0.966	0.184	0.756	0.048	0.422	0.01	0.16	0.0008	0.002
0.36	0.944	0.172	0.736	0.044	0.402	0.009	0.15	0.0007	0.0183
0.32	0.918	0.16	0.715	0.04	0.382	0.008	0.139	0.0008	0.0162
0.28	0.884	0.148	0.693	0.036	0.361	0.007	0.127	0.0005	0.0139
0.24	0.845	0.136	0.672	0.032	0.334	0.006	0.113	0.0004	0.0115
0.2	0.782	0.124	0.647	0.028	0.309	0.005	0.097	0.0003	0.089
0.16	0.715	0.112	0.625	0.024	0.281	0.004	0.08	0.0002	0.0062
0.12	0.638	0.1	0.594	0.02	0.25	0.003	0.062	0.0001	0.0033
0.08	0.542	0.088	0.564	0.016	0.216	0.002	0.043	0	0

4.7.1 Maximum Burn Time

Colossus will have a maximum burn time of 16 *sec*. The maximum burn time is based on the max mass flowrate of LOX as well as the tank parameters.

Table 18: Maximum Burn Time Calculations

Main Propellant Line Tubing Sizes	
Actual Tubing Inner Diameter	0.834
Actual Tubing Area (in^2)	0.546
Minimum Area Allowed (in^2)	0.20778
Actual Tubing Area (ft^2)	0.00379
LOX Side Parameters	
Max Line Speed Allowable, LOX (ft/s)	20
LOX Density (lbm/ft^3)	71.27
Max Volumetric flow rate, LOX (ft^3/s)	0.0759
Max Mass flow rate, LOX (lbm/s)	5.41
Vol flowrate, Kerosene (gal/s)	0.568
Tank Parameters (6 in. Seamless 80S, TP304 A312)	
OD (*in*)	8.625
Wall Thickness (*in*)	0.322
ID (*in*)	7.981
radius (*in*)	3.9905
height (*in*)	36
Volume (in^3)	2101
Volume (*gal*)	9.095
Max Burn Time	
	16.025 *sec*

5 Electronics and Instruments

The electrical system on Colossus plays a key role in integrating all mechanisms and instruments. This system of Colossus has two subsystems. The onboard PC with LabVIEW allows operators to have full control of the system remotely at a safe distance, as well as automating the test sequence. In conjunction, the data acquisition system will collect signals from the sensors on board of Colossus and record and send real time status reports back to the operator. The system is designed with redundancy mechanisms, in both physical design and procedure planning, to ensure reliable and safe operation. Details of the design and the operating procedure will be discussed in further detail in the following sections.

Overview of system plans and design goals:

- Estimated Budget: $12,000
- Acquire quality data
- Custom made command and control system with system status feedback
- Automated test sequence programmed and controlled by the onboard computer with LabVIEW backbone
- Can be operated up to 250ft away
- Allow inter-system communication
- Can be operated without external electricity power outlets
- Expandable inputs and outputs
- Easy maintenance

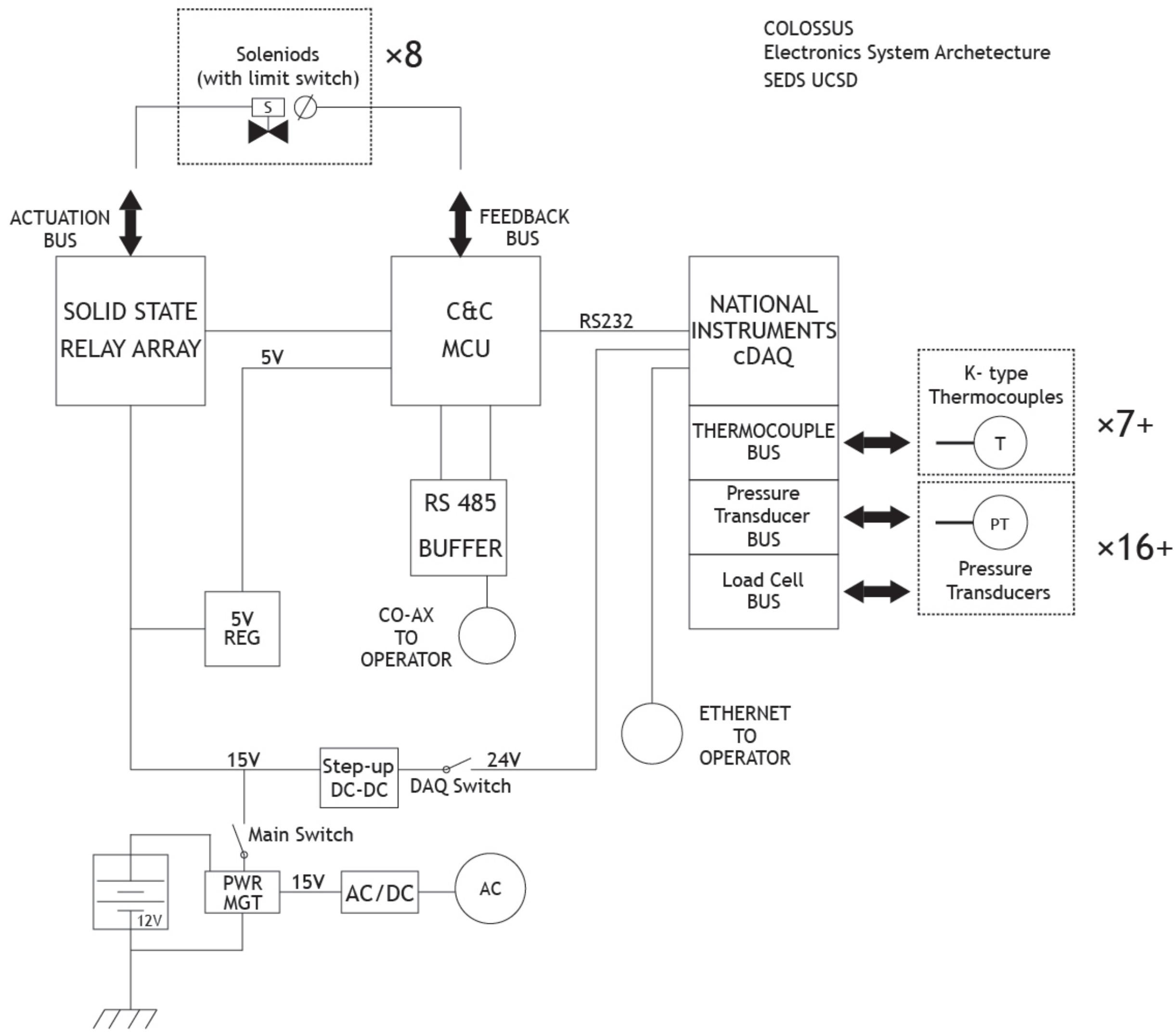


Figure 25: System Architecture Diagram

5.1 Command and Control Interface

A custom Command and Control system will be fabricated. This system consists of two isolated units, one unit is present at the instrument while the other provides an interface for the operator. These units will be connected together via coaxial cable (up to 250ft) via a half duplex of RS485 bus.

The instrument terminal of the Command and Control system is designed to be mounted in the electronics shelf along with the DAQ system of Colossus. This system has to meet the following design parameters:

- Actuation of 8 channels of electric solenoids
- Actuation of 1 channel ignitor
- Status detection of 8 channels of limit switches
- Carbon copy limit switches inputs to DAQ
- Serial communication with DAQ system
- Interface with the power system of Colossus

To start, an AT89C51 microcontroller was selected to use as the control unit of the sub-systems. 8051 Architecture micro controllers are reliable and simple to program. Though not compatible with popular operating systems and kernels, 8051 MCUs require minimal hardware configuration to function. This family of microcontrollers is also capable of operating at a varying supply voltage range from 4V to 6V, continuously (7V max transient Vcc). Secondly, a MAX482 chip is used to buffer RS-485 communication and a 74LS06 is used to buffer serial communication. The flow of information within the system is fulfilled by the following data flow structure.

Based on the system design parameters from plumbing, 12V car battery reservoirs were chosen as the main power source of the system. To actuate these solenoids quickly and reliably, an array of MOSFET relays are implemented. Since the solenoids are inductive loads, fly wheel diodes are added in parallel to the output to project the MOSFETs

The Gate of these MOSFETs are driven at 12V to ensure a high ON state transconductance. A diode is reverse biased between the 12V and the 12V rail to maintain actuating capability in the

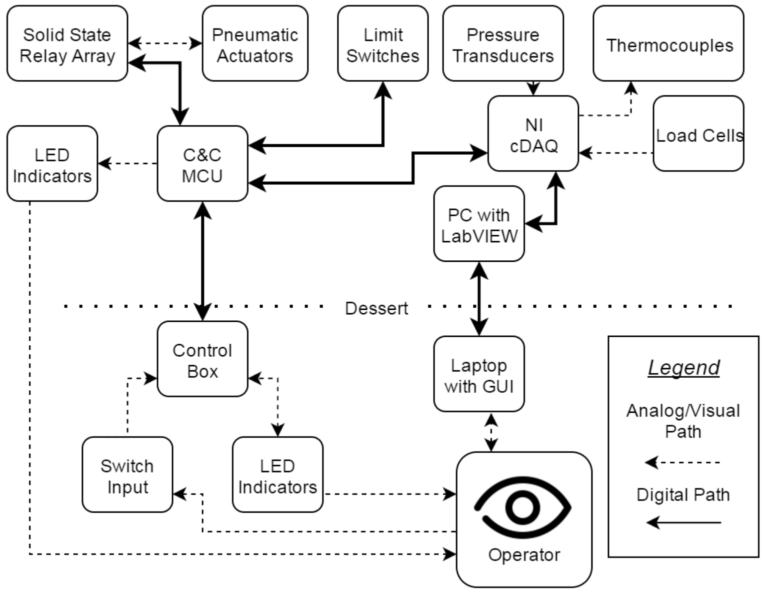


Figure 26: Data Flow Diagram

case of a 12V supply failure. Two LED indicators are connected to the MCU such that they can be programmed to indicate any basic operational information. Detailed interpretation of the LEDs will be discussed in section. Section 5.5

Since the microcontroller and other logic ICs operate at 5V, the solenoids, the MOSFETs and the cDAQ operate at 12V. Proper voltage conversion from the 12V battery rail must be done to accommodate the needs of all systems. Both the 1V rail and the battery rail voltage are monitored via a voltage divider network to feed to the internal ADC in the 8051 MCU. Calculations and design considerations regarding the voltage conversion methods and power management system details will be discussed in section 5.4

Layout

The PCB layout (Fig.28) of the Command and Control Receiver is designed using EAGLE CAD. All 8 channels of solenoid relay and the ignitor relay channel are located at the top section of the PCB; the power management systems sit at the bottom left portion of the board; the logic portion fills the bottom right.

Calculating Trace Width

Given that A is the area of a trace, I is the incident current, ΔT is the tolerable temperature change, and d is the thickness of the trace. k,c,d are standardized constants.

$$A = \frac{I}{k \times \Delta T^b}^{\frac{1}{c}} \tag{1}$$

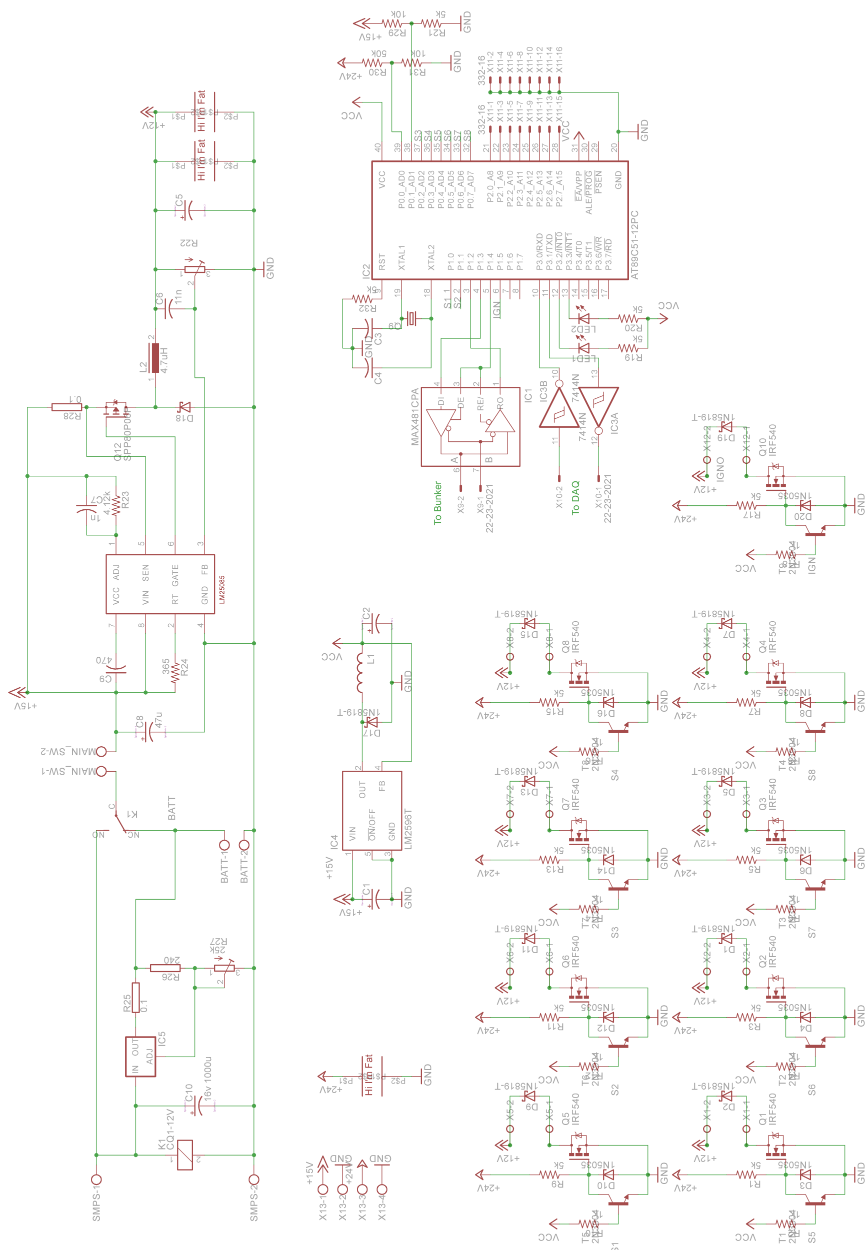


Figure 27: Command and Control System Receiver Schematics

Then, the Width is calculated:

$$Width[mils] = \frac{A}{d \times 1.378} \tag{2}$$

Where as for IPC-2221 external layers: k = 0.048, b = 0.44, c = 0.725

For the case of the solenoid output modules, each solenoid is rated to operate at 12V, 11.65W, draining on average of 1 Amp from its relay. Therefore the circuit should be able to withstand 1.5A(1A*1.5 safety factor) of constant current though each channel. Plugging 1.5A back to Equation 1 and 2, we yield a minimum trace width of 10.3 mil(Note: 1 mil is 1/1000 of an inch)

The same calculation can be applied to other current intensive parts of the PCB.

Net Description	Current	Min. Width
Relay output per Channel	1.5A	10.3mil
Power rail to all 9 relays	8×1.5A=12A	91.1mil
Battery input	15A	124mil
SMPS input	15A	124mil

The PCB layout is routed according to the minimum width guideline calculated above.

Thermal Management

This circuit board itself contains many heat emitting devices. Without proper thermal management, the system can easily overheat in the harsh environment of the desert. Information regarding the cooling methods will be discussed later.

There are 12 TO-220 packaged power electronic devices, nine of which belong to the SSRA. The MOSFETs being implemented for this array is IRFZ44N. It is rated at VDSS = 55V, RDS(on) = 17.5m&=, ID = 49A, and it has a total Junction to Case Thermal Resistance of 2.0°C/W.

Using Ohms Law, written in terms of power:

$$P = I^2 \times R \tag{3}$$

Each MOSFET carries 1.5A on average

$$P = 1.5A^2 \times 0.0175\Omega = 40mW \tag{4}$$

Heat dissipation on these MOSFETs is insignificant, therefore heat sinks are not required for the SSRA

On the other hand, the three power components that are not part of the SSRA are involved in the power management system. To estimate total heat balance, we assume the on-board DC-DC converter is 92.5% efficient. We also assume that the voltage drop across the charger regulator is

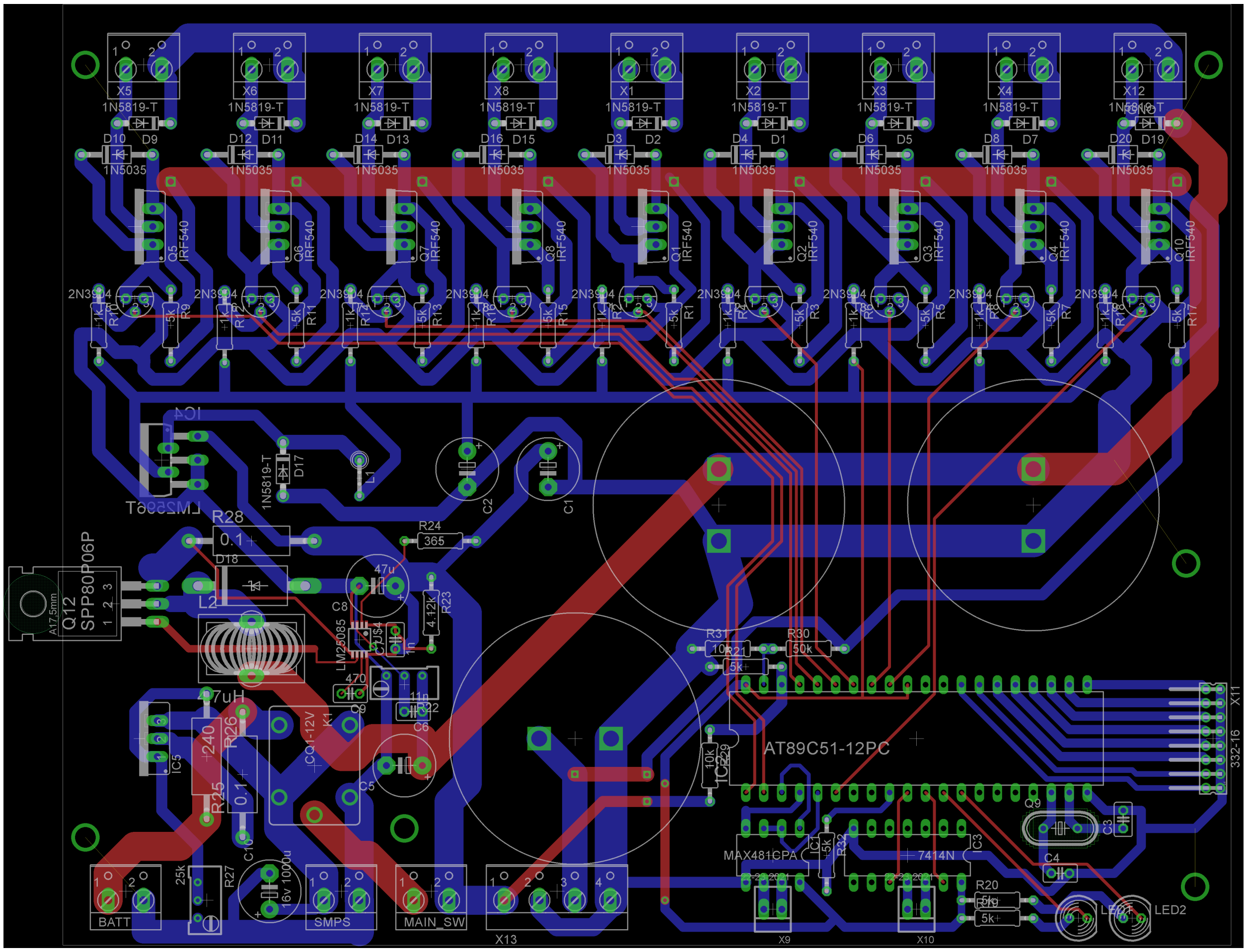


Figure 28: Command and Control System Receiver Layout

1.5V and the 5V regulator only dissipates up to 1W of heat. The total heat generated by these three components are approximated to be:

$$Pth = (1-0.925)\times 10A\times 12V + 1.5V\times 5A + 1W \approx 17.5W \tag{5}$$

To keep the components in the optimal operating range of 60°C or under, the allowed temperature rise should be capped off at 30°C.Given that the Junction to Case Thermal Resistance of the TO-220 package is 2.0°C/W, three of which share one heat-sink, the entire package would yield a total JtC of $0.6666°C/W$. The 17.5W of power dissipation already causes a 10.5°C rise. Thus, the heat-sink is only allowed to cause 20°C of additional temperature rise while radiating 17.5W of power. The Case to ambient Thermal Resistance of this heat sink must be lower than

$$R_{th,max} = \frac{20°C}{17.5W} = 1.15°C/W, \tag{6}$$

Therefore, the heat-sink attachment required for this circuit has to have a Case to Ambient Thermal Resistance of 1.15°C/W or lower.

5.1.1 Electronics Design of the Operator Interface (Control Box)

The Operator Interface is designed to meet the following design parameters:

- Switch inputs from all 9 actuatable channels
- LED status feedback for 8 channels of Pneumatic Ball Valve
- Serial Communication with Colossus
- Intact modular design with portable power unit
- Basic UI utilizing a LCD display

According to the given parameters, the Control Box is designed with a similar processor module and a similar but scaled down Power Management System as that of Colossus.
The control box will include an AT89C51 Microcontroller for processing, a MAX482 IC for RS-485 communication buffering with the Colossus, a 1602 LCD module for displaying system information, and switches and LEDs connected directly to the MCU's I/O. For the sake of simple modification and installation to the panel, all user related components are installed on a piece of PCB that is mounted directly to the top panel. All analog and digital electronic circuits are mounted on a separate piece of PCB located right below the interface board, connected to said interface board via an array of pins and sockets.(Figure.29)

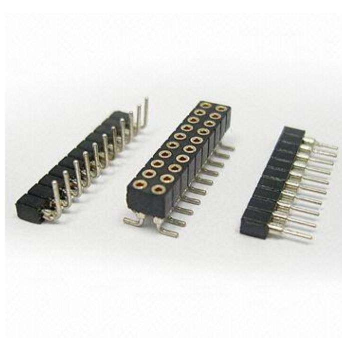


Figure 29: Pin and Socket Connectors

User Interface Board

To implement the interface parameters, the following schematic (Figure 30) was created along with the PCB layout (Figure 31) of the interfacing components. Switches, indicators and a display will be permanently installed onto this board (all together mounted on a plastic panel)

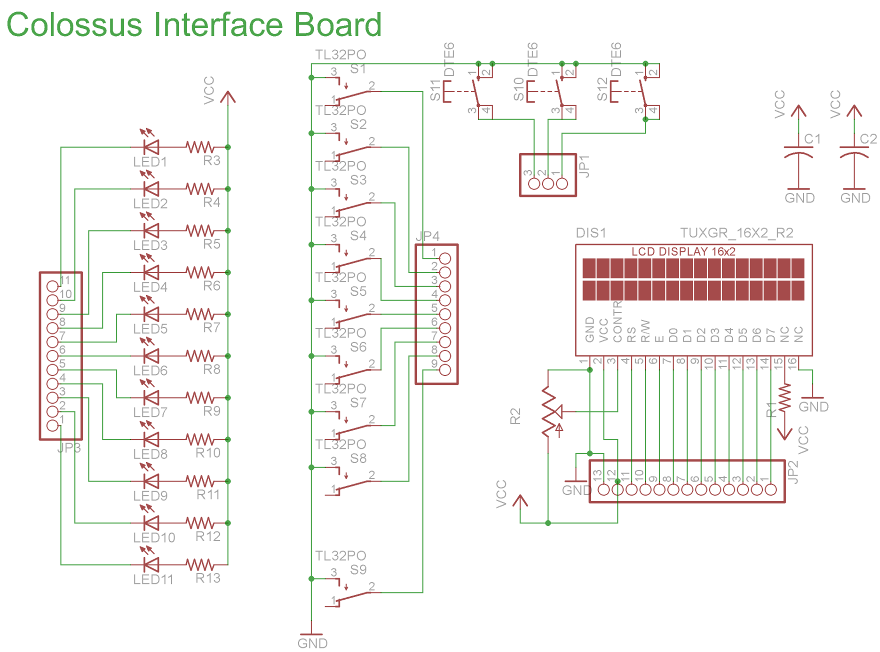


Figure 30: Interfacing Board Schematics

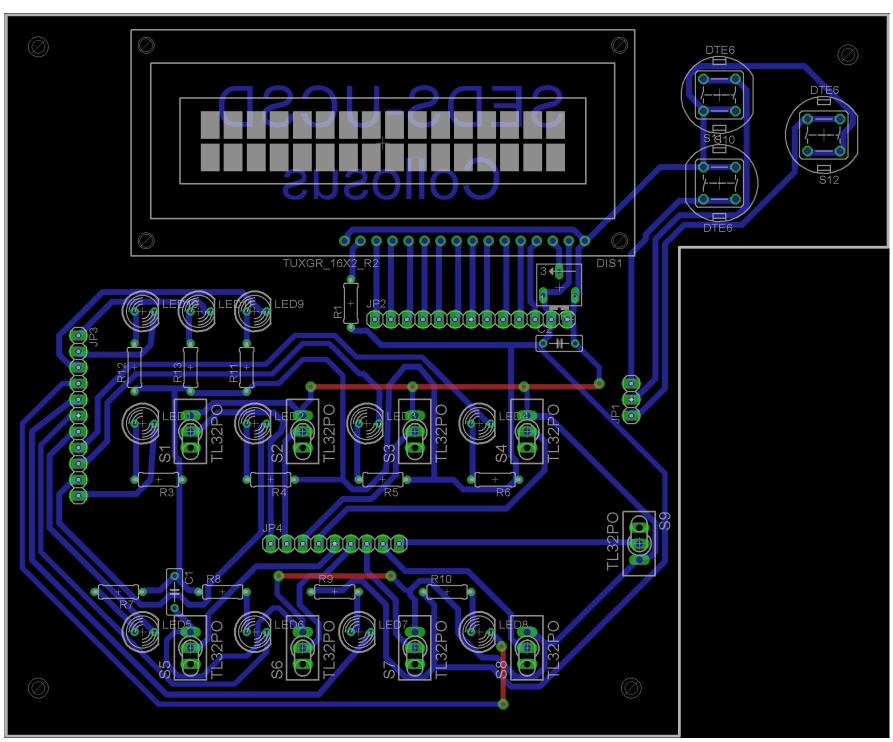


Figure 31: Interfacing Board Layout

As shown in Figure 31, three User Interface buttons are located to the right of the LCD to navigate the User Menu and confirm actions. Three LED indicators are located right below the LCD, each which indicate power, communication, and automation status. The exact interpretation of the modes of operation for these LEDs are covered in Section 6.

Logic Board

The Logic board of the Control Box carries the MCU, connectors to the Power Management System, and the communication buffer to the test stand. The schematics and layouts can be seen below in Figure 7 & Figure 8

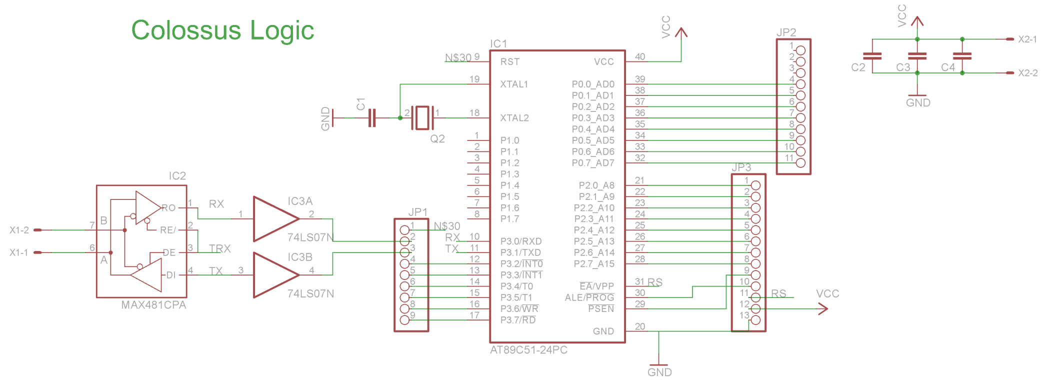


Figure 32: Interfacing Board Schematics

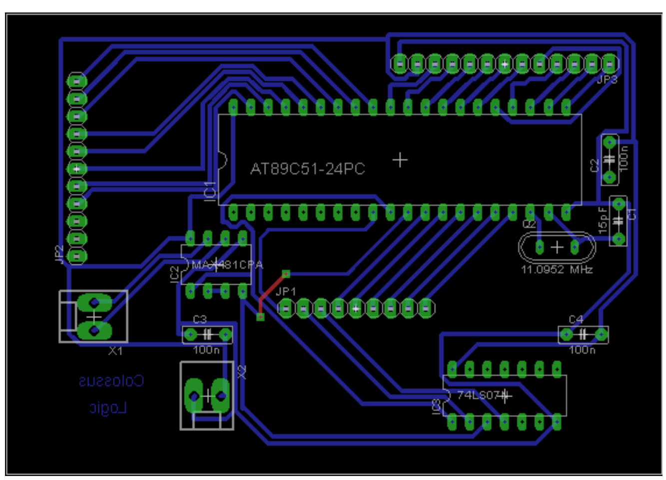


Figure 33: Interfacing Board Layout

Note that both board are designed as one-sided PCBs with a few jumpers for the ease of prototyping in-house.

5.1.2 Housing Design of On Board Electronics

The on-board electronics are housed in a box that has two sides with hinged doors, an air inlet and outlet, and a port for the limit switches. The air inlet is located adjacent to the heat-sink, allowing maximum air flow though the machined aluminium block. The air outlet also serves as a fan port for this boxed unit, and a fan would be used to sustain a slight amount of suction to keep the hinge doors closed.

Graphics/Electronics/CAD_Colossus.png

Figure 34: CAD Model of the Command and Control Receiver

Graphics/Electronics/CAD_Col_PCB.png

Figure 35: CAD Rendering of the PCB (Components are partially inaccurate)

5.1.3 Housing Design of the User Interface

The system will be housed in an acrylic box for the ease of creating panels and mounting connectors. Connectors for the AC power cord and the Coaxial terminal are also created on the front side of the box. Box assembly and panel design can be seen in the figures below.

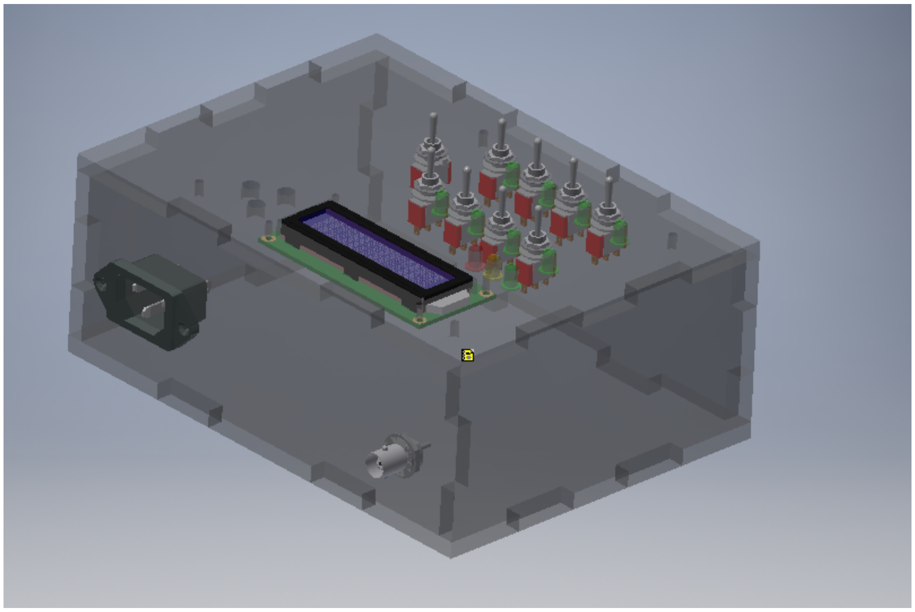


Figure 36: CAD Model of the Control Box

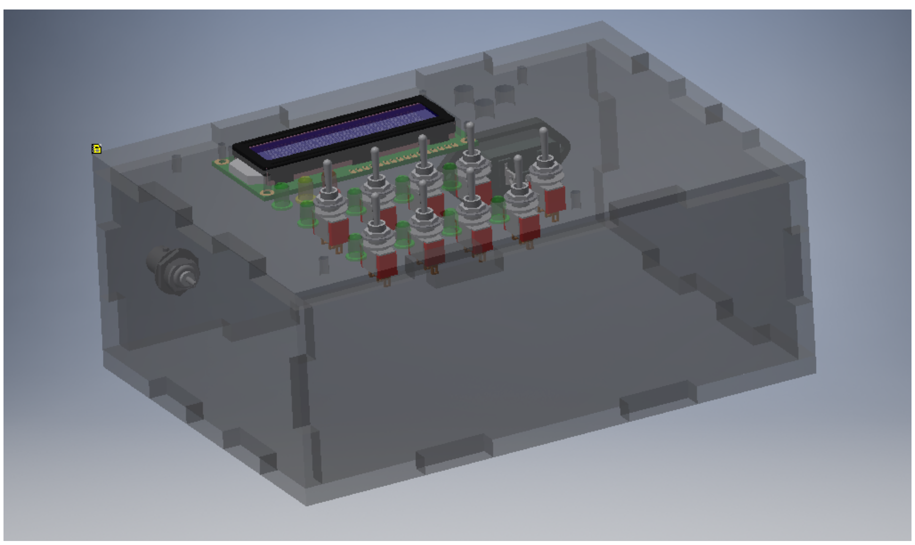


Figure 37: CAD Model of the Control Box Showing the Cable Connectors

5.2 Data Acquisition System

Colossus has a extensive network of sensors deployed around the system. These sensors will provide us with real-time temperature, pressure, and force data from various components of the teststand. Tab. 19 shows all of sensors that will be installed.

PNID P/N	Measurment
Pressure Transducers	
PT-FU-223	P Venturi Out, Fuel
PT-OX-323	P Venturi Out, Ox
PT-FU-222	P Venturi In, Fuel
PT-OX-322	P Venturi In, Ox
PT-N2-122	LOX Purge Pressure
PT-N2-121	Kerosene Purge Pressure
PT-N2-321	LOX Tank Pressure
PT-N2-221	Kerosene Tank Pressure
PT-N2-220	Fuel side Regulatur Pressure
PT-N2-320	LOX Regulator Pressure
PT-N2-120	Purge Regulatur Pressure
PT-N2-123	K Bottle Pressure
Thermocouples	
T-FU-292	Kerosene Line Temperature
T-OX-392	LOX Line Temperature
T-FU-291	T Venturi Out, Fuel
T-OX-391	T Venturi Out, Ox
T-FU-290	T Venturi In, Fuel
T-OX-390	T Venturi In, Ox
T-FU-293	Kerosene Tank Temperature
T-OX-393	LOX Tank Temperature
Load Cells	
LC-OX-300	Oxidizer Tank Weight
LC-FU-200	Propellant Tank Weight
LC-100	Axial Thrust
LC-101	Y-thrust deflection
LC-102	X-thrust deflection

Table 19: List of Sensors

In order to acquire quality data from these sensors, a reliable and high fidelity data acquisition system is needed. Colossus will employ a NI cDAQ system to acquire test data. A 8 slot USB cDAQ system is chosen to stream data to the on-board PC via the NI LabVIEW backbone with the NI TestStand add-on. The current part selection includes:

NI cDAQ-9178 CompactDAQ Controller, 8-Slot USB Chassis

NI 9237 ± 25 mV/V, Bridge Analog Input, 50 kS/s/ch, 4 Ch Module

Handles input from the load cells below the scale, and behind the engine interface.

NI 9213 ± 78 mV, Thermocouple Input, 75 S/s, 16 Ch Module

Handles all Thermocouples on board

NI 9206 ± 200 mV to ±10 V, Analog Input, 250 kS/s, 32 Ch Module

Handles all Pressure Transducers on board

NI 9403 5V, TTL Input Digital I/O 32 Ch Module

establishes parallel communication with command and control system

Figure 38: National Instruments cDAQ-9178 Chassis

5.2.1 Instrument Enclosure

In order to thermally protect the sensitive electronics on the cDAQ system, and to provide optimal operating conditions, the entire instrumentation block will be housed inside of an insulated enclosure with active refrigeration. The cooling mechanism will use a peltier cooling system. Two opposing heatsinks will be used, one to accept ambient air and another to transfer cooled air into the insulated container. The temperature change will be achieved by the active peltier cooling system. This works best when the temperature differnece is low.

Lastly, since the heatsink will be colder than the ambient temperature of the desert, water will inevitably condensate even though the native humidity is very low. This naturally creates a threat for onboard electronic systems. Water formed from condensation will be collected and funneled out of the enclosure before it poses any functional threat. Condensation will not appear on the electronics themselves however due to the very slow drop in temperature.

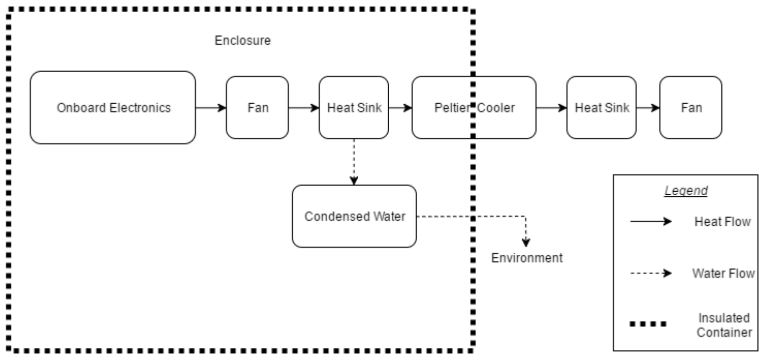


Figure 39: Instrumentation Enclosure Overview

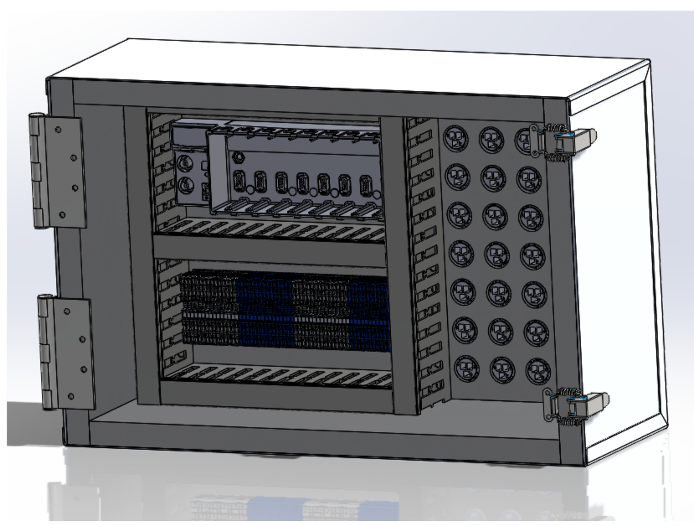


Figure 40: CAD Model of Enclosure

The main structure of the cooling system consists of 1/16 thick 6061 aluminum sheets that will be bent and bolted together. The door to the instrumentation system will be tightened by two corner mount draw-latches. The interior of the system will be surrounded by 1 inch thick insulated sheathing to provide thermal insulation from the environment. This material has an R-value of 3.85 at room temperatures (22C - 24C).

Thermaflect tape will be adhered to the outside of the container. This tape will assist in the cooling since it will slow down the heating by reflecting up to 90 percent of radiant heat away.

All components placed in the fridge will be mounted to one of two 35mm din rails laid out horizontally on the back wall. The cDAQ will be mounted on the top DIN rail, while 60 4-connection terminal blocks will be mounted on the lower one. Each din rail will be surrounded by 1 inch wide,

TEC1-12710

Performance Specifications

Hot Side Temperature (º C)	25º C	50º C
Qmax (Watts)	85	96
Delta Tmax (º C)	66	75
Imax (Amps)	10.5	10.5
Vmax (Volts)	15.2	17.4
Module Resistance (Ohms)	1.08	1.24

Figure 41: Peltier Cooler

3 inches tall slotted wire ducts to accommodate the wiring. All incoming and outgoing connections will be handled by three different types of connectors on the back of the system. 24 3-pin 206036-2 CPC Connectors for pressure transducers, 4 4-pin 206061-1 CPC Connectors for load cell connections, and 12 2-pin Connectors, for K-type thermocouples.

The Peltier (41) units consist of a hot side and a cold side, these are the specifications of the selected Peltier cooler. This information is critical to performance estimations.

To obtain optimal cooling on the hot side, a corsair H60 will be used for each Peltier (42). This all in one liquid cooling system is traditionally reserved for computer CPU's which can easily reach loads greater than 150 Watts. The systems come with fully integrated water blocks, tubes, pumps, and radiators. Higher airflow fans will be purchased to maximize cooling potential. It is critical that the temperature of the hot side approaches ambient temperature, this way the lower temperature threshold will be as low as permitted by the Peltier. The water cooling system will also be colored white to minimize heat absorption.

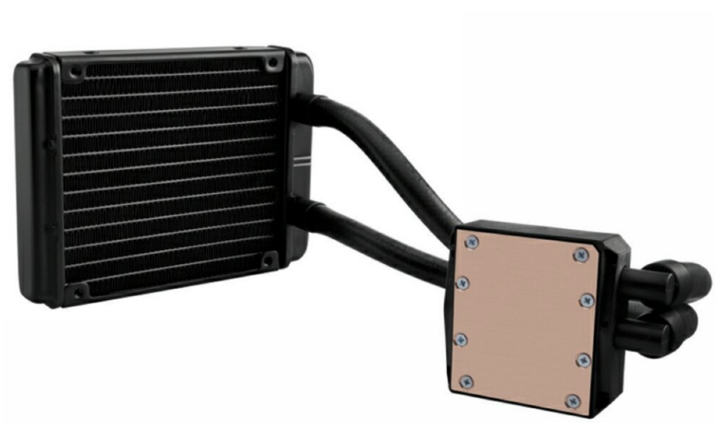


Figure 42: Self Contained Water Cooler

Figure 43: Internal Heatsink Attached to Cold Side of Peltier

The optimal voltage and amperage to operate the peltier at has been provided by the manufacturer. See (44) for efficiency curves with a hot side of temperature 50C. 40C of Delta T is optimal for this project, the target voltage and amperage is 10.5Vvolts and 9Amps respectively.

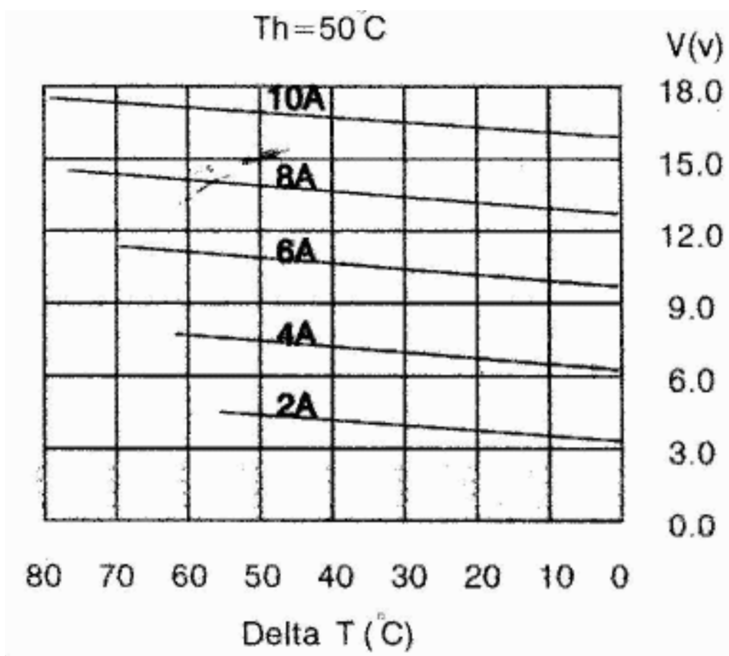


Figure 44: Efficiency Curves for Peltier provided by manufacturer

Lastly to minimize power consumption, the Peltier coolers, water pumps, and fans will only be turned on when the temperature of the interior is reported above some temperature threshold. If the temperature is reported to be below another much smaller temperature threshold then the system will turn off to preserve power. Since no insulation is perfect, the temperature will slowly climb toward the higher threshold ; at which point the cooling systems will turn on once more. See (45) for a general demonstration of this principle.

For example, at time 0 the interior could be at ambient temperature, which means the system

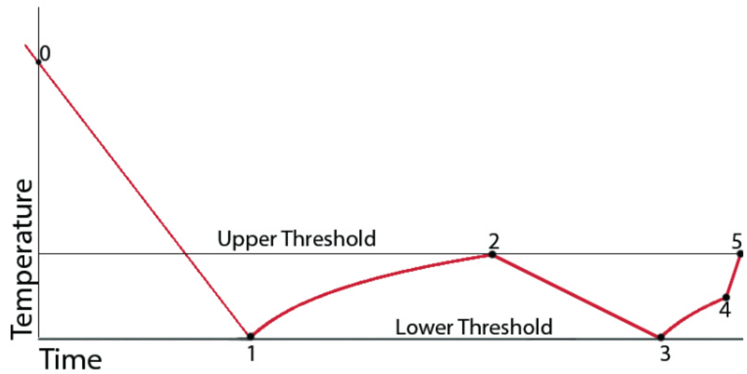


Figure 45

will turn on. Gradually the temperature will fall to the lower threshold at time 1. Afterwards the temperature will slowly climb until it reaches the upper limit and the cycle repeats. Time 4 is an example of opening the system, thereby exposing it to much more heat.

5.3 Communication

5.3.1 Inter-instrumental communication

Frequent status reports need to be transmitted from the DAQ system to the Command and Control System on board. For every 250ms, a packet of crucial system performance data is sent to the Command and Control microprocessor to aid its decision making in its automation function. This data is transmitted via a secondary UART port on the DAQ and patched to the C&C MCU via a twisted triplet. This communication is bidirectional and will employ a standard handshake protocol and checksum to ensure data integrity.

5.3.2 Ethernet(Cat 5e) Cable

The communication between the on board PC to the operator station computer is carried out via a single segment of Cat 5e cable. The safe operating distance of Colossus is set at 250ft, which is within the effective range of Cat 5e cable regulations (100m) without having to implement active repeaters. For plan A, this cable would be the only cable running between the bunker and the system, carrying both control and command and data acquisition signals.

5.3.3 Coaxial Cable

As for the custom system, a two-conductor coaxial cable is required to carry communication signals. Standard RS-485 differential communication protocol is utilized to preserve maximum data integrity while keeping the cord count to as low as 2. As specified in the EIA standard, the data rate on a RS-485 bus can go as high as 100kb/s within a range up to 4000ft. In order to accommodate the need to achieve half duplex communication, the effective duty cycle of each direction is adjusted to 25% with 25% of dead time for the bus to neutralize, yielding an effective 25kb/s duplex data transfer rate. The differential output that is connected to the shield of the coax cable is biased with low output impedance, and coupled to earth ground with a Y safety capacitor to prevent excessive charge building up on the transmission line.

5.4 Power Management

5.4.1 Power supply of the operator instruments

For the custom control box:
There will be a temporary battery power unit designed into the control box for the ease of field testing and leak checking. However, during the ignition sequence, it is required for the control box to be plugged into a 120V wall outlet with an 5v DC adapter. The batteries on board exist as a redundancy system.

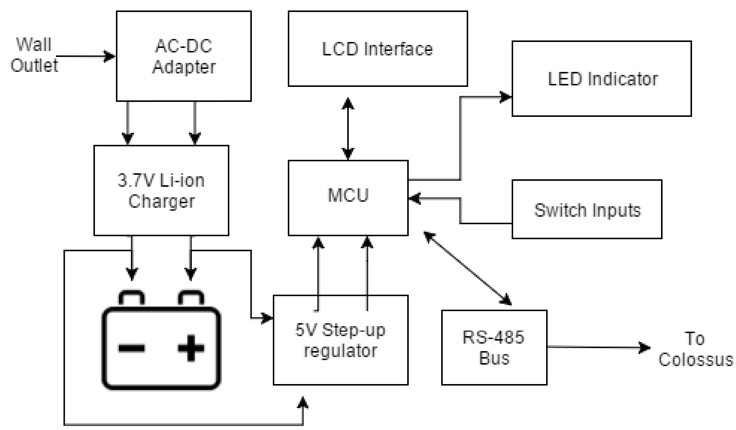


Figure 46: Control Box Power Distribution System Block Diagram

5.4.2 Power supply of the on board instruments

The Colossus test stand consists of two power rails, 120VAC rail to power the air compressor, and a 12-15V LV rail to power the instruments and actuators.
The main low voltage power rail of Colossus is powered by a system that consists of a 600W SMPS and a 12V car battery. These battery units will be mounted onto a detachable tray on the bottom shelf of Colossus for maintenance and charging. The power system distribution block diagram can be seen below.

The air compressor on board draws up to 15A of nominal current. At surge, the HVAC rail can draw up to 2000W of power. To supply power to this rail when external power is absent, a inverter capable of outputting 2500W of power is needed.

LV DC-DC module design parameters: The three LV active loads (Solenoids Array, PC and DAQ) of Colossus draw up to 300W of power when operating. Assuming the average rail voltage is set at 15V, the maximum nominal current is approximated to be 20A. The main Relay (CQ1-12V)

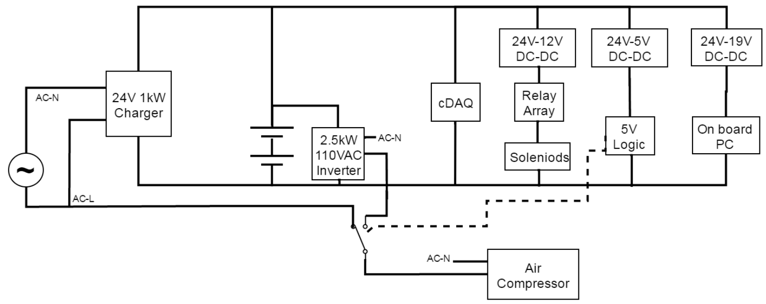


Figure 47: Colossus Power Distribution System Block Diagram

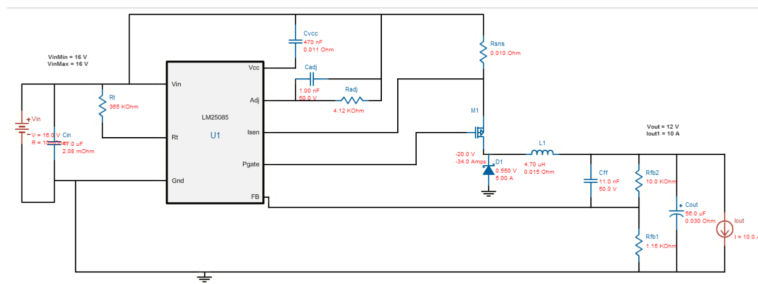


Figure 48: Output From TI PowerBench Design Aid

bridged to select the source of power to the main rail is rated to have a nominal contact current of 20A. The coil of the relay is connected at the 15V power supply output. Though the coil is rated to operate at 12V, loading on a 15V rail will raise the initial heat dissipation of

$$P = \frac{12V^2}{225\Omega} = 640mW, \tag{7}$$

to

$$P = \frac{15V^2}{225\Omega} = 1W, \tag{8}$$

which is within the acceptable range. If heating of the coil becomes a problem in the future, a diode can be easily added to the branch to remove 0.7V of potential from the coil, lowering the power consumption.

The 15-12V Regulator is set to be built on the main PCB. The circuit parameters are determined using the Texas Instruments PowerBench. This converter is rated to have a maximum output current of 15A at 12V.

The 15-24V Step-up Regulator is going to be a COTS component (see parts list). It is rated at 150W with 90% efficiency.

All power rails converge on the main PCB for monitoring and controlling purposes.

System Run-time Optimization & Battery Unit Sizing: Assuming the worst case scenario, the system will constantly induce a 20A load on the battery. Typically, a cold flow test would stress the system up to 8 hours to complete. To ensure power availability, Colossus would require a battery bank that holds 8hr*20A=160Ahr of charge. However, the cold flow procedure typically only requires the solenoids and DAQ to be activated about 20% of the time. Therefore, with normal amount of usage, Colossus should be able to realistically operate up to 40hrs in one charge.

The Charging Unit for the battery has a maximum output current of 5A. The charge cycle of the entire system can take up to

$$T = \frac{160Ahr}{5A} = 40hours, \tag{9}$$

to complete.

Incase of an immediate need to use the system, it is recommended to remove the batteries from the system and charge them externally. Otherwise, the built in charger itself can handle the normal maintenance cycle of the power system without human interactions.

Predicted Power Consumption and Power Supply Sizing(With Power Redundancy Safety Factor of 1.5): When Colossus is operating, there are 3 main loads that need to be taken into consideration when selecting the power supply: the solenoids on the 12V Rail, the cDAQ controller on the 24V Rail, and the Battery Charger loaded directly at the SMPS. To ensure the safety of the system and the performance of the instruments, a properly sized power supply is essential. The following analysis is conducted based on the assumption where all components are drawing maximum power.

12V Rail: Assuming all solenoids on: 11.65W each

$$P_{SSRA} = 8 \times 11.65W = 92.2W, \tag{10}$$

16v-12v DC-DC Efficiency: 95% Maximum Power Draw on 12V rail:

$$\frac{92.2W}{0.95} = 97.4W, \tag{11}$$

16v-12v DC-DC Power requirement

$$97.4W \times 1.5 \approx 150W, \tag{12}$$

24V Rail cDAQ factory packed power supply is rated at 24V, 5A Max Power draw:

$$24V \times 5A = 120W \tag{13}$$

*Factory parameter already had safety factor accounted for, therefore it is necessary to add extra room for chance of failure 15V-24V DC-DC efficiency 90Power requirement

$$Preq = \frac{120W}{0.9} = 134W \tag{14}$$

Battery Charger

LM338 limits current at 5A

Maximum charging voltage is obtained by subtracting the minimum voltage drop of LM338 from V_{supply}

$$V_{chg,max} = 15V - 1.2V = 13.8V, \tag{15}$$

$$P_{chg,max} = 13.8V \times 5A = 69w \tag{16}$$

$$P_{sys,min} = 69W + 134W + 150W = 353w \tag{17}$$

Therefore, any SMPS rated at 353W or more would be safe to use for Colossus

Colossuss power system is designed to handle the three following states of operation:

Plugged In To 120AC

Colossuss main relay will automatically switch to drain from the SMPS when its connected to a 120V AC outlet. The battery bank will cease to supply power and will be charged. The main rail will have a constant voltage of 15V.

Stand Alone

The relay will be be toggled to the off position. The battery begins to supply the main rail, which will provide a voltage range of 11.5-13.8V.

Transient of Switching

In case of power loss or disconnection of the system from the AC grid, Colossus will have to be able to automatically switch to its on-board power supply without discontinuation of power. However, the relay pin will be traveling through a non-contact region when it switches from a contact to another. This parameter is given in the datasheet, denoted as the operating time. The CQ1-12v series has an operating time of 3.5ms. Taking safety factor into account, we assume that the worst case scenario would result in needing 20ms to actuate. The solenoids array has a combined equivalent impedance of 1.5 ohms when fully loaded. With the assumption that the solenoids have the potential to drop out at 75% of the normal operating voltage, which is 12*0.75=9V, we will have to make sure that the RC discharge curve spans the drop from 12V to 9V over the minimal

period of 3.5ms.
Knowing the equation:

$$Vc = Vs \times e^{\frac{-t}{RC}}, \tag{18}$$

$$ln(\frac{Vc}{Vs}) = \frac{-t}{RC}, \tag{19}$$

$$RC = \frac{-t}{ln(\frac{Vc}{Vs})}, \tag{20}$$

$$C = \frac{-t}{R \times ln(\frac{Vc}{Vs})} = \frac{-0.02s}{1.5R \times ln(\frac{9V}{12V})} = 0.0463F \tag{21}$$

Which can be made up from two independent 16V 22000uF Capacitors

5.4.3 Grounding

The entire chassis of Colossus is required to be grounded to the earth via an external grounding rod. This will prevent ESD build up on the system, providing a safe operating environment for workers and eliminating the chance of electrical breakdown of the communication buffers on the RS-485 bus or Ethernet transceivers.

5.5 User Interface

5.5.1 Indicators and Interpretation

LED indicators on board of the system and the UI are reliable sources of system performance information. The color of the indicators and the interpretation of each LED indicator is listed below.

Control Box: Solenoid Indicators(x8):

- OFF: Solenoid at default
- Flash green: Actuation request sent
- Solid green: Actuation complete

Automation:

- OFF: System in manual
- Solid green: System in automation
- Slow flash green: System in automatic but
- Fast flash green: System in abort sequence

Communication:

- Latched (solid dark or solid yellow): Rx non-receiving
- Flashing yellow: Tx & Rx nominal

Power:

- Solid red: Power ON and nominal
- Flashing red: Internal battery unit low, charge immediately
- OFF: Power OFF

Colossus Command & Control: RS485 Communication:

- Latched (solid dark or solid yellow): Rx non-receiving
- Flashing yellow: Tx & Rx nominal

RS232 Communication:

- Latched (solid dark or solid yellow): Rx non-receiving
- Flashing yellow: Tx & Rx nominal

Power:

- Solid red: Power ON and nominal
- Flashing red: Internal battery unit low, charge immediately
- OFF: Power OFF

5.5.2 LCD UI Error Messages

The Control Box employs a LCD user interface system. The system is designed to report the following error
messages based on the information collected via the DAQ and the limit switches:
E00: System communication interrupted
E01: Over pressurization: Propellant
E02: Over pressurization: Oxidizer
E03-x: Over pressurization: Injector port x
E04: Engine temperature anomaly
E05: Oxidizer weight loss
E05: Propellant weight loss
E06: LOX flow rate anomaly
E07: RP Flow rate anomaly
E08-x: Solenoid #x actuation failed
E09: DAQ communication failed
E10: Power rail anomaly
E11: Electronics overheating

5.6 Software

5.6.1 LabVIEW

For the software implementation of this system we will use LabVIEW as our main interface. LabVIEW is preferable because it is a very robust and easy to manage platform due to it being a graphical programming language. LabVIEW also follows the Dataflow programming paradigm, meaning that it maps each process as a directed graph of data. Therefore, LabVIEW easily lends itself to concurrency/multiprogramming, allowing multiple processes/dataflows to run on seperate cpu's at the same time. This means that LabVIEW can enable very fast and efficient data acquisition.

5.6.2 Embedded Firmware

The system will use micro-controllers to govern the limit switches and control the Solid State Relay Array on-board. The micro-controllers will be used as the back-end of the Control Box to control to perform the desired task when the corresponding switch is flipped. These micro-controllers will then report it's status through the NI cDAQ, to the on-board PC tower, and by illuminating the corresponding LED. Refer to Fig. 26 for more detail. To program the micro-controllers we will use both UART and LabVIEW's Microprocessor SDK.

5.6.3 GUI

For the Graphic User Interface we will be creating a custom dashboard to display all of the data we collect from the system (thrust gauge, pressure graph, etc.) on an external PC, in real time. This allows us to have an independent PC tower on-board the system continuously acquiring and storing data. Porting the tower on-board will also allow for data redundancy in the case of any unexpected system failure or damage.

This will be achieved running LabVIEW's TCP/IP communication protocol on the PC tower to send all of the information it collects from the system, in packets, to the external PC via Ethernet. The external PC will process each packet of information and plot the information received on the corresponding graph or gauge on the dashboard. Running a real-time dashboard will allow us to monitor exactly what is happening during the static-fire and prevent system damage if some of the data is transient and/or outside of the necessary parameters for a safe static-fire with our system.

6 Standard Operating Procedures

6.1 Command and Control and DAQ System Preparation

Prior to any controlled operation of Colossus, proper installation of the entire electronics system is required. Before executing the following procedure, ensure that the Command and Control Receiver Unit on board is fully internally wired to the test stand. Details of the internal wiring of Colossus are outlined in section 3.3.

☐ 1. If AC power is available at the site of installation, plug Colossus into a 120AC outlet

☐ a. In the absence of AC power, measure the voltage on the battery to gauge charge, then proceed to the next step

☐ 2. Connect the coax cable from the test stand to the Control Box in the Bunker

☐ 3. Connect the Ethernet cable from the test stand to the laptop in the bunker

☐ 4. Turn ON the Main Switch and the DAQ switch

☐ 5. Plug in the Control Box to an outlet and turn the Main Switch ON

☐ 6. Monitor the communication indicator on the Colossus CnC Receiver and on the Control Box

☐ 7. Run LabVIEW and verify DAQ system status

☐ 8. After confirming system operational, Power OFF DAQ, toggle all solenoids to OFF

6.2 Leak Check

Leak checking includes applying snoop (soap solution) to the threads, inlets, and outlets of various fittings and instrumentation. Check to see if bubbles are continuously forming and clearly indicate a gas leak if there are. If the connection is leaking, wipe off the snoop with a rag and wrench-tighten the fitting. Repeat leak check until leaks no longer exists. Also, any personnel in the vicinity of the system must be wearing safety glasses if any of the lines are pressurized. Leak checking is implemented in two steps in order to inspect the low and high-pressure lines separately. The leak check should be monitored in LabVIEW as a redundancy check of the performance of the Command and Control System as well as the Data Acquisition System.

*Note that the engine should not be attached to the system during leak check procedures

Compressed Gas Lines (low pressure lines)

☐ 1. Put on safety glasses and make sure everyone is wearing them as well

☐ 2. Turn ON DAQ and enable data monitoring in LabVIEW

☐ 3. Turn ON Control Box

☐ 4. Dial up the twist knob regulator on the air compressor to 50 psi

☐ 5. Leak check connections prior to the solenoids (SV-CG-450 through SV-CG-453, and SV-CG-550 through SV-CG-553)

☐ 6. Leak check lines between solenoids and pneumatic actuators (all PBVs). If any pressure exists in the line diagnose functionality of solenoids and repair them

☐ 7. Using control box, power ON solenoid SV-CG-x5x

  ☐ a. Observe actuation of the corresponding pneumatic actuator (PBV) and ensure ball valve rotates 90°. Leak check valve

  ☐ b. Using control box, power OFF this solenoid

☐ 8. REPEAT procedure for remaining 7 solenoids

☐ 9. Leave compressed air lines on

☐ 10. Manually restore the original positions of the pneumatic actuators

☐ 11. Review pressure transducer data for any discrepancies

Gaseous Nitrogen Lines (high pressure lines)

☐ 1. Ensure that the fittings for the attachment of oxidizer and propellant are capped and sealed

☐ 2. Confirm HLR-N_2-100, HLR-N_2-201, and HLR-N_2-301 are at minimum 0 psi output

☐ 3. Slowly open N_2 K-bottle. You should hear a quick jet of air indicating line pressurization

  ☐ a. Leak check CGA fitting, and turn OFF immediately if leaking

☐ 4. Slowly turn up HLR-N_2-201, and HLR-N_2-301 both to 50 psi

☐ 5. Leak check all pressurized lines prior to valves PBV-N_2-250 and PBV-N_2-350

  ☐ a. Monitor pressure gauges for any obvious drops in pressure

☐ 6. Actuate (vents) PBV-N_2-251 and PBV-N_2-351 to closed position

☐ 7. Using control box, actuate SV-CG-450 and SV-CG-550 solenoids to actuate press ball valves to open

  ☐ a. Tanks are now pressurized

  ☐ b. Leak check all fittings on top of tanks

  ☐ c. Leak check all fittings between the bottom of tanks and main valves PBV-FU-253 and PBV-FU-353

☐ 8. Slowly turn up HLR-N_2-100 to 50 psi

  ☐ a. Leak check all fittings in the purge lines up to PBV-N_2-150 and PBV-N_2-151

☐ 9. Shut off N_2 K-bottle

☐ 10. Retreat to a safe distance away from system (i.e. bunkers)

☐ 11. Using the control box, open PBV-N_2-351, PBV-**N2**-251 (Vent) ,PBV-FU-253, PBV-OX-353 (Main), PBV-N_2-150, PBV-N_2-151 (purge line)

☐ 12. Leak check complete

☐ 13. Using the control box restore all valves to natural state

☐ 14. Review pressure transducer data for any complications

6.3 Abort Procedures

To ensure the safe execution of a manual operation, a dedicated observer will be designated to watch over the smooth progression of the testing procedure. In case of an anomaly, the observer is authorized to command the operator to cut the test sequence and abort test. These procedures are done by going through sequences on the control box with the exception on the post-pressurized abort procedure. This procedure is performed by pressing a single button that will automatically start up the abort procedure.

Abort Procedure During Fill

☐ 1. In the event of a severe leak immeadiately cease filling procedure by shutting off the dewar or fill tank valve

☐ 2. In the case of pooling LOx allow it to evaporate away

☐ 3. In the case of pooling fuel wrench tight the leaking fitting and clean excess fuel with a rag

☐ 4. Continue with Filling procedure

Manual Abort Procedure Post-Pressurizing System

☐ 1. Operator yell ABORT

☐ 2. Open PBV-N_2-351, PBV-N_2-251 (vent)

☐ 3. Close PBV-FU-253, PBV-OX-353 (Main S/O)

☐ 4. Open PBV-N_2-151, PBV-N_2-150 (purge)

☐ 5. Allow all nitrogen from the k-bottle to be released

☐ 6. Close PBV-N_2-250, PBV-N_2-350 (press)

☐ 7. Check tank liquid level, pressure, and temperature via DAQ

☐ 8. Data analyst gives ALL CLEAR to operator when all system parameters return to nominal according to DAQ readings

☐ 9. Operator yells ALL CLEAR

☐ 10. Close PBV-N_2-151 and PBV-N_2-150

☐ 11. Technicians return to system and shut off N_2 K-bottle hand valve and then assess system

6.4 Auto-Abort for Post-Pressurization

☐ 1. Operator yell ABORT, press the emergency abort button on the control box

☐ 2. Automation LED should quickly flash green

☐ 3. Press, main, purge and vent valves will be automatically placed into the position detailed in 'Detailed Abort Procedure', abort sequence comes to a halt once these commands are executed

☐ 4. When system ceases all events (liquid flow/ flame), press OK button on the UI

☐ 5. Purges will continue to discharge for 30 seconds

☐ 6. LabVIEW UI will automatically analyze sensors information and give an ALL CLEAR to the operator

☐ 7. Operator yells ALL CLEAR

☐ 8. Technicians return to system, shut off K-bottle hand valve and assess damage

6.5 K-Bottle Exchange

Prior to the fill procedures for either Cold Flow or Hot Fire, the operator needs to ensure that the K-bottle is to capacity.

Pre-fill K-bottle Preparation:

☐ 1. Before any pressurization begins ensure HLR-N2-10, HLR-N2-201, and HLR-N2-301 are all at minimum 0 psi output

☐ 2. Confirm PBV-N_2-250, PBV-N_2-350 are closed

☐ 3. Turn ON K-bottle hand valve

☐ 4. Read pressure from PT-N_2-123, and PG-N_2-130 if the reading is below 2000 psi, execute K-bottle exchange procedure

☐ 5. Before removing the CGA connection increase any of the three regulator's output by 500 psi and decrease to 0 psi to vent the line

☐ 6. Repeat this step until the input gauge on the regulator reads 0 psi

K-bottle Exchange

☐ 1. Tightly shut off K-bottle hand valve

☐ 2. Remove CGA fitting from the K-bottle, be sure to counter-torque

☐ 3. Open the latch on the port side of the system

☐ 4. Operators remove and exchange the K-bottle (be sure to keep vertical) with a new one

☐ 5. Close latch

☐ 6. Store ALL K-bottles vertically upwards, secured to a rigid structure at the top of height to prevent falling.

6.6 Engine Installation

☐ 1. Make sure steel blast plate is free of debris, and ready to be mounted to

☐ 2. Remove engine from lock box, and prepare combustion chamber alignment with fuel plumbing line

☐ 3. Remove injector from lock box, and insert O-Ring into O-Ring groove

☐ 4. Align injector flange against flange of combustion chamber, where the back of the injector flange is flush against the steel plate

☐ 5. Insert bolts in a star shaped format from the front of the plate to the back, having the nut on the backside

☐ 6. Tighten to specified torque rating based on engine, but do not perform final tightening until all bolts are moderately tight (see Lead Engineer)

☐ 7. Perform final tightening of bolts

☐ 8. Install pressure transducers using teflon tape as a leak stop mechanism, and be careful to not over-tighten

☐ 9. Engine installation complete

6.7 Cold Flow

Cold Flow Tests are the best way to emulate all parameters of an actual hotfire test. A Cold Flow test is recommended to be performed before every hot-fire test to ensure system test readiness. Instead of Propellant and Oxidizer, Isopropyl Alcohol and Cryogenic Liquid Nitrogen is filled into the system. Note that the purge line should contain positive pressure during the entire test sequence, (including fill).

6.7.1 Isopropyl Alcohol Fill

Note: Isopropyl Alcohol (IPA) is used in place of Fuel because it cleans the internals of the plumbing system while simultaneously acting as a mock propellant during cold flow.

☐ 1. Make sure small fill tank is clean and free of dust or dirt, and that hand valve is closed

  ☐ a. If using a large container to fill Fuel Fill Tank, make sure container is clean as well

☐ 2. Use a funnel, fill Fuel Fill Tank with the same amount of IPA as fuel in the hot fire and re-seal the Fuel Fill Tank

☐ 3. Confirm PBV-FU-251 is open

☐ 4. Attach Vent Tube Extender

☐ 5. Using an Air Compressor, pressurize Fuel Fill Tank to 35 psi

☐ 6. Attach Fuel Fill Tank to MBV-FU-252 (Fill valve) and wrench tighten fittings

☐ 7. Open hand valve on Fuel Fill Tank

☐ 8. Open manual valve on Fuel Fill Tank slowly

  ☐ a. Allow all IPA to exit Fuel Fill Tank, into fuel line

☐ 9. Close MBV-FU-252

☐ 10. Disconnect Fuel Fill Tank from Fuel MBV-FU-252

☐ 11. Repeat steps 2-10 until all fuel required is filled

  ☐ a. Note: it is better to slightly exceed fuel fill (+1 quart) than to not add enough

☐ 12. IPA fill complete, remove Vent Tube Extender

6.7.2 Liquid Nitrogen Fill

☐ 1. Evacuate all personnel into bunkers, aside from Fill Operators

☐ 2. Ensure anyone involved or close to LN fill is wearing proper safety attire

☐ 3. Ensure there are necessary wrenches available during fill

☐ 4. Confirm PBV-N_2-351 is open

☐ 5. Attach Vent Tube Extender if needed

☐ 6. Attach Cryogenic hose line to LN Dewar and wrench tighten fitting, do not remove wrenches

☐ 7. Attach the same Cryogenic hose to MBV-OX-352 and wrench tighten fitting, do not remove 2nd set of wrenches

☐ 8. Slowly open LN Dewar

☐ 9. Slowly open MBV-OX-352

☐ 10. Actuate PBV-OX-353 for pre-chill

☐ 11. Chill until engine reaches -200 F

☐ 12. Shut off PBV-OX-353

☐ 13. LN tank is now filling. Entire fill should take anywhere from 45 minutes to an hour

☐ 14. LN fill is complete when liquid is pouring out of PBV-OX-351

  ☐ a. As redundancy check, T-OX-393, T-OX-390, and T-OX-391 should report cryogenic temperature

  ☐ b. As secondary redundancy check, read mass increment of the LOX tank via the load cell beneath

☐ 15. Shut off Dewar

☐ 16. Shut off MBV-OX-352

☐ 17. Loosen fitting on MBV-OX-352

☐ 18. Loosen fitting on LN Dewar

☐ 19. Remove Cryogenic hose

☐ 20. Remove LN Dewar from vicinity, and store in a safe place outside or in a well ventilated area

☐ 21. Evacuate all personnel into bunkers aside from regulator operator

☐ 22. LN fill complete

6.7.3 Manual Cold Flow Procedure

Manual Cold Flow Sequence is purposed to reveal any potential point of failure in the system, thus this test will NOT be handled by the Command and Control System automatically. Instead, the sequence is executed by the operator step-by-step.

*Note: If any actuation LED fails to report successful valve actuation, abort test immediately

☐ 1. Confirm Compressed Gas system online for solenoid actuation (assumed ON after fill)

☐ 2. Make sure HLR-N_2-301 and HLR-N_2-201, and HLR-N_2-100 are all at minimal pressure output

☐ 3. Confirm that PBV-N2-250 and PBV-N2-350 are in the closed position

☐ 4. Turn HLR-N_2-100 to 5psi and confirm with reading on PG-N2-131

☐ 5. Actuate PBV-N_2-151, PBV-N_2-150

☐ 6. Shut off PBV-N_2-351, PBV-N_2-251

☐ 7. Activate data logging via DAQ

☐ 8. Open hand valve on the K-bottle

☐ 9. Check Pressure reading via LabView, expect values:

  ☐ a. PT-N_2-120: Above 2000 psi, else replace K-bottle

  ☐ b. PT-N_2-121: 5 psi

  ☐ c. PT-N_2-220: 0 psi(Pmin on HLR-N_2-201)

  ☐ d. PT-N_2-320: 0 psi (Pmin on HLR-N_2-301)

☐ 10. Check Temperature reading, expect

  ☐ a. T-OX-390, and T-OX-391: Cryo Temperature (-330 oF)

  ☐ b. T-OX-393: Cryo Temperature (-330 oF)

  ☐ c. If T-OX-390, and T-OX-391 is at -330 F and T-OX-393 is experiencing temperature drop, pause test and check for leak at likely at PBV-N_2-351

  ☐ d. Look for visual indications of leak via binoculars

☐ 11. Slowly turn HLR-N_2-201 to 770 psi, HLR-N_2-301 to 745 psi

☐ 12. Expect the following readings:

  ☐ a. PT-N_2-220, PT-N_2-221, PT-FU-222, PT-FU-223 at 770 psi

  ☐ b. PT-N_2-320, PT-N_2-321, PT-OX-322, PT-OX-323 at 745 psi

☐ 13. Turn HLR-N_2-100 to required purge pressure

☐ 14. Evacuate all personnel

☐ 15. Actuate PBV-N_2-250, PBV-N_2-350 (Press) to ON

☐ 16. Start countdown

☐ 17. T-5, light ignitor*(Ignitor is an optional part of Cold Flow, if the ignitor is not being tested, ignore this step)

☐ 18. T-4 Shut off PBV-N_2-151, PBV-N_2-150 (Purge)

☐ 19. T-2s, switch ON PBV-OX-353

☐ 20. T-1s, switch ON PBV-FU-253

☐ 21. Allow liquid flow for the duration of the test until the end condition is reached(depletion of propellant, flow volume goal reached, desired flow time reached, etc.)

☐ 22. Close PBV-FU-253, PBV-OX-353 (Main)

☐ 23. Open PBV-N_2-151, PBV-N_2-150 (Purge),

☐ 24. Open PBV-N_2-351, PBV-N_2-251 (Vent)

☐ 25. Close PBV-N_2-250, PBV-N_2-350 (Press)

☐ 26. Check system pressure and temperature, and tank weight via DAQ

☐ 27. Data analyst gives all clear to operator when all system parameter returns to nominal according to DAQ readings

☐ 28. Operator yells all clear

☐ 29. Technicians return to system

☐ 30. Shut off K-bottle

☐ 31. Make sure regulators HLR-N_2-100, HLR-N_2-201, and HLR-N_2-301 are fully backed to 0 psi

☐ 32. Shut off Air Compressor, and assess system

6.7.4 Semi-Automatic Cold Flow Procedure

The automatic Cold Flow procedure should be run at least once prior to a hot fire event. The system needs to be thoroughly inspected and tested prior to executing the automatic sequence during hot fire. The semi-automatic procedure is the same as the manual but instead of many different switches, it utilizes just one switch to be toggeld at the operators discretion.

☐ 1. Confirm Compressed Gas System is online (assumed on after fill)

☐ 2. Make sure HLR-N_2-301, HLR-N_2-201, and HLR-N_2-100 are both at minimal pressure output

☐ 3. Crank HLR-N_2-100 and watch readings on PG-N_2-130 to 5 psi

☐ 4. Actuate PBV-N_2-151, PBV-N_2-150

☐ 5. Shut off PBV-N_2-351, PBV-N_2-251

☐ 6. Activate data logging via DAQ

☐ 7. Open hand valves on the K-bottle and on the Air Compressor

☐ 8. Check Pressure reading via LabVIEW, expect values:

  ☐ a. PT-N_2-123: Above 1000 psi, else replace K-bottle

  ☐ b. PT-N_2-120: PURGE PRESSURE

  ☐ c. PT-N_2-220: 0 psi(Pmin on HLR-N_2-201)

  ☐ d. PT-N_2-330:0 psi (Pmin on HLR-N_2-301)

☐ 9. Check Temperature reading, expect

  ☐ a. T-OX-390, and T-OX-391: Cryo Temperature

  ☐ b. T-OX-393: Super-Cryo Temperature

  ☐ c. If T-OX-390, and T-OX-391 is at -330 F and T-OX-393 is experiencing temperature drop, pause test and check for leak at PBV-N_2-351

  ☐ d. Look for visual indications of leak via binocular

☐ 10. Actuate PBV-N_2-350, PBV-N_2-350 (Press) to ON

☐ 11. Slowly crank HLR-N_2-100 to 770 psi, HLR-N_2-301 to 745 psi

☐ 12. Expect the following readings:

  ☐ a. PT-N_2-220, PT-N_2-221, PT-FU-222, PT-FU-223 at 770 psi

  ☐ b. PT-N_2-320, PT-N_2-321, PT-OX-322, PT-OX-323 at 745 psi

☐ 13. Turn HLR-N_2-100 to 50 psi, evacuate all personnel

☐ 14. Activate automation via UI

☐ 15. System will quickly check through parameters and prompt final permission to execute automation script. Once execution confirmed, operator must be prepared to abort if necessary.

☐ 16. System discharge is now occuring

☐ 17. Once sequence is complete, check system pressure and temperature, and tank weight via DAQ

☐ 18. Data analyst gives all clear to operator when all system parameter returns to nominal according to DAQ readings

☐ 19. Operator yells all clear

☐ 20. Technicians return to system

☐ 21. Make sure regulators HLR-N_2-100, HLR-N_2-201, and HLR-N_2-301 are fully backed off then set at 0 psi

☐ 22. Shut off K-bottle hand valve, Air Compressor, and assess system

6.8 Hot Fire

6.8.1 Propellant Fill

☐ 1. Prior to loading fluids, perform instrumentation self check routine via pre-programmed UI command

☐ 2. Make sure small fill tank is clean and free of dust or dirt, and that hand valve is closed

  ☐ a. If using a large container to fill Fuel Fill Tank, make sure container is clean as well

☐ 3. Using a funnel, fill Fuel Fill Tank with fuel and re-seal the Fuel Fill Tank

☐ 4. Confirm PBV-FU-251 is open

☐ 5. Attach Vent Tube Extender

☐ 6. Using the Air Compressor, pressurize Fuel Fill Tank to 35 psi

☐ 7. Attach Fuel Fill Tank to MBV-FU-252 (Fill valve) and wrench tighten fittings

☐ 8. Open hand valve on Fuel Fill Tank

☐ 9. Open manual valve on Fuel Fill Tank slowly

- ☐ a. Allow all RP-1 to exit Fuel Fill Tank, into fuel line

☐ 10. Close MBV-FU-252

☐ 11. Disconnect Fuel Fill Tank from Fuel MBV-FU-252

☐ 12. Repeat steps 2-10 until all fuel required is filled

- ☐ a. Note: it is better to slightly exceed fuel fill (+1 quart) than to not add enough

☐ 13. RP-1 fill complete, remove Vent Tube Extender

6.8.2 Liquid Oxygen Fill

☐ 1. Evacuate all personnel into bunkers, aside from Fill Operators

☐ 2. Ensure anyone involved or close to LOX fill is wearing proper safety attire

☐ 3. Ensure there are necessary wrenches available during fill

☐ 4. Turn HLR-N2-301, HLR-N2-201, HLR-N2-100 to minimal output pressure

☐ 5. Slowly open K-bottle

☐ 6. Turn HLR-N2-301 until PG-N2-330 reads 100 psi

☐ 7. Turn HLR-N2-100 until PG-N2-130 reads 100 psi

☐ 8. Actuate PBV-OX-353, PBV-N2-350, PBV-N2-151, oxydizer side is now purging

☐ 9. 20 seconds later, shut off PBV-OX-353, PBV-N2-350

☐ 10. 10 seconds later, shut off PBV-N2-151

☐ 11. slowly close K-bottle

☐ 12. Manually open MBV-OX-352 to let the remaining pressure purge the fill port

☐ 13. Wait until purge is complete, close MBV-OX-352

☐ 14. Confirm PBV-N_2-351 is open

☐ 15. Attach Vent Tube Extender if needed

☐ 16. Attach Cryogenic hose line to LOX Dewar and wrench tighten fitting, do not remove wrenches

☐ 17. Attach the same Cryogenic hose to MBV-OX-352 and wrench tighten fitting, do not remove 2nd set of wrenches

☐ 18. Slowly open LOX Dewar

☐ 19. Slowly open MBV-OX-352

☐ 20. Actuate PBV-OX-353 for pre-chill

☐ 21. Chill until engine reaches -200 F

☐ 22. Shut off PBV-OX-353

☐ 23. LN tank is now filling. Entire fill should take anywhere from 45 minutes to an hour

☐ 24. LN fill is complete when a liquid is pouring out of PBV-OX-351

  ☐ a. As redundancy check, T-OX-393, T-OX-390, and T-OX-391 should report Cryogenic temperature

  ☐ b. As secondary redundancy check, read mass increment of the LOX tank via the load cell beneath

☐ 25. Shut off Dewar

☐ 26. Shut off MBV-OX-352

☐ 27. Loosen fitting on MBV-OX-352

☐ 28. Loosen fitting on LOX Dewar

☐ 29. Remove Cryogenic hose

☐ 30. Remove LOX Dewar from vicinity, and store in a safe place outside or in a well ventilated area

☐ 31. Evacuate all personnel into bunkers aside from regulator operator

☐ 32. LOX fill complete

6.8.3 Automatic Hot Fire Procedure

*Note: The Automatic Hot Fire Procedure needs to be perfected with data and observations made during the Automatic Cold Flow tests
**All regulators need to be calibrated to the desired pressure before executing the following procedure

- ☐ 1. Confirm Compressed Gas System is online (assumed on after fill)
- ☐ 2. Actuate PBV-N_2-151, PBV-N_2-150
- ☐ 3. Shut off PBV-N_2-351, PBV-N_2-251
- ☐ 4. Activate data logging via DAQ
- ☐ 5. Open hand valves on the K-bottle and on the Air Compressor
- ☐ 6. Evacuate all personnel
- ☐ 7. Check Pressure reading via LabVIEW, expect values:
  - ☐ a. PT-N_2-123: Above 1000 psi, else replace K-bottle
  - ☐ b. PT-N_2-120: PURGE PRESSURE
- ☐ 8. Check Temperature reading, expect
  - ☐ a. T-OX-390, and T-OX-391: Cryo Temperature
  - ☐ b. T-OX-393: Super-Cryo Temperature
  - ☐ c. If T-OX-390, and T-OX-391 is at -330 F and T-OX-393 is experiencing temperature drop, pause test and check for leak at PBV-N_2-351
  - ☐ d. Look for visual indications of leak via binocular
- ☐ 9. Actuate PBV-N_2-350, PBV-N_2-350 (Press) to ON
- ☐ 10. Slowly crank HLR-N_2-100 to 770 psi, HLR-N_2-301 to 745 psi
  - ☐ a. Expect the following readings:
  - ☐ b. PT-N_2-220, PT-N_2-221, PT-FU-222, PT-FU-223 at 770 psi
  - ☐ c. PT-N_2-320, PT-N_2-321, PT-OX-322, PT-OX-323 at 745 psi
- ☐ 11. Activate Automation via UI

- ☐ 12. System will quickly check through parameters and prompt final permission to execute automation script. Once execution confirmed, operator must be prepared to abort if necessary.
- ☐ 13. When test is complete, Press, Main and Vent valves will be automatically placed to default position, sequence comes to a halt once these commands are executed
- ☐ 14. Purge will continue to stay open for 30 seconds
- ☐ 15. When System ceases all events (liquid flow/ flame), press OK button on the UI, purges will be deactivated
- ☐ 16. PPS on LabView will automatically analyze sensors information and give an all clear to the operator
- ☐ 17. Operator yells All clear
- ☐ 18. Technicians return to system, shut off K-bottle hand valve, and assess damage

A Appendix

A.1 Regulator Sizing Calculations

Table 20: Fuel Regulator Sizing Calculations

FUEL SIDE PARAMETERS	
Engine Inlet Mass Flow Rate (lbm/s)	0.8034
Kerosene Density (lbm/ft^3)	49.9
Chamber Pressure (psig)	375
Injector Head Loss (psig)	75
Regen Cooling Head Loss (psig)	100
Engine Inlet Pressure (psig)	550
Venturi Pressure Percent Drop	0.3
Fuel Tank Pressure (psig)	785
Fuel Tank Pressure (psia)	799.7
25% Fuel Mass Flow Rate Correction Factor (lbm/s)	1.00425
*Correction to ensure surplus gas supply	
Corrected Fuel Volumetric Flow Rate (ft ^{3}/s)	0.02012525
GN2 PARAMETERS	
Volumetric Flow Rate Gn2 Needed (ft ^{3}/s)	0.02012525
Volumetric Flow Rate (Q) Gn2 Needed (ft ^{3}/min)	1.20751503
Density (lbm/ft ^{3}) of Nitrogen Gas (@STP)	0.0780724
Density (lbm/ft ^{3}) of Nitrogen Gas (@770psig)	3.9733
GN2 Mass Flow Rate (lbm/s)	0.07996
GN2 Mass Flow Rate (lbm/min)	4.79782
GN2 Specific Gravity	0.967
Nitrogen K-Bottle Pressure (psig)	3200
Nitrogen K-Bottle Pressure (psia)	3214.7
GN2 Qg (SCFM)	61.4528382
REGULATOR PARAMETERS	
Cv of Regulator (Required)	0.03987860025

Table 21: Ox Regulator Sizing Calculations

LOX SIDE PARAMETERS	
Engine Inlet Mass Flow Rate (lbm/s)	2.0567
LOX Density (lbm/ft ^{3})	71.27
Chamber Pressure (psig)	375
Injector Head Loss (psig)	75
LOX Manifolding Head Loss (psig)	80
Engine Inlet Pressure (psig)	530
Venturi Pressure Percent Drop	0.2
LOX Tank Pressure (psig)	665
LOX Tank Pressure (psia)	679.7
*25% LOX Mass Flow Rate Correction Factor (lbm/s)	2.5709
Corrected LOX Volumetric Flow Rate (ft ^{3}/s)	0.03607
*Correction to ensure surplus gas supply	
GN2 PARAMETERS	
Volumetric Flow Rate Gn2 Needed (ft ^{3}/s)	0.03607
Volumetric Flow Rate (Q) Gn2 Needed (ft ^{3}/min)	2.16434
Density (lbm/ft ^{3}) of Nitrogen Gas (@STP)	0.07807
Density (lbm/ft ^{3}) of Nitrogen Gas (@742psig, -250 F)	38.249
GN2 Mass Flow Rate (lbm/s)	1.37973
GN2 Mass Flow Rate (lbm/min)	82.78383
GN2 Specific Gravity	0.967
Nitrogen K-Bottle Pressure (psig)	3200
Nitrogen K-Bottle Pressure (psia)	3214.7
GN2 Qg (SCFM)	1124.70534
REGULATOR PARAMETERS OX	
Cv of Regulator (Required)	0.68808413

B Material Safety Data Sheets

The operation and maintenance of Colossus involves the use of potentially hazardous chemicals and materials. Review the MSDS of each component to ensure that SEDS and any related personnel are maintaining the proper safety and visual standards.
Materials specified:

- Compressed Nitrogen[1]
- Liquid Nitrogen[2]
- Liquid Oxygen[3]
- Isopropyl Alcohol[4]
- Jet-A[5]
- Kerosene[6]
- Simple Green[7]
- Krytox[8]

The first page of each Data Sheet are attached below.

[1] BOC Nitrogen, Compressed., https://www.boconline.co.uk/internet.lg.lg.gbr/en/images/tg-8347-nitrogen-v1.3410_39602.pdf.

[2] Airgas SAFETY DATA SHEET Nitrogen, Refrigerated Liquid., https://www.airgas.com/msds/001188.pdf.

[3] airgas SAFETY DATA SHEET Oxygen, Refrigerated Liquid., https://www.airgas.com/msds/001190.pdf.

[4] Airgas Isopropyl Alcohol (Isopropanol)., https://www.airgas.com/msds/001105.pdf.

[5] Phillips, C. Jet A Aviation Fuel., http://www.cpchem.com/msds/100000014588_sds_us_en.pdf.

[6] Lab, S. Material Safety Data Sheet Kerosene., http://www.sciencelab.com/msds.php?msdsId=9924436.

[7] Green, S. Simple Green All-Purpose Cleaner., http://simplegreen.com/downloads/SDS_EN-US_SimpleGreenAllPurposeCleaner.pdf.

[8] Chemours Krytox 240 Series Greases., https://3eonline.com/ImageServer/NewPdf/4287f9c2-11f0-48c7-9c16-7dd7ba2aafbf/7fd3f611-d6ce-4189-8a8d-90978bacab07.pdf.

SAFETY DATA SHEET

Nitrogen, compressed

SECTION 1: Identification of the substance / mixture and of the company / undertaking

1.1 Product identifier

Product name: Nitrogen, compressed

Trade name: Nitrogen (Oxygen Free), Nitrogen BTCA 75, Nitrogen BTCA LE (Low Emission) Grade, Nitrogen CP Grade N5.2, Nitrogen Food Grade, Nitrogen ECD Grade, Nitrogen Grade N6.0, Nitrogen Pharmaceutical Grade, Nitrogen Research Grade N5.5, Nitrogen Zero Grade

Additional identification

Chemical name: Nitrogen

Chemical formula: N_2
INDEX No. -
CAS-No. 7727-37-9
EC No. 231-783-9
REACH Registration No. Listed in Annex IV / V of Regulation (EC) No 1907 / 2006 (REACH), exempted from registration.

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses: Industrial and professional. Perform risk assessment prior to use.
Aerosol propellant. Balance gas for mixtures. Blanketing gas. Calibration gas. Carrier gas. Fire suppressant gas. Food packaging gas. Inerting gas. Inflating tyres. Laboratory use. Laser gas. Pressure head gas, operational assist gas in pressure systems. Process gas. Purge gas. Test gas.
Consumer use.
Beverage applications. Shielding gas in gas welding.

Uses advised against Industrial or technical grade unsuitable for medical and / or food applications or inhalation.

1.3 Details of the supplier of the safety data sheet

Supplier
BOC
Priestley Road, Worsley
M28 2UT Manchester

Telephone: 0800 111 333

E-mail: ReachSDS@boc.com

1.4 Emergency telephone number: 0800 111 333

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

Classification according to Directive 67 / 548 / EEC or 1999 / 45 / EC as amended.

Not classified

SAFETY DATA SHEET

Nitrogen, Refrigerated Liquid

Section 1. Identification

GHS product identifier : Nitrogen, Refrigerated Liquid

Chemical name : nitrogen

Other means of identification : LIN, Cryogenic Liquid Nitrogen, Liquid Nitrogen, Liquid Nitrogen NF, Liquid Nitrogen FG

Product use : Synthetic/Analytical chemistry.

Synonym : LIN, Cryogenic Liquid Nitrogen, Liquid Nitrogen, Liquid Nitrogen NF, Liquid Nitrogen FG

SDS # : 001188

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : GASES UNDER PRESSURE - Refrigerated liquefied gas

GHS label elements

Hazard pictograms :

Signal word : Warning

Hazard statements : Contains refrigerated gas; may cause cryogenic burns or injury.
May cause frostbite.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Always keep container in upright position. Do not change or force fit connections. Avoid spills. Do not walk or roll equipment over spills.

Prevention : Wear cold insulating gloves and face shield.
Use and store only outdoors or in a well ventilated place.

Response : Thaw frosted parts with lukewarm water. Do not rub affected area. Get immediate medical attention.

Storage : Store in a well-ventilated place.

Disposal : Not applicable.

Hazards not otherwise classified : Liquid can cause burns similar to frostbite.

SAFETY DATA SHEET

Airgas

Oxygen, Refrigerated Liquid

Section 1. Identification

GHS product identifier	:	Oxygen, Refrigerated Liquid
Chemical name	:	oxygen
Other means of identification	:	Liquid Oxygen; LOX; Liquid Oxygen USP
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	Liquid Oxygen; LOX; Liquid Oxygen USP
SDS #	:	001190
Supplier's details	:	Airgas USA, LLC and its affiliates 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
24-hour telephone	:	1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : OXIDIZING GASES - Category 1
GASES UNDER PRESSURE - Refrigerated liquefied gas

GHS label elements

Hazard pictograms :

Signal word : Danger

Hazard statements : May cause or intensify fire; oxidizer.
Contains refrigerated gas; may cause cryogenic burns or injury.
May cause frostbite.
Combustibles in contact with Liquid Oxygen may explode on ignition or impact.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Open valve slowly. Use only with equipment cleaned for Oxygen service. Always keep container in upright position. Do not change or force fit connections. Avoid spills. Do not walk or roll equipment over spills.

Prevention : Wear cold insulating gloves and face shield. Keep away from clothing, incompatible materials and combustible materials. Keep reduction valves free from grease and oil. Use and store only outdoors or in a well ventilated place.

Response : Thaw frosted parts with lukewarm water. Do not rub affected area. Get immediate medical attention. In case of fire: Stop leak if safe to do so.

Storage : Store in a well-ventilated place.

Disposal : Not applicable.

Hazards not otherwise classified : Liquid can cause burns similar to frostbite.

SAFETY DATA SHEET

Isopropyl Alcohol (Isopropanol)

Section 1. Identification

GHS product identifier : Isopropyl Alcohol (Isopropanol)

Chemical name : Isopropyl alcohol

Other means of identification : propan-2-ol; 2-Propanol; isopropanol; isopropyl alcohol

Product use : Synthetic/Analytical chemistry.

Synonym : propan-2-ol; 2-Propanol; isopropanol; isopropyl alcohol

SDS # : 001105

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

Emergency telephone number (with hours of operation) : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : FLAMMABLE LIQUIDS - Category 2
SERIOUS EYE DAMAGE/ EYE IRRITATION - Category 2
SPECIFIC TARGET ORGAN TOXICITY (SINGLE EXPOSURE) (Narcotic effects) - Category 3

GHS label elements

Hazard pictograms :

Signal word : Danger

Hazard statements : Highly flammable liquid and vapor.
May form explosive mixtures with air.
Causes serious eye irritation.
May cause drowsiness and dizziness.

Precautionary statements

General : Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand.

Prevention : Wear protective gloves. Wear eye or face protection. Keep away from heat, sparks, open flames and hot surfaces. - No smoking. Use explosion-proof electrical, ventilating, lighting and all material-handling equipment. Use only non-sparking tools. Take precautionary measures against static discharge. Keep container tightly closed. Use only outdoors or in a well-ventilated area. Avoid breathing vapor. Wash hands thoroughly after handling. Use and store only outdoors or in a well ventilated place.

Jet A Aviation Fuel

SECTION 1: Identification of the substance/mixture and of the company/undertaking

Product information

Product Name	:	Jet A Aviation Fuel
Material	:	1102484, 1103429, 1102481, 1103418, 1102485, 1102483, 1102482, 1024254, 1024255, 1024256, 1024257, 1104981, 1104992
Use	:	Fuel
Company	:	Chevron Phillips Chemical Company LP Specialty Chemicals 10001 Six Pines Drive The Woodlands, TX 77380

Emergency telephone:

Health:
866.442.9628 (North America)
1.832.813.4984 (International)
Transport:
CHEMTREC 800.424.9300 or 703.527.3887(int'l)
Asia: +800 CHEMCALL (+800 2436 2255) China:+86-21-22157316
EUROPE: BIG +32.14.584545 (phone) or +32.14583516 (telefax)
South America SOS-Cotec Inside Brazil: 0800.111.767 Outside Brazil: +55.19.3467.1600

Responsible Department	:	Product Safety and Toxicology Group
E-mail address	:	SDS@CPChem.com
Website	:	www.CPChem.com

SECTION 2: Hazards identification

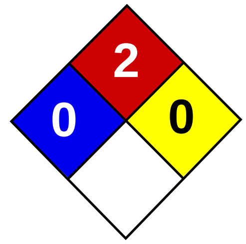
Classification of the substance or mixture
This product has been classified in accordance with the hazard communication standard 29 CFR 1910.1200; the SDS and labels contain all the information as required by the standard.

Emergency Overview

Danger

Form: Liquid **Physical state**: Liquid **Color**: Clear light yellow

OSHA Hazards : Flammable Liquid, Carcinogen, Mild skin irritant, Aspiration hazard, Delayed target organ effects



Health	2
Fire	2
Reactivity	0
Personal Protection	H

Material Safety Data Sheet
Kerosene MSDS

Section 1: Chemical Product and Company Identification

Product Name: Kerosene

Catalog Codes: SLK1048

CAS#: 8008-20-6 or 64742-81-0

RTECS: OA5500000

TSCA: TSCA 8(b) inventory: Kerosene

CI#: Not available.

Synonym: Astral Oil; Coal Oil, Fuel Oil No. 5, Deobase, Astral Oil, Jet A Fuel; Jet Fuel JP-1; JP-5 Navy Fuel; Kerosine, petroleum; Range Oil; K1 Kerosene; Kerosene, hydrodesulfurized; Kerosine

Chemical Name: Kerosene

Chemical Formula: Not available.

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Kerosene	8008-20-6 or	100
	64742-81-0	

Toxicological Data on Ingredients: Kerosene: ORAL (LD50): Acute: 15000 mg/kg [Rat]. 20000 mg/kg [Guinea pig]. 2835 mg/kg [Rabbit].

Section 3: Hazards Identification

Potential Acute Health Effects:
Hazardous in case of skin contact (irritant), of eye contact (irritant), of ingestion, of inhalation. Slightly hazardous in case of skin contact (permeator). Severe over-exposure can result in death.

Potential Chronic Health Effects:
Slightly hazardous in case of skin contact (sensitizer). CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Mutagenic for bacteria and/or yeast. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available. The substance is toxic to the nervous system. The substance may be toxic to blood, kidneys, liver, central nervous system (CNS). Repeated or prolonged exposure to the substance can produce target organs damage. Repeated exposure to a highly toxic material may produce general deterioration of health by an accumulation in one or many human organs.

Section 1: IDENTIFICATION

Product Name: Simple Green® All-Purpose Cleaner
Additional Names:

Manufacturer's Part Number: **Please refer to Section 16*

Recommended Use: Cleaner & Degreaser for water tolerant surfaces.
Restrictions on Use: Do not use on non-rinsable surfaces.

Company: Sunshine Makers, Inc.
15922 Pacific Coast Highway
Huntington Beach, CA 92649 USA

Telephone: 800-228-0709 ● 562-795-6000 *Mon – Fri, 8am – 5pm PST*
Fax: 562-592-3830
Email: info@simplegreen.com

Emergency Phone: Chem-Tel 24-Hour Emergency Service: 800-255-3924

Section 2: HAZARDS IDENTIFICATION

This product is not classified as hazardous under 2012 OSHA Hazard Communication Standards (29 CFR 1910.1200).

OSHA HCS 2012
Label Elements
Signal Word: None

Hazard Symbol(s)/Pictogram(s): None required

Hazard Statements: None
Precautionary Statements: None
Hazards Not Otherwise Classified (HNOC): None
Other Information: None Known

Section 3: COMPOSITION/INFORMATION ON INGREDIENTS

Ingredient	CAS Number	Percent Range
Water	7732-18-5	> 84.8%*
Ethoxylated Alcohol	68439-46-3	< 5%*
Sodium Citrate	68-04-2	< 5%*
Tetrasodium *N,N*-bis(carboxymethyl)-L-glutamate	51981-21-6	< 1%*
Sodium Carbonate	497-19-8	< 1%*
Citric Acid	77-92-9	< 1%*
Isothiazolinone mixture	55965-84-9	< 0.2%*
Fragrance	Proprietary Mixture	< 1%*
Colorant	Proprietary Mixture	< 1%*

**specific percentages of composition are being withheld as a trade secret*

Section 4: FIRST-AID MEASURES

Inhalation: Not expected to cause respiratory irritation. If adverse effect occurs, move to fresh air.
Skin Contact: Not expected to cause skin irritation. If adverse effect occurs, rinse skin with water.
Eye Contact: Not expected to cause eye irritation. If adverse effect occurs, flush eyes with water.
Ingestion: May cause upset stomach. Drink plenty of water to dilute. See section 11.

Most Important Symptoms/Effects, Acute and Delayed: None known.

Indication of Immediate Medical Attention and Special Treatment Needed, if necessary: Treat symptomatically

Krytox™ 240 Series Greases

Version 3.0

Revision Date 02/29/2016 Ref. 150000002935

This SDS adheres to the standards and regulatory requirements of the United States and may not meet the regulatory requirements in other countries.

SECTION 1. PRODUCT AND COMPANY IDENTIFICATION

Product name	:	Krytox™ 240 Series Greases
Product Grade/Type	:	240: AA, AB, AC, AD, AY, AZ, AZGR1
Product Use	:	Lubricant, For industrial use only.
Restrictions on use	:	Do not use product for anything outside of the above specified uses
Manufacturer/Supplier	:	The Chemours Company FC, LLC 1007 Market Street Wilmington, DE 19899 United States of America
Product Information	:	1-844-773-CHEM (outside the U.S. 1-302-773-1000)
Medical Emergency	:	1-866-595-1473 (outside the U.S. 1-302-773-2000)
Transport Emergency	:	CHEMTREC: +1-800-424-9300 (outside the U.S. +1-703-527-3887)
Other information	:	professional use

SECTION 2. HAZARDS IDENTIFICATION

Not classified as a hazardous substance or mixture according to the Occupational Safety and Health Administration (OSHA) Hazard Communication Standard 2012.

Other hazards

The product as such is not hazardous., The thermal decomposition vapours of fluorinated polymers may cause polymer fume fever with flu-like symptoms in humans, especially when smoking contaminated tobacco., Repeated episodes of polymer fume fever may result in persistent lung effects.

C Oxygen Compatibility Assessment Report

The operation of a liquid oxygen rocket engine is dangerous if the proper safety procedures are not in place. Since the safety of everyone is more important than anything else, SEDS members have an in depth oxygen compatibility assessment report of the Colossus static fire system.

Students for the Exploration and Development of Space
University of California, San Diego

Colossus
Liquid Rocket Engine Static Test Stand
Oxygen Compatibility Assessment Report

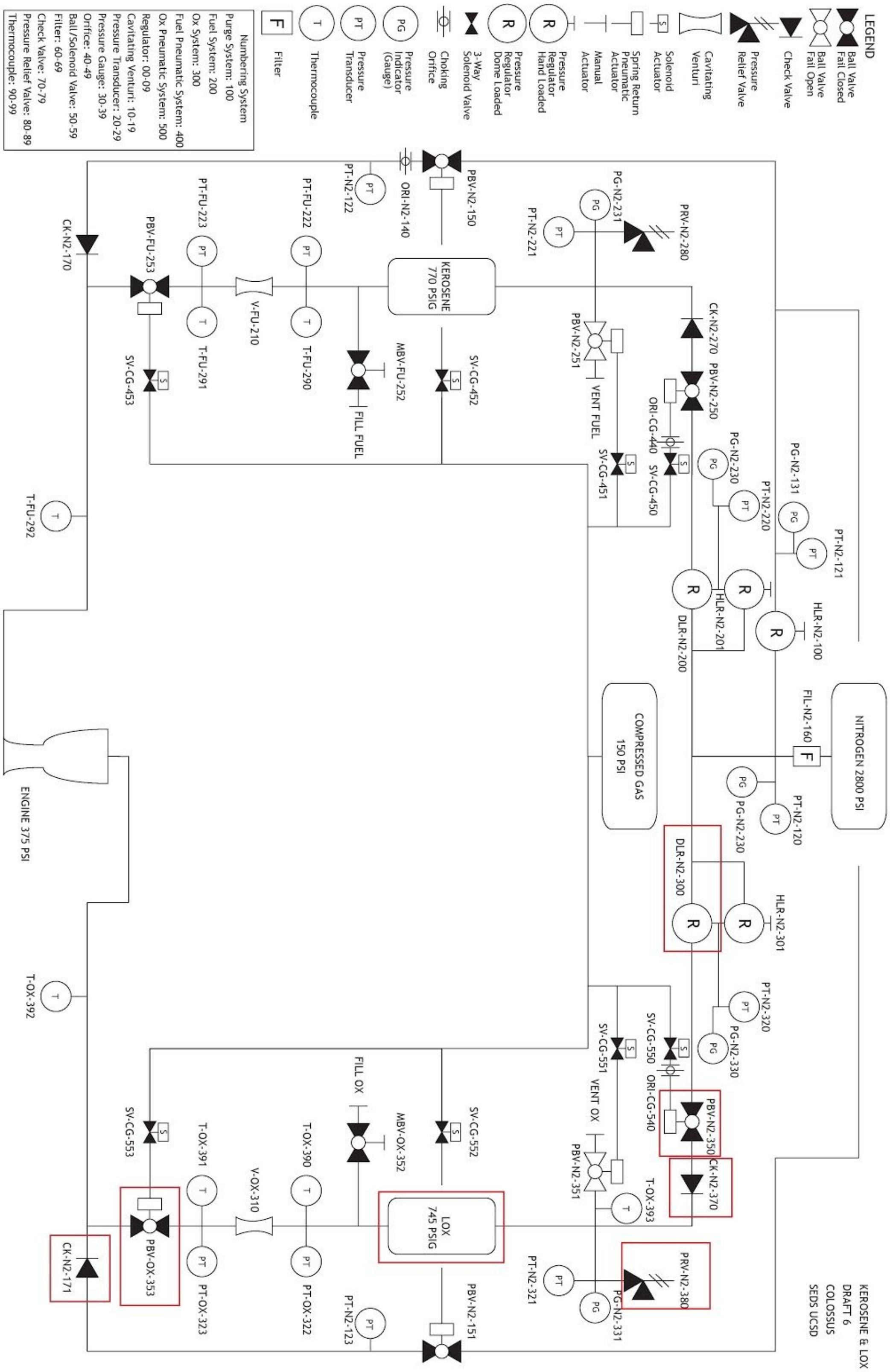
Submitted to:
NASA Marshall Space Flight Center
Program Office: Rocket Propulsion Testing

Table of Contents

1. Introduction

The Colossus Static Fire System Project is established to create a long-lasting hot fire capability for the SEDS UCSD program. The project will create a doubly cryogenic bi-propellant liquid rocket engine test stand the team can reuse and could potentially loan to other student programs with similar testing requirements. Given the team's previous design of the LOx/RP-1 Vulcan-1 engine and future designs utilizing liquid oxygen as an oxidizer, it is imperative that the system and the team be equipped for handling liquid oxygen. This means creating designs that maximize safety and undergoing a review process to ensure it is liquid oxygen compatible. To this end, a select team of SEDS UCSD students received technical professional training in ASTM's Fire Hazards in Oxygen Systems by Joel Stoltzfus, WSTF (retired) at the Open Source Maker Lab in Carlsbad, CA on May 14-15, 2016. This team of individuals has now assessed the oxidizer lines and valves on the Colossus Static Fire System for liquid oxygen compatibility in accordance with the training received on May 14-15th to present to the NASA Rocket Propulsion Test Program (RPT) on July 11, 2016. The results of this analysis are presented herein.

2. Plumbing and Instrumentation Diagram

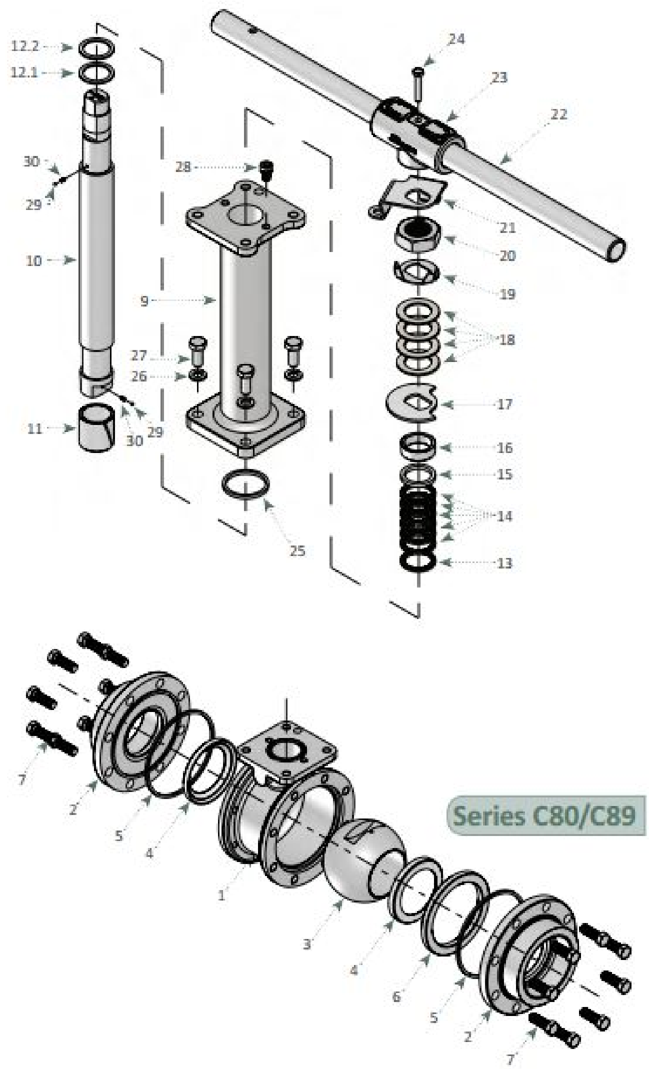


3. LOx Specific Risk Matrix

		Impact				
Probability		**Negligible**	**Minor**	**Moderate**	**Significant**	**Severe**
	Very Likely					
	Likely	Purge Check Valve Failure		Press Check Valve Failure		
	Possible		PRV Fire	Vent Valve Fire		
	Unlikely			Regulator Fire		
	Very Unlikely				Piping Fire	Main Valve Fire/Tank Fire

***The risk matrix focuses only on elements of Colossus that come into contact with LOx and/or GOx and therefore prove to be a significant risk factor.**

4. Main Ball Valve



Vendor: Sharpe
Part Number: ¾ Inch C89 Full Port Cryogenic Ball Valve
P&ID P/N: PBV-OX-353
Function Description:
The main ball valve serves as the main flow control mechanism from the oxidizer tank to the engine. It is responsible for controlling the sole source of oxidizer to the engine. This valve is in contact with LOx as soon as LOx filling begins. It remains in contact with LOx until the end of a test, when the entire system is depressurized and vented.
Oxygen Contact:

This valve is in contact with oxygen from the beginning of the LOx fill procedure to the end of the test. The downstream side of the valve will only be in contact with LOx during the hot fire sequence.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body, Stem	SS 316	1480	-361.82(Lo),150(Hi)	200 psi	N/A	1888.15	Yes
Stem Packing	PTFE	1480	-361.82(Lo),150(Hi)	95-100%	813	1701.24	Yes
Seat	PCTFE (Kel-F)	1480	-361.82(Lo),150(Hi)	N/A	N/A	N/A	Yes
Body Seal	Impregnated Graphite	1480	-361.82(Lo),150(Hi)	N/A	N/A	N/A	N/A

Ignition Mechanism Ratings**:**

Ignition Mechanism Ratings							Kindling Chain	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction/ Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
1	1	0	0	0	3	0	Yes	B

Ignition Mechanism Analysis:

Particle Impact: Particle velocity will not exceed 100 ft/s and there will be no impact since the particles run straight through the valve when open. As long as the particle velocity does not exceed 100 ft/s, the valve will be safe. When the valves are closed and the ball is impacted the line speed of 20 ft/s is not a enough to be a cause for concern.

Compressive Heating: The only scenario when there will be gas present at the valve is when the LOx starts boiling during the fill procedure. This GOx bubble will be compressed when the pressurization procedure begins. Since the press valve is designed to be a slow actuation, there is no instantaneous compression that would heat the gas faster than it can dissipate through the cryogenic environment. All materials are metal except for PTFE which has an ignition temperature of 813 F. The system temperatures will not reach anywhere near 800 F.

Friction/Galling: There are no rubbing materials. The body and the stem will rub when the ball valve is turned, but the rubbing speed is minimal compared to the 1.5 x 10^6 psi-ft/min required to ignite SS.

Mechanical Impact: Mechanical impact will not be an issue when the ball valve is closed. The velocity in the lines is not enough to cause ignition nor is there any nonmetal material present on impact.

Electric Arc/Spark: Since, the body is metallic there shouldn't be a potential difference that will cause an electric arc.

Flow Friction: Risks are introduced when there is a channeled flow created by a leak on the PTFE valve seat. Depending on the severity the leak, it is possible for the Teflon valve seat to be ignited due to flow friction.

5. Fill Ball Valve

<u>Vendor</u>: Sharpe
<u>Part Number</u>: ¾ Inch C89 Full Port Cryogenic Ball Valve
<u>P&ID P/N</u>: PBV-OX-352
<u>Function Description</u>:
The fill ball valve's sole function is to act like a door and allow the filling of the system. Opening the fill ball valve will allow for LOx to enter the system and then allow us to seal the opening when the fill valve is in the closed position. The fill valve will be exposed to LOx for the entire duration of the test-- from fill to end of the test. Due to the position of the valve, boiling oxygen bubbles would travel upwards to the tank and not accumulate locally.
<u>Oxygen Contact</u>:
The fill valve is the first component to come into contact with LOx. Both ends will be in constant contact while fill is occurring and then only the output end will be in contact with LOx.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body, Stem	SS 316	1480	-361.82	200 psi	N/A	1888.15	Yes
Stem Packing	PTFE	1480	-361.82	95-100 %	813	1701.24	Yes
Seat	PCTFE (Kel-F)	1480	-361.82	N/A	N/A	N/A	Yes
Body Seal	Impregnated Graphite	1480	-361.82	N/A	N/A	N/A	Yes

**note: LOx will pool during fill within the valve. Will be oxygen rich until fill is complete.

Ignition Mechanism Ratings:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction / Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
1	1	0	0	0	3	0	Yes	A

Ignition Mechanism Analysis:

Particle Impact: Particle velocity will not exceed 100 ft/s and no there will be no impact as the particles run straight through the valve when it is open. As long as the particle velocity does not exceed 100 ft/s, the component will be safe.When the valves are closed and the ball is impacted the 20 ft/s will not be significant enough to be a cause for conce

Compressive Heating: All materials are metal except for PTFE which has an ignition temperature of 813 F.; system temperatures will not reach anywhere near 800 F.

Friction/Galling: No rubbing materials; the body and the stem will rub when the ball valve is turned, but the rubbing speed is minimal compared to the 1.5 x 10^6 psi-ft/min required to ignite SS.

Mechanical Impact: Mechanical impact will not be an issue when the ball valve is closed. The velocity in the lines is not enough to cause ignition nor is there any nonmetal material present on impact.

Electric Arc/Spark: Since, the body is metallic there shouldn't be a potential difference that will cause an electric arc.

Flow Friction: Risks are introduced when there is a channeled flow created by a leak on the PTFE valve seat. Depending on the severity the leak, it is possible for the Teflon valve seat to be ignited due to flow friction.

6. Vent Ball Valve

Vendor: Sharpe
Part Number: 1.5 Inch C89 Full Port Cryogenic Ball Valve
P&ID P/N: PBV-OX-351
Function Description:
The venting ball valve allows the GOx to escape the system as it boils off. It will prevent the LOx tank from self pressurizing. The valve will be in contact with GOx for the duration of the filling process as well as during the firing process. During the firing process there is now ambient pressured GOx which is very unlikely to cause fire but still a concern.
Oxygen Contact:
The vent valve is in contact with cryogenic temperature GOx as soon as LOx filling starts. As the tank is filled to the desired liquid level constraint by the dipstick of the tank, GOx carrying LOx droplets will flow through this valve. When this valve is closed prior to pressurization of the tank, LOx will continue to boil off and self pressurize. During this period, this valve is in contact with pure GOx. As soon as the tank is pressurized by GN2, the concentration of Oxygen in the gas mixture will drop.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body,	SS 316	1480	-361.82	200 psi	N/A	1888.15	No

Stem, Ball							
Stem Packing	PTFE	1480	-361.82	95-100%	813	1701.24	*
Seat	PCTFE (CTFE) (Kel-F)	1480	-361.82	100	811.4	1473.68	No
Body Seal	Impregnated Graphite	1480	-361.82	N/A	N/A	N/A	*

*Flammability: When LOx tank is filled but before pressurizing, the oxygen concentration will be near 100%, which yields all non-metal materials flammable. However, after system is pressurized by Nitrogen gas, the oxygen concentration drops below the materials oxygen index.

<u>Ignition Mechanism Ratings</u>:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction/ Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
1	1	0	0	0	3	0	Yes	B

<u>Ignition Mechanism Analysis</u>

Particle Impact: When the valve is fully open, particle impact is not possible for ball valves because there is nothing obstructing the line-of-flow of any incoming particles. When the valve is opening, there is a chance that particle impact may occur, but the chance is very low because the valve handle is pneumatically driven and the transient time is short.

Speed of Impact: Particles will not be undergoing speeds fast enough to cause ignition of nonmetal components.

Compressive Heating: This valve will be in contact with LOx only when the system is pressurized. There is no gas to be compressed.

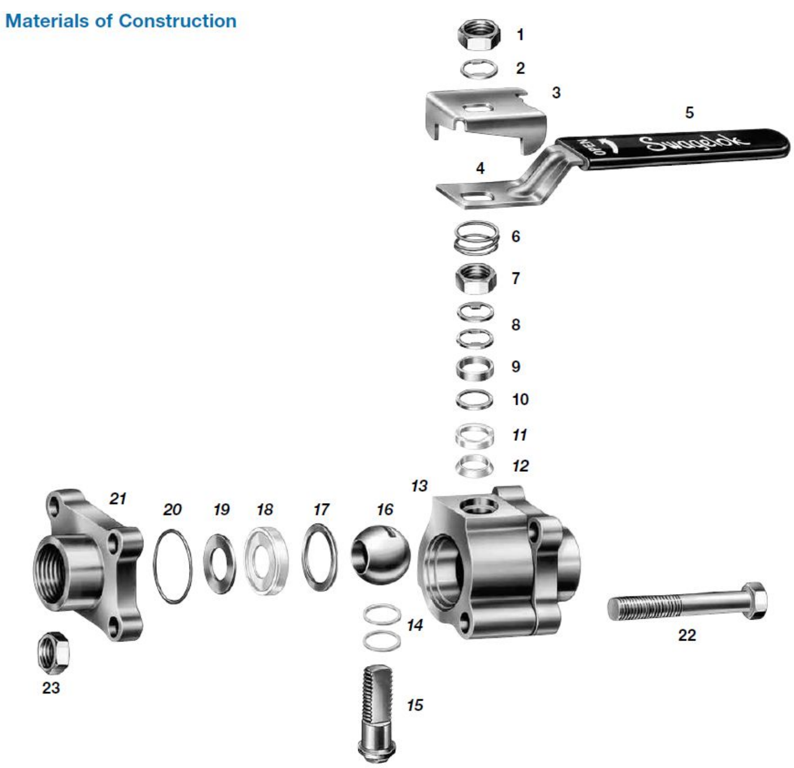
Friction/Galling: No rubbing materials; the body and the stem will rub when the ball valve is turned, but the rubbing speed is minimal compared to
the 1.5 x 10^6 psi-ft/min required to ignite SS.

Mechanical Impact: Will not be an issue when the ball valve is closed. The velocity is not high enough in the lines to cause ignition nor is there any nonmetal material present on impact

Electric Arc/Spark: The body is metallic, therefore there shouldn't be any potential difference within the body.

Flow Friction: Risks are introduced when there is a channeled flow created by a leak on the PTFE valve seat. Depending on the severity the leak, it is possible that the Teflon valve seat gets ignited due to flow friction. Flow friction is increased with the greater velocity of GOx. Our calculated velocity coming out of the vent valves will be 778 ft/s.

7. Press Ball Valve



Vendor: Swagelok
Part Number: ½ Inch SS-63TF8-33C
P&ID P/N: PBV-OX-350
Function Description:
The press ball valve will allow pressure provided by the regulator to go through the stainless steel lines and into the tank. It controls the start of the tank pressurization.
Oxygen Contact:

In the unlikely event of press check valve failure, GOx may backflow to the press ball valve when the vent valve is closed. Under this circumstance, the press ball valve will be in contact with 100% GOx up to 1440 psi set by the pressure relief valve.

Material Assessment :

		Worst-Case Operating Conditions		**Material Flammable?**			
Component	**Materials**	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body, Stem, Ball	SS 316	1440	-361.82	200 psi	N/A	1888.15	Yes
Stem Packing	PTFE	1440	-361.82	95-100%	813	1701.24	Yes
Seat	PTFE	1440	-361.82	95-100%	813	1701.24	Yes
Body Seal	Fluorocarbon FKM	1440	-361.82	57	462.2	12640	Yes

Ignition Mechanism Ratings:

Ignition Mechanism Ratings								
Particle Impact	Compression Heating	Friction Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other	Kindling Chain?	Reaction Effect (A-D)
1	0	0	0	0	1	0	No	B

Ignition Mechanism Analysis:

Particle Impact: Particle impact would not be possible to ignite any part of this component because its only contacts Oxygen when GOx leaks through the check valve seat for flows through a failed check valve at low speed.

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Compressive Heating: All materials are metal except for PTFE which has an ignition temperature of 813 F.; system temperatures will not reach anywhere near 800 F.

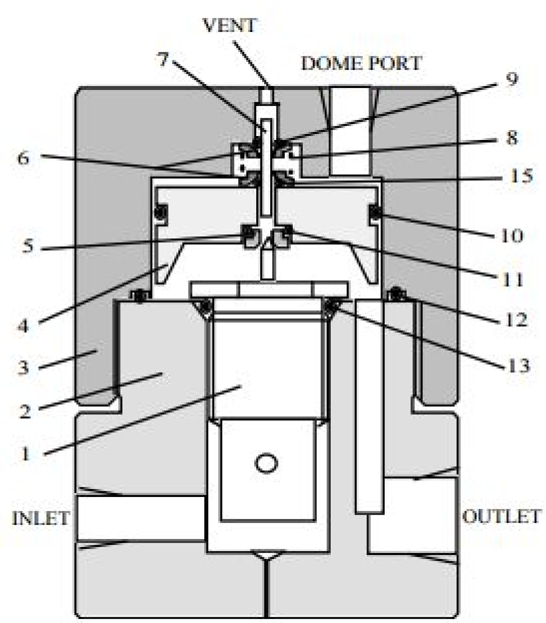
Friction/Galling: No rubbing materials; the body and the stem will rub when the ball valve is turned, but the rubbing speed is minimal compared to
the 1.5 x 10^6 psi-ft/min required to ignite SS.

Mechanical Impact: Will not be an issue when the ball valve is closed. The velocity is not high enough in the lines to cause ignition nor is there any nonmetal material present on impact

Electric Arc/Spark: The body is metallic, therefore there shouldn't be any potential difference within the body

Flow Friction: Risks are introduced when there is a channeled flow created by a leak on the PTFE valve seat. Depending on the severity the leak, it is possible that the Teflon valve seat gets ignited due to flow friction. Flow friction is increased with the greater velocity of GOx. Our calculated velocity coming out of the vent valves will be 778 ft/s.

8. Press Dome Regulator



Vendor: Aqua Environment
Part Number: 873-D High Flow Dome Loaded Reducing Regulators
P&ID P/N: DLR-N2-300
Function Description: The psi that exits the k-bottle is roughly around 3,000. That much psi is too much for a system like this,therefore we must decrease the pressure. The regulator will take the input pressure and only allows the set pressure out the other side. This allows us to regulate the psi through the system,

Oxygen Contact:

In the highly unlikely event of a check valve failure combined with insufficient pressure from the external K-bottles, self pressurized GOx may backflow to the regulator in event of trying to pressurize. In this case, GOx will flow through the vent of the regulator then to the environment.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body, Cap	Anodized Aluminum	1440 psi	-361.82(Lo), 150(Hi)	12.4 psia	N/A	7425.9	No
Stem	316 Stainless Steel			200 psia	N/A	1888.15	No
Poppet	Brass*			N/A	N/A	790.58	N/A
Seal	Viton/Kel-F			Viton=57 Kel-F=100	Viton=462.2 Kel-F=811.4	Viton=3019.01 Kel-F=1473.68	Viton = no, Kel-F = low

*Note: The brass values used are those for cartilage brass to provide for a bigger factor of safety. Information on the brass used in this part is unavailable.

Ignition Mechanism Ratings:

Ignition Mechanism Ratings (0 - 4)							Kindling Chain?	Reaction Effect (A - D)
Particle Impact	Comp. Heating	Friction/ Galling	Mechanical Impact	Elect. Arc/Spark	Flow Friction	Other (Chatter)		
1	1	2	0	0	3	2	No	A

Ignition Mechanism Analysis:

Particle Impact: Valve does not meet particle impact ignition criteria. Component will be taken apart and LOx cleaned, eliminating . existence of foreign particles inside. The impact point of any particles does not exist between a 45-90 ° angle. If there exists particles within the regulator, it is possible that they will exceed 100 ft/s. At maximum intended operating conditions, the impact of the flow of gaseous nitrogen is ~125 ft/s.

Compression Heating: Assuming an inlet (from Nitrogen k-bottle) pressure of 2800 psi and (max) outlet pressure of 1440 psi through the valve, the pf/pi pressure ratio will be 0.357. The small pressure ratio corresponds to a very low and non-concerning final temperature based of the isentropic compression equation. There is no exposed nonmetal in the heat affected zone. Rapid pressurization will not occur if there are positive pressures within the lines between the outlet of the regulator and lines that contain LOx. Because the regulator is intended to reduce pressure, the GOx coming from the failed check valve downstream will not be compressed from a low to a high pressure. In the event that there is an upstream negative pressure of GOx from the outlet to inlet of the regulator, and the inert gas in the k-bottle is depleted, there could exist rapid pressurization. This event is highly unlikely to occur but is still possible, so the ignition mechanism rating is 1.

Friction/Galling: Friction and Galling are possible due to the piston/seat/poppet assembly in the regulator moving up and down. This motion of the mechanical components is in contact with the working gas and fluid. As pressure changes in the inert k-bottle, the galling of the components may increase.

Mechanical Impact: Not likely due to the fact that the components are mostly non-reactive metals. Also, there will not be repeated and/or large mechanical impacts

Electric Arc and Spark: Not a probable occurrence because the valve is controlled manually/mechanically, and not electrically.

Flow Friction: Can occur in the rare event that there exists negative pressures in the system, causing flow of GOx/LOx upstream through the outlet of the regulator. The liquid/gas oxygen may come into contact with the Kel-F seals, which may generate heat. Also, if there exists a leak in the system, then the gas or fluid may escape the confines of the port and create friction within the piston/seat assembly.

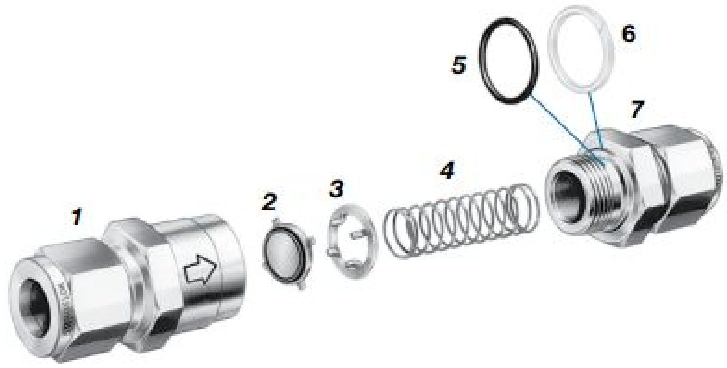
Other/Chatter: Chatter in the valve body is possible if there is an overpressurization in the tubing (could occur if incorrect line sizing) which requires the vent to be utilized. The continual use of the vent may wear down the valve components and the seat, which increase the change of ignition in an event of GOx back flow.

9. Press Check Valve

CH Series

Component	Material Grade/ ASTM Specification
1 *Inlet body*	*316 SS/A479*
2 *Poppet*	*Fluorocarbon FKM-bonded*① *316 SS/A479*
3 *Poppet stop*	*316 SS/A240*
4 *Spring*	*302 SS/A313*
5 *O-ring*	*Fluorocarbon FKM*
6 Backup ring	PTFE/D1710
7 *Outlet body*	*316 SS/A479*
Lubricant	*PTFE-based*

Wetted components listed in *italics*.
① Material Safety Data Sheet for bonding agent available on request.



Vendor: Swagelok
Part Number: ½ Inch SS-CHM8ST
P&ID P/N: CK-N2-370
Function Description: This valves acts as a one way passage for the nitrogen flow right before the tanks and after the regulator. This ensures that no pressure will backtrack and ensures all pressure will be forced to go into the direction of the tanks. This component will only be coming into contact with nitrogen on one end, and on the other it will be in contact with nitrogen and at some point GOx. This check is also here to ensure that no GOx travels to the press system during the fill process.
Oxygen Contact:
The press check valve is placed directly upstream to the LOx tank. Nominally, the check valve's poppet would stop any GOx from traveling up-stream. If the poppet gets too worn or is jammed by debris, it is possible that GOx may leak through the poppet and travel upstream.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body, Poppet stop	316 SS	1440	-361.82(Lo),150(Hi)	200 psia	N/A	1888.15	Yes
Spring	302 SS			200 psia	N/A	1888.15	Yes

Poppet,Backup ring	FFKM			100 %	617	1565.7	No
Oring	FFKM			100 %	617	1565.7	No
Lubricant	PTFE			95-100 %	813	1701.24	Yes

Ignition Mechanism Ratings:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction/ Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
0	0	0	0	0	1	0	Yes	C

Ignition Mechanism Analysis:

Particle Impact: The particle impact is not a possible source of ignition because the nominal direction of flow of this check valve should only allow N2 to flow through.

Heat of Compression: Since the cracking pressure of this check valve is below 30 psi, compression is not going to occur, as the valve poppet will open as soon as pressure starts accumulating.

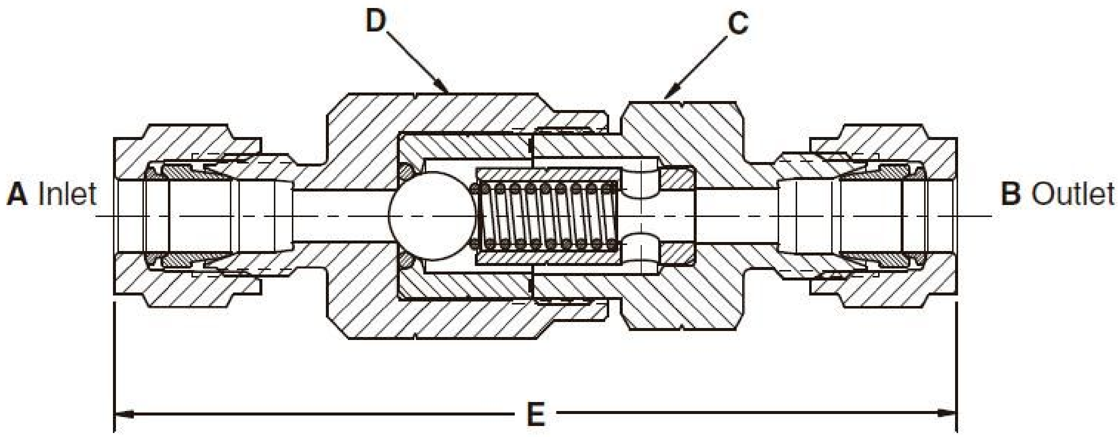
Mechanical Friction/Galling: Mechanical friction does not exist in this valve. There is no moving parts constantly rubbing against each other.

Mechanical Impact: When the downstream pressure difference is around the cracking pressure of the valve, the poppet ball will chatter and smash against the valve seat. Though this motion is menisque, the impulse may be high enough to provide the ignition energy to the PTFE valve seat. However, any pre-existing Oxygen in the valve body prior to the initial opening of the valve would have been purged away from the downstream high pressure nitrogen gas, thus ignition by mechanical impact is impossible.

Electrical Arc: This is impossible since there is not electrical fixtures near this device at all.

Flow Friction: Ignition by flow friction is only possible when there is a leak on the valve seat. Small stream of high velocity pure GOx would escape the tank and fill up the plumbing upstream to the check valve all the way to the press ball valve. To minimize this hazard, the check valve is placed close to the press ball valve to minimize the escape reservoir volume for the leaked GOx.

10. Purge Check Valve



Vendor: Generant
Part Number: ¾ Inch SS-63TF8-33C
P&ID P/N: CK-N2-171
Function Description: The purge check valve allows high pressure N2 gas to flow in only one direction to purge out the main oxidizer line, and prevents Oxygen from entering the purge lines.
Oxygen Contact:
The purge check valve is located past the main valve. It is in contact with cryogenic GOx which is boiled off from the LOx flowing from the main valve to the engine. Since there is static N2 sitting between the purge check valve and the main propellant line, the GOx which enters the branch to this valve is blended with the N2 creating a homogeneous O2-N2 mixture.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body, Poppet, Spring	316 SS	1440	-361.82(Lo),150(Hi)	200 psia	N/A	1888.15	No
O-ring Seat	Viton			57	462.2	3019.01	No

Body Gasket	PTFE			95-100%	813	1701.24	Yes

Ignition Mechanism Ratings:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction / Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
0	0	0	1	0	0	0	No	A

Ignition Mechanism Analysis:

Particle Impact: The normal direction of flow will only allow N2 to flow downstream to the engine. The downstream particles will not cause a fire as there is not enough oxygen present. Even if the valve fails, it will not allow particles to accelerate upstream. Therefore, particle impact is not possible.

Heat of Compression: When the main valve is opened, high pressure LOx will flow down to the engine. Since this valve is located on a service branch, there is no direct compression that occurs near the valve.

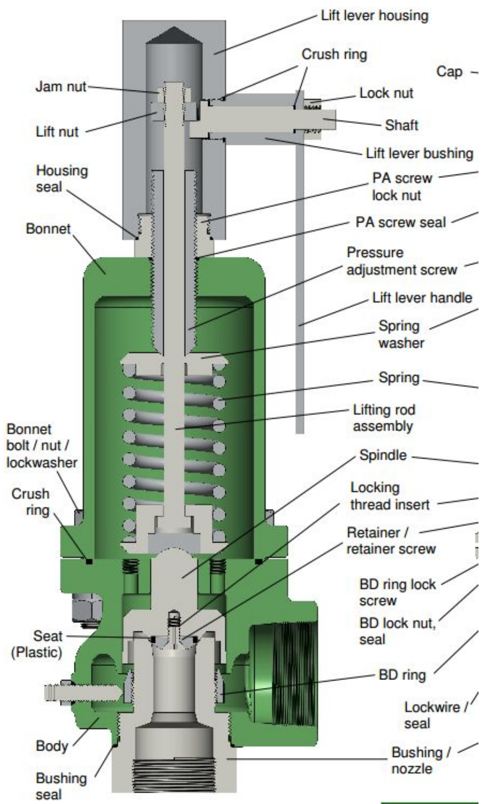
Mechanical Friction: There is no metal to metal contact that would cause sufficient amount of heat to become an ignition source. Ignition by friction or galling would be impossible in this case.
Mechanical Impact: Chattering is possible if there is a failure with the regulator for the purge system. The valve poppet would chatter back and forth, this makes ignition possible but unlikely.

Electrical Arc: There are no electrical parts that are attached to this valve. The valve body is also fully metallic, which allows for no potential difference. Therefore, no risk of electrical arcing

Flow Friction: Flow friction from the upstream N2 will not cause any fire. However, when the purge valve is closed and the check valve poppet is worn and damaged, small amount of GOx and N2 mixture may leak through the valve assembly. However, PTFE have a OI over 99.5%, therefore ignition by flow friction is not possible.

Kindling Chain: In the unlikely event of this component catching fire, the fire would not propagate further as the concentration of oxygen is not sufficient for Stainless Steel piping to burn.

11. Pressure Relief Valve



Vendor: Flowsafe
Part Number: ¼ inch F84-6
P&ID P/N: PRV-N2-380
Function Description: The pressure relief will be calibrated at a set psi that we do not want our tank pressure to reach. In the event that this given pressure is reached the relief valve will automatically release enough pressure until it drops back down to the calibrated psi. This is a safety factor installed to limit the chance of the tanks blowing up and causing someone injury.
Oxygen Contact: The pressure relief valve has the exact same oxygen contact schedule as the vent ball valve. It is in contact with cryogenic temperature GOx as soon as LOx filling begins. As the tank is filled to the desired liquid level constraint by the dipstick of the tank, GOx carrying LOx droplets will flow through this valve. When this valve is closed prior to pressurization of the tank, LOx will continue to boil off and self pressurize. During this period, this valve is in contact with pure GOx. As soon as the tank is pressurized by GN2, the concentration of Oxygen in the gas mixture will drop.

Material Assessment :

		Worst-Case Operating Conditions		Material Flammable?			
Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Body,	316 SS	1440	-361.82(Lo) ,150(Hi)	200 psia	N/A	1888.15	No
Seat, seals	PTFE			95-100%	813	1701.24	Yes
Cap	6061 Aluminium			12.4 psia	N/A	7425.90	No

Ignition Mechanism Ratings:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction / Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
1	0	0	1	0	2	0	No	A

Ignition Mechanism Analysis:

Particle Impact: When the valve is discharging in an event of overpressurization, any foreign debri added to the system during fill may get carried to the pressure relief valve and hit the seat-spindle assembly of the valve. When discharging to atmosphere, the air velocity is above 100 ft/s. This would ignite the valve seat given the pressure and oxygen concentration of the environment. However, since the GOx is from the boiling of LOx in the tank, it is less likely to carry debri upwards against the pull of gravity.

Heat of Compression: Ignition by heat of compression is not possible for this pressure relief valve because there is not trapped volume of air being compressed at any moment.

Mechanical Friction: Since there is no mechanical moving parts in constant relative motion, this ignition source is not possible.

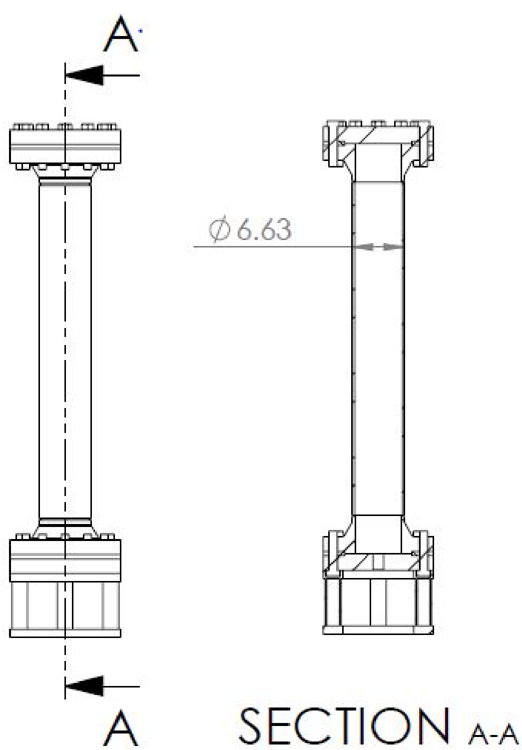
Mechanical Impact: Due to the nature of the pressure relief valve, is it possible to activate the chattering motion of the valve spindler when the tank pressure is maintained slightly above the relief threshold of the valve. Though very unlikely, if the valve does start chattering, there is a good chance that the PTFE is ignited since it is exposed to 100% GOx.

Electrical Arc: Electrical Arc ignition is not possible without the presence of any electrical power source.

Flow Friction: If the spindle becomes stuck and fails to open all the way then threshold pressure have been reached, flow would be pinched and really high friction can be observed

Kindling Chain: If this valve is caught on fire, the positive pressure from inside of the tank will prevent the fire from propagating into the rest of the system.

12. Oxidizer Tank



Custom Made; 6.63 inch ID, weld neck flange with ¾ inch exit port

<u>Material Assessment</u> :

		Worst-Case Operating Conditions	Material Flammable?

Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Straight Section	Stainless Steel 304	1440	-361.82(Lo),150(Hi)	200 psia	N/A	1888.145	Yes
Neck Flange	Stainless Steel 304	1440	-361.82(Lo),150(Hi)	200 psia	N/A	1888.145	Yes
Blind Flange	Stainless Steel 304	1440	-361.82(Lo),150(Hi)	200 psia	N/A	1888.145	Yes
Ring Gasket	PTFE	1440	-361.82(Lo),150(Hi)	95-100 %	813	1701.24	Yes

Ignition Mechanism Ratings:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction / Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
0	0	0	0	0	1		Yes	C

Ignition Mechanism Analysis:

Particle Impact: Since the propellant line speed is 20 ft/s, then the propellant speed exiting the tank is 20 ft/s and the 100 ft/s condition for particle impact will not be met. Because not all conditions for particle impact are present, then particle impact will not occur at either the entrance port or the exit port of the pipe tanks.

Heat of Compression: Assuming the worst-case initial temperature of 150 F and initial pressure of 14.7psia, the final temperature in the pipe tanks is 557.47 F. Since the Autogenous ignition temperature of PTFE is 813 F, then the 180 F gap recommended by the ASTM G Committee is met. As a result, the heat from compression will not pose a risk to the PTFE gasket O-ring. Additionally, the PTFE gasket ring will not be in direct contact with LOx or GOx during rapid pressurization.

Friction/ Galling: Since there are no moving parts within the pipe tanks or moving parts that make up the pipe tanks, there is no mechanical friction present and no ignition mechanism associated with mechanical friction.

Mechanical Impact: Since no non metals are present in the flow of oxygen within the pipe tanks, this ignition mechanism will not occur. There are additionally no large impact or repeated loading within the pipe tanks.

Electrical Arc/Spark: Since the pipe tanks are not electrical components, then there is no electric arcing ignition mechanism present.

Flow Friction: This ignition mechanism is present due to a PTFE ring gasket sealing the interface between the blind flanges and neck flanges. The ring gasket is along the flow path in an area of possible leakage due to the high pressures, However, because the flow path is very small, the conditions are present but weak.
Kindling Chain: Though extremely unlikely, if the tank is ever caught on fire, there will be sufficient enough of oxygen in the tank to sustain burning of the entire tank. This would to catastrophic to the system. However, it is unlikely to have personnel loss due to this failure because all personnel are required to be evacuated when the system is pressurized.

**Note: materials selected should have a 180 F margin between the worst-case operating temperature and the material's AIT (suggestion by ASTM G Committee)
1. This data has been obtained by calculation not experimentation.
2. The value found for SS 304 is specific to 300 series not 304 specifically.
3. Values based on a pressure = 300 psi instead of system pressure (1440 psi)
4. Note 3 will need to be corrected for.

13. Oxidizer Tubings

<u>Vendor</u>: McMaster Carr
Main: ¾ inch, Press: ½ inch

<u>Material Assessment</u> :

		Worst-Case Operating Conditions	Material Flammable?

Component	Materials	Pressure (psi)	Temperature (F)	OI (%) or PCT (psia)	AIT (F)	HoC (cal/g)	Flammability
Tube	SS 304	1440	150	200	N/A	1888.145	Yes
Cavitating Venturi Tube	SS 304	1440	150	200	N/A	1888.145	Yes

Ignition Mechanism Ratings:

Ignition Mechanism Ratings							Kindling Chain?	Reaction Effect (A-D)
Particle Impact	Compression Heating	Friction / Galling	Mechanical Impact	Electric Arc/Spark	Flow Friction	Other		
0	1	0	0	0	0	0	No	A

Ignition Mechanism Analysis:

Particle Impact: Because the maximum propellant line speed is 20 ft/s which does not exceed the 100 ft/s necessary condition of particle impact, particle impact ignition will not occur within the stainless steel tubing

Compressive heating: Compressive heating will not occur because gas will not be exposed to nonmetal in just the tube assuming that the system is completely cleaned prior to use. GOx is a possibility but due to the cleaning process will not ignite any nonmetal materials. (Note: depends on if there is nonmetal parts in components such as valves that creates downstream "dead end" but compressive heating will not happen in just the SS tube itself)

Friction/Galling: There are no rubbing surfaces present.

Mechanical Impact: Mechanical Impact will not occur because there will not be any large impact or repeated impact loading that occurs

Electric Arc/Spark: The stainless steel tubes are not electrically powered components.

Flow Friction: Flow friction ignition mechanism will not occur because oxygen will not be exposed to nonmetal materials in flow path. (Note: also depends on parts such as the regulators and valves and whether or not nonmetal material is present in these components.

Kindling chain: A kindling chain does not exist because even though the component is flammable under the temperature and pressure condition, it lacks possible ignition mechanism. However, the piping can serve as the propagating medium in the event of other components catching on fire.

D Itemized Parts List

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Sub-System	Part Name	Part Number	Price	Qty	Total
Electronics	Relays, 12V coil 30A contact current	T9AP1D52-12	$2.84	2	$5.68
	Cobra Vehicle Power Inverter	CPI-2575	$149.99	1	$149.99
	15v 600W power supply	SE-600-15	$91.08	2	$182.16
	15 A Circuit breaker	W51-A121B1-15	$3.70	4	$14.80
	350A 12v circuit breaker	PS82/300	$12.50	1	$12.50
	35mm din rails	1207651	$2.42	10	$24.20
	PCB		$800	1	$800
	25V 10,000 uF capacitor	ESMG250ELL103MP40S	$4.53	10	$45.30
	NI cDAQ	NI cDAQ-9178	$1,233	1	$1,233
	NI 9237		$1,572	1	$1,572
	NI 9213		$1,185	1	$1,185
	NI 9206		$1,262	1	$1,262
	NI 9403		$540	1	$540
	12v 5A peltier	Adafruit: 1330	$11.95	2	$23.90
	4 in cooling fan	N82E16835103052	$12.49	4	$49.96
	4*4 Aluminium heatsink	9SIA27C3TJ8433	$13.71	3	$41.13
	ferrules awg16	3200043	$9.10	1	$9.10
	ferrules awg18	3200030	$9.25	1	$9.25
	ferrules awg20	3200014	$9.10	1	$9.10
	schottky diode	PDS540-13	$1.18	4	$4.72
	DUCT, WIRE, 2 X 3, NARROW FNGR		16.43	1	16.43
	DUCT,WIRE,2,CVR,LG		1.92	1	1.92
	Electronics Container	1418JJ9	$431.42	1	$431.42
	Mini PC	HP 280 G1	$419.99	1	$419.99
	Touch Scren Monitor Powered by DC	ET1515L-7CWA-1-G	199.99	1	$199.99
		$8,043.55			

Sensors	Measurement	Part Number	Price	PNID P/N
Pressure Transducers	P Venturi Out, Fuel		owned	PT-FU-223
	P Venturi Out, Ox		owned	PT-OX-323
	P Venturi In, Fuel		owned	PT-FU-222
	P Venturi In, Ox		owned	PT-OX-322
	LOX Purge Pressure	PX309	$235.00	PT-N2-122
	Fuel Purge Pressure	PX309	$235.00	PT-N2-121
	LOX Tank Pressure		owned	PT-N2-321
	Fuel Tank Pressure		owned	PT-N2-221
	Fuel side Regulatur Pressure	PX309	$235.00	PT-N2-220
	LOX Regulator Pressure	PX309	$235.00	PT-N2-320
	Purge Regulatur Pressure	PX309	$235.00	PT-N2-120
	K Bottle Pressure	PX309	$235.00	PT-N2-123
Thermocouples	Fuel Line Temperature	SA1-T-120	$21.20	T-FU-292

	LOX Line Temperature	SA1-T-120	$21.20	T-OX-392	
	T Venturi Out, Fuel	SA1-T-120	$21.20	T-FU-291	
	T Venturi Out, Ox	SA1-T-120	$21.20	T-OX-391	
	T Venturi In, Fuel	SA1-T-120	$21.20	T-FU-290	
	T Venturi In, Ox	SA1-T-120	$21.20	T-OX-390	
	Fuel Tank Temperature	SA1-T-120	$21.20	T-FU-293	
	LOX Tank Temperature	SA1-T-120	$21.20	T-OX-393	
Load Cells	Oxidizer Tank Weight	LCCA-1K	$398.00	LC-OX-300	
	Propellant Tank Weight	LCCA-1k	$398.00	LC-FU-200	
	Axial Thrust	LCCA-5K	$620.00	LC-100	
	Y-thrust deflection	LCCA-750	$398.00	LC-101	
	X-thrust deflection	LCCA-750	$398.00	LC-102	
		$3,791.60			
Structures-Framework	Location	Part	SIZE/SPECS (INC	Quantity	Total
	Frame Width Supports and Shelving Lengt	1515	39	16	$624.00
	Middle Vertical Lengths	1515	80.25	2	$160.50
	Forward Shelf Supports	1515	30	4	$120.00
	Angled Supports	1515	35.6	3	$106.80
	Base Lengths	1530	96	2	$192.00
	Back Vertical Lengths	1530	80.25	2	$160.50
	Base Widths and Floor Supports	1530	39	5	$195.00
	Base Length Supports	1530	52.5	2	$105.00
	Front Shelf Vertical Lengths	1530	66.75	2	$133.50
	Recoil Plate Pivot Support	4383	15 series	6	
Structures-Framework To	Totals	Inches			
	Total 1515	$1,011.30			
	Total 1530	$786.00			
	Separate Extrustions Total	44			
	1515 Price Per Inch:	0.53			
	1530 Price Per Inch:	0.93			
	4383 Price Per Pivot	21.4			
Total Framework Cost:		$1,395.37			
Structures	Location	Part	Size/Specs (Inchs)	Unit Price	Quantity
	Pressure Gauge Panel	Steel Sheet	1/8 x 32 x 28	$50.70	1
	Tank Support Frame (Unistrut)	Unistrut	416	$18.00	4
	Tank Boot Rings	Steel Plate/Sheet	14 x 14 x 1	$160.01	2
	Tank Boot Struts	Steel block	4 x 6	$114.76	4
	Trailer Lockdown (Steel shared w/blast pla	Steel Plate	1/2	$0.00	0
	Lockdown Chain	Lockdown Chain	3410T97	$97.50	3
	TTO Engine Ring Interface	Steel Plate	0.5 x 11.12 x 11.12	$21.25	1

	TTO Struts	Steel Plate	16.3 x 11.12 x 11.1	$104.90	1
	TTO Engine interface plate	Steel Plate	12 x 11.82 x 2.08	172.52	1
	TTO Blast Plate	Steel Plate	1/2 x 54 x 48	$431.29	1
	TTO Truss	Steel Square 3 inch Tube	165	$528.80	1
	Frame	Trailer		$2,000	1
Total Cost		$4,453.02			
Purge System Plumbing	Part	Size/Specs	Price	Manufacturer	
100 Series	Nitrogen K-Bottle Filter	580 CGA to 1/4" NPT	$11.13	Medical Gas Fittings	
	Pressure Regulator - Hand Loaded	1/4" NPT Inlet 1/4" NPT outl	$264.00	Aqua Environment	
	Pneumatic Spring Return Ball Valve (Fuel	1/2" SAE-ORB	$545.40	Swagelok	
	Pneumatic Spring Return Ball Valve (Ox Si	1/2" SAE-ORB	$545.40	Swagelok	
	Machined Choking Orifice (Brass) (Fuel Si	TBD		SEDS	
	Pressure Gauge, Mechanical (Purge Press	1/4" SAE-ORB	$28.23	McMaster	
	Cryogenic Check Valve (Fuel Side)	3/4" SAE-ORB	$252.00	Generant	
	Cryogenic Check Valve (Ox Side)	3/4" SAE-ORB	$252.00	Generant	
Total Cost		$2,755.16			
Fuel System Plumbing	Part	Size/Specs	Price	Manufacturer	
200 Series	Pressure Regulator - Dome Loaded	1/4" NPT Inlet 1/2" NPT outl	$593.00	Aqua Environment	
	Pressure Regulator - Hand Loaded	1/4" NPT Inlet 1/4" NPT outl	$264.00	Aqua Environment	
	Pneumatic Spring Return Ball Valve (Fuel	1/2" SAE-ORB	$545.40	Swagelok	
	Pneumatic Spring Return Ball Valve (Fuel	1" SAE-ORB, Cryo Compati	$2,000.00	Sharpe	
	Pneumatic Spring Return Ball Valve (Fuel	3/4" SAE-ORB, Cryo Comp	$1,400.29	Sharpe	
	Manually Actuated Ball Valve (Fuel Fill)	3/4" SAE-ORB, Cryo Comp	$916.00	Sharpe	
	Check Valve (Fuel N2 Press)	1/2" SAE-ORB	$99.10	Swagelok	
	Cryogenic Pressure Relief Valve (Fuel Tan	1/4" SAE-ORB	$838.87	Flowsafe/MSFC	
	Fuel Pressure Vessel			SSC/MSFC	
	Cavitating Venturi	SS 304 Flared Tube Ends	$1,200.00	Flowmaxx	
	Pressure Gauge, Mechanical (Fuel Press)	1/4" NPT	$28.23	McMaster	
	Pressure Gauge, Mechanical (Fuel Tank)	1/4" NPT			
Total Cost		$7,884.89			
Oxidizer System Plumbin	Part	Size/Specs	Price	Manufacturer	
300 Series	Pressure Regulator - Dome Loaded	873-D	$593.00	Aqua Environment	
	Pressure Regulator - Hand Loaded	415-1500	$264.00	Aqua Environment	
	Pneumatic Spring Return Ball Valve (Ox P	SS-63TF8-33C	$545.40	Swagelok	
	Pneumatic Spring Return Ball Valve (Ox Vent)		$2,000.00	Sharpe	
	Pneumatic Spring Return Ball Valve (Ox S/O)		$1,400.29	Sharpe	
	Manually Actuated Ball Valve (Ox Fill)		$916.00	Sharpe	
	Check Valve (Ox N2 Press)	SS-8C4-1	$99.10	Swagelok	
	Cryogenic Pressure Relief Valve (Ox Tank	S844B-05FNO-01FNO-SS-	$838.87	Flowsafe/MSFC	

	Oxidizer Pressure Vessel			SSC/MSFC
	Cavitating Venturi		$1,200.00	Flowmaxx
	Pressure Gauge, Mechanical (Ox Press)	3845K5	$28.23	McMaster
	Pressure Gauge, Mechanical (Ox Tank)	3845K5	$28.23	McMaster
Total		$7,913.12		

Thread Fittings	Part	Part Number	Price	Quantity
	CGA to NPT	79215A665	$3.34	1
	SAE-ORB Female Cross		$120.00	1
	SAE-ORB to JIC/AN	SS-6400-04-04	$4.15	5
	SAE-ORB to JIC/AN Elbow	SS-6801-04-04	$17.90	5
	SAE-ORB to JIC/AN	SS-6400-08-08	$8.99	6
	AN Branch Tee with SAE-ORB	SS-6803-04-04-04	$28.75	1
	SAE-ORB to SAE-ORB Male Union	SS-6407-08-08	$29.99	4
	AN Tee	5482K52	$27.50	1
	FMF SAE-ORB Tee		$96.00	5
	SAE-ORB to AN Elbow	SS-6801-08-08	$28.49	2
	AN Elbow	5482K25	$21.44	2
	AN Cross	5482K247	$32.60	1
	AN Elbow	5482K27	$33.96	2
	SAE-ORB Female Tee		$100.00	2
	Reducing Bushing		$83.00	2
	Reducing Bushing		$83.00	2
	SAE-ORB Female Cross		$103.00	2
	MNPT to AN/JIC	SS-6400-24-24	$66.37	6
	SAE-ORB to AN/JIC Elbow	SS-6801-24-24	$110.62	2
	SAE-ORB to SAE-ORB Male Union	SS-6407-24-24	$106.59	1
	AN/JIC Male Union	50715K735	$135.00	2
	Plastic Tube (Push Connect to MNPT)	5779K109	$3.08	29
	AN tee with SAE-ORB	SS-6803-12-12-12	$110.57	2
	SAE-ORB to AN	SS-6400-12-12	$18.75	10
	AN Tee	5482K55	$80.00	2
	Plastic Tube Tee (Push Connect)	5779K34	$4.75	1
	Plastic Tube Cross (Push Connect)	5779K786	$7.83	3
	Tube Nut	5482K75	$3.50	22
	Tube Sleeve	5482K82	$1.40	22
	Tube Nut	5482K77	$6.60	12
	Tube Sleeve	5482K84	$2.44	12
	Tube Nut	SS-318-24	$44.99	12
	Tube Sleeve	SS-319-24	$19.55	12
	Tube Nut	5482K78	$14.80	24

	Tube Sleeve	5482K85	$6.40	24				
Total		$5,063.93						
Electronics and Sensors	$11,835.15							
Structures	$5,848.39							
Plumbing	$23,617.10							
Spare Maintenance	$4,000.00							
At-cost Engine Print	$15,000.00							
TOTAL BUDGET	$60,300.64							