SPACEPORT TORONTO X VIENNA

Base11 Space Challenge

STATIC-FIRE TEST APPROVAL REPORT

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Executive Summary

This report presents the design of the small scale test stand developed by TXV in Toronto, for the testing of a small-scale liquid bi-prop engine. This is part of the 2-part plan TXV is following towards it's ultimate goal of launching a liquid bi-prop rocket to space. Part 1 of the plan is the design and launch of a small liquid bi-prop rocket to an altitude of 30,000 ft, which would take place at one of various competitions such as Spaceport America Cup or Launch Canada. Once this is completed, the team can then fully shift its focus towards the full scale rocket. In addition to the test stand design, this report presents all the procedures required to safely conduct a hot-fire test. Given that this report is meant to present the safety critical elements of the test-stand design, detailed engineering design elements (i.e. the CFD used for analysing the injector performance, the bus systems design for avionics, the detailed FEA analysis on the thrust structure, etc..) will be omitted.

In order to facilitate the launch of the small rocket, a small scale test stand was developed to test a liquid engine in the range of 2000-3000N of thrust. This engine would have a short burn time of around 10-15s, and would require small quantities of propellants and high pressure fluids. This facilitates a safe and staggered development process, which the team will rely on to learn all there needs to be learned about the development of liquid engines. The team is also working on the design of a full scale test stand, which is expected to be constructed and finished mid-2020.

In addition to the liquid rocket project, the University of Toronto Aerospace Team has been developing a hybrid rocket to break the Canadian Amateur Altitude Rocketry record since 2017. Due to university constraints on the team's ability to test on university ground, and due to the time it took to obtain university approval for hot fire testing, the team has chosen to pursue a mobile test stand approach until mid-2020. In the meantime, the team is also pursuing a full-scale permanent test stand at the University of Toronto Institute for Aerospace Studies, which will be funded by the Engineering Dean's Strategic Fund. The full scale test stand proposal has been approved by the university's engineering dean, director of risk management and chief building officer, and is under design work by the university's projects department. Due to winter construction constraints and university approved contractor availability, this test stand will not be completed until mid-2020, (around mid June). Thus, in order to start engine testing as soon as possible, the liquid rocket team has opted to modify the hybrid engine test stand and utilize it as much as possible, in a small scale capacity, until the full scale test stand is available in mid-2020. This means that many design decisions were made as a result of being constrained to the existing and planned infrastructure for the hybrid test stand, and although this may not be *ideal* for the liquid engine (unconventional tank setup, tall tank frame, etc...), it has been deemed safe for small scale testing. To put things into perspective, the proposed small scale engine is expected to produce around 2500N of thrust, and the propellant tanks are expected to see a maximum working pressure of around 522 psi. In comparison, the hybrid engine is expected to produce around 6500N of thrust, with maximum working pressures of 900 psi. Given that all hybrid systems were designed with a minimum safety factor of 2, the liquid systems will thus have even larger safety factors. Communications with Base11 have indicated that the submission of the small scale test stand is sufficient for the time being, and a copy of the communications can be provided to the judging committee if needed. A report on the full scale test stand will be available in the upcoming months.

Preface

This document was heavily focused towards the safety critical items related to the test stand design. More specifically, things like testing procedures, safety analysis, risk and failure mode analysis were performed and presented in a very detailed manner. However, certain items were not presented in a thorough manner for various reasons. We would like to acknowledge the following areas of improvement in our report:

Electronic Control and Telemetry System (ECTS)
We will outline in detail the following safety capabilities built into our electronic control and telemetry system, which is the system that automatically and remotely controls the functionality of the test stand:

- Internal Safety Prioritization System: A system that analyzes the status of the test stand at each step of the process and determines if a go - no-go is issued for the next step. The system is automated although has human-in-the-loop and full over-ride capabilities.
- Auto-abort scenarios: Discuss the abort-test scenarios in more details and how the ECTS utilizes those abort scenarios to make go-no go decisions. Alot of those scenarios have been covered in the risk analysis section.
- Remote control capabilities: Discuss the system's remote control capabilities
- Backup solenoid power systems: Discuss the design of a backup and independent power system that ensures critical solenoid valves (mostly vents and dumps) are always powered and can respond to command.

Member Safety and Training
We will include more detailed checklists and analyses regarding the safety of members and member education. Such include:

- Test Hazard Checklist from the TXV Safety Handbook. A checklist used by the safety officer and the test personnel to assess test conditions.
- Discuss the Visual Qualification Identification system (VQID) from the TXV Safety Handbook. A method for visually identifying the training and qualification each member has and thus their privileges on the test side.
- Include the member training plan

Procedures
A few procedures were not discussed in this report due to time constraints. Those are:

- Clean component assembly procedure using the specialized apparatus
- A few items that were recently added are missing from the assembly procedure, however, this doesn't not alter the assembly procedure in any significant way

Risk Analysis
The risk analysis performed so far is very comprehensive, however, there is more planned for future updates:

- Leak specific risks and the propagating effects of leaks on member/system safety and performance
- Individual component specific failure analysis (relief valve failure, gear pump jamming, etc...) that are not directly related to loss of power and/or control

- Coupled failures of 2 components and their effects of system, along with a containment strategy for each failure.

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1 Test Stand Design

This chapter presents the overall structural design of the small scale test stand. It discusses the major design decisions that went into providing the design as it currently is. A few sample CAD pictures are provided to illustrate the design. The CAD was attached with the submission for closer inspection.

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1.1 Structure

Figures 1.1, 1.2, 1.3, and 1.4 provide 4 different views of the overall test stand CAD.

1.1.1 Fluid System Frame

The fluid system frame is comprised primarily of HSS steel tubing that we will have professionally welded together. This frame was chosen as it is the same frame which the University of Toronto Aerospace Team's hybrid rocket test stand's oxidizer tank mount. Conveniently the oxidizer tank of the hybrid rocket is so large that the support frame which holds it can house our entire run system. The frame's base will be bolted to the metal deck of the trailer used to transport it. Those frame pieces which are not HSS tubing will be attached via bolted connections. The Oxidizer and fuel run tanks are supported by water jet cut brackets sized to fit around the OD of the tanks with a small amount of clearance (0.08" clearance on the diameter in order to prevent excessive rattling during firing while not impeding on the load cells' ability to accurately measure the tank masses. The Oxidizer and fuel run tanks sit on four 3/8" pegs (four pegs per tank). Loose fit locating 0.1" holes will be machined into the bottom caps in order to ease assembly and ensure the tanks stay centered over the load cells. The nitrogen tank, unlike the fuel and oxidizer tanks, sits upright on its flat bottom at the base of the frame. High strength strapping will be used to secure it to one of the two vertical HSS members nearest the rear of the frame (ie closer to the trailer hitch). The frame also holds the 1/8" thick blast shielding used to shield the fluid run system from a possible engine failure. A minimal gap in the shield is provided for routing the propellant delivery lines to the injector manifold. Not shown in the frame CAD (due to time constraints) are a second set of tank brackets for both the fuel and oxidizer run tanks. Currently both tanks are supported at with only one set of brackets each in order to demonstrate the design, however two sets will be used per tank at two different points along each respective tank's height to prevent excessive rattling. Figures 1.5, 1.6, and 1.7 illustrate the frame's design.

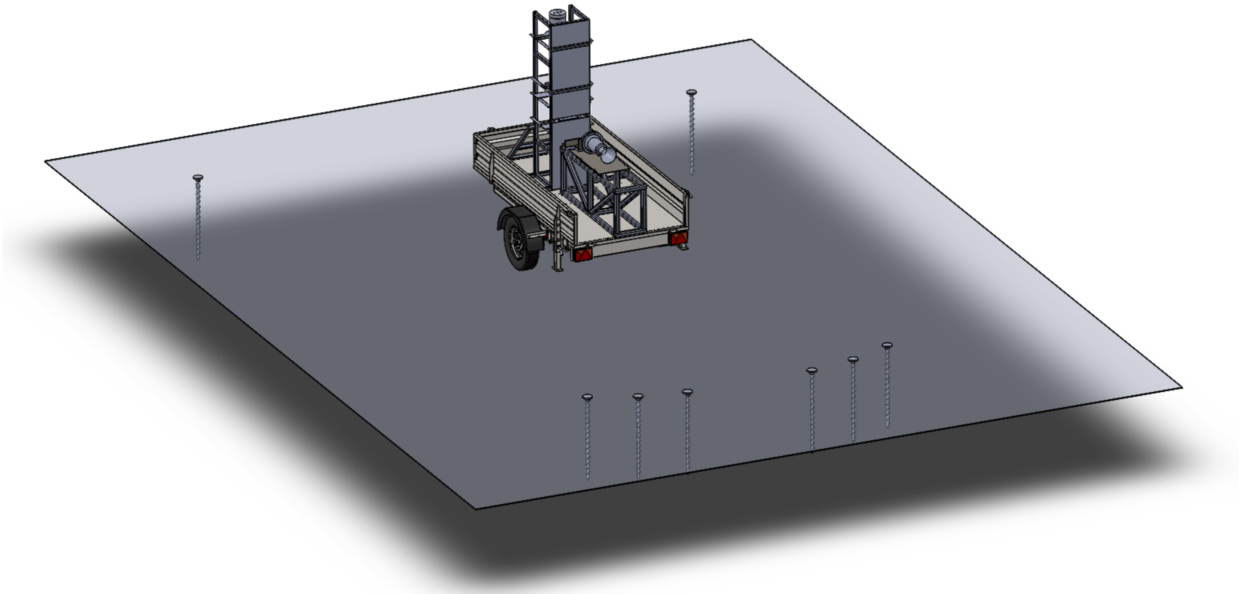

Figure 1.1: Test stand structure with ground anchor positioning ISO VIEW

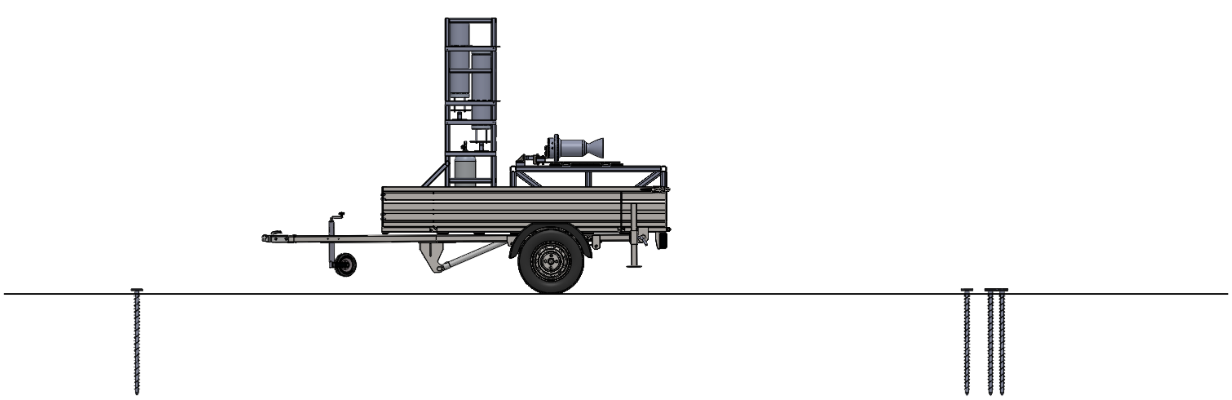

Figure 1.2: Test stand structure with ground anchor positioning SIDE VIEW

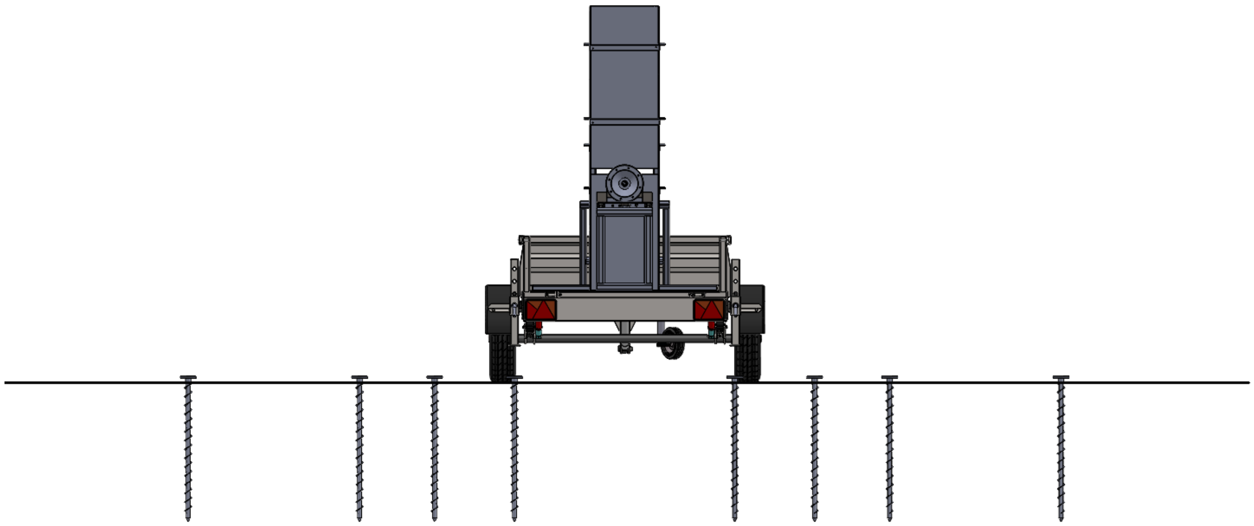

Figure 1.3: Test stand structure with ground anchor positioning BACK VIEW

1.1.2 Thrust Structure

Similar to the fluid system frame, the thrust structure will also be borrowed from the hybrid rocket project. However, in this case absolutely no modification to the frame was made. This was deemed the best and safest course of action since the original thrust structure was designed to bear the thrust of the hybrid rocket's 6.5 kN hybrid rocket engine, and so will provide more than enough support for 2.5 kN expected to be exerted by Houbolt Jr's engine. Like the fluid system frame, this too will be bolted to the metal deck of the trailer. However it is important to note that these bolts or for transportation purposes only. Thrust loads will be absorbed by the ground anchors through pre-tensioned steel cables. The engine is bolted through the injector assembly to the main thrust plate. All three of these sit on the engine mounting plate, which is a flat aluminum sheet that sits on two linear rails. These rails absorb the weight of the engine and thrust plate assemblies and provide a low friction sliding joint to allow the main thrust measuring load cell to accurately measure the thrust of the engine during the burn. Figures 1.8, 1.9, and 1.10 illustrate the design of the thrust structure.

1.1.3 Ground Anchors

The ground anchors are essentially large screws that penetrate 36" into the ground to provide solid anchor points for cables. We plan to use eight PE36 "Penetrator" ground anchors from American Earth Anchors. Six of these anchors will be used for absorbing the thrust loads while the other two will be placed in front of the test stand in order to provide pretension on the thrust cables and in order to constrain the test stand in all directions. For maximum safety, the ground anchor calculations were performed assuming the thrust loads would be directly in line with the axis of the anchors (ie the thrust would be trying to pull them straight out of the ground) when in fact the will be nearly perpendicular (ie the anchors will be cantilevered. The CAD assembly of the test stand (Houbolt Jr Test Stand.SLDASM) shows how deep into the ground they will be driven. Additionally, for the ground anchor calculations the soil type was assumed to be the worst case scenario of loose fine sand, providing a pullout force per anchor of about 1.55 kN. divided among six anchors this yields a safety factor of over 3.7, which is more than sufficient given the the extremely conservative assumptions. Pretensioning will be achieved

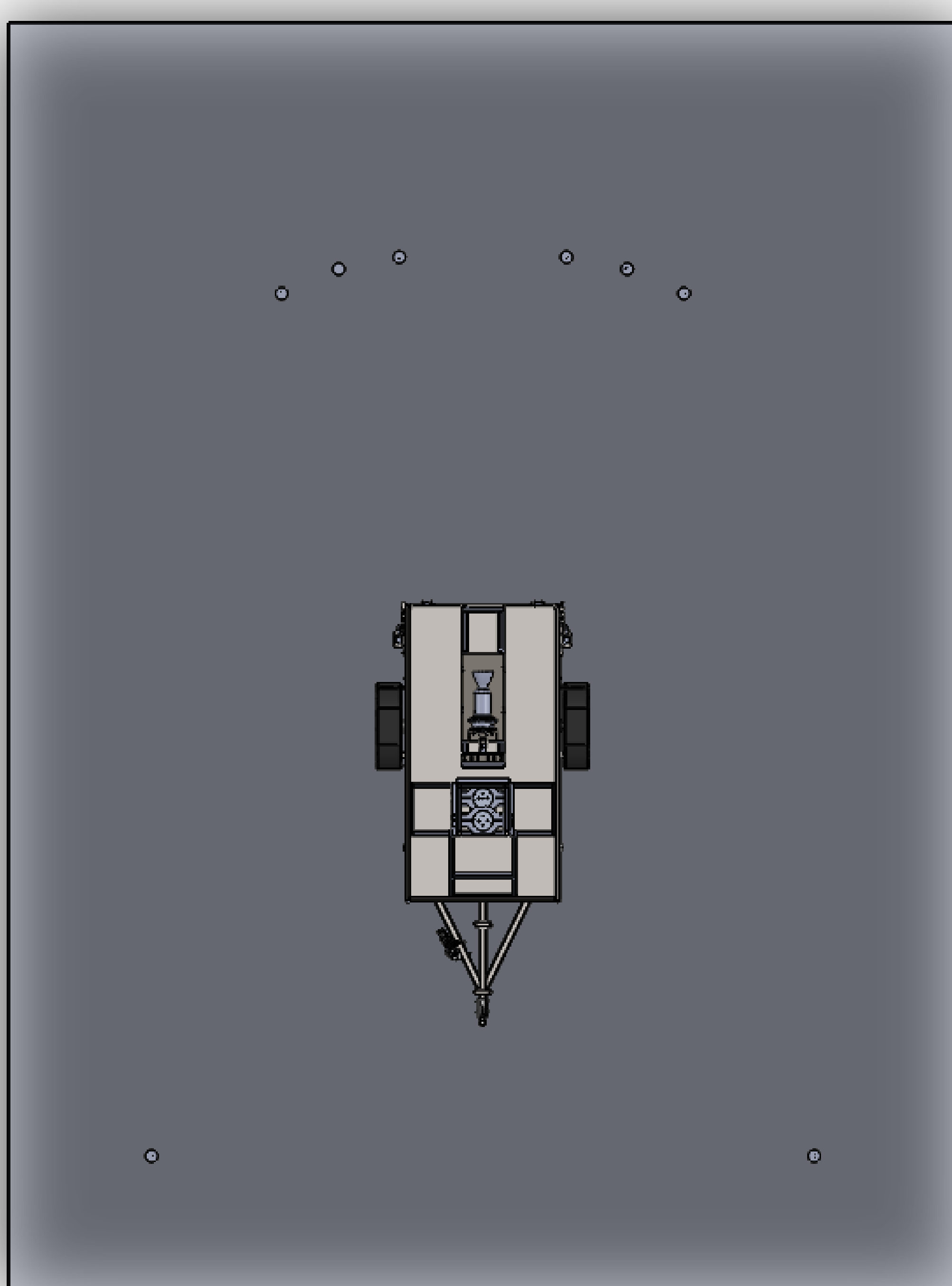

Figure 1.4: Test stand structure with ground anchor positioning TOP VIEW

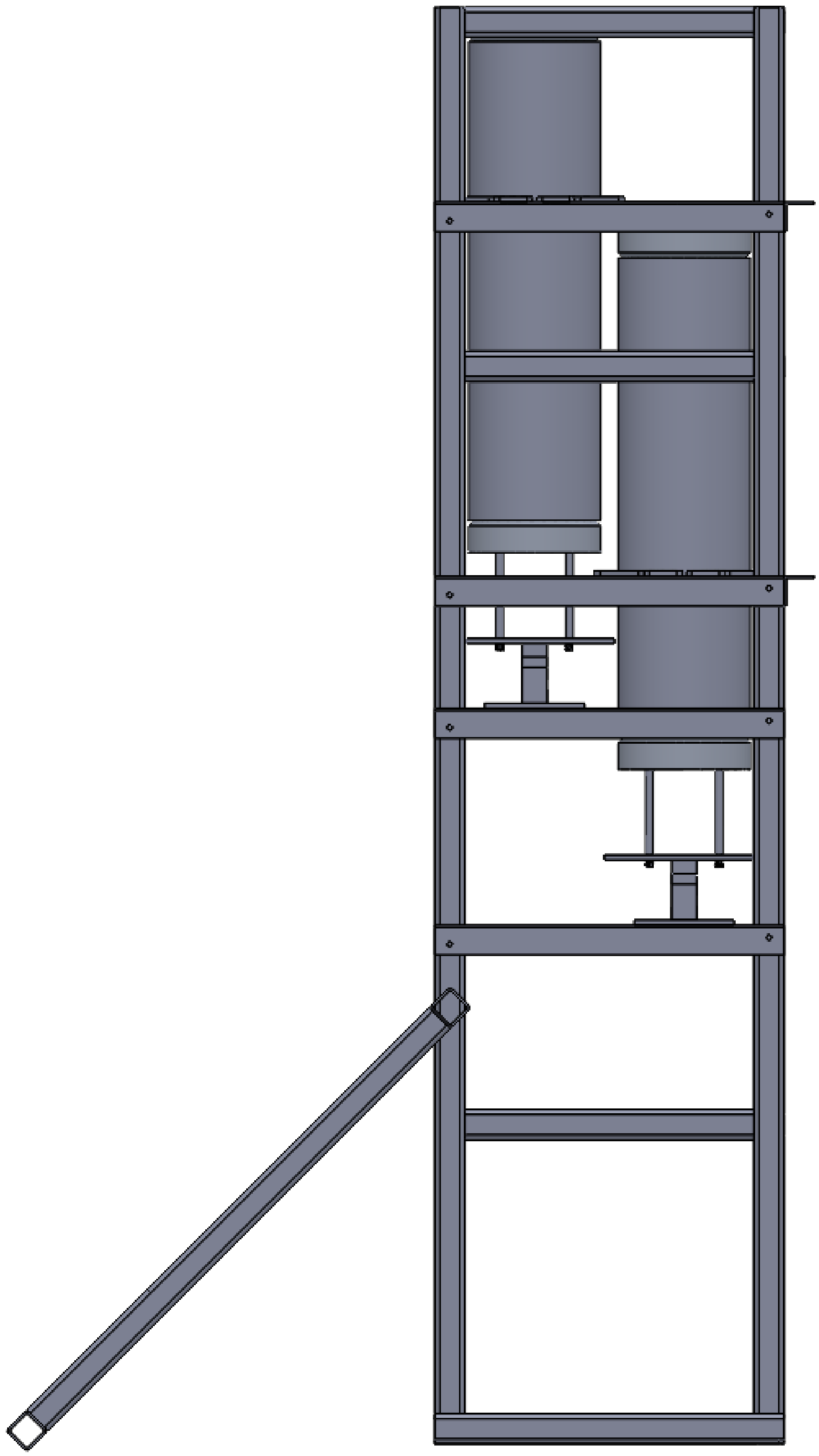

Figure 1.5: Fluid system frame SIDE VIEW

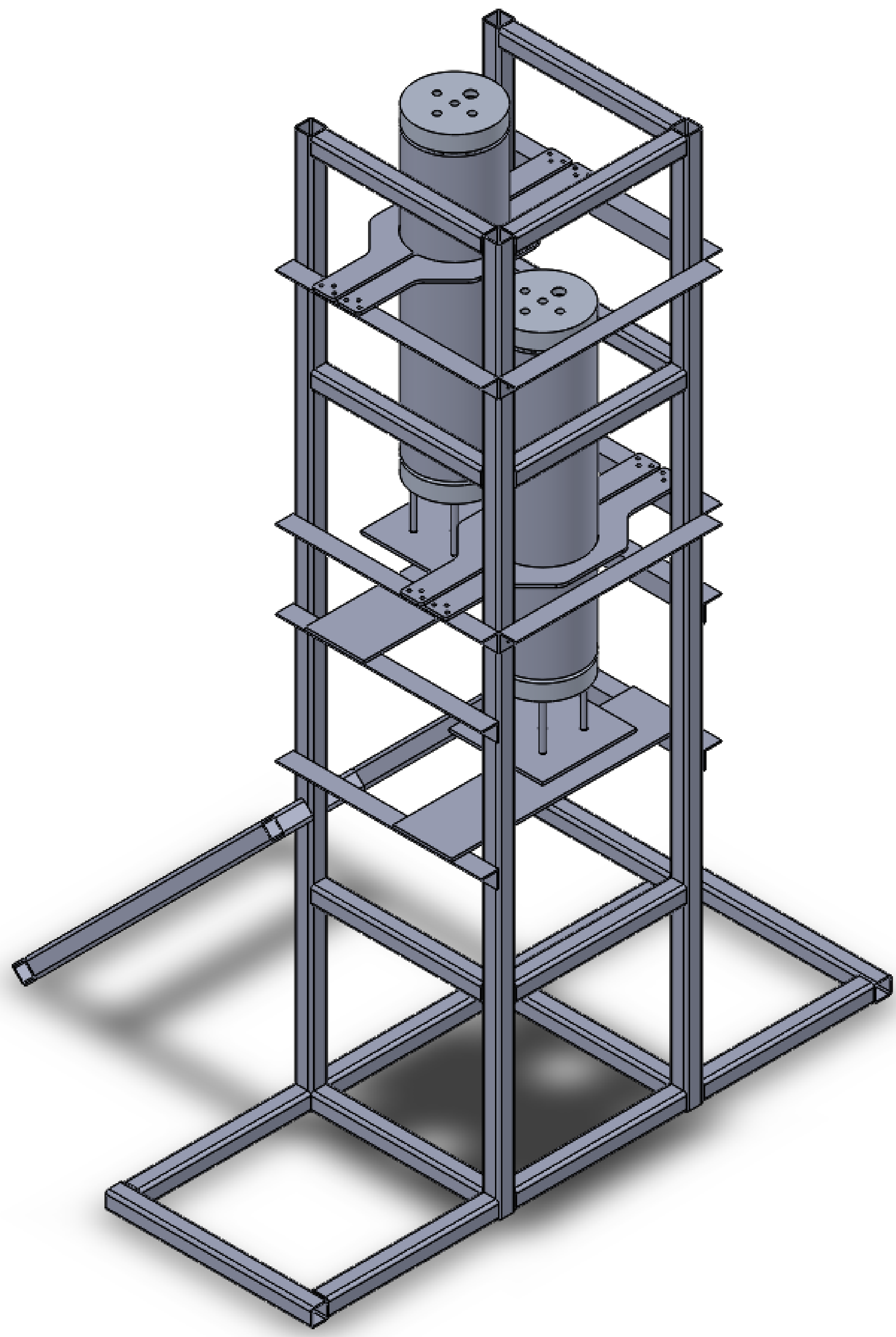

Figure 1.6: Fluid system frame ISO VIEW

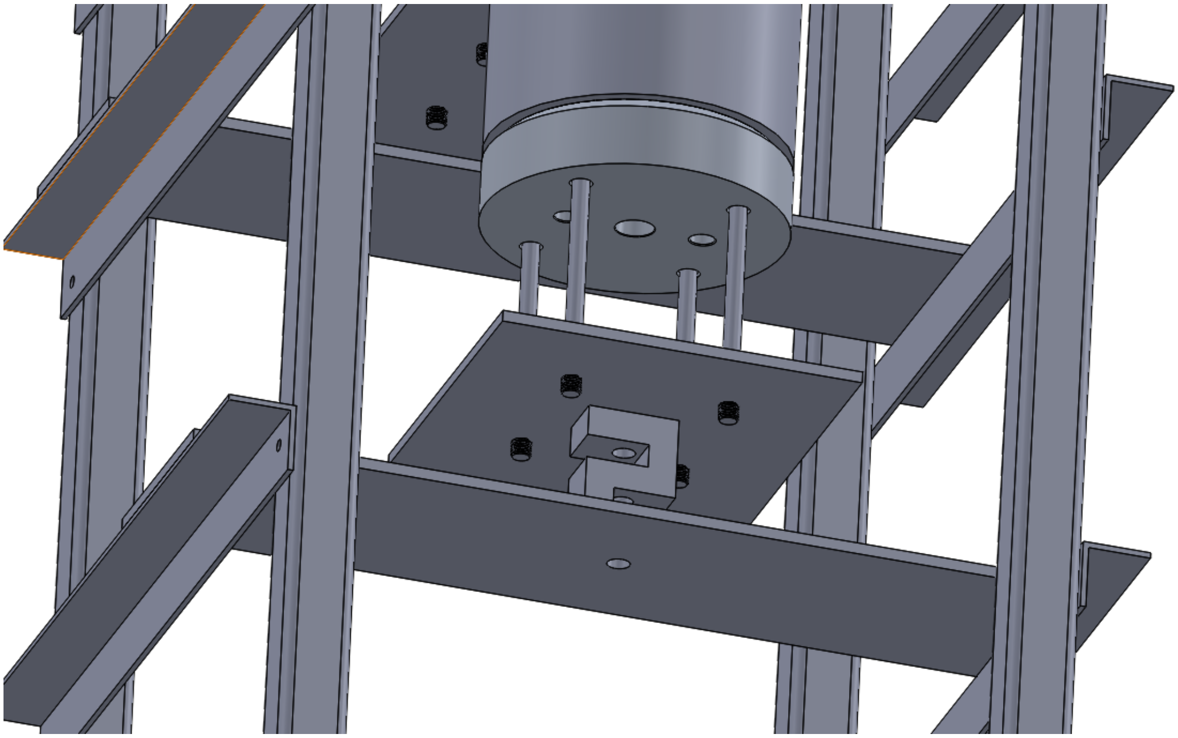

Figure 1.7: Fluid system frame - Tank mass measurement setup

using turnbuckles int erupting the steel cabling running from the ground anchors to the thrust structure and/or trailer.

1.2 Run Tanks

1.2.1 Tank Geometries

The fuel and Oxidizer run tanks were designed specifically as test tanks rather than flight tanks and so were designed for maximum safety, ease of assembly, and low cost. Both tanks are geometrically identical in order to simplify manufacturing and reduce costs. Each tank will be made of a 2ft section of 6061-T6 aluminum NPS 6 Schedule 40 pipe which provides a hoop stress factor of safety of over 6.5 (w.r.t an MAWP of 3.96 MPa). The ends will be capped with two custom machined professionally welded end caps. The ports on the bottom and top of the caps are properly reflected in the PID. Some connections used by the oxidizer (eg one of the 1/4" NPT ports on the bottom cap) are not used by the fuel and will be plugged. The nitrogen run tank is the simplest of all three run tanks as it is a standard 12L SCUBA tank rated for a nominal operating pressure of a little over 30 MPa.

1.2.2 Tank Arrangement

Priority was given to the oxidizer tank during the arrangement of the tanks in the frame. This is in order to minimize the length of plumbing between the oxidizer tank exit and the oxidizer port on the injector manifold. Liquid nitrous oxide is incredibly sensitive to pressure drops and easily cavitates, which at best reduces performance, or at worst traps pockets of gaseous nitrous oxide in the system during operation

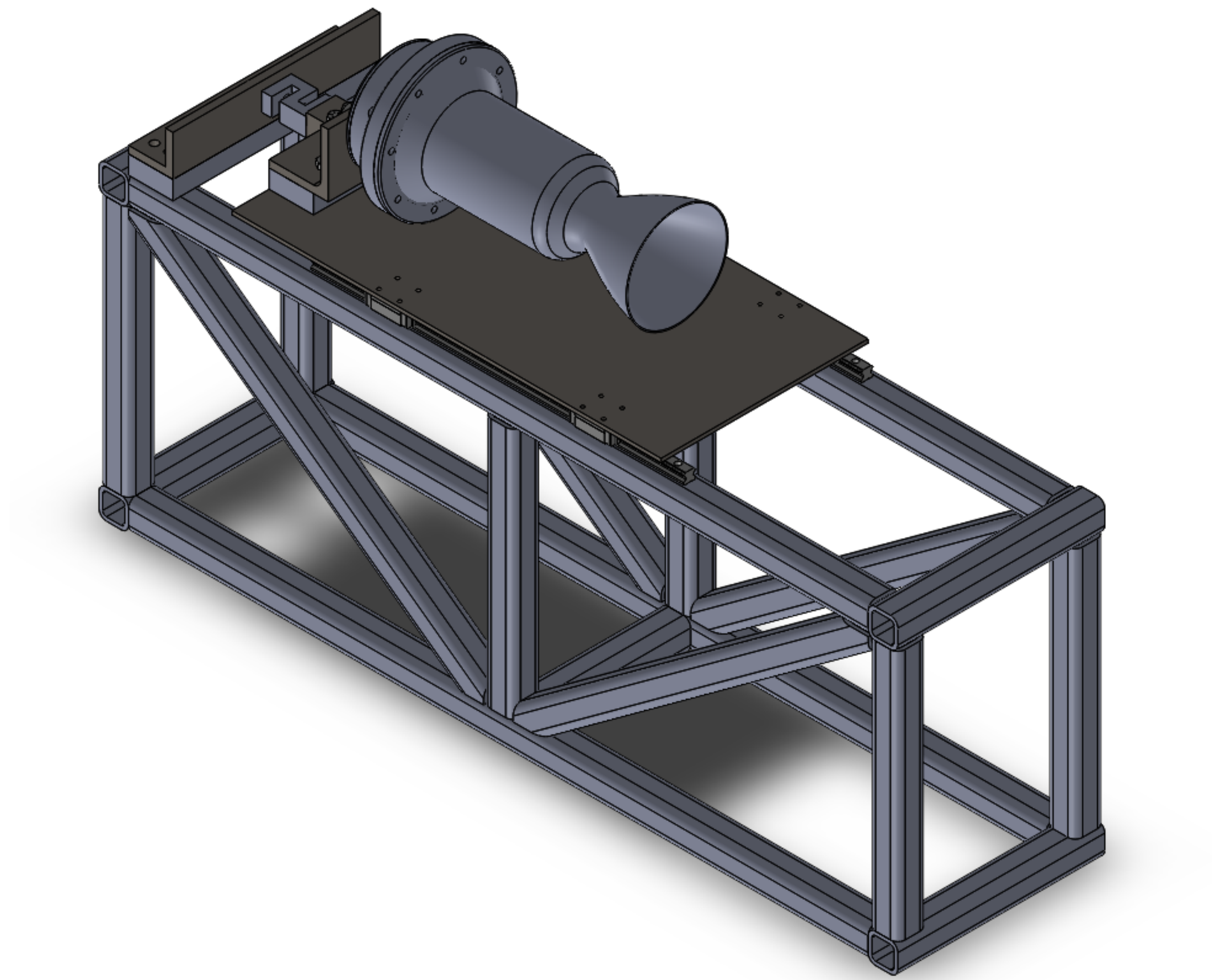

Figure 1.8: Thrust structure ISO VIEW

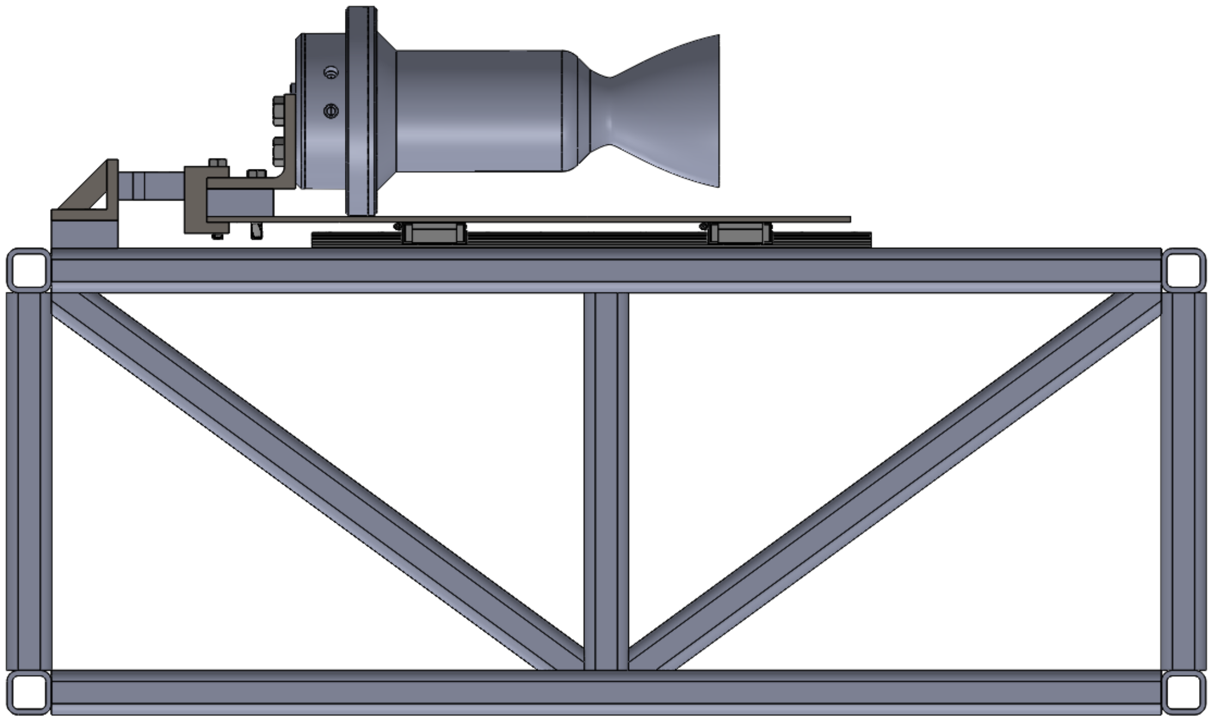

Figure 1.9: Thrust structure Side VIEW

which pose an increased risk of decomposition. Thankfully, the placement of the ethanol tank was not very critical as it is being pump fed. The gear pump chosen is rated to be able to sustain exit pressures of up to 250 bar. This affords us the freedom to use less direct routing for the fuel without much risk of performance reduction (at least not for the test stand). The only real affect this has is on the power draw of the pump's power head. It was placed above and behind the nitrous tank so that it's mounting frame and load cell structure would not interfere with those of the oxidizer tank, and to leave room at the bottom of the frame for the comparatively tall nitrogen run tank. The pump itself will be mounted closer to the blast shield gap mostly for routing convenience.

1.3 Engine Assembly

The engine assembly may seem peculiar, however it is important to understand that it was designed solely to test the chamber material and injector design. Many of its features will not be included on the final flight model. Two prominent examples of such features are the large bolt holes for mounting to the thrust plate and the annular water cooling channel used to supplement the poor cooling capability of the ethanol fuel. The injector itself is a single element oxidizer centered pintle and has been designed to maximize customizability in order to facilitate rapid iterative design. For example, the central pintle element itself can be unscrewed using a standard socket wrench without disassembling any other part of the injector manifold so that new geometries can be quickly and easily swap ed out. The chamber wall is clamped at the edge of the injector manifold assembly through providing a metal-metal seal between the aluminum of the injector assembly and the Dragon Scale metal matrix composite combustion chamber and nozzle. The light weight nature of this MMC chamber is what allows it to be hung off the end of the injector manifold as can be seen in the CAD.

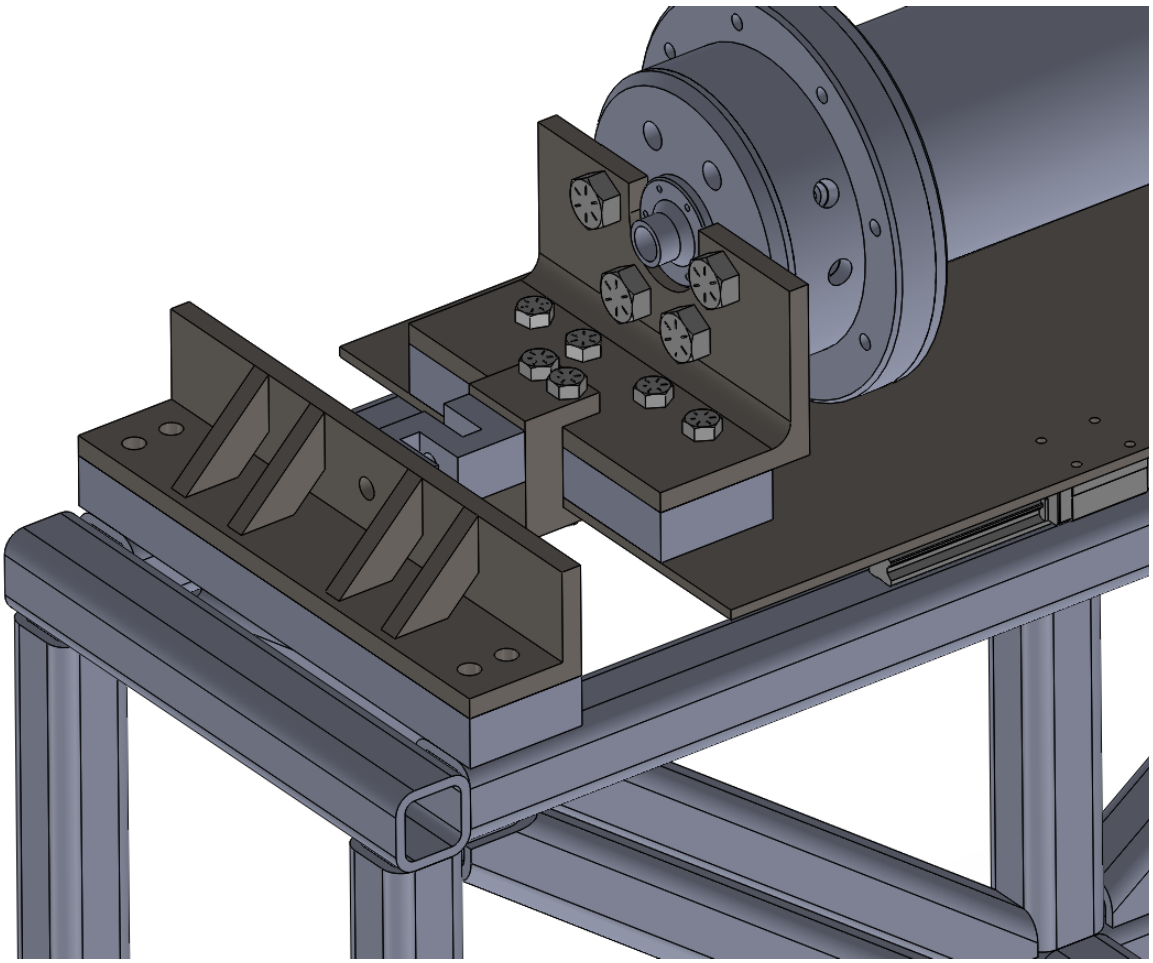

Figure 1.10: Thrust structure - Close up on load cell setup

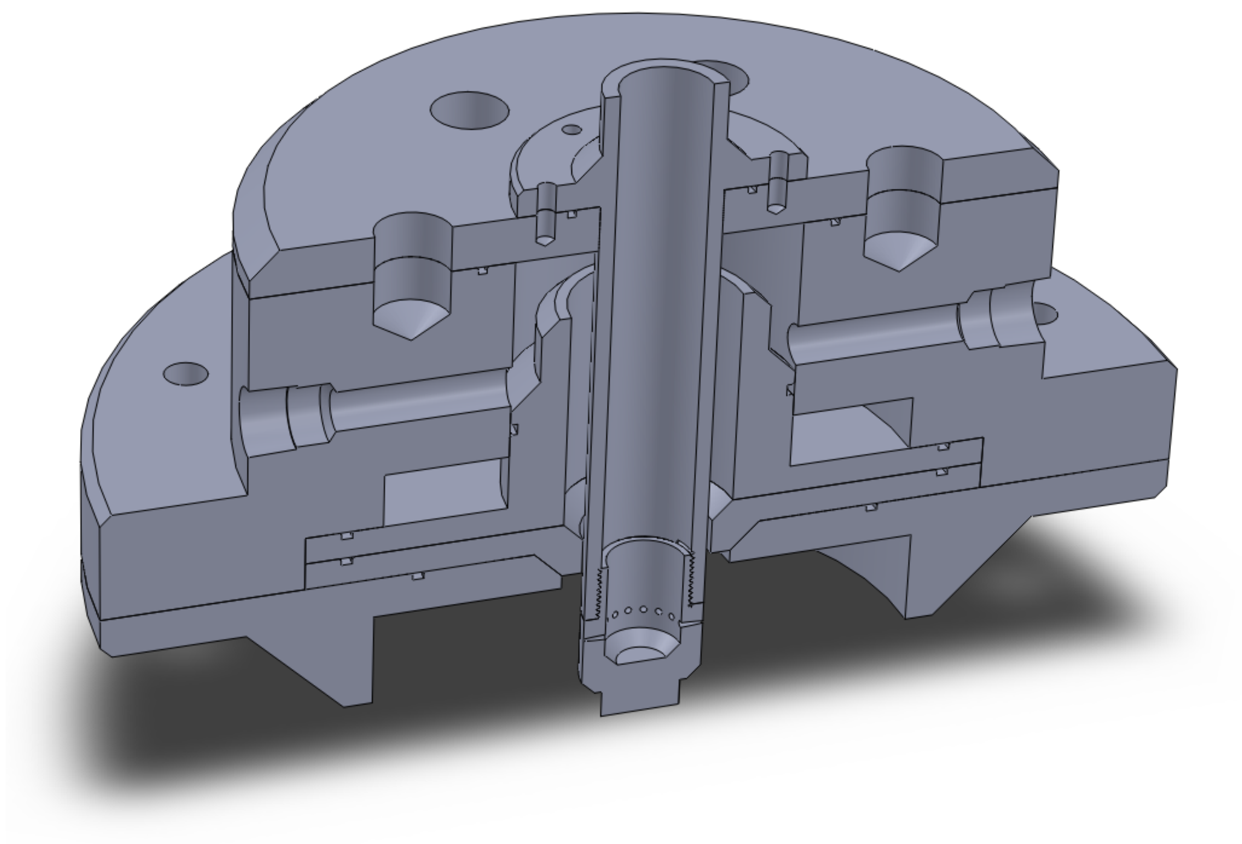

Figure 1.11: Pintle injector design

2 Fluid Systems Design

This section presents the fluid system design for the TXV small scale test stand. The fluid layout is presented in a **`Plumbing and Instrumentation Diagram`**

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2.1 Fluid Systems Layout

2.1.1 Plumbing and Instrumentation Diagram (P&ID)

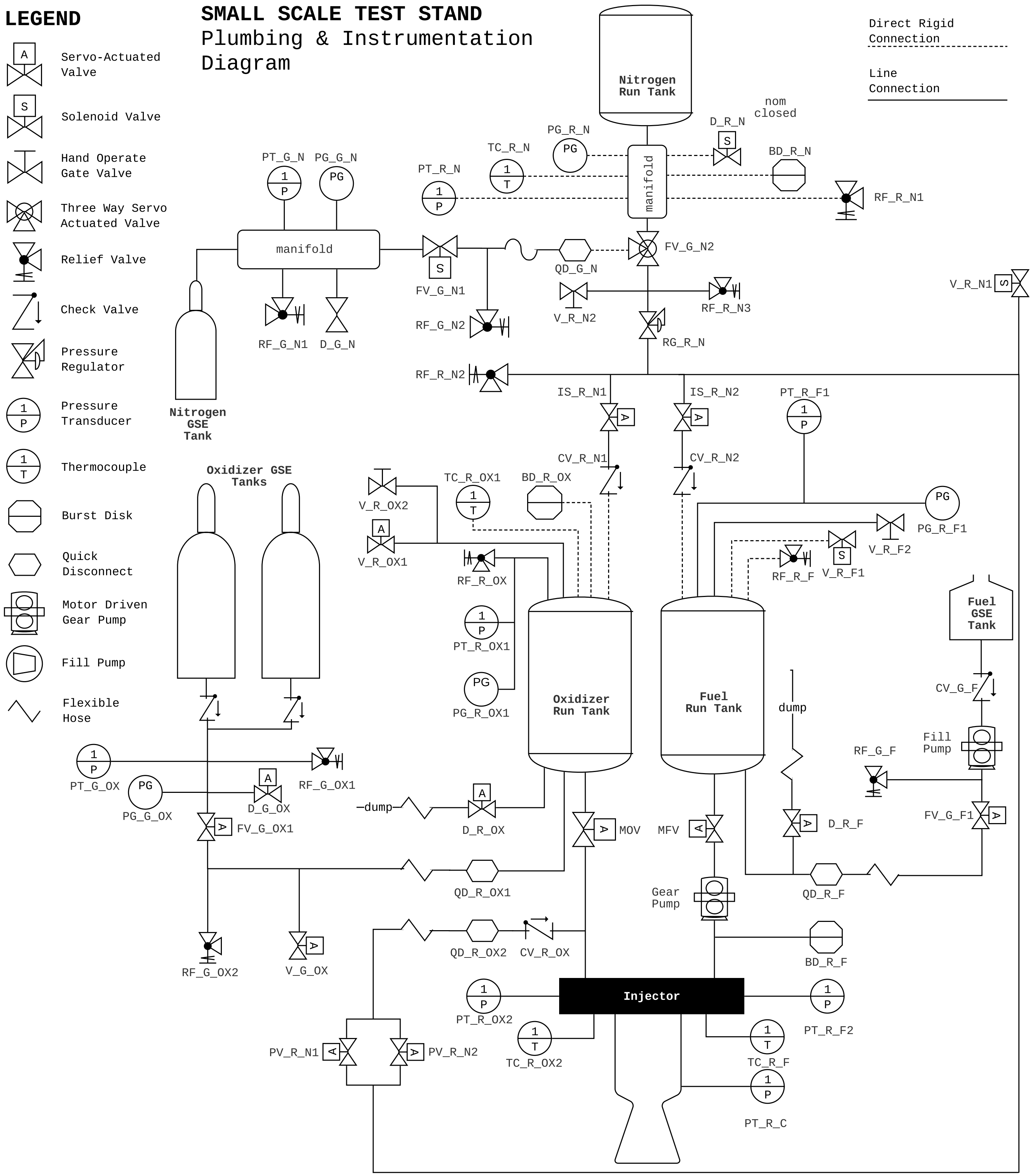

Figure 2.1: Plumbing and Instrumentation Diagram

2.1.2 P&ID Part Descriptions

Part ID	Name	Purpose	Initial State	Nominal state (unpowered)
RF_G_N1	Nitrogen GSE tank relief valve	Spring loaded relief valve to preotect nitrogen GSE tank from overpressure. Set pressure is 34.1 Mpa. Max orifice area is TBD sq.mm	Closed	Dependant on conditions
RF_G_N2	Nitrogen fill line relief valve	Spring loaded relief valve to preotect nitrogen fill line from overpressure. Set pressure is 33 Mpa. Maximum orifice area is TBD sq.mm	Closed	Dependant on conditions
RF_R_N1	Nitrogen run tank relief valve	Spring loaded relief valve to preotect nitrogen run tank from overpressure. Set pressure is 33 Mpa. Max orifice area is TBD sq.mm	Closed	Dependant on conditions
RF_R_N2	Nitrogen regulated line relief valve	Spring loaded relief valve to preotect nitrogen lines between the regulators and the isolation valves from overpressure. Set pressure is 3.96 Mpa. Max orifice area is TBD sq.mm	Closed	Dependant on conditions
RF_R_OX	Oxidizer run tank relief valve	Spring loaded relief valve to preotect the oxidizer run tank from overpressure. Set pressure is 3.96 Mpa. Max orifice area is TBD sq.mm	Closed	Dependant on conditions
RF_G_OX1	Oxidizer GSE tank(s) relief valve	Spring loaded relief valve to preotect the oxidizer GSE tank(s) from overpressure. Set pressure is TBD Mpa. Max orifice area is TBD sq.mm	CLosed	Dependant on conditions
RF_G_OX2	Oxidizer fill line relief valve	Spring loaded relief valve to preotect the oxidizer fill line from overpressure. Set pressure is TBD Mpa. Max orifice area is TBD sq.mm	Closed	Dependant on conditions
RF_R_F	Fuel run tank relief valve	Spring loaded relief valve to preotect the fuel run tank from overpressure. Set pressure is 3.63 Mpa. Max orifice area is TBD sq.mm	Closed	Dependant on conditions

RF_G_F	Fuel fill pump relief valve	Spring loaded relief valve to preotect the line between the fill pump output and the fuel fill valve from overpressure. Set pressure is 137 kPa, which is 1.1 times the hydrostatic pressure of 3 m of ethanol. 3 m was chosen as it is not so high as to require the fuel fill system (prior to and excluding the fill valve) to be rated for high pressure (eg in the MPa range) but not so low as to inconveniently restrict where/how we mount the fuel run tank. Max orifice area is TBD sq.mm	Closed	Dependant on conditions
RG_R_N	Notrogen pressure reducing regulator	Pressure reducing regulator to reduce the nitrogen run tank pressure down to 3.6 Mpa for use as propellant presurant and system purging. Maximum flow rate is 50 SCFM for a nitrogen run tank nominal operating pressure of 30 Mpa.	Closed (ambient pressure down and upstream)	Dependant on conditions
FV_G_N1	Nitrogen fill valve	A solenoid valve with two 1/4" female NPT ports. It is rated for 34.1 MPa MAWP and has a flow factor of TBD.	Closed,	Closed
FV_G_N2	Nitrogen line select valve	A servo actuated 3-way ball valve for switching the nitrogen run tank, its safety equipment, and its instrumentation, between the fill line and the line running to the nitrogen pressure reducing regulator RG_R_N. All ports are 1/4" NPT, with the unchanging port being connected to the nitrogen run tank. This allows us to isolate the feed system during the test and also provides redunandant isolation in the, albeit unlikely, event that FV_G_N1 fails open. Rated for 34.1 MPa MAWP.	Fill position	Latching

FV_G_OX1	Oxidizer fill valve	Servo actuated, full bore, stainless steel ball valve with 1/4" NPT female ports. Rated for TBD Mpa MAWP. This valve is used to control the flow of the oxidizer from the oxidizer GSE tank(s) to the oxidizer run tank during the filling process.	Closed	Latching
FV_G_OX2	Oxidizer injector manifold purge valve			
FV_G_F	Fuel fill valve	Servo actuated, full bore, stainless steel ball valve with 1/4" NPT female ports. Rated for 3.96 Mpa MAWP. This valve is used to control the flow of the fuel from the fill pump to the fuel run tank during the filling process.	Closed	Latching
D_R_N	Nitrogen run tank dump valve	Solenoid valve with 1/4" NPT ports rated to 33 Mpa MAWP. Used for post burn purging/dumping, emergency dumping, and loss of power fail-safe dumping of the nitrogen run tank. Has a flow factor of TBD.	Open	Open
D_R_F	Fuel run tank dump valve	Servo actuated stainless steel ball valve with 1/4" NPT ports rated for 3.96 Mpa MAWP. This serves as an primary means of dumping any remaining fuel during post burn purging, but does not serve as the emergency depressurization valve (see V_R_F1 and 2). Prior to the burn, so long as the ullage is vented, there are very few, if any, emergency scenarios where dumping the full tank of liquid fuel would be safer than leaving it in the vented tank, hence why a servo actuated valve was chosen over a nominally open solenoid valve or other nominally open valve options.	Closed	Latching

D_R_OX	Oxidizer run tank dump valve	Servo Actuated stainless steel ball valve with 1/4" NPT ports rated for 3.96 Mpa MAWP. This serves as the primary means of dumping remaining liquid oxidizer during post burn purging. A latching or latching style valve is preferred due to the temperature sensitive nature of liquid oxidizers. Unpowered redundancy is provided by V_R_OX2 in the case of a loss of power.	Closed	Latching
D_G_OX	Oxidizer GSE tank(s) dump valve	Manual stainless steel ball valve with 1/4" NPT female ports rated for TBD Mpa MAWP. Serves as an unpowered means of dumping the oxidizer GSE tank(s) in an emergency or for venting the oxidizer fill system in order to remove empty oxidizer GSE tanks for refilling.	Closed	Manual Valve
D_G_N	Nitrogen GSE tank dump valve	Manual stainless steel ball valve with 1/4" NPT female ports rated for 34.1 MPa MAWP. Serves as an unpowered means of dumping the nitrogen GSE tank in an emergency or for venting the nitrogen fill system in order to remove an empty nitrogen GSE tank for refilling.	Closed	Manual Valve
V_G_OX	Oxidizer fill line vent valve	Solenoid valve with 1/4" NPT ports rated to TBD Mpa MAWP. Used for post burn purging/dumping, emergency dumping, and loss of power fail-safe dumping of the nitrogen run tank. Has a flow factor of TBD.	Closed	Closed
V_R_OX1	Oxidizer run tank vent valve	Servo actuaed stainless steel ball valve with 1/4" NPT female ports rated for 3.96 Mpa MAWP. Used during filling to vent nitrogen displaced by liquid oxidizer. Additionally provides quick way to drop temperature oxidizer if temperature begins rising faster than oxidizer tank conditioning system can control.	Closed	Latching

V_R_OX2	Oxidizer run tank manual vent valve	Manual stainless steel ball valve with 1/4" NPT female ports rated for 3.96 Mpa MAWP. Serves as redundant, unpowered means of venting oxidizer run tank.	Closed	Manual Valve
V_R_F1	Fuel run tank vent valve	Solenoid valve with 1/4" NPT ports rated for 3.96 Mpa MAWP. This serves both as a means of venting displaced nitrogen during the fuel filling process and as a fail-safe means of depressurizing the fuel tank.	Open	Open
V_R_F2	Fuel run tank manual vent valve	Manual stainless steel ball valve with 1/4" NPT female ports rated for 3.96 Mpa MAWP. Serves as redundant, unpowered means of venting fuel run tank.	Closed	Manual Valve
BD_R_N	Nitrogen run tank burst disc	Secondary means of over pressure protection. Burst pressure is set to 36 Mpa (1.2 times nitrogen run tank nominal operating pressure). Connects via 1/2" male NPT threads. Flow rate at 36 Mpa internal pressure TBD kg/s. Made of stainless steel.	Intact	Dependant on conditions
BD_R_OX	Oxidizer run tank burst disc	Secondary means of over pressure protection. Burst pressure is set to 4.32 Mpa (1.2 times oxidizer run tank nominal operating pressure). Connects via 1/2" male NPT threads. Burst orifice has flow factor of TBD. Made of stainless steel.	Intact	Dependant on conditions
BD_R_F	Fuel gear pump burst disc	Stainless steel burst disc rated to burst at TBD MPa. Connects via 1/2" NPT male threds. Burst borifice has a flow factor of TBD. Provides over pressure protection to the line between the output of the gear pump and thefuel injector manifold. This is standard practice for positive displacement pumps. A burst disc was selected over a relief valve due to the high flow rates expected from the pump outlet during hot fire testing.	Intact	Dependant on conditions

MOV	Main oxidizer valve	Servo actuated, stainless steel, full bore ball valve rated for 3.96 MAWP. Controls flow of liquid oxidizer from oxidizer run tank to injector manifold.	Closed	Latching
MFV	Main fuel valve	Servo actuated, stainless steel, full bore ball valve rated for 3.96 MAWP. Controls flow of liquid fuel from fuel run tank to gear pump.	Closed	Latching
Pump, Gear	Gear pump	Positive displacement gear pump powered by DC electric motor that pumps fuel from the fuel run tank to the injector manifold at a roughly constant flow rate. Pumps TBD L/s of fuel during nominal operation.	Off	Off
Pump, Fill	Fill Pump	Positive displacement pump powered by DC electric motor that pumps fuel from the fuel GSE tank to the fuel run tank during fuel filling process. Fuel run tank vent will be open during this process, so the pump does not need to operate at high pressure, only at a pressure high enough to move the fuel from one tank to the other and account for the increase in elevation. Pumps TBD L/s of fuel during nominal operation.	Off	Off
CV_R_N1	Oxidizer pressurant check valve	Prevents liquid and vapour in the oxidizer run tank from flowing backward into the pressurant feed line.	Closed	Dependant on conditions
CV_R_N2	Fuel pressurant check valve	Prevents liquid and vapour in the fuel run tank from flowing backward into the pressurant feed line.	Closed	Dependant on conditions
CV_G_F	Fuel GSE tank check valve	Prevents any possible back flow from the fuel fill system back into the fuel GSE tank. Any fuel that leaves the GSE tank is considered contaminated in so far as it should either be used for a hot fire test or discarded. This is to avoid any possibility of introducing contaminants into the GSE tank which serves as our long term fuel storage.	Closed	Dependant on conditions

CV_G_OX	Oxidizer GSE tank(s) check valve	Prevents any fluids from the fill or run systems from flowing back into the nitrous GSE tanks in order to avoid possible contamination of the tanks or stored oxidizer.	Closed	Dependant on conditions
FT_R_OX	Oxidizer run tank force transducer	For measuring mass of oxidizer in run tank during filling	N/A	N/A
FT_R_F	Fuel run tank force transducer	For measuring mass of fuel in run tank during filling	N/A	N/A
FT_R_C	Thrust measurement force transducer	For recording thrust during hot fire test	N/A	N/A
QD_R_OX	Oxidizer fill line quick disconnect	Provides a fast way to separate the oxidizer fill system from the run system in the event that modification, testing, maintenance, or reapirs to the oxidizer fill system are necessary. Both male and female sides of the connector have internal poppet valve which close when the two halves are disconnected. While unnecessary during initial testing, they are a crucial part of the flight planned flight system filling prcedure and as such must be tested to both ensure functionality, and train relevant personnel in their proper care and handling procedures.	Connected	N/A

QD_R_F	Fuel fill line quick disconnect	Provides a fast way to separate the fuel fill system from the run system in the event that modification, testing, maintenance, or reapirs to the oxidizer fill system are necessary. Both male and female sides of the connector have internal poppet valve which close when the two halves are disconnected. They are a crucial part of the planned flight system filling prcedure and as such must be tested to both ensure functionality, and train relevant personnel in their proper care and handling procedures. Additionally, they serve as means of purging the low pressure fuel fill system of air prior to the run tank filling process in a simple and verifiable way through use of the DFQD.	Connected	N/A
IS_R_N1	Oxidizer pressurant isolation valve	Servo actuate, stainless steel, full bore ball valve with 1/4" NPT female ports rated for 3.96 Mpa MAWP. This valve controls the flow of nitrogen into the oxidizer run tank during the burn.	Closed	Latching
IS_R_N2	Fuel pressurant isolation valve	Servo actuate, stainless steel, full bore ball valve with 1/4" NPT female ports rated for 3.96 Mpa MAWP. This valve controls the flow of nitrogen into the fuel run tank prior to the burn. During the burn it remains closed in order to simulate the intended flight tank conditions.	Closed	Latching
PT_G_N	Nitrogen GSE tank pressure transducer	For monitoring pressure in nitrogen GSE tank and fill system	N/A	N/A
PT_G_OX	Oxidizer GSE tank(S) pressure transducer	For monitoring pressure in noxidizer GSE tank(s) and fill system	N/A	N/A
PT_R_N	Nitrogen run tank pressure transducer	For monitoring pressure in nitrogen run tank	N/A	N/A

PT_R_OX1	Oxidizer run tank ullage pressure transducer	For monitoring pressure in oxidizer run tank ullage	N/A	N/A
PT_R_OX2	Oxidizer injector manifold pressure transducer	For monitoring pressure in oxidizer injector manifold	N/A	N/A
PT_R_F1	Fuel run tank ullage pressure transducer	For monitoring pressure in fuel run tank ullage	N/A	N/A
PT_R_F2	Fuel injector manifold pressure transducer	For monitoring pressure in fuel injector manifold	N/A	N/A
PT_R_C	Combustion chamber pressure transducer	For monitoring combustion chamber pressure during hot-fire test	N/A	N/A
TC_R_N	Nitrogen run tank thermocouple	For monitoring temperature in nitrogen run tank and used by nitrogen run tank temperature controller to maintain 5°C prior to the start of the ingnition sequence.	N/A	N/A
TC_R_OX1	Oxidizer run tank ullage temperature transducer	For monitoring temperature in oxidizer run tank and used by oxidizer run tank temperature controller to maintain 5°C prior to the start of the ingnition sequence.	N/A	N/A
TC_R_OX2	Oxidizer injector manifold thermocouple	For monitoring temperature of oxidizer just prior to injection for use in analyzing injector performance.	N/A	N/A
TC_R_F	Fuel injector manifold thermocouple	For monitoring temperature of fuel just prior to injection for use in analyzing injector performance.	N/A	N/A

Fuel Run Tank	Fuel Run Tank	6061-T6 Aluminum preffessionally welded pressure vessel. Uses custom designed endcaps welded onto a 0.55m long section of NPS 6 schedule 40 pipe. The top cap has one 1/2" NPT port and four 1/4" NPT ports. The 1/2" port is plugged. The 1/4" ports are used for the remote actuated vent valve, the manual vent valve, the pressurant inlet, and the line running to the relief valve and pressure transducer. The bottom cap has one 1/2" NPT port and one 1/4" NPT port. The 1/2" port is the fuel outlet and is routed to the MFV. The 1/4" port is used for the line which connects to the fill line and dump valve.	Filled with ambient air	N/A
Oxidizer Run Tank	Oxidizer Run Tank	End caps and pipe geometry are identical to the fuel run tank, however the functions of the ports differ and this tank includes a built in gas diffuser for the nitrogen inlet port. For the top cap the 1/2" port is used for the burst disc, while the 1/4" ports are used for the pressurant inlet, vent line (shared by the manual and remote actuated vent valves), ullage thermocouple, and ullage pressure transducer. For the bottom cap the 1/2" port is the oxidizer outlet which runs straight to the MOV and the 1/4" port gets split into the fill line and dump line.	Fiiled with ambient air	N/A
Nitrogen Run Tank	Nitrogen Run Tank	This is an off the shelf TBD L Scuba tank rated for up to TBD Mpa with a single TBD port at the top (tank will be mounted upsidedown). All the necessary connections and instrumentation will be connected via a 1 inlet 6 outlet manifold. All manifold outlets will be 1/4" NPT with the exception of the burst disc outlet which will be 1/2" NPT.	Filled with ambient air	N/A

Fuel GSE Tank	Fuel Ground Side Equipment Tank	Unpressurized TBD L storage tank. Ullage is allowed to draw in atmosphere to replace the volume of fuel removed by the fill pump.	Full of TBD L of liquid fuel at ambient pressure	N/A
Oxidizer GSE Tank(s)	Oxidizer Ground Side Equipment Tank(s)	One or more K tanks (DOT spec 3AA2400) initially filled with TBD kg of liquid nitrous each supplied by our sponsor Air Liquide. At 25°C this brings the pressure to TBD Mpa.	Full of TBD L of liquid oxidizer at TBD Mpa and 25°C	N/A
Nitrogen GSE Tank	Nitrogen Ground Side Equipment Tank		Full of TBD L of nitrogen at 31 MPA and 25°C	N/A
DFQD	Dummy Female Quick Disconnect		Connected	N/A
QD_R_OX2			Connected	N/A
RF_R_N3			Closed	Dependant on conditions

Table 2.1: P&ID Part Descriptions

3 Fluid Systems Assembly Procedure

The assembly of the fluid system will happen in 7 stages. Each stage will begin with the assembly of one of the seven fluid sub-systems (three fill systems, three run systems, and one engine section), followed by a leak check of the added system, and, upon passing the leak check, will conclude with a small battery of tests. This incremental approach is designed not only to keep careful track of all stages of the assembly process, but also to gain experience with each new system before proceeding to add a subsequent system.

During the assembly of any of the fluid subsystems, strict control over the unpack aging, and if necessary reassembling, of the oxidizer service cleaned components. The cleaning process can be found in section 5 of this report. For parts that require reassembling and/or lubricating, special cleaned tools (cleaned and packaged in the same manner as any fluid component) will be placed, still in their packaging, into a glove box. The box will have clear ply carbonate walls with a hinged lid and have all seams sealed from the outside with calking. Although not the usual manner for applying calking, the internal pressure will only be marginally greater than ambient, and it serves more to prevent any ingress of contaminants than to block the egress of air. To one side of the glove box will be a circular inlet duct to which the output ducting of the filtration unit (see section 5 for details of the filtration unit) will connect. To the other side will be the output duct which will have one ore more layers of fine wire mesh in order to ensure a positive pressure differential across the entire outlet cross section. Once the tools, precut sheets of aluminum foil, and and any required oxidizer safe lubricants have been placed in the box, the filtration unit will be turned on and left on until all components of the system in question have been assembled onto the test stand. The component assembler will retrieve the required component from storage, place it still in its packaging into the glove box, and then close and latch the lid. They then place their hands into the gloves and proceed to open the outer bag, and then only open each individual part bag as it is needed during the component assembly. Once assembly of the component is complete and all sealing threads have been wrapped in Teflon tape, they will cover all open orifices in heavy duty aluminum foil before removing their hands from the gloves and open the lid. Once they have received instruction from the assembly supervisor (who will only give said instruction once the rest of the assembly team is ready to install the component) they will personally transport the component to the assembly personnel outside for immediate installation. The component will not leave their hands until the installation personnel request it from them. Similarly, the installation personnel will either install the component immediately, or hand it back to the component assembler. Never shall a cleaned and assembled component be set down, and never shall aluminum foil be removed from an orifice until the subsequent component is available to be installed. Once the installation personnel has installed a component, it is their responsibility to make sure that it is set to its indicated starting state.

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3.1 Nitrogen System

3.1.1 Nitrogen Fill System

Step	Part ID.	Connects to	Notes/Action
1.1.1	PT_G_N	1/4" Male Run Tee N1	
1.1.2	RF_G_N1	1/4" Male Run Tee N2	Screw this tee to 1/4" Male Run Tee 1 from step 1.1
1.1.3	D_G_N	1/4" Male Tee N1	Screw this tee to 1/4" Male Run Tee 2 from step 1.2
1.1.4	FV_G_N1	1/4" Male Tee N1	
1.1.5	RF_G_N1	1/4" Male Run Tee N3	Screw this tee to 1/4" Male Tee 1 from step 1.4
1.1.6	Hose_N	1/4" Male Run Tee N3	Screw via a male NPT adapter
1.1.7	QD_G_N	Hose_N1	Screw the female end of the quick disconnect into the end of the hose via a female NPT adapter

Table 3.1: Nitrogen Fill System Assembly Procedure

3.1.2 Nitrogen Run System

Step	Part ID.	Connects to	Notes/Action
1.2.1	Nitrogen Run Tank	1/2" Tubing line N1	Assemble Swagelok tube fitting and screw this into an NPT adapter for the run tank
1.2.2	Manifold	1/2" Tubing line N1	Using the Swagelok tube fitting to attach a male NPT thread, screw the male NTP into the top of the manifold
1.2.3	PG_R_N	Manifold	Screw directly into the manifold
1.2.4	TC_R_N	Manifold	Screw directly into the manifold
1.2.5	PT_R_N	Manifold	Screw directly into the manifold
1.2.6	BD_R_N	Manifold	Screw directly into the manifold
1.2.7	RF_F_N1	Manifold	Screw directly into the manifold

1.2.8	D_G_N	1/2" Tubing line N2	Ensure that the tube is long enough to lead sufficiently far away from the manifold and the attached components in the case where the dump is actuated. Assemble Swagelok tube fittings on both ends of the tube, screw male NPT threads on both sides, and screw one side into this component
1.2.9	Manifold	1/2" Tubing line N2	Connect the other end of the tube into the manifold
1.2.10	FV_G_N2	1/2" Male Run Tee N4	Screw the male end of this tee into this component
1.2.11	RF_R_N3	1/2" Male Run Tee N4	Screw directly into the top of the tee
1.2.12	QD_G_N	FV_G_N2	Screw in the male end of the quick disconnect into this component
1.2.13	FV_G_N2	1/2" Tubing line N3	Assemble Swagelok tube fittings on both ends of the tube, screw male NPT threads on both sides, and screw on side into this component
1.2.14	Manifold	1/2" Tubing line N3	Connect the other end of the tube into the manifold
1.2.15	RG_R_N	1/2" Tubing line N4	Using Swagelok tube fittings, and a male NPT fitting on one end, connect to the inlet of the regulator
1.2.16	RG_R_N	1/2" Tubing line N5	Assemble Swagelok tube fittings and a male NPT fitting on one end, connect to the outlet of the regulator
1.2.17	1/2" Tubing line N4	1/2" Male Run Tee N4	Screw other end of this tube into the remaining port of the 1/2" Male Run Tee N4
1.2.18	1/2" Female Cross	1/2" Male Run Tee N5	Screw the male run on the tee into the cross
1.2.19	RF_R_N2	1/2" Female Cross	
1.2.20	1/2" Tubing line N5	1/2" Female Cross	Screw other end of this tube into a port adjacent to RF_R_N2
1.2.21	IS_R_N1	1/2" Tubing line N6	Assemble Swagelok tube fittings and male NPT adapters on both ends of the tube. Screw one end into this component
1.2.22	IS_R_N2	1/2" Tubing line N7	Assemble Swagelok tube fittings and male NPT adapters on both ends of the tube. Screw one end into this component
1.2.23	IS_R_N1	1/2" Tubing line N8	Assemble Swagelok tube fittings and male NPT adapters on one end of the tube and a female on the other. Screw the male end into the remaining connection on this component

1.2.24	IS_R_N2	1/2" Tubing line N9	Assemble Swagelok tube fittings and male NPT adapters on one end of the tube and a female on the other. Screw the male end into the remaining connection on this component
1.2.25	1/2" Tubing line N6	1/2" Male Run Tee N5	Screw the other end of this tube into the remaining connections on this component
1.2.26	1/2" Tubing line N7	1/2" Male Run Tee N5	Screw the other end of this tube into the remaining connections on this component
1.2.27	PV_R_N	1/2" Female Cross	Screw this in with via a nipple
1.2.28	PV_R_N	Hose_N2	Connect a hose to this component via a male NPT adapter. This hose should be sufficiently long enough to reach the injector
1.2.29	QD_G_OX2	Hose_N2	Screw the female end of this quick connect into the other end of the hose via a female NPT adapter
1.2.30	QD_G_N	QD_G_N	When the fill system and the run systems have independently been tested and are ready for the nitrogen system run, connect the ends of the quick disconnect to each other

Table 3.2: Nitrogen Run System Assembly Procedure

3.2 Fuel System

3.2.1 Fuel Fill System

Step	Part ID	Connects to	Notes
	CV_G_F	Fill Pump	Screw in male check valve directly the inlet of the Fill Pump
	RF_G_F	1/4" Male Run Tee F1	Screw this component into the 90deg female port
	FV_G_F1	1/4" Male Run Tee F1	Connect this componet to the male port of the tee
	Fill Pump	1/4" Tubing line F1	Assemble Swagelok fittings and male NPT adapters on both ends of the tube. Connect one end of this line to the fill pump
	1/4" Tubing line F1	1/4" Male Run Tee F1	Connect the other end of this line to the remaining female connection
	FV_G_F2	FV_G_F1	Connect these components together via a nipple

	FV_G_F2	Hose_F	Attach the hose to this component via a male adapter
	QD_R_F	Hose_F	Attach this component to the other end of the hose via a female adapter

Table 3.3: Ethanol Fill System Assembly Procedure

3.2.2 Fuel Run System

Step	Part ID	Connects to	Notes
	CV_R_N2	Fuel Run Tank (top)	Screws in directly to the female threads on the bulkhead (there are a total of 5)
	RF_R_F	Fuel Run Tank (top)	Screws in directly to the female threads on the bulkhead
	V_R_F2	Fuel Run Tank (top)	Screws in to the female threads on the bulkhead via a nipple
	V_R_F1	Fuel Run Tank (top)	Screws in to the female threads on the bulkhead via a nipple
	1/2" Male Run Tee F1	Fuel Run Tank (top)	Male end screws in directly to the female threads on the bulkhead
	PG_R_F1	1/2" Male Run Tee F1	
	PT_R_F1	1/2" Male Run Tee F1	
	MFV	1/2" Tubing Line F1	Assemble Swagelok fittings and male NPT adapters on both ends of the tube. Screw in one end into the MFV
	1/2" Tubing Line F1	Fuel Run Tank (bottom)	Screw in the other end into the base of the run tank (there will be 2 female NPT threads at the base)
	D_R_F	1/2" Male Tee F1	Screw this component into the 90deg female port
	QD_R_F	1/2" Male Tee F1	Connect these components together via a female coupler
	1/2" Male Tee F1	Fuel Run Tank (bottom)	Use the male port of this tee to screw into the remaining female threads on the base of the fuel run tank
	QD_R_F	QD_R_F	When the fill system and the run systems have independently been tested and are ready for the ethanol system run, connect the ends of the quick disconnect to each other

Table 3.4: Ethanol Run System Assembly Procedure

3.3 Oxidizer System

3.3.1 Ethanol Fill System

Step	Part ID	Connects to	Notes
8.1.1	1/4" Female Cross OX1	1/4" Female Tee OX1	Connect these fittings together via a nipple
8.1.2	1/4" Male Tee OX1	1/4" Female Cross OX1	Screw this fitting onto the cross such that it forms a 180 deg angle with the female tee
8.1.3	CV_G_OX1	1/4" Female Tee OX1	
8.1.4	CV_G_OX2	1/4" Female Tee OX1	
8.1.5	PT_G_OX	1/4" Female Cross OX1	
8.1.6	RF_G_OX1	1/4" Female Cross OX1	
8.1.7	FV_G_OX1	1/4" Female Cross OX2	Connect these together via a nipple
8.1.8	FV_G_OX1	1/4" Male Tee OX1	
8.1.9	RF_G_OX2	1/4" Female Cross OX2	Screw this fitting onto the cross such that it forms a 180 deg angle with FV_G_OX1
8.1.10	D_G_OX	1/4" Tubing Line OX1	Assemble Swagelok fittings and female NPT adapters on both ends of the tube. Ensure that the tubing line is sufficiently long enough such that the component reaches a place in the ground where NOX can be safety dumped. Screw one of the NPT adapters into this component
8.1.11	1/4" Tubing Line OX1	1/4" Male Tee OX1	Screw in the other end of the tube into the tee
8.1.12	V_G_OX	1/4" Tubing Line OX2	Assemble Swagelok fittings and male NPT adapters on both ends of the tube. Ensure that the tubing line is sufficiently long enough such that the component reaches a place in the ground where NOX can be safety dumped. Screw the one of the NPT adapters into this component
8.1.13	1/4" Tubing Line OX2	1/4" Female Cross OX2	Screw in the other end of the tube into a connection on the cross
8.1.14	Hose_OX	1/4" Female Cross OX2	Connect a hose to this component via a male adapter
8.1.15	QD_R_OX1	Hose_OX	Screw in the female end of the quick disconnect to the other side of the hose via a female adapter

Table 3.5: Oxidizer Fill System Assembly Procedure

3.3.2 Ethanol Run System

Step	Part ID	Connects to	Notes
8.2.1	RF_R_OX	1/2" Female Cross OX1	

8.2.2	PG_R_OX1	1/2" Female Cross OX1	
8.2.3	PT_R_OX1	1/2" Female Cross OX1	
8.2.4	1/2" Female Cross OX1	Oxidizer Run Tank (top)	Screw in to the female threads on the bulkhead via a nipple (there are a total of 5)
8.2.5	CV_R_N1	Oxidizer Run Tank (top)	Screw in directly to the female threads on the bulkhead
8.2.6	BD_R_OX	Oxidizer Run Tank (top)	Screw in directly to the female threads on the bulkhead
8.2.7	TC_R_OX1	Oxidizer Run Tank (top)	Screw in directly to the female threads on the bulkhead
8.2.8	D/V_R_OX1	1/2" Male Tee OX1	
8.2.9	V_R_OX1	1/2" Male Tee OX1	Screw these components on opposite ends of the tee branch
8.2.10	1/2" Tubing line OX1	1/2" Male Tee OX1	Assemble Swagelok fittings and male and female NPT adapters on either ends of the tube. Ensure that the tube is an appropriate length such that it offers clearance from the existing components at the top of the run tank
8.2.11	1/2" Tubing line OX1	Oxidizer Run Tank (top)	Screw the male adapter into the remaining female thread on the bulkhead
8.2.12	D_R_OX	1/2" Male Elbow OX1	
8.2.13	1/2" Male Elbow OX1	Oxidizer Run Tank (bottom)	Screw in directly to one of the two female threads on the bulkhead at the base of the run tank
8.2.14	QD_R_OX1	1/2" Male Run Tee OX1	Screw this component such that it forms a 90deg angle with the male connection
8.2.15	1/2" Male Run Tee OX1	Oxidizer Run Tank (bottom)	Screw the male end directly to the remaining female thread on the bulkhead at the base of the run tank
8.2.16	MOV	1/2" Tubing line OX1	Assemble Swagelok fittings and male NPT adapters on both ends of the tube. Screw in one end into the MOV
8.2.17	1/2" Tubing Line F1	1/2" Male Run Tee OX1	Screw in the other end of this tubing line into the remaining branch of the tee

Table 3.6: Oxidizer Run System Assembly Procedure

3.4 Engine System

3.4.1 Engine Fuel System

Step	**Part ID**	**Connects to**	**Notes**

12.1.1	PT_R_F2	Injector Manifold	Screw this component directly into the inject manifold
12.1.2	TC_R_F2	Injector Manifold	Screw this component directly into the inject manifold
12.1.3	BD_R_F	1/2" Male Run Tee E1	
12.1.4	1/2" Male Run Tee E1	Injector Manifold	Attach the tee into the injector manifold via a nipple
12.1.5	MFV	1/2" Tubing Line E1	Assemble Swagelok fittings and male NPT adapters to both ends of the tube. Connect one end of the tubing to the MFV
12.1.6	Gear Pump	1/2" Tubing Line E1	Screw the other end of this tubing section into the gear pump
12.1.7	Gear Pump	1/2" Tubing Line E2	Assemble Swagelok fittings and male NPT adapters to both ends of the tube. Connect one end of the tubing to the gear pump
12.1.8	1/2" Tubing Line E2	1/2" Male Run Tee E1	Screw the other end of this tubing section into the 1/2" Male Run Tee

Table 3.7: Engine Fuel Section Assembly Procedure

3.4.2 Engine Oxidizer System

Step	**Part ID**	**Connects to**	**Notes**
12.1.1	PT_R_F2	Injector Manifold	Screw this component directly into the inject manifold
12.1.2	TC_R_F2	Injector Manifold	Screw this component directly into the inject manifold
12.1.3	BD_R_F	1/2" Male Run Tee E1	
12.1.4	1/2" Male Run Tee E1	Injector Manifold	Attach the tee into the injector manifold via a nipple
12.1.5	MFV	1/2" Tubing Line E1	Assemble Swagelok fittings and male NPT adapters to both ends of the tube. Connect one end of the tubing to the MFV
12.1.6	Gear Pump	1/2" Tubing Line E1	Screw the other end of this tubing section into the gear pump
12.1.7	Gear Pump	1/2" Tubing Line E2	Assemble Swagelok fittings and male NPT adapters to both ends of the tube. Connect one end of the tubing to the gear pump
12.1.8	1/2" Tubing Line E2	1/2" Male Run Tee E1	Screw the other end of this tubing section into the 1/2" Male Run Tee

Table 3.8: Engine Fuel Section Assembly Procedure

3.5 Leak Check Procedure

In order to maintain system cleanliness and to build team experience with the various fluid systems prior to the first hot fire testing, leak system assembly and leak checking will be performed incrementally. As each system is added to the test stand, the first operation will be to fill the system with nitrogen and track pressure via pressure transducers over time. If the loss rate is immeasurably small or sufficiently low, the system will pass the leak check test. If a leak is detected, the system will be depressurized in order to allow test personnel to approach and apply oxidizer safe leak detect fluid to all threaded seals (available from *AircraftSpruceCanada* and/or *McMaster Carr*). After the application of leak detect fluid a camera will be trained on the system in question. Testing personnel will then retreat back to the remote observation and control station and begin to re pressurize the assembled systems in order while watching the camera feed so spot the tell-tale bubbles in order to spot the troublesome connection(s). Once located, the system will again be depressurized to a point where it is safe for personnel to approach so that they may tighten to the connection in question. If after tightening the leak is not solved, the system will be isolated, disassembled, re cleaned, and have fresh Teflon thread tape applied to all connections, with one additional wrap applied to the troublesome connection. This process is repeated until all leaks in a system are eliminated.

The first system to be assembled will be the nitrogen fill system up to the male side of the quick disconnect (the side attached to the hose). All parts of the nitrogen fill system are designed to have a minimum factor of safety of four so that it may be pressurized with personnel near by. However, despite this factor of safety, once pressurized (ie once the nitrogen GSE tank's integral valve is opened) no work will be allowed to be conducted on or near the system other than to open D_G_N to depressurize the system. Once leaks have been eliminated, the nitrogen GSE tank's integral valve is closed, D_G_N is opened slightly to allow system to depressurize nearly to ambient pressure. Using the analog gauge PG_G_N the operator will close D_G_N just prior to reaching ambient pressure (eg 1.1 atm) in order to leave some positive pressure in the system to prevent any possible ingress of contaminants.

The second system to be assembled will be the nitrogen run system. Assembly of this system will only begin after a the nitrogen fill system passes its leak check. The assembly procedure is described in table 3.2, and end at the two isolation valves `IS_R_N1` and `IS_R_N2`. The leak check procedure is very similar to the nitrogen fill system, once the system is pressurized, personnel will observe the live telemetry from a safe distance and watch from pressure decay. The run system, un-nlike the fill system, is not human rated (FOS < 4), and this, if a leak is detected, the system is depressurizes as stated in (see **SP1** in 6.2). Once the system is depressurized, the fill system can be approached for depressurization as stated previously. The leak detect fluid is applied to all potentially leaky connections, and the leak detect procedure mentioned before is performed again. It is critical to remember that **NO MEMBERS ARE ALLOWED TO WORK ON ANY OF THE SYSTEMS WHEN THEY ARE PRESSURIZED, EVEN ONES WITH HUMAN RATING (EXCEPTION IS DEPRESSURIZING THE NITROGEN RUN SYSTEM)**, and this will be enforced with no exceptions.

4 Engine Testing Procedures

This section presents the full engine testing procedure, starting with an assembled test stand in power-up mode, and ending with a safe-to-approach test stand. The complete fill procedure can be broken down into 6 main phases: Nitrogen fill, ethanol system purge, ethanol fill, nitrous system purge, nitrous fill, and finally nitrous recharge. The nitrogen fill procedure utilizes external high pressure nitrogen cylinders to fill the main nitrogen run tank up to 300 bar, at around room temperature. The ethanol purge procedure replaces all air in the ethanol fill and run systems with either ethanol or nitrogen. The ethanol fill procedure fills the ethanol run tank with ethanol, and pressurizes it with nitrogen up to 33 bar. The nitrous purge procedure replaces all air in the nitrous fill and run systems with nitrogen. The nitrous fill procedure supercharges the nitrogen tank with nitrogen at 36 bar to facilitate direct liquid nitrous filling, which occurs right after the super charge is complete. And finally, the nitrogen recharge procedure replenishes the used nitrogen in the nitrogen run tank to bring the system into a test-ready state.

Upon completion of the fill procedure, the test stand is ready to undergo a full leak test, which is outlined in chapter 3. Once no leaks have been confirmed, a final check of the test stand state is done both by software and by the lead test engineer via telemetry. Meanwhile, the range safety officers ensure no one is within the minimum safety distance, and that all environmental and operating conditions are acceptable. If all parameters are nominal, the final test countdown shall begin, with all test personnel retreated to the command and control center. During the count own, the ignition sequence is initiated, and upon the **`fire`** command, the system she execute the engine start sequence and nominal combustion, if no anomalies occur, shall resume for the expected burn duration. Upon the **`MECO: Main Engine Cut-Off`** command, the engine shutdown sequence is commanded, and the system executes the nominal engine shutdown procedure. Once the engine is safely shut down, the system executes the post-burn safeing procedure, which de-energizes the system into an inert state that is safe for approach.

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4.1 Nitrogen Fill Procedure

Starting at the initial state described in section XX, and with all systems connected and ready for operation, a nominally closed solenoid valve opens and allows for nitrogen to flow from the nitrogen GSE tanks to the nitrogen run tank. Both tank pressures are monitored with pressure transducers, whose data are actively transmitted to the ground control station via live telemetry. Once the run tank pressure reaches the nominal 300 bar, the solenoid fill valve closes and isolates the run and fill systems. In case of an anomaly that raises the tank pressure above nominal, relief valves activate at 110% of the nominal pressure to relief the system. In case the relief valves are incapable of relieving the pressure fast enough to stabilize the system, the crew can either activate one of two dump valves available on either system to rapidly dump the nitrogen and bring the system into a depressurized safe state. In case an anomaly escalates rapidly and human intervention is not fast enough, a burst disk available on the nitrogen run system can blow and quickly depressurize the system. If all proceeds nominally, the procedure ends with a climate conditioning of the nitrogen run tank to maintain the required 278.15K temperature. This is done using a simple air-conditioned Styrofoam box that encloses the run tank, a method that the team has utilized many times in the past with success. The procedure is summarized in checklist form below in table XX. Once the system is stable at nominal conditions, the fill procedure can proceed to the next step: Ethanol purge.

Step	Part ID	Action	Notes
1.1	FV_G_N1	Opens	To begin filling
1.2	FV_G_N1	Closes	Once nitrogen run tank reaches 300 bar
1.3	TC_R_N	Monitor for conditioning	Nitrogen tank is encased in a temperature controlled insulated box. Controller monitors TC_R_N to maintain 5°C nitrogen temperature. Pressure will increase as a result of controlled heating. RF_R_N1 will handle excess pressure above 330 bar.

Table 4.1: Nitrogen Fill Procedure

4.2 Ethanol Purge Procedures

Starting with a filled and stable nitrogen run tank, the first step doesn't involve any nitrogen purging, instead, the procedure starts with an ethanol purge of the ethanol fill system from the ethanol GSE tank up to the fill quick-disconnect. The fill quick-disconnect is disconnected to isolate the ethanol fill system from the rocket, and is subsequently connected to an external dummy quick-disconnect female end to enable flow throughput. Then, a servo-actuated ball valve activates to open the fill lines from the fill pump to the quick-disconnect. Then, the ethanol fill gear-pump is turned on to pump a small quantity of ethanol through the system, until an ethanol discharge is observed through the dummy quick-disconnect. Now, all air has been purged out of the ethanol fill system and replaced with ethanol. The servo-actuated ball valve closes to block any flow of ethanol through the system, and the female end of the dummy quick-quick disconnect is removed. The next part of the ethanol purge procedure involves a nitrogen purge of the ethanol run system. The three-way servo actuated ball valve turn from the fill position to the run position, allowing nitrogen to flow from the nitrogen run tank through the ethanol and nitrous run systems. Downstream servo-actuated isolation ball valves separate the oxidizer and ethanol systems, and allows the team to chose which system to purge. After the three-way valve is set to run position, the ethanol tank nominally closed solenoid vent valve opens, and then, the servo actuated ethanol dump-valve opens to allow for nitrogen expulsion. Then the ethanol system servo-actuated isolation ball valve opens to allows nitrogen to flow from the run tank, through the pressure regulator, into the ethanol run tank, and out the opened vent and dump valves. Once 10s of flow is established through the valves, the main fuel valve is opened, followed by the closure of the vent and dump valves. Now, nitrogen is flowing through the injector and out the combustion chamber, and purges everything downstream the main fuel valve of air. Once a few seconds of flow is established, the servo-actuated isolation ball valve is closed to halt nitrogen flow from the nitrogen run tank to the ethanol run system. Still pressurized to higher than atmosphere, the ethanol run tank will still expel nitrogen through the main fuel valve and out the chamber. The tank pressure is monitored until the pressure reaches around 2 bar, after which, the main fuel valve is closed to end the flow of nitrogen. Now, the ethanol run system is free of air at least up to the main fuel valve (the lines downstream of the main fuel valve will continue to vent through the injector until pressure is equalized, after which, air could potentially flow back into the system. However, there is no chance for that air to propagate back into the run system, eliminating the risk of contamination). Once this is complete, the quick-disconnect is them re-connected to the ethanol run system (the test stand is safe to approach due to the human rating on the nitrogen run tank).

Step	Part ID	Action	Notes
2.1	QD_R_F	Disconnects	Isolate fill system from run system
2.2	Dummy Quick Disconnect	Connects	Connect line to an external quick-disconnect
2.3	FV_G_F	Opens	Allow ethanol to run from fill tank through fill lines
2.4	Fill Pump	Turns On	Start pumping ethanol through ethanol fill lines
2.5	Fill Pump	Turns Off	Halt ethanol run once observed leaving the dummy quick disconnect
2.6	FV_G_F	Closes	Block ethanol from flowing through ethanol fill lines
2.7	Dummy Quick Disconnect	Disconnects	Ethanol fill lines are suffieciently purged
2.8	FV_G_N2	Set to run position	Allow nitrogen to flow through ethanol run system
2.9	V_R_F1	Opens	Ethanol run tank vent valve open to allow venting of its connecting line
2.10	D_R_F	Opens	Ethanol fill system dump valve open to allow venting of its connecting line
2.11	MFV	Opens	Allow nitrogen to flow from ethanol tank through pump feed system, injector, and engine
2.12	IS_R_N2	Opens	Allow ethanol tank and lines to be purged
2.13	V_R_F1	Closes	Shut off purge point
2.14	IS_R_N2	Closes	Nitrogen no longer flows through ethanol lines
2.15	D_R_F	Closes	Shut off purge point
2.16	MFV	Closes	Shut off purge point
2.17	QD_R_F	Reconnects	Reconnect fill system to run system

Table 4.2: Ethanol Purge Procedure

4.3 Ethanol Fill Procedures

Once the ethanol system has been purged, the fill procedure can start. The nominally closed solenoid vent valve on the ethanol tank is open to allow venting of the nitrogen in the tank during the liquid fill. The servo actuated isolation ball valve on the ethanol fill system is opened to allow for ethanol flow from the ethanol GSE tank to the run tank. Then, the ethanol fill gear pump is turned on to supply a constant mass flow rate to the ethanol tank. The amount of ethanol in the run tank is monitored by using load cells, along with the usage of timing (a gear pump supplies a constant mass flow rate, so the amount supplied can be calculated by multiplying the pump run time by its supply mass flow rate. However, this may introduce inaccuracy since the pump has a spool-up time that is hard to determine without extensive testing, so combining this method with the load cell method is a good way of ensuring a sufficient amount has been supplied to the tank). Once the right amount of ethanol has been supplied, the gear pump is turned off, and is given around 2 seconds to completely stop rotating. Then, then servo-actuated isolation ball valve is close to halt any further flow to the tank, followed by the closure of the solenoid vent valve. Finally, the tank will be pressurized to its nominal starting pressure of 33 bar. After the vent valve is closed, the ethanol system servo-actuated isolation ball valve is opened to allow for nitrogen to flow from the nitrogen run tank to the ethanol run tank. The tank pressure is monitored via live telemetry until the pressure reaches nominal, after which, the isolation valve is turned off, and the system is now filled with ethanol. The procedure is summarized in table XX below, and the procedure can move on to the nitrous system purge.

Step	Part ID	Action	Notes
3.1	V_R_F1	Opens	Valve open to allow venting of its connecting line
3.2	FV_G_F	Opens	Allow ethanol to run from fill tank through fill lines
3.3	Fill Pump	Turns On	Start pumping ethanol through ethanol fill lines
3.4	FT_R_F	Monitor For Tank Filling	Monitor force transducer for weight
3.5	Fill Pump	Turns Off	Halt ethanol pump once specific weight is observed
3.6	FV_G_F	Closes	Block ethanol from flowing through ethanol fill lines
3.7	V_R_F1	Closes	Block venting of its connecting line

Table 4.3: Ethanol Fill Procedure

4.4 Nitrous Purge Procedures

Starting with a the system filled with ethanol, the nominally closed solenoid vent valve on the nitrous tank is opened, the servo-actuated dump ball valve on the bottom of the nitrous tank is opened, and the nitrous fill line servo-actuated ball vent valve is opened to allow for nitrogen expulsion. Then the nitrous system servo-actuated isolation ball valve is opened to allow for nitrogen to flow from the nitrogen run tank to the nitrous tank, and through the three opened valves. Once around 10s of flow is established, the main oxidizer valve is opened, followed by the closure of the 3 opened vent and dump valves. Now, nitrogen is running through the main oxidizer line, through the injector, and out the combustion chamber. Once a few seconds of flow is established, the nitrous system servo-actuated isolation ball valve is closed to halt the flow of nitrogen from the nitrogen run tank to the nitrous run system. Still pressurized to higher than atmosphere, the nitrous run tank will still expel nitrogen through the main oxidizer valve and out the chamber. The tank pressure is monitored until the pressure reaches around 2 bar, after which, the main oxidizer valve is closed to end the flow of nitrogen. Now, the nitrous run system is free of air at least up to the main oxidizer valve (the lines downstream of the main oxidizer valve will continue to vent through the injector until pressure is equalized, after which, air could potentially flow back into the system. However, there is no chance for that air to propagate back into the run system, eliminating the risk of contamination). Now, the nitrous run system is purged of air and ready for filling.

Step	Part ID	Action	Notes
4.1	V_G_OX	Opens	To allow the nitrous fill line to be purged
4.2	V_R_OX1	Opens	To allow vent line to be purged
4.3	D_R_OX	Opens	To allow dump line to be purged

4.4	IS_R_N1	Opens	To begin purging air from nitrous tank, dump/vent line, and fill line
4.5	MOV	Opens	To begin purging air through the injector and chamber
4.6	V_G_OX	Closes	To seal nitrous fill line
4.7	V_R_OX1	Closes	To seal nitrous tank
4.8	D_R_OX	Closes	To seal nitrous tank
4.9	IS_R_N1	Closes	To stop purging nitrous tank, main oxidizer line, injector and chamber
4.10	PT_R_OX1	Monitored	MOV stays open until tank pressure reaches 2 bar, monitored through live telemetry
4.11	MOV	Closes	To end nitrogen flow through chamber

Table 4.4: Nitrous system purge procedure

4.5 Nitrous Fill Procedures

The first part of the nitrous fill procedure is supercharging the nitrous run tank to facilitate liquid nitrous filling. The nitrous system servo-actuated isolation ball valve is opened to allow nitrogen to flow from the nitrogen run tank to the nitrous run tank. During the supercharge, the pressure in the tank is monitored via live telemetry through a pressure transducer reading the nitrous tank pressure. Once the pressure reaches the nominal 36 bar, the nitrous system servo-actuated isolation ball valve is closed to halt further flow of nitrogen. This marks the end of the supercharge phase. The next phase is the liquid nitrous fill, which starts with the opening of a nominally closed solenoid vent valve to allow for the existing nitrogen in the tank to be replaced by liquid nitrous. Then, the nitrous fill system servo-actuated ball fill valve is opened to allow for the flow of nitrous from the nitrous GSE tank to the nitrous run tank. The nitrous run tank is now being filled with liquid nitrous. The nitrous tank servo-actuated vent valve is actively controlled to maintain the nominal pressure of 36 bar in the tank, which would minimize the amount of nitrous boil-off during the fill procedure. In case of an anomaly, servo-actuated ball dump valves are installed on both the nitrous fill line and the nitrous tank, in case the fill needs to be halted and nitrous dumped. The nitrous tank is also equipped with a relief valve and a burst disk in case pressure rises and must be relieved. During the liquid fill, a load cell on the nitrous tank will measure the mass of nitrous loaded into the tank, and once the correct amount is loaded, the liquid fill portion is finished. Due to various reasons, the temperature in the run tank can rise and artificially pressurize the tank. Temperature is continuously monitored via live telemetry, with data supplied using a thermocouple on the nitrous tank. Safety takes precedence over operation, so in case this happens, the fill must be halted with the tank reaches its rated operating pressure, even if the mass loaded is below required. Like the nitrogen run tank, the nitrous run tank is also enclosed in an air conditioned Styrofoam box, which will be used for climate reconditioning if needed. This system can be used to cool the tank and drop the pressure back to nominal, after which the liquid fill can resume. Once the right amount is loaded at the right conditions, the nitrous fill system servo-actuated ball fill valve is closed to halt any further flow of nitrous into the run tank. Finally, the nitrous tank solenoid vent valve is shut to halt the further venting of nitrogen from the nitrous run tank. The system is now filled with nitrous. The procedure is summarized below in table XX.

Step	Part ID	Action	Notes
5.1	IS_R_N1	Opens	Begin pressuring the oxidizer tank with 36 bar.
5.2	PT_R_OX1	Monitored	Monitor tank pressure during supercharge
5.3	IS_R_N1	Closes	Once the nitrous run tank reaches 36 bar.

5.4	V_R_OX1	Opens	Opens Partially to allow for nitrogen venting
5.5	FV_G_OX	Opens	Allows for NOX flow through fill lines
5.6	V_R_OX1	Actively controlled	Vent is actively controlled to remain at 36 bar
5.7	FT_R_OX	Monitored	Monitor force transducer for weight
5.8	FV_G_OX	Closes	No more NOX flows through lines
5.9	V_R_OX1	Closes	No more NOX being vented

Table 4.5: Nitrous fill procedure

4.6 Nitrogen Recharge Procedures

The last fill procedure to be completed is the nitrogen recharge procedure, which replenishes the used nitrogen from the nitrogen run tank, and bring the test stand into test-ready mode. The three-way valve is moved from the run position to the fill position, reconnecting the nitrogen run tank to the nitrogen GSE tanks. The nitrogen fill solenoid valve is opened, allowing nitrogen to from and refill the nitrogen run tank. The run tank pressure is monitored via live telemetry, and once the pressure reaches 300 bar, the valve is shut off to prevent any further flow. The same climate reconditioning procedures performed earlier is repeated to bring the run tank conditions to nominal. Once this is done, the three-way valve is moved to run position, and the fill procedure is completed. This procedure is summarized below in table XX.

Step	Part ID	Action	Notes
6.1	FV_G_N2	Moves to fill position	To reconnect nitrogen run tank to nitrogen fill system
6.2	FV_G_N1	Opens	To begin refilling the nitrogen run tank
6.3	FV_G_N1	Closes	To stop refilling nitrogen run tank once pressure has risen back up to 300 bar
6.4	TC_R_N	Monitor for control	Nitrogen run tank temperature controller monitors TC_R_N to maintain 5°C
6.5	FV_G_N2	Moves to run position	To reconnect nitrogen run tank to pressurant feed system

Table 4.6: Nitrogen Recharge Procedure

4.7 Ignition Sequence and Engine Startup

Once the fill procedures are completed, a final leak check takes place, as described in chapter 3. If no leaks are detected, the system will perform a final check of all fluid conditions. If found nominal, and if no environmental or operational safety hazards are detected, the system may move onto the ignition sequence. The ignition sequence starts by arming the igniters, ensuring that the power system responsible for triggering them has signal continuity. Then, the system automatically opens valve `IS_R_N1` to press the oxidizer. Once `IS_R_N1` is fully open, the igniters are lit, and valve `MOV` is opened to start oxidizer flow. At the same time, valve `MFV` is opened, and the gear pump is turned on to actuate the flow. The spool up time of the gear pump ensures that the fuel lags the oxidizer, which helps mitigate hard start. The engine should burn nominally if no anomalies occcur. The procedure is summarized in the following table:

Step	Part ID	Action	Comments
	Igniters	Armed	Electrical continuity supplied to power-supply for igniter activation
	IS_R_N1	Open	Open nitrogen line to pressurize oxidizer (oxidizer is already pressurized, this is just re-connecting the oxidizer and pressurant systems).
	Igniters	ON	Electrical power supplied to igniters for ignition start
	MOV	Opens	Steady 1sec long opening of fuel oxidizer valve
	MFV	Opens	Steady 1sec long opening of main fuel valve
	Gear Pump	ON	Initiate fuel pumping to injector, delay in pump spool-up insures fuel lags oxidizer (mitigate hardstart)

Table 4.7: Engine Start Procedure

4.8 Main Engine Cut-Off (MECO)

Once the correct burn time has passed, the system automatically executes the `Main Engine Cut-Off (MECO)` sequence. This is a forced engine shut-off (the engine is loaded with slightly more fuel than it requires such that the fuel lines are never filled with fumes/vapour. The system closes the valve `MOV` to shutoff oxidizer flow, and opens valve `PV_R_N1` to purge the main oxidizer line downstream MOV. This also serves a second purpose of forcing a large amount of inert nitrogen into the chamber, helping quench and put out the flame and start the engine cool down process. Once `MOV` is closed, the gear pump is turned off and a 2 second delay is measured, after which, the valve `MOV` is closed, shutting off fuel flow to the engine. The engine is now not burning. This procedure is summarized in the table below:

Step	Part ID	Action	Comments
	IS_R_N1	Close	Halt oxidizer pressurization
	MOV	Close	Steady 1sec closing of main oxidizer valve (mitigates water hammering)
	PV_R_N1	Opens	Opens as soon as MOV close signal is given, steady 1sec long opening, purges main oxidizer line downstream MOV and provdies high flowate of nitrogen to quench combustion and initiate engine cooldown. Valve is redundant with PV_R_N2
	Gear Pump	Stop	Halt supply of fuel to injector. Steady 1-2 second decrease in mass flow rate as pump spools down.
	MFV	Close	Shutoff fuel flow to injector

Table 4.8: Main Engine Cut-Off Procedure

4.9 Post-Burn Procedures

The post burn procedures involves bringing the test stand into an intert, safe-to-approach status. This starts with a pressure fed dump of oxidizer (see **SP9** in table 6.2), followed by a pressure fed dump of fuel (see **SP12** in table 6.2), followed by an oxidizer system purge (see table 4.4), followed by a fuel system purge (see table 4.2), and finally, a dump of the nitrogen pressurant system (see **SP1** in table 6.2).

5 Fluid Systems Cleaning Procedures

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5.1 General Process

This section outlines the processes and procedures that will be used to ensure that all fluid system components are free of any and all contaminants prior to system assembly. For clarity, a "component" is an item that can be found on the Plumbing and Instrumentation Diagram (eg. a relief valve, a ball valve, the fuel tank, etc) and which can, in some cases, be disassembled into individual "parts". Additionally, "contaminants" include, but are not limited to, hydrocarbon lubricants and particulate, loose metal and metal oxide particulate, and organic matter (eg. hair, skin cells, lint, etc). Of primary concern are the oxidizer system and the nitrogen system which supplies the oxidizer system with pressurant. Contaminants in either of those two systems during a test could result in catastrophic failure either due to mechanical damage from particulate or even decomposition and subsequent deflagration of the oxidizer (nitrous oxide) due to the presence of incompatible hydrocarbons. While the fuel (ethanol) is incredibly stable and effectively insensitive to contamination, for the sake of minimizing any potential unforeseen hazards and in order to gain additional practice with the cleaning process, the fuel system components will undergo an identical cleaning regimen to that of the nitrogen and oxidizer systems.

The process consists of six main phases. Phase I is the soaking phase where the individual parts of each component are immersed in baths of diluted industrial degreaser. Phase II, mechanical washing, is where all components and/or parts are either manually scrubbed or pressure washed, both using diluted degreaser. In Phase III, rinsing, all degreaser is thoroughly washed away using distilled water. Phase IV is the drying phase in which components and parts are dried using a constant stream of HEPA filtered air. Phase V, inspection, consists of a visual inspection of each component or part under first white and then UV light. Finally in Phase VI components and parts are packaged in heat sealed polyethylene bags and properly labelled for storage until they are needed for assembly of the fluid system. This process is based on cleaning methods and practices described in the ASTM G93-03 standard.

5.2 Roles and Definitions

5.2.1 Cleaning Supervisor

The Cleaning Supervisor is responsible for overseeing the entire cleaning process for one or more scheduled cleaning sessions and ensuring the success of each phase during said sessions. To this end, it is the Cleaning Supervisor's name that goes on every sealed bag in Phase VI and it is they who will be held responsible should those components prove unsatisfactorily clean. The Cleaning Supervisor must be trained to perform all the duties of the Cleaning Personnel during each phase of the process. However, the Cleaning Supervisor must remain purely in a supervisory role except when direct participation in the cleaning process is deemed necessary for the success of the cleaning operation (eg. If any Cleaning Personnel is unable to complete their cleaning duties midway through the process for a non-emergency reason, the the Cleaning Supervisor can choose to take over these duties themselves). The standard organizational approach for assigning duties to the Cleaning Personnel is described in section 3.2.3. However, the Cleaning Supervisor can request special approval for proposed modifications to the organization of the Cleaning Personnel from the team's Safety Officer (not the Safety Duty Officer). Finally, in addition to the required training, the Cleaning Supervisor must be selected by the CEO and/or the Chief Engineer and/or Propulsion Lead.

5.2.2 Safety Duty Officer

The Safety Duty Officer is responsible for ensuring the safety of the every member involved in a cleaning session. They are not responsible for the success of the cleaning operation and, when forced to choose, must always choose to halt operations if it is needed to ensure safety even if it results in the cleaning session having to restart from Phase I. To this end, they are under no circumstances allowed to participate in the cleaning process and must remain purely in a supervisory role. They are responsible for ensuring that all required PPEs are being used/worn properly by all members (including the Cleaning Supervisor) at all times. They are also responsible for the maintaining the safety of the work environment by inspecting the area prior to the commencement of cleaning. After this inspection they must inform the Cleaning Supervisor of any safety hazards that need to either be dealt with before work commences, or that prohibit work from commencing at all that session if more intensive corrective active action is required. While they do not have the authority to direct the Cleaning Personnel in their cleaning related duties (a power held solely by the Cleaning Supervisor) they do hold the authority to veto any instruction given by the Cleaning Supervisor which they deem unsafe as well. Additionally, they have the authority to halt the cleaning session at any point if they deem it necessary to ensure the safety of the present team members and a safe working environment. They are also responsible for all relevant safety documentation including SDS sheets for all hazardous materials involved, PPE usage instructions, a safety go/no go checklist, and a list of emergency services' numbers (eg 911, Campus Police, Ontario Poison Centre, etc). Despite not being able to participate in the cleaning process, just like the Cleaning Supervisor the Safety Duty Officer must be trained in all aspects of the cleaning process in order to know what hazards to be aware of and when. Unlike the Cleaning Supervisor, the Safety Duty Officer must and can only be appointed be the team's Safety Officer. The Safety Officer can appoint themselves so long as they have all the requisite training. Any conflicts/disagreements of authority that arise between the Safety Duty Officer and the Cleaning Supervisor that are not already explicitly covered in this document will be arbitrated by a committee consisting of the CEO, Chief Engineer, and Safety Officer.

5.2.3 Cleaning Personnel

Cleaning Personnel can be any team member who has received the requisite training for all steps in the cleaning process (Preparation, Phase I-VI, and Clean Up), on how to use all required PPEs, and on all emergency protocols. The standard approach for distributing cleaning duties amongst Cleaning Personnel is through parallel workflows rather than the more time efficient assembly line style approach. In this method, each Cleaning Personnel is given a component which they must disassemble and clean through to the start of Phase IV, rather than having one person handle Phase I and then passing on components to someone who handles Phase 2, etc. The assembly line process, while theoretically more time efficient, requires a minimum number of personnel equal the number of steps in the assembly line. Being a student team, scheduling is always a nightmare, and so using a parallel workflow approach allows for a cleaning process that can scale down to as little as a single Cleaning Personnel and up to as many as one has space for. Of course, if the Cleaning Supervisor can ensure a sufficient number of Cleaning Personnel attend such that an assembly line becomes feasible, this is why the option is given for them to request approval to modify the workflow strategy for that session from the Safety Officer. Finally, regarding the onus of safety, it is not only the responsibility of the supervisory members (see 3.2.1 and 3.2.2), it is, like most aspects of this project, a team effort. Just as the Safety Duty Officer is responsible for ensuring a safe working environment, Cleaning Personnel are responsible for for following all safe working practices and for pointing out potential hazards to the Safety Duty Officer as soon as they notice them. Additionally, as per the worker's rights declared in the Ontario Health and Safety Act, any Cleaning Personnel has the right to know about all hazards and potential hazards in the work environment as well as the right to refuse unsafe work(the third right, "the right to participate" primarily concerns employer/employee relationships and so is not very applicable to a non-professional team of peers).

5.2.4 Cleaning Session

A session starts with the Preparation step and ends at the final Clean Up step regardless of whether those two steps happen on the same day or on consecutive days. When a session is planned, a specific time frame is decided upon first based on availability of trained members. Following this, a list of components that will be cleaned during the session is decided upon. If not all components on the list could be cleaned the Cleaning Supervisor must inform whichever of the three appointing authorities appointed them (CEO, Chief Engineer, or Propulsion Lead). However, if the session is running ahead of schedule, the Cleaning Supervisor may not start cleaning components which were not already on the list. Although this may slow down the cleaning process, from a logistics standpoint it errs on the side of cation. Things like logistics and inventory tracking are as critical to overall system safety and reliability as the cleaning process itself.

5.3 Preparation

Preparation begins with the Cleaning Supervisor giving a short but clear briefing on the planned workflow strategy (parallel or assembly line), the list of components to be cleaned, a recap of the cleaning process (everyone should have already been trained in this process), a list of PPEs and when/where they are required, and finally the division of labour. If any of the Cleaning Personnel have questions, comments, or concerns with the Cleaning Supervisor's plan they should say so at this time. The cleaning team begins by setting up or preparing all non-hazardous equipment or materials on the Cleaning Supervisor's "Non-Hazardous Prep" checklist (some items will be explained in later cleaning steps:

Non-Hazardous Items:

- Sweep and mop floor (if not done recently)
- Set up tables (cleaning table(s), materials table, drying table, inspection & packaging table, and dirty components table)
- Clean tables with consumer surface cleaner product (make sure cleaning fluid is wiped off before beginning hazardous prep)
- Set up degreaser solution bucket(s) next to materials table
- Place X many jugs of distilled water on materials table
- Place Y many jugs of Blue Gold Industrial Cleaner on materials table

- Place polyethylene bag roll on packaging table
- Place bag heat sealer on drying on packaging table
- Set up component drying station
- Check dryer air flow and HEPA filter
  - Check airflow is sufficient
  - If insufficient flow change HEPA filter
- Set up cleaning stations (2 or 3 per table)
  - Microfiber cloth roll/box (1 per table)
  - Dirty parts tray (1 per station)
  - Soaking container (1 per station)
  - Squirt bottle of distilled water (1 per station)
  - Nylon bristled brush (1 per station)
  - Nylon bristled pipe cleaning brush (1 per station)
  - Waste water bucket (1 per table)
- Set up pressure washer (if required)
- Retrieve cleaned and packaged rinsing pitchers, check that package is still sealed (if needed)
- Remove drying trays from dryer and place on dirty components table
- Decide which Cleaning Personnel will clean which components and in what order
- Disassemble all components into their individual parts
- Place all parts of a given component into a dedicated drying tray (do not place parts from more than one component in to the same tray)

Once all of these items have been taken care of the Safety Duty Officer will give a short safety briefing which will include pointing out the locations of the first aid kit and the eye wash station as well as reviewing the required PPEs and the hooded coveralls, which, although not required for safety, are there to control human related contaminants (hair, dead skin, etc). The three PPEs required are splash resistant goggles, chemically resistant gloves, and half-face respirators with organic vapour cartridges (the SDS for the Blue Gold Industrial Cleaner does not require masks, however the room our university has provided for us is in a basement with only a small window in the corner of the room for ventilation). Once everyone has put on their coveralls and all PPEs, the Safety Duty Officer will go around and check that all PPEs are being used properly and are functioning nominally (eg asking each person to perform a suction check by blocking the mask filter inlets and trying to draw air to ensure no air is bypassing the filters). After this, the Cleaning Supervisor resumes operations by running through the "Hazardous Prep" checklist:

- Mix 5% solution of Blue Gold Industrial Cleaner in solution bucket(s) (total volume=# of components to clean X soaking container volume)
- Fill soaking containers with degreaser solution
- Fill pressure washer detergent tank with Blue Gold Industrial Cleaner (if required)
- Check pressure washer functionality (if required)

At this point the Safety Duty Officer will do one final check of the work space to identify any potential hazards not already accounted for, and if none are found they will give the Cleaning Supervisor permission to begin Phase I of the cleaning process.

5.4 Phase I: Soaking

Cleaning Personnel retrieve the drying tray (see 3.7 for detailed description of drying trays) containing the parts of the component they are assigned to clean first and take them to their assigned cleaning station. They then place the entire tray into the soaking bath and leave it there for a minimum of 30 seconds. This gives time for the degreasing solution to work its way under surface contaminants such as dust or oil films. This reduces the amount of work needed to be done in Phase II and allows for some flexibility in how the Cleaning Personnel need to be in Phase II (of course they will be trained to be as meticulous as possible, but there will inevitably be some variation in technique between different Cleaning Personnel). The two exceptions to this phase of the process are tanks and long tubing sections, neither of which can fit into the soaking baths (which will have a foot print somewhere between that of a 13" to 17" laptop for comparison). For long tubes, one end will be placed in a waste water bucket and tilted over so that the other end is at the Cleaning Personnel's shoulder height. A second Cleaning Personnel will then take a small pitcher filled with cleaning solution and begin to slowly pouring it down the tube while the one holding the tube will begin to slowly rotate the tube (they should rotate fast enough to complete at least one revolution before the pitcher is empty). For tanks, they will be placed on their side and partially filled with solution. They will then be slowly rolled to allow the pool of solution to wet all internal surfaces. Using handles affixed by straps, two Cleaning Personnel will then lift the tank to drain it into a waste water bucket. They will be required to wear steel toed shoes during this operation.

5.5 Phase II: Mechanical Washing

After at least 30 seconds has passed they will then remove the dying tray (leaving the parts in the soaking bath), scrub it with the nylon hard bristled brush, rinse it (see Phase III), and place it on a sheet of microfiber cloth to one side of the soaking tray (leaving some distance to avoid splashing it with degreaser solution). They then proceed to scrub each part by hand one at a time using the nylon brush. If the part has an internal cavity such as a manifold, section of tubing, or a valve body, the pipe cleaning brush will be used. If the part is sensitive to abrasion, such as an O-ring, a piece of microfiber cloth will be used instead of brushes. After they have scrubbed a part it must be immediately rinsed without allowing it to reenter the soaking bath. For long sections of tubing, after soaking a pipe cleaning brush (with a diameter greater than the tube's inner diameter) affixed to a plumbing augur will be used to scrub the internal surfaces. For tanks a pressure washer (with special attachments for reaching into tanks with small port diameters) will be used in lieu of manual mechanical scrubbing.

5.6 Phase III: Rinsing

Parts (including the drying tray) should be rinsed with squirt bottles of type II distilled water[1] over the waste water bucket or over a temporary receptacle at their station (to be emptied into the waste water bucket before starting on the next component) to avoid diluting the solution. The rinsed part will then be placed on to the already scrubbed and rinsed drying tray before proceeding to scrub the next part. Phases II and III are repeated for each part of a component one at a time to avoid re-contamination. For long sections of tubing rinsing is essentially the same process as soaking only instead of using pitchers of tap water, distilled water is poured into the tube directly from the jug in a "waterfall" manner to avoid contaminating the jug's contents. The distilled water wasted from missing the tube is more preferable than the risking contamination. For tanks they too will be rinsed the same way they were soaked, only using distilled water. As soon as all parts of a component are fully rinsed, they will be immediately sent to the dryer. After the drying tray is placed in the dryer, the soaking container is emptied into the waste water bucket and rinsed with tap water (this water is also collected in th waste bucket).

5.7 Phase IV: Drying

As described earlier, after disassembly, all parts of a component are placed on a drying tray which follows them through every phase of the cleaning process up to this one. Drying trays are essentially stainless steel bread pans, only smaller (roughly 4" wide and 6" long) and with $\frac{1}{8}$" holes perforating the bottom

[1]See ASTM D1193-06

and all four walls. If a component has any part which could slip through these holes, a fine mesh stainless steel screen will be laid on the bottom. The overwhelming majority of our fluid components will be stainless steel, however for any non stainless steel components or parts of components a Teflon mesh will be laid on the bottom to prevent any dissimilar metal corrosion.

The part dryer will be a sealed, front loading cabinet with a horizontally swinging door and two circular ports for ducting (one on either side). The rims of the drying trays will be curled over (again in the same manner as bread pans) so that they can be suspended by rails The cabinet fit 24 drying trays total; 3 trays high, 4 trays wide, and 2 trays deep (deep meaning from the door to the back wall), where the 4" long side of the trays being parallel to the door. Filtered air will enter via the port on one side and exit via an identical port on the opposite side (ie airflow is parallel to the door). The outlet of the dryer is fitted with a short section of circular ducting with one or more mesh screens to ensure all regions of the outlet maintain at least a slight positive pressure relative to ambient pressure. This helps mitigate the possibility of localized regions of back flow in the outlet.

The filtration unit will consist of an inline blower fan ducted to the filtration box (which contains the HEPA filter), which is in turn ducted to the inlet port of the dryer cabinet via flexible ducting. The filter will have an MERV rating[2] of at least 16 for the required operating flow rate (operating flow rate will be determined based on volume of dryer cabinet final design).

Once a all the parts of a component and their drying tray are finished rinsing, they will be placed in the dryer cabinet. The blower will be turned on prior to inserting first drying tray and allowed to run continuously as the remaining trays become ready for drying in order to maintain a clean environment. While trays are not being added to the cabinet, the door will remain closed and latched to avoid possible contamination. Trays will be loaded starting from the top of the cabinet and working down so that the still wet trays do not drip onto already partially dried trays. Drying will be permitted to run overnight for a minimum of 12h. If upon return the blower fan is found to have shutdown, it will be assumed that the parts inside have become contaminated again.

For tanks and long tube sections, instead of a drying cabinet the outlet of the filtration unit will be ducted to one end of the tank or tube via polyethylene bagging that is secured and sealed with tape (making sure adhesive only touches exterior surfaces of the tube or filtration unit ducting).

Before leaving for the night, the jugs of degreaser and distilled water are placed back into storage while the waste water and any remaining degreaser solution are disposed of in accordance with University of Toronto waste disposal policies. However no other clean up should be done at this point in order to minimize the amount of particulate ejected into the air.

5.8 Phase V: Inspection

The following day the Cleaning Supervisor, Safety Duty Officer, and at least four Cleaning Personnel will return to the cleaning room to begin Phases V and IV. They will start by putting on hooded coveralls, but goggles, respirators, and chemical proof gloves are not required for these phases. However, they will put on sterile latex (or equivalent material) surgical gloves to avoid contamination of cleaned parts. As well, the blower will remain on until the final tray is removed from the dryer for the same reason.

A single tray is then removed from the dryer and handed to the first of the two Cleaning Personnel tasked with inspection. The first inspection is with bright white light using a diffused LED flash light. This inspection is for primarily for spotting debris and particulate. Upon passing the white light inspection the part is then passed to the second inspector who uses UV light to perform the second visual inspection. This inspection is primarily for revealing residual hydrocarbon films or patches. For parts that are sensitive to UV light or which have cavities into which the inspectors cannot see well enough, specialized clean room swabs with white highly absorbing tips will be wiped the various problematic surfaces and checked for contaminants instead (without a sponsorship these swabs are not economically feasible for a student

[2] Minimum Efficiency Reporting Value, see ANSI/ASHRAE 52.2-2017

team to use on every part, and the proposed visual inspection method is a commonly used approach described in ASTM G93-03). After passing inspection a part is handed to the packaging team.

For long tubes specialized clean room wipes are attached to a cleaned length of fishing line and dragged through the tube to check for any contaminants. For tanks, the swab method is used by attaching the swab to a cleaned stainless steel rod bent in a manner to facilitate swabbing of any surface in the tank.

5.9 Phase VI: Packaging and Storing

After passing inspection, a part must be immediately packaged. The packaging is heat sealed polyethylene bags.The "bags" (as they are not bags yet) come in the form of a continuous roll of flattened polyethylene tubing. Upon receiving the roll in the mail, the end is immediately heat sealed shut. When A bag is needed, the required length is measured out and heat sealed at that point. The roll is then cut just prior to this second heat seal so that the packagers now have a bag with only one open end while the main roll itself is never got exposed to the ambient atmosphere during the packaging process. Once a part goes into a bag the open end is heat sealed shut and the bag is gently squeezed to check for leaks. If a leak is detected the bag is cut open and a new bag is made.

Each part of a component receives its own bag and is labeled with the part name and component ID. Once all the parts of a given component have been bagged, all those bags get put into a larger heat sealed bag both for additional protection and for organizational purposes. The larger bag is labeled with the component ID, the date it was packaged, the full legal name of the Cleaning Supervisor, and a label reading "Cleaned for Oxidizer Service". All components will be given the label "Cleaned for Oxidizer Service" regardless of whether or not they directly pertain to the oxidizer fluid systems since it is a description of the degree of cleanliness rather than the component's function. This of course introduces the potential for some confusion during preparation for assembly of the system, however this confusion will most likely take the form of hesitation to unseal a part labeled "Cleaned for Oxidizer Service". But we will not simply rely on people's fear of disobeying directions to induce this hesitation. To ensure this reaction is an almost trained response, the team members who are unsealing and reassembling the components prior to assembly of the system will not only be required to have Cleaning Personnel training, but must have participated in at least three cleaning sessions. The idea of breaking the seal of the wrong component should not just feel like a loss for the team, but also personal loss for them. As stated previously, logistics are as critical to safety and project success as any other aspect the project, and with logistics come human factors like psychology which must be accounted for.

Tanks and long tubes get polyethylene bags with only one heat sealed side slid over either end and tape is used to seal the bags to the exterior walls. Tags are applied to the polyethylene in the same style as for small components. They will be stored horizontally on padded racks to avoid their own weight and sharp geometries puncturing the bags.

5.10 Clean Up

After all components are bagged, tagged, and placed into storage, coveralls and gloves can be taken off for convenience. The empty drying trays are placed back into the dryer cabinet, the duct feeding it with filtered air is removed, both ports are capped shut, and the door is closed and latched. The open end of the filtered air duct (ie the flexible duct coming from the outlet of the filtration box) is sealed with a polyethylene bag in the same manner as tubes and tanks are packaged. The Safety Duty Officer takes inventory of all the PPEs as they are returned to their proper storage locations. The Cleaning Supervisor does the same for all non-safety related equipment. Both the Cleaning Supervisor and the Safety Duty Officer record any inventory discrepancies, including any consumables used (ie distilled water and degreaser) beyond the originally planned amounts. It is important that the safety officer take note of how much time each respirator was used for and records it. of the respirators reach the maximum cartridge life recommended by the manufacturer, they must mark the expended cartridges as "DEAD" in black permanent marker (if light background colour) directly on the cartridge and place in the garbage (or other disposal method if required by University of Toronto waste disposal policies). However they should not install new cartridges as this should only be done the next time the masks are required in order to maximize their lifetime.

6 Risk Analysis

This section presents the risk and failure mode analysis performed to assess the expose of personnel and the system itself to its own failure points and hazards. The failure mode analysis is performed in a bottom-up fashion, starting with every component in the system and analysing the effect of a power or control loss to it at each step of the test procedure (fill and hot fire). Each component's failed state is identified, along with its effect on the system. For each failure, a detailed step-by-step containment strategy is defined and outlined. In addition, a top-down risk analysis is performed to assess the various risks associated with the major subsystems (nitrogen, oxidizer, fuel and engine sections), levels of severity and mitigation strategies.

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6.1 Loss of Power or Control

6.1.1 Failure Mode Analysis

The safeing procedures are outlined in table 6.2.

Comp ID	Phase of Test Procedure	Failed State	Consequence	Containment Strategy

PT_G_N	Prior to nitrogen fill	N/A	Unknown pressure in nitrogen fill system	Halt current phase of test procedure. Use camera to check system pressure from PG_G_N. If pressure is under the MAWP, approach nitrogen fill system, close nitrogen GSE tank's integral valve, and open D_G_N to vent fill line to diagnose issue.
PT_G_N	Nitrogen fill	N/A	Unknown pressure in nitrogen fill system	Open D_R_N, check PG_G_N on camera. If camera shows building pressure pull rope to open D_G_N and wait for both run and fill systems to depressurize. If pressure is nominal then wait for run system to depressurize, approach nitrogen fill system, close nitrogen GSE tank's integral valve, and open D_G_N to vent fill line to diagnose issue.
PT_G_N	Fuel purge	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
PT_G_N	Fuel Fill	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
PT_G_N	Oxidizer purge	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
PT_G_N	Oxidizer fill	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
PT_G_N	Nitrogen recharge	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
PT_G_N	Engine burn	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
PT_G_N	Post-Burn	N/A	Unknown pressure in nitrogen fill system	Refer to PG_G_N using camera
FV_G_N1	Prior to nitrogen fill		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging

FV_G_N1	Nitrogen fill		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging
FV_G_N1	Fuel purge		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging
FV_G_N1	Fuel Fill		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging
FV_G_N1	Oxidizer purge		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging
FV_G_N1	Oxidizer fill		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging
FV_G_N1	Nitrogen recharge		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state. Halt the ongoing procedure and refer to debugging
FV_G_N1	Engine burn		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state.
FV_G_N1	Post-Burn		Valve closes shutting any nitrogen flow from fill system to run system	Mitigation unnecessary due to nominally closed state.
FV_G_N2	Prior to nitrogen fill		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Nitrogen fill		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.

FV_G_N2	Fuel purge		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Fuel Fill		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Oxidizer purge		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Oxidizer fill		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Nitrogen recharge		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Engine burn		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.
FV_G_N2	Post-Burn		Lose ability to switch nitrogen run system between run and fill configurations	Mitigation unnecessary due to the latching nature of the valve. Halt the ongoing procedure, and refer to debugging.

FV_G_N2	State transition during the ethanol purge procedure		Expose the nitrogen run, nitrogen fill and ethanol run system to each other. Loss on correct supply ot nitrogen to ethanol run system	IS_R_N1, IS_R_N2, and FV_G_N1 isolate FV_G_N2 from the oxidizer run system, the fuel run system, and the nitrogen fill system respectively. The latching nature of IS_R_N1 and IS_R_N2 mean that at this stage exposure to the oxidizer and fuel run systems is highly improbable, and the nominally closed state of FV_G_N1 ensures that even a system wide power out would keep the systems isolated. The presence of RF_R_N3, RF_R_N1, RF_G_N2, and BD_R_N provide pressure relief capability if needed. Perform SP2
FV_G_N2	State transitions during the nitrogen recharge procedure		Expose the nitrogen run, nitrogen fill and ethanol run system to each other. Loss on correct supply ot nitrogen to ethanol run system	IS_R_N1, IS_R_N2, and FV_G_N1 isolate FV_G_N2 from the oxidizer run system, the fuel run system, and the nitrogen fill system respectively. The latching nature of IS_R_N1 and IS_R_N2 mean that at this stage exposure to the oxidizer and fuel run systems is highly improbable, and the nominally closed state of FV_G_N1 ensures that even a system wide power out would keep the systems isolated. The presence of RF_R_N3, RF_R_N1, RF_G_N2, and BD_R_N provide pressure relief capability if needed. Perform SP2
D_R_N	Prior to nitrogen fill		Lose ability to vent nitrogen run system upstream of FV_G_N2	System unpressurized. Halt testing and debug.
D_R_N	Nitrogen fill		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and Perform SP1 or perform SP2 if applicable.

D_R_N	Fuel purge		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 if applicable.
D_R_N	Fuel Fill		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 if applicable.
D_R_N	Oxidizer purge		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 if applicable.
D_R_N	Oxidizer fill		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 if applicable.
D_R_N	Nitrogen recharge		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 if applicable.

D_R_N	Engine burn		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 if applicable.
D_R_N	Post-Burn		Lose ability to vent nitrogen run system upstream of FV_G_N2	RF_R_N1 and BD_R_N provide redundant pressure relief capability. Redundant safeing capability is provided by the Emergency Solenoid Power System. Halt ongoing procedure and refer to Perform SP1 or perform SP2 as applicable.
PT_R_N	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in nitrogen run system	System unpressurized. Halt testing and debug.
PT_R_N	Nitrogen fill	N/A	Loss of ability to detect pressure in nitrogen run system	Perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
PT_R_N	Fuel purge	N/A	Loss of ability to detect pressure in nitrogen run system	Perform SP3, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
PT_R_N	Fuel Fill	N/A	Loss of ability to detect pressure in nitrogen run system	Turn of fill pump, close FV_G_F1, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
PT_R_N	Oxidizer purge	N/A	Loss of ability to detect pressure in nitrogen run system	Perform SP4, perform SP3, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
PT_R_N	Oxidizer fill	N/A	Loss of ability to detect pressure in nitrogen run system	Close FV_G_OX1, perform SP5, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
PT_R_N	Nitrogen recharge	N/A	Loss of ability to detect pressure in nitrogen run system	Perform SP8, perform SP5, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.

PT_R_N	Engine burn	N/A	Loss of ability to detect pressure in nitrogen run system	Perform emergency MECO, perform SP5, perform SP8, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
PT_R_N	Post-Burn	N/A	Loss of ability to detect pressure in nitrogen run system	Perform SP5, perform SP8, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Prior to nitrogen fill	N/A	Loss of ability to detect temperature in nitrogen run system	System unpressurized. Halt testing and debug.
TC_R_N	Nitrogen fill	N/A	Loss of ability to detect temperature in nitrogen run system	Perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Fuel purge	N/A	Loss of ability to detect temperature in nitrogen run system	Perform SP3, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Fuel Fill	N/A	Loss of ability to detect temperature in nitrogen run system	Turn of fill pump, close FV_G_F1, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Oxidizer purge	N/A	Loss of ability to detect temperature in nitrogen run system	Perform SP4, perform SP3, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Oxidizer fill	N/A	Loss of ability to detect temperature in nitrogen run system	Close FV_G_OX1, perform SP5, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Nitrogen recharge	N/A	Loss of ability to detect temperature in nitrogen run system	Perform SP8, perform SP5, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
TC_R_N	Engine burn	N/A	Loss of ability to detect temperature in nitrogen run system	Perform emergency MECO, perform SP5, perform SP8, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.

TC_R_N	Post-Burn	N/A	Loss of ability to detect temperature in nitrogen run system	Perform SP5, perform SP8, perform SP1 or perform SP2 as applicable. PG_R_N provides redundant pressure readout via camera feed.
IS_R_N1	Prior to nitrogen fill	Closed	Lose ability to connect the nitrogen run system to the oxidizer run system	System is depressurized
IS_R_N1	Nitrogen fill	Closed	Lose ability to connect the nitrogen run system to the oxidizer run system	System downstream of FV_G_N2 is at system nominal starting pressure
IS_R_N1	Fuel purge	Closed	Lose ability to connect the nitrogen run system to the oxidizer run system	Perform SP3, perform SP1.
IS_R_N1	Fuel Fill	Closed	Lose ability to connect the nitrogen run system to the oxidizer run system	Perform SP11, perform SP1.
IS_R_N1	Oxidizer purge Beginning	Closed	Lose ability to purge oxidizer run system	Perform SP8, perform SP1.
IS_R_N1	Oxidizer purge End	Open	Lose ability to isolate oxidizer run system from nitrogen run system	Open V_R_OX1, open D_R_OX, open MOV
IS_R_N1	Oxidizer fill	Closed	Lose ability to purge oxidizer run system of oxidizer vapour in case of dump	Perform SP5, perform SP8, perform SP1.
IS_R_N1	Nitrogen recharge	Closed	Lose ability to purge oxidizer run system of oxidizer vapour in case of dump.	Close FV_G_N1, perform SP5, perform SP8, perform SP1, open V_R_N1. When all venting is observed to have stopped (via visual venting indicators) approach test stand and open V_R_N2.
IS_R_N1	Engine burn Beginning	Closed	Lose ability to supply pressurant to oxidizer tank for engine burn	Perform SP5, perform SP8, perform SP1.

IS_R_N1	During engine burn	Open	Lose ability to isolate oxidizer run system from nitrogen run system	Perform emergency MECO, perform SP10, perform SP8, perform SP1 or perform SP2 as applicable.
IS_R_N1	Post-Burn Beginning	Closed	Lose ability to purge oxidizer run system	Open V_R_OX1, open D_R_OX, perform SP4, perform SP1
IS_R_N1	Post-Burn Beginning	Open	Lose ability to isolate oxidizer run system from nitrogen run system	Open V_R_OX1, open D_R_OX, open MOV, perform SP4
IS_R_N2	Prior to nitrogen fill	Closed	Lose ability to connect the nitrogen run system to the fuel run system	System is at nominal starting pressure
IS_R_N2	Nitrogen fill	Closed	Lose ability to connect the nitrogen run system to the fuel run system	System is at nominal starting pressure
IS_R_N2	Fuel purge Beginning	Closed	Lose ability to purge fuel run system of air	Perform SP1.
IS_R_N2	Fuel purge end	Open	Lose ability to isolate fuel run system from nitrogen run system	Open V_R_N1, V_R_F1, and D_R_F then perform SP1.
IS_R_N2	Fuel fill prior to pressurization	Closed	Lose ability to pressurize fuel run system	Perform Perform SP1.
IS_R_N2	Fuel fill before end of pressurization	Open	Lose ability to isolate fuel run system from nitrogen run system during pressurization. Fuel ullage reaches full 36 bar	Open V_R_F1 then perform SP1.
IS_R_N2	Oxidizer purge	Closed	Lose ability to purge fuel run system	Perform SP17, perform SP8, perform SP1.
IS_R_N2	Oxidizer fill	Closed	Lose ability to purge fuel run system	Perform SP9, perform SP8, perform SP1.

IS_R_N2	Nitrogen recharge	Closed	Lose ability to purge fuel run system	Close FV_G_N1, move FV_G_N2 from fill to run position, perform SP9, perform SP8, perform SP1, open V_R_N1. When all venting is observed to have stopped (via visual venting indicators) approach test stand and open V_R_N2.
IS_R_N2	Engine burn	Closed	Lose ability to purge fuel run system	Perform emergency MECO, perform SP5, perform SP8, Perform SP1.
IS_R_N2	Post-burn Beginning (after oxidizer dump and purge, before fuel dump and purge)	Closed	Lose ability to purge fuel run system	Perform standard post-burn procedure minus ethanol run system dump and purge. Perform SP6.
IS_R_N2	Post-burn during fuel dump and purge	Open	Lose ability to isolate fuel run system from nitrogen run system	Open D_R_F. When liquid draining has finished close D_R_F and open MFV until liquid draining from injector has finished then reopen D_R_F, open V_R_N1 and D_R_N.
V_R_OX1	Prior to nitrogen fill	Closed	Loss of ability to vent oxidizer run system through vent line	System is at nominal starting pressure
V_R_OX1	Nitrogen fill	Closed	Loss of ability to vent oxidizer run system through vent line	System is at nominal starting pressure
V_R_OX1	Fuel purge	Closed	Loss of ability to vent oxidizer run system through vent line	System is at nominal starting pressure
V_R_OX1	Fuel Fill	Closed	Loss of ability to vent oxidizer run system through vent line	System is at nominal starting pressure, perform SP11 or perform SP8 as applicable
V_R_OX1	Oxidizer purge (just prior to Beginning)	Closed	Loss of ability to vent oxidizer run system through vent line	Close V_G_OX, perform SP8, perform SP1.
V_R_OX1	Oxidizer purge (just prior to ending)	Open	Loss of ability to seal oxidizer run system.	Close MOV, IS_R_N1, D_R_OX, and V_G_OX, perform SP8, perform SP1.
V_R_OX1	Oxidizer fill (during supercharge)	Closed	Loss of ability to vent oxidizer run system through vent line	Perform SP4 minus opening V_R_OX1, perform SP8, perform SP1.

V_R_OX1	Oxidizer fill (during fill)	Open	Loss of ability to seal oxidizer run system	Close FV_G_OX1, open D_R_OX, open V_G_OX, open IS_R_N1, when oxidizer run system and fill line drained of liquid close IS_R_N1, perform SP8, perform SP1.
V_R_OX1	Nitrogen recharge	Closed	Loss of ability to vent oxidizer run system through vent line	Close FV_G_N1, move FV_G_N2 to run position, open D_R_OX, open V_G_OX, open IS_R_N1, when oxidizer run system and fill line drained of liquid close IS_R_N1, perform SP8, perform SP1.
V_R_OX1	Engine burn	Closed	Loss of ability to vent oxidizer run system through vent line	Perform emergency MECO, perform SP8 except use D_R_OX to control final system pressure, perform SP4, perform SP1
V_R_OX1	Post-Burn (prior to system purge)	Closed	Loss of ability to vent oxidizer run system through vent line	Perform standard post-burn purge procedure except for all V_R_OX1 commands. Use D_R_OX to control final system pressure
V_R_OX1	Post-Burn (during purge)	Open	Loss of ability to seal oxidizer run system	Perform standard post-burn purge procedure except allow oxidizer run system to vent to ambient pressure
V_R_F1	Prior to nitrogen fill	Open	Lose ability to seal fuel run system	System is at nominal starting pressure
V_R_F1	Nitrogen fill	Open	Lose ability to seal fuel run system	Close FV_G_N1, Perform SP1.
V_R_F1	Fuel purge (before V_R_F1 has opened)	Open	Lose ability to seal fuel run system	Perform SP1.
V_R_F1	Fuel purge (after IS_R_N2 is open)	Open	Lose ability to seal fuel run system	Close IS_R_N2, close MFV, close D_R_F, perform SP1.
V_R_F1	Fuel Fill (during filling)	Open	Lose ability to seal fuel run system	Stop fuel fill pump, close FV_G_F1, perform SP1.
V_R_F1	Fuel Fill (during or after pressurization)	Open	Lose ability to seal fuel run system	Perform SP8, perform SP1.
V_R_F1	Oxidizer purge	Open	Lose ability to seal fuel run system	Perform SP17, open D_R_F, perform SP1.
V_R_F1	Oxidizer fill	Open	Lose ability to seal fuel run system	Perform SP9, open D_R_F, perform SP1.
V_R_F1	Nitrogen recharge	Open	Lose ability to seal fuel run system	close FV_G_N1, move FV_G_N2 to run position, perform SP9, open D_R_F, perform SP1.

V_R_F1	Engine burn	Open	Lose ability to seal fuel run system	Perform emergency MECO, perform SP9, perform SP1
V_R_F1	Post-Burn	Open	Lose ability to seal fuel run system	Perform standard system purge except allow fuel run system to vent to ambient pressure
D_R_OX	Prior to nitrogen fill	Closed	Loss of ability to dump oxidizer tank	System is at nominal starting pressure
D_R_OX	Nitrogen fill	Closed	Loss of ability to dump oxidizer tank	System is at nominal starting pressure, perform SP1.
D_R_OX	Fuel purge	Closed	Loss of ability to dump oxidizer tank	System is at nominal starting pressure, perform SP3, perform SP1.
D_R_OX	Fuel Fill	Closed	Loss of ability to dump oxidizer tank	System is at nominal starting pressure, perform SP11 or perform SP8 as applicable, perform SP1.
D_R_OX	Oxidizer purge (prior to opening D_R_OX)	Closed	Loss of ability to dump oxidizer tank	Close V_G_OX, close V_R_OX1, perform SP8, perform SP1.
D_R_OX	Oxidizer purge (during purge)	Open	Loss of ability to seal oxidizer run system	Perform SP17 minus D_R_OX commands, perform SP8, perform SP1.
D_R_OX	Oxidizer fill (during supercharge)	Closed	Loss of ability to dump oxidizer tank	Close IS_R_N1, open V_R_OX1, open V_G_OX, perform SP8, perform SP1.
D_R_OX	Oxidizer fill (during fill)	Closed	Loss of ability to dump oxidizer tank	Close FV_G_OX1, close V_R_OX, open V_G_OX, open IS_R_N1, when liquid has drained close IS_R_N1 and V_G_OX, open V_R_OX1 until system is at 200 kPa, perform SP8, perform Perform SP1.
D_R_OX	Nitrogen recharge	Closed	Loss of ability to dump oxidizer tank	Close FV_G_N1, move FV_G_N2 to run position, open V_G_OX, open IS_R_N1, when liquid has drained close IS_R_N1 and V_G_OX, open V_R_OX1 until system is at 200 kPa, perform SP8, perform Perform SP1.
D_R_OX	Engine burn	Closed	Loss of ability to dump oxidizer tank	Perform emergency MECO, perform SP9 except use V_G_OX to dump instead of D_R_OX, perform SP4, perform SP1

D_R_OX	Post-Burn	Closed	Loss of ability to dump oxidizer tank	Perform SP9 except use V_G_OX to dump instead of D_R_OX, perform SP4, perform SP1
D_R_F	Prior to nitrogen fill	Closed	Loss of ability to dump fuel tank	System is at nominal starting pressure
D_R_F	Nitrogen fill	Closed	Loss of ability to dump fuel tank	System is at nominal starting pressure, perform SP1.
D_R_F	Fuel purge (during purge)	Open	Loss of ability to seal fuel run system	Close IS_R_N2, close MFV, close V_R_F1, perform SP1.
D_R_F	Fuel Fill (during filling)	Closed	Loss of ability to dump fuel tank	Perform SP11, perform SP16, perform SP1.
D_R_F	Fuel Fill (after pressurization)	Closed	Loss of ability to dump fuel tank	Perform SP8, perform SP16, perform SP1.
D_R_F	Oxidizer purge	Closed	Loss of ability to dump fuel tank	Perform SP17, perform SP8, perform SP16, perform SP1.
D_R_F	Oxidizer fill	Closed	Loss of ability to dump fuel tank	Perform SP9, perform SP8, perform SP16, perform SP1.
D_R_F	Nitrogen recharge	Closed	Loss of ability to dump fuel tank	Perform SP9, perform SP8, perform SP16, perform SP1.
D_R_F	Engine burn	Closed	Loss of ability to dump fuel tank	If no other failures and telemetry indicates otherwise nominal operation then continue through to nominal MECO.
D_R_F	Post-Burn (prior to system purge)	Closed	Loss of ability to dump fuel tank	Perform dump and purge of oxidizer run system, perform SP4 except leave V_R_F open to vent to ambient pressure, perform SP1
D_R_F	Post-Burn (during system purge)	Open	Loss of ability to dump fuel tank	
MOV	Prior to nitrogen fill	Closed	Loss of ability to connect oxidizer run system to propellant delivery system	System at nominal starting pressure
MOV	Nitrogen fill	Closed	Loss of ability to connect oxidizer run system to propellant delivery system	System at nominal starting pressure, perform SP1.
MOV	Fuel purge	Closed	Loss of ability to connect oxidizer run system to propellant delivery system	System at nominal starting pressure, perform SP3, perform SP1.

MOV	Fuel Fill	Closed	Loss of ability to connect oxidizer run system to propellant delivery system	System at nominal starting pressure, perform SP11 or perform SP8 as applicable, perform SP1.
MOV	Oxidizer purge (during purge)	open	Loss of ability to purge oxidizer half of propellant delivery system	Close IS_R_N1, close D_R_OX, close V_G_OX, close V_R_OX, perform SP8, perform Perform SP1.
MOV	Oxidizer fill	Closed	Loss of ability to deliver oxidizer to propellant delivery system	Perform SP9, perform SP8, perform SP1.
MOV	Nitrogen recharge	Closed	Loss of ability to deliver oxidizer to propellant delivery system	Perform SP9, perform SP6, perform SP1.
MOV	Engine burn (prior to opening MOV)	Closed	Loss of ability to deliver oxidizer to propellant delivery system	Perform SP9, perform SP8
MOV	Engine burn (After initiating MOV open command but prior to opening MFV)	Partially open	Loss of ability cutoff oxidizer flow to engine	Close IS_R_N1, open PV_R_N1, open D_R_OX, open V_R_OX1, close PV_R_N1 after 10 seconds, purge oxidizer run system (using standard procedure minus MOV commands), perform SP8, perform SP1.
MOV	Engine burn (After initiating MOV open command but prior to opening MFV)	Fully open	Loss of ability cutoff oxidizer flow to engine	CLose IS_R_N1, open PV_R_N1, open D_R_OX, open V_R_OX1, close PV_R_N1 after 10 seconds, purge oxidizer run system (using standard procedure, minus MOV commands), perform SP8, perform SP1.
MOV	Engine burn (just prior to burnout)	Open	Loss of ability to cutoff oxidizer flow prior to burnout resulting in loss of ability to force MECO	CLose MFV, close IS_R_N1, open PV_R_N1, open D_R_OX, open V_R_OX1, close PV_R_N1 after 10 seconds, purge oxidizer run system (using standard procedure, minus MOV commands), perform SP8, perform SP1.
MOV	Post-Burn (prior to system purge)	Closed	Loss of ability to perform nominal system purge.	

MOV	Post-Burn (during system purge)	Open	Loss of ability to seal oxidizer run system.	
MFV	Prior to nitrogen fill	CLosed	Loss of ability to connect fuel run system to propellant delivery system	System at nominal starting pressure
MFV	Nitrogen fill	Closed	Loss of ability to connect fuel run system to propellant delivery system	System at nominal starting pressure, perform SP1.
MFV	Fuel purge (before opening MFV)	Closed	Loss of ability to connect fuel run system to propellant delivery system	Close D_R_F and V_R_F1, perform SP1.
MFV	Fuel purge (during purge)	Open	Loss of ability to isolate fuel run system to propellant delivery system	Close IS_R_N2, perform SP1.
MFV	Fuel Fill (during fill)	Closed	Loss of ability to connect fuel run system to propellant delivery system	Perform SP11, perform SP7, perform SP1.
MFV	Fuel Fill (during pressurization)	Closed	Loss of ability to connect fuel run system to propellant delivery system	Perform SP6, perform SP1.
MFV	Oxidizer purge	Closed	Loss of ability to connect fuel run system to propellant delivery system	Perform SP17, perform SP6, perform SP1.
MFV	Oxidizer fill	Closed	Loss of ability to connect fuel run system to propellant delivery system	Perform SP9, perform SP6, perform SP1.
MFV	Nitrogen recharge	Closed	Loss of ability to connect fuel run system to propellant delivery system	Perform SP9, perform SP6, perform SP1.

MFV	Engine burn (After opening MOV but prior to opening MFV)	Closed	Loss of ability to connect fuel run system to propellant delivery system	Close MOV then IS_R_N1, open PV_R_N1, open D_R_OX, open V_R_OX1, close PV_R_N1 after 10 seconds, purge oxidizer run system (using standard procedure minus MFV commands), perform SP6, perform SP1.
MFV	Engine burn (just prior to burnout)	Partially open	Loss of ability to cutoff fuel flow prior to burnout resulting in loss of ability to force MECO	Close MOV then IS_R_N1, open PV_R_N1, open D_R_OX, open V_R_OX1, turn off gear pump, close PV_R_N1 after 10 seconds, purge oxidizer run system (using standard procedure minus MFV commands), perform SP6, perform SP1.
MFV	Engine burn (during burn)	Fully open	Loss of ability to cutoff fuel flow prior to burnout resulting in loss of ability to force MECO	Close MOV then IS_R_N1, open PV_R_N1, open D_R_OX, open V_R_OX1, turn off gear pump, close PV_R_N1 after 10 seconds, purge oxidizer run system (using standard procedure minus MFV commands), perform SP6, perform SP1.
MFV	Post-burn (prior to system purge)	Closed	Loss of ability to connect fuel run system to propellant delivery system	
MFV	Post-Burn (during system purge)	Open	Loss of ability to connect fuel run system to propellant delivery system	
PV_R_N1	Prior to nitrogen fill	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	System at nominal starting pressure
PV_R_N1	Nitrogen fill	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	System at nominal starting pressure, perform SP1.

PV_R_N1	Fuel purge	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	Perform SP3,Perform SP1
PV_R_N1	Fuel Fill	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	System at nominal starting pressure, perform SP11 or perform SP8 as applicable, perform SP1.
PV_R_N1	Oxidizer purge	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	Perform SP17, perform SP6, perform SP1.
PV_R_N1	Oxidizer fill	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	Perform SP9, perform SP6, perform SP1.
PV_R_N1	Nitrogen recharge	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	Perform SP9, perform SP6, perform SP1.
PV_R_N1	Engine burn	Closed	Loss of ability to purge main oxidizer line downstream of MOV when it is closed	Switch command to redundant valve PV_R_N2
PV_R_N1	Post-Burn	Open	Loss of ability to halt main oxidizer line purge downstream of MOV	Open IS_R_N1, D_R_OX and V_R_OX1 to purge nitrous system, perform SP8, perform SP1
FV_G_OX1	Prior to nitrogen fill	Closed	Loss of ability to fill oxidizer run system	System at nominal starting pressure
FV_G_OX1	Nitrogen fill	Closed	Loss of ability to fill oxidizer run system	System at nominal starting pressure, perform SP1.
FV_G_OX1	Fuel purge	Closed	Loss of ability to fill oxidizer run system	Perform SP3,Perform SP1
FV_G_OX1	Fuel Fill	Closed	Loss of ability to fill oxidizer run system	System at nominal starting pressure, perform SP11 or perform SP8 as applicable, perform SP1.
FV_G_OX1	Oxidizer purge	Closed	Loss of ability to fill oxidizer run system	Perform SP17, perform SP6, perform SP1.
FV_G_OX1	Oxidizer fill (prior to start of filling)	Closed	Loss of ability to fill oxidizer run system	Perform SP4, perform SP8, perform SP1

FV_G_OX1	Oxidizer fill (during filling)	Open	Loss of ability to stop filling oxidizer run system	Open V_G_OX, open D_R_OX, ensure that V_R_OX1 is open, dump nitrous fill system until all liquid draining is done, the open MOV and IS_R_N1 to purge the oxidizer fill system of all nitrous vapor. The close IS_R_N1, MOV, D_R_OX, V_G_OX, and when the tank pressure reaches 200 kPa, close V_R_OX1, perform SP8, perform SP1
FV_G_OX1	Nitrogen recharge	Closed	Loss of ability to fill oxidizer run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
FV_G_OX1	Engine burn	Closed	Loss of ability to fill oxidizer run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
FV_G_OX1	Post-Burn	Closed	Loss of ability to fill oxidizer run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
FV_G_F	Prior to nitrogen fill	Closed	Loss of ability to fill fuel run system	System at nominal starting pressure
FV_G_F	Nitrogen fill	Closed	Loss of ability to fill fuel run system	System at nominal starting pressure, perform SP1.
FV_G_F	Fuel purge	Closed	Loss of ability to fill fuel run system	,Perform SP20
FV_G_F	Fuel Fill (before the start of fuel filling)	Open	Loss of ability to fill fuel run system	Close V_R_F1, perform SP1
FV_G_F	Fuel Fill (during the fuel fill)	Closed	Loss of ability to shut-off fuel fill	Shutoff the fill pump, open D_R_F, open MFV, once all liquid in tank is done draining, open IS_R_N2 to purge fuel run system for 10s, then close IS_R_N2, MFV, D_R_F, and once the fuel run system pressure reaches 200 kPa, close V_R_F1, perform SP1
FV_G_F	Oxidizer purge	Closed	Loss of ability to fill fuel run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
FV_G_F	Oxidizer fill	Closed	Loss of ability to fill fuel run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.

FV_G_F	Nitrogen recharge	Closed	Loss of ability to fill fuel run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
FV_G_F	Engine burn	Closed	Loss of ability to fill fuel run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
FV_G_F	Post-Burn	Closed	Loss of ability to fill fuel run system	Non-critical component at this stage, both from safety and operational perspectives. Continue testing with caution.
V_G_OX	Prior to nitrogen fill	Closed	Loss of ability to vent oxidizer fill line	System at nominal starting pressure
V_G_OX	Nitrogen fill	Closed	Loss of ability to vent oxidizer fill line	System at nominal starting pressure, perform SP1.
V_G_OX	Fuel purge	Closed	Loss of ability to vent oxidizer fill line	Perform SP3, perform SP1
V_G_OX	Fuel Fill	Closed	Loss of ability to vent oxidizer fill line	System at nominal starting pressure, perform SP11 or perform SP8 as applicable, perform SP1.
V_G_OX	Oxidizer purge	Open	Loss of ability to seal oxidizer fill line	Perform SP17, perform SP8, perform SP1
V_G_OX	Oxidizer fill (during supercharge)	Closed	Loss of ability to vent oxidizer fill line	Perform SP4, perform SP8, perform SP1
V_G_OX	Oxidizer fill (during fill)	Closed	Loss of ability to vent oxidizer fill line	Close V_R_OX1, FV_G_N1 and FV_G_OX1, ensure that MOV is closed and that FV_G_N2 is set to the run position, then open D_R_OX and IS_R_N1 (in that order), when tank is empty of liquid (confirmed visually by watching tank dump line exit orifice), close IS_R_N1, open V_R_OX1, and allow 1-2min for all liquid oxidizer trapped in the fill line to boiloff and exit the tank through D_R_OX and V_R_OX1. Once the boiloff time has passed, perform the standard oxidizer system purge procedure, excluding V_G_OX actions, perform SP8, perform SP1
V_G_OX	Nitrogen recharge	Closed	Loss of ability to vent oxidizer fill line	Oxidizer line vented at this point, proceed with caution
V_G_OX	Engine burn	Closed	Loss of ability to vent oxidizer fill line	Oxidizer line vented at this point, proceed with caution

V_G_OX	Post-Burn (before oxidizer run system purge)	Closed	Loss of ability to vent oxidizer fill line	Oxidizer line vented at this point, proceed with caution
V_G_OX	Post-Burn (During oxidizer run system purge)	Open	Loss of ability to seal oxidizer fill line	Proceed normally with post-burn procedures
TC_R_OX1	Prior to nitrogen fill	N/A	Loss of ability to detect temperature in oxidizer run system	System is at nominal starting temperature (ambient)
TC_R_OX1	Nitrogen fill	N/A	Loss of ability to detect temperature in oxidizer run system	System is at nominal starting temperature (ambient), perform SP1
TC_R_OX1	Fuel purge	N/A	Loss of ability to detect temperature in oxidizer run system	System is at nominal starting temperature (ambient), perform SP3, perform SP1
TC_R_OX1	Fuel Fill	N/A	Loss of ability to detect temperature in oxidizer run system	System is at nominal starting temperature (ambient), perform SP11 or perform SP8 as applicable, perform SP1
TC_R_OX1	Oxidizer purge	N/A	Loss of ability to detect temperature in oxidizer run system	Perform SP17, perform SP8, perform SP1
TC_R_OX1	Oxidizer fill (during supercharge)	N/A	Loss of ability to detect temperature in oxidizer run system	Perform SP4, perform SP8, perform SP1
TC_R_OX1	Oxidizer fill (during filling)	N/A	Loss of ability to detect temperature in oxidizer run system	Perform SP9, perform SP8, perform SP1. Mass and pressure of oxidizer in run tank can be used to calculate rough estimate of temperature during dump process to determine if boil-off cooling is ever required.
TC_R_OX1	Nitrogen recharge	N/A	Loss of ability to detect temperature in oxidizer run system	Perform SP9, perform SP8, perform SP1. Mass and pressure of oxidizer in run tank can be used to calculate rough estimate of temperature during dump process to determine if boil-off cooling is ever required.

TC_R_OX1	Engine burn	N/A	Loss of ability to detect temperature in oxidizer run system	
TC_R_OX1	Post-Burn	N/A	Loss of ability to detect temperature in oxidizer run system	
PT_R_OX1	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in oxidizer run system	System is at nominal starting pressure. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_OX1	Nitrogen fill	N/A	Loss of ability to detect pressure in oxidizer run system	System is at nominal starting pressure, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_OX1	Fuel purge	N/A	Loss of ability to detect pressure in oxidizer run system	System is at nominal starting pressure, perform SP3, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_OX1	Fuel Fill	N/A	Loss of ability to detect pressure in oxidizer run system	System is at nominal starting pressure, perform SP11 or perform SP8 as applicable, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_OX1	Oxidizer purge	N/A	Loss of ability to detect pressure in oxidizer run system	Perform SP17 except allow system to equalize with ambient pressure, perform SP8, perform SP1
PT_R_OX1	Oxidizer fill (during supercharge)	N/A	Loss of ability to detect pressure in oxidizer run system	Perform SP4, perform SP8, perform SP1
PT_R_OX1	Oxidizer fill (during fill)	N/A	Loss of ability to detect pressure in oxidizer run system	Perform SP5, perform SP8, perform SP1
PT_R_OX1	Nitrogen recharge	N/A	Loss of ability to detect pressure in oxidizer run system	Close FV_G_N1, switch FV_G_N2 to run position, perform SP5, perform SP8, perform SP1
PT_R_OX1	Engine burn	N/A	Loss of ability to detect pressure in oxidizer run system	
PT_R_OX1	Post-Burn	N/A	Loss of ability to detect pressure in oxidizer run system	

PT_R_F1	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in fuel run system	System is at nominal starting pressure. PG_R_F1 provides redundant pressure readout via camera feed.
PT_R_F1	Nitrogen fill	N/A	Loss of ability to detect pressure in fuel run system	System is at nominal starting pressure. Perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Fuel purge	N/A	Loss of ability to detect pressure in fuel run system	Perform SP3 except allow system to equalize to ambient pressure, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Fuel Fill (during fill)	N/A	Loss of ability to detect pressure in fuel run system	Perform SP11, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Fuel Fill (during pressurization)	N/A	Loss of ability to detect pressure in fuel run system	Perform SP8 except allow system to equalize to ambient pressure, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Oxidizer purge	N/A	Loss of ability to detect pressure in fuel run system	Perform SP17, perform SP8 except allow system to equalize to ambient pressure, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Oxidizer fill	N/A	Loss of ability to detect pressure in fuel run system	Perform SP9, perform SP8 except allow system to equalize to ambient pressure, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Nitrogen recharge	N/A	Loss of ability to detect pressure in fuel run system	Perform SP9, perform SP8 except allow system to equalize to ambient pressure, perform SP1. PG_R_OX1 provides redundant pressure readout via camera feed.
PT_R_F1	Engine burn	N/A	Loss of ability to detect pressure in fuel run system	
PT_R_F1	Post-Burn	N/A	Loss of ability to detect pressure in fuel run system	

TC_R_OX2	Prior to nitrogen fill	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Nitrogen fill	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Fuel purge	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Fuel Fill	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Oxidizer purge	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Oxidizer fill	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Nitrogen recharge	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.

TC_R_OX2	Engine burn	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_OX2	Post-Burn	N/A	Loss of ability to detect temperature in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Nitrogen fill	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Fuel purge	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Fuel Fill	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Oxidizer purge	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.

PT_R_OX2	Oxidizer fill	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Nitrogen recharge	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Engine burn	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_OX2	Post-Burn	N/A	Loss of ability to detect pressure in oxidizer injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Prior to nitrogen fill	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Nitrogen fill	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Fuel purge	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.

TC_R_F	Fuel Fill	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Oxidizer purge	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Oxidizer fill	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Nitrogen recharge	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Engine burn	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
TC_R_F	Post-Burn	N/A	Loss of ability to detect temperature in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.

PT_R_F2	Nitrogen fill	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Fuel purge	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Fuel Fill	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Oxidizer purge	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Oxidizer fill	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Nitrogen recharge	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_F2	Engine burn	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.

PT_R_F2	Post-Burn	N/A	Loss of ability to detect pressure in fuel injector manifold	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Nitrogen fill	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Fuel purge	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Fuel Fill	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Oxidizer purge	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Oxidizer fill	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.

PT_R_C	Nitrogen recharge	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Engine burn	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_R_C	Post-Burn	N/A	Loss of ability to detect pressure in combustion chamber	Non-safety critical sensor. Non-operationally critical sensor. Purely for performance characterization. Testing procedure can proceed through nominal engine burn without risk.
PT_G_OX	Prior to nitrogen fill	N/A	Loss of ability to detect pressure in oxidizer fill system	Check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty
PT_G_OX	Nitrogen fill	N/A	Loss of ability to detect pressure in oxidizer fill system	Close FV_G_N1, perform SP1, check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty

PT_G_OX	Fuel purge	N/A	Loss of ability to detect pressure in oxidizer fill system	Perform SP3, perform SP1, check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty
PT_G_OX	Fuel Fill	N/A	Loss of ability to detect pressure in oxidizer fill system	Perform SP11 or perform SP8 as applicable, perform SP1, check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty
PT_G_OX	Oxidizer purge	N/A	Loss of ability to detect pressure in oxidizer fill system	Perform SP4, perform SP8, perform SP1, check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty

PT_G_OX	Oxidizer fill	N/A	Loss of ability to detect pressure in oxidizer fill system	Perform SP9, perform SP8, perform SP1, check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty
PT_G_OX	Nitrogen recharge	N/A	Loss of ability to detect pressure in oxidizer fill system	Perform SP9, perform SP8, perform SP1, check PG_G_OX on camera feed, if pressure is nominal approach and manually close oxidizer GSE tank integral valve(s), retreat back to Observation and Control Station, open D_G_OX to vent fill system without dumping GSE tanks, return to oxidizer fill system to debug the issue. If PG_G_OX shows pressure above MAWP and relief valve is not relieving fast enough, open D_G_OX until oxidizer GSE tanks are empty
PT_G_OX	Engine burn	N/A	Loss of ability to detect pressure in oxidizer fill system	
PT_G_OX	Post-Burn	N/A	Loss of ability to detect pressure in oxidizer fill system	

Table 6.1: Loss of Power or Control Failure Mode Analysis

6.1.2 Safeing Procedures

Safeing Procedure ID	**Safeing Procedure Name**	**Description**	**Comments**

SP1	Nitrogen Run System - Depressurizing	Ensure FV_G_N1 is closed, open V_R_N1 and D_R_N until system reaches 200 kPa.	
SP2	Nitrogen Run System - Depressurizing Special Circumstance	Perform SP1, wait for all venting to stop (via venting indicators) then approach system and open V_R_N2.	FV_G_N2 stuck in fill position. DEFUNCT
SP3	Fuel Run System - Depressurization	Ensure IS_R_N2 and MFV are closed then open D_R_F and V_R_F1, leave D_F_R and V_R_F1 open until the run system pressur reaches 200 kPa, then close both.	No fuel in run tank
SP4	Fuel Run System - Filled Depressurization	Ensure IS_R_N2 and MFV are closed then open V_R_F1 until system reaches 200 kPa	
SP5	Fuel Run System - Pressurized Dump	Ensure IS_R_N2, MFV, and V_R_F1 are closed then open D_R_F. Once liquid draining is completed close D_R_F and open V_R_F1. Close V_R_F1 when tank pressure reaches 200 kPa.	Ensure conditions for fuel dump have been met. See section [NEED SECTION]
SP6	Fuel Run System - Unpressurized Dump	Ensure IS_R_N2 and MFV are closed, ensure V_R_F1 is open then open D_R_F	Perform an unpressurized dump of filled or partially filled fuel run system
SP7	Oxidizer Run System - Depressurization	Ensure IS_R_N1 and MOV are closed then open D_R_OX and V_R_OX1	No oxidizer in run tank
SP8	Oxidizer Run System - Autogenous Dump	Ensure IS_R_N1, FV_G_OX1, and MOV are closed then open D_R_OX and V_G_OX	Ensure conditions for oxidizer dump have been met. See section [NEED SECTION]

SP9	Oxidizer Run System - Pressure-Fed Dump	Ensure MOV, V_R_OX1, FV_G_N1 and FV_G_OX1 are closed and that FV_G_N2 is set to the run position, then open D_R_OX and IS_R_N1 (in that order), when tank is empty of liquid (confirmed visually by watching tank dump line exit orifice) open V_G_OX to purge fill line. Wait 2 seconds to purge remaining oxidizer vapour before closing D_R_OX and closing V_G_OX. Then close IS_R_N1. Open V_R_OX1 to 10 Ensure conditions for oxidizer dump have been met. See section [NEED SECTION]	
SP10	Oxidizer Run System - Pressurize-fed Dump Special Circumstance	Ensure MOV and FV_G_OX1 are closed. Open V_R_OX1, D_R_OX, and V_G_OX.	lose power or control of IS_R_N1 when open. Ensure conditions for oxidizer dump have been met. See section [NEED SECTION]
SP11	Fuel Fill System - Halt Fuel FIlling	Stop fuel fill pump, close V_R_F1, close FV_G_F1	
SP12	Fuel Run System - Pressure-Fed Dump	Ensure MFV and FV_G_F1 are closed and that FV_G_N2 is set to the run position. Open D_R_F and IS_R_N2.	
SP13	Oxidizer Run System - Halt Oxidizer Purge	Close IS_R_N1, MOV, D_R_OX, and V_G_OX. Leave V_R_OX1 open until pressure reaches 200 kPa then close V_R_OX1	
SP14	Oxidizer Run System - Boiloff Cooling	Ensure MOV and D_R_OX are closed, open V_R_OX1 until system reaches desired temperature	
SP15	Fuel Run System - Emergency Pumped Fuel Dump	Open V_R_F1, open MFV, run gear pump to dump through engine, once empty stop gear pump, close MFV	Dumps fuel through the engine

Table 6.2: Safeing Procedures

6.2 Nitrogen Fill System Risks

6.3 Nitrogen Run System Risks

6.4 Oxidizer Fill System Risks

6.5 Oxidizer Run System Risks

6.5.1 Oxidizer Tank

Failure Type	**Cause**	**Severity**	**Likelihood**	**Mitigation**
BLEVE due to mechanical failure of oxidizer tank at operating pressure	corrosion, design error, damage, Decomposition	High	Low	High factor of safety, regular inspection, certified components, strict storage, handling and transport protocol
Change in oxidizer temperature and pressure due to environmental effects (nominal during fill process)	Sunlight, Environment, insufficient climate control	Low	High	Boil off cooling through relief valve, if necessary adaptation of supercharging pressure
Overheating and pressure rise due to environmental effects	Sunlight, insufficient cooling/ defect cooling system	Low	Medium	Boil off cooling through relief valve, manual venting, insulation, reflective surface, cooling system, in worst case vent through safety valve, burst disc, test abort
Overheating and pressure rise due to external effects	Fire at test stand, especially under oxidizer tank	High	Low	Fire suppression system, water purge system under oxidizer tank, Boil off cooling through relief valve, manual venting, safety valve, and burst disc, safety distance, evacuation strategy, location wise separation of oxidizer and fuel system (e.g. fuel lines not under oxidizer tank)

Decomposition of Nitrous Oxide in storage tank due to transgression of the critical point	Failure of all tank relief mechanisms (relief valve, safety valve, burst disc, manual relief), heating source (Sunlight or external), failure of climate control system	High	Low	Safety Distance, Evacuation Strategy, Suitable testing location
Decomposition or overheating due to chemical reaction	Impurities, non compatible material	High	Low	Thorough oxidizer cleaning, careful design and choice of materials and lubricants, Burst Disc, Safety Vent Valves
Decomposition due to local overheating	electrical malfunction inside tank, Electrostatic Discharge, local fire at oxidizer tank or piping	High	Low	Proper grounding, fire suppression, ethanol purge systems, suitable electronic devices, location wise separation of propellant lines, Burst Disc, Safety Vent Valves
Leak in nitrous oxide tank	improper assembly, damage (before operation or during operations)	Medium	Medium	Leak check, visual inspection, ensuring of steady airflow (given at outdoor test location), if strong leak, evacuation of immediate surrounding, fragrancing
Excessive venting of Nitrous oxide	Pressure rise, failure of safety valves	Low	Medium	Evacuation of immediate surrounding, possible eventual test abort, venting ports mounted at maximum distance from fuel, electronics or testing chamber
Venting of Nitrous oxide	Slight pressure imbalance	Low	High	Venting pots mounted at a safe place
Nitrous oxide cavitation during test operation	Flow induced pressure drops	Medium	Medium	Smooth design, large flow diameters, Nitrogen Supercharging

Cavitation of Nitrous Oxide during Fill procedure	Handling error, design error, nominal operation (non-supercharged filling)	Low	High	Automated fill procedure, Smoothed design, low fill speed system designed to handle cavitation, no fast closing valves, nitrogen dilution
Nitrous Oxide Leak during Fill procedure	Handling error, component malfunction	Medium	Low	Leak Testing, visual inspection, Connection/ Disconnection of Nitrous Oxide Tank only by trained personnel, automated fill procedure
Nitrous Oxide Decomposition during filling procedure	Handling error, Design Error, component malfunction	High	Low	Automated fill procedure, no fast closing valves, plumbing diameter under quenching diameter, plumbing outfitted with burst discs/ safety valves
Tank corrosion	Handling error, design error, insufficient cleaning	Medium	Low	Visual inspection, proper cleaning after testing, suitable material pairing, adequate storage
Unknown state of Nitrous Oxide Tank	Sensor malfunction	Medium	Low	Sensor redundancy, Self-Stabilizing Boil Off system, analog sensors (observable by drone or redundant camera), possible test abort or emergency dump
Venting obstruction	Electronics breakdown, vent valve malfunction	Low	Low	Boil Off and emergency vent through main oxidizer valve, Manual vent valve bypass (rope actuation, fail open vent valve, manual pneumatic bypass)
Nitrous Oxide rich atmosphere around the test stand	Venting, cold flow testing	Low	High	no prohibited electronic devices, no ignition sources, dispersal by wind, evacuation

Oxidizer Tank damage by debris	Operation Anomaly	High	Low	Sufficient protective measures, high safety factor on Oxidizer Tank
Psychoactive interference due to Nitrous Oxide exposure	Venting, Oxidizer rich atmosphere around test stand	Medium	Medium	Evacuation, Relief of Duty, fragrance

Table 6.3: Oxidizer Tank Risk Analysis

6.6 Ethanol Fill System Risks

6.7 Ethanol Run System Risks

Failure Type	**Caused by**	**Severity**	**Likelihood**	**Mitigation**
Mechanical Failure of Fuel Tank	Over pressurization, Design error, Foreign Object Debris Impact, Weld failure	High	Low	Certified Tanks, High Safety Factor, Professional welding, Pressure Relief Valves, Test only in suitable weather conditions, make sure testing side it clear of potentially hazardous debris
Fuel Tank Fuel Leakage	System damage, failure of seals in connected components such as ball valves, solenoid valves, failure of thread seals at connection interface to components such as ball valves, solenoid valves, relief valves, pressure transducers, thermocouples, pressure gauges, and plumbing lines. Improper assembly	Low	Low	Leakage Test, ethanol purge system, proper assembly, visual inspection, depressurization, if necessary, test abort

Fuel Tank pressurant leakage	System damage, failure of seals in connected components such as ball valves, solenoid valves, failure of thread seals at connection interface to conponents such as ball valves, sonenoid valves, relief valves, pressure transducers, thermocouples, pressure gauges, and plumbing lines. Improper assembly	Low	Low	Leakage Test prior to every test, leak test during assembly procedure, proper assembly, if necessary, depressurization & test abort, if necessary purge by fire suppression system
Fuel Spill during Operation	System damage, failure of seals in connected components such as ball valves, solenoid valves, failure of thread seals at connection interface to conponents such as ball valves, sonenoid valves, relief valves, pressure transducers, thermocouples, pressure gauges, and plumbing lines. Improper assembly, wrong handling of material	Low	High	No ignition sources during fuel handling, purging of contaminated areas, proper and sufficient training for all personnel
Fuel Tank Clogging	Fuel impurities, improper tank and plumbing cleaning, assembly error	Low	Medium	High flow Diameters, Visual Check of Fuel, filtering, fuel tank cleaning, eventual test abort
Fuel Tank corrosion	Fuel Impurities, insufficient cleaning, material issue, wrong storing conditions	Medium	Low	Right material pairing, proper posttest cleaning/ purging, suitable storing condition/ location/ prevention of humidity diffusion
Fuel Tank damage by debris	Operational Anomaly, unsuitable weather conditions, unsuitable testing location	High	Low	Sufficient protective measures, high safety factor on Fuel Tank
Unexpected pressure buildup	Pressure system error	Medium	Low	Pressure relief devices, high safety factor
Unexpected depressurization	Electronics error, component malfunction	Low	Low	Standard test abort procedures
Depressurization prohibition	Electronics error, component malfunction	Low	Low	Means for manual depressurization (e.g. manual valve)

Fuel Tank overheating	Sunlight, external heat source	Medium	Low	Direct sunlight protection, if necessary, depressurization, cooling by fire suppression system
Combustible gas mixture within tank	Excess air in system, fuel remains after testing	Medium	Low	Nitrogen purge before fueling, distilled water purge after testing
Mechanical failure of pressurant tanks	Improper handling, overheating	High	Low	Use of stock high pressure vessels, regular checks (by officials and internally) handling according to prescription, if necessary cooling by fire suppression system
Corrosion of pressurant tanks	Improper handling/ storage	High	Low	Regular checks, suitable storing/operating measures (never empty tanks completely and if, close valve), visual checks
Pressurant leakage	Improper handling/ storage, component malfunction	Low	Low	Leakage check (also when stored), correct assembly, visual checks
Pressurant tank failure due to fire exposure	Fuel leak combustion/ other fire sources	High	Low	Fire suppression system, pressure relief devices, safety distance evacuation
Pressurant Tank contamination	Working fluid Backflow	High	Low	Keeping residual pressure within tanks, check valves
Connector Damage Transport only with safety cap and in permitted state. Adequate crash protection/ system securing	Improper Handling, car accident	High	Low	Handling
Pressurant tank overheating other heat sources, tank venting, fire suppression system for cooling	Sunlight exposure, other heat sources	Medium	Medium	Adequate protection from direct sunlight
Fire at Fuel Section	Electronic error, Fuel leakage, other ignition/ fuel source	High	Low	Ethanol Purge System, elimination of ignition sources, fire suppression system, evacuation

Table 6.4: Ethanol system risks

6.8 Engine Section Risks

6.9 Nitrous Oxide Safety Analysis

Nitrous Oxide is unarguably the most safety critical substance involved in the Houbolt Propulsion Unit. Special focus will be put on performing a detailed safety analysis and developing reliable safety procedures. This paper will serve as a guideline and state of the art summary for further works on the topic of Nitrous Oxide safety.

A series of Nitrous Oxide incidents have been reported, where exothermic decomposition of Nitrous Oxide within storage tanks or feed lines lead to devastating and even fatal incidents. However, due to several reasons (improper investigations, investigation papers kept secret from the public, low probability of occurrence), the reason for these incidents are still "unknown." Though some research has been conducted on Nitrous Oxide decomposition reaction and possible mechanisms of initiation, there are still wild theories and guessing due to lack of data available. The famous Scaled Composite incident in 2007, that resulted in the death of a number of workers (reports vary from 3 to 10) during a Nitrous Oxide cold flow test, made the rocketry community question whether Nitrous Oxide can be used as safe oxidizer. Nitrous oxide has been used successfully (satellite thruster, big hybrids, liquid bi-propellants etc.) and considered a safe oxidizer for decades without major incidents (N2O ullage decomposition in self pressurized hybrid rockets due to injector flashback at most). Nitrous Oxide is regularly used in many applications outside of rocketry and is handled in large quantities, such as the pharmaceutical and food industries. The handling procedures of Nitrous Oxide in industry are not clearly regulated, they simply consist of a series of recommendations. Following recent incidents, the development of more detailed safety standards has been strongly suggested. National safety considerations do not rate Nitrous Oxide as significantly dangerous (same level and free transport volume, as compressed nitrogen, oxidation hazare only secondary property. However, with respect to rocketry, there is little to know agreement on the topic of Nitrous Oxide — opinions range from "Safest oxidizer available" up to "absolutely dangerous, detonates violently under random conditions." For this reason, it is much more difficult to address Nitrous Oxide safety training than that of more common oxidizers like Liquid Oxygen.

The following points of this document will outline; known Nitrous Oxide incidents, successful rocketry applications, and possible modes of triggering Nitrous Oxide decomposition. An evaluation of N2O safety and the development of a suitable strategy may then be possible. Seven large scale incidents with Nitrous Oxide decomposition has been reported since 1973, resulting in a total of 6 deaths and 21 injured. A list of the incidents is given below:

Year	Location	Deaths	Injured
	West Palm Beach, USA		
	Richmond, USA		
	Reading, USA		
	Eindhoven, Netherlands		
2007	Mojave, USA		
	Moncada, Spain		
	Cantonment, USA		

Table 6.5: Summary of Nitrous Oxide related failures

The best-known and most referenced accident involving Nitrous Oxide in rocketry is the Scaled Composites incident in 2007, as was previously mentioned. A Nitrous Oxide Tank filled with five tons of Nitrous Oxide failed during a cold flow test for the SpaceShipOne hybrid rocket engine due to Nitrous Oxide decomposition. As a result, a number of workers standing in close proximity were injured and some were killed. Investigations were conducted of Scaled Composites, the results of which have not been published until now. While the casualties could have been easily avoided by application of strict safety procedures (the Nitrous Oxide cold flow test was presumably considered safe, otherwise the area would have been evacuated). However the actual trigger of the decomposition reaction (as well as the intensity and mechanism of energetic reaction) is known to the public (some people assume an explosion, others are assuming overpressurization failure due to decomposition and a following BLEVE event as the main source).

An independent investigation on the incident has presumably been performed by a team around the developers of the Bloodhound SSC hybrid engine. Though cited in a paper, the actual report could not be found. The report suggests a series of severe handling errors regarding the Nitrous Oxide. The Nitrous Oxide was filled into a class V composite pressure vessel without adequate pressure relief valves and left in the sunlight for hours, allowing for heating, pressure buildup, and possibly reaching supercritical state. Scaled Composites implemented a tank temperature of 21 C and a tank pressure of 27 bar. This, however, is not compliant to saturated Nitrous Oxide, whereas the pressure should be around 52 bar at the given temperature. The hybrid feed system was designed as a blowdown type, no diluting pressurant gas was injected into the ullage. 3(10) seconds following the start of the test, the Nitrous Oxide in the tank decomposed, leading to the fatal incident. While being in a supercritical state and in direct contact with the polymer matrix of the tank seems to make decomposition events more likely, the actual trigger is believed to be “dieseling” or ESD. Since the anomaly occurred in steady state operation after a significant amount of time, the ESD theory is considered more likely.

The Cantonment incident report suggests adiabatic compression as major reason for the incident. A review on the Cal/OSHA report conducted by the Knights Arrow Team suggests that the Nitrous Oxide was in the Tank for a long time, thereby heating to supercritical condition. Also, the Nitrous Oxide may have dissolved and absorbed some of the polymer matrix of the class V pressure vessel. For the Cold Flow Test, a counter pressure chamber was used in order to simulate the Pressure within the Combustion Chamber. The report suggested, that a pressure spike occurred in the chamber, therefore leading to a decomposition reaction of the supercritical Nitrous Oxide (a detonation, as stated by the report) in the chamber, which was propagating into the tank or a pressure wave travelling back to the tank, initiating the decomposition there. One possible explanation would be the formation of larger liquid droplets, leading to a sudden drop in choking velocity (speed of sound in biphase flow may be significantly lower than either gas or liquid, this is dependent on vapour fraction) and therefore to a pressure spike. Since the orifice of the counter pressure chamber is significantly smaller than the throat of the actual nozzle, this could lead to a sudden rise in pressure. The Final expanding step from the chamber to ambient pressure significantly cools down the fluid. This, and the fact that Nitrous Oxide was considered a safe Oxidizer before the accident, supports the theory that a series of inadequate actions and procedures led to the incident. The fact that the report is classified also supports this assumption. Scaled Composites continued the development of the hybrid engine and the system has been used successfully in manned suborbital flights of SpaceShipTwo. This suggests that the issues that triggered the incident might have been solved, therefore suggesting that the issue is not intrinsic to Nitrous Oxide.

The second most often cited incident is the energetic failure of a Linde Tank Car during pumping operation of Nitrous Oxide from a large storage vessel into the trailer in Eindhoven, Netherlands. No one was injured but the filling station and tank car were destroyed. The incident was caused by decomposing Nitrous Oxide in the tank car. An ignition source, the graphite bearing of a centrifugal pump, which was running hot due to (unauthorized) dry operation is assumed. This may be untrue due to the fact that the filling procedure was going on for many minutes until the decomposition happened, therefore ESD is also considered. Dry running of the Nitrous Oxide pump could also occur, if the storage vessel is running low, therefore not providing sufficient inlet pressure for strong cavitation. Though heavily damaged by the blast, decomposition did not propagate into the large storage tank. Unfortunately no further details are known to the author regarding this incident. Similar events involving overheating

Nitrous Oxide Pumps led to explosive decomposition events in Richmond, Moncada and Cantonment. The Cantonment incident is documented and investigated well, suggesting insufficient safety standards at the plant. The piping in Cantonment, and probably also the other pump incidents used piping bigger than the suggested quenching diameter for the operating conditions. The ESD flame arrestors were not tested and most likely not sufficient for preventing decomposition propagation.

The Nitrous Oxide Tank explosion, that occurred in Reading, was triggered by a worker performing welding works close to a tank filled with Nitrous Oxide. The incident in West Palm Beach at a Pratt Whitney facility was most likely triggered by adiabatic compression, hence quick filling of a Nitrous Oxide vessel. The vessel was pressurized to about 90 bar, having a temperature of 90 C, when the decomposition happened. Aside from the West Palm Beach and Reading incidents, contamination of Nitrous Oxide with metal particles or hydrocarbons has been identified.

Four of the seven incidents were most likely triggered by overheating or dry running centrifugal pumps. All incidents, except West Palm Beach and Reading, showed signs of Nitrous Oxide decontamination. The incidents in West Palm Beach and Reading are both anomalies, differing strongly from the intended procedures and operating conditions for rocketry application.

A series of incidents involving tank or valve/plumbing rupture in amateur hybrid and liquid rocket engines have been reported. In these cases backflash decomposition from the combustion chamber, due to an insufficient injector design, is assumed to be the most likely cause. Valve rupture and valve seat fire is also assumed to be the trigger of certain destructive events. Unfortunately, no detailed investigations have been performed.

A graduate student at the University of London was performing experiments regarding the solubility of gaseous Nitrous Oxide and hexane at various pressures, as during operation of a faulty instrument a spark within the Nitrous Oxide chamber triggered a sustaining decomposition reaction, which destroyed parts of the test setup and injured the student. This seems to be one of the earliest well documented cases of self sustaining Nitrous Oxide decomposition reactions since the student followed up on the incident resulting in a PhD thesis regarding these decomposition phenomena.

Outside rocketry, general safety considerations regarding Nitrous Oxide are relatively relaxed. Transport and handling of relative large amounts of Nitrous Oxide is not sanctioned by European law, the biggest concern seems to be its use as a recreational drug. In the USA, Nitrous Oxide is not marked as oxidizing and only has the pressurant gas mark, putting it at the same hazard level as Nitrogen or Helium. There are calls for stricter safety regulations on Nitrous Oxide systems, as it seems that the international handling recommendations are often not followed by the industry. In the car tuning industry, Nitrous Oxide handling is also not conducted by strict safety rules and procedures. It can be assumed that this low level safety attitude was transferred into Nitrous Oxide Rocketry applications. This is supported further by the discussion of whether, after the Scaled Composites incident, Nitrous Oxide shall be further considered as a "perfectly safe oxidizer." Recommendations were made that it might be necessary to rank up Nitrous Oxide safety hazards and handling precautions to the same level as gaseous oxygen. These recommendations strongly suggest that before Nitrous Oxide was not handled with particular care with respect to material compatibility, ignition sources, and oxidizer cleanliness.

On the other hand, Nitrous Oxide has been used successfully used as an oxidizer in a variety of hybrid and liquid propulsion applications of various sizes. Frequently used by student teams, amateur rocketeers, and research institutes, Nitrous Oxide has been referred to as "the perfect academic oxidizer." Especially when it comes to liquid propellant engines and large hybrids, there are many examples of successful operations. Rocket Motor 2 (SpaceShipTwo) is a large scale hybrid rocket motor (15 kN) running on Nitrous Oxide. The system was developed by Scaled Composites and has been successfully used on manned suborbital flights with SpaceShipTwo. The system is using simple self pressurized blowdown. The Stratos III/Stratos IV hybrid rocket engine is a large scale hybrid motor designed for powering the Stratos rockets to altitudes around 100 km. The system was developed and tested by students of TU Delft. The system is using simple self pressurized blowdown. A Rocket Engine built by the Boston University with a thrust of 5 kN running on Nitrous Oxide and Ethanol. The system was successfully run on a test stand. A stronger version with 15 kN is currently under development. The system is using supercharged blowdown for Nitrous Oxide delivery. A Rocket Engine running on Nitrous Oxide and Ethanol was built and tested as a Masters thesis at the University of New Mexico. The system was using supercharged blowdown for Nitrous Oxide delivery. The development process is documented well. XCOR built a small Nitrous Oxide and Ethanol engine, which is capable of running as pulsed RCS thruster. The Snark engine, a throttleable Nitrous Oxide and Isopropanol Engine was built and tested by the British company "Airborne Engineering."

There are many other small amateur bipropellant rocket engines and even more hybrid engines running successfully on Nitrous Oxide. There is no record of major incidents, especially regarding Nitrous Oxide decomposition. Lately, there has been research on Nitrous Oxide fuel blends, premixed Fuel and Oxidizer mixtures acting the same way as a monopropellant but delivering higher ISP. DLR is currently working on an acording system involving Nitrous Oxide and Ethene. It is worth mentioning that this has not been attempted with other oxidizers. There has been successful firing of Nitrous Oxide fuel blend thrusters at DLR, Germany.

Decomposition of Nitrous oxide is posing the highest threat in terms of safety. It has been known for a long time that Nitrous Oxide, as soon as it is superheated to a supercritical state close to 600C, can decompose to Nitrogen and Oxygen, thereby releasing energy. For a while it was assumed that this reaction was not self-sustaining at states below the critical point, and even above high amounts of activation energy was needed. Though these conditions cannot be reached under standard conditions, Nitrous Oxide handling was considered safe and simple. Being used as a solvent for Hydrocarbons (supercritical N2O is considered one of the best solvents for Hydrocarbons available) in many industry branches, handling of N2O in various states was conducted at various research institutes. However, from time to time unexpected pressure rises occurred in sub critical Nitrous Oxide systems, leading to damage of equipment and light injuries of personnel. Investigation of the incidents led to the conclusion that these incidents were linked to self-sustaining Nitrous Oxide decomposition, a mechanism that previously was considered nonexistent. Since Nitrous Oxide was used in large quantities in industry, a variety of tests were conducted with the goal of determining the factors which allow for self-sustaining Nitrous Oxide decomposition. For rocket applications the bulk of the Nitrous Oxide is not going to reach superheated conditions well above the critical point unnoticed, therefore, the mechanism of self sustaining Nitrous Oxide decomposition poses a much greater threat and is therefore considered the by far the most relevant type of failure. The actual characteristics of the reaction as well as positive or negative amplification factors will be discussed in the upcoming pages.

6.9.1 Decomposition Reaction in Pure Nitrous Oxide

Pure Nitrous Oxide at room temperature is capable of sustaining auto-decomposition, which, when the Nitrous Oxide is stored in a closed vessel, leads to significant rise in pressure and likely to an "explosion," or a mechanical failure of the pressure vessel with all its consequences (debris, pressure wave, BLEVE if liquid Nitrous Oxide is present). However, it is important to outline that pure Nitrous Oxide is not capable of detonating, hence the speed with which the decomposition is propagating through the medium is well below the speed of sound. Experiments regarding decomposition of Nitrous Oxide in a cylindrical pressure vessel, showed that the laminar flame speed of the Nitrous Oxide decomposition at 60 bar is about 1cm/s, which is significantly slower than most combustion reactions. It has been discovered that, due to the slow flame speed, the actual propagation speed of the decomposition is highly dependent on convection, which makes the procedure of decomposition strongly dependent on the point of initial decomposition (propagation with or against gravity), and volume and shape of the reaction vessel. Even though these specific factors had a strong influence on the decomposition reaction, a pattern could be discovered in the pressure, and therefore decomposition curve, within the test vessels. Overall decomposition reaction lasted a few seconds, and the complete bulk of Nitrous Oxide did not always decompose. After initiation of the decomposition reaction, pressure, and therefore decomposition rate, rose slowly then rapidly increasing in speed while at the end slowing down again when reaching full decomposition. In some cases (lower starting pressure), the reaction rate reduces briefly at 40 bars, then picks up speed again. When reducing the diameter of the test vessel, initiation of a decomposition reaction became harder, being prohibited completely at a certain diameter (quenching diameter). This diameter has been determined to be about " at standard conditions, this is, however, strongly dependent on pressure and temperature. Self sustaining decomposition only occurs, when a certain threshold in activation energy is exceeded. For gaseous nitrous oxide, simple glow wire may not trigger decomposition while exploding wire, or strong electric arcing, was capable of delivering sufficient activation energy. Again, this changes significantly with temperature and pressure. In general, decomposition reaction in pure Nitrous Oxide seems to be triggered and sustained more easily when closing in on the critical point, and becomes even more likely and violent if critical conditions are exceeded. Trying to initiate a decomposition reaction in liquid Nitrous Oxide under standard conditions is not possible, even small charges of explosives did not trigger a decomposition reaction. This was independent of temperature and pressure (except when exceeding the critical point). Only the gaseous part, hence the tank ullage as seen in self pressurizing systems, is capable of decomposing. However, a significant initiation event (small explosion, strong ESD/spark) has to occur, as long the state of the Nitrous Oxide is kept away from its critical point. The use of plumbing below the quenching diameter should prevent the propagation of decomposition reactions between connected vessels. However, there is a series of factors and characteristics of Nitrous Oxide that change the prescribed behaviour to good or bad, and respectively can pose certain risks for initiating a decomposition reaction. The Knights Arrow Report states that supercritical Nitrous Oxide can not only deflagrate but can also detonate.

6.9.2 Dilution of Hydrocarbons in Nitrous Oxide

Nitrous oxide, especially when it is supercritical, is an excellent solvent for Hydrocarbon molecules and thus is often used as a pressurant gas for whipped cream or for decaffeination of coffee beans. Some literature even claims Nitrous Oxide is the best solvent for Hydrocarbons. Having even small amounts of Hydrocarbons diluted in Nitrous Oxide affects the resistance for auto decomposition significantly. Mixtures of gaseous Nitrous Oxide and Hydrocarbons showed an increased sensitivity to initiating a self-sustaining decomposition reaction, even at lower temperatures and small vessel diameters the speed of the decomposition reaction was still increased. Similar behaviour may be the case for supercritical Nitrous Oxide. Both reaction speed and sensitivity for auto decomposition may be the result of Hydrocarbons reacting with the oxygen released by self- decomposition, thus creating additional heat for sustaining the reaction. Being an excellent solvent, Nitrous Oxide can absorb Hydrocarbons from a variety of sources ranging from gases, liquids, lubricant oils and fats, as well as solids, such as polymers. Special attention must be put on the selection of compatible plumbing and tank materials, lubricants, and any form of Hydrocarbon contamination within the Nitrous Oxide system. Following strict cleaning procedures, as implemented with liquid or gaseous oxygen systems, is therefore mandatory. This also has suggested that Nitrous Oxide shall be handled with the same procedures and precautions as gaseous Oxygen systems. The good solubility of Nitrous Oxide also allows it to dilute in solid Hydrocarbons, such as various polymers. Having a polymer component infiltrated with Nitrous Oxide can result in a violent combustion reaction, if ignited. Even though some substances are not dissolved in Nitrous Oxide, and are therefore considered compatible, they can absorb a significant amount of Nitrous Oxide when under pressurized conditions, thereby swelling to a larger size. Not only can this damage or temporarily disable certain components, it also poses the risk of an unwanted Nitrous Oxide reservoir. When using thin liner Type IV or Type V vessels, material compatibility as well as diffusion resistance must be ensured.

6.9.3 Electrostatic Discharge

Electrostatic Discharge, ESD, is considered a relevant ignition source for Nitrous Oxide auto decomposition events. ESD can be triggered by any potential difference coming from the inside or the outside. While external ESD may occur during handling, especially fueling operations, a good grounding strategy can prevent any ESD between the test stand and fuelling crew. This problem is not present under nominal operating conditions, where the test stand is not touched or actively manipulated. However, due to its molecular setup, Nitrous Oxide itself is capable of producing electric charge while flowing across a surface.

This behaviour greatly increases the chance of ESD by internal charging. Especially components, like ball valves, that may be insulated from the grounded test stand by rubber seals, are at risk of being charged during active operation. Putting additional attention on identifying and grounding these components is thereby recommended. The likeliness and intensity of Nitrous Oxide charging components increases with lower fluid temperatures.

6.9.4 Dilution of gaseous Nitrous Oxide with non-reacting gases

Introducing a non-reactive gas (with respect to Nitrous Oxide) into gaseous Nitrous Oxide (Nitrogen, Oxygen, Helium) has significant effects on auto decomposition sensitivity. A moderate amount (about 10%) can still lead to a significant reduction in sensitivity, making it unlikely to introduce self-sustaining decomposition of gaseous Nitrous Oxide, even in high temperatures. The effect is increased when the concentration of non-reacting gas is increased. Using external Nitrogen or Helium pressurization of a fuel system would, therefore, not only ensure a stable tank pressure, but also reduce the risk of any gaseous Nitrous Oxide ullage within the tank. However, Nitrogen gas may dissolve in liquid Nitrous Oxide, up to a certain level, which may have an influence on the characteristics, or performance, of a rocket engine. Furthermore, the presence of diluted Hydrocarbons annihilate and outweigh the stabilizing effect of non-reactive gases. Auto decomposition is, therefore, possible in contaminated systems. Besides that, supercharging Nitrous Oxide tanks and mixing the ullage with a non-reactive pressurant gas seems to be a practical way of preventing gaseous Nitrous Oxide decomposition triggered, for example by ESD.

6.9.5 Adiabatic compression and dieseling

Adiabatic compression can heat up a gaseous compound significantly when compression ratios are high. In real life, near adiabatic compression can be obtained if the compression process is significantly faster than the heat transfer effects. This could be the case during compressor operation for liquifying Nitrous Oxide, however, this will not be the case in this specific application. Another situation where fast compression ratios may occur is external pressurization of the Nitrous Oxide tank with an inert gas. Additionally, mixing of the cold inert gas with the Nitrous Oxide may reduce compression temperatures and may also decrease the chance of decomposition. However, limiting pressurization rate is considered a good idea. Sharp corners and bends, or Eddy currents in a gaseous Nitrous Oxide line may also cause heating of the gas. It is suggested that these effects may serve as a heat source for initiating a decomposition reaction, however, no incident has been reported yet. Fast closing valves may create some kind of water hammer in a gaseous flow of Nitrous Oxide, which could lead to compression heating. Being relevant during venting of a tank, fast closing of a valve with high mass flow may be avoided. No incidents have yet been reported suggesting this effect. Effects observed during Nitrous Oxide venting, that were possibly caused by Nitrous Oxide decomposition, such as warming of a certain pipe area for a few degrees or pressure fluctuations, were traced back to Eddy currents or the formation of liquid Nitrous Oxide droplets during the expansion.

Due to the fact that Nitrous Oxide is stored at its saturation line, a drop in pressure leads to gas bubble formation in liquid Nitrous Oxide. While in low concentration these gas bubbles may not affect flow characteristics, if the flow velocity, and therefore the line diameter, is higher, or if under certain situations stagnation zones with high pressure drop occur, the amount of gas bubbles may increase and therefore the cavitation effect can influence flow characteristics. If, however, a sudden change in pressure is acting on these bubbles, either by a high pressure field in recirculation zones or when the fluid flow is suddenly stopped for example by a fast closing valve (water hammer effect), the bubbles are compressed since changing state back to liquid takes some time. These water hammer effects can especially create high pressure ratios and, therefore, can cause significant heating within the gas bubbles due to adiabatic compression. These bubbles may act as a source for local decomposition. It is suggested that this effect may be what triggered the Scaled Composites incident. However, since liquid Nitrous Oxide does not seem to support a decomposition reaction at all, it is not clear how these compression reactions are capable of triggering a runaway reaction. Since Scaled Composites stated that they have to enhance cleaning procedures and check tank liner compatibility, the behaviour of liquid Nitrous Oxide may change significantly with high amounts of contamination. Nitrous Oxide systems in cars use solenoid valves for controlling mass flow into the engine.

6.9.6 External Sources of Heat or Ignition

Since most external sources of heat are significantly stronger and more likely to occur, they shall be avoided altogether. Five of the Seven catastrophic events with Nitrous Oxide, as well as a few smaller incidents, had an external source of ignition. Sources of ignition could be heat induced by; performing metalwork (brazing, welding, cutting etc.) at or close to the tank and plumbing system, fire or overheating electronic elements (servos, solenoids), or electrical arcing (sensor defect). Sunlight may not induce sufficient heat for initiating a decomposition reaction but can lead to heating of the Nitrous Oxide, bringing it closer to its critical point, thereby enhancing the chance of a decomposition reaction. Having a climate control concept (boil off or cooling system) implemented is therefore recommended.

6.9.7 Catalytic Effects

It is reported that Nitrous Oxide decomposition can occur at lower activation energy levels if certain metallic catalysts are present. Use of these substances shall be prevented in the storage and feed systems. Contamination with catalyst particles may be prevented by good cleaning procedures. Nitrous Oxide is compatible with common piping and tank materials, such as Chromium, Nickel and Manganese Steel, Stainless Steel and Brass components.

6.9.8 Boiling Liquid Expanding Vapour Explosion (BLEVE)

Even though this effect is not directly related to Nitrous Oxide decomposition itself, the occurrence of a Boiling Liquid Expanding Vapour Explosion (BLEVE) is likely the result of a Nitrous Oxide decomposition reaction within a Nitrous Oxide storage vessel. If a pressurized vessel filled with liquid at its boiling point, failure of the pressure vessel, and an accordingly rapid drop in pressure, will lead to flash evaporation of the liquid. The sudden change in volume creates a strong blast wave (no detonation, blast wave is below the speed of sound) and releases stored pressure energy in the liquid. Since the event happens very fast, the heat available for the vaporization of the liquid is limited to the internal energy of the liquid. This also means that depending on the fluid characteristics (latent heat of vaporization, heat capacity), only a certain amount of liquid can change into the gaseous phase. This is important in order to estimate the energy released by the BLEVE event. Decomposition of the released gas is not likely. A gaseous Nitrous Oxide decomposition occurring in a vessel filled with both gas and liquid, will likely over pressurize the vessel, leading to structural failure. This, on the other hand, will cause a BLEVE event of the remaining liquid within the tank, adding additional energy to the blast.

6.9.9 Stored Energy TNT Equivalent of Nitrous Oxide Decomposition

Nitrous Oxide decomposes to Nitrogen and Oxygen as follows:

N2O N2 + O2 + 82.05 KJ/mole

Gaseous Nitrous Oxide has a molar mass of 30.006 g/mole, therefore, 2734.45 KJ/kg is released. TNT being at 4184 KJ/kg, the decomposition reaction alone yields a TNT equivalent of 0.6535. Since, in most cases, the decomposition event is accompanied by the rupture of the pressure vessel, the stored gas energy resulting from a BLEVE event has to be accounted for. In order to obtain an upper boundary for stored pressure energy, a simple energy balance approach can be used. More sophisticated models are available, if desired. In the first step, the total amount of gaseous substance available is calculated by determining the amount of gas in the vessel before failure, and then by obtaining the amount of liquid that is turned to gas phase by flash evaporation. This is done by determining the flash factor of the substance as a function of its initial conditions. Finally, it is assumed that the total gas mass is equalizing with ambient pressure by isentropic expansion. The obtained energy value is used to calculate the TNT equivalent of the BLEVE event. Total release of energy in the vessel can be calculated in different ways depending on the assumed scenario.

Since decomposition does not occur in liquid Nitrous Oxide, the liquid portion of Nitrous Oxide does not provide reaction energy. Also, the portion of gaseous Nitrous Oxide released by the BLEVE event is not likely to decompose, as observed during accidents. So, only the portion of the gas present in the tank is providing decomposition energy. This makes the energy stored in the Nitrous Oxide tank dependent on tank fill grade as well as initial conditions (pressure and temperature). So, no single value for energy release per mass Nitrous Oxide can be determined.

A more conservative approach would be assuming the decomposition of all gaseous Nitrous Oxide present, including the gas released by flash evaporation. As mentioned above, stored energy in the tank is dependent on fill grade and initial conditions. An even more conservative approach would be the assumption of decomposition of all Nitrous Oxide during the BLEVE.

The most conservative approach would be using a flash factor of 1, meaning full flash evaporation as well as full decomposition. This allows the calculation of energy content per mass of the substance, and therefore TNT equivalence, that is only dependent on initial conditions.

When looking at TNT equivalency, it is important to point out that this does not give information about reaction speed, but only stored energy (Firewood has a TNT equivalence of about 4, but is less volatile due to its slow energy release rate). Nitrous Oxide is decomposing significantly slower than TNT, therefore making the reaction less destructive. It is vital to point out that Nitrous Oxide decomposition can still be fatal.

Since these approaches are not verified, use of the most conservative value may be recommended.

6.9.10 Handling Design Recommendations

6.9.10.1 Flashback Prohibition/Pressure Oscillation Prevention

In order to decouple pressure fluctuation in the combustion chamber from the oxidizer system and also reduce the risk of backflash, the injector must be designed in order to accommodate for sufficient pressure drop between oxidizer systems. Using a similar principle as the cavitating venturi, the Nitrous Oxide flow can be choked in the injector orifices, decoupling mass flow from chamber pressure, preventing any form of backflash that is not a detonation, and prohibiting pressure transduction from the chamber to the feed system, reducing the chance of an adiabatic compression event.

6.9.10.2 Decomposition quenching/Propagation Prohibition

The hot combustion gases within the rocket engine combustion chamber easily provide sufficient energy for enabling decomposition reaction, if by any chance they get introduced into the oxidizer piping, for example by sudden pressure rise in the chamber, hard start, or an insufficient injector design. If, for example, at the end of the combustion process, gaseous Nitrous Oxide is present in the oxidizer lines, propagation of decomposition through the piping and into the tank may be effectively prevented by choosing a piping diameter which is below the quenching diameter of Nitrous Oxide at given operating conditions. For ambient temperature, the quenching diameter is at about ". If a higher flow diameter is required, using of flame retainers may be necessary. Since the Houbolt Rocket engine allows for " piping, a diameter within the quenching zone will be used. Any other piping involving the oxidizer will be similarly kept below quenching diameter, since ignition sources other than combustion gases may be present (ESD, electric spark, overheating components, Eddy heating etc.)

6.9.10.3 External Pressurization/Dilution of Ullage

Diluting the Nitrous Oxide ullage within the oxidizer tank by external pressurization reduces the chance of a decomposition reaction within tanks and feed lines. Besides the dilution effect, adding external pressurization adds to stable running, more steady oxidizer properties, and enhances resistance to cavitation, since the pressure of the liquid Nitrous Oxide is initially above its saturation value. When using a pressurization system, proper separation of fuel and oxidizer pressure supply lines is absolutely necessary. The safest approach would be the use of two separate systems for fuel and oxidizer. Recommended gases for pressurization are Nitrogen or Helium. The use of Oxygen seems also possible.

6.9.10.4 Pressurization Rate/valve actuation

Even though achieving a decomposition event by quick pressurization of the oxidizer tank, limiting pressurization speed of the oxidizer tank, will be on the safe side, XCOR suggests a safe pressurization rate of about 1 bar/sec. Since fast acting valves and large fluid bulks can create pressure spikes, all electrical valves shall be operated with a moderate speed. Servo actuated valves may be the best pick, since opening and closing rates can be controlled accurately. Solenoid valves may be used, if the flow rate is small. Self closing valves at high flow rates may cause unexpected pressure spikes.

6.9.10.5 Component Overheating

Electrical components close-to or in contact with Nitrous Oxide, such as servo valves, solenoid valves, and pressure and temperature sensors, shall be kept from overheating by using minimum power input and only powering the component when it is actively operating (especially servos). Furthermore, external component material shall not support easy combustion, therefore reducing heat generation in the case of a malfunction. For servo valves, the connection between servo and valve ball may be a thermal insulator in order to prevent valve body heating in the event of a servo heat up. Solenoid valves may develop significant heat, if operated for an extended amount of time, so they may only be used for operations with short ontimes. For longer ontimes, servo valves may be more suitable.

6.9.10.6 Grounding/Spark ESD Protection

Good grounding of the test stand, electronic systems, fuelling equipment, and fueling personnel is necessary. Since Nitrous Oxide itself tends to generate electrostatic charge, when flowing over surfaces, components that are isolated by seals (balls of ball valves) have to be determined and also connected to the ground. Electrical systems that are in contact with Nitrous Oxide (pressure sensors and temperature sensors) may only use low voltage and low current power supply. It is necessary to protect the low voltage supply from accidentally connecting to the high power systems present. High power cables for servos and solenoids shall be shielded, grounded, and sealed, no blank cables shall be present. As with overheating, the power supply shall only switch on for components when they are in use.

6.9.10.7 Material Compatibility

Especially when it comes to polymers within plumbing, seals, and tanks, compatibility with Nitrous Oxide regarding both dissolving and swelling shall be ensured. This also includes parts of sensors subjected to Nitrous Oxide. When it comes to metals, Nitrous Oxide is compatible with most Steel alloys, however, due to corrosion resistance and eventual low temperatures, Stainless Steel may be the best material. If weight is relevant, Aluminium might be an interesting alternative, however, Standard Aluminium Pressure Components are hard to find. When it comes to composite tanks, the resin (Class V) or the liner (Class IV) must be compatible with Nitrous Oxide. The use of Hydraulic hoses may be suitable for Nitrous Oxide plumbing. Good Oxidizer cleaning of the hoses would be necessary.

6.9.10.8 Avoiding Supercritical Fluid

Since the critical point of Nitrous Oxide can be reached simply by standard conditions, special measures shall be implemented to the system to prevent it from reaching its supercritical state. This is achieved by a double redundancy safety/bleed valve. The bleed valve, being set to operating pressure, stabilizes the desired tank pressure by venting, and thereby evaporating and cooling, the Nitrous Oxide within the tank, eventually stabilizing the system. A safety valve, which is set to go off closer to the critical point, provides the redundancy needed for preventing the Nitrous Oxide from going supercritical. Temperature and pressure are logged during operation, so closing in on the critical point will be detected and therefore the servo vent valve will be opened. Since bleeding off too much oxidizer is inefficient, an active cooling system for the tank may be helpful. All enclosed piping sectors need some kind of vent. This especially counts for ball valves, which are capable of enclosing portions of the Nitrous Oxide, that might lead to a crack in the valve body due to overpressure or even a decomposition reaction. Having a relief tap at the ball of the valve solves that issue.

6.9.10.9 Personnel Involvement

When studying the incident reports of the big Nitrous Oxide mishaps, besides criticism on technical safety measures and system design, it is almost always mentioned that, with the correct personnel management strategy, incidents would have been less severe or even prevented. This includes proper personnel training and clarification on Nitrous Oxide risks, suitable safety zones, and personnel positioning during critical operations. Appropriate safety training, a good on site safety qualification identification concept, as well as minimum personnel on-site strategy, are strongly recommended.

6.9.11 Conclusion

After studying the behaviour of Nitrous Oxide, it is determined that Nitrous Oxide is not safe. However, the same may be said of all other known oxidizers. Oxidizers suitable for rocket applications are, without exception, highly reactive substances that must be treated and handled with the necessary respect and precautions. A safe oxidizer, as being used without having to deal with extended safety procedures, is nonexistent, and assuming this of Nitrous Oxide has led to a series of accidents. This opinion on Nitrous Oxide has to be consequently opposed.

It is, however, possible to use Nitrous Oxide as an oxidizer in a rocket engine in a safe manner. Due to its decomposition hazard, the substance requires a variety of special design features and considerations. These features provide good integrability, low implementation effort, and even certain benefits, especially when used in small pressure-fed rocket engines and propulsion systems. Carefully designing the system may lead to a concept that, in its inherent safety, is comparable, if not superior, to LOX (with respect to safety). If, however, the system is treated the wrong way, and required safety considerations are ignored, results may be devastating. Due to its nontoxic and non cryogenic state, Nitrous Oxide is, under the right treatment, a promising candidate for smaller, storable rocket propulsion systems, and its good characteristics have been shown in a variety of successful small engine concepts.

Appendix