RL-36 Liquid Rocket Engine

Project Technical Report

This document details the design, manufacture, and testing of the RIT Launch Initiative Propulsion Team's first liquid rocket engine, designated RL-36 *Mosquito*. This engine will burn a combination of gasoline and gaseous oxygen to produce 36lb of thrust with a specific impulse of 248 seconds. Initial target burn time is 7 seconds, after which the condition of the engine will be evaluated to determine if a longer burn is practical. In the interest of time, the engine will be attached to a test stand used for a previous hybrid engine. Pending a successful hot fire test, a new test stand will be built, which will be capable of measuring engine thrust. The purpose of this project is to gain introductory knowledge of and experience with liquid rocket engine design and manufacturing, which will lead to more powerful engines for static test fires and eventually launching of high powered rockets.

I. Introduction

THE RIT Launch Initiative is a multidisciplinary student organization that applies the principles of rocket design and manufacturing for learning and competition. The team aims to prepare students for excellence in aerospace, to conduct novel research and development, and put RIT at the forefront of the emerging space push. This year the team has expanded, introduced numerous new projects, and made great strides towards becoming a leading competition team in the college of engineering here at RIT. The team has successfully flown three L3 rockets, seven L2 rockets, and has certified 35 members to fly L1 rockets under the National Association of Rocketry (NAR), with 40 more certifications pending completion the month after IREC. Additionally, several team members hold individual L2 and L3 high-powered rocketry NAR or Tripoli certifications.

RIT LI is split into 5 primary project teams, each consisting of 6 to 20 members, Propulsion Team being one of them. The team is directed by two student co-leads, who oversee both the training of new members and the designing and manufacturing of liquid engines. Members participate in any fields in which they have experience and/or interest, but they are not necessarily locked into any one specific subsystem. The project as a whole also reports to the executive board, which consists of technical experts that review designs, the project manager who oversees timelines and development work, the treasurer who coordinates funding, sponsorships, and purchasing, and the chief safety officer, who oversees safety, operations, and training of members.

This is the Propulsion Team's first attempt to build a liquid rocket engine. The team has supported a number of MSD teams working on hybrid rocket engines, but this is the first Launch Initiative project not associated with an MSD team. The team is mainly focused on building a foundation of knowledge and experience by working on small engines for static test firing, eventually working up to launching rockets with student-built liquid engines. While taking risks is necessary for progress and innovation, safety will always be the primary concern of any Propulsion Team project.

II. System Architecture Review

1. Combustion Chamber and Nozzle

Propellants

RL-36 *Mosquito* is a liquid bipropellant rocket engine in which a fuel and an oxidizer are mixed and burned in the combustion chamber to produce thrust. For this engine, gasoline is used as the fuel and gaseous oxygen is used as the oxidizer. These were chosen because they are relatively easy to obtain. From this combination, *How to Design, Build, and Test Small Liquid-Fuel Rocket Engines* gives a mixture ratio (oxidizer/fuel) of 2.5 at an estimated chamber pressure of 300 psi, with a flame temperature of 5742 °F and a specific impulse of 261 seconds. We chose a total thrust of 36 lbf, which was used to calculate the total propellant flow rate:

$$w_T = F/I_{sp}$$

The mixture ratio (r) was then used to calculate oxidizer and fuel flow rates:

$$w_O = w_T * r/(r + 1)$$

$$w_F = w_T/(r + 1)$$

Geometry

Once the propellants, O/F ratio, chamber pressure, and mass flow rates have been determined, the dimensions of the combustion chamber can be calculated. The following equations were obtained from *How to Design, Build, and Test Small Liquid-Fuel Rocket Engines* and executed using a MATLAB script.

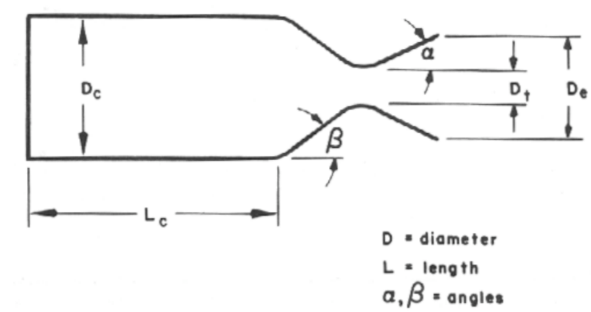


Figure #: Definition of key variables for combustion chamber design.

In order to calculate the diameter of the nozzle throat, the appropriate nozzle throat area is found first.

$$A_t = \frac{w_t}{P_t}\sqrt{R(T_t/\gamma)g_c}$$

R is the gas constant (in this case, approximately 65 ft-lb/lb °R), gamma is the ratio of specific heats (1.2), and g is the acceleration due to earth's gravity. T_t is the temperature at the throat, which simplifies to T_t=(.909)T_c, where T_c is the chamber temperature in absolute units. For gaseous oxygen and gasoline at a chamber pressure of 300psi and a mixture ratio of 2.5, T_c=5742°F, or 6202°R. P_t is the throat pressure, which simplifies to P_t=(.564)P_c, where P_c is the chamber pressure. By using the following table of nozzle parameters, the expansion ratio (A_{exit}/A_{throat}) can be found to be 3.65. The exit area is then found by multiplying the throat area by the expansion ratio.

P_c	M_e	A_e/A_t	T_e/T_c
100	1.95	1.79	0.725
200	2.33	2.74	0.65
300	2.55	3.65	0.606
400	2.73	4.6	0.574
500	2.83	5.28	0.55

Figure #: Table of nozzle parameters for various chamber pressures, γ = 1.2, P_{atm} = 14.7 psi.

The diameters of both the throat and the exit are calculated as follows:

$$D = \sqrt{4A/\pi}$$

The converging and diverging angles, α and β, are recommended to be α = 15° and β = 60° to prevent internal flow losses. The exact geometry of the radii of curvature has been proven to be non-critical to engine performance.

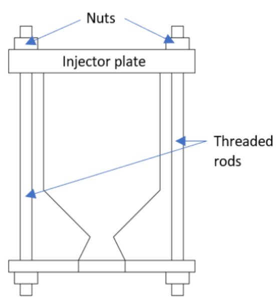
To find the dimensions of the combustion chamber, a parameter known as characteristic length (L*) is used, which is a substitute for determining the chamber residence time of the reacting propellants. It is a simplification to more easily calculate the necessary chamber volume needed for complete combustion. For the chosen propellants of this engine, an L* of 50”-100” has been found to be satisfactory. Chamber volume can be found by multiplying L* by area of the nozzle throat. To prevent flow losses in the chamber, the chamber cross-sectional area should be three times or more than that of the throat cross-sectional area. The chamber volume (which was already calculated using L*) is equal to the chamber area times the chamber length plus the volume of the convergent section, which can be approximated as 1/10 of the cylindrical portion of the chamber. This means that $V_c = 1.1(A_c L_c)$, which can be solved to find the chamber length. Lastly, the wall thickness is found by:

$$t = PD/S$$

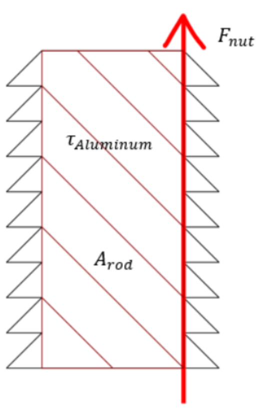
where P is the chamber pressure, D is the mean diameter of the chamber, and S is the maximum allowable stress of the material being used.

Structures

RL-36 is held together by four threaded rods that connect the injector to a plate at the bottom of the nozzle. The threads on the rods and the nuts holding them in place must have high enough shear strength to withstand the maximum operating pressure in the chamber (300 psi).



The shear stress on the threads was calculated in the following manner.



Total force on rods due to CC pressure:

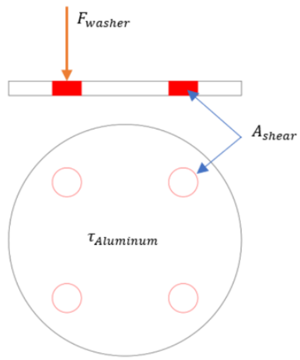
$$F_{pressure} = P_c A_c \approx 4000\ lb_f$$

Max shear force rods can withstand:

$$\tau_{Al} = \frac{F_{max}}{4A_{rod}} \Rightarrow F_{max} \approx 11750\ lb_f$$

$$FS = \frac{F_{max}}{F_{pressure}} = \mathbf{2.9}$$

The shear stress on the injector plates and washers was calculated in the following manner.



$Total\ force\ on\ plate\ due\ to\ CC\ pressure:$

$$F_{pressure} = P_c A_c \approx 4000\ lb_f$$

$Max\ shear\ force\ plate\ can\ withstand:$

$$\tau_{Al} = \frac{F_{max}}{4A_{shear}} \Rightarrow F_{max} \approx 58800\ lb_f$$

$$FS = \frac{F_{max}}{F_{pressure}} = \mathbf{14.7}$$

As shown in these calculations, the engine is designed with more than sufficient factors of safety.

Heat Transfer

Heat transfer through the combustion chamber walls was calculated to ensure that the aluminum will not reach its melting point during the burn time. A thin-walled chamber is assumed. The modes of heat transfer are conduction and convection. Radiation is neglected. The convective heat transfer coefficient on the inside wall of the chamber is assumed to be 26.4 Btu/h*ft2*F, and the convective heat transfer coefficient on the outside wall is assumed to be 5.0 Btu/h*ft2*F. The thermal conductivity of the chamber wall is that of 6061 aluminum, which is 89.2 Btu/h*ft*F. Since the convection and conduction occur in series, the heat rate is the same through the inside film, the wall, and the outside film. The following equations represent the convective and conductive heat rates, respectively:

$$\dot{Q}_{conv} = hA(T_1 - T_2)$$
$$\dot{Q}_{cond} = \frac{kA}{d}(T_1 - T_2)$$

h = Convective heat transfer coefficient, $[\frac{Btu}{hr*ft^2*°F}]$

k = Thermal conductivity, $[\frac{Btu}{hr*ft\ *°F}]$

A = Area of heat transfer surface, $[ft^2]$

d = thickness of wall, $[ft]$

$\dot{Q}$ = Heat transfer rate, $[\frac{Btu}{hr}]$

First, conductances for the three resistors of the heat transfer circuit were calculated:

$$G_{conv} = hA \qquad G_{cond} = \frac{kA}{d}$$

G = Conductance

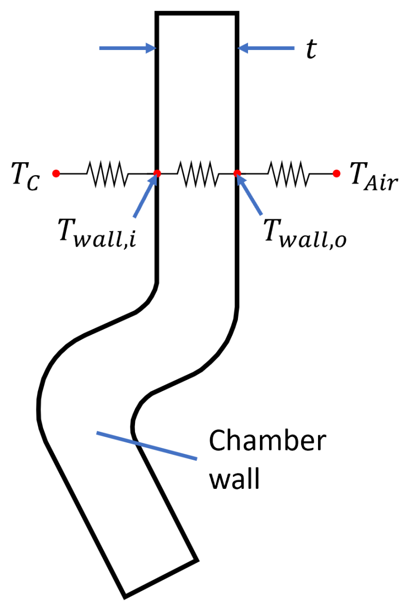
The equivalent conductance is the reciprocal of the sum of the reciprocals of the three conductances:

$$G_{eq} = (1/G_1 + 1/G_2 + 1/G_3)^{-1}$$

The heat transfer rate is the equivalent conductance time the total temperature difference:

$$\dot{Q}= G_{eq}(T_1 - T_4) = 1020\ Btu/h = 2.83\ Btu/s$$

At this net heat transfer rate, the temperature of the inner chamber wall after the 7-s burn time is



Machining

2. Injector

A showerhead injector was chosen because of its manufacturability. A showerhead is simple to analyze because it does not involve impinging jets. Thus, atomization is based on the Reynolds number and Ohnesorge number of the fuel flowing through the orifices.

Orifice sizes

Because the oxidizer is in the gas state, atomization calculations are not required, and only one orifice is used. The fuel orifice sizes were determined based on manufacturability and atomization parameters. Iterations were done with different orifice diameters. A diameter of 0.02 in, which results in atomization, was chosen. The flow velocity with this orifice size is in the best practice range of 30-100 ft/s. A minimum pressure drop of 100 psi was chosen so that backflow of combustion gases through the piping system is unlikely. The mass flow rate through each orifice was determined using the following equation:

$$\dot{m}_o = \rho C_d A\sqrt{\frac{2\Delta P}{\rho}} = 0.0085\ kg/s$$

The number of orifices was determined by dividing the total fuel mass flow rate by the mass flow rate through each orifice:

$$n = round\left(\frac{\dot{m}}{\dot{m}_o}\right) = 2$$

Since flow rates are small and pressure drop is relatively low, only two orifices are required. The orifice length is six times the orifice diameter, which is based on best practices. The velocity is 100 ft/s, which is in the desired range.

Atomization

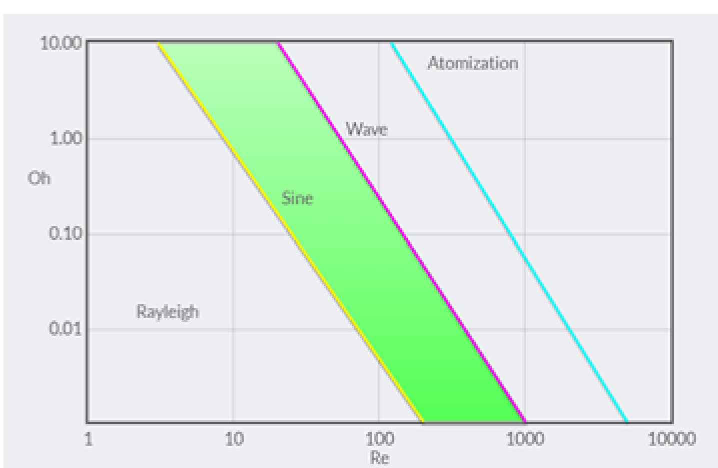
The Reynolds and Ohnesorge numbers are required to determine whether the gasoline will atomize after passing through the injector orifices. Calculation of the Ohnesorge number requires calculating the Weber number first. The equations for the Reynolds, Weber, and Ohnesorge number are given below.

$$Re = \frac{\rho V D}{\mu} = 2.09 * 10^4$$

$$We = \frac{\rho V^2 D}{\sigma} = 1.72 * 10^4$$

$$Oh = \frac{\sqrt{We}}{Re} = 0.0063$$

Fig. [#], below, was used to determine whether the atomization is achieved based on the Reynolds and Ohnesorge numbers.



Since the Reynolds number is higher than 10000, the chart indicates that atomization will occur. This ensures that combustion will be effective and that gasoline residue will not develop in the combustion chamber.

Machining

3. Feed System

Layout

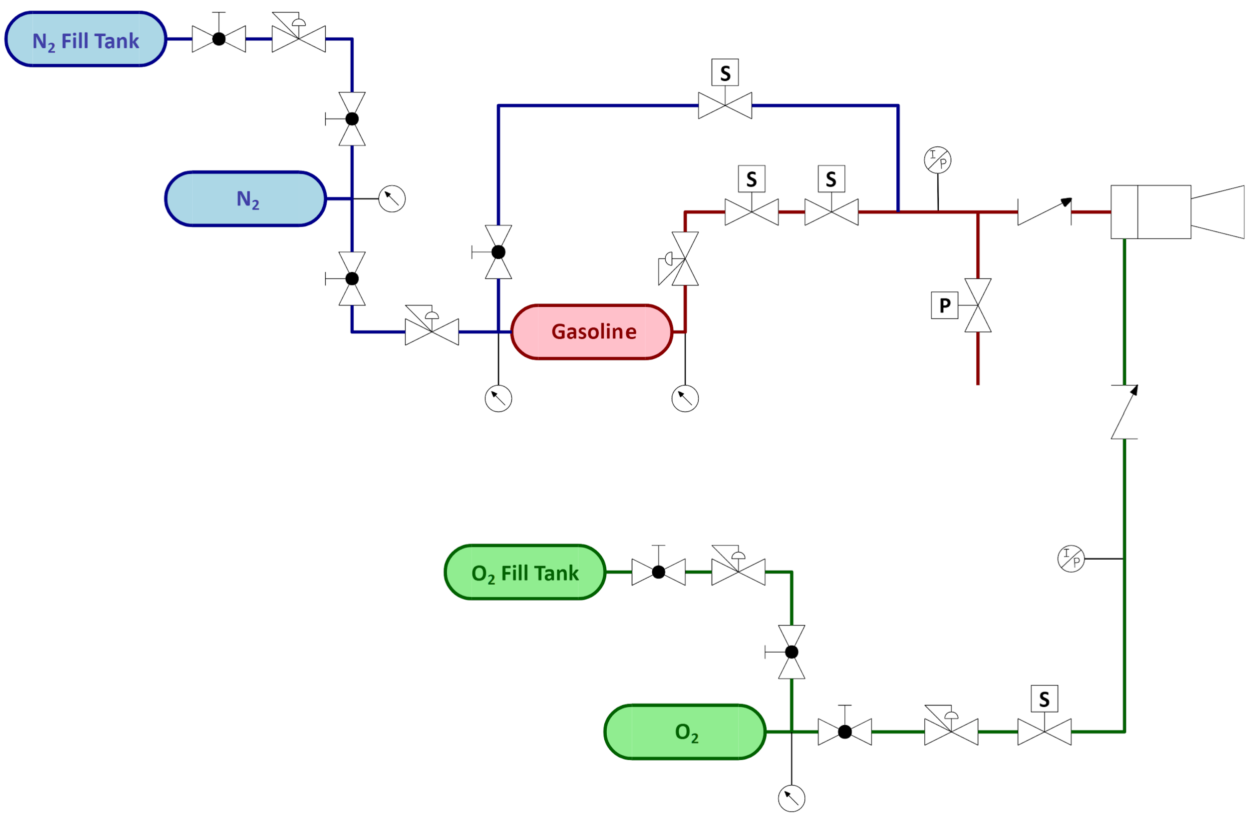


Figure #. Feed system piping and instrumentation diagram.

The feed system can be broken down into two subsystems, the fuel line and the oxidizer line.

The fuel line consists of three tanks: the nitrogen fill tank, the pressurizing nitrogen tank, and the fuel tank. The fill tank is off the shelf and is delivered at 2000 psi. This tank will be temporarily connected to the rest of the system to fill the nitrogen tank. There are two manual shutoff valves (one attached to the tank) and a CGA 580 regulator between the fill tank and the pressurant tank. For the tank fill procedure, see Appendix [-]. The pressurant tank is a custom composite tank filled with nitrogen. Its starting pressure is 510 psi. This tank was manufactured by SCI Composites and was pressure tested to 5400 psi. Thus, it will be operating at a factor of safety of around 10. The fuel tank is filled with gasoline and also has a starting pressure of 510 psi. Between the nitrogen tank and the gasoline tank are two valves, a manual shutoff valve and a pressure regulator. The manual shutoff valve will be closed when the fuel tank is being transported to prevent a gas spill. The pressure regulator is built into the system for possible use with a larger engine containing higher pressures. In this engine, the flow rates are too low for a noticeable pressure drop across this regulator. Downstream of the gas tank are a pressure regulator, redundant solenoid valves, a pressure transducer, and a check valve. Similar to the first regulator, this regulator will have no pressure drop across it. The solenoid valves are remotely operated and normally closed. The pressure transducer is connected to the data acquisition system. The purge valve will be used if the injector is clogged and pressure must be relieved from the fuel line. The check valve prevents combustion gases from back flowing into the line.

The oxidizer line contains the off-the-shelf, 2000-psi oxygen fill tank and the oxygen tank. The line between the fill tank and the oxygen tanks contains two manual shutoff valves (one attached to the tank) and a CGA 540 regulator. The oxygen tank will be at a maximum pressure of 500 psi. Downstream of the oxygen tank is a manual shutoff valve, a pressure regulator, a solenoid valve, a pressure transducer, and a check valve. The manual shutoff is closed during oxygen tank filling. Because of low flow rates, pressure drop across the regulator is negligible. The solenoid valve is remotely operated and normally closed. The check valve prevents combustion gases from back flowing into the line.

Tank pressurization

1. Gasoline tank

The fuel tank, which will be filled with gasoline, will be pressurized to approximately 400.1 psi. This pressure was determined using the Bernoulli equation to solve for the pressures of the feed system pipes upstream and downstream of the fuel tank. The following equation was used to calculate the pressures upstream and downstream of the tank.

$$\frac{p_{tank,downstream}}{\rho} = \frac{p_{inj,upstream}}{\rho} + gh_L$$

$$p_{tank,downstream} = 400.1\, psi \quad p_{inj,upstream} = 400.0\, psi$$

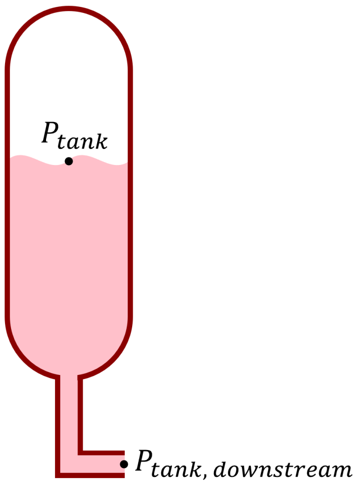
Then, the tank pressure was determined based on piping losses. The velocity inside the tank is considered negligible and due to the short length of the tank so is the head loss. The following equations represent those calculations.

$$\frac{p_{tank,downstream}}{\rho} = \frac{p_{inj,upstream}}{\rho} + gh_L$$

$$p_{tank} = p_{tank,downstream} + \frac{1}{2}\left(\frac{\dot{m}}{\rho A_{pipe}^2}\right)$$

$$\dot{m} = \rho v_{pipe} A_{pipe}$$

Since the flow velocity passing through the tank is low, the pressure drop due to the increase in velocity as it exits the tank is negligible. This results in the pressure of the tank being 400psi.



2. Nitrogen tank
The nitrogen tank, which is used to pressurize the fuel tank, will be filled with a mass of pressurized nitrogen dependent on the required mass of the tank. The required mass is based on the following equation.

$p_p \equiv Required\ fuel\ tank\ pressure$
$V_p \equiv Total\ fuel\ volume$
$T_0 \equiv Initial\ fuel\ temperature$
$p_g \equiv Minimum\ fuel\ tank\ pressure$
$p_0 \equiv Initial\ N_2\ tank\ pressure\ (500\ psi)$

$$m_0 = \frac{p_p v_p}{RT_0}\left(\frac{k}{1-\frac{p_g}{p_0}}\right) = 0.0394\ kg$$

If the custom nitrogen tank is used then the required mass is determined by the following equations.

$$\rho = \frac{p_0}{RT_0} = 39.0\ \frac{kg}{m^3}$$

$\rho \equiv Required\ N_2\ density$
$V_{COTS} \equiv Fill\ tank\ volume$

$$m = \rho(V_{cust} + V_{ullage} + V_{COTS}) = 6.08\ kg$$

The commercial off-the-shelf nitrogen fill tank that will be used to fill the custom nitrogen tank will have to be filled to a certain pressure to fill our tank correctly, that pressure was determined using the following equation.

$$p \geq \frac{m}{V_{COTS}} RT_0 = 1466\, psi$$

3. Oxygen tank

The oxygen tank must be filled to an initial pressure that will result in the final pressure after the burn being equal to the injection pressure, 400 psi.

$P_f \equiv Final\ tank\ pressure\ (400\ psi)$
$P_i \equiv Initial\ tank\ pressure$
$m_f = Final\ mass\ of\ O_2\ in\ tank$
$m_i = Initial\ mass\ of\ O_2 in\ tank$

$$P_f = \frac{m_f RT}{V_{tank}} = 400\, psi$$

$$P_i = \frac{m_i RT}{V_{tank}}$$

The mass of the oxygen that will be expelled during the burn in terms of other variables:

$$m_{ex} = 0.356\, kg \ = m_f - m_i = \frac{V_{tank}}{RT}(P_f - P_i)$$

The initial pressure required to have the final pressure of 400 psi is determined by the equation below:

$$P_i = P_f + \frac{m_{ex} RT}{V_{tank}} = 504\, psi$$

4. Controls System

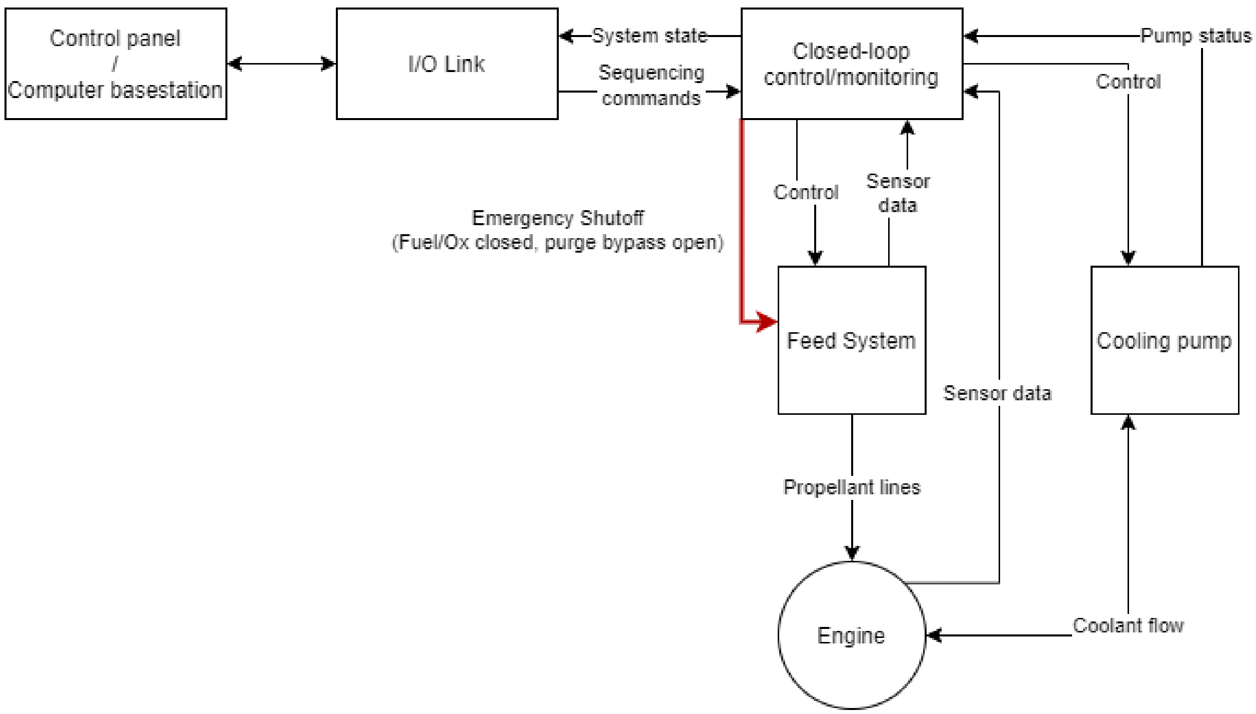


Figure 1: Control System Diagram

The Command and Control system consist of a PC connected to the Teensy 4.1 microcontroller by a [X] foot ethernet cable. The PC will be positioned [x] feet away from the test bunker. Along with a micro sd card for storage and ethernet connection to ensure data is being sent and received at a usable speed. The Control system has two purposes: controlling flow through the feed system and monitoring pressures within the feed system.

Our feed control system consists of multiple Solenoid valves to control the flow through the feed system. As shown in Fig [x](plumbing diagram), the valves are positioned between the oxidizer and fuel tanks and the injector so that no flow is allowed while the valves are closed. The solenoid valves are normally closed

the to read the different pressures within the feed system and Solenoid relay drivers to amplify the signal and become readable for the microcontroller. The solenoids are able to be open and closed using our microcontrol in the command system.
Specifically to check the pressure and ensure a halt if the pressures exceeds our calculated values.This system will also read data from our data acquisition system and store them onto the PC.

In addition this will be powered by two 12 Volt Batteries and a 5 Volt Regulator.

III. Mission Concept of Operations Overview

The RL-36 mission has been divided into 10 phases, beginning with engine assembly. The engine consists of four machined parts: the top and bottom sections of the injector, the combustion chamber, and a retention plate. The top section of the injector threads onto the bottom section, with two O-rings at critical locations to prevent oxygen and fuel from mixing prematurely. The bottom section of the injector is then slid into the top of the combustion chamber, and another O-ring is inserted between the two to prevent combustion gases from escaping through any opening other than the nozzle. The nozzle fits into a counterbore in the retention plate, and four threaded rods are inserted through holes in the retention plate and both sections of the injector, then secured in place with nuts and washers. This prevents the injector from separating from the combustion chamber. The engine is then ready to be mounted to the test stand.

The test stand is placed in the bunker and secured with two heavy I-beams sitting on the base of the stand. The weight of these beams is far more than enough to prevent the test stand from moving while the engine is fired. The engine itself is mounted to the test stand via two hose clamps that wrap around the threaded rods and a steel bracket on the test stand. The hose clamps are positioned in such a way that if the engine were to slip, the hose clamps would interfere with the retention plate, thereby eliminating the risk of the engine disconnecting from the stand. Finally, a blast shield used by a previous team will be placed behind the engine, which will protect the valuable components of the feed system in the unlikely event of a catastrophic failure.

Each tank will then be placed in their respective stands and the piping components will be connected to the tanks and the engine. Most of the feed system will be already pre-assembled, saving time and mitigating the possibility of error. Certain sections of the feed system will also be mounted to the wall of the bunker with tube brackets already in place. Then the solenoid valves and pressure inducers will be connected to the controls system using a 100ft Ethernet cable, which will be fed through a grate in the wall of the bunker leading to a computer outside the bunker as far away as the cable will reach. The spark igniter must also be inserted and secured inside the combustion chamber. Controls engineers will conduct a brief test of all electronic components to ensure solid connections, then all solenoid valves will be closed. At this time, all team members will retreat to the minimum safe distance and access to the bunker will be strictly limited to only necessary personnel.

Once all team members have been accounted for, two test engineers will approach and enter the bunker to fill the propellant tanks. First, they will pour ??? gallons of gasoline into the fuel tank and close the fill valve. Then they will attach the nitrogen supply tank to the composite tank and slowly fill the composite tank until the 510 psi pressure is reached. Both tanks will be closed and the piping connecting the two tanks will be removed. The same piping will then be connected between the oxygen supply and composite tanks. The composite tank will be slowly filled to 500 psi. Once completed, the tanks will be closed and the piping connecting them will be removed. The supply tanks will be removed from the bunker and taken past the safe distance. Lastly, the test engineers will open the manual shut-off valves. The propellants will not yet flow to the injector because the solenoid valves are closed. Before returning to the controls computer, one of the test engineers will place the camera on the tripod with a clear view of the engine and press the record button. Once the test engineers leave the bunker, no personnel will be allowed past the minimum safe distance until after either a successful hot-fire or mission abort.

After verifying that all team members are at the safe distance, the controls system will open the solenoid valves to allow the propellants to flow into the engine, and the igniter will spark and begin the combustion reaction. The engine will burn for 7 seconds, then the controls system will shut the solenoid valves and open the nitrogen purge line, which allows the nitrogen to bypass the fuel tank and flow directly into the injector. The nitrogen will flush out any remaining propellants to prevent any possibility of reignition. Before any personnel approach the engine for disassembly, a period of at least 15 minutes will pass to allow the engine to cool and to be as safe as possible. When it is determined to be safe, the team will disassemble the engine and remove all testing apparatus from the bunker.

Phase	**Start of Phase**	**End of Phase**
Engine Assembly	Layout all components of engine	Engine is fully assembled with O-rings in critical locations
Engine Mounting to Test Stand	Test stand is secured in bunker	Engine is firmly mounted to test stand using hose clamps and blast shield is placed behind engine
Feed System Assembly	Tanks are mounted in stands and feed system components are delivered to the bunker	All feed system components are connected to both tanks and the injector
Controls System Setup	Electrical components of feed system are connected to controls system a safe distance of 100ft away from bunker	Each electrical component is remotely tested from controls system to confirm connections
Tank Pressurization	Gasoline is poured into fuel tank, and oxygen/nitrogen tanks are connected to their respective fill tanks	Fuel tank has appropriate amount of gasoline and composite tanks are at correct pressures, manual shutoff valves are opened
Camera Setup	Camera batteries are fully charged and all necessary accessories are brought to bunker	Camera is mounted on tripod with good view of engine, recording is started
Ignition	All personnel are safe distance from bunker and ignition signal sent to engine	Controls system opens solenoid valves to allow fuel and oxidizer to flow into injector, spark ignites propellants in combustion chamber
Engine Burn	Successful ignition has occurred	After 7 seconds of burn time, controls system automatically closes solenoid valves to stop flow of propellants
Engine Shut-off and Purge	Fuel/oxidizer solenoid valves shut and nitrogen purge line is opened	Nitrogen forces any excess propellants out of combustion chamber to prevent accidental

		reignition
Visual Inspection and Disassembly	Engine is allowed to cool and excess pressures in feed system are relieved	Engine and all subsystems are disassembled and removed from bunker

Appendix A: Feed System Parts List

Part Number	Manufacturer	Serial Number	Quantity	Type	Port 1	Port 2
1	Airgas	NI 200 (on tank)	1	Manual Shutoff Valve	Tank	CGA-580
2	Airgas	Unknown	1	Pressure Regulator	CGA-580	1/4 MNPT
3	Apollo Valves	SS-0962	4	Manual Shutoff Valve	1/2 MNPT	1/2 MNPT
4	Swagelock	KPP1LSM422P20000	1	Pressure Regulator	1/2 MNPT	Yor Lock
5	Tescom	BB-13AH2VBA4	1	Pressure Regulator	1/4 FNPT	1/4 FNPT
6	Peter Paul Electronics	H22G9DCM	4	Solenoid Valve	1/4 NPT	1/4 NPT
7	Honeywell	MLH03KPSL01A	2	Pressure Transducer	1/4 MNPT	N/A
8	Parker	8M-C8L-50-BN-SS	1	Check Valve	1/2 MNPT	1/2 MNPT
9	Jamesbury	5H36HBRT 107	1	Manual Shutoff Valve	1/4 FNPT	1/4 FNPT
10	Matheson	8-580	1	Pressure Regulator	1/4 FNPT	1/4 FNPT
11	Airgas	OX 200 (on tank)	1	Manual Shutoff Valve	Tank	CGA-540
12	Unknown	Unknown	1	Pressure Regulator	CGA-540	1/4 MNPT
13	SCI Composites	N/A (custom)	2	Custom Composite Tank	N/A	Tank
14	Unknown	N/A (custom)	1	Custom Fuel Tank	N/A	1/4 FNPT

Appendix B: Control System Parts List

Part Number	Manufacturer	Serial Number	Quanity	Name
1	PJRC	Unknown	1	Teensy 4.1 Microcontroller
2	MightyMax	Unknown	2	12 Volt Batteries
3	Shenzhen Zhinengpai Tech Ltd	SRD-05DC-SL-C	1	30 Volt Multi-Relay
4	Dell	Unknown	1	Dell XPS-150

Appendix C: Risk Assessment for Cold Flow Test

Team Propulsion, RIT Launch Initiative	**Rocket Project/Name** RL-36	**Tentative Test Date** 2/27/2021		
Hazard	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury After Mitigation**
Custom composite tank explodes during fill, causing shrapnel to be propelled and causing injury to operators	-High tank pressure of up to 700 psi during fill operation	-Low -Composite tanks, unlike metal tanks, explode (instead of cracking), causing debris to fly rapidly in all directions	-Composite tanks were tested at over 5400 psi and are thus operated at a factor of safety of 7.5 -Only two operators will be inside the concrete bunker while tanks are being filled -Operators will wear personal protective equipment, including safety glasses, face shields, hard hats, coats,	Very low

			and steel toe boots	
Backflow occurs, causing water to flow back in the system, leaving internal damage	-Higher pressure in combustion chamber than piping system due to fittings and valves not being fastened tightly enough -Water tank becomes depressurized due to failure of valves	-Low -Tanks have much higher pressure than expected combustion chamber pressure, especially during cold flow test	-Check valves prevent water from flowing back toward the tanks -All valves are made to handle pressures of 2000 psi or more, which is higher than the highest pressure in the system during testing	Very low
Combustion chamber detaches from test stand and becomes a projectile	-Mechanical failure of threaded rods securing the injector and plate at the bottom of the combustion chamber -Threaded rods rip through nuts, causing chamber to fly off -Washers rip through injector plate, causing chamber to fly off	-Low -Forces generated by the engine are not expected to be able to cause the failure of 4 threaded rods	-Four threaded rods, with nuts and washers, are securing injector to combustion chamber -Al rod and nut axial max force withstood has approximate factor of safety of 5.5 when compared to max axial pressure force on chamber -Injector plate max force withstood has approximate factor of safety of 14 when compared to max axial pressure force on chamber	Very low

Appendix D: Risk Assessment for Hot Fire Test

Team Propulsion, RIT Launch Initiative	**Rocket Project/Name** RL-36	**Tentative Test Date** 2/27/2021		
Hazard	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury After Mitigation**
Custom composite tank explodes during fill, causing shrapnel to be propelled and causing injury to operators	-High tank pressure of up to 700 psi during fill operation	-Low -Composite tanks, unlike metal tanks, explode (instead of cracking), causing debris to fly rapidly in all directions	-Composite tanks were tested at over 5400 psi and are thus operated at a factor of safety of 7.5 -Only two operators will be inside the concrete bunker while tanks are being filled -Operators will wear	Very low

			personal protective equipment, including safety glasses, face shields, hard hats, coats, and steel toe boots	
Premature combustion occurs, causing combustion chamber to explode and injuring distant spectators	-Gasoline leaks into combustion chamber prior to valves being opened, leading to too much gasoline in chamber at time of ignition	-Low -Hotfire testing cannot occur without filling fuel tank with gasoline	-Fuel line includes two redundant solenoid valves between gasoline tank and combustion chamber -Engine is operated remotely, so when ignition starts operators are outside of bunker and not in the path of possible debris -Non-operator team members are 100 ft away from bunker and not in the path of debris	Very low
Backflow occurs, causing combustion to travel up to fuel tank, triggering an explosion and injuring distant spectators	-Higher pressure in combustion chamber than feed system because gasoline tank becomes depressurized due to failure of solenoid valves or check valves -Higher pressure in combustion chamber than piping system due to fittings and valves not being fasten tightly enough -Water tank becomes depressurized due to failure of valves	-Low -Tanks have much higher pressure than expected combustion chamber pressure	-Check valves prevent propellants from flowing back toward the tanks	Very low

Combustion chamber detaches from test stand and becomes a projectile	-Mechanical failure of threaded rods securing the injector and plate at the bottom of the combustion chamber -Threaded rods rip through nuts, causing chamber to fly off -Washers rip through injector plate, causing chamber to fly off	-Low -Forces generated by the engine are not expected to be able to cause the failure of 4 threaded rods	-Four threaded rods, with nuts and washers, are securing injector to combustion chamber -Al rod and nut axial max force withstood has approximate factor of safety of 5.5 when compared to max axial pressure force on chamber -Injector plate max force withstood has approximate factor of safety of 14 when compared to max axial pressure force on chamber	Very low
Fuel and flame spread to the bunker floor or outside ground, causing fire to spread out of control	-Mechanical failure of gasket or o-ring in combustion chamber due to high pressure or overheating	-Low -Gasket and o-rings are sealed by force of threaded rods and nuts, which is at minimum 5.5 stronger than the maximum pressure force on the combustion chamber -Gasket and o-rings are rated for pressures above expected engine operating pressure	-Bunker floor is made of concrete and has no flammable material on it, thus making it difficult for fire to spread on bunker floor -Ground is wet or damp outside of bunker, thus making it very difficult for fire to spread outside of bunker	Very low

Appendix E: Cold Flow Test Procedure

IMPORTANT: During the entire test procedure, all team members must wear safety glasses. Use this as a checklist, checking off each step as it is done.

1. Transport equipment to bunker
    a. Park transportation car outside of KGCOE machine shop
    b. Use cart to transport fuel tank stand from basement to car
    c. With valve caps on, have two team members carry each tank (nitrogen fill, nitrogen, fuel) from machine shop to car
    d. Use cart to transport piping system and valve boxes from basement to car
    e. Have two team members carry test stand and I-beam weights from basement to car

    f. Have two team members carry control system and data acquisition system (DAQ) from basement to car
    g. Slowly drive transportation car from machine shop to bunker
2. Transport tanks to bunker
    a. Have two team members place stand inside bunker
    b. Place nitrogen fill tank upright outside bunker, and strap to bracket
    c. Plate nitrogen tank inside bunker, and strap to wooden bars
    d. Place fuel tank upright on fuel tank stand
3. Transport piping system to bunker
    a. Remove screens from bunker
    b. Connect fuel line to fuel tank
    c. Connect fuel tank to nitrogen tank
    d. Connect nitrogen tank to nitrogen fill tank, threading fill line through hole in bunker
    e. Make sure that all shutoff valves and regulators are closed
4. Transport test stand to bunker
    a. Place test stand on ground close to bunker exit
5. Fasten combustion chamber to test stand
    a. Using metal straps, tightly fasten combustion chamber to V-shaped mount on test stand
    b. Place spill tray underneath combustion chamber
    c. Thread fuel line into injector
6. Set up control system
    a. Place Arduino and laptop outside of bunker, next to fill tank
    b. Connect wires from control system to solenoid valves
    c. Connect laptop to control system, and check that solenoid valves are working
7. Set up data acquisition system
    a. Place DAQ outside of bunker, next to control system
    b. Wire control system to pressure transducers and force plates, and check that readings are occurring
8. Fill up fuel tank
    a. Remove shutoff valve from top of fuel tank
    b. Use funnel to pour desired amount of water into tank
9. Fill up nitrogen tank
    a. Slightly open manual shutoff valve (MSV) closest to custom tank
    b. Slightly open CGA 580 MSV on fill tank
    c. Slightly open Airgas CGA 580 regulator
    d. Check readings on all pressure gauges to make sure there are no leaks
    e. When custom tank pressure gauge indicates desired nitrogen tank starting pressure of 500 psi, slowly close regulator
    f. Close both MSVs in fill line
    g. Crack connection downstream of CGA 580 regulator to release pressure in fill line
    h. When fill line is depressurized, disconnect fill line from both custom and COTS tanks; set line aside
10. Fill up oxygen tank
    a. Slightly open MSV closest to custom tank

    b. Slightly open CGA 540 MSV on fill tank
    c. Slightly open Airgas CGA 540 regulator
    d. Check readings on pressure gauge on custom tank
    e. When custom tank pressure gauge indicates desired oxygen tank starting pressure of 500 psi, slowly close regulator
    f. Close both MSVs in fill line
    g. Crack connection downstream of CGA 580 regulator to release pressure in fill line
    h. When fill line is depressurized, disconnect fill line from both custom and COTS tanks; set line aside

11. Manually prepare fuel line for test
    a. Slowly open Tescom regulator
    b. Check that fuel tank pressure gauge reads 500 psi, the required starting pressure
12. Manually prepare oxygen line for test
    a. Slowly open Matheson regulator
    b. Check that fuel tank pressure gauge reads 500 psi, the required starting pressure
13. Run engine (operators only)
    a. Set up camera next to combustion chamber and start video
    b. Clear inside of bunker
        i. Operators stand outsides of concrete wall next to control system
        ii. All other members stand on opposite side of road
    c. Turn on data acquisition system
        i. Check that data is being recorded
    d. Run Arduino code for solenoids
        i. Solenoids open up
        ii. Water flows for 7 seconds
        iii. Solenoids are shut down for 20 seconds
        iv. Fuel and oxidizer line solenoids are opened for 1 minute to empty out water and depressurize custom tanks
        v. All solenoids are closed
14. Power off control system, and disconnect control system from feed system
15. Disassemble feed system and load into transportation car (all members)
    a. Disassemble feed system components while keeping shutoff valves closed
        i. Be careful not to release pressure in custom tank for sake of saving money
    b. Load parts into transportation car, and drive slowly back to machine shop