THE COLLEGIATE PROPULSIVE LANDER CHALLENGE

SAFETY GUIDE

Revision History

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1.0 INTRODUCTION

This guide in part represents experience and best practices from amateur and high-power rocketry. Like with any such guidelines, they represent approaches that have been proven to work well under typical circumstances for these rockets. They are not necessarily the only way to do things, nor are they necessarily universally applicable in every conceivable situation, and it is not the intent of *CPLC* to discourage novel approaches. But in all cases, the recommendations of this guide reflect deeper underlying principles or requirements that must be satisfied. Insofar as a design or approach demonstrates an understanding of those underlying principles and can be shown to meet them, it may be perfectly acceptable. In all such cases though, it is the responsibility of the *Individual* to prove the acceptability of their approach through careful analysis and testing.

1.1 ACKNOWLEDGEMENT

The CPLC credits the original development of this document to Friends of Amateur Rocketry (FAR), Launch Canada, and the Experimental Sounding Rocket Association (ESRA). This document incorporates elements of the *Tripoli Rocketry Association (TRA) Safety Code, the National Fire Protection Association (NFPA) Code for High Power Rocketry (NFPA 1127)*, industry expertise, and FAR's observations of amateur launches. It draws heavily from and builds on the documentation and experience of the Experimental Sounding Rocket Association (ESRA)'s Intercollegiate Rocket Engineering Competition (IREC), the world's largest advanced student rocket competition. Although NFPA 1127 is a United States regulation and *CPLC* has no formal affiliation with the TRA, these documents remain excellent supplemental resources for *Individuals* to learn more about best practices adopted by the amateur high- power rocketry community.

1.2 CONVENTION AND NOTATION

The following conventions shall be used to represent different parties referred to by this document as CPLC or individual.

CPLC: Represents the Board of Directors, Officers, employees, and volunteers of the Collegiate Propulsive Lander Challenge.

Individual: Students organized as individuals, groups, or teams who have designed, fabricated, tested, static fired, or launched a vehicle or static fire an engine.

The following definitions differentiate between requirements and other statements.

Must: This is the only verb used to denote mandatory requirements.

Should: This verb is used for stating non-mandatory goals.

Will: This verb is used for stating facts and declarations of purpose. The authors use these statements to clarify the spirit and intent of requirements and goals.

1.3 REVISION

It is expected that *CPLC* may require revisions based on the lessons learned by both *CPLC* and *Individuals*. Such revisions will be reflected in updates to the document's effective date. The authority to issue revised versions of this document rests with *CPLC*.

2.0 PROPULSION SYSTEMS

2.1 PROPULSION TYPES AND BASIC REQUIREMENT

2.1.1 ENGINE VERSUS MOTOR

For the purposes of this *Safety Guide*, no distinction is made between motors and engines and this document shall use the term "engine".

2.1.2 COMMERCIAL VERSUS EXPERIMENTAL COMPONENTS

For the purposes of this Safety Guide, a distinction is made between commercial and experimental components.

Commercial: Commercial components are defined as: those that have been designed, fabricated, inspected, and tested to National standards by a licensed or certified entity.

Experimental: Experimental components are defined as: components that have been designed, built, and tested by *Individuals*; commercial components that have been modified in any way; or commercial components utilized outside their specified operating parameters (pressure or temperature).

2.1.3 TOTAL IMPULSE LIMITATIONS

R2.1.3.1 The total impulse for a vehicle made with commercial or experimental engines shall not exceed 40,960 Newton-seconds (9,208 pounds-seconds, i.e., "O" impulse motor).

R2.1.3.2 The total impulse for a vehicle made with commercial or experimental engines that exceed 40,960 Newton-seconds (9,208 pounds-seconds, i.e., "O" impulse motor) shall require the application of a new FAA Certificate or Authorization to get flight status approval.

2.2 PRESSURIZED FLUID SYSTEMS

Any vessel used for the storage or handling of a fluid or gas under positive or negative pressure is considered a pressure vessel. A pressure system is an assembly of components under pressure (e.g., tanks, piping, valves, fittings, relief devices, pumps, gauges, etc.). A distinction is typically drawn between ground systems (e.g., test stands, Ground Support Equipment (GSE)) and flight systems.

Ground Pressure Systems: These systems that are ground-based, particularly those that will have personnel operating nearby, safety factors (based on ultimate strength) of 4 or greater are required.

Flight Pressure Systems: These systems that fly on the vehicles, are typically not designed with such a high factor of safety, and therefore additional restrictions such as remote monitoring, pressurization, and depressurization shall be put in place to mitigate the risk of hazard exposure.

2.2.1 GENERAL

2.2.1.1 DESIGN STANDARDS

R2.2.1.1.1 Any system, subsystem, or component that will be pressurized with personnel in proximity shall comply with a recognized standard for the design and safe operation of such systems.

The ASME Boiler & Pressure Vessel Code should be followed for pressure vessels, and ASME B31.3 (Process Piping code) should be followed for general pressure system components.

R2.2.1.1.2 Any system, subsystem or component that will be transported while pressurized shall comply with the applicable US Department of Transportation (DOT) standards.

While not a requirement, it is strongly recommended that pressurized systems for flight be designed in consultation with appropriate standards such as ANSI/AIAA S-080 (Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components) or ANSI/AIAA S-08 (Space Systems – Composite Overwrapped Pressure Vessels). Department of Transportation, The American Society of Mechanical Engineers (ASME), or AFSPCMAN 91-710 (Air Force Space Command Manual) standards are also acceptable.

2.2.1.2 WETTED MATERIALS

R2.2.1.2.1 All wetted materials (i.e., those exposed to a fluid) employed in a vehicle or static test stand fluid systems shall be compatible with the fluid(s) and conditions (e.g., temperature, pressure) to which they will be exposed.

This includes structural materials, components, fittings, hoses, soft goods (seals, gaskets) and lubricants.

R2.2.1.2.2 Any materials in a fluid system or component that would not normally be directly exposed to a given fluid but could be exposed during a credible failure or by migrating downstream shall similarly be compatible with that fluid.

A common example would be a lubricant used in a pressurization system component upstream of an oxidizer tank or line: while that lubricant might normally be exposed only to inert pressurant gas, it could potentially contaminate downstream plumbing and so should be compatible with the oxidizer.

2.2.1.3 GENERAL CLEANLINESS

R2.2.1.3.1 All fluid systems shall incorporate provisions in design, assembly, and operation to prevent any contamination or foreign object debris (FOD) that would impede the operation and safety of the system.

R2.2.1.3.2 Caps, plugs or other protective covers shall be used on all ports and openings in fluid systems to prevent contamination when not in use.

2.2.1.4 OXIDIZER SYSTEM CLEANLINESS

R2.2.1.4.1 No hydrocarbons shall be employed in any oxidizer system component, or in wetted components upstream of an oxidizer system.

R2.2.1.4.2 All oxidizer system components (valves, fittings, plumbing, etc.) shall be thoroughly cleaned to an acceptable standard for oxygen service.

R2.2.1.4.3 After cleaning, components shall be thoroughly dried in such a way that contamination is not introduced.

R2.2.1.4.4 Cleaned components shall be maintained in that condition. This is typically done by capping and plugging all ports, and then further protecting the part by bagging.

R2.2.1.4.5 All ball valves shall be taken apart for cleaning and drying.

Oils and liquids can become trapped behind the ball such that surface cleaning and drying will not reach them.

R2.2.1.4.6 All caps, plugs, bags or other protective material that will be used with an oxidizer system shall themselves be cleaned for oxygen service to avoid re-contamination.

R2.2.1.4.7 All components shall be presumed contaminated unless all the following are satisfied:

- ***They were supplied in an oxygen clean condition, or were known to have been cleaned to an acceptable standard, AND***
- ***They have been constantly maintained in that condition, for example by capping, double bagging, etc.***

2.2.2 PRESSURE VESSELS

2.2.2.1 METALLIC PRESSURE VESSELS

R2.2.2.1.1 Vehicle propellant tanks shall not have a burst pressure of less than 1.5 times the maximum expected operating pressure, and other pressure vessels shall not have a burst pressure of less than 2.0 times the maximum expected operating pressure. Maximum operating pressure is the maximum pressure expected at any point during pre-launch, flight, and recovery operations.

R2.2.2.1.2 If a propellant tank is designed with a burst pressure of less than 2.0 times the maximum expected operating pressure, or if the tank is composite, hydrostatic burst testing shall be performed to demonstrate that the design and manufacturing process achieved or exceeded the design burst pressure.

R2.2.2.1.3 If a tank incorporates welds, the weld and vicinity shall be designed for a factor of safety at least 20% greater than that of the tank overall, to account for inconsistency and imperfections in the welding process. Full-weld penetration shall be ensured, and the weld shall be performed by an individual experienced with pressure vessel welding.

2.2.2.3 EXPERIMENTAL PRESSURE VESSEL TESTING

The following requirements concern design and testing of experimental pressure vessels. Pressure vessels shall be considered experimental by the following:

- Pressure vessels and rocket engines that are fabricated by an *Individual*.
- Commercial pressure vessels and rocket engines modified by an *Individual*.

- Unmodified commercial pressure vessels utilized outside their advertised specifications.

CPLC recommends completing these tests by at least 2 months prior to the launch date. While not a requirement, this is recommended to assure individuals are prepared for the launch.

R2.2.2.3.1 Individuals shall comply with all rules, regulations, and best practices imposed by the authorities at their chosen test location(s).

2.2.2.3.1 PROOF TESTING

R2.2.2.3.1.1 Prior to use, pressure vessels intended for static firing or flight shall be proof tested.

R2.2.2.3.1.2 The tank shall be designed such that the above requirement can be met with a proof pressure not less than 1.1 times the maximum expected operating pressure.

R2.2.2.3.1.3 The proof pressure shall be held for not less than twice the maximum expected system working time.

The maximum system working time is defined as the maximum uninterrupted time duration the vessel will remain pressurized during pre-launch, flight, and recovery operations, or during the longest static test in the case of a test stand tank.

R2.2.2.3.1.4 Proof testing shall always be performed with an incompressible fluid such as water and NEVER with a gas.

2.2.3 PROPELLANT AND PRESSURIZATION SYSTEMS

2.2.3.1 PRESSURIZATION

R2.2.3.1.1 Any pressure system, vessel, or component thereof with a burst pressure less than 4.0 times the maximum expected operating pressure (i.e., factor of safety of 4.0) shall never be approached by personnel while pressurized to more than 25% of its proof pressure.

R2.2.3.1.2 Any experimental tank above 25% of its proof pressure or a commercial tank operated above its rating, shall only be pressurized and de-pressurized remotely.

This is a standard requirement for "non-code" pressure vessels, i.e., those that are not designed, fabricated, and tested per the requirements of the ASME Boiler & Pressure Vessel Code or equivalent. A non-code tank should be considered an explosion hazard when it is pressurized and thus this should only be done remotely at a safe location to ensure that a tank failure will not endanger personnel or property.

R2.2.3.1.3 Any experimental tank above 25% of its proof pressure or above 120-psig, shall incorporate electronic pressure measurement and telemetry to allow tank pressures to be monitored remotely.

Because of the hazards associated with pressurized systems, it is critical to always know what the system pressure is. Simply knowing the state of the pressure system should not be considered sufficient. For example, sending a signal to open a vent valve does not guarantee that the system was vented: valves or their actuators can fail, stick, jam, etc. Use of remote pressure monitoring allows the system to be confirmed to be in a safe, depressurized state before personnel can approach. It also allows system pressures to be verified to be in their nominal ranges before proceeding with a launch or engine test.

R2.2.3.1.4 Commercial tanks used for pressurant shall incorporate electronic temperature measurement and telemetry to allow the tank temperature to be monitored remotely.

R2.2.3.1.5 Commercial tanks used for pressurant shall not be pressurized rapidly such that they exceed their maximum rated operating temperature.

Because of the hazards associated with pressurized systems, it is critical to know what the pressurant tank temperature is during loading. Rapidly pressurizing a pressurant tank from ambient to over 1000-psig will result in Joule Thompson heating that could overheat a tank and cause it to rupture. Use of remote temperature monitoring allows the pressurant tank loading to be monitored and pressurization halted when tank temperature hits the maximum operating limit. Once the tank cools down sufficiently, pressurization may resume.

2.2.3.2 OVERPRESSURE PROTECTION

R2.2.3.2.1 Pressure relief devices or features shall be incorporated on all systems having a pressure source which can exceed the maximum allowable pressure of the system, or where the malfunction or failure of any component can cause the maximum allowable pressure to be exceeded.

Relief devices are required downstream of all regulating valves and orifice restrictors unless the downstream system is designed to accept full source pressure.

R2.2.3.2.2 Relief devices shall be sized based on the worst credible failure that would cause the pressure to rise to a hazardous level.

For propellant tanks, a failed full-open or to-lock-up pressure regulator would be a common sizing case.

R2.2.3.2.3 Relief devices shall be selected to ensure the pressure does not exceed 110% of the maximum expected operating pressure of the system or does not exceed a value that would cause general yielding of the pressure vessel or system. All pressure relief devices shall be sized to provide relief at full flow capacity at the pressure specified above, or lower.

For engine test stands and ground support equipment, incorporation of redundant overpressure protection features is strongly recommended. A pressure relief valve plus a burst disk set to a slightly higher pressure would be typical examples.

R2.2.3.2.3 Only commercial burst disks shall be utilized to satisfy these requirements.

Burst disks are typically hard to fabricate by any *Individual* with a reliable burst pressure.

Note: Experimental (including modified commercial) propulsion system combustion chambers are exempted from this requirement, although they are technically pressure vessels.

2.2.3.3 FILLING, DRAINING, AND VENTING

R2.2.3.3.1 Propellant tanks shall be filled and drained from the bottom of the tank.

Filling and draining from the bottom of the tank has several advantages:

- It makes it possible to fill and drain from the same place, potentially simplifying the system.
- It makes it possible to drain all the propellants from a vehicle while only utilizing gravity.
- If the propellant is poured in from the top, propellant is prone to splashing around or spill on the ground. In the case of a cryogenic propellant, this would significantly increase the boiloff of the propellant. Also, for non cryogenic propellants it would require tipping the vehicle upside down to drain the propellant in the event of an abort.
- On flight vehicles, it keeps the fill and drain connection low down on the vehicle, making it easier to access and potentially avoiding the need to work on a ladder to make critical connections.

R2.2.3.3.2 Propellant tanks shall be vented from the top of the tank.

When liquid propellants are filled from the bottom of the tank, gases in the tank are displaced and forced out the vent at the top of the tank. When draining propellants from a tank, opening the vent at the top of the tank allows air to enter the tank and the propellants to drain out the bottom fill and drain with gravity.

R2.2.3.3.3 If a propellant has a high vapour pressure (i.e., above 120 psia) and the propellant tank is experimental, the system shall be designed to allow remote filling and draining of the propellant.

R2.2.3.3.4 If a cryogenic or high vapour pressure propellant is used, any section of plumbing that could be isolated and trap propellant shall include overpressure protection.

A cryogenic liquid trapped in an enclosed section of plumbing – for example, between two valves – can easily over pressurize and burst the plumbing as it boils and expands.

R2.2.3.3.5 Vents shall be routed to minimize the hazard they pose to personnel.

This typically means ensuring they are not at eye level and are not in a location where personnel are likely to be exposed to them.

R2.2.3.3.6 Fuel and oxidizer vents shall be kept separate to preclude the potential mixing of vented propellants. For vehicles, fuel and oxidizer vents shall be routed to opposite sides of the vehicle.

A fluid venting under pressure can pose a hazard to personnel. A strong blast of gas can dislodge an eye from its socket, rupture an eardrum, or induce hemorrhaging. A vent of gas at as little as 40-psig can project debris with enough force to penetrate an eyeball or the skin. A jet of 100-psi gas venting through a 1/8" opening can directly penetrate the skin, inflate the flesh, and even introduce bubbles to the bloodstream.

A venting oxidizer such as oxygen or nitrous oxide can saturate hair or the fabric of clothing, posing a danger of severe burns if they ignite. Flammable fluids venting into the atmosphere can pose a severe fire hazard. For all these reasons, vents should be located to minimize the hazard they pose to personnel.

Having both fuel and oxidizer vents, as would be typical on liquid bipropellant systems, makes it important to avoid propellant or vapours from one tank migrating into the other, or mixing externally. This would typically be done by ensuring the vents are kept as far apart as possible, ideally pointing in opposite directions.

2.2.3.4 FAILURE CONSIDERATIONS

2.2.3.4.1 FAILSAFE REMOTE VENTING

R2.2.3.4.1.1 Pressurized systems shall be designed to ensure that there is no credible failure case that would cause the loss of the ability to remotely depressurize the system. This requirement applies to all high-pressure sources on a vehicle: propellant tanks, pressurant tanks, etc.

A vent valve designed to fail open upon loss of power or signal would be one common example.

A hybrid or liquid vehicle with pressurized tanks is a significant hazard due to the amount of stored energy, combined with the fact that flight-weight vehicle tanks are typically not designed, fabricated, and tested with the extremely high safety factors required by the ASME Boiler & Pressure Vessel Code, US Department of Transportation, and/or Transport Canada for pressure vessels that will have personnel in proximity. As a result, it is essential for these systems to be depressurized remotely from a safe distance. Hybrid and liquid propulsion systems must implement a means for remotely controlled venting or offloading of all high-pressures (i.e., those greater than 40 psia) in the event of a launch abort. Further, this function must be fault-tolerant such that there are no credible failure cases (for example loss of power or loss of communications) that would prevent the venting of the high-pressure sources. It is strongly encouraged that they also implement remote offloading of all propellants, but this is only a hard requirement for liquid and gaseous propellants having vapor pressures greater than 40 psia (e.g., N_2O).

2.2.3.4.2 PROPELLANT MIXING

R2.2.3.4.2.1 Bipropellant systems that incorporate both a fuel and an oxidizer shall be designed such that a single malfunction of either the oxidizer or the fuel subsystems cannot result in the mixing of fuel and oxidizer.

2.2.3.4.3 LEAKAGE

R2.2.3.4.3.1 Any separable fluid fitting is prone to leakage. Propellant systems shall be designed to ensure, as far as possible, that simultaneous leaks in fuel and oxidizer plumbing do not result in the propellants leaking to the same place and mixing.

2.2.3.4.4 USE OF CHECK VALVES

Check valves are notoriously prone to leakage and sensitive to contamination. As such, a single check valve should never be relied upon in cases where leakage could lead to an extreme hazard. For example, if one leaking check valve could allow fuel to backflow into an oxidizer tank, or vice versa, the design is intrinsically hazardous. While such approaches are not uncommon on amateur rockets, it is important that the potential failure be understood.

R2.2.3.4.4.1 A single check valve shall never be used in a situation where leakage would expose personnel to danger.

2.2.4 CRYOGENIC SYSTEMS

2.2.4.1 CRYOGENIC MATERIALS CONSIDERATIONS

R2.2.4.1.1 All materials used in a cryogenic environment shall be evaluated to ensure they are safe for this application.

R2.2.4.1.2 Carbon steels shall never be used in cryogenic service due to their brittleness at low temperatures.

R2.2.4.1.3 Teflon/Polytetrafluoroethylene (PTFE), or other polymer hoses shall never be used in a cryogenic application due to the brittleness of the material at low temperatures. Flexible hoses for this application should be of an all-metal (bellows) construction only.

R2.2.4.1.4 If insulation is used on an oxidizer system, and there is the potential for an oxidizer leak or spillage onto the insulation, the insulation shall either be compatible with the oxidizer, or it shall be protected to ensure it is not exposed.

Many insulation materials are flammable or even explosive in an oxygen-enriched environment.

R2.2.4.1.5 All tanks, lines, valves, and fittings used with cryogenics should be insulated.

Uninsulated tanks, lines, valves, and fittings can cause excessive boiloff of cryogenics making propellant loading difficult and time consuming. Uninsulated tanks can also cause the cryogenics to warm up resulting in lower-density propellant and low-thrust performance of the engine.

2.2.4.2 VALVES FOR CRYOGENIC SERVICE

R2.2.4.2.1 Valves used for cryogenic service shall either be rated for such applications or tested under cryogenic conditions to confirm correct operation and ensure no unacceptable leakage.

R2.2.4.2.2 Ball valves used for cryogenic service shall include a vent hole in the ball leading to the upstream side of the valve when the valve is in the closed position.

Cryogenic service poses unique challenges for valves.

- Valve seats and stems can be prone to leakage due to thermal shrinkage.
- Distortion of valve components can occur due to temperature gradients.
- Icing and sticking of moving parts can occur.
- Elastomeric seals (e.g., O-rings) do not seal effectively at low temperatures.
- Lubricants will freeze at cryogenic temperatures, not only losing their lubricity but potentially causing moving parts to stick.

In the specific case of ball valves, conventional ball valves can explode if some of the cryogenic fluid is trapped in the ball when the valve closes and then warms up.

It should also be noted that the torque required to actuate a valve can be significantly greater under cryogenic conditions than at room temperature.

The usual material compatibility considerations for cryogenic service also apply (e.g., no carbon steel).

Special purpose cryogenic valves are available that address these challenges. These valves typically incorporate elongated valve stems to keep stem seals warm, springs to maintain seat loads, and upstream vents in valve balls to prevent overpressure.

While a purpose-built cryogenic valve is not the only possible solution, any valve that is built or modified for cryogenic service will need to address these challenges and will need to be tested under cryogenic conditions both to confirm proper sealing and to ensure proper operation. Liquid nitrogen is commonly used as the test fluid for any cryogenic valve testing.

2.3 IGNITION

2.3.1 PROPULSION SYSTEM SAFING AND ARMING: GENERAL

Arming and safing are range safety concepts that are often applied to pyrotechnics and other energetic devices, or the initiators for those devices.

Safed: Where a device is in its most safe state.

Safing: Is the act of changing from an *Armed* to a *Safed* state.

Armed: Where a device is in a state where one additional command or action can create a hazardous condition.

Arming: Is the act of changing from a *Safed* to an *Armed* state.

Section 5.0 of this document discusses this general concept in greater detail, while this section discusses the concept as applied to propulsion systems specifically.

It should be emphasized that as applied to propulsion systems, the concept is primarily used in relation to solid- propellant rocket engines. It is less meaningful when describing the state of hybrid or liquid systems, as these typically involve more complex start sequences. See section 2.3.2 for discussion of hybrid or liquid system considerations specifically.

A solid rocket engine or pyrotechnic device is considered *Armed* if only one action (e.g., an ignition signal) must occur for the propellant(s) to ignite.

The action that brings a system to the *Armed* state is usually something (e.g., a switch in series) that enables an ignition signal to ignite the propellant(s).

R2.3.1.1 The action that arms the igniter must be independent of the action that ignites it.

For example, a software-based control circuit that automatically cycles through an "arm function" and an "ignition function" does not, in fact, implement arming. In this case, the software's arm function does not prevent a single action (e.g., starting the launch software) from causing unauthorized ignition: a software glitch could conceivably cause the software to prematurely fire the igniter.

This problem may be avoided by incorporating an additional interlock switch or physical disconnection in the cable that delivers firing current to the igniter.

R2.3.1.2 All ground-started propulsion system ignition circuits or sequences shall not be "armed" until all personnel are at least 50 ft (15 m) away from the launch vehicle.

R2.3.1.3 The engine igniter shall be both physically and electrically isolated from the power source by a minimum of two independent inhibits.

R2.3.1.4 The engine igniter shall be electrically isolated by switches in both the power and return legs.

R2.3.1.5 The igniter shall be locked out to prevent any sort of ignition event when personnel are in the vicinity, and this lockout shall short and ground the igniter leads.

R2.3.1.6 If pyrotechnic or otherwise electromagnetic interference (EMI) sensitive igniters are employed, the igniter wiring shall be in a separate cable, which is twisted, shielded, double insulated, and independent of all other systems.

R2.3.1.7 Protection of igniter wiring by use of physical barriers or by physical location of components shall be employed such that short circuits to other power systems are impossible, even

assuming loose or broken wires.

2.3.2 PROPULSION SYSTEM SAFING AND ARMING: LIQUID OR HYBRIDS

Unlike solid engines, where firing the igniter leads directly to the ignition of the engine, most liquid and hybrid systems employ a more complex ignition sequence such that merely firing the igniter is insufficient to start the engine. For example, they might additionally require the opening of propellant valve(s) after firing the igniter.

The primary value of the arming and safing concept is in describing the state of a hazardous system. This is straightforward with solid rocket engine, which can be thought of as occupying one of two states prior to firing:

- *Safed*, its most inert state, with the igniter removed.
- *Armed*, with just a single action required to initiate it.

In other words, the act of *Arming* the engine brings it to a more-hazardous state, while the act of safing it maintains it or returns it to a less-hazardous state. In contrast, a liquid or hybrid propulsion system is more nuanced when describing its hazard level because it has a greater number of potential hazards, and a greater number of hazard states. For example:

- When it has no propellant and no pressurant source on board, it is completely inert – just "metal and plumbing".
- When a fuel is loaded, it has the hazards associated with that flammable fluid.
- When an oxidizer is loaded, it takes on the hazards associated with the oxidizer.
- When both a fuel and oxidizer are loaded, it takes on the additional hazard posed by the potential for the two propellants to mix.
- When a pressurant gas is loaded, there are the hazards of a high-pressure gas.
- When the propellant tanks are themselves pressurized, the hazard level increases again: there are now pressurized flight tanks, often with relatively low safety factors, filled with flammable and/or oxidizing fluids ready to be expelled at high-pressure, or for cryogens ready to BLEVE.
- When the igniter or other pyrotechnic device is installed and *Armed*, there are the hazards associated with an armed pyrotechnic device (assuming a pyrotechnic igniter is used).
- Depending on the propellant valve(s) and their actuation and control system, the valves themselves may be considered *Armed* if there exists a state where they are one action away from opening and allowing propellants to flow and potentially mix.

At the same time, the nature of liquid or hybrid systems can mean that there are more potential safeguards in place to protect against the inadvertent ignition of the engine. Unlike a solid engine, which always contains a mixed fuel and oxidizer, a hybrid or liquid system is completely inert until propellant, pressurant and pyrotechnics are loaded. Also, unlike a solid engine, merely igniting the igniter might (depending on the specific design of the engine and its control system) be insufficient to also trigger the flow of propellants to the combustion chamber.

As a result, while the concept of *Arming* may be applied to specific components of a liquid or hybrid system such as the igniter or valves, it is not a particularly meaningful concept to apply to the entire propulsion system. Instead, a liquid or hybrid system should be treated based on the actual hazards that are present at any given time, and controls put in place to prevent the inadvertent release of those hazards. Alternatively, *Arming* a liquid or hybrid system could mean enabling the capability to command propellant tank pressurization, igniter activation, and main valve open.

In general, as the hazard level increases, the number of people exposed to that hazard should decrease. The launch or static firing test area should be cleared of non-essential persons prior to commencing hazardous operations such as loading pressurants or propellants. In addition to the requirements for remote *Arming* of engine igniters, note R2.2.3.1.1, which requires that pressurization only commanded remotely, and

R2.2.3.3.3, requiring that high vapor pressure propellants such as nitrous oxide be filled and drained remotely.

If a pyrotechnic igniter is used, the R2.3.1.3 requirement for independent inhibits against premature firing of the igniter applies as well due to the hazards posed by a pyrotechnic igniter firing prematurely.

It should be noted that a liquid or hybrid engine might employ a non-pyrotechnic ignition system. A spark torch igniter would be one example, wherein a spark plug ignites a small flow of liquid or gaseous propellants to the igniter, producing the igniter flame. In such a design, a sequence of several events is required to start the igniter itself: activating a spark plug, then opening valves to admit propellants to the igniter, for example.

If the igniter design is such that the action which initiates the spark plug is independent of the action that admits fuel to the igniter, this could meet the requirement for an inhibit in the igniter.

2.3.3 PROPELLANT VALVE INTERLOCK

In liquid rockets, an extremely hazardous condition can occur if the fuel and oxidizer valves are opened but the igniter has failed to fire, due to a misfire or other fault. The resulting mixing of large quantities of fuel and oxidizer constitutes an extreme explosion hazard.

While hybrid rockets have their propellants in different physical states, which can prevent propellant mixing to the same degree as for a bipropellant liquid system, it should be emphasized that hybrids are not necessarily immune to a similar hazard. Certain fuel grains can absorb oxidizer, creating an explosion hazard. As a result, the following requirement applies:

R2.3.3.1 The system shall incorporate features that prevent the main propellant valve(s) from opening until confirmation of nominal igniter operation has been received.

This could include:

- A "human interlock": requiring the operator to command the opening of the propellant valve(s) independently of firing the igniter, such that they can verify that the igniter has fired before proceeding to open the valves. Such verification might be visual (e.g., watching for smoke), or it could involve another means of verification (e.g., burn wire, thermocouple, pressure measurement, etc.).
- Use of an automated ignition sequence that incorporates a means of detecting nominal igniter operation and inhibits the opening of the propellant valve(s) until igniter operation has been detected. Such systems shall be biased to avoid a "false positive" and shall be tested to ensure reliable operation.

R2.3.3.2 Systems that employ a fully automated open loop start sequence that automatically opens the propellant valve(s) after igniting the igniter, without any confirmation that the igniter is operating nominally, are deemed to be a hazard, and shall not be used.

2.4 PROPULSION SYSTEM CONTROL

R2.4.1 Propellant main valves shall be actuated opened and closed remotely.

R2.4.2 Tank vent valves shall be actuated remotely.

R2.4.3 If remote controlled vent valves are controlled by a computer-based system, they shall be operable independently of the computer, in case of a software or control system failure.

R2.4.4 Vehicles and static test stands shall incorporate a "lock-out / tag-out" approach that ensures it is physically impossible for the propellant tanks to be pressurized, main propellant valves to be opened, or otherwise brought to a hazardous state while someone is present at the launch pad or test stand.

One example of such an approach would be to incorporate key switches at both the launch pad or test stand and at "launch control", and have those switches use the same single key. Key switches come with many different options, one of which is the position in which the key can be removed. Switches may be specified to allow the key to be removed in the "on" position or the "off" position, and this is a useful safety feature here. The switch at the launch pad should prevent igniter ignition, main pressurant valve open, or main propellant valves open when the key is inserted and turned to the “safe” position, and the key should not be removable when in this position.

The switch at launch control should similarly prevent igniter ignition, main pressurant valve open, or main propellant valves open from being sent when the key is turned to the “safe” position and removed. The key should not be removable when turned to the “arm” position.

This ensures that the key switch at launch control cannot be in the “arm” position and the key cannot be present when the pad or test stand switch is in the “safed” position, and vice versa.

2.4.1 LAUNCH OR STATIC FIRING ABORT

R2.4.1.1 The abort sequence shall autonomously perform functions needed to shut down and depressurize the oxidizer and fuel feed systems in a manner that prevents propellant fire or explosion.

For example, an abort should avoid dumping fuel and oxidizer through the engine, as this would constitute a severe hazard.

R2.4.1.2 Following an abort sequence, certified ground personnel shall perform approved operational procedures to safely offload pressurization gases and propellants and return the launch vehicle or static firing test set up to a SAFE configuration.

2.4.2 OPTIONAL PROPULSION SYSTEM SHUTDOWN

In most cases, it is typical to allow the vehicle on a static test stand to burn propellant to depletion, without any commanded propulsion system shutdown. Burning to exhaustion ensures that the propellant tank(s) will be empty and any pressurant gases will have been vented through the engine by the end of the mission or static firing thereby avoiding the hazards of propellants or high-pressure sources on the vehicle or static test stand. If for some reason the mission does not allow for burning to propellant depletion, and instead requires a controlled engine shutdown, the shutdown must nevertheless ensure that propellant and pressurant tanks are empty and de-pressurized by the time the vehicle lands or static firing is finished. The need for recovery personnel to approach a vehicle (with possible structural damage) or static test stand which could have propellants and high-pressures on board must be avoided.

R2.4.2.2 The shutdown sequence shall shut off propellant feed systems in a manner that prevents propulsion system instability, propellant fire, or explosion.

R2.4.2.3 The vehicle shall initiate a nominal propellant and pressurant offload sequence.

R2.4.2.4 The offload sequence shall control opening and closing feed system valves to expel remaining oxidants, fuel, and pressurants to the atmosphere in a manner that prevents propellant fire or explosion.

Simultaneous venting of fuel and oxidizer through the engine that could allow mixing of propellants and formation of an explosive mixture is not considered acceptable.

R2.4.2.5 At the completion of offload, feed system valves shall be open.

2.5 PROPULSION SYSTEM TESTING

The following requirements concern verification testing experimental propulsion systems. *CPLC* **STRONGLY** recommends *Individuals* to complete these tests at least 2 months before the launch.

R2.5.1 Individuals shall comply with all rules, regulations, and best practices imposed by the authorities at their chosen test location(s).

2.5.1 LEAK TESTING

Leak testing is important to perform on pressurized fluid systems prior to a static test firing or launch, especially where leakage could involve release of propellants. It should be remembered that fluid fittings and other separable fluid joints are prone to leaking. Temperature changes, particularly in cryogenic systems, can lead fittings to start leaking. The vibrations and shocks associated with transportation and handling can also lead to fittings loosening and leaking. As a result, in addition to performing leak testing at the component or subsystem level, it is good practice to perform leak testing on the final system after setup at the static test firing or launch site. It should never be assumed that a system that was leak free in the shop will still be leak free in the field.

R2.5.2.1 Leak testing shall be performed on fluid systems prior to operation, and any time a change to the system that could impact leak-tightness has occurred.

Helium is the ideal fluid for such testing due to the ease with which it leaks, but other inert gases such as nitrogen may be used.

R2.5.2.2 Air from a compressor shall not be used for leak testing an oxidizer system, as it is highly prone to contaminating the system with moisture or oil.

R2.5.2.3 Leak testing shall be performed at pressures well below operating pressure typically, less than 120-psig, and not more than 25% of normal operating pressure.

R2.5.2.4 Leaks shall be tested with a water soap solution, a leak detection fluid such as Swagelok "Snoop", or a suitable leak detector.

R2.5.2.5 Any leak detecting fluid used on an oxidizer system shall be compatible with the oxidizer to avoid a fire or explosion hazard in case the fluid leaks into the system, or the oxidizer leaks out.

2.5.2 LIQUID PROPELLANT TANKING TESTS

R2.5.3.1 A hybrid or bipropellant rocket or rocket engine which employs liquid propellant(s) shall successfully complete propellant loading and unloading testing in the "launch or static-firing configuration" without any anomalies that would prevent test completion or compromise safety. This test may be conducted using either actual propellant(s) or suitable proxy fluids.

R2.5.3.2 If a fluid other than the propellant is used, the system shall be disassembled, cleaned, and dried as necessary to prevent contamination of the propellant.

Residual water, for example, will freeze in a cryogenic system and cause blockages and failure of valves and fluid controls. It can do the same in systems involving gases or high vapour pressure liquids that undergo expansion.

R2.5.3.3 Under no circumstances shall a hydrocarbon-containing test fluid be used in an oxidizer system.

This test may be performed as part of Sections 2.5.4 or 2.5.5.

2.5.3 WATERFLOW TESTING

R2.5.4.1 During development of a propulsion system employing hybrid or liquid propellants, waterflow testing shall be performed prior to progressing to a hot-fire test.

The purposes of waterflow testing are:

- To verify the correct operation of the test stand, instrumentation, and fluid systems.
- Ensure that it will provide leak-free operations.
- Ensure pressurants are delivered at the correct pressure(s) and flow rate(s) to the propellant tanks.
- Ensure propellants are delivered at the correct pressure(s) and flow rate(s) to the engine.

Because no combustion occurs in this test, the engine and injector shall be replaced with cavitating orifices. Calculations shall be performed to determine the volumetric flow rates of each propellant during nominal combustion. Each cavitating orifice shall be designed for an equivalent water volume flow rate at the combined injector pressure drop and combustion pressure for that propellant.

R2.5.4.2 When water is used, the system shall be disassembled, cleaned, and dried to prevent

contamination of the propellant.

Residual water will freeze in a cryogenic system and cause blockages and failure of valves and fluid controls.

R2.5.4.4 The waterflow test shall be treated as a hazardous test due to propellant tanks with low safety factor being pressurized at full operating pressures.

This would pose an extreme fire and explosion hazard, and it is far better to eliminate major sources of contamination than to attempt to thoroughly remove them after the fact.

2.5.4 DRESS REHEARSAL

R2.5.4.1 During development of an experimental propulsion system employing hybrid or liquid propellants, a dress rehearsal shall be performed prior to progressing to a hot-fire test.

The purpose of a dress rehearsal is:

> To serve as a complete "dress rehearsal" of the test, allowing the setup and test procedures to be worked through and shortcomings to be discovered and corrected.

A dress rehearsal may be conducted with actual propellant(s) or suitable proxy fluids. It is strongly recommended that inert fluids be used in place of reactive propellants due to the hazards that propellants can pose (particularly oxidizers). Nitrous oxide can exothermically decompose.

R2.5.4.2 If a dress rehearsal test will involve release of propellants or test fluids to the environment, those fluids shall pose no hazard of environmental contamination.

For example, water, liquid nitrogen, CO2, or alcohols are generally safe and environmentally benign. Kerosene, by contrast, is a persistent pollutant that will contaminate soil if spilled.

Common proxy fluids include liquid nitrogen (for cryogenic systems), liquid CO2 (for N2O systems), water (for any system), or alcohol (for fuel systems).

R2.5.4.3 If a fluid other than the propellant is used, the system shall be disassembled, cleaned, and dried as necessary to prevent contamination of the propellant.

Residual water, for example, will freeze in a cryogenic system and cause blockages and failure of valves and fluid controls. It can do the same in systems involving gases or high vapour pressure liquids that undergo expansion.

R2.5.4.4 Under no circumstances shall a hydrocarbon-containing fluid be used in an oxidizer system.

This would pose an extreme fire and explosion hazard, and it is far better to eliminate major sources of contamination than to attempt to thoroughly remove them after the fact.

2.5.5 CRYOGENIC TESTING

R2.5.5.1 Load the cryogenic portions of the propulsion system with liquid nitrogen and perform a countdown and see that all valves actuate properly and that the valve stems don't leak.

2.5.6 ENGINE STATIC-FIRING TEST

A static-firing test of the rocket engine is a critical part of any rocket propulsion development and is also one of the most hazardous steps in the process of developing a rocket. It is during the testing phase that the propulsion system is at its least understood, so thorough testing is important to safely bring major problems to light and allow them to be addressed before attempting a launch.

Flight systems typically strive to minimize weight, at the expense of lower margins of safety and/or more involved design, analysis, and testing. An engine static-firing test stand, by contrast, can and should be designed with large margins of safety on fluid systems and structural members, and robust, redundant safety features. It is on the test stand that an engine's flaws are first revealed (often via a RUD - "Rapid, Unscheduled Disassembly"), so the test stand and its systems should be designed to withstand the inevitable failures that it will be exposed to. Large safety factors, and compliance with the ASME Boiler & Pressure Vessel Code for tankage are strongly recommended.

Similarly, while a flight vehicle has many space constraints, an engine static-firing test stand typically does not. Fluid systems can be laid out to maximize accessibility and safety to a greater degree than they can on a vehicle, and it is strongly recommended that these opportunities be taken. At the same time, plumbing systems can have a large impact on engine performance. The lengths and routing of lines and the locations of main propellant valves should reflect the flight configuration as much as possible. Think carefully about how the static test stand might differ from the flight conditions, what the consequences of those differences might be, and how they can be minimized while still maintaining the desired robustness and ease of use of the system.

R2.5.6.1 An engine shall successfully complete an instrumented (chamber pressure and/or thrust measurement at minimum) full-thrust for a full-burn duration static-firing test prior to the launch.

In the case of solid rocket engine, this test need not be performed with the same engine casing and/or nozzle components intended for use for the launch (e.g., *Individuals* must verify their casing design but, are not forced to design reloadable/reusable motor cases).

A successful engine static-firing test shall be one that meets the full operational burn duration and demonstrates thrust and specific impulse within the *Individual's* designed-for limits.

R2.5.6.2 The engine static-firing test stand shall be firmly anchored to the ground in such a way that it cannot move, fall over, or slide under at least 2x the maximum load to which it will be exposed.

R2.5.6.3 All participants at the engine static firing whether associated with the individual static firing or as observers shall be either a safe distance away from the static-firing test stand or inside a bunker or blockhouse.

2.5.7 VEHICLE STATIC-FIRING TEST

Flight systems typically strive to minimize weight, at the expense of lower margins of safety and a more involved design, analysis, and testing. A vehicle static-firing test stand, by contrast, can and should be designed with large margins of safety on structural members. It is on the static-firing test stand that a vehicle's flaws are first revealed by having low thrust.

R2.5.7.1 If a vehicle static-firing test stand is used with liquid propellants, it shall employ materials that are tolerant of propellant spills and minimize the chance of a fire occurring or spreading.

R2.5.7.2 For a vehicle static firing, a flame deflector shall be employed using materials that are tolerant of propellant spills and can tolerate impingement of full-thrust with a full-burn duration static-firing.

R2.5.7.3 The vehicle static-firing test stand structural members shall attach to the vehicle thrust structure.

R2.5.7.4 Vehicles shall successfully complete an instrumented (tank pressures and thrust measurement at a minimum) full-thrust with a full-burn duration static-firing test prior to the launch.

A successful vehicle static-firing test shall be one that meets the full operational burn duration and demonstrates thrust and specific impulse within the *Individual's* designed-for limits.

R2.5.7.5 The vehicle static-firing test stand structural members shall be designed to at least 2x the maximum load to which it will be exposed.

R2.5.7.6 The vehicle static-firing test stand shall be firmly anchored to the ground in such a way that it cannot move, fall over, or slide under at least 2x the maximum load to which it will be exposed.

R2.5.7.8 All participants at the vehicle static firing whether associated with the individual in static firing or as observers shall be either a safe distance away from the static-firing test stand or inside a bunker or blockhouse .

R2.5.7.9 A vehicle full-range throttle test shall be performed.

R2.5.7.10 A vehicle thrust vector control test shall be performed.

R2.5.7.11 A hanging non propulsive test shall be performed where the vehicle is pushed, turned, and tilted; where the thrust vector control is verified to move in the proper direction.

2.5.8 VEHICLE DROP LANDING AND TETHERED HOVER TESTS

R2.5.8.1 During a drop landing or hover test, a tether shall be used that has a break strength of at least twice the maximum thrust of the vehicle.

R2.5.8.2 Perform center-of-gravity analysis that CG is always above the center-of-control.

R2.5.8.2 Flight control must account for changes in mass and CG and throttle thrust.

R2.5.8.3 During a drop landing and tether hover tests, a tether shall be used that has at least a capability to stretch 10%.

R2.5.8.4 During a drop landing and tether hover test, a tether shall be suspended above the vehicle from a solid structure that cannot move or fall over during testing.

R2.5.8.5 Both kill commands shall be functionally tested before propellant loading.

2.5.9 VEHICLE HOP

R2.5.9.1 Both kill commands shall be functionally tested before propellant loading.

R2.5.9.2 Before performing an untethered hop, control directions must be verified (TVC/veins/etc move in correct direction), static fires must confirm throttle control, and successful tether hover tests must be performed.

3.0 AVIONICS AND TELEMETRY

Many of the electrical systems onboard a rocket constitutes “SAFETY CRITICAL WIRING”. For the purposes of this document, safety critical wiring is defined as electrical wiring associated with engine ignition, engine shutdown, propellant venting, pressurant venting, thrust vector control, kill commands, and flight control. In addition to the following requirement statements, all safety critical wiring should follow the safety critical wiring guidelines described in Appendix B of this document.

R6.1 Electrical assemblies and devices shall be compatible with the external and self-induced electromagnetic environments that will exist during flight or testing.

R6.2 All onboard electrical systems, including avionics, global positioning system (GPS), and telemetry; shall be tested as an integrated system to ensure that no components cause any apparent interference with any others.

R6.4 Electrical systems shall be designed to limit or prevent a short in one system from disabling other flight- or safety-critical systems.

3.1 WIRING, HARNESS, AND CABLE MANAGEMENT

R6.1.1 All safety critical wiring shall implement a cable management solution (e.g., wire ties,

wiring, harnesses, cable raceways) which will prevent tangling and excessive free movement of significant wiring/cable lengths due to expected launch and other loads.

R6.1.2 ***All wiring, and cables shall include enough slack at all connections/terminals to prevent unintentional de-mating due to expected launch loads transferred into wiring/cables at physical interfaces.***

R6.1.3 ***All safety critical wiring/cable connections shall be sufficiently secured to prevent de-mating due to expected launch loads. This will be evaluated by inspection and by a "tug test", in which the connection is gently but firmly "tugged" by hand to verify it is unlikely to break free in flight.***

It is strongly recommended that all separable cable connectors incorporate a positive locking feature and strain relief backshells.

3.2 TELEMETRY

There are two main options for telemetry and GPS tracker frequencies.

- 70 cm (440 MHz) / automatic packet reporting systems (APRS) are the most common, operating on a portion of the UHF spectrum internationally allocated to amateur radio and amateur satellite use and requiring an Amateur Radion Amateur Radio license.
- 900 MHz (33 cm) units are somewhat less common but have the advantage of not requiring an Amateur Radio license. They typically have a shorter range than those transmitting on the 70 cm band.

R3.2.1 ***Transmitters and receivers used onboard the vehicle and those used for ground operations shall have the necessary characteristics and protections to perform required communication functions during all phases and operating environments of the mission.***

R3.2.2 ***Antennas shall be in a part of the vehicle that does not significantly attenuate the signal. Notably, carbon fiber and metal will block radio frequency (RF) signals. Fiberglass is preferred for RF transparency.***

3.3 KILL COMMAND

R3.3.1 The vehicle shall contain two kill capabilities.

R3.3.2 Each kill capability shall be independent of the vehicle subsystems and each other.

R3.3.3 Each kill capability shall have its own antennas, receivers, and batteries.

R3.3.4 Each kill capability shall be able to receive kill commands from any orientation of the vehicle.

R3.3.5 One of the kill capabilities shall not utilize software.

R3.3.6 One of the kill capabilities shall include venting propellant tank pressures down to atmospheric pressure.

R3.3.7 One kill capability shall include an engine shutdown method.

Acceptable engine shutdown methods include:

a. A separate shutdown command to the flight controller to shutdown the engine.
b. One or more valves that shutdown propellant flow to the engine.
c. One or more valves that dump propellants overboard.
d. One or more valves that vent pressurants overboard.

R3.3.8 Pressurant and propellant dump ports shall be non-propulsive.

R3.3.9 A demonstration test shall be performed before flight testing, showing that each kill capability can receive the kill commands in all five vehicle orientations (bottom, front, back, right side, and left side).

R3.3.9 Each kill capability shall be tested preflight before propellant loading.

4.0 AIRFRAME STRUCTURES

The following requirements address some key points applicable to almost all amateur high-power rockets but are not exhaustive of the conditions affecting each unique design.

Individuals are ultimately responsible for thoroughly understanding, analyzing, and mitigating their design's unique load set and other structural considerations.

4.1 ADEQUATE VENTING

R7.1.1 Vehicles shall be adequately vented to prevent unintended internal pressures developed during flight from causing either damage to the airframe or any other unplanned configuration changes.

Typically, a 1/8 to 3/16-inch (3.18 to 4.76 mm) hole is drilled in the booster section just behind the nosecone or payload shoulder area, and through the hull or bulkhead of any similarly isolated compartment/bay.

4.2 OVERALL STRUCTURAL INTEGRITY

R7.2.1 Vehicles shall be constructed to withstand the operating stresses and retain structural integrity under the conditions encountered during handling as well as during the most severe possible conditions experienced during flight.

4.3 MATERIAL SELECTION

R7.3.1 PVC (and similar low-temperature polymers) and Public Missiles Ltd. (PML) Quantum Tube shall not be used in any structural (i.e., load bearing) capacity, most notably as vehicle airframes.

R7.3.2 Carbon steel shall never be used in cryogenic or sub-ambient applications.

R7.3.3 Structural metallic airframe components manufactured using additive manufacturing processes shall be structurally analyzed and tested for compression, tension and bending.

Teams are always encouraged to innovate with new manufacturing technologies, but due to the variability in the source material and the anisotropic nature of additively produced parts, careful analysis and testing is important. Note also that additive components exhibit a significant reduction in fatigue performance compared to wrought materials unless certain postprocessing is employed.

4.4 IDENTIFYING MARKINGS

R7.4.1 The Individual's name and address shall be clearly identified on the vehicle airframe, nosecone, and other locations where possible.

APPENDIX A: ACRONYMS, ABBREVIATIONS, AND TERMS

A.1 ACRONYMS & ABBREVIATIONS

ACS	Attitude Control System
AGL	Above Ground Level
AIAA	American Institute of Aeronautics and Astronautics
AKA	Also Known As
APCP	Ammonium Perchlorate Composite Propellant
APRS	Automatic Packet Reporting System
ASME	The American Society of Mechanical Engineers
CAR	Canadian Association of Rocketry
CAS	Control Actuator System
CFR	Code of Federal Regulations
CG	Center of Gravity
CONOPS	Concept of Operations
COPV	Composite Overwrapped Pressure Vessel
Commercial	Commercial Off-the-Shelf
CP	Center of Pressure
CPLC	Collegiate Propulsive Lander Challenge
CSFM	California State Fire Marshal
DOT	Department of Transportation
DTEG	Design, Test & Evaluation Guide
ERD	Natural Resources Canada Explosives Regulatory Division
ESRA	Experimental Sounding Rocket Association
EMI	Electromagnetic Interference
FAA	Federal Aviation Administration
FOD	Foreign Object Debris
GPS	Global Positioning System
GSE	Ground Support Equipment
Individual	Persons or students individually or organized in groups or teams
IREC	Intercollegiate Rocket Engineering Competition
JLCR	Jolly Logic Chute Release
LOX	Liquid Oxygen
NAR	National Association of Rocketry
NFPA	National Fire Protection Association
NTO	Dinitrogen Tetroxide
PML	Public Missiles Ltd.
PPE	Personal Protective Equipment
RF	Radio Frequency
RFNA	Red Fuming Nitric Acid
SCAPE	Self Contained Atmospheric Protective Ensemble
Experimental	Individual built, modified commercial, or commercial used outside of its parameters.
TRA	Tripoli Rocketry Association

A.2 TERMS

Amateur Rocket	14 CFR, Part 1, 1.1 defines an amateur rocket as an unmanned rocket that is "propelled by a motor, or motors having a combined total impulse of 889,600 Newton-seconds (200,000 pound-seconds) or less, and cannot reach an altitude greater than 150 kilometers (93.2 statute miles) above the earth's surface".
Body Caliber	A unit of measure equivalent to the diameter of the launch vehicle airframe in question.
Excessive Damage	Excessive damage is defined as any damage to the point that, if the systems intended consumables were replenished, it could not be launched again safely. Intended Consumables refers to those items which are - within reason - expected to be serviced/replaced following a nominal mission (e.g., propellants, pressurizing gasses, energetic devices), and may be extended to include replacement of damaged fins specifically designed for easy, rapid replacement.
FAA Class 2 Amateur Rocket	14 CFR, Part 101, Subpart C, 101.22 defines a Class 2 Amateur Rocket (aka High-Power Rocket) as "an amateur rocket other than a model rocket that is propelled by a motor or motors having a combined total impulse of 40,960 Newton-seconds (9,208 pound-seconds) or less."
FAA Class 3 Amateur Rocket	14 CFR, Part 101, Subpart C, 101.22 defines a Class 3 Amateur Rocket as "an amateur rocket that is propelled by a motor or motors having a combined total impulse of greater than 40,960 Newton-seconds (9,208 pound-seconds)."
Non-toxic Propellants	For the purposes of Launch Canada, the event organizers consider ammonium perchlorate composite propellant (APCP), potassium nitrate and sugar (aka "rocket candy"), nitrous oxide, liquid oxygen (LOX), hydrogen peroxide, kerosene, propane and similar, as non-toxic propellants. Toxic propellants are defined as requiring breathing apparatus, special storage and transport infrastructure, extensive personal protective equipment, etc.

APPENDIX B: SAFETY CRITICAL WIRING GUIDELINES

Introduction

With the aim of supporting recovery reliability and overall safety, this white paper sets out guidelines for all safety critical wiring. The wiring techniques described here are optimized for inspection and ease of field repair. All non-critical wiring is outside the scope of this white paper.

Wiring Guidelines

1. All wire should be stranded, insulated, 22 AWG or larger. Strands should be copper, plated with either silver or tin (entire wire, not just the ends).
    1.1. When an off-the-shelf component includes flying leads, those leads may be used unmodified. For example, an E-match may contain solid wire, a battery connector may integrate 26 AWG wire, etc.
    1.2. Stranded wire of sizes smaller than 22 AWG may be used only when needed by an off-the-shelf component. For example, if the terminal block on an altimeter is sized to accept 24 AWG wires then that is the size of wire that should be used for that portion of the circuit.
    1.3. Wire strands should never be removed to allow a wire to fit into a smaller hole or terminal. Use smaller wire for this purpose.
2. Wire should be stripped only with a wire stripping tool of the correct gauge. Any severed strands should be cause for rejection.
    2.1. The best wire stripping is achieved with thermal strippers and Teflon/Tefzel wire, however these are not necessary. PVC-insulated wire is acceptable and may be stripped with thermal strippers (preferred; Digikey part no. PTS-10-ND, $80, for example) or good quality mechanical strippers (Digikey part no. K503-ND, $34, for example, also available on Amazon for $27.88. Other similar strippers on Amazon are "Seatek SA200SK" $22.25, "Paladin Tools 1116" $18.20, "Fluke Networks 11230002" $22.99, "Wiha 44220" $26.57, though we have not tried these).
    2.2. Personnel using a new stripper for the first time should practice on a piece of scrap wire the same gauge and type as will be used. Strip a short length and then strip more insulation from the same wire. If you can now see scratches or nicks in the wire strands from the first strip, something is wrong with either tool or technique.
    2.3. Pocket knives and teeth are right out!
3. Each end of a wire should be terminated in one of the following approved methods, with exceptions in Paragraphs 4 and 5 below:
    3.1. Crimped into a crimp terminal (preferred). This includes crimp terminals on multiconductor connectors such as 9-pin D-sub connectors (see table below).
    3.2. Screwed into a binding screw terminal (acceptable).
4. Wires should be terminated into a terminal block, only if a piece of off-the-shelf equipment (i.e., an altimeter) has built-in terminal blocks, thus allowing no other choice. Two-piece terminal blocks must be positively secured together – friction fit is insufficient.
5. Wires should be terminated by soldering only if a piece of off-the-shelf equipment (e.g., an arming key switch) has built-in solder terminals and so there is no other choice.
    5.1. There is nothing wrong with solder, of course. The issue is that the reliability of a solder joint cannot be established by visual inspection alone. There are a number of process parameters (temperature profile, solder alloy, flux, gold removal, etc.) that must be well controlled to give reliable results, and these cannot be inspected post-fact.
6. All crimp operations should be performed with the correct tooling, using crimp terminals sized for the appropriate wire gauge. Where multiple wires are crimped into a single terminal, calculate the effective gauge (for example, two 22 AWG are effectively 19 AWG).
    6.1. Crimp tooling should not be improvised from pliers, vices, or other incorrect tools. Crimp features of

multitools (Leatherman, Gerber, etc.) should not be used.

6.2. Crimp tooling can be expensive (the cheapest one from Digikey is $262!). You may want to borrow it from a sponsor. The following crimpers are available on Amazon, though we have not tried them ourselves: “Ratcheting Crimper from CML Supply” $25.33, “S&G Tool Aid 18920” $75.00, “Astro Pneumatic 9477” $73.99, “Ancor 701030” $63.59. Harbor Freight 97420 is only $9.99—we may buy one just to try it out.

7. Terminals with insulated plastic sleeves (usually colour-coded to indicate barrel size) should not be crimped.
    7.1. If a terminal is supplied with an insulated plastic sleeve, it should be removed prior to use. It maybe necessary to adjust the crimp tooling to get a tighter squeeze.
    7.2. The crimp quality of insulated terminals is difficult to inspect. There is normally no need for insulation when terminals are mounted properly in barrier blocks. If insulation is needed, add clear heat-shrink tubing.
8. When a bare wire is held down by a binding screw terminal the wire should make a 180-degree hook, and strands must be visible exiting the screw head. Only one wire should be permitted per screw. The wire bend should be clockwise, so that it will tighten as the screw is torqued.
9. When ring or spade terminals are held down by binding screw terminals, a maximum of two terminals are allowed per screw.
10. A maximum of three wires should be crimped into a single terminal barrel. Butt-splice terminals are considered to have separate barrels in each end.
11. If two or more wires must be joined, one of the following approved methods should be used:
    Note: for the purposes of this white paper, “barrier blocks” have screw terminals between insulating barriers, and often have metal jumpers between screws to allow electrical connections of screws across the block. The screws are usually larger than those in terminal blocks and are easily visible for inspection. The screws are designed to allow the connection of bare wires (turned in a clockwise “J” shape) or ring terminals.
    11.1. Crimp a ring terminal onto each wire, and then screw them into a barrier block. Add approved barrier block jumper pieces if many wires must be joined.
    11.2. Screw bare wires under binding head screws in a barrier block. Add approved barrier block jumper pieces if many wires must be joined.
    11.3. Crimp the wires into an un-insulated butt-splice terminal, and then insulate with clear heat-shrink tubing.
    11.4. Any wire-twisting splice method (including wire nuts) is explicitly forbidden. Forget everything you know about household wiring. Houses do not see launch vibration!
12. All insulating tubing (usually heat-shrink) should be transparent.
    12.1. This allows inspection of the underlying hardware. It is a good habit to get into.
13. No tape, glue or RTV should be used to insulate or bundle any element of the wire harness.
    13.1. If you have followed these guidelines properly there should be no exposed metal in need of insulation.
    13.2. Tape (especially PVC electrical tape) is messy and can not be inspected.
14. The following rules apply to connectors:
    14.1. They should use crimp contacts, as soldering has been forbidden.
    14.2. They should use a positive locking mechanism to keep the two halves mated under vibration and tension. Friction fit alone is not acceptable.
    14.3. Plastic connector latches should not be used (such as found on automotive applications), but circular connectors with plastic coupling nuts are acceptable.
    14.4. They should use backshells with cable clamps.
15. Individual wires should be bundled together to make a harness (factory multi-conductor wiring in a common outer jacket is also acceptable). The safety critical harness should be kept separate from the payload harness (if any). Bundling should be accomplished by:
    15.1. A light twist (for mechanical reasons only, no EMC mitigation is intended).
    15.2. Short (1 cm) lengths of clear heat-shrink tubing or zip-ties every 5 cm
    15.3. Wire mesh sleeving provided it allows for inspection of the wiring inside.

16. The harness should be supported by plastic P-clamps. It should not be permitted to touch any sharp edge or screw thread.
17. All items that are connected by the harness (barrier blocks, sensors, batteries, actuators, switches, etc.) should be rigidly fixed to the vehicle structure so that they cannot move. Rigid fixing implies attachment with threaded fasteners or a solid glue bond. Cable ties and/or tape are not acceptable examples of rigid fixing.
18. No wire should be tight. All wire must have some slack, demonstrated by a curve at its termination.
19. Batteries should be connected appropriately:
    - 19.1. 9V transistor batteries should be secured in clips and connected using proper snap terminals.
    - 19.2. Gel-cell batteries should be secured with clamps and connected using "fast on" crimp terminals.
    - 19.3. Cylindrical batteries (AAA, AA, C, D, etc.) should be mounted into commercial holders. The holders should be rigidly secured to the structure, and the batteries should then be strapped into the holders.

Circuit Board Guidelines

All heavy components should be staked. All IC sockets and press-fit contacts should be positively restrained so that they cannot de-mate under vibration. Provided they are done right, wirewrap, through-hole solder, and surface-mount solder are all acceptable fabrication methods. Solderless breadboard (aka plug-in breadboard) should not be used. Any commercial board for the high-power rocketry market should be considered to be of sufficient quality, provided it is in an undamaged factory state.

Recommended Parts

Here are some recommended components that can be bought from Digikey, Mouser, and Amazon that will help to satisfy the wiring guidelines. These are recommendations only, and you are free to choose other parts and buy from other suppliers. Look up the catalog pages associated with each Digikey or Mouser number to find similar parts of different sizes.

Part	Number	Notes
Wire	Digikey A5855W-100-ND	This is good 22-gauge, tinned, Teflon insulated wire. Cold-flow is a long-term consideration, but shouldn't be a problem for a short lifetime vehicle.
Wire	Digikey C2016L-100-ND	22-gauge tinned PVC-insulated wire. Note that the "L" designates the insulation color (other colors are B,R,A,Y,N,W)
Wire	Digikey W120-100-ND Digikey W121-100-ND	2-conductor, 22-gauge 3-conductor, 22-gauge
Wire	Amazon "Tinned marine grade wire"	18-gauge, available in 35-ft or 100-ft rolls
Ring terminals, uninsulated	Digikey A27021-ND (#6 hole)	The Solistrand series is a high quality terminal. Various crimp tools are available. You get what you pay for – the expensive ones are very nice, but the basic ones will do in a pinch.
Butt-splice terminal	Digikey A09012-ND	Another Solistrand series terminal
"Faston" terminal	Digikey 298-10011-ND (check size)	These terminals are useful for connecting switches, gel cell batteries, and many automotive devices

9V battery holder, with solder terminals	Digikey 708-1409-ND	Screw this holder to your chassis, and then cable tie the battery in. Note: snap-on 9V battery connectors such as Digikey BS12I-ND are not acceptable.
4 AA battery holder	Digikey 708-1399-ND	This is a nice enclosed battery box for 4 AA cells
P-clamp	Digikey 7624K-ND (check size)	This particular unit is for a 0.25" dia harness. Select the correct size.
Heat-shrink tubing	Digikey A014C-4-ND (check size) Mouser 650-RNF100 (check size)	Material is clear polyolefin with a low shrink temperature. Shrink with a hot-air gun or oven.
Barrier block (double row)	Digikey CBB206-ND Mouser 538-2140 or 4140 (0.375" pitch), 538-2141 or 4141 (0.438" pitch)	Available in a range of lengths. Can accept ring or spade terminals (preferred), or bare wire (acceptable).
Barrier block jumper	Digikey CBB314-ND	Connect adjacent strips, when many wires need to be connected together
D-sub connectors (9 contact)	Digikey A31886-ND (male shell) Digikey A34104-ND (female shell) Digikey A1679-ND (male pins) Digikey A1680-ND (female pins)	The connectors and contacts are cheap, but the crimp tools are expensive.
D-sub fixing hardware	Digikey MDVS22-ND (screw) Digikey MDVS44-ND (socket)	These kits convert the D-sub friction fit into a proper positive lock.
MIL-C-38999 connectors	Digikey 956-1017-ND (13 pin panel mount receptacle with pins) Digikey 956-1020-ND (13 pin plug with sockets)	These connectors approach the style and quality used on orbital launch vehicles. Extremely robust, but very expensive!

About the Author

The original author, Doug Sinclair, is a Level 3 high-power rocketry flier and certified Institute of Printed Circuits (IPC) trainer for J-STD-001ES. He is the principal of Sinclair Interplanetary, which develops star trackers, momentum wheels, and other spacecraft hardware.

APPENDIX C: IGNITION CONTROL SYSTEM DESIGN GUIDELINES

Introduction

The following white paper is written to illustrate safe fire control system design best practices and philosophy to *Individuals* static firing or launching. When it comes to ignition (static firing or launch) systems for amateur rockets, safety is paramount. This is a concept that everyone agrees with, but it is apparent that few deeply appreciate what constitutes a "safe" firing system. Whether they have ever seen it codified or not, most rocketeers understand the basics:

- The control console should be designed such that two deliberate actions are required to ignite the system.
- The system should include a power interrupt such that ignition current cannot be sent to the ignition leads while personnel are at the pad and this interrupt should be under the control of personnel at the pad.

These are good design concepts and if everything is working as it should, they result in a perfectly safe firing system. But "everything is working as it should" is a dangerous assumption to make. Control consoles bounce around in the backs of trucks during transport. Cables get stepped on, tripped over, and run over. Switches get sand and grit in them. In other words, components fail. As such there is one more concept that should be incorporated into the design of a firing system:

The failure of any single component should not compromise the safety of the firing system.

Proper Fire Control System Design Philosophy

Let us examine an ignition system that may at first glance appear to be simple, well designed, and safe (Figure C-1). If everything is functioning as designed, this is a perfectly safe ignition system, but let us examine the system for compliance with proper safe design practices.

The control console should be designed such that two deliberate actions are required to static fire or launch the vehicle. Check! There are three deliberate actions required at the control console: (1) insert the key, (2) turn the key to arm the system, (3) press the ignition button.

The system should include a power interrupt such that ignition current cannot be sent to the firing leads while personnel are at the pad and this interrupt should be under control of personnel at the pad. Check and check! The ignition relay effectively isolates the electric match from the ignition power supply (battery) and as the operator at the pad should have the key in his pocket, there is no way that a person at the control console can accidentally fire the vehicle.

But all of this assumes that everything in the ignition system is working as it should. Are there any single component failures that can cause a compromise in the safety of this system? Yes. In a system that only has five components beyond the ignition lines and e-match, three of those components can fail with potentially lethal results.

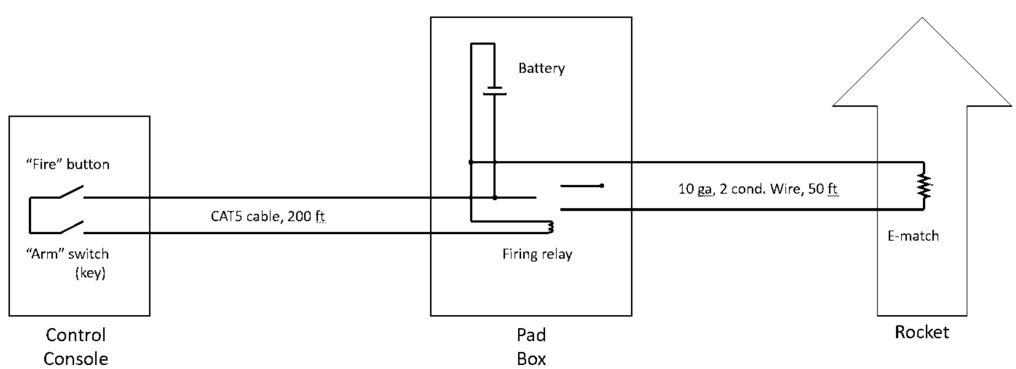


Figure 1, A simple high current ignition control system.

Ignition Relay. If the ignition relay were stuck in the ON position: The vehicle would fire the moment it was hooked to the ignition lines. This is a serious safety failure with potentially lethal consequences as the vehicle would be igniting with pad personnel in immediate proximity.

Arming Switch. If the arm key switch failed in the ON position, simply pushing the ignition button would result in an ignited vehicle whether intentional or not. This is particularly concerning as the launch key – intended as a safety measure controlled by pad personnel – becomes utterly meaningless. Assuming all procedures were followed, the launch would go off without a hitch. Regardless, this is a safety failure as only one action (pressing the fire button) would be required at the control console to launch the vehicle. Such a button press could easily happen by accident. If personnel at the pad were near the vehicle at the time, we are again dealing with a potentially lethal outcome.

CAT5 Cable. If the CAT5 cable was damaged and had a short in it the ignition relay would be energized, and the vehicle would ignite the moment it was hooked to the ignition lines. This too is a potentially lethal safety failure.

Notice that all three of these failures could result in the vehicle being ignited while there are still personnel in immediate proximity to the vehicle. A firing system of safe design does not allow single component failures to have such drastic consequences. Fortunately, the system can be fixed with relative ease. Consider the revised system (Figure C- 2). It has four additional features built into it: (1) A separate battery to power the relay (as opposed to relying on the primary battery at the pad), (2) a flip cover over the fire button, (3) a lamp/buzzer in parallel with the firing leads (to provide a visual/auditory warning in the event that voltage is present at the firing lines), and (4) a switch to short out the firing leads during hookup (pad personnel should turn the shunt switch ON anytime they approach the vehicle).

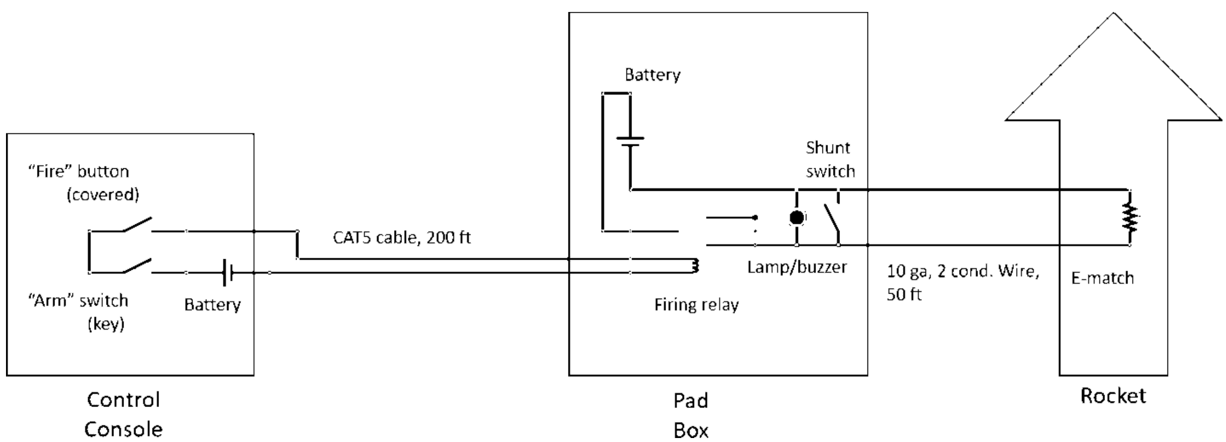


Figure 2, An improved high current fire control system.

In theory, these simple modifications to the previous firing circuit have addressed all identified single point failures in the system. The system has 8 components excluding the firing lines and e-match (part of the vehicle itself). Can the failure of any of these components cause an inadvertent firing? That is the question. Let us examine the consequences of the failure of each of these components.

Ignition Button. If the ignition button fails in the ON position, there are still two deliberate actions at the control console required to fire the vehicle. (1) The key must be inserted into the arming switch, and (2) the key must be rotated. The firing will be a bit of a surprise, but it will not result in a safety failure as all personnel should have been cleared by the time possession of the key is transferred to the Firing Officer.

Arm Switch. If the arm switch were to fail in the ON position, there are still two deliberate actions at the control console required to fire the vehicle. (1) The cover over the fire button would have to be removed, and (2) the fire button would have to be pushed. This is not an ideal situation as the system would appear to function flawlessly even though it is malfunctioning and the key in the possession of personnel at the launch pad adds nothing to the safety of the overall system. It is for this reason that the shunting switch should be used. Use of the shunting switch means that any firing current would be dumped through the shunting switch rather than the e-match until the pad personnel are clear of the vehicle. Thus, personnel at the pad retain a measure of control even in the presence of a malfunctioning arming switch and grossly negligent use of the control console.

Batteries. If either battery (control console or pad box) fails, firing current cannot get to the e-match either because the firing relay does not close or because no firing current is available. No fire means no safety violation.

CAT5 Cable. If the CAT5 cable were to be damaged and shorted, the system would simply not work as current intended to pull in the firing relay would simply travel through the short. No fire means no safety violation.

Firing Relay. If the firing relay fails in the ON position the light/buzzer should alert the pad operator of the failure before he even approaches the pad to hook up the e-match.

Shunt Switch, Lamp/Buzzer. These are all supplementary safety devices. They are intended as added layers of safety to protect and/or warn of failures of other system components. Their correct (or incorrect) function cannot cause an inadvertent firing.

Is this a perfect firing system? No. There is always room for improvement. Lighted switches or similar features could be added to provide feedback on the health of all components. Support for firings at multiple launch pads could be included. Support for the fueling of hybrids and/or liquids could be required. A wireless data link could provide convenient and easy to set up communications at greater ranges. The list of desired features is going to be heavily situation dependent and is more likely to be limited by money than good ideas.

Hopefully, the reader is getting the gist: The circuit should be designed such that no single equipment failure can result in the inadvertent firing of the e-match and thus, the rocket motor. Whether or not a particular circuit is applicable to any given scenario is beside the larger point that in the event of any single failure a firing system should always fail safe and never fail in a dangerous manner. No matter how complicated the system may be, it should be analyzed in depth and the failure of any single component should never result in the firing of a vehicle during an unsafe range condition. Note that this is the bare minimum requirement; ideally, a firing system can handle multiple failures in a safe manner.

APPENDIX D: MANDATORY SAFETY CHECKLIST TEMPLATE

D.1 CPLC Pressure Tank Safety Worksheet	
Fuel Tank	
Maximum Expected Operating Pressure (MEOP) (psi)	
Test Method**	
Calculated Proof Pressure (psi) 1.1 x MEOP	
Rated or Tested Proof Pressure (psi)	
Relief Valve Pressure (psi)	
Oxidizer Tank	
Maximum Expected Operating Pressure (MEOP) (psi)	
Test Method**	
Calculated Proof Pressure (psi) 1.1 x MEOP	
Rated or Tested Proof Pressure (psi)	
Relief Valve Pressure (psi)	
Pressurant Tank	
Maximum Expected Operating Pressure (MEOP) (psi)	
Test Method	DOT or ASTM or Hydro
Rated Pressure (psi)	
**<u>NOTE</u> -- DOT Rated -- ASTM Rated -- Hydrostatic Test (Professional Only) -- Water Pressure Test	

PRESSURE TANK SAFETY WORKSHEET (CONTINUED)

DANGER: OPERATING PRESSURIZED TANKS OF AN UNKNOWN PRESSURE RATING OR ABOVE THEIR PRESSURE RATING IS EXTREMELY DANGEROUS AND MAY CAUSE SEVERE INJURY OR DEATH.

DANGER: HANDLE PRESSURE TANKS WITH CARE. A DAMAGED TANK CAN EASILY RUPTURE BELOW ITS RATED PRESSURE AND MAY CAUSE SEVERE INJURY OR DEATH.

DANGER: DO NOT USE PRESSURIZED GAS TO PROOF PRESSURE TEST YOUR TANK. EITHER HAVE A HYDROSTATIC TEST DONE BY A PROFESSIONAL OR BUY A TANK OF KNOW PRESSURE RATING. A TANK RUPTURE, WHEN USING COMPRESSED GAS, MAY CAUSE SEVERE INJURY OR DEATH.

<u>Instructions for each tank</u>

1. Write in your tank expected operating pressure (OP).
2. Write in the test method for your tank: DOT rated, ASTM rated, professional hydrostatic tested, or water pressure tested.
3. Write in the tank calculated proof pressure: OP times 1.5
4. Write in the tank rated or tested proof pressure.
5. If your tank is DOT, ASTM, or professionally hydrostatic tested and the tank pressure rating is above the calculated proof pressure; you do not need to test it any further. **DANGER:** DO NOT TRY TO PERFORM A HYDROSTATIC TEST YOURSELF. IF THE TANK FAILS IT CAN KILL YOU. Water pressure testing with a hand pump will need to be performed on any self-fabricated tanks or prefabricated tanks of unknown pressure rating.
6. Write in the calculated relief pressure: OP times 1.25
7. Select a relief valve with a relief pressure as close to the calculated relief valve pressure as possible. The relief valve pressure must be greater than or equal to the calculated relief pressure. The relief valve pressure must be less than or equal to the rated or tested tank pressure.

D.2 PROOF TEST

DANGER: HANDLE PRESSURE TANKS WITH CARE. A DAMAGED TANK CAN EASILY RUPTURE BELOW ITS RATED PRESSURE AND MAY CAUSE SEVERE INJURY OR DEATH.

WARNING: YOU MAY GET WET. TO PROOF TEST A TANK OF UNKNOWN PRESSURE RATING, A TANK THAT YOU
HAVE FABRICATED YOURSELF, OR UTILIZING A TANK ABOVE ITS RATED PRESSURE; PERFORM A WATER PRESSURE TEST USING A HAND-PUMP. WATER IS INCOMPRESSIBLE AND THE PRESSURE WILL DROP RAPIDLY AND NOT HAVE PROPULSIVE FORCE WHEN THE TANK RUPTURES.

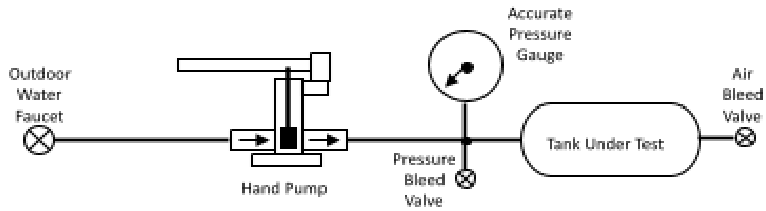
DANGER: KEEP EXTENSION CORDS, POWER STRIPS, LIGHTS, AND ELECTRIC POWER TOOLS AWAY FROM THIS TEST. YOU COULD POSSIBLY GET ELECTROCUTED WHILE STANDING IN WATER OR TOUCHING ELECTRIC EQUIPMENT WITH WET HANDS CAUSING SEVERE INJURY AND DEATH.

Water Proof Test Procedure

1. Set up the pressure tank to be tested with a hand-pump, pressure bleed valve, air bleed valve, and accurate pressure gauge. **WARNING:** VERIFY THAT THE ACCURATE PRESSURE GAUGE IS FUNCTIONAL BEFORE YOU TEST A TANK, YOU CAN OVERPRESSURE AND DAMAGE YOUR TANK.
2. Turn on the outdoor water faucet, fill the tank with water, tip the tank up, and bleed out all the air using the air bleed valve. Close the air bleed valve when no more air bubbles come out.
3. Lay the tank under test on its side and block the tank to prevent it from rolling and damage.
4. Utilizing the hand pump, slowly pump up the water pressure in the tank under test.
5. The pressure should increase with each cycle of the hand pump.
6. Stop pumping when you reach the desired proof pressure.
7. While you are pumping and the pressure stops increasing and you have not reached your proof pressure goal, stop pumping, turn off the outdoor water faucet, and relieve the pressure on the tank under test with the pressure bleed valve. **DANGER:** DO NOT USE THIS TANK FOR YOUR VEHICLE. THE TANK IS YIELDING AND MAY BURST.
8. Allow your tank to sit at the proof pressure for one-minute.
9. Bleed the tank under test pressure with the pressure bleed valve to about half the proof pressure.
10. Repeat steps 3 through 9 two more times.
11. Turn off the outdoor water faucet.
12. Bleed the pressure to zero using the air pressure bleed valve.
13. Drain the water from the tank under test.
14. Dry the tank thoroughly.

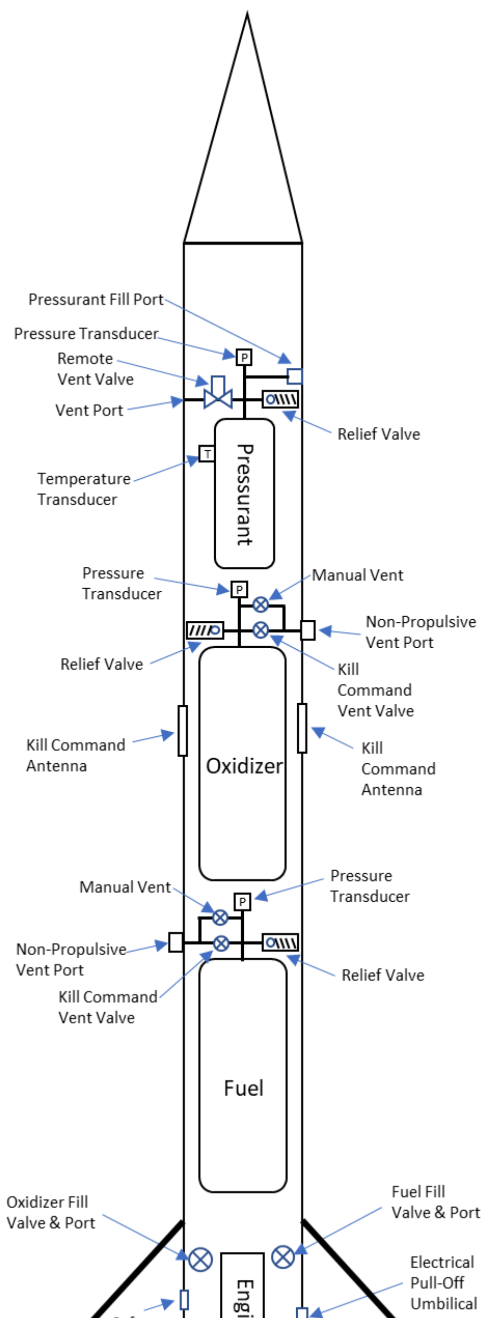
WARNING: IT IS VERY IMPORTANT TO DRY YOUR TANKS WHEN THEY ARE USED TO HOLD OR PRESSURIZE LIQUID-OXYGEN OR LIQUID-METHANE. WATER OR WATER VAPOR, WHEN EXPOSED TO LIQUID-OXYGEN OR
LIQUID-METHANE TEMPERATURES, WILL FREEZE AND CAUSE ICE YOUR VEHICLE FROM OPERATING PROPERLY.

Water Proof Test Setup



NOTE: Make sure that your hand pump, pressure gauge, valves, and lines are rated for more than the desired proof pressure. Any leaks in your plumbing will make it difficult to attain the desired proof pressure and hold that pressure. Make sure all fittings and connections are leak tight.

D.3 VEHICLE SAFETY LAYOUT SHEET



Draw a diagram of your vehicle showing the location of the following:

- Pressurant Tank
- Pressurant Tank Relief Valve
- Pressurant Remote Vent Valve
- Pressurant Pressure Transducer
- Pressurant Fill Port
- Pressurant Fill Port and Umbilical
- Fuel Tank
- Fuel Non-Propulsive Vent
- Fuel Tank Relief Valve
- Fuel Kill Command Vent Valve
- Fuel Pressure Transducer
- Fuel Fill Valve & Port at Bottom
- Oxidizer Tank
- Oxidizer Non-Propulsive Vent
- Oxidizer Tank Relief Valve
- Oxidizer Kill Command Vent Valve
- Oxidizer Pressure Transducer
- Oxidizer Fill Valve & Port
- Electrical Pull-Off Umbilical
- Kill Command Antennas
- Safety Key
- Igniter