LAUNCH CANADA CHALLENGE

Design, Test & Evaluation Guide

REVISION HISTORY

REVISION	DESCRIPTION	DATE
R0	Initial Release	7-Aug-19
R1	Major edits to document, such as addition of sections and requirements.	4-Jan-21
R2	Updates for 2022-23. Incorporation of oxygen cleaning appendix.	20-Mar-23
R3	Updates for 2024-25. Major edits and additions.	1-Nov-24

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1.0 INTRODUCTION

The Launch Canada Rocketry Association (LCRA)'s mission is to support and advance the science, engineering and business of rocketry and space launch in Canada, and to use the excitement of rocketry to educate students and the public in science, technology, engineering and mathematics. We bring together Canada's passionate and rapidly growing amateur and student rocketry community with academia, industry and government to help unlock their full innovative potential and show Canadians that there is no limit to what we can achieve in this country.

Canadian students have increasingly been taking rocket innovation into their own hands and winning top awards at major international competitions. The Launch Canada Rocket Innovation Challenge (LC Challenge) exists to provide this burgeoning community with the opportunity to launch advanced experimental rockets and demonstrate cutting-edge rocket-related technologies here in Canada and take Canadian grassroots rocketry to new heights, while fostering an unmatched culture of safety and rigour.

1.1 BACKGROUND

The world is experiencing an unprecedented new era in spaceflight, with entrepreneurial launch companies like SpaceX, Rocket Lab and Blue Origin disrupting the industry and showing that space launch is no longer the sole domain of global superpowers and large government-run programs. Here in Canada, there are now multiple startup companies working on space launch and rocket propulsion technologies, and work is underway on an orbital spaceport in Nova Scotia. Inspired by this, Canada has seen a stunning rise of grassroots rocketry, and especially of university rocket teams. All are building sophisticated vehicles, most are developing hybrid and liquid rocket engines, and some even have their eyes on suborbital space. Rocketry may not be among our traditional niches in Canada, yet these students have demonstrated incredible talent against all odds. But having talent means nothing without opportunity: opportunity to learn, to grow, and to do those things that motivate it to go beyond and excel. Launch Canada is about creating these opportunities, right here in Canada.

The Launch Canada (LC) organization aims to serve as a locus for amateur experimental rocketry activities in Canada, working with its network of experienced professionals to introduce safety standards and make resources and mentors available to support rocketry activities in a coordinated way.

At the same time, students who succeed in challenging, highly multidisciplinary rocket engineering projects build transferrable skills that equip them for success in any area of engineering. They learn to work as teams to conduct complex aerospace systems engineering projects and make the leap from theory to practice, equipping them for success in their future careers in a way that few other things can.

1.2 PURPOSE & SCOPE

This document defines the minimum design, test, and evaluation criteria the event organizers expect LC teams to meet before launching. The event organizers use these criteria to promote flight safety. Departures from the guidance this document provides may negatively impact an offending team's score and could result in being denied the opportunity to launch, depending on the severity. For reference, the foundational, qualifying criteria for LC are contained in the *Launch Canada Rules & Requirement Guide* [1].

This guide defines the formal technical requirements for projects participating in the Launch Canada competition. Requirements are statements relating to design, construction or operation of vehicles and related systems that shall be complied with. For clarity, these are shown in this guide in italic font and consist of a prefix "R" followed by a number. E.g., "R2.1.1".

As far as possible, the requirements have been developed to avoid being any more prescriptive than necessary and to allow teams flexibility in how they choose to comply with them. Where appropriate, additional background is provided to explain the context behind requirements and provide recommendations or examples of typical means of compliance.

In addition to the formal requirements, this document includes various recommendations that do not constitute requirements but are good practices that can help teams to be successful.

Teams are always encouraged to seek clarification and feedback from LCRA and may contact LCRA at any time with questions or concerns regarding their project plans' alignment with the spirit and intent of the *Launch Canada Design, Test, & Evaluation Guide* (DTEG). Similarly, if a team wishes to propose an alternate means of complying with the intent of a requirement, they are encouraged to do so. They will be required to demonstrate that their proposed approach provides an equivalent level of safety to the original requirement.

This document incorporates elements of the *Tripoli Rocketry Association (TRA) Safety Code* [2], *the National Fire Protection Association (NFPA) Code for High Power Rocketry (NFPA 1127)* [3], industry expertise, and the LCRA's observations on student launch initiatives. It draws heavily from and builds on the documentation and experience of the Experimental Sounding Rocket Association (ESRA)'s Intercollegiate Rocket Engineering Competition (IREC) [4], the world's largest advanced student rocket competition. Although NFPA 1127 is a United States regulation and LCRA has no formal affiliation with the TRA, these documents remain useful supplemental resources for student researchers to learn more about best practices adopted by the amateur high-power rocketry community.

1.3 LIMITATIONS OF THE GUIDE

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 the circumstances "typical" 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 Launch Canada to discourage novel approaches. But in all cases, the recommendations of this guide reflect deeper underlying principles or requirements that shall 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 team to prove the acceptability of their approach to Launch Canada through careful analysis and testing.

1.4 CONVENTION & NOTATION

The following definitions differentiate between requirements and other statements. The degree to which a team satisfies the spirit and intent of these statements will guide the competition officials' decisions on a project's overall score in the LC Challenge as well as their flight status or test approval.

Shall: This is the only verb used to denote mandatory requirements. Failure to satisfy the spirit and intent of a mandatory requirement will always affect a project's score and flight status or test approval.

Should: This verb is used for stating non-mandatory goals. Failure to satisfy the spirit and intent of a non-mandatory goal may affect a project's score and flight status or test approval, depending on design implementation and the team's ability to provide thorough documentary evidence of their due diligence on-demand.

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.

Flight status refers to the granting of permission to attempt flight, and the provisions under which that permission remains valid. Similarly, test status refers to the granting of permission to attempt a potentially hazardous ground test such as an engine static firing. A project's flight or test status may be either nominal, provisional, or denied.

Nominal: A project assigned nominal flight / test status meets or exceeds the minimum expectations of this document and reveals no obvious safety concerns during the flight / test safety review at the LC Challenge.

Provisional: A project assigned provisional flight / test status generally meets the minimum expectations of this document but reveals safety concerns during flight / test safety review at the LC Challenge which may be mitigated by field modification or by adjusting launch environment constraints. Launch may occur only when the prescribed provisions are met.

Denied: Competition officials reserve the right to deny flight / test status to any project which fails to meet the minimum expectations of this document or reveals un-mitigatable safety concerns during flight / test safety review at the LC Challenge.

1.5 DEVIATIONS

Although the requirements of this document are meant to be as broadly applicable as possible, they can never account for every conceivable situation or circumstance. Further, the goal of the requirements is not to be overly restrictive, but to ensure that basic safety standards are being met. In recognition of this, a team may seek an exemption or deviation from a requirement of this document, if they feel that the requirement ought not to apply in their particular case. Deviations shall be requested in writing to LCRA, via email to safety@launchcanada.org and competition@launchcanada.org. Any request for a deviation shall explain:

- Why the team is unable to comply with the requirement;
- What they propose to do instead; and
- Why their non-compliance with the requirement will not adversely impact the safety of their system and/or operations.

LCRA will review the request and may seek additional information and/or a meeting to review with the team. The onus is on the team to make their case on why any exceptions to the requirements in this document are required for the team's activities. Teams anticipating the need to request a deviation are strongly encouraged to reach out as early as possible to avoid going too far down a path that would be unacceptable to LCRA.

1.6 REVISION

It is expected the *LC DTEG* may require revision from one competition to the next, based on the lessons learned by both host organizations and the participants. Major revisions will be accomplished by complete document reissue. "Real world events" may require smaller revisions to this document in the months leading up to a competition. Such revisions will be reflected in updates to the document's effective date. The authority to issue revised versions of this document rests with the LCRA.

1.7 DOCUMENTATION

The following documents include standards, guidelines, schedules, or required standard forms. The documents listed in this section are either applicable to the extend specified in this document or contain reference information useful in the application of this document.

Table 1 - Applicable and Reference Documentation [2, 3, 5]

DOCUMENT	FILE LOCATION
TRA Safety Code	http://www.tripoli.org/SafetyCode
CAR Safety Code	https://canadianrocketry.org/High-Power-Rocketry
NFPA 1127: Code for High-Power Rocketry	NFPA Website
Canadian Aviation Regulations	https://tc.canada.ca/en/corporate-services/acts-regulations/list-regulations/canadian-aviation-regulations-sor-96-433
14 CFR, Part 1, 1.1 General Definitions	eCFR :: 14 CFR 1.1 -- General definitions.
14 CFR, Part 101, Subpart C, 101.22 Definitions	eCFR :: 14 CFR Part 101 -- Moored Balloons, Kites, Amateur Rockets, and Unmanned Free Balloons

2.0 PROPULSION SYSTEMS

2.1 PROPULSION TYPES & BASIC REQUIREMENTS

2.1.1 PROPULSION TYPES

Chemical rocket propulsion systems are typically classified by the number of propellants they use, and the physical states of the propellants they employ.

Monopropellant engines employ a single propellant that decomposes exothermically, typically with the aid of a catalyst. Hydrogen Peroxide and the hydrazines are common examples. These are most commonly seen on in-space systems.

Most familiar rocket propulsion systems used in amateur rocketry, as well as for sounding rockets and launch vehicles, are bipropellant systems, employing both a fuel and an oxidizer.

A solid motor is a Commercial Off-The-Shelf (COTS) or Student Researched And Developed (SRAD) motor that employs propellants consisting of a solid fuel and oxidizer. Most common solid propellants additionally include a rubber binder and are referred to as a "composite propellant".

A hybrid motor is a SRAD motor that employs propellants in different physical states: most commonly a liquid or gaseous oxidizer and solid fuel.

A liquid engine is a SRAD propulsion system whose fuel and oxidizer are both stored in tanks in the liquid state.

2.1.2 COTS & SRAD PROPULSION

For the purposes of this Guide, a distinction is made between COTS motors, and those that are SRAD.

- COTS motors are defined as those that have been certified by the Tripoli Rockery Association, National Association of Rocketry (NAR), and/or the Canadian Association of Rocketry (CAR). Note that such motors are currently limited to solids and some hybrids. The Canadian Association of Rocketry's current list of certified motors may be found on their website: http://legacy.canadianrocketry.org/MotorIndex.php [6]

Tripoli and NAR curate their own similar lists that largely overlap, and the organizations collaborate extensively.

- SRAD propulsion systems are defined as any motor that has been designed by a student team. This also includes COTS motors that have been modified in any way. Unlike "certified" motors, which have undergone testing and characterization as part of the certification process, it is the responsibility of the student teams to test their SRAD motors prior to competition. For safety reasons, no untested SRAD motors are permitted to be flown.

R2.1.1 ***All SRAD motors shall be static fired, well characterized and tested before arrival at the competition, per Section 2.5. No second-party motors (i.e., those that are not COTS and not developed by the participating team) are permitted.***

2.1.3 TOTAL IMPULSE LIMITS

R2.1.2 ***The total impulse for a rocket made with COTS components and entered into the Basic category shall not exceed 40,960 Newton-seconds (9,208 pounds-seconds, i.e., "O" impulse motor).***

2.1.4 NON-TOXIC PROPELLANTS

R2.1.3 ***Launch vehicles entered in the LC Challenge shall use non-toxic propellants.***

Commercial ammonium perchlorate composite propellant (APCP), potassium nitrate and sugar, nitrous oxide, liquid oxygen (LOX), hydrogen peroxide, kerosene, propane, alcohol, and similar substances, are all considered non-toxic. Toxic propellants are defined as those requiring breathing apparatus, extensive personal protective equipment (PPE) such as Self Contained Atmospheric Protective Ensemble (SCAPE) suits and posing significant public and/or environmental hazards in the event of a spill. Hydrazines, dinitrogen tetroxide (NTO) and red fuming nitric acid (RFNA) are examples.

2.1.5 "SPARKIE" PROPELLANTS

R2.1.4 ***Launch vehicles entered in the LC Challenge shall not use propellants with large particle size metal with the intent to leave the combustion chamber unreacted such that they create a shower of sparks as the large metal particles combust in the air.***

Certain commercial propellants and some experimental propellants are designed to produce a shower of sparks effect and are referred to as sparkies. It is the duty of the team to ensure their chosen motor is not a sparkie propellant. Teams showing up with a sparkie propellant will not be allowed to fire it for participation in any category.

The "sparky" effect is typically accomplished with titanium sponge. Ti sponge is a high surface area large particle size foamed metal that is heated during the burn of the propellant but does not fully combust prior to passing through the nozzle. This material exits into the air at high temperature and continues to burn producing bright sparks. The amount of titanium sponge is regulated in motors by percent mass of total propellant. Other metals are not regulated but there are certain large particle sizes which do not fully react with halogens or oxidizers in the combustion chamber in either solid or hybrid motors.

Particularly with hybrid motors the choice of particle size is important along with the use of halogen containing hydrocarbons to aid in the combustion of moderate particle size aluminum. Given the propellant density benefits of high metal content in hybrid fuel grains, hybrid sparkies are particularly problematic. It can be alleviated by matching aluminium powder stoichiometrically with the halogens in halogen-containing plastics. Commercial hybrid sparkies are designed with mixed metals to maximize the sparkie effect. Given that LC's launch site is in a forested area this presents an unacceptable fire risk. The following are companies that produce sparkie motors and their respective sparkie propellant names:

Aerotech/Quest - Dark Matter

Cesaroni Technology Incorporated - Skidmark

Contrail Rockets - Sparky

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, relief devices, pumps, gauges, etc.). A distinction is typically drawn between ground systems (e.g., test stands, Ground Support Equipment (GSE)) and flight systems. For ground-based systems, particularly those that will have personnel operating nearby, safety factors (based on ultimate strength) of 4 or greater are typically used. Flight pressure vessels and systems are typically not designed with such a high factor of safety, and therefore additional restrictions such as remote pressurization and de-pressurization shall be put in place to mitigate the risk of hazard exposure.

2.2.1 GENERAL

2.2.1.1 Pressure Levels

This section defines and explains various terms used to describe the operations and levels in a pressurized system. Figure 2.1 illustrates the conditions, which are fully detailed below.

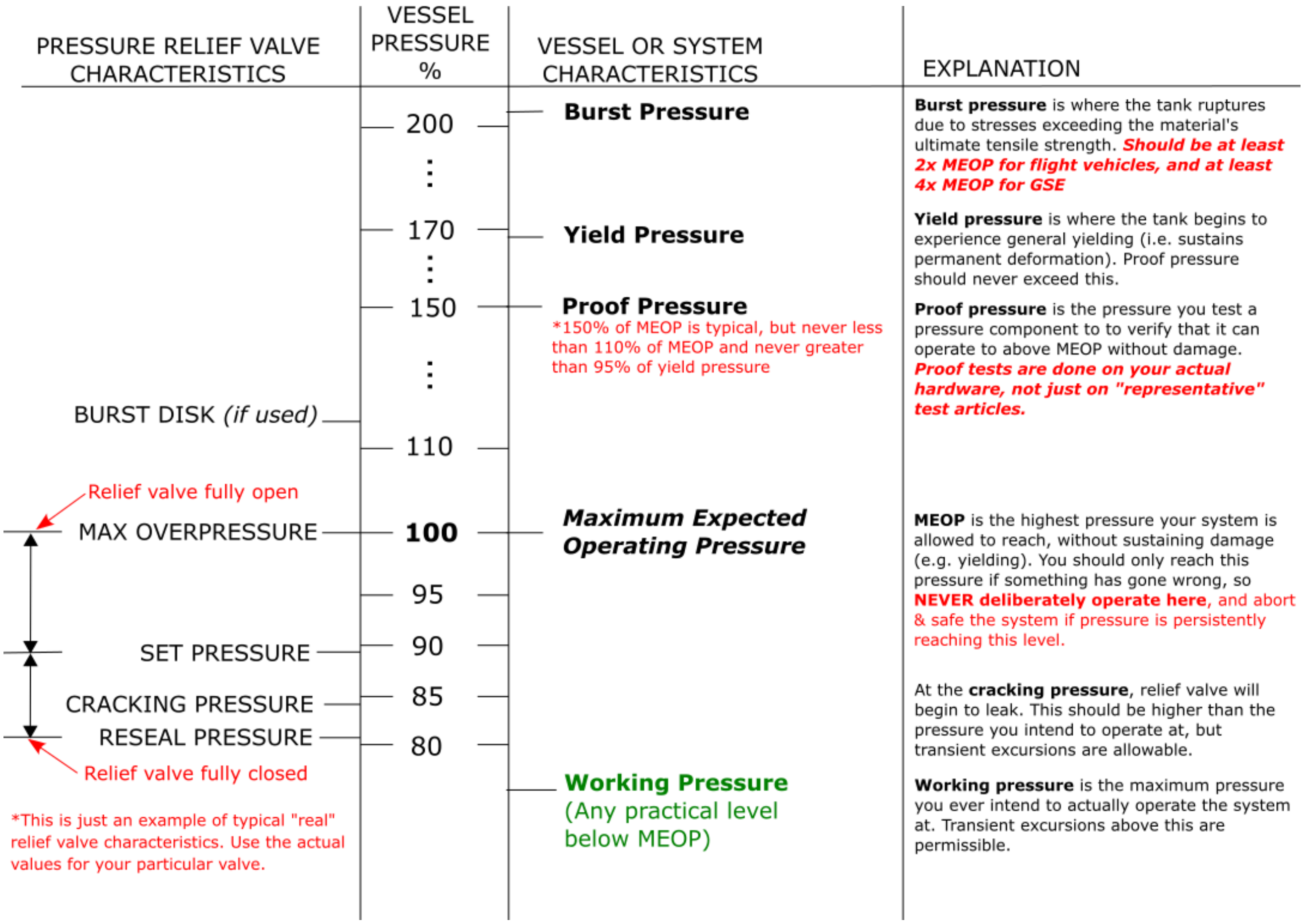

Figure 2.1 - Pressure levels and operational characteristics.

Working Pressure (WP)

This represents the maximum nominal pressure your component or system is being designed to operate under. For a propellant tank used with self-pressurized nitrous oxide, this might be defined by the vapour pressure of N_2O on a typical summer day. The required working pressure is driven by the specific needs of your system.

Maximum Expected Operating Pressure (MEOP)

Maximum Expected Operating Pressure is defined as the highest pressure that a pressure vessel, pressurized structure, or pressure component is expected to experience during its service life in association with its applicable operating environments, while still retaining normal functionality. This pressure is greater than the WP, because it includes the effects of potential pressure transients and off-nominal situations, such as fluid hammer or hard starts, temperature extremes, extreme operating environments, relief valve operating variability, or specific malfunctions. It typically also includes margin to allow for inherent uncertainty in your analysis. The system's MEOP should generally be at least 20% above the WP to allow for the unexpected. Note that the MEOP is a system parameter and not defined for any individual component. As such, MEOP is distinct from rated pressure for individual components.

A system should NEVER be deliberately operated at MEOP, but it must be capable of it without sustaining any adverse effects, and there must be margin between MEOP and the pressure at which damage such as general yielding of the vessel could occur.

Pressure relief devices (see Section 2.2.3.2) are necessary on all systems having a pressure source that could exceed the MEOP of the system, or where the malfunction or failure of any component could cause the MEOP to be exceeded. The MEOP of the system must factor in the operation of those devices.

Proof Pressure

SRAD pressurized components must be proof tested before being used (see Section 2.2.2.3.1). These tests are intended to take the component to a pressure that is HIGHER than MEOP, but less than the pressure at which the tank would sustain permanent damage (e.g. yield pressure). This test demonstrates that the component can comfortably reach MEOP without failure. Proof testing must be performed on each actual SRAD pressurized component, and not just on "similar" test articles.

Yield Pressure

This is the pressure at which general yielding of the vessel or component would occur. At this pressure, your system is permanently deforming. NEVER LET IT REACH THIS POINT.

Burst Pressure

At this pressure level, the tank will rupture due to stresses exceeding the ultimate tensile strength (UTS) of the material.

2.2.1.2 Sealed Systems

R2.2.1 Any sealed system or segment shall have a pressure relief device.

If any normally closed actuated valve or a check valve closes part of your plumbing system, it is considered a separate system requiring pressure relief. In a hypothetical system a mother bottle is connected to a fill valve which is connected to the rocket through a fill line which passes a normally closed valve into the oxidizer tank. You have three potentially sealed systems each requiring a pressure relief valve. In the case of higher working load rated plumbing between the mother tank and the fill valve a dump is not necessary but would help in your operations, while the potential for over pressurizing the line between the mother bottle and the fill valve exists so a pressure relief valve is required to be set at the MEOP of that closed subsystem so you do not feed higher pressure into the rest of the system. In the event of an abort prior to removal of the fill line the rocket side normally closed valve could be held open and would allow purging of oxidizer through the fill line dump valve in addition to the rocket oxidizer tank dump system, thereby decreasing the abort time. In the case of abort after removal of the fill line, the rocket side oxidizer dump system would have to complete the abort by itself. This requires a dump valve capable of draining the entire onboard tank within the abort time requirements (30 minutes for < 41 kN·s, 60 minutes for ≥ 41 kN·s). While the maximum time for an abort is given by the preceding requirement, well designed systems do not take as much time as the maximum time allowed for poorest designed systems that are allowed to fly.

2.2.1.3 Operational Envelope

In addition to defining the pressure levels that your system and components can handle, it is also essential to define the operating conditions that your engine can accept while functioning nominally and achieving safe and successful operation and a safe flight.

R2.2.2 Teams shall define the operational ranges their engines can launch under in terms of fill percentage and oxidizer pressure.

An unsafe combination of fill state and pressure is defined as a launch condition that is either:

1. Under requirements for rail exit velocity
2. Under requirements for stability

3. Under the minimum altitude for altimeters to register a launch

This data should be organized into a table of expected altitude and rail exit velocity for fill state and pressure of your oxidizer tank. The team might even want to keep a few different charts with wind speeds to help with altitude determination for scoring.

2.2.1.4 Design Standards

R2.2.3 ***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 [7] should be followed for pressure vessels, and ASME B31.3 [8] (Process Piping code) should be followed for general pressure system components.

R2.2.4 ***Any system, subsystem or component that will be transported while pressurized shall comply with the applicable Transport Canada and 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 [9] (Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components) or ANSI/AIAA S-081 [10] (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.

2.2.1.5 Wetted Materials

R2.2.5 ***All wetted materials (i.e., those exposed to a fluid) employed in a rocket's fluid systems shall be compatible with the fluid(s) and conditions (e.g., temperature, pressure, shock, vibration) to which they will be exposed.***

This includes structural materials, soft goods (seals, gaskets), sealants, thread lockers and lubricants.

R2.2.6 ***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 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.

2.2.1.6 General Cleanliness

R2.2.7 ***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.***

R2.2.8 ***Caps, plugs or other protective covers shall be used on all ports and openings in fluid systems to prevent contamination when not in use.***

2.2.1.7 Oxidizer System Cleanliness

R2.2.9 ***No hydrocarbons shall be employed in any oxidizer system component, or in wetted components upstream of an oxidizer system.***

R2.2.10 ***All oxidizer system hardware (valves, plumbing, etc.) shall be thoroughly cleaned to an acceptable standard for oxygen service.***

R2.2.11 ***After cleaning, components shall be thoroughly dried in such a way that contamination is not introduced.***

R2.2.12 ***Cleaned components shall be maintained in that condition. This is typically done by capping / plugging all ports, and then further protecting the part by bagging.***

R2.2.13 ***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.***

R2.2.14 ***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

R2.2.15 ***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.***

R2.2.16 ***If a propellant tank is designed with a burst pressure of less than 2.0 times the maximum expected operating pressure, hydrostatic burst testing shall be performed to demonstrate that the design and manufacturing process actually achieved or exceeded the design burst pressure.***

R2.2.17 ***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 on the whole, to account for inconsistency and imperfections in the welding process.***

R2.2.18 ***Full penetration shall be ensured for all pressure vessel welds.***

R2.2.19 ***Welding shall be performed by an individual experienced with pressure vessel welding.***

R2.2.20 ***Any pressure vessels that will be pressurized indoors or on the road, or with personnel in the vicinity shall be suitably certified and issued a Canadian Registration Number (CRN).***

This is a legal requirement. Due to the hazards associated with pressure vessels operated or transported in the vicinity of people, manufacturers of such vessels must be certified, and shall stamp their products to verify compliance.

2.2.2.2 Composite Pressure Vessels

R2.2.21 ***All SRAD and modified COTS pressure vessels either constructed entirely from non-isotropic materials (e.g. fiber reinforced plastics; commonly called "composites"), or implementing composite overwrap of a metallic vessel (aka composite overwrapped pressure vessels; COPV), shall be designed to a burst pressure no less than 3 times the maximum expected operating pressure, where the maximum operating pressure is the maximum pressure expected during pre- launch, flight, and recovery operations.***

R2.2.22 ***If composite pressure vessels or fluid components are to be used with an oxidizer such as liquid oxygen, nitrous oxide or hydrogen peroxide, and the material could come in contact with the oxidizer, material testing shall be undertaken in accordance with ASTM D2512 - 17: Standard Test Method for Compatibility of Materials with Liquid Oxygen [11], or an equivalent approved standard, to demonstrate that the risk of ignition in a high pressure oxidizer environment is acceptably low.***

R2.2.23 ***Hydrostatic burst testing shall be performed for all SRAD composite pressure vessels, regardless of the tank's design safety factor. This includes both overwrapped and linerless vessels.***

The strength of a composite pressure vessel is highly dependent on the manufacturing process, and composite vessels have been known to fail at a small fraction of their design pressure. Burst testing is required as a result to help validate the manufacturing process and demonstrate that it is capable of producing pressure vessels within specification.

2.2.2.3 SRAD Pressure Vessel Testing

The following requirements concern design and verification testing of SRAD and modified COTS pressure vessels. Unmodified COTS pressure vessels utilized for other than their advertised specifications will be considered modified, and subject to these requirements. SRAD (including modified COTS) rocket motor propulsion system combustion chambers are included as well. LCRA recommends teams complete these tests by at least 2 months prior to the competition date. While not a requirement, this is recommended to assure teams are prepared for the LC Challenge.

R2.2.24 ***Teams 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

R2.2.25 ***Prior to use, pressure vessels intended for static testing or flight shall be proof tested.***

R2.2.26 ***Proof pressure shall be selected such that the gross stress level in the tank during the proof test does not exceed 95% of the yield strength of the material and does not exceed 75% of the ultimate strength of the material.***

R2.2.27 ***The tank shall be designed such that the above requirement can be met with a proof pressure not less than 1.5 times the maximum expected operating pressure.***

R2.2.28 ***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, abort or recovery operations, or during the longest static test in the case of a test stand tank.

R2.2.29 ***Proof testing shall always be performed with an incompressible fluid such as water - NEVER with a gas.***

2.2.2.3.2 Burst Testing

A rigorous verification & validation test plan typically includes a series of both non-destructive (i.e., proof pressure) and destructive (i.e., burst pressure) tests. Per the requirements of 2.2.2.1 (Metallic Pressure Vessels) and 2.2.2.2 (Composite Pressure Vessels), burst testing shall be performed to demonstrate that the design and manufacturing process actually achieved or exceeded the design burst pressure. This shall be done for:

- Any metallic pressure vessels with a design burst pressure of less than 2.0 times the maximum expected operating pressure;
- Any composite pressure vessel.

R2.2.30 ***Any tank used for burst testing shall be identical in terms of design, materials and manufacturing process, to the tank that will be used in the rocket system.***

R2.2.31 ***Burst testing shall always be performed with an incompressible fluid such as water – NEVER with a gas.***

A well-designed burst test should also aim to detect the point at which general yielding of the tank begins.

2.2.3 PROPELLANT & PRESSURIZATION SYSTEMS

Dump Valve

A dump valve is a valve designed to allow flowing liquid oxidizer through it to depart the rocket under the pressure in the oxidizer tank. This is accomplished by placing the dump valve at the bottom of the tank and plumbing the connector on the other side of the valve from the tank outside the airframe. In the event that the underside of the oxidizer tank is inaccessible due to its design, a top mounted dump valve is possible through the installation of siphon tube, only where the pressure of the boiled off oxidizer or pressurant gas is sufficient to push the liquid oxidizer up the siphon tube and out of the rocket. In the case of an unobstructed fill line through the combustion chamber such as in a UC valve hybrid the lowest point of the rocket side oxidizer tank pressure system is not actually on the rocket and it can be drained from the ground side dump valve on the fill line side of the fill valve. Your team is required to be able to quickly drain the liquid oxidizer from your rocket in the case of an abort which requires the removal of liquid oxidizer through the flow of the liquid out of the pressure vessel and not by boil off and gaseous removal.

The dump valve cannot dump through the combustion chamber unless the dump line is sealed and plumbed from the combustion chamber and out of the nozzle. Actuation of a dump valve shall always be able to be actuated independently of tank or fill state.

The effective orifice of any plumbing used for draining or dumping the tank shall be in excess of the area of a single ⅛" diameter orifice for oxidizer tanks over 100mL, ¼" for oxidizer tanks over 2L, ⅜" for oxidizer tanks over than 10L, ½" for oxidizer tanks over 25 L commensurate with a discharge coefficient of at least 0.3. If you are unable to determine your discharge coefficient of your entire abort pathway, use the orifice standards above. These dimensions are roughly set to meet the abort time requirements. This is repeated in multiple places to avoid any potential confusion.

Vent Valve

A vent valve is a valve designed to lower the pressure of a propellant tank by allowing gasses to escape. A vent valve is not a primary abort valve. Generally, its operation slows the rate of an abort by dropping the pressure over the liquid oxidizer slowing the flow rate out of a dump valve. In abort procedures the dump valve should be the primary abort valve until it fails or there is no liquid oxidizer left at which point both the dump and vent would be fully opened to quickly drain pressure. In the event of a dump valve freezing, the vent operation is needed to lower the pressure. This allows the chilling of the remaining liquid oxidizer during any manual intervention operation or for boil off if state detection of oxidizer mass shows a level that is minimal. Since the vent is used for venting gas, it is not subject to orifice sizing constraints. The size of your vent valve orifices is rather unique to your rocket and sized to prevent gas buildup and allow for adequate depressurization.

Constricted Vent Fitting

For some designs employing self-pressurizing oxidizers, rather than incorporating an actuated valve to seal the onboard oxidizer tank, a vent constrictor is used to allow gasses to escape during the fill of saturated liquid in the flight tank. This constricted vent is tuned in the design process to allow for a fast fill and some amount of hold time before launch is required due to loss of pressure. The rocket can be topped off by the higher-pressure mother bottle for some period of time, but the use of this style of vent constrictor allows for quick, less complicated operations. For the use of a constantly vented tank there is no requirement for a vent valve. Dump valves are still required.

Pressure Relief Valve (PRV)

Any sealed system shall have an automatically actuating pressure relief valve. The pressure at which this valve opens fully shall less than MEOP, requiring a set point even lower (as illustrated in Figure 2.1). This valve can be as simple as a pressure relief poppet valve or even a burst disk. Note that the full open pressure of PRVs (not actuation/set pressure) contributes to the actual MEOP. If PRVs fully open too far below your 'expected' MEOP, the 'actual' MEOP will be lower. As such, it is important to use PRVs that fully open near your designed MEOP for optimal performance and operation.

For vehicle-mounted PRVs, it is imperative that the released gasses or liquids are plumbed out of the airframe. Venting into an airframe section is known to freeze internals which could lead to issues in abort operations.

Manual Dump Valve

If at any point in the operation of a launch vehicle and its ground support equipment, a section of the plumbing is isolated behind a valve or check valve for any amount of time, it is considered an isolated system. If that isolated system in time and flow has a working pressure less than 4 times that system's MEOP then it is required that it possesses a manual relief valve to depressurize it in the case that primary flow control fails to function nominally. If an umbilical is released using a sealed valve to seal behind it, that creates a closed system separate from the fill system. If a check valve is used in such a way that it seals off a manual relief device from the system it seals, then that system in that transient shall have a manual dump device. All manual relief devices shall be accessible from the outside of the rocket in its fully assembled state, such that no disassembly is required for its operation. The Manual Dump Device shall be on the bottom of the oxidizer tank or connected to an internal siphon at the top of the tank (this is not a preferred location due to the need for a ladder). In the case of UC valve hybrid or umbilical hybrid without any flow restriction, such as a check valve that would prevent backflow in the opposite direction of fill, the manual relief device can be located off the rocket and this is a preferred method as it pulls safing staff off the rocket in the event of manual intervention. The effective orifice of any plumbing used for dumping or draining the tank shall be in excess of the area of a single ⅛" diameter orifice for oxidizer tanks over 100mL, ¼" for oxidizer tanks over 2L, ⅜" for oxidizer tanks over than 10L, ½" for oxidizer tanks over 25 L commensurate with a discharge coefficient of at least 0.3. If you are unable to determine your discharge coefficient of your entire abort pathway, use the orifice standards above. These dimensions are roughly set to meet the abort time requirements. This is repeated in multiple places to avoid any potential confusion.

A socket fitting plug on a T is an acceptable manual dump valve. A manual ball valve with a carabiner attachment point is acceptable so long as a 100' rope can actuate it if pulled normal to the axis of the rocket and such rope and carabiner is provided to range safety prior to retreat for launch ops. A panel with no more than two bolts may be used to protect from the airstream only if a cordless driver with the proper bit and a magnetic parts tray is given to the range safety operation leader at the time prior to retreat for launch ops.

2.2.3.1 Remote Operation

R2.2.32 ***Any experimental pressure vessel, system 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 only be pressurized and de-pressurized remotely.***

R2.2.33 ***Experimental pressure vessels shall never be approached by personnel while pressurized to more than 25% of its burst pressure.***

R2.2.34 ***Commercial pressure vessels pressurized above their rated pressure shall only be remotely pressurized and depressurized.***

R2.2.35 ***Commercial pressure vessels pressurized above their rated pressure shall never be approached by personnel while pressurized above its rated pressure.***

These are standard requirements for "non-code" pressure vessels, i.e., those that are not designed, manufactured and tested per the requirements of the ASME Boiler & Pressure Vessel Code [7] or equivalent.

Experimental pressure vessels are non-code and they should be considered an explosion hazard when 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.

R2.2.36 ***Experimental pressure vessels shall incorporate electronic pressure measurement and telemetry to allow tank pressures to be monitored remotely.***

R2.2.37 ***Commercial pressure vessels pressurized above their rated pressure shall have electronic pressure measurement and telemetry to allow pressure vessels to be monitored remotely.***

Because of the hazards associated with pressurized systems, it is critical to know what the system pressure is. Simply knowing the state it "should" be in is not 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 it is approached.

It also allows system pressures to be verified to be in their nominal ranges before proceeding with a launch or engine test.

2.2.3.2 Overpressure Protection

R2.2.38 ***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 / 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.

R2.2.39 ***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 pressure regulator would be a common sizing case. Given the remote nature of our launch and test site resettable pressure relief devices may help in the team's operations.

R2.2.40 ***Under no circumstances shall the pressure in the system exceed 110% MEOP. Relief devices shall be used where necessary to satisfy this requirement.***

This is to ensure under no circumstances that in worst case operation you cannot still operate valves remotely and safely abort without manual intervention.

R2.2.41 ***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.

R2.2.42 ***Only commercial burst disks shall be utilized to satisfy these requirements.***

Burst disks are typically hard to fabricate with a reliable burst pressure.

Note: combustion chambers are exempted from this requirement, although they are technically pressure vessels. Dedicated burst disks are not common on combustion chambers, nor are they recommended.

R2.2.43 ***If a cryogenic 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.

R2.2.44 ***When a relief device is installed on a flight vehicle to output of the relief device shall be plumbed to the outside of the airframe.***

Pressurized fluids are not to be released within any enclosed airframe section. All dump and vent outlets shall have their exits plumbed outside the airframe. There will be no exceptions made to this rule.

2.2.3.3 Filling, Draining & Venting

R2.2.45 ***Propellant tanks shall be filled and drained from the bottom of the tank, near the top of the main propellant valves.***

Filling and draining from the bottom of the tank and above the top of the main propellant valves 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 most of the propellants, leaving only a small residual in the system.
- If the propellant is poured in from the top, it is prone to splashing around. In the case of a cryogenic propellant, this would significantly increase the boiloff of the propellant.
- On flight vehicles, it keeps the fill/drain connection low down on the rocket, making it easier to access and potentially avoiding the need to work on a ladder to make critical connections.
- With the vent at the top of the tank, it makes it possible to drain propellant using gravity alone, with no additional pressurization required.

R2.2.46 If a propellant has a high vapour pressure (i.e., above 40 psia) and its propellant tank is not a certified vessel with a safety factor of 4.0 or greater, the system shall be designed to allow remote filling and draining of the propellant.

R2.2.47 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.

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.

Pressurants, nitrous oxide, and fuel gases can pose an asphyxiation hazard.

Alcohols, WFNA and hydrogen peroxide pose toxicity and inhalation hazards.

WFNA and hydrogen peroxide cause chemical burns or bleaching of exposed skin.

Cryogenic venting poses a freezing hazard.

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.

R2.2.48 All dump and vent outlets shall exit the airframe in such a manner that if they were capped they would hold pressure.

This could be accomplished by screwing in a pipe nipple to a female connection from the outside of the airframe. This requirement is introduced to ensure that dump and vent lines are sufficiently strong and routed in such a way as to ensure that no fluids can be discharged inside the airframe especially in the case of rapid pressurization of the dump line as would be experience as the dump valve opens. If the dump line were to be dislodged upon opening this could result in dumping into the airframe which has been seen to stall abort operations.

R2.2.49 No dump or vent outlets shall be capped for flight.

Use of Remove Before Flight (RBF) tags would be highly suggested.

R2.2.50 Drainage shall be present at the bottom (lowest point) of all airframe sections that have oxidizer plumbing present to prevent pooling of liquid oxidizers on top of a baffle and further cooling

of an airframe section, especially if it contains electronics or valves.

R2.2.51 ***Oxidizer plumbing shall be separated from recovery bays to avoid filling a space with energetics (especially black powder) from experiencing enhanced yield or to prevent pressurization of a recovery bay potentially pneumatically opening it. If this requires moving through a tank wall above the pressure vessel then this shall be present at the time of hydrotesting.***

R2.2.52 ***The average oxidizer flow rate during abort shall be measured in testing, and data of this test shall be provided to LC staff.***

This applies to both SRAD and COTS systems. For systems that are assembled from only COTS components, this test is still necessary.

R2.2.53 ***The effective orifice of any plumbing used for draining the tank shall be in excess of the area of a single ⅛" diameter orifice for oxidizer tanks over 100 mL, ¼" for oxidizer tanks over 2 L, ⅜" for oxidizer tanks over than 10 L, ½" for oxidizer tanks over 25 L commensurate with a discharge coefficient of at least 0.3.***

If you are unable to determine your discharge coefficient of your entire abort pathway use the orifice standards above. These dimensions are roughly set to meet the abort time requirements. This is repeated in multiple places to avoid any potential confusion.

R2.2.54 ***For an engine test stand, fuel and oxidizer vents shall be kept separate to preclude the potential mixing of vented propellants.***

R2.2.55 ***For vehicles, fuel and oxidizer vents shall be routed to opposite sides of the vehicle.***

Having both fuel and oxidizer vents, as would be typical on liquid bipropellant systems, makes it important to avoid propellant liquid 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. For vehicles with self-pressurizing propellants, whichever propellant has the highest vapor pressure is to be fully dumped first to not create fuel oxidizer mixes around the rocket. After the higher vapor pressure fluid is dumped, time should be given to allow the first offloaded propellant to dilute in air before the next self-pressurizing fluid is released. If dump is possible through the ground support equipment, then dump through that system can be used to create more distance between outlets.

2.2.3.4 Failure Considerations

2.2.3.4.1 Failsafe Remote Venting

R2.2.56 ***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 or static test stand: 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 rocket with pressurized tanks is a significant hazard due to the amount of stored energy, combined with the fact that flightweight vehicle tanks are typically not designed, built and tested with the extremely high safety factors required by the ASME Boiler & Pressure Vessel Code [7], US Department of Transportation, and/or Transport Canada for pressure vessels that will have personnel in close proximity. As a result, it is essential for these systems to be de-pressurized remotely from a safe distance.

R2.2.57 ***A rocket or engine test stand shall implement an emergency vent capability to relieve pressure to a safe level (less than 689 kPa (150 psig)) for all the pressurant and propellant tanks that is independent of the nominal control system.***

R2.2.58 ***Liquid and gaseous propellants having vapor pressures greater than 150 psig (e.g., N_2O) shall implement remote offloading for these propellants.***

Hybrid and liquid propulsion systems shall implement a means for remotely controlled venting or offloading of all high pressures (i.e., those greater than 100 psia) in the event of a launch abort. Further, this function shall 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.

2.2.3.4.2 Propellant Mixing

R2.2.59 ***A rocket or engine static test stand that incorporates 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

R2.2.60 ***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

Launch Canada has seen many instances where teams have misunderstood the functionality of check valves and used them incorrectly. Unnecessary or inappropriate use of check valves is heavily discouraged. In many cases, check valves can create separate pressurant systems that require dump, vent, manual dump, and pressure relief requirements that add weight and complexity to your rocket. They can also complicate abort procedures. A higher-pressure difference will prevent mixing upstream. Designs using unnecessary check valves will be penalized for poor design, as they can create additional points of failure and unnecessary hazards and risks. That said, there are reasons for the use of check valves in some cases.

Many cases for a check valve can be replaced with a solenoid with ground power in the case of an umbilical, where the power could be provided through a magnetic electric cable that is disconnected in launch or via onboard power, among other solutions that do not restrict abort capabilities prior to takeoff. Solutions also include normally open valves that are powered closed at the time of umbilical release or the use of a piloted valve with similar function.

R2.2.61 ***Check valves shall not be used as flow restrictors, especially on high flow lines.***

R2.2.62 ***Check valves shall not be used as flame flashback arrestors.***

In most circumstances (e.g., nitrous decomposition, etc.), check valve response times are too slow to close to prevent flashback.

In many cases, check valves can create separate pressurant systems that require dump, vent, manual dump, and pressure relief requirements that add weight and complexity to your rocket. They can also complicate abort procedures. A higher-pressure difference will prevent mixing upstream. Designs using unnecessary check valves will be penalized for poor design, as they can create additional points of failure and unnecessary hazards and risks. That being said, there are reasons for the use of check valves in some cases.

R2.2.63 Check valves shall not be used to seal the fill line after umbilical retraction unless the valve is inline with and actuatable through the connector.

R2.2.64 Check valves shall not be placed downstream of a 90° elbow/bend.

R2.2.65 Under no scenario shall a team use two check valves in a row.

Shared pressurant systems are not recommended. Teams should avoid using designs that require use of doubled inline check valves.

2.2.3.4.5 Use of Umbilicals / Fill Arms

R2.2.66 Umbilicals shall remain connected at least until the 30-count of the launch sequence.

This minimizes the time secondary abort systems on the ground side are not attached to the flight tank allowing a second means of abort. Efforts should be made to extend ground power capability until launch. Efforts should be made to allow for remote reattachment of umbilicals to aid in abort capability.

R2.2.67 Any check valve used in an umbilical/fill line shall be able to be manually opened from the outside of a vehicle.

In the event that a check valve or quick disconnect is used for an umbilical with a sealing fitting, there is a potential method of manual abort where a simplified connector similar to the umbilical arm can be manufactured to press open the check valve on the rocket. Such a jig can be made and given to LC staff as a method of manual abort rather than having a manual valve or fitting. Only the umbilical quick connect check valve can be used and a manual plug can be provided to range personnel that when inserted holds the check valve open while the intervening staff can depart. The jig shall have a 8 inch straight pipe attached that is insulated to allow manual insertion.

2.2.3.4.6 Valves

R2.2.68 Piloted valves shall abort in the depressurized state.

R2.2.69 Control valves which provide the pressure to operate piloted valves shall depressurize the pilot line when the control valve is de-energized.

Piloted lines require a second solenoid to depressurize the actuation line. Piloted dump/dump valves shall be normally open with the pressurant actuator valve set up to vent (resulting in a dump) in the de-energized state. Many valves on rockets make use of pneumatic actuators. When pneumatic actuation is used, it is good practice to ensure that de-pressurizing the pneumatic "pilot" line will result in the valve returning to the desired safe state. Typically, this will mean propellant valves should close, dump and vent valves should open.

R2.2.70 Dump and Vent Valves shall have a duty cycle 3 times the abort time or operational time whichever is more. Fill valves shall have a duty cycle 2 times the fill time or operational time whichever is more.

Duty cycle refers to the time that a valve can hold position in an energized or pressurized state. For electrically actuated valves, this is determined by the time the valve can remain energized to hold a position or actuate without the energy required for activation preventing the actuation. In the case of a solenoid valve this is the time it can be held in its non normal state. In the case of a piloted valve this is the time that the valve that holds open the pressurant line to the pilot can remain open. In the case of an electrically operated valves this is the time until the as built leak rate might freeze a line preventing actuation. Some valves have naturally longer duty cycles.

R2.2.71 SRAD valves for use in a remotely operated system shall have a demonstrated probability of failure less than 5% over at least 20 tests using the same starting conditions, preparation and lubrication.

These are for valve actuation tests, not full pressurant tests. These tests shall be performed at the 110% MEOP of your system. Low pressure tests will also help diagnose low risk issues with early stages of fill and help point out where low pressure leaks are not properly seating sealing surfaces.

SRAD valves can offer many advantages, providing a team with a valve that is tailored to their requirements for weight, flow, opening time, etc. Because these valves are often critical to the safety of the entire launch system, all such valves must be tested to demonstrate their reliability. This testing must be performed on each actual valve that is to be flown, and not just on "representative" test units. Burst disk flow actuation and UC valves must be tested representatively prior to a static hot fire test but those requirements fall under preheater or igniter testing as it also starts combustion within the combustion chamber. Single actuation pyro valves must be tested as any other SRAD valve yet there are consumables that will be expended and replaced.

This testing shall demonstrate reliable actuation, leakage rates that are acceptable for your particular application, and any other characteristics that are critical for your application. Tests should demonstrate actuation across a pressure gradient defined as 110% of MEOP to atmospheric pressure. Test must be resettable to the same conditions including pressure gradient and operating temperature (especially for valves to be used with cryogenic fluids). Flow rate does not have to be tested with each actuation. Wear of parts should be analyzed prior to the first test and after the last test in a series. If the testing series ends prematurely due to excessive wear the maximum allowable cycles shall be set as the number of tests in that series and used for representative data.

These tests shall be performed at 110% MEOP, using either the actual working fluids or ones that are analogous (e.g., water as a substitute for alcohol or kerosene, CO2 as a substitute for N2O, LN2 as a substitute for LOX, etc.). These tests must also be performed at the actual operating temperature of the valve, since valve performance and required actuation forces can be strongly temperature dependent.

In addition to this reliability testing, low pressure tests can also be useful during development to help validate designs and diagnose problems.

R2.2.72 Flight hardware must be tested at least 3 times but not more than 30% of the maximum number of allowable cycles if wear does not permit the full 20 tests.

R2.2.73 SRAD valves shall be flow tested to determine the valve's discharge coefficient.

The discharge coefficient of a valve must be known to model the flow characteristics of a propellant or pressurant system. Valves with lower than anticipated flow coefficients can reduce propellant flow to the engine, thereby reducing thrust.

2.2.3.4.7 Nitrous Line Filters

R2.2.74 Nitrous line filters shall not be used in-line with any nitrous flow pathway between the mother / supply bottle and the engine.

Nitrous filters are not to be used in place of proper chemical hygiene nor as covers to exposed orifices. This rule is being introduced under an abundance of caution to prevent potential blockages and concentration of contaminants potentially depositing in the filter forming something similar to a catalytic bed.

2.2.4 CRYOGENIC SYSTEMS

2.2.4.1 Cryogenic Material Considerations

R2.2.75 ***All materials used in a cryogenic environment shall be evaluated to ensure they are safe for this application.***

R2.2.76 ***Carbon steels shall never be used in cryogenic service due to their brittleness at low temperatures.***

R2.2.77 ***Teflon or other polymer hoses shall never be used in a cryogenic application due to the brittleness of the material at low temperatures.***

R2.2.78 ***Flexible hoses for cryogenic applications shall be of an all-metal (bellows) construction only.***

R2.2.79 ***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.

Note that insulation is strongly recommended on cryogenic components to the extent that is practical. This reduces boiloff during and after propellant loading. If components are not insulated, it may cause an incomplete propellant loading and lower than expected propellant density.

2.2.4.2 Valves For Cryogenic Service

R2.2.80 ***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.***

R2.2.81 ***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 actually 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. As far as practical, testing should aim to account for operating loads, pressures and vibrations.

2.3 IGNITION

2.3.1 SAFING & 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. Section 5 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 motors. 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 on hybrid / liquid system considerations specifically.

A solid rocket motor or pyrotechnic device is considered armed if only one action (e.g., an ignition signal) is required for it to release its energy (i.e. 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).

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

- “Inert”, no oxidizer, no self-pressurizing fuels, no flammable solids, no igniter or preheater present. This is just plumbing and pressure vessels. All pyros for pyro actuated valves are removed. This state is allowed to be in the convention center.
- “Safed”, where the rocket may have solid fuels, preheater, igniter, pyro-actuators installed but any initiator, e-match, or igniter is mechanically shunted to prevent any stray current from initiating any pyro-actuated event.
- “Armed”, with just a single action required to initiate it.

In other words, the act of arming the motor brings it to a more hazardous state, while the act of safing it maintains it or returns it to a less hazardous state.

R2.3.1 The action that arms the igniter shall be independent of the action that fires 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.

The LCRA-provided launch control system described in Section 11.2 of this document provides sufficient propulsion system arming functionality for almost all launch vehicles using single stage, solid rocket propulsion systems. Therefore, these requirements generally concern more complex propulsion systems (i.e., hybrid, liquid, and multistage systems) and all team-provided launch control systems. Additional requirements for team-provided launch control systems are defined in Section 12.0 of this document.

R2.3.2 ***All ground-started propulsion system ignition circuits/sequences shall not be "armed" until all personnel are at least 15 m (50 ft) away from the launch vehicle.***

The LCRA provided launch control system satisfies this requirement by implementing a removable "safety jumper" in series with the pad relay box's power supply. The removal of this single jumper prevents firing current from being sent to any of the launch rails associated with that pad relay box. Furthermore, access to the socket allowing insertion of the jumper is controlled via multiple physical locks (Lock-Out / Tag-Out) to ensure that all parties have positive control of their own safety. The Range Safety Officer or a designated member of the Range Safety team has jurisdiction over this lockout.

R2.3.3 ***The engine igniter shall be both physically and electrically isolated from the power source by a minimum of two independent inhibits.***

R2.3.4 ***The engine igniter shall be electrically isolated by switches in both the power and return legs.***

R2.3.5 ***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.***

R2.3.6 ***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.***

R2.3.7 ***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 INERT, SAFING & ARMING: LIQUIDS & HYBRIDS

Unlike solid motors, where firing the igniter leads directly to the ignition of the motor, 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. Furthermore, igniters and preheaters might be tightly integrated into the combustion chamber creating issues with physically removing the igniter or preheater and requiring safing by shunting the igniter in a way that would not be appropriate for solid motors whose grains are flammable solids with premixed oxidizers rather than just flammable solid fuel as seen in a hybrid.

Without the oxidizer present, a hybrid fuel grain is effectively inert. In the case of low vapor pressure liquid fuels such as ethanol, methanol and kerosene, these liquids may remain onboard and unpressurized without creating significant hazard to those conducting operations around the launch pad.

In contrast to solid rocket motors, a liquid or hybrid propulsion system requires more nuance 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, no pyrophoric material, 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 or solid but without the presence of an oxidizer to burn it or a pyrogen to initiate the reaction it is at a relatively safe state.
- In the case of most hybrid engines with a rubber or plastic solid fuel grain without mixed in oxidizer the ignition hazard of the fuel inside a partially sealed vessel (only open to atmosphere through the nozzle throat) is often less than the folding table the rocket is displayed on, which might actually in some cases be the same material.
- In the case of a preheater puck or igniter booster for these hybrid or liquid engines, such "ignition media" has the same properties as a solid motor fuel grain as it contains its own oxidizer. Therefore, if ignition media is present the rocket cannot be considered to be inert and cannot be allowed into the convention center, as neither can a loaded solid motor. While some ignition media is harder to light than others a blanket rule is enacted to remain safe.
- 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 and potentially explode or deflagrate.
- 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 leak or vent at high pressure, or tank burst resulting in an explosion with shrapnel or fireball. With a cryogenic or high vapour pressure propellant, there is the possibility of a boiling liquid expanding vapour explosion (BLEVE) with large tank fragments and possible fireball.
- When the igniter and/or other pyrotechnic devices are installed such that current can flow through and initiate combustion they become "armed", there are the hazards associated with an armed pyrotechnic (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 firing of the engine. Unlike a solid motor which always contains a mixed fuel and oxidizer, a hybrid or liquid system is completely inert until propellant, pressurant or pyrotechnics are loaded. Also, unlike a solid motor, merely firing 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 as a whole. 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.

In general, as the hazard level increases, the number of people exposed to that hazard should decrease. The launch or test area should be largely or completely clear prior to commencing hazardous operations such as loading pressurants or propellants.

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 reactants 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 bi-liquid system, it should be emphasized that hybrids are not necessarily immune to similar hazards. Certain fuel grains can absorb oxidizer, creating an explosion hazard. As a result, the following requirement applies:

R2.3.8 ***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.

R2.3.9 ***Systems that employ a fully automated open-loop start sequence that automatically opens the propellant valve(s) after firing the igniter, without any confirmation that the igniter is actually operating nominally, are deemed to be a safety hazard and shall not be used.***

2.4 ENGINE CONTROLS & FUNCTION

R2.4.1 ***The main pressurant valve open command shall be considered a hazardous command.***

R2.4.2 ***The main pressurant valve close command shall be considered a safety critical command.***

R2.4.3 ***The main pressurant valves shall be actuated remotely.***

R2.4.4 ***The main fuel and oxidizer propellant valve open command shall be considered a hazardous command.***

R2.4.5 ***The main fuel and oxidizer propellant valve close command shall be considered a safety critical command.***

R2.4.6 ***The main fuel and oxidizer propellant valves shall be actuated remotely.***

R2.4.7 ***The fuel and oxidizer propellant tank vent valve open commands shall be considered a safety critical command.***

R2.4.8 ***The fuel and oxidizer propellant tank vent valves shall be actuated remotely.***

R2.4.9 ***If vent valves are controlled by a computer-based system, they shall be operable independently of the computer, in case of a software, power or control system failure.***

R2.4.10 ***Launch vehicles and test stands shall incorporate a "lock out" approach that ensures it is physically impossible to bring the system to a hazardous state (e.g. open the main pressurant valves, open the main propellant valves to the engine, or fire the igniter) while personnel are present at the launch pad or engine test stand.***

One example of such an approach would be to incorporate key switches at both the launch pad / test stand and at the control point, and to have those switches use the same 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 or test stand should prevent firing / actuation signals from reaching the engine when in the "safe" position, and the key should not be removable when in this position.

The switch at the control point should similarly prevent firing / actuation signals from being sent when in the "safe" position. The key should not be removable when turned to the "arm" position.

This ensures that the switch at the control site cannot be in the "arm" position and the key cannot be present there when the pad / test stand switch is "safed", and vice versa.

The commands to open the main pressurant valve, open the main propellant valve, and fire the ignite are considered hazardous commands and should not be sent while personnel are present at the test stand or launch pad.

R2.4.11 ***When the pad controller is in the "lock out" condition, the control point shall be capable of commanding safety critical commands (vent valves open for the pressurant and propellant tanks).***

The pressurant and propellant tank vent valve are considered safety critical commands.

R2.4.12 ***When the pad controller is in the "lock out" condition, the control point shall be capable of monitoring safety critical measurements (pressurant and propellant tank pressures and temperatures).***

The pressurant and propellant tank pressure and temperature measurements are considered safety critical measurements.

R2.4.13 ***When the rocket or static test stand pressurant or propellant loading operations are in progress, the pressurant and propellant tank pressures and temperatures shall be continuously monitored at the control point.***

R2.4.14 ***When the rocket or static test stand pressurant or propellant tank pressures and temperatures are at unsafe levels, the control point shall:***

- ***Warn the pad personnel to immediately stop loading pressurant or propellants into the rocket or static firing test stand.***
- ***Warn the pad personnel to immediately evacuate the area around the rocket or static firing test stand.***
- ***Command the pressurant and propellant tank vent valves open to vent the tank to safe levels.***

R2.4.15 ***The rocket or static test stand shall protect safety critical command, hazardous command, and safety critical measurement wiring and pneumatic controls from fire during a launch or static firing.***

During a static firing or launch, fire can rise from the rocket engine while running or during shutdown causing unprotected wiring and pneumatic lines to burn or melt causing loss of control of the rocket or rocket static firing test stand.

2.4.1 LAUNCH ABORT

R2.4.16 ***The launch abort sequence shall autonomously perform functions needed to shut down 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.

R2.4.17 ***The launch abort sequence shall drain the propellant tanks.***

R2.4.18 ***The launch abort sequence shall depressurize the pressurant tank, if the pressurant tank has a FOS of less than 4.0.***

R2.4.19 ***Following a launch abort sequence, certified ground personnel shall perform approved operational procedures to safely offload propellants and pressurization gases and return the launch vehicle to a SAFE configuration.***

2.4.2 OPTIONAL PROPULSION SYSTEM SHUTDOWN

In most cases, it is typical to allow an amateur rocket to burn to propellant depletion, without any commanded propulsion system shutdown. Burning to depletion 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 boost phase of flight, thereby avoiding the hazards of propellants or high-pressure sources on the vehicle after landing (or crashing). If for some reason the mission does not allow for burning propellants to depletion, and instead requires a controlled engine shutdown, the shutdown shall nevertheless ensure that propellant and pressurant tanks are empty and de-pressurized by the time the rocket lands. The need for recovery personnel to approach a rocket which could have high pressures on board after a landing and conceivably some undetermined structural damage is a hazard that shall be avoided.

R2.4.20 ***If a controlled engine shutdown is desired, or necessary to guarantee compliance with altitude or total impulse restrictions, the rocket shall include all necessary provisions for implementing it in compliance with the remaining requirements within this section. Otherwise, the propulsion system shall run until propellant depletion.***

R2.4.21 ***The shutdown sequence shall shut off propellant feed systems in a manner that prevents propulsion system instability, propellant fire, or explosion.***

R2.4.22 ***The shutdown sequence shall initiate a nominal propellant and pressurant offload sequence.***

R2.4.23 ***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.

R2.4.24 ***At the completion of offload, feed system valves shall be opened or set to known positions needed for safe ground recovery operations.***

2.5 SRAD PROPULSION SYSTEM TESTING

The following requirements concern verification testing of student researched and developed (SRAD) propulsion systems. LCRA STRONGLY recommends teams complete these tests at least 2 months before a launch. Testing is an integral part of the development and validation of rocket systems and components. A thorough series of propulsion system tests is a major contributor to a successful launch.

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

R2.5.2 ***The following test shall be performed before firing a rocket engine:***

- ***Rocket Engine Combustion Chamber Test***

R2.5.3 ***The following tests shall be performed before each rocket or rocket engine test:***

- ***Function Verification Test***
- ***Leak Test***

R2.5.4 ***The following tests shall be performed as part of a rocket engine static firing:***

- ***Rocket Engine Test Stand Propellant Fill and Drain Test***
- ***Rocket Engine Test Stand Propellant Cold Flow Test***
- ***Rocket Engine Static Test Firing***

R2.5.5 ***Student teams shall static fire their rocket engine and rocket before they are given the go-ahead to launch.***

2.5.1 COMBUSTION CHAMBER PRESSURE TESTING

R2.5.6 ***SRAD and modified COTS propulsion system combustion chambers shall be designed and tested according to the SRAD pressure vessel requirements defined in Section 2.2.2.3 of this document.***

Note that although combustion chambers are technically “pressure vessels”, they are exempted from the requirement for a relief device.

2.5.2 LEAK TESTING

Leak testing is important to perform on pressurized fluid systems prior to a 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 test 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.

R2.5.7 ***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.

R2.5.8 ***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.***

R2.5.9 ***Leak testing shall be performed at pressures well below MEOP: typically, less than 150 psig, and not more than 25% of normal operating pressure.***

R2.5.10 ***Leaks shall be tested with soap solution, a leak detection fluid such as Swagelok "Snoop", or a suitable leak detector.***

R2.5.11 ***Leak testing shall be performed on all fitting and line joints, valve stems and flanges.***

R2.5.12 ***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.***

2.5.3 PROPELLANT FILL & DRAIN TEST

R2.5.13 ***Rockets or rocket engine test stands employing SRAD or modified COTS propulsion systems using liquid propellant(s) shall successfully complete a propellant fill and drain test in their final 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. This test may be conducted as part of a cold flow test (see 2.5.4, below).

R2.5.14 ***Any anomalies encountered during a test shall be documented and provided to Launch Canada upon completion of the test.***

R2.5.15 ***If a proxy fluid 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.

R2.5.16 ***Under no circumstances shall a hydrocarbon-containing test fluid be used in an oxidizer system.***

R2.5.17 ***A full fill and drain or full abort test shall be conducted after a ten-minute hold or a quoted maximum hold time which if less than 10 minutes will not be allowed to exceed 10 minutes.***

An Abort test shall be made from a full tank after a ten-minute hold or quoted maximum hold time. This can be made after a failed ignition in a failed static fire or with an oxidizer simulant at the operations rehearsal. If multiple failed static fires occur be sure to test primary and secondary abort systems.

2.5.4 COLD FLOW TESTING

R2.5.18 ***During development of a SRAD propulsion system employing one or more liquid propellants, cold flow testing shall be performed prior to progressing to hot-fire testing.***

R2.5.19 ***A cold flow test shall be performed on both rocket engine test stands and the rocket vehicles prior to first firing.***

The purposes of cold flow testing are:

1. To serve as a complete “dress rehearsal” of the static test firing, allowing the setup and test procedures to be worked through and shortcomings to be discovered and corrected.
2. To verify the correct operation of the test stand, instrumentation and fluid systems, ensuring that they will provide leak-free operation and deliver propellants at the correct pressure(s) and flow rate(s) to the engine.

As with a vehicle tanking test, cold flow testing 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 in particular can exothermically decompose.

R2.5.20 ***For cold flow tests performed without a thrust chamber, you shall ensure that the discharge does not present a hazard to personnel and equipment via the impact energy of the flow.***

R2.5.21 ***Cold flow tests shall provide the same pressure drop as the injector and combustion chamber and develop the same volumetric flowrate of the proxy fluid as would be expected with the real propellant.***

An excessive drop in tank pressure observed during the test may indicate one or more of the following:

- Regulator unable to supply pressurant at a sufficient flowrate (i.e. C_v of regulator is too low)
- Insufficient pressure upstream of regulator, for example due to a pressurant cylinder valve with too small an orifice, or other excessive restriction in the plumbing
- Excessive pressure drop in the plumbing between the regulator and the propellant tank
- Pressurant collapse in a cryogenic propellant tank, for example due to the use of nitrogen to pressurize a cryogenic fluid.

R2.5.22 ***If a cold flow 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).

R2.5.23 ***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.

R2.5.24 Under no circumstances shall a hydrocarbon-containing fluid be used in an oxidizer system.

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

R2.5.25 For any propulsion system where emptying a propellant tank by dumping a propellant through the combustion chamber is part of the abort procedure, or an option, the thrust generated by that action shall be determined.

If such an abort is performed, it is critical for safety planning to know whether the resulting thrust would cause the vehicle to lift off, and if so, whether it would reach sufficient altitude for the flight computer to deploy the recovery system. This can be done with a cold flow test using a suitable analog fluid (CO2 in place of N2O, water in place of alcohol or kerosene), using a load cell to restrain the vehicle and measure the resulting thrust curve. The team shall use this thrust data to perform a flight simulation on their rocket under "cold thrust".

2.5.5 STATIC HOT-FIRE TESTING

Static test firing of engines 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.

Launch Canada’s most important goal is to help promote a culture of safety, and just like in industry, a major part of that is ensuring designs and procedures are reviewed to catch any problem areas and provide feedback before the start of hazardous operations.

We want to make sure that all rocket testing is up to an acceptable standard that helps ensure that neither the team members nor the uninvolved public are ever placed at risk of injury during engine testing.

R2.5.26 SRAD propulsion systems in the “Launch” categories shall successfully complete an instrumented (propellant tank pressure, chamber pressure and thrust measurement at minimum), full thrust, full burn duration static hot-fire test prior to the competition.

In the case of solid rocket motors, or hybrid or liquid systems using ablative or otherwise consumable motor casing and/or nozzle components, this test need not be performed with the same motor casing and/or nozzle components intended for use at the competition (e.g., teams shall verify their casing design but, are not required to design reloadable/reusable motor cases).

A successful test shall be one that meets the full operational burn duration and demonstrates thrust and specific impulse within the team’s designed-for limits.

- Test data shall be made available to LCRA after testing (see Rules & Requirements Guide for details).
- The test motor setup shall be representative of the flight motor in all respects.
- Any changes to the flight motor shall be substantiated by subsequent hot-fire testing and resubmitted along side the previous test.

R2.5.27 Prior to hot fire testing, the team shall submit their test stand design and procedures for a safety review per the Launch Canada Requirements for Static Test Firing Approval.

In case of a no-go decision, feedback will be provided to the teams to detail any shortcomings and recommended corrective actions, and when they have been addressed to Launch Canada’s satisfaction, testing can commence.

2.5.6 ENGINE TEST STANDS

While it may be tempting to maximize use of flight hardware as part of a test stand, and indeed it is important for the test stand to be as "flight like" as possible, it should be emphasized that a test stand ultimately fulfills a different function than a flight system, and its design should reflect this.

In particular, flight systems typically strive to minimize weight, at the expense of lower margins of safety and/or more involved design, analysis and testing. A 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 a rocket engine's flaws are first revealed (often via a RUD - "Rapid, Unscheduled Disassembly"), so the 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 [7] for tankage are strongly recommended.

Similarly, while a flight vehicle has many space constraints, a 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 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.

R2.5.28 ***Final testing for all deliverables including cold flow, hot fire and abort testing shall be performed on the flight hardware with all systems available on the flight vehicle present.***

See Section 2.2.3.4.6 for test requirements on flight hardware. Additional ground-based abort systems may be present but shall not be used for the abort test. Use of an abort system not present on the flight vehicle (after the abort systems available in the flight configuration fail) in the abort test or a failed static fire test counts as a failure of your abort test and shall be documented to LC if it occurs. Never lose an opportunity to test flight abort systems.

R2.5.29 ***If a 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.***

R2.5.30 ***The test stand shall be firmly anchored to the ground in such a way that it cannot move or slide under at least 2x the maximum load to which it will be exposed.***

Make sure that mounting of the test stand is rigid enough not to result in disproportionate loading of anchors or anchor bolts resulting in subsequent overloading (zippering of bolts) resulting in the loss of anchoring. In the zippering case a safety factor of 2 might not be sufficient. Take precautions to limit the chance that if a motor carriage or cradle becomes loose that the motor or engine crashes into the ground or is caught so it does not create a hazard to the local population or terrestrial or aerial infrastructure, in other words, don't hit your neighbours or aircraft.

2.5.7 STATE DETECTION

R2.5.31 ***The propellant loading state of the rocket in all operations (including, but not limited to, filling and aborting) shall be available to launch control personnel at all times.***

For example, this could be accomplished by a load cell on the launch rail measuring the rocket's mass, a capacitive measurement of propellant level, etc.

R2.5.32 Any state detection system shall be tested and tuned prior to arrival at competition and checked after pad setup in case anything was damaged, or calibration was lost in transit.

Given the history of these systems, load cell measurements are the most likely to work reliably and integrate easily into launch control systems. Development of another method carries the risk of a low starting technology readiness level. Pressure measurement of the oxidizer tank is also required to make sure the vehicle is safe to approach.

R2.5.33 Thermally controlled supply tanks shall have adequate temperature and pressure control and state detection. This includes mass of supply tanks.

R2.5.34 For all fill systems, the pressure of the mother (also referred to as the "supply") bottle(s) shall be readily available to both pad and launch control personnel at all times.

This may include the use of pressure transducers for transmission to LCO and mechanical gauges for people conducting operations at the pad for leak tests, final launch setup and safing operations.

As stated in Section 2.2.1.1, any sealed system shall have a pressure relief device at the assumed maximum expected operating pressure. If you are heating a mother bottle that isn't supposed to supply N_2O to your system at, say 1,000 psi, you would require a 1,000 psi pressure relief valve to prevent over pressurization due to overheating.

R2.5.35 If the team intends to conduct temperature control autonomously, they shall also have a PID control loop to control power to any heater or chilling unit to prevent over or under pressure on your supply. A team member can be designated to watch valves and form a human version of this programming by turning on and off a heater or chiller.

R2.5.36 The PID/human loop shall be tuned or trained to the acceptable pressure ranges of your engine to prevent operation outside expected pressure ranges which would trigger your pressure relief valves and lead to loss of propellant.

3.0 STAGED ROCKETS

3.1 BASIC REQUIREMENTS

Because of the greater complexity of multi-stage flights, teams are required to provide additional information on the details of their system. See Appendix B of the Launch Canada Rules & Requirements Guide.

R3.1.1 ***All upper-stage ignition systems shall comply with the requirements and goals for "redundant electronics" as defined in section 4.8 and "safety critical wiring" as defined in section 6—understanding that in this case "initiation" refers to upper-stage ignition rather than a recovery event. The exception to this is that a redundant flight computer for ignition is NOT required.***

The above requirement applies generally to upper-stage ignition **systems** as these are deemed to be a safety-critical function. So, for example, redundant igniters shall be employed. It is however necessary to employ a single flight computer for ignition. In general, a failure that results in a premature ignition of the upper stage, or ignition when the vehicle is in an improper orientation, is worse than one that simply results in the upper stage failing to ignite, and the use of a second flight computer could increase the probability of this type of failure.

R3.1.2 ***Staged flights shall have a minimum thrust-to-weight ratio of 10 on the booster.***

R3.1.3 ***The sustainer shall have a minimum thrust-to-weight ratio of 5.***

R3.1.4 ***All upper-stage propulsion systems shall be designed to:***

- ***Prevent motor ignition during arming on the ground or in the event of a misfire;***
- ***Inhibit motor ignition in the event of a non-nominal flight (e.g., a rocket that is tumbling);***
- ***Be capable of being disarmed in the event the rocket is not launched***

3.2 STAGED FLIGHT COMPUTER REQUIREMENTS

R3.2.1 ***Ignition of air-starting upper stage motors shall be accomplished using a COTS flight computer that has the capability of performing an "altitude check" that can inhibit air-start ignition below a pre-selected altitude and tilt lockout***

R3.2.2 ***Multi-stage projects shall employ tilt inhibition.***

Projects using tilt-inhibit may be allowed to launch at an elevation of 87º±1º, rather than at 84º±1º, at the discretion of launch officials. Tilt limit shall not exceed 15º but should be less than 10º.

Currently available flight computers that have this capability include, but are not limited to:

- Multitronix Kate 2
- Featherweight Raven (You shall epoxy the capacitor to the board, as this can fold in high g flight otherwise)
- Altus Metrum Telemega, EasyMega and EasyTimer
- MARSA Systems MARSA 54 or MARSA 33 with Tilt Module & Interface

R3.2.3 ***Student-built, non-commercial flight computers shall not be used for the purpose of igniting***

air-start motors due to reliability concerns for this safety-critical operation.

A team may request a deviation to this requirement in cases where their flight computer has been thoroughly tested both on the ground and in flight. Redundant flight computers may be used for air-start ignition but are neither required nor recommended.

R3.2.4 ***Simple timers shall not be used except when used in combination with altitude and tilt lockouts.***

3.3 STAGED FLIGHTS: ARMING PROCEDURES

R3.3.1 ***All projects shall have provisions for preventing sustainer motor ignition on the ground.***

A provision to open the circuit between the flight computer and the initiator during power-up of the flight computer is mandatory. Shunting the sustainer igniters is required. Examples of recommended switch designs are provided in Appendix D.

R3.3.2 ***Flight computers shall not be armed until the rocket is in a vertical position.***

R3.3.3 ***The electronics configuration shall be designed such that the provision used to open the circuit to the initiator can be used to again open the circuit to the initiator in the event that the rocket is not launched.***

3.4 STAGED FLIGHTS: MOTOR INHIBIT DURING FLIGHT

R3.4.1 ***The flight computer controlling air-start motor ignition shall be configured to inhibit ignition of the air-start motor unless boost burnout has been detected and the rocket has reached an altitude of at least 80% of the simulated altitude for nominal initiator firing.***

R3.4.2 ***The flight computer shall be configured to prevent the air-start motor from firing at a later time if the altitude threshold was not achieved.***

4.0 RECOVERY

4.1 DUAL-EVENT PARACHUTE & PARAFOIL RECOVERY

R4.1.1 Each independently recovered launch vehicle body anticipated to reach an apogee above 1,500 ft (457 m) above ground level (AGL) shall follow a "dual-event" recovery operations concept (CONOPS).

Dual event recovery consists of an initial deployment event with a drogue parachute deployment (or a reefed main parachute) at or near apogee, followed by a main deployment event (e.g., a main parachute deployment or main parachute un-reefing) at much lower altitude.

Independently recovered bodies whose apogee is not anticipated to exceed 1,500 ft (457 m) AGL are exempted and may feature only a single/main deployment event.

The Jolly Logic Chute Release (JLCR) is NOT considered to be “redundant electronics” and will not be permitted to be used for any main parachute over 48” in diameter or for rockets over 10 kg at the time of separation.

Tender Descender and other “cable cutter” systems that are appropriately rated for large parachutes are acceptable as long as they have been thoroughly tested. Teams are strongly encouraged to be aware of the known failure modes of such systems given the extremely chaotic and violent environment experienced by a rocket during the deployment phase and take steps to mitigate them to the extent possible. Proper operation shall be realised through reading the manual and careful following of procedures.

4.2 INITIAL DEPLOYMENT EVENT

R4.2.1 The initial deployment event shall occur at or near apogee to stabilize the vehicle's attitude (i.e., prevent or eliminate tumbling) and prevent or eliminate a ballistic landing.

R4.2.2 The drogue chute shall also reduce the vehicle’s descent rate enough to permit the main deployment event yet not so much as to exacerbate wind drift.

Appropriate descent speeds under drogue should be between 75 and 100 ft/s [23-30 m/s]. The descent rate under drogue shall be between 50 and 150 ft/s but it should be noted that low speed descents may drift beyond acceptable limits and high-speed descents require excess working load limits for recovery systems. A new tool has been made to help teams in planning for selecting parachutes and hardware taking into account desired descent velocity and working load limits.

Recovery Spreadsheet Calculator: Recovery Working Loads, Parachute Sizing, Charge Sizes, etc

https://docs.google.com/spreadsheets/d/1AezgY8HW-Kr7_4ONDssi1_jQIH061h8b4-JzhElPhQU/edit?usp=sharing

4.3 MAIN DEPLOYMENT EVENT

R4.3.1 The main deployment event shall occur at an altitude no higher than 1,500 ft (457 m) AGL and reduce the vehicle's descent rate sufficiently to prevent excessive damage upon impact with ground (i.e., less than 30 ft/s [9 m/s)]). The touch down velocity should be closer to 20 ft/s to reduce damage upon touchdown when calculated drift allows.

While it is often assumed that the highest loading on a rocket is during the highest thrust level of a motor or at max q, in amateur sounding rockets the highest forces are observed in rapid main parachute openings. These hard openings have sheared quicklinks, shock cords, swivels and particularly eye bolts and eye nuts. A recovery system shall do a few things for a successful rocket flight: set down the rocket at a low enough velocity that the rocket is not damaged, prevent the rocket from drifting out the waiver, preventing the rocket from drifting so far as to make recovery efforts too arduous, and to prevent the rocket from accelerating past a velocity on the way down that the main opening forces destroy the recovery system.

4.4 EJECTION GAS PROTECTION

R4.4.1 ***The recovery system shall implement adequate protection (e.g., fire resistant material, pistons, baffles etc.) to prevent hot ejection gases (if implemented) from causing burn damage to retaining chords, parachutes, and other vital components as the specific design demands.***

4.5 PARACHUTE LINKS

R4.5.1 ***The recovery system rigging (e.g., parachute lines, risers, tethers, etc.) shall implement swivel links at connections to relieve torsion as the specific design demands.***

This will mitigate the risk of torque loads unthreading bolted connections during recovery.

R4.5.2 ***If quick links are used, they shall be torqued adequately and/or incorporate a locking feature to prevent loosening in flight.***

Use of Loctite is a simple means of securing threads against vibration.

As a good practice, masking or coloured tape may be added around the link after torquing to provide a visual indication that it was torqued and to help prevent impact damage to the structure.

4.6 PARACHUTE COLORATION & MARKINGS

R4.6.1 ***When separate parachutes are used for the initial and main deployment events, these parachutes should be highly dissimilar from one another visually.***

This is typically achieved by using parachutes whose primary colours contrast those of the other chute. This will enable ground-based observers to more easily characterize deployment events with high-power optics. Colours of parachutes should be chosen to enhance visibility in the sky, evergreen canopy and among field wood. Use of multi colour chutes with contrasting panels but different colours from between a drogue and main will maximize visibility while maintaining the ability to easily distinguish between parachutes.

4.7 NON-PARACHUTE RECOVERY SYSTEMS

R4.7.1 ***Teams exploring other (i.e., non-parachute or parafoil based) recovery methods shall notify LCRA of their intentions at the earliest possible opportunity and keep LCRA apprised of the situation as their work progresses.***

LCRA may make additional requests for information and draft unique requirements depending on the team's specific design implementation.

Range Safety personnel may deem the design as unsafe if they feel there is a possibility that the recovery system could allow the vehicle to depart the recovery area.

4.8 RECOVERY SYSTEM REDUNDANCY

R4.8.1 ***Launch vehicles shall implement completely independent and redundant recovery systems, including:***

- ***Arming switch***
- ***sensors/flight computers***
- ***power supply***
- ***energetics***
- ***"electric initiators"***

R4.8.2 The systems shall be designed such that if the primary system fails, the backup system will ensure a safe recovery of the launch vehicle.

In this context, the electric initiator is the device energized by the sensor electronics (i.e., flight computer), which in turn initiates some other mechanical or chemical energy release to deploy its portion of the recovery system. Examples of an electric initiator include electric matches, nichrome wire, etc.

Note that for a system to be considered redundant, it shall be possible to completely remove or disable ANY single component and still have the system performing nominally. In other words, if any component is shared by both the primary and the backup system, those systems are not fully redundant.

R4.8.3 At least one redundant recovery system electronics subsystem shall implement a proven COTS flight computer (e.g., StratoLogger, G-Wiz, Raven, Parrot, AIM, EasyMini, TeleMetrum, RRC3, etc.).

This flight computer may also serve as the official altitude logging system specified in Section 2.6 of the *LC Rules & Requirements Guide* [1]. Teams should have a second cots altimeter to increase the likelihood of successful deployment.

R4.8.4 The COTS flight computer shall fire either the primary or backup energetic system.

To be considered COTS, the flight computer (including flight software or firmware) shall have been developed and validated by a commercial third party. Commercially designed flight computer “kits” (e.g., the Eggtimer) will not be considered COTS, nor will any student developed flight computer be assembled from separate COTS components. Similarly, any COTS microcontroller running student developed flight software will not be considered a COTS system.

There is no requirement that the redundant/backup system be dissimilar to the primary; however, there can be advantages to using dissimilar primary and backup systems. Such configurations are less vulnerable to any inherent environmental sensitivities, design, or production flaws affecting a particular component.

R4.8.5 The COTS flight computer shall be fully electrically isolated from any other avionics.

The COTS flight computer shall have a truly independent electrical circuit. No electric match may be shared with any other deployment device. The CO2 or black powder ejection system to be activated by the COTS system shall not be shared with any other deployment device. Any remote disarming switch for the COTS flight computer shall be solely used for that COTS flight computer. The power supply and switching for the COTS flight computer cannot be shared with any other avionics.

4.9 SRAD RECOVERY ELECTRONICS

Teams are encouraged to develop their own flight computers, however SRAD flight computers shall be well documented and provide proof of function.

R4.9.1 ***To be acceptable for use as part of a recovery system at the competition, SRAD flight computers shall be thoroughly ground tested.***

Note that testing shall include accelerometer and / or barometric functionality testing. Voltage and current measurements over time shall be taken of any deployment test for simulated operation including all phases marked in the plots of voltage and current from boot up, arming, launch detection, Mach, motor burn out, apogee, main deployment, and touch down. Teams shall also conduct tests to ensure that settings are saved after shutdown. Avionics testing shall also be conducted to determine what happens in an aborted boot up sequence. Brown out testing shall also be conducted.

R4.9.2 ***SRAD flight computers that will be performing a recovery or other safety-critical function should additionally be flight tested prior to the competition, for example as a payload on a smaller vehicle.***

Note that while the use of a COTS system in addition to an SRAD system can safeguard against the failure of the SRAD system to fire a recovery event, it does not address the case where the SRAD system fires prematurely. Passing through the sonic region in particular will lead to a sudden pressure change which can be erroneously detected as apogee if the system has not been specifically designed to avoid this. Teams wishing to fly a SRAD system as part of their recovery avionics are strongly encouraged to implement safeguards against the premature firing of the SRAD system. Teams should conduct a flight test for SRAD altimeters intended for control of flight events. This testing need not be done on the full-scale vehicle as subscale testing can be conducted at a fraction of the cost. It is recommended that a separate board be used to measure voltages across an incandescent (ohmic not a diode) Christmas light (as they are cheap after December). The voltage vs times plots can be backed up with a photosensor to check that the flight computer is delivering enough current to set off an electronic match (tested with this reusable indicator). If the team intended to have an extensive flight computer production team including the assembly of Egg timer rocketry products such a watchdog board would allow rapid quality control testing for your team.

4.10 RECOVERY SYSTEM ENERGETIC DEVICES

R4.10.1 ***All stored-energy devices (i.e., energetics) used in recovery systems shall comply with the energetic device requirements defined in Section 5.0 of this document.***

4.11 RECOVERY SYSTEM TESTING

The following requirements concern verification testing of all recovery systems. LCRA recommends teams complete these tests by no later than 1.5 months before the competition. While not a requirement, this date is recommended to ensure teams have time to address any problems revealed during testing in time for the competition.

R4.11.1 ***Teams shall comply with all rules, regulations, and best practices imposed by the authorities at their chosen test location(s).***

4.11.1 GROUND TEST DEMONSTRATION

R4.11.2 ***All recovery system mechanisms shall be successfully (without anomalies) tested prior to the LC Challenge, either by flight testing, or through one or more ground tests of key subsystems.***

R4.11.3 ***In the case of such ground tests, sensor electronics shall be functionally included in the demonstration by simulating the environmental conditions under which their deployment function is triggered.***

4.11.2 OPTIONAL FLIGHT TEST DEMONSTRATION

While not required, a flight test demonstration may be used in place of some ground testing. In the case of such a flight test, the recovery system flown will verify the intended design by implementing the same major subsystem components (e.g., flight computers, deployment mechanisms and parachutes) as will be integrated into the launch vehicle intended for the LC Challenge (i.e., a surrogate booster may be used).

Flight testing of subsystems does not have to occur on a full-scale flight vehicle. Subscale testing can be rather affordable and allow for more flights per dollar maximizing subsystem testing.

5.0 STORED ENERGY DEVICES

5.1 HAZARD TYPES & STATES

A useful concept for how to approach hazards is found in the NASA Wallops Flight Facility Range Safety Manual (GSFC-STD-8009) [20].

A hazard is defined broadly as "a state or condition that could lead to an undesirable consequence (i.e. casualty or property damage)". Hazards may be broken down into:

- CATASTROPHIC HAZARD: A hazard, condition or event that could result in a mishap causing fatal injury and/or loss of vehicle, payload or ground facility.
- CRITICAL HAZARD: A hazard, condition or event that may cause severe injury or occupational illness, or major property damage.
- MARGINAL HAZARD: A hazard, condition or event that may cause minor injury or minor occupational illness to personnel.

A HAZARDOUS SYSTEM is one that, by the expenditure of its own energy, or because it initiates a chain of events, may result in one of those three categories of hazard.

Hazardous systems may be broken down into two categories:

- CATEGORY 1: A hazardous system whose consequence of inadvertent initiation **cannot be physically contained**, regardless of hazardous system state. Reducing the likelihood of inadvertent initiation of a Category 1 system (i.e. using inhibits) does not change the consequence of the associated hazard. A manned spacecraft would be one example.
- CATEGORY 2: A hazardous system whose consequence of inadvertent initiation **is physically contained when personnel would be exposed to the hazard**. Containment of the hazard mitigates the safety consequence of the hazard effects to a negligible level. A **properly designed and executed** engine static test or amateur rocket launch would be examples.

The system's HAZARDOUS STATE defines the likelihood of hazard exposure, and this is what is used to determine personnel restrictions while working on or within the system's hazard area (i.e. the area within which personnel could be exposed to the hazard).

- A-STATE: The system has **increased potential** of inadvertent actuation or has a **high likelihood of hazard exposure** if inadvertently actuated. Generally, personnel restrictions (i.e. safety clear zones) are implemented and in effect when hazardous systems are in an A-State.
  An armed rocket on the launch rail or a pressurized liquid engine on the test stand are examples.
- B-STATE: The system has **decreased potential** for inadvertent actuation or has a **low likelihood of hazard exposure** if inadvertently actuated. Personnel restrictions are generally more relaxed and access to the system's danger area is permitted as long as it is consistent with the operation taking place.
  Setting up and fueling for a rocket launch or engine test would be an example of a system in the B-State.

The removal of inhibits, restraints or other safeties during processing may change the hazardous system from B-State to A-State, and increase the likelihood of inadvertent initiation. So when a solid-propellant rocket is on the launch rail, the act of arming the system moves it from B-State to A-State.

It is recommended that you keep these concepts in mind when designing, developing and operating your own systems

5.2 ENERGETIC DEVICE SAFING & ARMING

An energetic device is considered safed when two separate events are necessary to release the energy.

An energetic device is considered armed when only one event is necessary to release the energy. For the purpose of this document, energetics are defined as all stored-energy devices – other than propulsion systems – that have reasonable potential to cause bodily injury upon energy release. The following table lists some common types of stored-energy devices and overviews in what configuration they are considered non-energetic, safed or armed.

Table 2 - Some Common Types of Stored-Energy Devices

DEVICE CLASS	NON-ENERGETIC	SAFED	ARMED
Igniters/Squibs	Small igniters/squibs, nichrome, wire or similar	Large igniters with leads shunted (shorted together) and grounded	Large igniters with no-shunted leads
Pyrogens (e.g., black powder)	Very small quantities contained in non- shrapnel producing devices (e.g., pyro-cutters or pyro-valves)	Large quantities with no igniter, shunted igniter leads, or igniter(s) connected to unpowered avionics	Large quantities with non-shunted igniter or igniter(s) connected to powered avionics
Mechanical Devices (e.g., powerful springs)	De-energized/relaxed state, small devices, or captured devices (i.e., no jettisoned parts)	Mechanically locked and not releasable by a single event	Unlocked and releasable by a single event
Pressure Vessels	Un-pressurized pressure vessels	Pressurized vessels with two events required to open main valve	Pressurized vessels with one event required to open main valve

Note that these definitions are consistent with the ignition arming definition provided in Section 2.3 of this document, this requirement is intended to be more broadly applicable to sources of stored energy, for example energetics used by recovery systems, control systems, payloads, etc.

Note also that while R2.3.2 requires pyrotechnic engine igniters to be armed only after the launch rail area is evacuated to a specified distance, this requirement may permit personnel to arm other stored-energy devices at the launch rail, so long as their inadvertent actuation would not create an unacceptable hazard. Recovery system pyrotechnics, for example, can often be armed at the launch rail, whereas a pyrotechnic valve that could lead to the inadvertent flow of propellant or the premature pressurization of a system not rated for operation with personnel in proximity shall comply with all requirements for remote arming.

Teams should not bring excessive amounts of pyrogenic materials to the event. Do not transport more than one large container (~1 lb) of BP to the event.

R5.2.1 ***All energetics shall be safed until the rocket is in the launch position, at which point they may be "armed".***

R5.2.2 ***All energetics that could create a hazard to personnel if inadvertently actuated shall only be armed remotely when all non-essential personnel have been cleared to a safe distance.***

Only the individual arming the altimeters may be within the length of the longest shock cord from the base of the rocket. If there is a second individual to confirm arming beeps of an altimeter as part of procedures, then the arming individual may swap places with the accounting individual and they may swap again before moving to the next step in the procedure. Personnel attempting to confirm GPS lock do not have to be directly next to the tower while deployment charges are armed. If there are issues with the GPS then require the telemetry team to be next to the rocket fixes shall be made while deployment charges are off. In the event that the GPS processes active deployment functionality the arming individual and a telemetry team member can swap places.

R5.2.3 ***All energetic device arming features shall be externally accessible/controllable. This does not preclude the limited use of access panels which may be secured for flight while the vehicle is in the launch position.***

R5.2.4 ***All energetic device arming features shall be located on the airframe such that any inadvertent energy release by these devices will not impact personnel arming them.***

For example, the arming key switch for an energetic device used to deploy a hatch panel shall not be located at the same airframe clocking position as the hatch panel deployed by that charge, to ensure that if the panel inadvertently deploys when armed, the operator will not be in its path.

6.0 ELECTRONICS, AVIONICS & TELEMETRY

6.1 GENERAL

Many of the electrical systems onboard a rocket constitute “SAFETY CRITICAL WIRING”. For the purposes of this document, safety critical wiring is defined as electrical wiring associated with recovery system deployment events, any "air started" rocket motors (e.g. sustainers), or thrust vectoring / flight control functions. 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. See also Section 4.0 for relevant requirements applicable to recovery systems in particular.

R6.1.1 ***Electrical assemblies and devices shall be compatible with the external and self-induced electromagnetic environments that will exist during flight or testing.***

R6.1.2 ***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.***

R6.1.3 ***Onboard avionics and control systems shall be electrically isolated from any pyrotechnic or electro-explosive devices such that a short of a pyrotechnic device cannot disable the control system.***

R6.1.4 ***Electrical systems shall be designed to limit or prevent a short in one system from disabling other flight- or safety-critical systems.***

6.2 WIRING, HARNESS & CABLE MANAGEMENT

R6.2.1 ***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.***

R6.2.2 ***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.***

R6.2.3 ***All safety critical wiring/cable connections shall be sufficiently secure as 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.***

R6.2.4 ***Any overboard wiring harness connecting a run or abort valve to a control board located elsewhere in the vehicle shall be protected and secured from the airflow, and from abrasion with the launch tower.***

R6.2.5 ***In the event of a severed overboard wire harness, the attached electrical control system shall fail in a way that there is no effect outside the now isolated bay.***

It is strongly recommended that all separable cable connectors incorporate a positive locking feature and strain relief. Remember that electrical connectors are one of the most common sources of failures in amateur rocket projects. Use of suitable, high-quality, secure and vibration-tolerant electrical connectors can prevent a lot of wasted time spent debugging intermittent electrical problems and help ensure reliable operation in the high vibration and acceleration environment in flight.

6.3 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 a HAM license.
- 33 cm (900 MHz) units are somewhat less common but have the advantage of not requiring a HAM license. They typically have a shorter range than those transmitting on the 70 cm band.

R6.3.1 Transmitters and receivers used onboard the rocket 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.

R6.3.2 Antennas shall be located in sections of the vehicle that do not significantly attenuate the signal. Notably, carbon fiber and metal will block radio frequency (RF) signals. Fiberglass is preferred for RF transparency.

R6.3.3 RF transmitting antenna(s) should be located as far away from a receiving antenna as possible.

For example, a telemetry transmitter located next to a GPS receiver is not a good practice, with each transmission potentially swamping the receive section of the GPS and other electronics. The effect of this can range from intermittent operation of the GPS, to unlocking the position fix. Best practice is to keep the antennas one wavelength apart.

6.4 GPS TRACKING REQUIREMENTS

R6.4.1 All rockets at the Launch Canada challenge shall incorporate a GPS tracking solution.

R6.4.2 Teams shall be required to prove their tracking solutions are functioning before proceeding to the launch pads.

R6.4.3 At minimum, telemetry shall provide altitude, GPS coordinates and descent rate in m/s or ft/s.

This allows the state of the rocket in flight to be easily assessed and provides easy verification of recovery events.

6.5 FREQUENCY MANAGEMENT

Launch Canada will coordinate the assignment of frequencies to teams in the months leading up to the competition to ensure that each team has a frequency that is approved for use at the launch range and does not conflict with other teams. All frequencies used for team operations for communications, video streaming, ground control systems, GPS packet transmission frequency, and any telemetry shall be communicated to LC. Teams should conduct frequency analysis of RF devices to determine if any potential harmonics are present.

R6.5.1 ***Teams shall be able to quickly change frequencies on their transmitting and receiving stations if needed onsite.***

6.6 GPS REDUNDANCY

Teams may employ multiple GPS tracking solutions within their rocket.

R6.6.1 ***If multiple GPS tracking solutions are employed, at least one of these solutions shall meet the requirements highlighted in this section.***

6.7 RECOMMENDED COTS GPS TRACKER

Approved COTS GPS solutions for high power rocketry are easy to use and available at low cost. A few examples include:

Table 3 - Approved COTS GPS Solutions [12-14]

Vendor	Product		Website
Altus Metrum	TeleGPS, TeleMega, etc	70cm, APRS	https://altusmetrum.org
Big Red Bee	Beeline GPS, 2m, Iridium SBD	70cm APRS, 2m APRS NLOS Sat link	https://shop.bigredbee.com/
Featherweight	Featherweight GPS	900MHz	https://www.featherweightaltimeters.com /featherweight-gps-tracker.html
Multitronix	Kate 1/3	900MHz	https://www.mult itronix.com/kate3-transmitter.htm l
Missileworks	RTx/GPS	900MHz	https://www.missileworks.com/rtx
	T3	900MHz	https://www.missileworks.com/t3
Entacore	Aim XTRA	70cm, APRS	http://entacore.com/electronics/aimxtra

6.8 GPS FOR MULTI-STAGE ROCKETS

Projects involving multiple stages or deployables are encouraged to use the Big Red Bee 70cm GPS units or The Featherweight GPS system in each of the rocket stages and/or deployables. The Big Red Bee 70cm GPS unit has built-in GPS timeslot capability, which allows multiple transmitters aboard the vehicle to use the same frequency. Otherwise, each individual transmitting device aboard the vehicle would require its own unique frequency.

6.9 APRS SUPPORT

Though not a requirement, for 70cm GPS solutions, APRS solutions are **highly recommended**. The APRS protocol uses 1200 baud AFSK and the APRS packet format. See **http://www.aprs.org/doc/APRS101.PDF**

[15].

Using a standard and known protocol such as APRS aids the LCO, RSO and Recovery support teams in independently receiving transmitted data to determine rocket flight profiles. It also allows recovery volunteers to watch and locate landing areas.

6.10 SRAD GPS TRACKING SYSTEMS

SRAD GPS solutions are permissible but require significant additional documentation and testing. In particular, they shall meet the following requirements.

R6.10.1 ***SRAD GPS systems shall be able to easily and rapidly change frequency as needed on the launch range.***

R6.10.2 ***Transmit rep shall be set to 2 sec. Transmissions on the same frequency from different stages (transmitters) shall be shifted using GPS time slotting.***

R6.10.3 ***SRAD GPS units shall be thoroughly tested to 20% over the simulated apogee line of sight over the ground***

6.11 AMATEUR RADIO LICENSING

All student teams are **STRONGLY** encouraged to work towards obtaining their Amateur Radio Operator Certificate (HAM license).

The 70cm APRS GPS tracking solutions require a minimum of the primary user to be licensed at the Basic Qualification level or higher. This is a relatively simple certification to obtain. See https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf01862.html

R6.11.1 ***Teams shall have at least two members present at competition with a HAM license if they employ devices that transmit outside the license-exempt (e.g., 33 cm) bands.***

R6.11.2 ***The primary user shall know their callsign and use it on their transmissions.***

6.12 GPS TRACKING SOFTWARE SAFETY SOLUTIONS

Inspectors will insure:

- Team is using their assigned frequency.
- Members have appropriate HAM licensing (if required).
- All teams should label their rockets with their GPS frequency, in addition to the team name and number, and this label should be duplicated on each part of the rocket which could separate either by design or by accident.
- Transmitters and receivers are properly prepared.

6.13 FINAL GPS TRACKING SYSTEMS CHECKOUT

At the pads, teams will be instructed by the pad managers to turn on all electronics and confirm flight systems and GPS tracking systems are functioning properly.

- The team shall be able to communicate with their receiving station and confirm that GPS signals are acquired and functioning properly.
- Teams who cannot confirm GPS tracking signal will not be permitted to launch until the issue is resolved. Teams will not be allowed to delay launch operations and may have to return their rocket to the prep area.

6.14 ROCKET TELEMETRY SUMMARY

At the pads, teams will be instructed by the pad managers to turn on all electronics and confirm flight systems and GPS tracking systems are functioning properly.

Table 4 - Summary of Rocket Telemetry Solutions

Band	144-148 Mhz (2 meter band)	430-450 Mhz (70 cm band)	902-928 Mhz (33 cm band)
Licence type	Amateur	Amateur	None required
Antenna sizing (mid band)[1]	½ wave 1 meter ¼ wave 50 cm	½ wave 34 cm ¼ wave 17 cm	½ wave 16.4 cm ¼ wave 8.2 cm
RF Propagation in the air 100mW 90db loss budget[2]	>10km	>10 km	>10 km
RF Propagation <u>on</u> the ground 100mW 90db loss budget[2]	<4 km	<2 km	<1 km
APRS Protocol Products[3]	Big Red Bee Byonics	Altus Metrum Big Red Bee	Big Red Bee
APRS Pros	APRS is a mature, well supported protocol. While most amateurs use this on a specific frequency, the protocol is frequency independent. Thus, many Amateur radios will receive, decode, and provide direction right from the radio on any frequency. This location information can be provided to open-source products to show location on laptops, tablets, and cell phones. Software defined radios (SDR's) are also a receive option with the same mapping support.		
APRS Cons	No specific event transmissions such as launch, burnout, apogee. Generally, only GPS information is transmitted but extra information can be included if the manufacturer implements that feature. Amateur Licence is required for 2M and 70 cm bands		
Other Protocols Products[2]		AIM	Eggtimer Featherweight Missleworks Multitronics Real Flight Systems
Other Protocol Pros	No licence. Transmitter and receiver generally come as a package. Event triggers are planned for within the protocols such as launch detect, burnout apogee, landed etc. Some systems are more on a professional level and offer a better experience. Some have audio prompts		
Other Protocol Cons	Interoperability between manufacturers is nonexistent. Protocols are proprietary and not published. SDR's could open mapping options. Check software compatibility (IOS, Android, Apple, Linux, and Windows) for each manufacturer.		

<u>Notes:</u>
The bands listed are not the only bands available but are the typical ones used by available commercial products.
1:

Most manufacturers provide a suitable antenna for their product, the sizing above indicates what to expect.
All antennas should be impedance matched, in situ to gain best performance. ¼ wave antenna do better with matching when a ground plane is introduced but a ground plane is almost impossible to do in a rocket.
There are good enough Vector Network Analyzers (VNA) that offer a cheap way ($75-$200) to determine impedance matching. Search for "Nano VNA" and look for ones covering the frequency range you will be using (you probably don't need one going past 1.5 Ghz). There are a lot of choices available so look carefully.

2:

Free space path loss (dB)(FSPL)= 20 $\log_{10}$(distance(meter)) + 20 $\log_{10}$(freq (mhz))-27.55
Link Budget =(TX power (dBm) + TX antenna gain(dB) + RX antenna gain (dB) - RX sensitivity (dBm)) – FSPL
Above formulas could add other losses. Ensure a minimum link budget of 25-35 dB to deal with rolling ground features, forest, water.
3:
Product links
AIM
http://entacore.com/electronics/aimxtra

Altus Metrum
https://altusmetrum.org/index.html

Big Red Bee
https://shop.bigredbee.com/

Byonics
https://www.byonics.com/microtrak

Eggtimer
https://eggtimerrocketry.com/home/eggfinder-gps-tracking-system/

Featherweight
https://www.featherweightaltimeters.com/featherweight-gps-tracker.html

Missile Works
https://www.missileworks.com/rtx/

Multitronix
https://www.multitronix.com/

Real Flight Systems
https://realflightsystems.com/

7.0 ACTIVE FLIGHT CONTROL SYSTEMS

7.1 RESTRICTED CONTROL FUNCTIONALITY

R7.1.1 ***Launch vehicle active flight control systems shall be optionally implemented strictly for pitch, yaw and/or roll stability augmentation, or for aerodynamic "braking".***

R7.1.2 ***Under no circumstances shall a launch vehicle entered in the LC Challenge be actively guided towards a designated spatial target.***

LCRA may make additional requests for information and draft unique requirements depending on the team's specific design implementation.

7.2 UNNECESSARY FOR STABLE FLIGHT

R7.2.1 ***Launch vehicles implementing active flight controls shall be naturally stable without these controls being implemented (e.g., 2 launch vehicles implementing active flight controls shall be naturally stable without these controls being implemented (e.g., the launch vehicle may be flown with the control actuator system (CAS) – including any control surfaces – either removed or rendered inert and mechanically locked, without becoming unstable during ascent).***

R7.2.3 ***Attitude control systems (ACS) shall serve only to mitigate the small perturbations which affect the trajectory of a stable rocket that implements only fixed aerodynamic surfaces for stability.***

Stability is defined in Sections 10.3 and 10.4 of this document. LCRA may make additional requests for information and draft unique requirements depending on the team's specific design implementation.

7.3 DESIGNED TO FAIL SAFE

R7.3.1 ***CAS or ACS shall mechanically lock in a neutral state whenever either an abort signal is received for any reason, primary system power is lost, or the launch vehicle's attitude exceeds 30° from its launch elevation. Any one of these conditions being met shall trigger the fail-safe, neutral system state.***

A neutral state is defined as one which does not apply any moments to the launch vehicle (e.g., aerodynamic surfaces trimmed or retracted, gas jets off, etc.).

7.4 BOOST PHASE DORMANCY

R7.4.1 ***CAS or ACS shall mechanically lock in a neutral state (defined in Section 7.3 of this document) until the mission's boost phase has ended (i.e., all propulsive stages have ceased producing thrust).***

7.5 ACTIVE FLIGHT CONTROL SYSTEM ELECTRONICS

Wherever possible, all active control systems should comply with requirements and goals for "redundant electronics" and "safety critical wiring" as recovery systems—understanding that in this case "initiation" refers to CAS commanding rather than a recovery event. These requirements and goals are defined in Sections 4.8 and 6.0, with best practices for safety-critical wiring included in Appendix B of this document.

Flight control systems are exempt from the requirement for COTS redundancy, given that such components are generally unavailable as COTS to the amateur high-power rocketry community.

7.6 ACTIVE FLIGHT CONTROL SYSTEM ENERGETICS

R7.6.1 ***All stored-energy devices used in an active flight control system (aka energetics) shall comply with the energetic device requirements defined in Section 5.0 of this document.***

8.0 AEROSTRUCTURES

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.

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

Teams are strongly encouraged to research standard practices for aerospace structural design, analysis and testing, and to study the common practices used within the high power rocketry community. While innovation is always encouraged, gaining an understanding of common designs and approaches that have a long track record of success can foster a greater understanding of the underlying considerations and improve the chances of success.

For specific questions or interpretation of rules and best practices, teams are strongly encouraged to consult their mentor. LCRA can provide a list of available mentors if a team does not have one. Thermal expansion is a real factor to consider. Your rocket won't remain at room temperature throughout its flight. You need to account for the expansion and contraction of motor mount tubes due to temperature changes, including extreme Canadian temperatures and the high heat generated after the motor burns. Proper tolerancing is essential to handle these variations.

8.1 DESIGN DATA

Teams are strongly encouraged to create 3D CAD models and assemblies of their complete flight vehicle, down to the component level, to understand how each part meets its intended function. This information will help LCRA understand how the design meets requirements. It will also help the team in understanding the overall integration of the vehicle and avoid clashes or accessibility problems in the final hardware. Teams may also benefit from the use of visual models, where with modern 3D printers components can be drafted in cheap plastic and fit checked and used for integration tests before final components are machined. This is especially helpful to more tactile minds.

8.2 STRESS ANALYSIS

Teams are strongly encouraged to create Free Body Diagrams of the complete flight vehicle and break down the analysis to component level to understand how each part functions and carries the load(s) it is subjected to.

Analysis should also consider non-ideal conditions and remember to account for worst-case part tolerances. For example, if two sections of airframe are joined with a coupler, those sections could end up being canted slightly with respect to each other. The resulting loads could be very different than if the sections were assumed to be perfectly coaxial. Similarly, sudden gusts of wind can occur in flight, and a rocket passing through the jet stream can easily encounter winds of well over 150 km/h. Analyses should aim to capture such non-ideal phenomena.

Use of more advanced tools and analysis methods such as FEM and CFD is encouraged where necessary only, but not mandatory.

8.3 OVERALL STRUCTURAL INTEGRITY

R8.3.1 ***Launch vehicles shall be designed and 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.***

All critical load cases for all flight phases, including ground loads, shall be identified and analyzed.

A partial list of flight load cases to be considered are: launch phase, high-speed deployment, wind gust, fin flutter, thermal loads due to aerodynamic compression or motor operation, landing impact.

Some examples of ground load cases that need to be considered: handling, abuse and transportation.

Note that some of these cases may not be part of normal operation but they shall still be considered.

8.4 MATERIAL SELECTION

R8.4.1 PVC, PCL, PLA, PET, rPLA, rPETG, PE(and other similar low-strength 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 launch vehicle airframes.

Teams can use weaker plastics for fit testing and prototyping but for the parts that go onto the rocket properly chosen materials are of the utmost importance.

R8.4.2 Carbon steel shall never be used in cryogenic or sub-ambient applications.

Note that material selection also includes the proper selection of adhesives and hardware, and not just the obvious main structural components.

R8.4.3 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 technologies, but due to the variability in the source materials and the lack of mature industry standards in the processing of these types of parts, ground testing is required. Also be aware that fatigue can be a significant problem for additive materials, with a fatigue life that can be as much as 90% less than an equivalent machined part. This will be especially important to consider for components that might experience or be affected by vibration, flutter, or pressurization cycles: for example, fins, canards, other aerodynamic surfaces, any attachment components connected to them, and engine closures. Evaluation of such components shall consider fatigue effects.

R8.4.4 Additively Manufactured Parts shall be designed to exceed loading requirements.

For the use of additively manufactured structural parts the proper choice of printing processes, materials, slicing, and orientation of the part are high critical decisions that will impact safety. Teams shall develop standards and testing for printed parts for flight.

Moderate temperature filaments (such as PETG, ABS, ASA) and certain UV curative resins have been employed for years in supersonic flights. Some common cheap low temperature filaments such as PLA+ have shear modulus approaching Polycarbonate and with proper mechanical design and thermal protection can outperform plywood. It is the duty of the teams to develop appropriate slicer settings for the expected loading of the printed parts. It is of the utmost importance that print quality control is maintained to ensure that parts with poor layer adhesion, warping, and significant stress concentrators do not make it onboard the launch vehicle.

For subsonic flights heating can be minimal and, in some low stress cases, PLA+ is suitable for some structural airframe components. Moderate temperature filaments such as PETG, ABS, and ASA have shown sufficient thermal and mechanical properties for even transonic and low supersonic flight, which covers the flight envelope of the majority of competition rockets. Teams should determine thermal loading of leading edges and surfaces in the airstream to determine which are acceptable plastics such that the glass transition temperature of the material is not exceeded. FEA and topology analysis should be utilized to minimize part mass and select appropriate infill levels at an acceptable safety factor. Subscale testing is also important when it is possible.

There are modern 3D printers that employ randomly oriented fiber-reinforced plastic materials and even oriented fiber-reinforcement. These have appreciably higher strength than non-reinforced plastics and might be suitable for certain structural applications.

Range safety will be examining the use and potential over reliance of additively manufactured parts. When used properly additive manufacturing is a powerful tool that shall be wielded with care, cunning, and skill.

8.5 METALLIC TUBES

When the airframe is used as an integrated pressure vessel, it shall comply with the requirements for pressure vessels (see Section 2.2.2).

It is strongly recommended that seamless tubes be used rather than welded tubes.

Tubing should callout proper aerospace specifications and be sourced from appropriate suppliers to guarantee material properties and quality. Remember that properties of “mystery metal” tubing can vary significantly from the “theoretical” properties of the base material.

8.6 COMPOSITE TUBES

Composite tubes, particularly those made of carbon fiber / epoxy or fiberglass / epoxy, are commonly used for rocket airframes. Teams are encouraged to design and manufacture their own tubes, but these should be analyzed and tested. This is particularly critical when structures are being aggressively optimized for minimum weight. The lower the margins, the more important it is to thoroughly test!

Very long, slender tubes should be analyzed for buckling, as this is a very common failure mode.

R8.6.1 SRAD tubes shall be ground tested.

Ideally, testing should be under conditions as per R.8.3.1, but this may prove difficult and expensive. As a minimum test, tubes should be put in compression using the maximum thrust (not the average) that the motor can produce, plus a margin of at least 1.5 - 2.0.

Note that COTS composite tubes (usually filament-wound), procured from composite tube suppliers or rockery component suppliers can be used as-is when testing documentation is provided either for the individual tube or batch testing of a mass-produced tube.

R8.6.2 SRAD tubes shall not present obvious gross manufacturing defects.

Just a few examples of defects are large voids or delamination, improper fiber angle and/or wrinkling.

Local defects can be acceptable if the part has been designed, analyzed and tested accordingly; Margins of Safety shall take into account the inherent nature and difficulty of producing and inspecting high-quality composite components.

As a recommendation, teams should consider having in-field repair procedures defined to ensure their project is not grounded at the last moment.

8.7 MAJOR SECTIONS & COMPONENTS

The following paragraphs will describe typical components of the most common high power rocket configuration, using dual parachute deployment as a baseline. Depending on the vehicle design, not all the following sections may be applicable.

8.7.1 NOSECONE

The nosecone can experience thermal loads due to aerodynamic heating if the speed is high enough; supersonic flight regimes will create shockwaves and result in local heating due to compression. Proper material selection is important as is recognition of the flight regime experienced and expected thermal loads due to air friction and stagnation temperature. When the nosecone also houses antennas (e.g. GPS or telemetry), it shall also be made of a RF-transparent material such as fiberglass, and keep any metallic parts away from the antenna(s).

8.7.2 PAYLOAD BAY

If present, this bay often contains the rocket's useful payload as well as the main parachute and its recovery harness.

8.7.3 AVIONICS BAY

This bay usually holds the electronics used to monitor flight and activate the deployment charges. This short section commonly acts as a transition between the booster and the payload section. If RF transmitting or receiving electronics are included in this section, such as GPS or telemetry, it shall be made of an RF-transparent material such as fiberglass.

8.7.4 BULKHEADS

Bulkheads are primarily meant to seal one section from another, but they can also contribute to overall airframe stiffness as they can help stiffen the tubes when these are subjected to bending loads.

Bulkheads are also often used as a primary load path for the recovery harness and can thus be subjected to very high loads. Careful design and attachment is essential.

8.7.5 SUSTAINER

On multi-stage rockets, the sustainer section contains the upper stage motor, used after main motor burnout and booster separation. This section is a largely self-contained rocket in its own right and functions similarly to the booster section below.

8.7.6 BOOSTER

This section transfers the thrust from the motor to the airframe, as well as supporting the aerodynamic fins that passively stabilize the rocket.

8.7.7 AERODYNAMIC FINS

For unguided rockets, aerodynamic fins serve as the primary means of passively stabilizing the rocket. As such, they are among the most critical aerodynamic components on the rocket. Because they are relatively large but thin surfaces exposed to the airflow, they can experience extremely high loads.

Similar to the nosecone, fin leading edges are another area where thermal loads due to aerodynamic heating can be an issue and shall be addressed.

Aerodynamic forces on the leading edge of composite fins can cause delamination, where the layers of material separate at high speeds, especially if the edges are exposed. The bare leading edge of composite fins should not be exposed to supersonic or hypersonic airflow, as standard laminating epoxies cannot withstand the thermal loads at these speeds. While epoxy coating may be sufficient for short-duration high transonic and low-supersonic flights (with potential re-epoxying of the leading edge after flight), it is inadequate for high-supersonic speeds and beyond.

To minimize the risk of delamination, especially in composite or sandwich panels, the leading and trailing edges should be coated with epoxy after beveling or shaping. For short-duration transonic and low-supersonic flights, epoxy coating is usually enough. For longer durations or higher speeds, aluminum siding tape offers better thermal and mechanical protection. For high-supersonic speeds and beyond, stainless steel tape is recommended to provide greater resistance to the extreme temperatures and thermal loads from air friction.

Landing impact loads can also be surprisingly high and can often break an exposed fin, particularly when using "swept-back" fins that extend past the bottom of the airframe.
Adequate design, fabrication and attachment of the fins is essential for a safe and successful flight.

R8.7.1 All aerodynamic surfaces shall be designed to avoid flutter and divergence under all anticipated operating conditions.

Unless properly designed and built, one of the most common fin failure modes is flutter. Proper fin geometry and stiffness are key to avoid this issue. Left uncontrolled, fin flutter can quickly lead to catastrophic failure where one or more fins can detach and result in loss of stability of the rocket. This is an especially important consideration for rockets reaching the transonic or supersonic speeds. For an overview of fin flutter, refer to NACA Technical Note 4197 [21].

When the fins are attached to the main structure using adhesive, sufficient fillet radius to disperse the load is critical.

Common practice in high power rocketry is to use "through-the-wall" fin mounting, where instead of bonding the fin root to the surface of the airframe, slots are cut in the airframe to allow a tab on the root edge of the fin to pass through the airframe wall. The fin root is bonded to the outside of motor mount tube and reinforced with epoxy fillets. Generous epoxy fillets are additionally applied between the fin and the outside of the airframe, resulting in a fin that is securely bonded to both the airframe and the motor mount tube inside it.

Figure 8.1 - Through-Wall Fin Mounting [http://jcrocket.com/kitbuilding.shtml]

For added strength, additional lamination of composite may be used, with plies running down the surface of one fin, along the body, and up the neighbouring fin, joining the fins and the body in a single solid structure. This approach provides significantly greater strength than epoxy fillets alone. This technique is particularly important on minimum diameter rockets that do not have the necessary internal space for through-the-wall fin mounting. An illustration of this technique is shown in Figure 8.2.

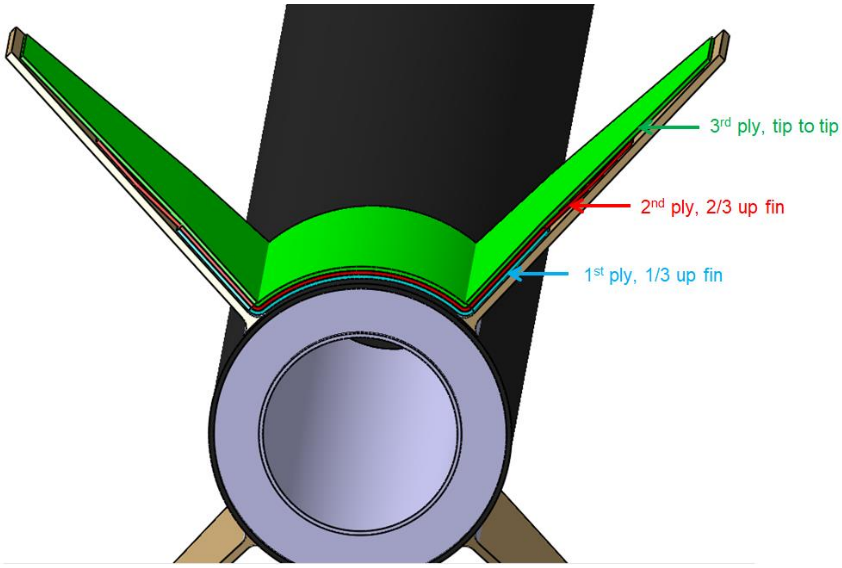

Figure 8.2 - Tip to Tip Fin Reinforcement

8.7.8 MOTOR MOUNT

The role of the motor mount is to safely transfer the large thrust loads from the motor to the vehicle, while also securely holding the motor in place and retaining it so that it cannot come loose from the vehicle at any time in flight. It shall be designed with careful consideration of the load path, ensuring that loads are only transferred through components that are designed for that purpose.

Manufacturing technique and build quality are critical due to the loads involved. Bonded structures should employ suitable epoxies and all bonded surfaces should be properly prepared.

In high power rocketry, common practice is to make use of a motor mount tube that the motor can slip inside. Multiple centering rings are bonded to the inside of the airframe and outside of the motor mount tube to keep the tube carefully aligned within the airframe. When combined with the use of through-the-wall fin mounting (see 8.7.7), the fins, airframe, centering rings and motor mount tube all work together to form a strong structure.

R8.7.2 Motors shall be secured to the airframe by mechanical retention.

Friction fitting of motors within the mount is not suitable for large high power rockets.

R8.7.3 Motor mounts shall secure or retain the motor such that no loads are transferred through any motor components that are not specifically designed to be in the load path.

In particular, COTS motors with floating forward closures (i.e. ones that are not rigidly secured to the motor case, with threads for example) are **not designed to transfer thrust loads through the forward closure**. Doing so can lead to forward closure failure. In such motors, thrust loads shall be transferred to the vehicle via the motor case, and **not through the forward closure**. A common practice is to transfer thrust directly to the airframe from the aft end of the rocket via a thrust plate.

Figure 8.3 - Allowable Thrust Transfer Locations on Motors with Floating Forward Closures

R8.7.4 Motor mounts and all materials composing them shall be designed to withstand all temperatures to which they will be exposed.

COTS motor cases are typically certified in the United States to an average temperature of 200°F. While the Canadian requirement is 200°C none of certified reloads are Certified only in Canada meaning all certified reloads in Canada match the American standard of 200°F. Also if a motor got to 200°C the aluminium could lose its temper leading to case failure. This is a case averaged temperature such that there might be hot spots that exceed this temperature typically near the top of the nozzle and where a forward seal disk is present. It can be exacerbated by propellant bubbles or ungreased or glued o-rings in a bates grain. Some of this thermal energy will dissipate into the motor mount and airframe. As a result, any such components shall be capable of withstanding these temperatures without being structurally compromised. For example, low temperature plastic components such as PLA will tend to soften at these temperatures. If FDM printed parts are utilized in a thrust structure there should be an insulative layer of a higher temperature insulating material such as cardboard on the lower impulse end and even phenolic or other composites at the higher end where most printed parts would not be appropriate except in some extreme examples outside the scope of this section.

8.7.9 AIRFRAME COUPLERS

Coupler joints are usually present at all sections where the rocket shall be disassembled. Some joints shall come apart in flight as part of the recovery system deployment sequence, while others shall remain attached throughout the complete flight sequence and are only used to service the rocket on the ground.

R8.7.5 Airframe joints, regardless of the specific implementation (e.g., coupler tube, RADAX or other joint types), shall be sufficiently stiff to limit bending under flight loads.

Coupler joints which shall separate as part of recovery system deployment should be free and smooth, and offer minimal resistance to separation. At the same time, these joints should be as snug as possible to keep the whole rocket assembly as stiff as possible and minimize the possibility of "cocking" should they need to be separated in flight.

R8.7.6 Airframe joints shall be designed, manufactured and assembled to ensure the required concentricity of the airframe sections.

If airframe sections do not have feature(s) that ensure precise alignment, it is easy for the sections to end up canted with respect to each other after assembly. This can lead to very high loads on the joint in flight and potential failure. It is critical to ensure proper concentricity through design and assembly practices.

As well, there should be no visible gaps between mating sections to ensure loads are transferred evenly along their periphery.

R8.7.7 Airframe joints which implement "coupling tubes" should be designed such that the coupling tube extends no less than one body caliber on either side of the joint – measured from the separation plane.

Couplers shorter than this tend to allow an unacceptable amount of play and fail to keep the airframe sections sufficiently concentric. They also tend to result in excessive loads being transferred to the airframe when subjected to bending. Short couplers can additionally be prone to binding when attempting to separate the sections.

When friction is the main means of retention (e.g., no shear pins are used), there should be no “clocking of components” required to fit the sections together. The mating faces should have good control of their diameters and roundness.

R8.7.8 Rocket joints using friction as part of their deployment system shall have enough holding force to prevent premature separation in flight.

R8.7.9 Single stage rocket joints on vehicles in the Advanced category shall not rely on friction fit only.

Friction as a means of retention is only permitted for basic category, and/or for separation of booster to sustainer. Although simple to implement, friction fit is difficult to measure and control in the field and is very subjectively inspected.

8.8 DETAIL DESIGN

8.8.1 HARDWARE

R8.8.1 Load bearing eyebolts of the open eye, bent wire type shall not be used.

Any load-bearing eyebolts should be of the closed-eye, forged type. Welded eyebolts are also an acceptable solution to meet this requirement, as are U-bolts.

R8.8.2 All load bearing eyebolts shall be sized to handle the maximum loads to which they will be exposed.

Note that stainless steels typically have much lower tensile strength than the non-stainless steel alloys typically used for eyebolts or fasteners. This means that a stainless steel eyebolt or fastener of a certain size cannot be assumed to be interchangeable with an alloy steel one of the same size and shall be properly sized for the application. It should be noted due to the shape of eyebolts and eye nuts with their continuous curvature of the loop forces have to be directed around the loop which in high loading transient conditions such as the shock of a main opening tend to bend the eye into an ovular shape. When possible, u-bolts are preferred as they are more effective at transferring load into a bulkhead.

R8.8.3 Threaded components of the deployment system and attached to the structure shall be properly torqued and secured against loosening.

Hardware is often buried deep into the structure and can be difficult to reach and inspect after assembly. To prevent loosening in flight, use of permanent thread locking adhesive and/or epoxy potting is recommended. To prevent pull out when possible, washers of backplates should be used to help distribute loading on the back of the plate.

R8.8.4 Reefing rings should be used to minimize shock load by extending the duration of the opening transient

Reefing rings help reduce shock loads by extending the parachute's opening time.

A reefing ring is a metal loop that temporarily constrains the parachute’s skirt by sliding up the suspension lines as the parachute deploys, keeping it more compact, like a ballute, when it first encounters the airstream. As the parachute inflates, the suspension lines pull outward, but the ring holds them together, balancing the forces until it slides down to the swivel. The friction between the ring and the lines increases as the outward force grows, slowing the ring’s descent.

As the ring gradually moves down the lines, the canopy opens wider, increasing the drag progressively. Initially, at high speeds, the parachute stays constrained as a ballute, but as the speed decreases, the force and friction lessen, allowing the ring to slide further down. This process lengthens the parachute’s opening time, reducing peak shock loads without requiring complex mechanisms.

The parachute still fully deploys within a few hundred feet of descent, but using reefing rings minimizes the risk of main parachute damage, especially in cases where drogue deployment fails.

R8.8.5 All recovery hardware including COTS attachment points shall be designed to handle expected maximum recovery loads.

It is generally recommended to use dual-break, dual-deploy systems due to their reliability. When combined with positive retention of motors and thrust transfer structures, it is common to anchor the recovery system to the forward closure.

Many amateur rocketeers suggest attaching the drogue chute to the lower recovery bay and the main chute to the upper recovery bay, often citing the increased mass of the main parachute as a reason for improved stability. However, this explanation overlooks key considerations about why attaching the main chute to the forward closure is not ideal.

Forward closures are primarily designed for securing a motor, and in minimum diameter retainers, the larger thread at the top of the retainment baffle handles higher loading. The baffle is adhered to both the airframe and the engine, which helps distribute the loading. When a recovery system is directly attached to a forward closure, it works for smaller rockets where the opening force of the main parachute is lower, such as with a smaller drogue chute.

However, the forward closure limits the size of the eye nut or eyebolt that can be used, capping the maximum load that can be transferred through that connection point. To improve strength, it is preferable to use thicker U-bolts when possible, or even a Y-harness for additional support.

R8.8.6 Spin out prevention on eye bolts and eye nuts is required.

Rockets can spin under a parachute in windy conditions, so teams use swivels on every parachute to prevent tether tangling. A swivel on the tether line also helps prevent the line from wrapping over itself, though these systems can jam under high deployment forces.

To prevent eye bolts and eye nuts from spinning loose, rotation protection is essential. Loctite can be used, but it is less effective and should be considered as an additional measure, as it requires 24 hours to fully cure. For stronger protection, using thicker, stronger lock wire (safety wire) mounted off-center is recommended. Additionally, safety washers (such as Nord-Lock or Schnorr) should be placed under every eyebolt or eyenut to help distribute load and prevent loosening. However, the most secure solution is always to use a U-bolt.

8.8.2 VENTING

R8.8.7 ***Launch 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.

8.8.3 SHEAR PINS

Shear pins are commonly used to securely hold joined airframe sections together, while being designed to fail and allow the sections to separate when the ejection system fires. This helps ensure that the airframe sections do not prematurely separate due to internal pressure on ascent, vibration or shock loads. It is common practice to have at least 3 shear pins evenly distributed along the periphery of the joint to avoid cocking.

Shear pins shall be properly analyzed to ensure they are adequately sized.

R8.8.8 ***When shear pins are used as part of the deployment sequence, the deployment system shall be ground tested.***

Typically, this is done as part of a full recovery system deployment test.

R8.8.9 ***PEM nuts or press fit nuts should be used where possible to ensure a consistent shear and thread for nylon shear pins.***

There is a nut referred to as a PEM nut or a press fit nut that is designed with teeth for biting into a composite or metal sheet. There is also a PEM nut installation tool that is prohibitively expensive that really only works well for sheets and has little value to you. Instillation can be done with a grade 8 bolt, a nut, a wrench and a screwdriver and it works better for tubes regardless. Don't buy the insertion tool. These nuts work by drilling a specific hole size for that PEM nut and then pulling the nut into the hole such that the hardened steel nut provides a long-term female thread for screwing in nylon bolts (shear pins) or steel bolts for rigid connection points between airframe sections. If used with shear pins it makes the shear force required to break all shear pins consistent and prevents a zippering effect of the shear pins where they might be loaded one at a time which is a common failure mode in hand drilled shear pin holed. used in conjunction with a hole drilling guide effective standardized hole patterns can help with integration by removing clocking issues. Don’t buy the installation kit; get a bolt, a normal nut, a screwdriver and a wrench and pull it in from the other side. IF you have money at the end of the year do not buy instillation tools it will be a waste of money unless you do a lot of bolting to sheet metal. Seriously, PEM nuts are magnificent.

Other threading solutions exist such as threaded brass inserts but keep in mind the effective strength of a non-isotropic FDM printed part with an infill percentage less than unity and with and that one might insert the brass insert into needs to be of a higher shear strength than the injection molded nylon shear pin.

8.8.4 CHARGE WELLS

When pyrotechnic charges are employed for recovery system deployment, they are typically contained in a “charge well”. If used, the charge well should be designed and its material chosen to ensure it does not fracture and create shrapnel when in use. They should also aim to minimize any sparking potential. The use of brass or copper is suggested. Many plastic materials can readily build up a static charge which could cause premature ignition. PVC end caps, if they fragment while an e-match is being installed, can cause even more injury.

Note that charge well volume shall be no more than twice the volume of the intended black powder charge. Similarly, there are very few instances where charge size under 1 gram is appropriate as that often contributes to misalignment of an electronic match and failure to fire, let alone failure to generate enough pressure in competition sized recovery bays. Open volume of charge wells after inserting the e-match into the well should be packed with cellulosic insulation and taped down to maintain a seal during the boost phase and to help keep the pressure in the charge well until the BP is fully combusted.

Note that vinyl or pex tubing is also sometimes used to contain pyrotechnic charges for deployment especially at higher altitudes where wrapping epoxy or silicone sealed tubes in electrical tape can maintain pressure long enough to fully combust the black powder charges in reduced air pressures above 10,000 ft.

8.8.5 RAIL GUIDES

R8.8.10 Rail guides shall be mounted to reinforced "hard points" for mechanical attachment to the launch vehicle airframe.

These hardened/reinforced areas on the vehicle airframe, such as a block of wood installed on the airframe interior surface where each rail guide attaches, will assist in mitigating lug "tear outs" during operations. Fastening or bonding the rail guide to unreinforced airframe skin is typically not adequate for larger rockets. Where possible two bolts should be used to secure conformal rail guides to prevent spin out of bolts on mono bolt designs.

R8.8.11 Both rail guides shall be able to support the launch vehicle's fully loaded launch weight while vertical.

As the vehicle ascends, once the forward rail guide clears the rail, the aftmost guide will be carrying all the loads. At the LC Challenge, competition officials may require teams to lift their launch vehicles by the rail guides and/or demonstrate that the bottom guide can hold the vehicle's weight when vertical before permitting them to proceed with launch preparations. Teams should test the load carrying capacity of their rail guides in tension and compression. Given that the forces pull out when the rocket is vertical, and the forces push in while the rocket is being slid onto the rail.

R8.8.12 If the team intends to use one of the LCRA-provided launch rails, the rail guide shall be compatible with the system defined in Section 11.1.

It is strongly recommended that teams procure a section of the rail specified in Section 11.1 and perform a fit check well in advance of the competition. This is a good way to catch an improperly sized and/or aligned set of rail guides in advance. It is also a good way to verify that no other features on the vehicle, for example switches, camera windows, umbilicals or fairings, are in danger of clashing with the rail. Discovering this while installing your rocket on the rail at the launch pad is strongly discouraged!

8.8.6 IDENTIFYING MARKS

R8.8.13 The team's Team ID (a number assigned by LCRA prior to the LC Challenge), project name, academic affiliation(s) and contact information shall be clearly identified on the launch vehicle airframe, nose cone, and other locations where possible.

In case a rocket is lost, contact information for the team should be marked on the vehicle so that it can be returned if found.

R8.8.14 The Team ID especially, shall be prominently displayed (preferably visible on all four quadrants

of the vehicle, as well as fore and aft), assisting competition officials to positively identify the project hardware with its respective team throughout the LC Challenge.

There are no further requirements for airframe coloration or markings; however, LC offers the following recommendations to student teams.

- Mostly white or lighter tinted color (e.g., yellow, red, orange, etc.) airframes are especially conducive to mitigating some of the solar heating experienced during a launch on a hot day in the summer.
- High-visibility schemes (e.g., high-contrast black, orange, red, etc.) and roll patterns (e.g., contrasting stripes, “V” or “Z” marks, etc.) may allow ground-based observers to more easily track and record the launch vehicle’s trajectory with high-power optics.
- Any form of green and/or brown colours, for example as associated with camouflage patterns, are strongly discouraged. Remember, you may need to find your rocket in a forest, so make sure it stands out!

R8.8.15 ***The CG and CP location of the fully-loaded vehicle shall be clearly marked on the rocket. For liquid/hybrid rockets, the fully-fueled CG can be a calculated value.***

9.0 PAYLOAD

9.1 GENERAL

R9.1.1 ***Payloads shall be designed and integrated such that they do not compromise the safety or performance of the launch vehicle and its systems.***

9.2 PAYLOAD RECOVERY

R9.2.1 ***Payloads may be deployable or remain attached to the launch vehicle throughout the flight.***

R9.2.2 ***Deployable payloads shall incorporate an independent recovery system, reducing the payload's descent velocity to less than 30 ft/s (9 m/s) before it descends through an altitude of 1,500 ft AGL.***

R9.2.3 ***The payload recovery system shall ensure that any payloads recovered independently of the vehicle remain within the approved recovery area of the launch range.***

Note that deployable payloads implementing a parachute or parafoil based recovery system (for example to accommodate certain scientific / engineering packages requiring extended mission time) are not strictly required to comply with the dual-event requirements described in Section 4.0 of this document, unless it is impossible to ensure the payload remains within the recovery area without it.

9.3 PAYLOAD RECOVERY SYSTEM ELECTRONICS & SAFETY-CRITICAL WIRING

R9.3.1 ***Payloads implementing independent recovery systems shall comply with the same requirements and goals as the launch vehicle for "redundant electronics" and "safety critical wiring".***

These requirements and goals are defined in Section 4.0 and Appendix B of this document.

9.4 PAYLOAD RECOVERY SYSTEM TESTING

R9.4.1 ***Payloads implementing independent recovery systems shall comply with the same requirements and goals as the launch vehicle for "recovery system testing".***

These requirements and goals are defined in Section 4.11 of this document.

9.5 PAYLOAD ENERGETIC DEVICES

R9.5.1 ***All stored-energy devices (aka energetics) used in payload systems shall comply with the energetic device requirements defined in Section 5.0 of this document.***

10.0 TRAJECTORY & FLIGHT PERFORMANCE REQUIREMENTS

10.1 LAUNCH AZIMUTH & ELEVATION

R10.1.1 Launch vehicles shall nominally launch at an elevation angle of 84° ±1° and a launch azimuth defined by competition officials at the LC Challenge.

Range safety officers reserve the right to require certain vehicles' launch elevation be lower if potential flight safety issues are identified during pre-launch activities.

Competition officials may allow staged flights to launch at 87° ±1° if the rocket is using “tilt” to inhibit air-start motor ignition.

Note the tolerance expressed within the nominal launch azimuth is intended as nothing more than an expression of acceptable human error by the operator setting the launch rail elevation prior to launch.

10.2 LAUNCH STABILITY

R10.2.1 Launch vehicles shall have sufficient velocity upon "departing the launch rail" to assure they will follow predictable flight paths.

“Departing the launch rail” is defined as the first instant in which the launch vehicle becomes free to move about the pitch, yaw, or roll axis. This typically occurs at the instant the forward rail guide departs the launch rail. More generally, it is the moment that the ***last rail guide forward of the vehicle's center of gravity (CG)*** separates from the launch rail.

In lieu of detailed analysis, a rail departure velocity of at least 100 ft/s (30.5 m/s) is generally acceptable.

Teams unable to meet this requirement may use detailed analysis to prove stability is achieved at a lower rail departure velocity (greater than 50 ft/s [15.24 m/s]) either theoretically (e.g., computer simulation) or empirically (e.g., flight testing).

Note that LCRA will provide teams with launch rails defined in Section 11.1. Teams whose designs anticipate requiring a longer launch rail to achieve stability during launch shall provide their own. The requirements for team provided launch rails are defined in Section 12.0 of this document.

Note that given common placements of rail buttons and the length of the LC rails for the COTS teams that in order to achieve a rail exit of the ideal 100 ft/s a TWR (regardless of mass of the rocket and only dependant on the placement of the upper rail guide or button) of between 10-12 is needed. Given shifting mass budgets within the year we strongly recommend that in your initial designs and motor selection you prepare for a TWR of 12 or more in the Basic Category. In the Advanced Category many bring their own rails or towers which may have different length and their engines might not have a constant thrust on the rail so other factors remain but even in those categories higher TWRs mean higher stability and shorter launch towers.

10.3 ASCENT STABILITY

R10.3.1 Launch vehicles shall remain "stable" for the entire ascent.

“Stable” is defined as maintaining a static margin of at least 1.5 to 2 body calibers, regardless of CG movement due to depleting consumables and shifting center of pressure (CP) location due to wave drag effects (which may become significant as low as 0.5 Mach).

Stability will be considered nominal as long as it does not fall below 1.5 body calibers. Anything below this threshold will be considered a loss of stability.

R10.3.2 Two plots of stability (CP/CG) as a function of time shall be provided as part of the team's design review documents. The first shall detail the initial phase of flight up to rail departure, and the second shall cover the full ascent phase.

R10.3.3 If there is a maximum wind speed limit above which the rocket's stability could be compromised, this shall be identified by the team.

Note that Launch Canada allows launches to occur as long as ground wind speed does not exceed 30 km/h. Your stability analysis should demonstrate that acceptable stability will be achieved under this condition. If a lower wind limit is required, this shall be clearly indicated as part of your launch commit criteria.

10.4 OVER-STABILITY

R10.4.1 All launch vehicles should avoid becoming "over-stable" during their ascent.

A launch vehicle may be considered over-stable with a static margin significantly greater than 2 body calibers. While there is no clearly-defined threshold for over-stability, 6 body calibers or more will be considered over-stable as a general guideline. Over-stable rockets are especially vulnerable to crosswind or wind shear and are prone to weather-cocking hard into the wind.

11.0 GROUND SUPPORT EQUIPMENT

11.1 LCRA-PROVIDED LAUNCH SUPPORT EQUIPMENT

11.1.1 LCRA-PROVIDED LAUNCH RAILS

LCRA provides launch pads that feature 18.5 foot long, 1.5” x 1.5” aluminum guiderails of the 80/20® 1515 type. More details on 80/20® rail profiles may be located on the 80/20® Inc. website: https://8020.net/ [16]).

The rail segments mount onto a boom made of aluminum square tubing, and the boom mounts to a base. A boom rest allows the boom to be supported in the horizontal position for installation of the rocket. The angle of the boom is adjustable over a range of approximately ±6° from the vertical, at the discretion of the RSO, to ensure the rocket stays in the approved ballistic zone.

These rails are designed to be suitable for “typical” high power solid rockets using simple M through O motors. Optional guy wires are also available to provide additional stability to the rail, if desired. **It is up to each team to evaluate whether this launch rail is suitable for their own vehicle or not**, and whether to use the guy wires or not. Detailed drawings and CAD are available upon request.

Note that teams that have unique requirements, a particularly large rocket, or a mission that could be especially sensitive to flexing of the rail are encouraged to develop and bring their own rails. Teams flying hybrid or liquid rockets, where vehicle weights tend to be high and significant integration with ground support equipment is usually necessary, are strongly encouraged to develop and bring their own rails.

Teams that require access to elevated parts of their vehicle while it is on the launch rail should ensure they bring whatever equipment they need for this (e.g. ladders).

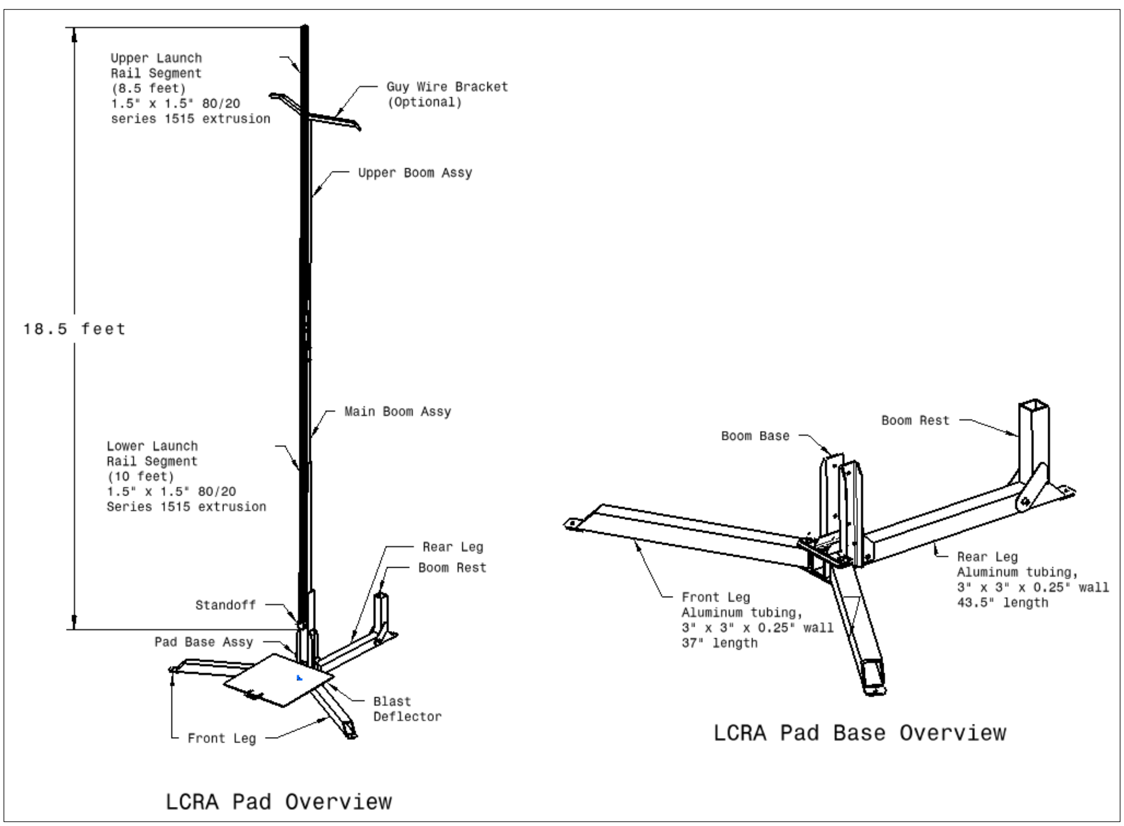

Figure 11.1 - Launch Canada Standard Pad Overview

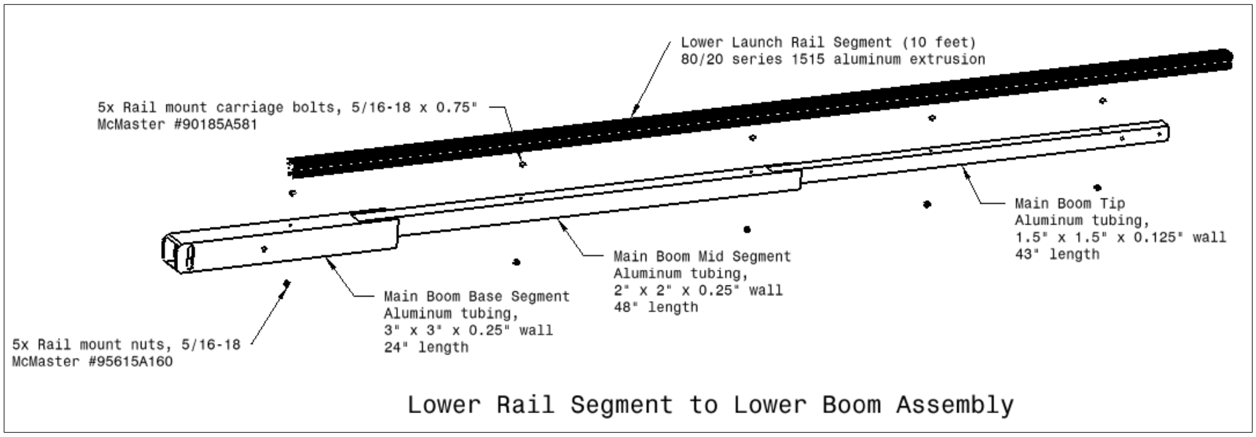

Figure 11.2 - Launch Canada Pad Main Boom

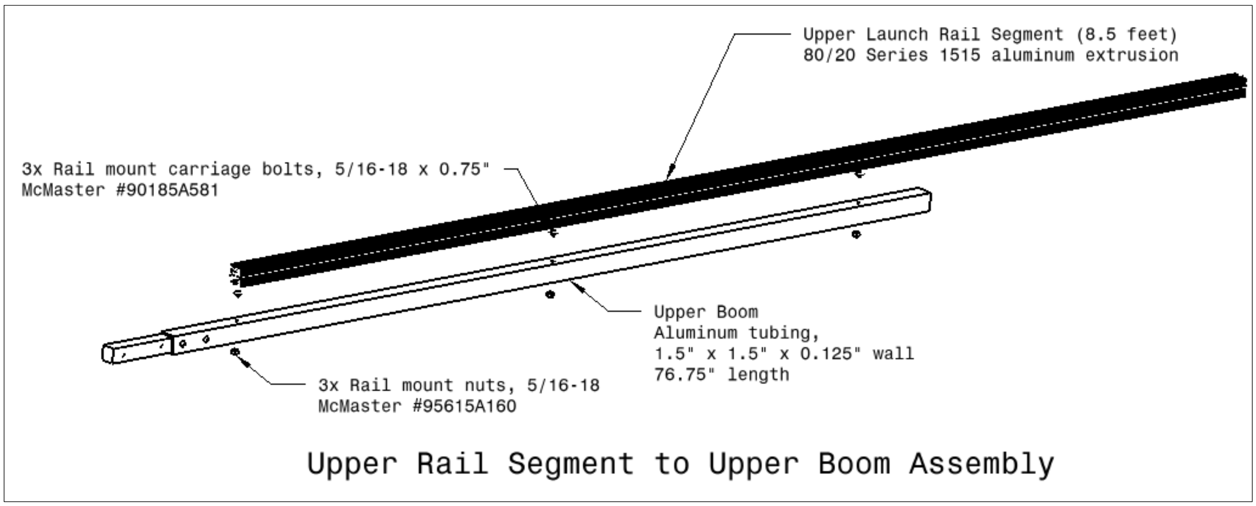

Figure 11.3 - Launch Canada Pad Upper Boom

11.1.2 LCRA-PROVIDED LAUNCH CONTROL SYSTEM

LCRA will provide a Wilson F/X Wireless Launch Control System consisting of one LCU-64x launch control unit and one PBU-8w encrypted pad relay box (More details on Wilson F/X Digital Launch Control Systems may be found on the Wilson F/X website: www.wilsonfx.com [17]).

Each pad relay box may connect as relay a launch command to as many as eight independent launch pads, and LCU-64x can accommodate up to eight relay boxes, enabling the launch control unit to command as many as 64 independent launch pads when fully configured.

Connection is by free wire ends from the motor igniter(s) into alligator clips wired to the pad relay box.

Fault tolerance, including propulsion system arming functionality is provided for simple/non-complex, single stage solid propellant rockets by signal encryption and physical arming keys located on the pad relay boxes and launch control unit.

11.2 TEAM-PROVIDED LAUNCH SUPPORT EQUIPMENT

11.2.1 EQUIPMENT OPERABILITY

R11.2.1 ***If possible/practicable, teams should make their launch support equipment man-portable over a short distance (a few hundred feet).***

Environmental considerations at the launch site permit only limited vehicle use vehicle use beyond designated roadways, campgrounds, and basecamp areas.

11.2.2 LAUNCH RAIL ELEVATION

R11.2.2 ***Team provided launch rails shall implement the nominal launch elevation specified in Section 10.1 of this document and shall be adjustable within the specified range.***

Actual elevation will be provided and confirmed by the range safety officer at the event.

11.2.3 OPERATIONAL RANGE

R11.2.3 ***All team provided launch control systems shall be electronically operated and have a minimum operational range of no less than 3,000 ft from the launch rail. An operational range of 3,500 ft or greater is preferred.***

The maximum operational range is defined as the range at which launch may be commanded reliably.

11.2.4 FAULT TOLERANCE & ARMING

R11.2.4 ***All team provided launch control systems shall be at least single fault tolerant by implementing a removable safety interlock (i.e., a jumper or key to be kept in possession of the arming crew during arming) in series with the launch switch.***

Appendix C of this document provides general guidance on assuring fault tolerance in amateur high-power rocketry launch control systems.

11.2.5 SAFETY-CRITICAL SWITCHES

R11.2.5 ***All team provided launch control systems shall implement ignition switches of the momentary, normally open (aka "deadman") type so that they will remove the signal when released.***

Mercury or "pressure roller" switches are not permitted anywhere in team provided launch control systems.

12.0 SAFETY

12.1 CHIEF SAFETY OFFICER

All members of a team share in the responsibility for safety of the team's activities and final products, and all have a vital role to play. But it is nevertheless important to have an individual who has explicit safety oversight for the team.

Per the *LC Rules & Requirements Guide* [1], each team is required to have a member who fulfills the role of Chief Safety Officer. Among other things, this individual is responsible for becoming familiar with the complete contents of this guide and ensuring that the team complies with them in their designs and operations.

R12.1.1 ***The Chief Safety Officer, or a designated member of the safety team, shall have oversight and insight for the technical requirements in this document and will be responsible for ensuring these requirements are met.***

12.2 ANALYSIS

12.2.1 HAZARD ANALYSIS

R12.2.1 ***Working with all leads, the safety officer shall conduct and maintain a hazard analysis to:***

- ***Identify and describe hazards, including but not limited to each of those that result from component, subsystem or system failures or faults; software errors; environmental conditions; human errors; design inadequacies; or procedural deficiencies.***
- ***Determine cost of replacement components probability of failure in order to outline what parts the team might need spares. A team for their own benefit might want to locate suppliers for parts near the competition to alleviate the need to purchase additional parts.***
- ***Working from your procedures as a starting point and your teams history of failure modes, prepare a probabilistic quantitative Failure Mode and Effect Analysis (FMEA) or PRA (Probabilistic Risk Assessment). For each branching step in your operational procedure a probability of success and failure should be assigned and a pathway to safe your system and then to mitigate any loss.***
- ***Identify and select risk mitigation measures that ensure that:***
  (a) any hazardous conditions that could cause death or serious injury to the public will be remote, and
  (b) any hazardous condition that could cause major property damage to the public, major safety-critical system damage or reduced capability, a significant reduction in safety margins, or a significant increase in crew workload will be remote.
- ***Risk mitigation measures should be selected in the following order of preference:***
  (1) safety design features;
  (2) incorporate safety devices;
  (3) provide warning devices; or
  (4) implement procedures and training.
- ***Ensure that approved mitigation systems or procedures are implemented.***
- ***Ensure the continued accuracy and validity of the hazard analysis throughout the project lifecycle.***

R12.2.2 ***The safety officer shall ensure that safety requirements derived from the hazard analysis are captured early in the system requirements development phase wherever possible.***

12.2.2 GROUND SAFETY ANALYSIS

R12.2.3 ***No overflight or impact (impact hazard area) shall occur outside of pre-determined exclusion zones. Exclusion zones will be determined by each team, in collaboration with Launch Canada.***

R12.2.4 ***For all SRAD propulsions systems used in either the launch or technology development categories, the team shall calculate safety clear zones for hazardous preflight and post-flight operations (including recovery operations) in accordance with FAA Guide 437.53-1, Calculation of Safety Clear Zones for Experimental Permits under 14 CFR Part 437.53(a) [18] or an equivalent method.***

This analysis will be supported by Launch Canada.

12.2.3 FLIGHT SAFETY ANALYSIS

R12.2.5 ***For all launches in the Advanced category, i.e. those involving SRAD propulsion systems or multiple stages, the team shall define flight criteria and calculate a maximum impact range and flight impact hazard area in accordance with FAA publication Supplemental Application Guidance for Unguided Suborbital Launch Vehicles, Attachments 1 – 4 [19], or an equivalent method (see figure below).***

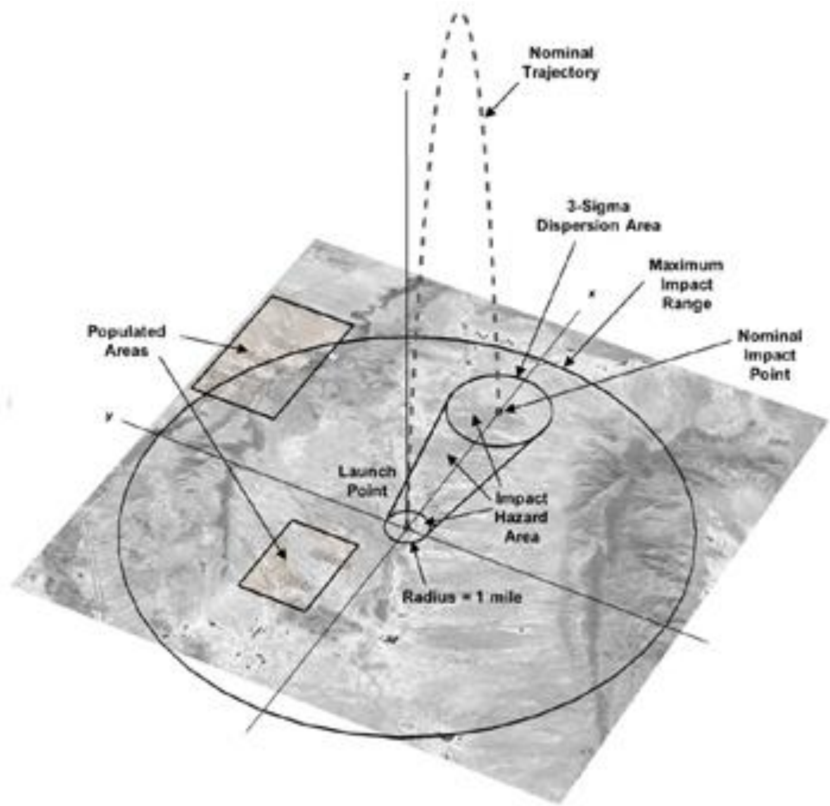

Figure 12.1 - Impact Range and Flight Hazard Area [19]

Rocket launches are always governed by a set of ***launch commit criteria***, also known as “go/no-go” criteria. These are the conditions that shall be met in order for a launch to be able to safely proceed, and these criteria will be derived from a number of different sources. These include:

- Government regulations
- Launch Canada / CAR / Tripoli rules
- The team's flight safety analysis
- Requirements and operating limits of the team's own hardware

Commit criteria will typically define limits and requirements related to the following.

Weather Conditions:

Rockets are famously sensitive to weather. This can include wind, rain, cloud, visibility, temperature and precipitation.

There are often limits imposed due to rules and regulations. For example, it is typically not permitted to launch into cloud, or when there is lightning in the vicinity. It is also not permitted to launch when the ground winds exceed 30 km/h.

Teams may have additional weather requirements. Some vehicles might be tolerant of small amounts of rain, or wide temperature ranges. Others might not. Commit criteria should define any such limits and restrictions.

When performing trajectory and/or flight safety analyses, there might be wind conditions (speed and direction) that would compromise the vehicle's stability, or cause excessive drift or an undesirable trajectory. Such conditions shall be incorporated into the launch commit criteria, per Requirement R10.3.3.

Telemetry:

At minimum, it is required that teams have onboard GPS on their rockets, and a telemetry downlink to receive telemetry data during the flight. Confirmation that GPS data is being received at the ground station is one important launch commit criterion.

Personnel Readiness:

A launch of a complex rocket will require a certain number of key people occupying key roles in order to be able to safely perform all the necessary operations. Launch commit criteria will typically specify the readiness of those people. It is also common professionally to require that all personnel have had a certain minimum amount of sleep.

Other Safety-Related Conditions:

Commit criteria shall incorporate all safety related conditions that shall be met to initiate launch and each phase of flight thereafter. Many of these may be specific to the team's own systems. On hybrid or liquid systems, it might include propellant temperature, pressure, or weight ranges, or verification of the status of key hardware or systems.

R12.2.6 The safety officer shall oversee the development of the launch commit criteria and ensure that they are adhered to.

The team and RSO will only allow a launch to proceed when the flight commit criteria are all met.

12.3 OPERATIONS

12.3.1 PLANNING

R12.3.1 All mission ground operations shall be governed by approved operating procedures.

Any deviation from procedures shall be approved by the relevant team lead(s), and by the Range Safety Officer (or team member with similar function).

R12.3.2 ***All persons executing ground operations shall be suitably trained in their execution.***

R12.3.3 ***The safety officer shall oversee development of a ground operations plan that identifies each operation to be performed and establishes the sequence and timing for their execution***

R12.3.4 ***Operating procedures shall ensure that any critical cleanliness requirements (e.g., for oxidizer plumbing) are maintained and no unacceptable contamination can occur.***

12.3.2 HAZARDOUS OPERATIONS

It is particularly important that all hazardous operations be defined and explicitly noted in the procedures. These operations shall only be performed by individuals who understand the operation, the hazards involved, and the practices and protective equipment required to ensure safety. Hazardous operations should only be performed by the minimum number of people required, with all others evacuated to a safe distance.

R12.3.5 ***The safety officer shall oversee the preparation of step-by-step procedures and/or checklists for every hazardous ground operation. These may be contained within an overall safety plan but should be separable as needed during actual operation and training.***

R12.3.6 ***Hazardous operations shall be planned such that, should an incident occur, they will cause the least possible injury to personnel or damage to facilities or surrounding property.***

Typically, this involves defining a hazard zone such that people or property outside that zone would not be exposed to the hazard, and ensuring this area is kept clear at all times when the hazard is present.

R12.3.7 ***Hazardous operations shall be planned such that the minimum number of people will be exposed to the hazard.***

R12.3.8 ***The safety officer shall identify hazardous operations that will require operators to use PPE.***

R12.3.9 ***The safety officer shall make arrangements for necessary PPE to be acquired and available in time for use in the operation and for any necessary training.***

12.3.3 BUDDY SYSTEM

A very common practice for hazardous operations is to use a “buddy system”, with one person overseeing the operation and one (or more) person(s) performing it. This is a good practice when executing procedures in general, but it is particularly advisable when hazardous operations are being performed. The person in the supervising role should have ready access to whatever basic emergency equipment might be needed (for example, a fire extinguisher), and should carefully watch for the presence of hazards or unauthorized individuals entering the hazard area.

12.3.4 PERSONAL PROTECTIVE EQUIPMENT (PPE)

Personal protective equipment (PPE) is one of the most basic tools for ensuring safety when potentially hazardous operations are being performed. Teams shall carefully identify and familiarize themselves with the hazards associated with their operations, and the specific PPE required. Common PPE can include eyewear, face shields, gloves of various types, clothing, respiratory protection, safety footwear, hardhats, and ESD protective gear, among others. Chemicals and hazardous substances will always include a Safety Data Sheet (SDS) which will identify the hazards and the required PPE. Always be sure to do your research, find and read the SDS, and familiarize yourselves with best practices for performing the operation in question. When in doubt, don't hesitate to reach out for additional guidance!

R12.3.10 ***If electronic, pyrotechnic or other devices are employed that are sensitive to electrostatic discharge (ESD), suitable static dissipating equipment such as a wrist strap shall be worn when handling them.***

R12.3.11 ***Personnel conducting operations where an ocular hazard may exist shall wear safety glasses or face shields.***

This includes ALL machining operations, and ALL operations with pyrotechnics, including preparation of black powder charges and insertion of igniters or e-matches into motors or charges.

R12.3.12 ***Personnel conducting operations under potentially dangerous overhead objects (such as crane and lifting operations) shall wear hardhats with a chin strap.***

R12.3.13 ***Personnel conducting hazardous chemical operations shall use PPE (identified on a case-by-case basis) to provide adequate protection.***

R12.3.14 ***Personnel performing operations involving propellants shall have completed the necessary training to do so and shall employ the appropriate PPE and practices for the specific propellant.***

12.3.5 PYROTECHNICS

Pyrotechnics such as black powder or solid rocket propellants are among the larger hazards present at a typical rocket launch, and all the requirements related to hazardous operations apply to any operations involving them. There are a number of particular good practices involving their use that all teams shall observe.

R12.3.15 ***Eye protection such as safety glasses or goggles shall be worn by all personnel working with pyrotechnics. This includes black powder.***

R12.3.16 ***The "buddy system" shall be used with all pyrotechnic operations.***

R12.3.17 ***A suitable fire extinguisher shall be present at all times when pyrotechnic operations are being performed.***

R12.3.18 ***No sparks, smoking, or other ignition sources shall be present within a 12-foot radius of the pyrotechnics.***

R12.3.19 ***Working surfaces shall be kept clean and free of clutter.***

R12.3.20 ***Quantities of open black powder shall be kept as small as possible. Make sure to measure out a small amount from the black powder container, and then immediately seal the container before measuring out precise weights of BP for deployment charges or other propellant actuated devices.***

R12.3.21 ***Supply containers for pyrotechnic chemicals such as black powder shall be kept closed at all times when not pouring or scooping.***

R12.3.22 ***Ejection charges and other pyrotechnic devices shall never be pointed at a person.***

Situational awareness is critical when performing operations with pyrotechnics. Always ensure that if the pyrotechnic device were to ignite, no person will be in the line of fire.

R12.3.23 ***Black powder charges shall not be made up in advance and kept or transported in the rocket, except when the rocket is being taken from the assembly area to the pad.***

R12.3.24 ***Igniter or e-match leads shall be kept shorted / shunted together at all times prior to and during installation.***

R12.3.25 ***Igniters / e-matches shall only be connected to electronics that are fully de-energized (e.g. battery removed or power switch off).***

12.3.6 GROUND RECOVERY SAFETY

R12.3.26 ***Any mechanical hazards shall have a means of restraining all stored energy that remains prior to ground recovery.***

In other words, the system shall be placed in a safe, zero-energy state. Methods of reducing this hazard include venting high-pressure sources and/or applying approved mechanical restraints, while limiting access to recovery areas.

R12.3.27 ***If risk reduction cannot be accomplished (reducing the energy of hazardous systems to their lowest energy states or consuming the hazardous materials), then a suitably trained 2-person ground recovery team shall perform any necessary safing tasks after a strategy has been agreed upon with the Range Safety Officer.***

R12.3.28 ***A procedure shall be put in place for recovering a crashed rocket that ensures all pieces are bagged and removed from the site***

12.3.7 ADVANCED LAUNCH VOTING

An advanced launch salvo involves one or more rockets filling and attempting to launch. Typically, teams participating in a salvo will fill concurrently with the difference in fill to fire operational times resulting in different launch times. If the fill to fire time of two teams in a salvo are the same one team might be delayed slightly so as to not end up with two rockets attempting takeoff at the same time. To create a fair process to remove teams during operations that require clearing the pad a voting system has been introduced.

Teams that are not conducting operations including setup or testing on the pads are assumed for any vote (unless they come to vote otherwise) to abstain. Teams that have been grounded are unable to vote and are counted as abstention until their grounding is cleared.

R12.3.29 Advanced launch teams start with 2 infinitely divisible votes.

All advanced launch teams start with two infinitely divisible votes to clear the pads of other teams to conduct high pressure tests or conduct a launch salvo. Voting values start off equal but are not equal as time goes on. In short, the more the team gets what it votes for the less that team's vote value becomes. Each vote the teams participate in the team leads can vote in favor, vote against or abstain. Abstention results in zero change to vote value. If the sum of the votes in favor exceeds the sum of the votes against the motion is carried and the value of the teams' (that voted in favor) votes in subsequent decisions is halved while the value of the votes of the teams that voted against remain unchanged. If the balance of the vote is reversed then those who voted against lose half their vote value as the motion is not passed. Since each time vote value is consumed in a vote the vote value is divided by two the team never lacks a vote but it creates a weighting favoring the teams that are able to conduct operations around other team's needs, keep the duration of testing and launching attempts to short and accurate times, can minimize restrictive on-site testing, and do not conduct launch attempts when they are not ready.

At the end of a launch day there will exist a distribution of vote values. Teams that were present on the pad that voted for a launch or test will preserve their vote values at the end of the day. Teams that were not present on the pad will see their vote values drop to the mean vote value of the new day. Teams that were present that did not vote in favor of any launch or test will drop in vote value by half.

R12.3.30 Team leads can call for a vote and other team leads can vote for, against, or abstain.

Votes are taken for when a pad clearing is required for high pressure tests or launch. The vote comes with a defined time to clear the pad and commence operations. It is recommended that Team leads use their votes strategically and diplomatically, and perhaps more importantly learn to not require votes to take place. A negotiated agreement between teams preserves vote value. Arriving earlier than other teams to conduct tests, therefore not requiring a vote, preserves vote value.

At any time, a team lead can come to the Advanced Launch Manager and request a vote with a specific time of clearing, commencement of operation, and duration (if it is a test). At this point the team requesting a vote will expend their vote as in favor at that time. Pad managers will seek out the other team leads for Yea, Nay, or abstain decisions. A decision will be rendered and vote values will change accordingly. By requesting a vote, it is for the times and durations given to the Advanced Launch Manager. If other teams vote against the measure because of the timing and the vote fails then the proposing team cannot call for a vote for a time within the duration after the time of the voted time of commencement of operation. So, if a one-hour test at noon was requested the requesting team cannot ask for another withdrawal until after 1PM. It is imperative that a team wants to evacuate the pads for a launch or test consult and poll the other team leads to negotiate a time that gets them enough votes to pass the measure.

Historically teams can expect that voting will likely take place for two launch slots in the day. Teams can negotiate outside the vote to conduct testing but if that is agreed upon by the teams any evacuation for testing or launch has to be under unanimous consent and has to be communicated to the Advanced Launch Manager. If it is not unanimous a vote shall take place.

R12.3.31 Forced extension voting takes place if operations exceed the voted upon operational time.

Forced Extension Voting happens in the event that a test runs longer than the agreed upon duration. The team can either end the test immediately or an immediate vote is called on whether to extend the test by the originally proposed duration of the test. The testing team(s) can call for less time for extended duration but if they do not wish to immediately end their test their votes will be registered as for the extension by a duration no longer than the original agreed upon duration. This leads to a situation that results in teams misjudging their testing time losing vote value accordingly. It also allows frustrated teams waiting for a test to end, the means to stop a test that is prolonging a work stoppage. It is best to ask for a likely duration of testing and not try to undersell the time your test will likely run. So, asking for 45 minutes to run a 15-minute test is preferred to requesting 15 minutes for a 45-minute test and dropping almost an order of magnitude in vote value.

R12.3.32 In the statistically unlikely event of a tie, the tie breaking vote will be placed by the advanced launch manager.

In the unlikely event of a tie which becomes less and less likely as the week moves on, the Advanced Launch Manager will cast the tie breaking vote on whatever reasoning he deems reasonable. This might be based on perceived capability to launch, historical discrepancy between quoted test time and actual test time, weather, or even a culturally significant binary decision making that relies on rotational dynamics of stamped metal disks accepted as currency or a common disk such as a washer with markings if metallic currency cannot be found. Alternative measures of decision making can be employed such as drawing different lengths of wire or zip ties in place of straws. All to say is that a method that might seem calculated or random can be used at the advanced launch manager's discretion.

12.3.8 ADVANCED LAUNCH OPERATIONAL LOGISTICS

R12.3.33 Teams shall not arrive before sunrise and shall leave by sunset.

LC Advanced Launch Staff shall be on site for energetics testing, tower raises and pressure testing starting at 7:00 AM and shall leave by 7:30 PM. Teams can unpack in the morning between sunup and 7:00 AM or pack between 7:30 PM and sundown but they shall not do any of the aforementioned operations without LC Advanced Launch Staff present. Teams shall arrive no earlier than sunup and shall leave no later than sundown. Arrival and departure times will be enforced by bears and mosquitos.

R12.3.34 Launch salvo times will be voted on but will commence between 9:00 AM and 5:00 PM

Launch slots will be voted on but fill start times shall be after 9:00 AM or before 5:00 PM. Launch operations begin one hour prior to the voted fill time. Rockets for a 5:00 PM attempt shall be vertical by 4:00 PM. Teams shall be at their launch control stations at 5:00 PM. Launching teams shall be prepared to leave the pad, with rockets armed, at 4:45 PM. Failure to be ready by either of these two steps shall scrub that team's end of day launch attempt. While voting times are voted on historically when teams show up at sunup, most teams become ready for an attempt at noon and sometimes a reattempt at the end of the day. If your team wishes to have two launch attempts in a day, the time to take down your rocket from a rail, take it to your work area, de-integrate at least one component, swap it for a working system, and re-rail it would need to be less than two and a half hours. Optimizing for ease of swapping components will maximize the number of launch opportunities for your team and maximizes the probability of launch.

R12.3.35 Fill and abort times shall remain with the limits defined below.

For a class 2 rocket (<41kNs), fill times under testing conditions shall be under 30 minutes to count as a successful test. Fill times under launch conditions shall be under 45 minutes or the team will be forced to abort. For class 3 rockets fill times but not exceed 60 minutes for a test and 90 minutes for launch or the team will be forced to abort. Abort times shall not last longer than the fill time without triggering a grounding of the vehicle. While fill and abort times shall be under the durations outlined above, they should be minimized further. 5-minute fill and abort times for O and P impulse class engines have been designed, built, and flown or in the case of abort demonstrated in the field.

R12.3.36 Teams that are not part of the nominal launching procedure may not last longer than 10 minutes past the quoted fill time.

Operational checks part of the launch procedure that are accounted for in the Fill to Fire time do not count as a hold. Team ordered holds may not last more than 10 minutes. LC staff holds can last longer based on range safety issues. If a team is unable to hold, they may order an abort at any time. The design for a capability of longer hold durations is at the team's discretion. In other competitions there have been holds due to mismanagement of recovery teams, aircraft, and other solid flights. LC has been unaffected by these situations as of yet. In one case a single aircraft flew near the pads but they were ushered away in less than a few minutes and not at the time of a launch attempt. The probability of a necessary hold by LC extending more than a few minutes is extremely unlikely, but the loss of propellants due to an abort will not be compensated.

R12.3.37 Launch Authorization requires constant persistent consent of the Advanced Launch Manager and the Team Launch Director.

Teams shall only launch after approval of the Advanced Launch Manager (ALM). For a launch to proceed a double coincidence of consent shall be present. Teams shall coordinate a 10 count prior to launch, during which either the team or the ALM can order an abort. Both shall consent for a launch. An indicator shall be made available to denote tank fill state and expected times of procedures based on operation tempo averaged between tests. A 5 or 10 count is required prior to launch which should incorporate timing of valve opening or firing of pyros. A hypothetical example might be a go for a ten-count indicated to the ALM so that it can be announced on the radio. The ALM gives confirmation to the team to begin the procedures for the last 10s and that would include a vocalized count umbilical arm detach at 8s. Confirmation of internal power at 5s. Preheater puck ignition at 3s. Confirmation at 2s that it is burning. And Main Valve opening at 0s. Another example can also be visual detection of constant constricted vent, go/no go from ALM. A Go is received and a 5 count is initiated for firing of a pyro value at 0. This go/no go condition form ALM does create a situation where a hold at full fill for much longer than a minute is hard to handle and not result in abort. There are methods for extending the holds of such a style of motor, specifically a normally open valve between the tank and the vent constrictor and some ullage to prevent hydraulically failing the pressure vessel. Having a non-zero hold time allows a team a third option from go/no go, to go, wait, abort.

R12.3.38 Teams that fail to successfully abort without LC staff intervention shall be grounded.

A failed abort is defined as an abort procedure that does not completely safe the rocket. In most cases, this is due to oxidizer still pressurizing the rocket’s tank. A failed abort requiring intervention by LC staff requires temporary grounding until root cause can be determined and remedied. A team does not have voting privileges until the grounding is removed. After intervention leading to a successful abort, if the field is too busy for investigation by advanced pad safety staff, then that investigation will wait until after the pad is closed for the day and all other vehicles have been safed from any remaining salvo. Vote value is dropped to the lowest value of any other team on the field once at the time the grounding is revoked. A second failed abort requiring intervention will result in permanent grounding. This should be taken into account when determining the level of testing your team wishes to make.

12.4 TRAINING & CERTIFICATION

Training and verification of skills are fundamental to the success and safety of an operation. For something as complex and multidisciplinary as an advanced amateur rocket, this is especially important. Teams are strongly encouraged to take advantage of all opportunities for relevant training available at their universities and through external organizations. Teams are also expected to develop their own specialized training for their members, and Launch Canada is always available to assist in this.

Typical training includes:

- **General safety training:**
  Most schools as well as many other organizations offer formal training in many subjects that are relevant to experimental rocketry. These often include:
  - Basic laboratory safety
  - Chemical safety
  - Compressed gas safety
  - Machine shop safety
  - Cryogenic safety
  - First aid
- **Specific training in the team's own equipment and procedures:**
  All teams are expected to develop operating procedures for their launch and/or test operations. Teams will also often have their own internal operations that might include manufacturing, specialized equipment, university-mandated procedures, etc. In all cases, teams should ensure that the members who will be carrying out those operations have the opportunity to build experience with them ahead of time. This can include:
  - Formal training through talks, courses or presentations
  - An apprentice system, where newer members shadow experienced ones to build experience in a particular procedure or operation.
- **Rocketry-related training:**
  Rocketry organizations such as the Canadian Association of Rocketry, Tripoli Rocketry Association, and National Association of Rocketry offer formal high power rocketry certification programs, allowing participants to progressively build expertise in high power rocketry and the common technology and practices associated with them. Members of student rocket teams are strongly encouraged to build their own high-power rockets and get certified with a local high power rocketry organization if at all possible. The experience gained will be invaluable.
  Launch Canada also offers resources, talks and opportunities for training on advanced rocketry subjects.

Teams participating in Launch Canada are expected at minimum to observe the following requirements with regards to training.

R12.4.1 ***All persons who will be assigned to perform any launch or recovery operation shall be trained and proficient to perform that operation.***

R12.4.2 ***All persons who will be assigned to perform a hazardous operation shall be trained and certified to perform that operation.***

"Certified" in this context refers to internal training to ensure that only personnel who are cognizant of the procedure and associated hazards and safety aspects shall perform a given operation. In any cases where the operation is governed by other regulatory bodies (for example Natural Resources Canada Explosives Regulatory Division (ERD) in the case of explosives), "Certified" shall be as per the relevant regulations.

R12.4.3 ***Trained and/or certified personnel shall perform operation rehearsals to ensure proficiency before operations are to take place.***

R12.4.4 ***Persons who will be required to use PPE shall be trained on their proper use and care.***

R12.4.5 ***All persons who will be assigned to perform any launch or recovery operation shall be trained and proficient to perform that operation.***

R12.4.6 ***All persons who will be assigned to perform a hazardous operation shall be trained and certified to perform that operation.***

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APPENDIX A: ACRONYMS, ABBREVIATIONS & TERMS

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
CARs	Canadian Aviation Regulations
CAS	Control Actuator System
CFR	Code of Federal Regulations
CG	Center of Gravity
CONOPS	Concept of Operations
COPV	Composite Overwrapped Pressure Vessel
COTS	Commercial Off-the-Shelf
CP	Center of Pressure
CTF	Chlorine Trifluoride
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
IREC	Intercollegiate Rocket Engineering Competition
JLCR	Jolly Logic Chute Release
LC	Launch Canada
LC Challenge	Launch Canada Innovation Challenge
LCRA	Launch Canada Rocketry Association
LOX	Liquid Oxygen
NAR	National Association of Rocketry
NFPA	National Fire Protection Association
NRC	Natural Resources Canada
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
SRAD	Student Researched And Developed
TC	Transport Canada
TRA	Tripoli Rocketry Association

TERMS	
Amateur Rocket[1]	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 outer 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[1]	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."
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.

1. LCRA is currently following the definition in the United States Code of Federal Regulations as the CARs do not comprehensively define amateur rockets and their subclasses.

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. This is defined as wiring associated with drogue (or other drag device) deployment, main parachute deployment, and any air-start rocket motors. The wiring techniques described here are optimized for inspectability 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 in order 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 absolutely 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 shall 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's 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 shall 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 may be 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 shall 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 shall 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 shall be joined.
   11.2. Screw bare wires under binding head screws in a barrier block. Add approved barrier block jumper pieces if many wires shall 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 don't see launch vibration!
12. All insulating tubing (usually heat-shrink) should be transparent.
   12.1. This allows inspection of the underlying hardware. It's 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 uninspectable
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.
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 rocket 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 shall 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 "faston" crimp terminals.
    19.3. Cylindrical batteries (AAA, AA, C, D, etc.) should be mounted into holders utilizing positive retainment or a compliant mechanism. The holders should be rigidly secured to the structure, and the batteries should then be strapped into the holders.
    19.4. Lithium batteries (Li-ion, Li-poly), particularly those in flexible foil packs, should have an external housing to protect the battery from flight forces. Simply "tie-wrapping" them to a board can puncture the protective foil and cause a fire within the avionics bay during flight and even ground testing. 3D printing a container for these battery types is a good option, and one that can be readily adapted to the various battery sizes available.

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 rocket.
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

Part	Number	Notes
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 low shrink temperature. Shrink with 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: FIRE CONTROL SYSTEM DESIGN GUIDELINES

Introduction

The following white paper is written to illustrate safe fire control system design best practices and philosophy to student teams participating in Launch Canada. When it comes to firing (launch) systems for large amateur rockets, safety is paramount. This is a concept that everyone agrees with, but it is apparent that few truly appreciate what constitutes a "safe" firing system. Whether they've 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 fire the system.
- The system should include a power interrupt such that firing current cannot be sent to the firing 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 a firing 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 firing system, but let's examine the system for compliance with proper safe design practices.

The control console should be designed such that two deliberate actions are required to launch the rocket. Check! There are actually three deliberate actions required at the control console: (1) insert the key, (2) turn the key to arm the system, (3) press the fire 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 Firing relay effectively isolates the electric match from the firing 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 rocket.

But all of this assumes that everything in the firing 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 firing lines and e-match, three of those components can fail with potentially lethal results.

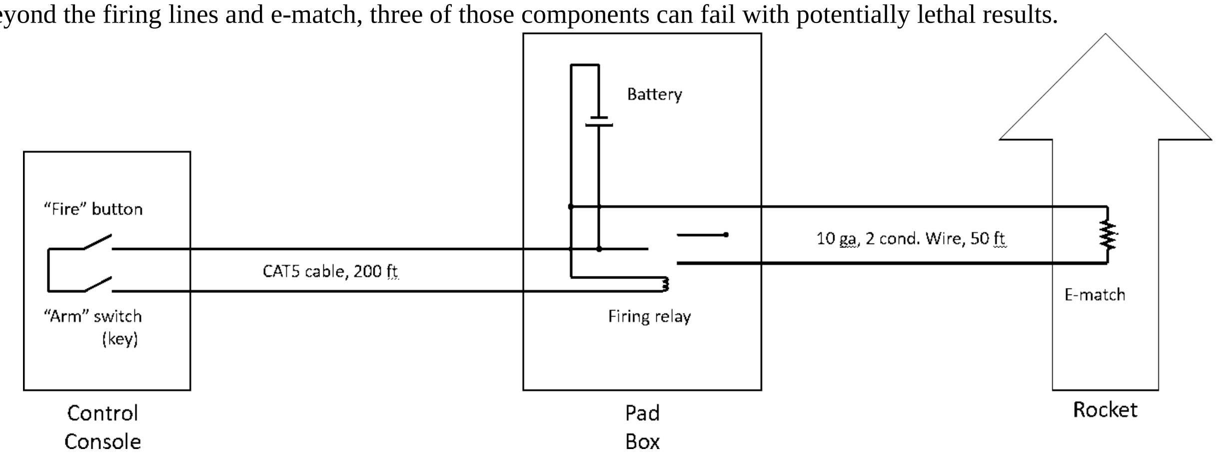


Figure C-1 - A simple high current fire control system

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

Arming Switch. If the arm key switch failed in the ON position, simply pushing the fire button would result in a fired rocket 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 rocket. Such a button press could easily happen by accident. If personnel at the pad were near the rocket 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 firing relay would be closed and the rocket would fire the moment it was hooked to the firing lines. This too is a potentially lethal safety failure.

Notice that all three of these failures could result in the rocket being fired while there are still personnel in immediate proximity to the rocket. A properly designed firing system 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 rocket).

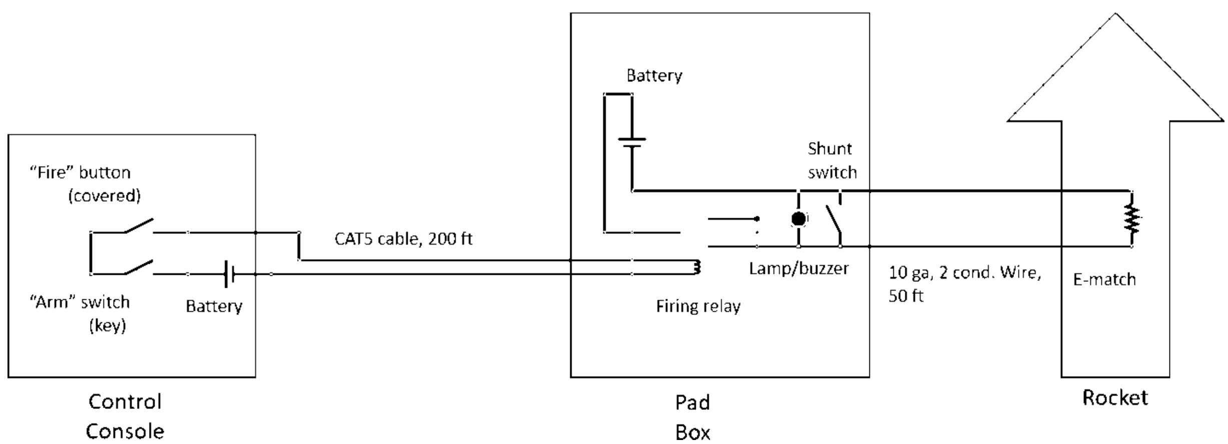


Figure C-2 - An improved high current fire control system.

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 rocket 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.

Fire Button. If the fire button fails in the ON position, there are still two deliberate actions at the control console required to fire the rocket. (1) The key shall be inserted into the arming switch, and (2) the key shall 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 rocket. (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 rocket. 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.

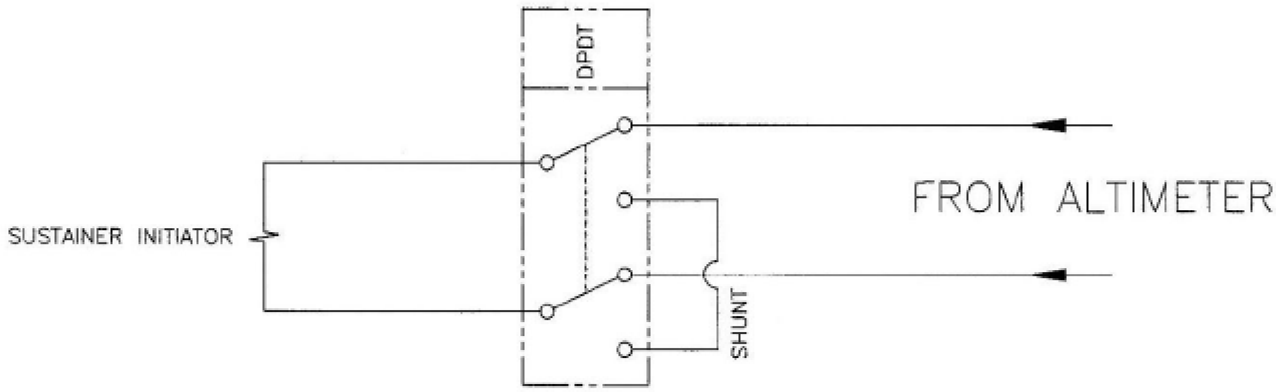
Firing Relay. If the firing relay fails in the ON position the light/buzzer should alert the pad operator of the failure before he even approaches the pad to hook up the e-match.

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.

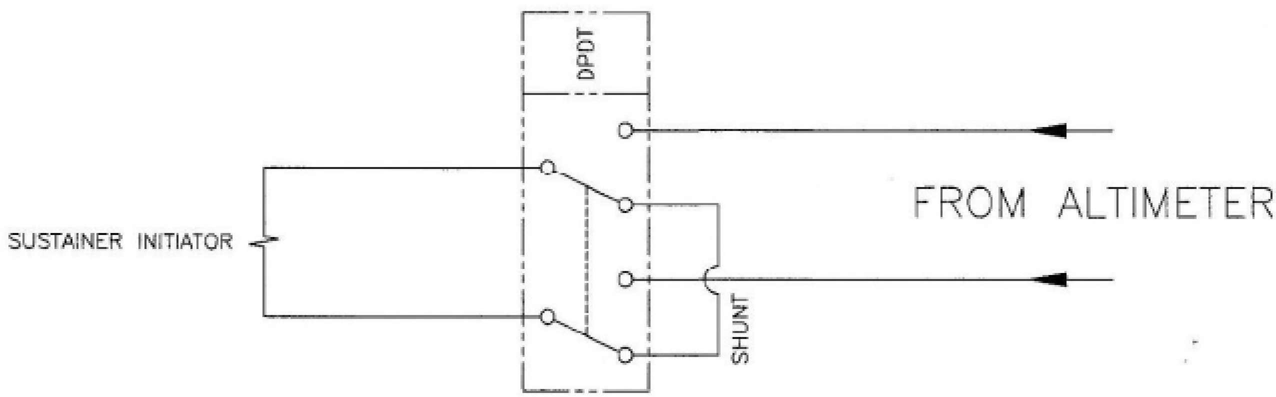
Is this a perfect firing system? No. There is always room for improvement. Lighted switches or similar features could be added to provide feedback on the health of all components. Support for firings at multiple launch pads could be included. Support for the fueling of hybrids and/or liquids could be 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 rocket 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: AIRSTART IGNITION WIRING DIAGRAM



SUSTAINER INITIATOR ARMED



SUSTAINER INITIATOR SAFE

APPENDIX E: OXYGEN CLEANLINESS GUIDELINES

Introduction

Cleaning of components for oxidizer service, and ensuring they remain clean subsequently, is **absolutely critical** in any system employing a liquid or gaseous oxidizer. It's also very important to use a reliable cleaning method, because dangerous contamination isn't always obvious and doesn't necessarily cause an obvious problem like a fire or explosion every single time. For fire to occur, you need fuel, oxidizer and an energy source, so it's possible that even with the first two present, you might "get lucky" for a while and not have a major disaster simply because the conditions necessary to ignite the contaminant didn't occur… this time. But in reality it takes very little energy to start many contaminants burning in an oxidizer-enriched environment and that energy can be supplied from almost anything, and if you have contamination, you shall assume that sooner or later it WILL find an ignition source and your luck will run out, with potentially catastrophic results.

But it's very easy to be fooled into believing that your system is cleaner than it really is, just because you've gotten lucky in the past.

Don't take chances, and be very rigorous about cleanliness – even if you might feel like it is overkill. It only takes one fire to destroy large amounts of extremely expensive hardware, potentially pose a serious safety hazard, and set back your rocket activities or even end them for good.

Recommended Resources

It is strongly recommended to obtain a copy of ***ASTM's "Safe Use of Oxygen and Oxygen Systems" guide***. It has a very good section giving an overview of cleaning practices, as well as some additional resources.

Basic Principles

One of the first things to remember when cleaning something is that there isn't really a single "one size fits all" answer: the right solvent / cleaning fluid and process for the job depends on what type of contamination you're trying to remove, and what the material is you're trying to clean. Certain solvents will attack certain materials, and not every solvent will be effective on every type of contamination, so those are all considerations.

That said, there are several common principles. Remember that cleaning for oxidizer service is always a multi-step process: you don't just wash your part once, you do it repeatedly. At minimum, you should be cleaning two or three times, if not more (at least three if it's a part that's known to be contaminated, such as something you just machined that's covered in cutting fluid or coolant, or a valve that was lubricated with a hydrocarbon). And it's a good idea to use multiple different solvents / detergents to increase your chances of successfully removing contaminants with one solvent that another one might have missed.

If you are doing multiple washes with the same cleaning solvent, be sure to use a different, dedicated batch of solvent for each step: that way any contamination removed in one cleaning operation cannot get re-deposited in the subsequent operation. Certain lubricants such as the silicone grease sometimes found in valves can easily contaminate your cleaning solution and get deposited on everything. Your cleaning process will be ineffective if contamination is removed only to get re-deposited.

When performing multiple cleaning passes, a distinction should be made between "pre-cleaning", "intermediate cleaning", and "final cleaning".

Different, dedicated tools should be used for each step. So, if you're using toothbrushes, tube brushes, etc, have a dedicated set that is ONLY used for final cleaning and stop using brushes before they deteriorate to prevent deposition of strands. If you're using some sort of container to clean the parts in, try to have dedicated ones that are only used for final cleaning. That way you avoid contaminating the tools you'll be using for final cleaning. As mentioned above, make sure to also use different cleaning solution for each pass: don't wash a part in the same batch of cleaning solution for multiple steps, since that can re-deposit contaminants that were previously removed if your particular cleaning solution doesn't thoroughly dissolve or emulsify a given contaminant.

It shall also be recognized that there is a fundamental “state change” between something that is oxygen cleaned and something that is not, and whenever something that has been cleaned comes into contact with something that is not, your cleaned part can no longer be considered clean. So it is not enough to just clean the part: everything it will ever come in contact with needs to be just as clean. That could include:

- Tools the part will come in contact with
- Any bags or containers the cleaned part will be placed in
- Drying apparatus the part will be used with
- Air, gas or fluid it gets used with for drying or subsequent testing
- Hoses, regulators, valves or fittings the part will be dried or tested with
- The gloves you use to handle it
- Any surfaces you place it on

A part can only be considered to be as clean as the dirtiest thing it touches including yourself or the glove you are wearing!

Precleaning

Precleaning is the most open-ended step: it's where you do whatever you need to do to get rid of whatever obvious contamination is on the part, and do as many precleaning steps (wash, rinse, repeat) as you need to achieve that. If there's obvious grease or oil on it, start by wiping it off. If there's rust, use a rust remover, scrub it, etc. This doesn't need to be done in a particularly clean environment: the goal is just to get it "mostly clean".

It is recommended to complete the precleaning step(s) by rinsing under water at as high a pressure as possible. Tap water with a nozzle, or even a pressure washer, is useful for this as the force of the water can help to mechanically dislodge contaminants and ensure they do not re-contaminate the part.

Intermediate Cleaning

Once the part is "mostly clean", you can progress to intermediate cleaning. This step is more stringent than precleaning. You should be using fresh cleaning solution(s) for this, and fresh cleaning implements, not reusing ones that were contaminated during precleaning. Again, this step should include rinsing under water at as high a pressure as possible to dislodge contaminants and help prevent re-contamination.

Final Cleaning

By the time you begin the final cleaning step(s), your part should already look perfectly clean. If it looks so clean that you're questioning whether it really needs more cleaning, you know you're ready for final cleaning. It should also have no odour to it: if you smell oil or something on the part, that's a good sign that it's not yet clean enough. The final cleaning steps are the most critical. For these ones, you should be very conscious of your workspace. It doesn't need to be a cleanroom, but it shouldn't be dirty. Countertops should be clean. Tools should be clean. You should be clean. Try to get rid of anything that could re-contaminate a cleaned part. Wear POWDER FREE nitrile gloves (this is important to emphasize: some gloves come lightly powdered to make them easier to put on and take off. NEVER use powdered gloves for any clean oxygen system work, since the powder is a contaminant. Clean your gloves before touching your parts. Always buy powder-free gloves. And never reuse gloves for final cleaning: gloves are cheap, so always use a fresh pair to avoid cross-contamination.

Fresh cleaning solution should be used for the final cleaning step. This will ensure it's maximally effective and isn't already saturated with contaminants. It will also allow you to qualitatively assess the cleanliness of your part by inspecting your cleaning solution after you wash it. The part should already be clean when you start the final cleaning steps, so if you see there's contamination in your cleaning solution, you know that it wasn't and you should wash it again until your cleaning solution looks just as crystal clear after washing as it did when it was fresh.

Cleaning Techniques and Practices

Note that HOW you clean is just as important as what you clean with. For smaller parts, an ultrasonic cleaner is just about the most thorough way to get something clean, especially if the part has features that tend to trap contamination, such as threads, small grooves, small holes, etc. Having dedicated ultrasonic cleaners (for example, one for cleaning, one for rinsing) is a good idea and can help reduce the probability of cross-contamination. Be careful though: ultrasonic cleaners are very aggressive. If you have thin parts, the cavitation bubbles can cause pitting or erosion. The tips of threads, for example, can be worn down during ultrasonic cleaning. As an extreme example, if you put a strip of aluminum foil in an ultrasonic cleaner, after a few minutes you'll see it's full of tiny punctures. So if you have something that's comparably thin and fragile, you should probably avoid putting it in the ultrasonic. It's usually a good idea to limit a part's time in the ultrasonic to 5 - 10 minutes, depending on how robust the part is.

Remember also that assemblies of parts (e.g. valves) shall be disassembled before cleaning. Flushing a valve with a cleaning solution will not be enough to clean it, and you will NEVER get it dry.

Temperature is another factor: any cleaning solution will have a range of temperatures it performs best at. Generally they like to be fairly warm or hot, the exception typically being flammable solvents.

And as mentioned, always make sure that whatever tools you use to clean with, whether that's a toothbrush, ultrasonic cleaner, tray, bin, bucket, rag, etc, are themselves clean and do not produce additional contamination. So a sponge or rag that will shred and leave small fibers is not acceptable for final cleaning. For the same reason, you should never use paper towel anywhere near a part that has been through its final cleaning: paper products (at least those not specifically rated for cleanroom use) will leave fibers behind.

Some Typical Cleaning Fluids

There are too many cleaning solutions on the market to list. Some are more suitable for oxygen cleaning than others. In all cases, avoid cleaners that leave a residue behind. “Hand safe” detergents designed to replenish the oils in your skin are wonderful for dishes, but not acceptable for oxygen cleaning. Some useful cleaning solutions are discussed below.

Water-Based Degreasers:

Blue Gold Industrial Cleaner: great, very benign basic degreaser, rated by NASA for use on oxygen systems. It can be purchased as a concentrate and diluted with distilled water. It's a very good general-purpose degreaser and is safe to use on most things. Smells pepperminty. Often good practice to heat it to about 50 - 60 deg C.

Tri Sodium Phosphate (TSP): Strong degreaser, somewhat caustic, easy to obtain from Home Depot, Canadian Tire, etc. There's a US Navy guide for oxygen cleaning that recommends it. It usually comes in two forms: either as a crystalline powder, or as a concentrated liquid. For precision cleaning, it is usually preferable to use the crystalline form and mix it to a concentration of 4.5 lbs to 5 gallons of distilled water (59.9 g / L). For general purpose pre-cleaning, the concentrated liquid may be used somewhat diluted. Often will be heated to 60 - 70 deg C.

Important! TSP is NOT compatible with aluminum. It will attack it (very severely if the aluminum isn't anodized).

Simple Green is another water-soluble degreaser that is commonly used.

Solvents:

There are many chemical solvents available. Each will have their own areas of applicability, and some will have hazards associated with them such as flammability or toxicity. In all cases, familiarize yourself carefully with the Safety Data Sheet (SDS) and standard safety practices for the specific solvent you will be using.

Isopropyl Alcohol (isopropanol, IPA): This is often used for rinsing parts. Typically after I wash a part, I'll first rinse it with hot DI water, then I'll rinse it with isopropanol. Isopropanol is a wonderful drying agent and will get rid of water and then evaporate. You can also easily tell when the isopropanol is all gone by smelling it. Since many metals are prone to some degree of corroding when wet, rinsing the water away ASAP with isopropanol is a good idea.

But IPA is also an excellent solvent, so that IPA rinse or bath can help to remove contaminants that your washing step might have missed.

Note that you want to use pure isopropanol (99%+). Isopropyl rubbing alcohol like what you'd get at the drug store is often diluted to 70% or less, and that addition of water destroys its solvent properties. So be sure to get the pure stuff.

CRC Brakleen: This is sold as a brake cleaner that can be obtained at places like Canadian Tire. Functionally, it's perchloroethylene ("perc"), which is a spectacularly good degreaser. Fun fact: if you've ever been in or near a drycleaner, the rather distinctive odor you'll probably smell is likely to be perchloroethylene.

It's quite volatile so should only be used in a very well-ventilated area, typically outdoors or in a fume hood, and wear an organic vapor respirator, lab coat and gloves. It's also best to avoid contaminating the water supply with it, so don't pour it down the drain or into the soil. Good practice is to catch it and store it in a jug for proper disposal as hazardous waste.

I will usually use this as part of my precleaning or intermediate cleaning. Typically, I'll begin precleaning with a degreaser like Blue Gold or TSP to remove as much contaminant as possible, then I'll follow up by blasting the part with Brakleen and/or soaking the part in a bath of it.

Note also that this is a very strong solvent, so it will dissolve many plastics / rubbers. It will quickly eat a toothbrush (yes, I discovered that early on) and will also degrade nitrile gloves fairly quickly. So best to use this on metal parts only.

I don't use this for all cleaning, but if I have a part that is known to have oil or grease contaminants, I typically will.

Water: Yes, water is a solvent too! It is a very common choice for rinsing of parts. Ideally, distilled / deionized water should be used for pretty much everything, and it should be fairly hot (often about 50 - 60 deg C). When cleaning with water-based degreasers, I will usually begin by rinsing with hot tap water to remove most of the degreaser. A pressure washer or a nozzle attachment for the end of a garden hose can be valuable to obtain a strong jet of hot water to rinse with. I then follow up quickly with a deionized water rinse to remove the tap water. When using the ultrasonic, I have a dedicated ultrasonic cleaner filled with deionized water that I will run for a couple minutes for that, and then finish with an IPA rinse / bath.

Drying:

This step is critical (particularly after the final cleaning), and easy to overlook: the most thorough cleaning job in the world doesn't matter if the part just gets re-contaminated again while it's drying, so this is actually one of the most important steps in the whole operation.

A full cleanroom isn’t required, but drying does require a location that is as clean and dust-free as humanly possible. Whatever drying method is used, it is essential to limit the chances of recontamination, including dust settling on the part. At the same time, airflow is important in order to properly dry something. An enclosed space with stagnant air is a great way to guarantee that a part will never dry. That's also why internal passages in parts (e.g. tubes or hoses) are so hard to dry: you really need that airflow. Rinsing with IPA to remove the water first does make all this easier though, since IPA will evaporate much more readily than room temperature water.

When I was starting out, I just used a heat gun set at a fairly low temperature setting, in an environment that was as clean as I could manage, in order to get it dry as quickly as possible. I didn't like this approach though, and changed it as soon as I could. Professionally, there are really only two approaches that are considered acceptable for drying:

1. Using a clean, gas-purged oven or vacuum oven (suitable for smaller parts that will actually fit)
2. Purging the hardware with a clean, dry gas such as nitrogen or air.

If the part being cleaned is a hose or tube, connecting a GN2 cylinder to it, preferably while also warming the gas, to give a very gentle purge is about as easy as can be, though of course this consumes nitrogen.

My approach is to use a blower and a HEPA filter to provide a source of clean air. I built an open-ended enclosure with a drying rack inside it, with the opposite end connected to a HEPA filtered blower. For smaller parts, I'll put them in the enclosure and let it blow clean filtered air over and through them overnight to get them thoroughly dry while also ensuring the environment stays clean.

I built another similar system for tubing, with the HEPA filtered blower connected to a manifold block that I can connect tubing or hoses to in order to blow air through them.

That was a fairly simple project and was extremely worthwhile.

The other fairly easy way to dry parts is to get a laminar flow bench. This is fairly common lab equipment. A laminar flow bench is basically an "inverse fume hood" that sucks in air and blows it out through a HEPA filter and into a chamber, creating a cleanroom environment within that chamber. The trick is ensuring the airflow stays laminar, so that dust from outside the chamber isn't accidentally entrained and drawn inside.

Many university labs will have laminar flow benches. They can also be found as surplus for not too much money, and there are even some cheap Chinese-made ones available on eBay and other such places that might do.

Packaging and Protecting:

Once a part has been cleaned and dried, it is important to ensure it stays clean, or all your hard work was for nothing. For small parts, the standard approach is to double bag: seal the part in a CLEAN ziploc bag, and then seal that bag in another ziploc bag.

For fluid system parts with fittings or ports, standard practice is to cap or plug the ports (you can get protective caps & plugs for most standard fluid fittings) before bagging.

For larger fluid system parts like tanks or rocket engines that are too large to bag, ports should be capped or plugged, and then the caps covered with aluminum foil or cleanroom tape for added protection.

When the part is ready to be installed in the system, clean, powder-free gloves should be worn, the amount of time the part is left unpackaged / unprotected should be minimized, and any unconnected ports should remain capped and covered.

When In Doubt:

Finally, if there is ever any doubt as to the cleanliness of a part, don't take chances: clean it again. All parts should be assumed dirty unless it is known for a fact, they have been cleaned for oxidizer service and kept clean.