Half Cat Rocketry

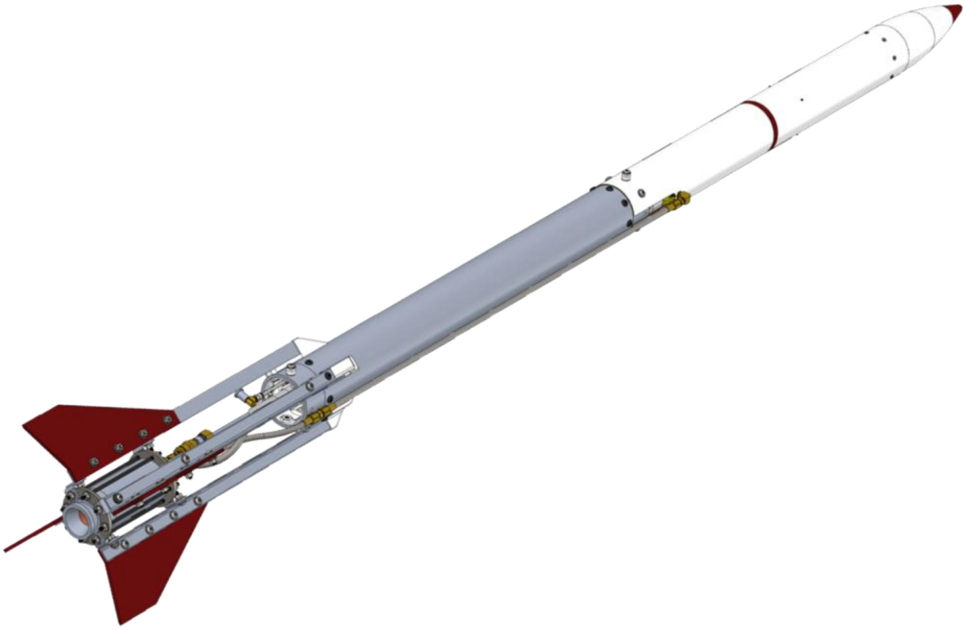
Vehicle Design Guide

HCR-5100

MOJAVE SPHINX

Liquid Bipropellant Rocket

BUILD, INTEGRATION, *AND* ***LAUNCH*** *GUIDEBOOK*



AUTHORED BY

AUSTIN SENNOTT & CHARLES SHARP

Warning

Rockets are dangerous! This publication is intended to provide information on the safe construction and operation of amateur liquid rockets, but it is no guarantee of safety. Always follow relevant safety guidelines and best practices when handling hazardous substances or situations – never assume that any situation is inherently safe. Half Cat Rocketry is not liable for the usage of this document, and the authors bear no responsibility for the usage of its content. Read the disclaimer on the next page before continuing.

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Build, Integration, and Launch Guidebook

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Authored by **Austin Sennott** and **Charles Sharp**

About **Half Cat Rocketry**

Half Cat Rocketry began as a project to build a liquid bipropellant rocket in our final undergraduate semester at the University of Central Florida. From September through December 2020, we constructed, iterated, and finally test fired *Half Cat Walking*. From participating in introductory rocket projects, to leading them, to producing solid motors, to designing hybrid systems, four years of learning culminated in four months of innovation and success.

We are Austin Sennott and Charles Sharp. For eight years, we have been relentlessly gaining experience in amateur rocketry, woven together with education and careers in aerospace engineering. Today, our focus is on pioneering simple, reliable liquid rocket motors and supporting students and individuals looking to build their own. Our goal is to demonstrate that they can be accomplished quickly and economically, for the benefit of both the hobby and the careers of students everywhere. We were once students ourselves, and still produce rockets with our own time and money, so we are well acquainted with the need to reduce scope and budget as much as possible.

Half Cat is the name of a meme, unique and recognizable. We do serious work, but we don't take ourselves too seriously - our brand and project names are a lighthearted nod to the industry, which can too often lack originality.

Half Cat Rocketry is ongoing, and we will continue to build rockets and publish information about them. Our hope is to redefine what's possible for students and amateurs to achieve with a little bit of creativity, leading the way for ever more awesome projects.

About the Authors

Austin Sennott is a rocket propulsion engineer and Level 2 certified in high-power rocketry. Since 2018, he has been building experimental solid, hybrid, and liquid motors, including the first liquid bipropellant rocket fired at UCF.

LinkedIn

Charles Sharp is Level 3 certified in high-power rocketry and employed as a rocket propulsion engineer. In over 10 years of building rockets, he has gained expertise in all types of rocket propulsion, including the first high-power rocket propelled by liquid CO_2.

LinkedIn

Version History

Revision	Description	Date
01	Initial Release	**17 Aug 2024**

The latest version may be found on both the Half Cat Rocketry website and GitHub repository:

Half Cat Rocketry Website

GitHub Repository

Scope

Mojave Sphinx is a high-power amateur rocket with a liquid bipropellant propulsion system powered by nitrous oxide and any number of solvent or hydrocarbon fuels. It is designed to be as simple and economical as possible so that an individual or team with high-power or experimental rocketry experience can build and launch it within a reasonable timeline and budget.

This guidebook covers:

- Background and fundamentals of Half Cat Rocketry's propulsion architecture, standards, and safety
- Design, analysis, test history, parts list, and assembly instructions of Mojave Sphinx
- Design, parts list, and assembly instructions for ground support equipment
- Preparation, launch, and recovery procedures
- Design and manufacturing reference materials

Understanding of the fluid mechanics and thermodynamics of liquid bipropellants and their combustion is not required to construct and operate Mojave Sphinx, and those topics will not be covered in detail. Understanding of solid mechanics is useful but by no means required, and the necessary concepts and calculations are provided. Aerodynamic efficiency is not a priority for Mojave Sphinx, and no knowledge of this subject is required beyond the ability to use basic flight simulation tools such as OpenRocket.

It is assumed that the reader is familiar with high-power rockets and their typical conventions, construction, and recovery systems. Basic familiarity with hardware, fasteners, and hand tools is also assumed. While not a strict pre-requisite, prior experience with experimental rocket motors is extremely helpful.

With these assumptions in mind, this publication is intended to be a practical guide to building an amateur liquid bipropellant rocket which can be launched repeatedly and reliably.

Table of Contents

Section I – Liquid Rocketry Standards and Safety

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1.1 Background

Half Cat Rocketry focuses on demonstrating that liquid bipropellant rockets do not need to be complicated. They certainly can be, and many choose to make them complicated for the sake of taking on a challenging endeavor. However, oftentimes an individual or team will become mired in unnecessary, self-imposed requirements when the goal was just to get a liquid rocket to the launchpad. Most people, when thinking about a liquid rocket project, will picture multiple pressurized fluid tanks, lots of tubing, precisely controlled valves, months of intense design work, and complex operating procedures. It doesn't need to be that way – picture, instead, a typical high-power rocket, launching at the press of a button.

Mojave Sphinx is a liquid rocket that has just two actuated valves onboard and one on the ground system. There are a total of three control channels: one for the rocket's propellant valves, one for the ground-side valve, and one for the igniter. The entire system can be controlled using an off-the-shelf RC transmitter and receiver. Once started, the rocket operates completely passively with pressure blowdown. The whole system has been intentionally designed to be simple to use, easy to understand, and safe to operate.

The purpose of Mojave Sphinx, and a set of design standards based upon it, is to make liquid bipropellant propulsion an available option for amateur rocketry alongside solid and hybrid motors. The lack of documentation for how to build a practical, reasonable liquid rocket presents a barrier to entry, which this document aims to substantially lower.

1.1.1 Required Experience

Experimental rocket motors, also called research or home-built motors, are not a beginner project. Building a motor oneself is a step beyond typical hobby rocketry, where motors are commercially manufactured and certified. At a minimum, anyone attempting to build an experimental rocket motor should have prior experience with commercial motors, both to grasp the fundamentals of how rockets work and to gain a respect for their power and danger. This guide will do as much as feasible to educate readers about building a simple liquid rocket, but some concepts – such as force and pressure – are taken to be already understood.

Machining experience is not required – the parts involved in Mojave Sphinx are simple enough to serve as a beginner machining project, or they can be procured from a commercial machining service – but it is very helpful. The number of machined parts is kept to a minimum, and each part requires only a few basic machining operations. These include turning, facing, boring, drilling, internal and external grooving, and using the compound slide. Notably, parting – a more difficult lathe operation than standard cutting, boring, or grooving - is not required when working with the recommended stock sizes.

1.1.2 Suggested Projects

For those who are not yet ready to build a liquid rocket, there are a number of projects that can form a path to gaining the required experience. The best option, the baseline for any project in amateur rocketry, is to build and launch rockets with commercial motors. As stated above, this builds a foundation of understanding and safety for rocket motors. Mojave Sphinx is liquid-fueled, but it shares much in common with any other high-power rocket.

Building an experimental solid motor is a very strong step toward the eventual goal of a liquid bipropellant. The important aspects to focus on are the design and construction of the motor casing (solid grains can be bought off the shelf and put into a custom-made casing), getting a good feel for how chamber pressure, thrust, and burn time are related, and understanding how each parameter affects the performance of a rocket. *There is a distinction between making a research solid motor and making the propellant!* Making solid propellant can be expensive and dangerous, and does not necessarily contribute to knowledge needed for a liquid-fuel rocket. Any experimental motor effort should be done under the guidance of a mentor and follow established safety codes.

Hybrid rockets, both commercial and research, are the most immediately relevant step which could be taken before a liquid rocket. As it is, Mojave Sphinx is only slightly more involved than a hybrid motor. There are benefits to a hybrid rocket project:

- Commercial hybrid motors are available to build, launch, and study
- Commercial hybrid motors operate on many of the same principles as liquid bipropellants
- Experimental hybrid motors can be tested and launched at certain officially sanctioned rocket events
- The ground support equipment presented in this guide can be built for a hybrid motor, then re-used for a liquid bipropellant

The most common type of hybrid motor is the Urbanski-Colbourn design (UC valve), used in Contrail motors (the only commercial hybrids still produced). Again, the most important parts to focus on are the fundamental principles of how these motors work, and how those principles are applied to liquid motors.

Besides rockets, any other practical, hands-on project experience can contribute to building the necessary skills. If one has ever replaced a spark plug, repaired a leaky sink, or tuned up a bicycle, Mojave Sphinx will be similarly straightforward.

1.1.3 HPR Certifications

At the end of the day, the vehicle described in this guidebook is merely a high-power rocket. High-Power Rocketry (HPR) certification is the best way to become familiar with rockets of increasing size and power, and the challenges one will face besides the propulsion system. For example, recovering a rocket intact can be just as demanding as ensuring it will survive its ascent. Familiarity with electronically controlled pyrotechnic dual deployment systems typical of high-power rockets will greatly increase the chances of success in returning a Mojave Sphinx safely to the ground under parachutes. In addition, certification will establish familiarity with the community and the resources out there to help with experimental motor construction.

Level 2 certification with the Tripoli Rocketry Association also unlocks the ability to test and launch research motors at sanctioned events. While liquid rockets are not currently allowed, solid and hybrid motors are a pathway to building one, as previously described.

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1.2 How to Use This Guidebook

This publication is provided as-is: Readers are free to use it as they wish. However, many will be only starting out in liquid rocketry and may be intimidated by the size and detail of the following sections. Thus, let us contextualize this guide and discuss how it use it successfully.

1.2.1 Summary of Sections

Section 1 presents a general primer on Half Cat-style liquid rocket design, which may be broadly applicable to any project aiming to produce a low-cost liquid rocket. Section 1 especially focuses on rockets intended to fly and discusses liquid bipropellant motors as simply another type of propulsion for amateur rocketry.

While rigorous explanations of the fundamentals of rocket propulsion are largely left to other preexisting texts, this guide discusses practical elements of design that can be directly applied to the creation of real-world hardware in a manner accessible to students and hobbyists. The authors' learnings collected from many designs – and tests and launches thereof – are distilled into the Half Cat Rocketry Liquid Motor Standard (HCR-1100), which is introduced and explained in Section 1. The Standard is intended to provide a framework of strongly recommended design approaches which maximize probability of success. It is not formally binding, nor is it enforced by any organization or agency, but seeks to establish a set of general principles and standard techniques for amateur liquid rockets. Unlike solid and hybrid motors, which have had tried-and-true architectures for decades, this type of guideline has not previously existed for liquids, and the lack of documentation is part of why bipropellant motors may seem to be much more difficult.

Section 2 is a detailed examination of a specific liquid rocket design, Mojave Sphinx. This section delves into the "why" behind every feature of each component, as well as the analyses used to predict motor performance, critical structural margins, flight profile, and maintenance schedule. Section 3 shows each static test and launch of the prototype rocket, along with a brief description and available data. This section adds context for the progression of the design, explains lessons that were learned along the way, and showcases design heritage.

The remaining sections of the guidebook present detailed instructions accompanied by a Bill of Materials to enable the reader to replicate and operate Mojave Sphinx. The same is provided for the ground support equipment (GSE), which can be used for any "Half Cat style" liquid rocket.

1.2.2 Advice For Experience Levels

For Newcomers to Hobby Rocketry

Half Cat Rocketry welcomes those who have never touched a rocket before, or have only made smaller hobby rockets. While Mojave Sphinx may be beyond a reasonable immediate scope, this guide is nonetheless good reading material on how the simplest of amateur liquid rockets work, and the skills which will be needed for building one. Section 1.1 outlines the path to liquid bipropellant rockets, which are very achievable for amateur rocketeers who put their mind to it.

For High-Power Certified Readers

Individuals who have already built high-power rockets (especially ones with dual deployment recovery systems) are well positioned to think about a liquid bipropellant project. The first criteria to establish is whether it is feasible to travel to FAR with the rocket (which can brought on a plane as checked luggage). If this is not possible, then launching a Mojave Sphinx may be off the table. Building the rocket can still be a good exercise, and it may be held onto until funds are available for a trip to FAR. It is recommended that the first project be a by-the-book build of Mojave Sphinx to become familiar with the workings of standard liquid rockets, and that modifications be kept to a minimum to avoid unnecessary delays and expenses that could jeopardize the completion of the project.

For Student Teams

Similarly to HPR certified individuals, student teams who are starting out in liquid rocketry should go by-the-book as written. One of the most frustrating outcomes of a project is to get to the end and not be able to launch. This rocket is designed to ensure success.

Mojave Sphinx is ideal for a one-semester project in teams of 2-5 members. The following is a suggested timeline for a four-month semester, where the launch would occur either in December or January for the fall semester, or May or June for the spring semester. There may be GSE available to use at FAR, rather than needing to build a new one from scratch, and teams should contact either FAR or Half Cat Rocketry to coordinate during the planning phase. For some teams, Mojave Sphinx may also be appropriate for a full-year project, especially if that involves an annual competition such as FAR 51025 or FAR-OUT.

Time	Phase	Activity
1 Month	Plan	Forming team Reading guidebook Scheduling launch trip
2 Months	Build	Ordering components Machining parts Assembling rocket
1 Month	Launch	Packing rocket & tools Arranging trip logistics Traveling & launching

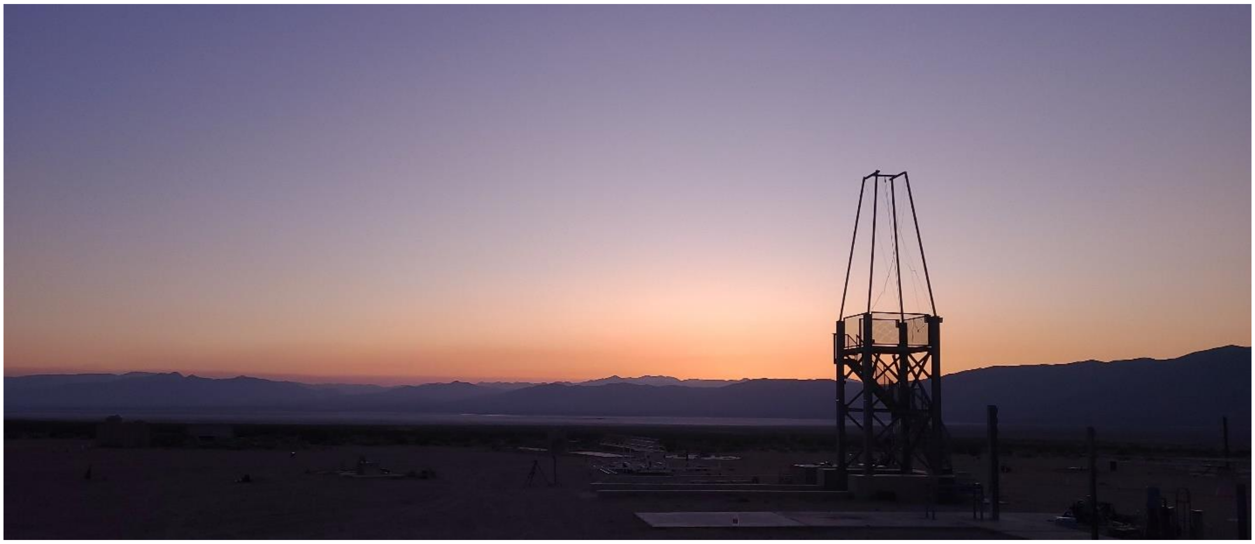
Table 1.1: Recommended schedule of Mojave Sphinx project

For the Experienced Reader

Those who have already built a liquid rocket likely have a good understanding of what goes into making one. Thus, this guide should serve as a reference book for Half Cat Rocketry's design methodology and operations. Mojave Sphinx represents years of optimizations, and every piece is designed to reduce cost and difficulty as much as may ever be possible for this style of bipropellant rocket. There are also useful design and safety resources which can be referenced for projects beyond Mojave Sphinx.

1.2.3 Serial Numbering

Mojave Sphinx is not one specific rocket but a design of liquid rocket, to be replicated and modified. Although the first vehicle bears the name of the design, readers are encouraged to give their builds fun or unique names (and paint jobs). Half Cat Rocketry maintains a list of constructed Mojave Sphinx rockets, each assigned a serial number; contact HCR to register a build. To avoid a 'Ship of Theseus' situation – where all parts are gradually replaced over time until nothing original is left – the serial number is attached to the propellant tank casing tube, the single largest and most costly component. Appendix J lists all registered Mojave Sphinx builds and will be updated in future editions to showcase the work of other teams.



1.3 Standard Liquid Rocket Design

For the purpose of making amateur liquid motors as accessible as possible, Half Cat Rocketry has created a standard design for bipropellant rockets. Much in the same way that there are particular styles of solid and hybrid motor construction which are widely favored and recommended for their simplicity, this architecture gives a baseline of success from which anyone can clone, modify, and improve. The standard design is sometimes called a "Half Cat style" rocket. This section gives a summary of the Half Cat Rocketry standard liquid rocket design.

The standard is intended to provide guidance and a bounding framework for maximizing success, based on years of experience. However, these are merely guidelines. Experienced readers may choose to operate outside of them, making specific and intentional choices for potential benefit in exchange for an increased chance of failure.

1.3.1 Propellant Selection

Oxidizer

> The oxidizer shall be nitrous oxide (N_2O) that is loaded, stored, and utilized in a saturated liquid condition. Oxidizer shall only be loaded into the rocket's propellant tank through a remotely operated valve, when all personnel are at a safe distance.

Nitrous oxide (N_2O) is a molecule which can decompose into diatomic nitrogen and oxygen, making it an oxidizer. It has a few properties which make it the ideal choice for an amateur liquid rocket, and which make the Half Cat standard design as simple as it is. The most important property of N_2O is that it is used as a *liquified gas* - when stored in a closed container, it is in a saturated liquid state with a high vapor pressure around room temperature. This means that it is indefinitely storable (unlike liquid oxygen, which constantly vents off to keep its temperature and pressure down) and self-pressurizes at normal temperatures. It is also not corrosive or toxic like hydrogen peroxide, nitric acid, or other more exotic oxidizers. See section 1.4 for safety information regarding nitrous oxide systems.

Automotive (or racing) grade nitrous oxide is the most commonly available for amateurs. It typically contains up to 500 ppm sulfur dioxide, which does not have any effect on performance.

Fuel

> The fuel shall be any non-toxic alcohol, ketone, or hydrocarbon which is a free-flowing flammable liquid at atmospheric pressure and temperature. The fuel may contain a maximum of 15% (nominally) by mass of gasoline, any amount of dissolved non-toxic solid additives, and up to 30% of water as dilutant.

Many liquid fuels can be used, but alcohols are the best choice. They are generally cheap, easy to acquire, non-toxic, and evaporate cleanly so as to not leave residue. Ethanol can easily be acquired in varying grades and prices, especially those with a small gasoline content (E98 and E85). Almost any flammable liquid will work with varying levels of performance - see Section 2.6 for common fuels.

1.3.2 Propellant Tank

> The Propellant Tank shall be made from aluminum alloy round tube (recommended) or pipe, with bulkheads at each end radially sealed with elastomeric O-rings and retained by radial fasteners. The bulkheads shall include threaded ports for fittings to permit discharge of oxidizer and fuel from the tank to the propellant feed system, as well as filling of the oxidizer tank from the ground support system. The bulkheads shall be supported against internal pressure by a retaining ring, which may be a separate piece (recommended) or integral to the bulkhead. Radial fasteners shall pass through clearance holes in the tank wall and through the retaining ring and may be secured either with nuts placed on the inner diameter of the retaining ring (recommended) or by threading into tapped holes in the retaining ring itself.
>
> The oxidizer tank may comprise the lower portion of a tank consisting of a single tube (stacked tanks; recommended) or a larger-diameter outer tube concentric to the inner tank tube (concentric tanks), with its outlet on the aft bulkhead. The oxidizer tank shall always have a static pressure vent drawing fluid from the forward end of the oxidizer tank. The static vent may be either a hole drilled directly in the side of the oxidizer tank or a hole drilled in a fitting that is stood off from the oxidizer tank. Siphon tubes may be used to locate the static vent in a position aft of the oxidizer tank. The internal fluid path from oxidizer tank to static vent shall never be impeded by valves, seals, or other obstructions.
>
> The fuel tank may comprise of the upper portion of a tank consisting of a single tube, with its outlet on the

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forward bulkhead such that fuel is expelled by upwards motion of the propellant piston (stacked tanks; recommended) or a smaller-diameter inner tube concentric to the outer tank tube, with its outlet on the aft bulkhead such that fuel is expelled by downward motion of the propellant piston (concentric tanks).

The fuel and oxidizer shall be separated by a piston, which is free to slide inside the tank in order to expel the fuel using the pressure applied by the oxidizer vapor. The length of the piston shall be not less than one half of the inner diameter of the tube, and shall include a minimum of two elastomer seals between the fuel and oxidizer. Pistons may use O-rings (recommended) or other types of seals such as U-cups, X-rings, square rings, T-rings, or similar. If directional pressure-assisted seals such as U-cups are used, they shall be oriented in opposite directions, such that each seal is assisted by the pressure of the propellant on the side of the piston to which it is closest. Non-elastomer seals including PTFE O-rings, PTFE spring-energized seals, metallic seals, or braided packing seals shall not be used on propellant pistons.

The oxidizer tank shall include a minimum of 5% ullage volume in case of sudden, rapid heating. Ullage may be formed in a stacked tank either by a set distance between the level of the static vent (or siphon tube) and the oxidizer side of the piston or by a hollowed-out pocket in the piston. Ullage may be formed in a concentric tank by any arrangement that forms a cavity which liquid cannot rise to during fill.

The fuel and oxidizer must be stored in a pressure vessel: the propellant tank. A question often asked by teams and individuals looking to build a liquid rocket is where to get tanks from. The answer is simply to make them, as the resulting product will be lighter, cheaper, and easier to use than a commercially manufactured pressure vessel.

The answer is also related to another frequently asked question: How are the fuel and oxidizer pressurized? This single question, more than any other, will determine the level of complexity and scope in a liquid rocket project, and can make or break it before it begins. Thus, in standardizing a simple liquid bipropellant architecture, the pressurization scheme was made an entirely passive byproduct of the physical design.

Dual-Acting Vapor Pressurization is a method which requires no additional gases or components to pressurize either the fuel or oxidizer. The concept is simple: A "floating" piston sits inside the propellant tank, free to move when pushed. It is exposed to liquid N_2O on one side, and liquid fuel on the other, with seals in between to prevent them from mixing. N_2O's vapor pressure is quite high – in the hundreds of psi for typical temperatures – meaning that it does not need a pressurant gas. Since the N_2O is pushing on the piston, that pressure is applied to not only itself but the fuel as well. This means that when the main propellant valves open, both liquids are forced out.

Because N_2O is stored as a saturated liquid, it always wants to maintain a specific pressure corresponding to its bulk temperature. Thus, it rapidly boils off some liquid while the tank drains to maintain pressure until all liquid has been expelled. In the boiling process, it expends some internal energy in the form of temperature. As it cools down during expulsion, the corresponding saturation temperature drops, and the tank pressure decays. The thermodynamics work out such that the pressure decays over time to a final value which is always about 70% of the initial. Therefore, it can be seen that the energy to maintain pressure – rather than being provided by a pump or compressed gas – is the heat energy stored within the liquid oxidizer itself.

All standard liquid rockets include a **static vent** at the top of the N_2O tank. It has two critical purposes:

1. *Oxidizer loading.* Without a way for gas to escape from the tank, only a little bit of N_2O would fill before it became fully pressurized and nothing more could enter (a pressure gradient is required for fluid to move). Therefore, the static vent allows air and N_2O gas to escape and be replaced with liquid drawn out of the supply bottle.
2. *Safety.* The static vent ensures that in any scenario there will always be a way for N_2O to eventually boil out and depressurize. Since the static vent is quite literally a hole in the tank, it can never fail into a condition where pressure gets trapped in the system.

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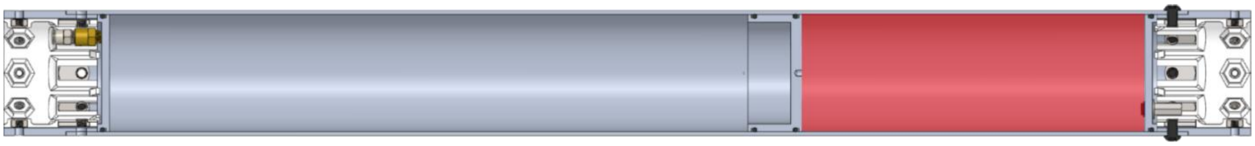

Figure 1.1: Stacked propellant tank with upwards-moving piston (to the right, as pictured), after manual fueling and prior to oxidizer loading operations. The fuel tank is sealed and the rocket may be handled without hazard as long as the fuel valve is kept closed.

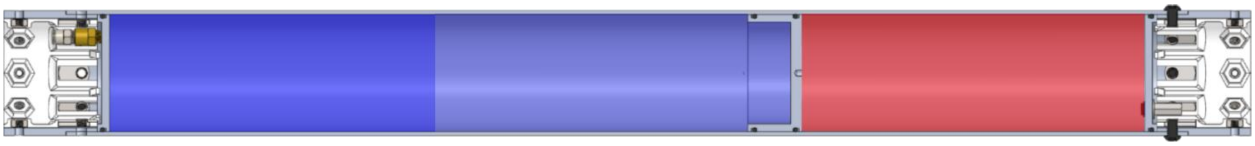

Figure 1.2: Stacked propellant tank with upwards-moving piston (to the right, as pictured), at an arbitrary time during oxidizer fill. The static vent is located just below the oxidizer side of the propellant piston (on the left of the piston, as pictured). Even though the oxidizer tank is sealed, the rocket is hazardous at any time when pressure or oxidizer are present. No personnel are allowed to be near the propellant tank at this point, and must remain away until it has completely depressurized.

Figure 1.3: Stacked propellant tank with upwards-moving piston (to the right, as pictured), prior to starting operation. Note that in reality, the propellant tank must be upright relative to gravity, so that the oxidizer (blue) drains to the outlet at the bottom (on the left, as pictured) and fuel (red) drains to the outlet at the top (on the right, as pictured).

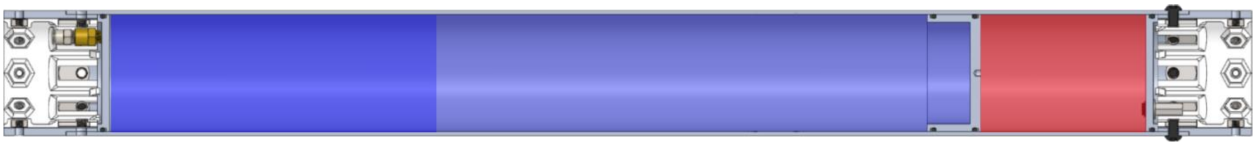

Figure 1.4: Stacked propellant tank with upwards-moving piston (to the right, as pictured), at an arbitrary time during operation. In a stacked tank configuration, the piston moves upwards to force fuel out while oxidizer drains. The drained portion of the tank is replaced by gaseous oxidizer.

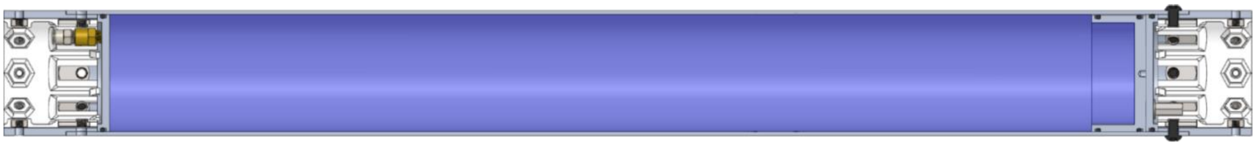

Figure 1.5: Stacked propellant tank with upwards-moving piston (to the right, as pictured), after exhausting all liquid fuel and oxidizer. Once all liquid has been expelled, the remaining pressurized gas discharges through the oxidizer outlet.

The ends of a standard liquid bipropellant tank are formed by O-ring sealed bulkheads with fluid fittings and a retaining ring held in by radial bolts. The bulkheads and retaining rings may be combined into a single part, but separate pieces are generally easier and cheaper.

Another rather unique aspect of standard Half Cat rockets is the tank arrangement. Oxidizer is stored below the piston and fuel above it, so that the propellant tank can be formed from a single metal tube. This is called a **stacked tank**. It contrasts with concentric tanks, where the fuel tank sits completely inside the oxidizer tank and both outlets are at the bottom end. As a consequence of the stacked tank design, fuel first travels *up* out of the top bulkhead, then back down through an external **downcomer**. It has no detrimental effect on the system except for a minor fuel pressure loss through the downcomer. Furthermore, this has been found to act as a sort of natural filter for large particulates in the fuel tank, which sink to the bottom (the piston side).

1.3.3 Thrust Chamber Assembly

> The Thrust Chamber Assembly shall consist of an injector, combustion chamber, nozzle, igniter, and may include an ablative thermal liner inside the combustion chamber.
>
> The injector shall include threaded ports to permit ingestion of oxidizer and fuel from the propellant feed system, contain any number and shape of orifices to permit injection of oxidizer and fuel into the combustion chamber, and be sealed to the combustion chamber with radial elastomeric O-ring(s).
>
> The nozzle shall include a throat to exhaust propellant to ambient and be radially sealed to the combustion chamber by either elastomeric O-ring(s) or a flat flexible-graphite gasket which may only be used in conjunction with flange plate retention. If a thermal liner is included in the combustion chamber, the nozzle shall also seal to it in addition to the combustion chamber. The nozzle may consist of either A) a single piece or B) separate nozzle carrier and throat insert pieces.
>
>> A. Single piece nozzles shall be made from aluminum or copper.
>>
>> B. Nozzle carriers shall be made from aluminum or copper. Throat inserts shall be made from 300-series stainless steel, any grade or alloy of copper, 600- or 700- series nickel superalloy, graphite, or phenolic-based composite material.
>
> The combustion chamber shall be made from aluminum or copper.
>
> The injector, nozzle, and combustion chamber shall be retained against internal pressure by either A) retaining rings or B) flange plates.
>
>> A. Radial fasteners shall pass through clearance holes in the wall of the combustion chamber and through the retaining rings, which may be separate pieces or integral to the injector/nozzle, and may be secured either with nuts placed on the inner diameter of the retaining ring or by threading into the tapped holes in the retaining ring itself.
>>
>> B. Axial rods, which may be all-thread or partial-thread, shall pass through clearance holes in the faces of the flange plates, which may be separate pieces (recommended) or integral to the injector/nozzle, and shall be secured with nuts threaded onto the rods and tightened onto the face of the flange plate such that the injector and nozzle are compressed in contact with the combustion chamber.
>
> As an exception to the above, the combustion chamber and nozzle may together consist of a single piece made from any alloy of either aluminum or copper and be sealed and retained to the injector in same manner as described previously.
>
> The igniter shall be a cartridge made of aluminum, brass, or stainless steel threaded into a port on either the injector or combustion chamber to permit discharge of hot gas into the combustion chamber. The igniter may consist of one piece or multiple separate pieces. The igniter cartridge shall contain solid propellant which is started by an electronic initiator that is triggered by a ground-side ignition command.

The thrust chamber assembly (TCA) is the part of the rocket which ingests propellant, combusts it, and exhausts gas to produce thrust. It consists of an injector, combustion chamber, and nozzle.

The most common type of chamber for standard liquid rockets is the **heatsink**. This means that it is not cooled in any way; rather, it is intended to absorb heat for a limited amount of time. Heatsink chambers are heavier than an equivalently sized ablative or regenerative cooled chamber, but extremely simple to make and require no maintenance. Aluminum heatsink chambers are made possible by short burns times and a low mixture ratio which sacrifices performance efficiency to lower combustion temperature dramatically.

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Fig. 1.8 depicts a typical thrust chamber assembly, where the nozzle is made from solid round bar and the barrel section from extruded tube, with a flexible graphite gasket seal at the interface. The chamber can also be made in a single piece (monolithic) from solid round bar if desired. The chamber may include a throat insert, a separate piece made of a more heat-resistant material like copper or graphite which replaces a small portion of the nozzle around the throat. This increases chamber survivability against longer burn times or more intense operating conditions.

The exact design of an injector is open to personal choice, but it will usually take the basic form of a groove-manifold (Figs. 1.6 and 1.7). **Groove-manifold injectors** are simple lathe parts with minimal drilling required. The actual injection elements themselves may be simple impinging doublets, a scrintle, or a more complicated scheme such as coaxial shear.

In addition to the radially-bolted retention method used in the propellant tank, the thrust chamber assembly may be retained with axial compression as shown in Fig. 1.4. In this method, two **flange plates** clamp the injector and chamber with threaded rods and fastening hardware. Since the flange plates can be laser- or waterjet-cut from flat metal plate, they are very economical; they also eliminate the need for fastening features on the chamber and injector themselves, which greatly reduces the machining time and required precision. Note that the combustion chamber can be made from one or two pieces, but the flange plate clamping works the same either way.

The igniter is responsible for initiating combustion. It must provide a large heat input to overcome the energy barrier to nitrous decomposition and break it down into nitrogen and oxygen, which then burns with fuel to sustain combustion. Ignition must be highly reliable, and the best method to achieve this is with a solid propellant **cartridge igniter**. The benefit of a cartridge igniter over igniters inserted through the throat is that it moves the igniter itself away from the liquid propellant stream; the blast of cold propellants is capable of forcibly ejecting an igniter or simply extinguishing the igniter flame. With a cartridge igniter, where a solid propellant (typically an Estes blackpowder motor or similar) is contained within a housing stood off from the chamber, there is no possibility that either of these scenarios can occur - in fact, in all cases where the E-match has fired and both propellant valves opened, cartridge igniters have demonstrated 100% reliability in Half Cat Rocketry motors.

The cartridge igniter (Fig. 1.9) may be threaded into either the injector or chamber wall. Placement on the injector is better for aerodynamics because the cartridge will be fully within the profile of the vehicle, although it can be challenging to route the igniter through-hole between the central oxidizer port and the fuel groove-manifold. Placement on the chamber wall is typically only possible in heatsink chambers, which are thick enough to drill and tap a port into.

Cartridge igniters also make convenient chamber pressure transducer locations. Since the igniter is open to the combustion chamber, a transducer on the cartridge will read chamber pressure; since it somewhat removed from the chamber, the sensor itself it protected from high heat flux and is able to survive the full duration of the burn.

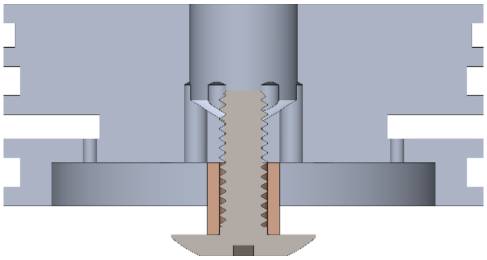

Figure 1.6: Basic groove-manifold scrintle injector (Shown in section plane with injection orifices)

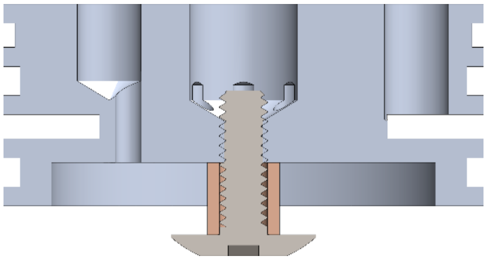

Figure 1.7: Basic groove-manifold scrintle injector (Shown in section plane with fuel inlet and igniter pass-through holes)

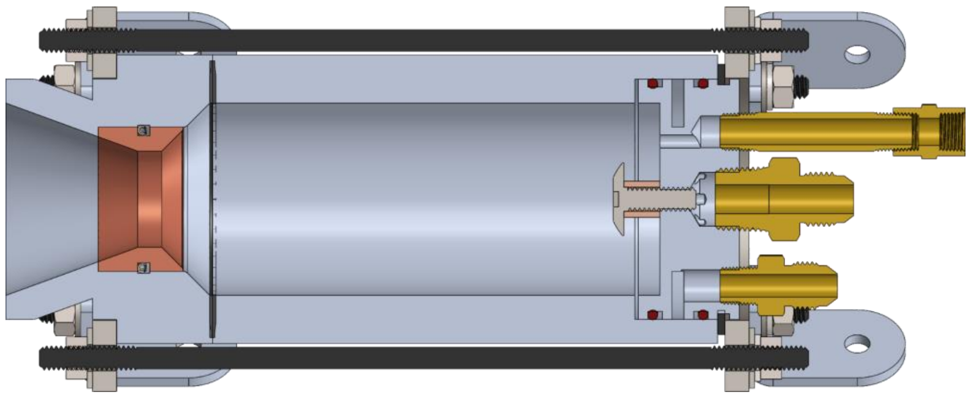

Figure 1.8: Standard thrust chamber assembly, with scrintle injector and throat insert (cartridge igniter omitted)

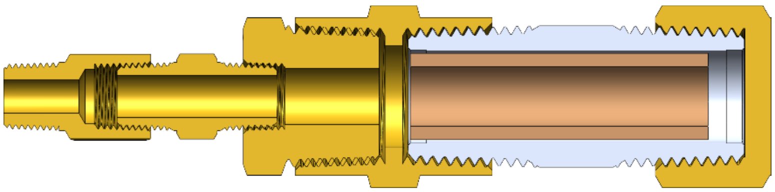

Figure 1.9: Cartridge igniter, made with off-the-shelf components

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1.3.4 Fluid System

The fluid system consists of various plumbing components which direct and control propellant flow between the tank and chamber. In the Half Cat standard, this has been reduced as much as possible since it is very easy for a feed system to grow in complexity and rapidly become the most cumbersome part of a liquid rocket project.

Main Propellant Valves

> The flow of oxidizer and fuel from the Propellant Tank to the Thrust Chamber Assembly shall be controlled by a main oxidizer valve and a main fuel valve. Each main propellant valve shall be either A) a servo-actuated ball valve (recommended) or B) a Half Cat style pneumatic poppet valve.
>
> > A. The servo mechanism and ball valve may be directly connected by fastening the handles (recommended), by a coupling between the shafts, or by gears. Shaft couplings and gears shall not be 3D printed in plastic.
> >
> > B. The body of a Half Cat style pneumatic valve shall be made of aluminum. The poppet shall be made of either PTFE (Teflon) or acetal (Delrin).

Both of the main propellant valves are typically **servo-actuated ball valves**. These are robust and uncomplicated mechanisms made entirely from off-the-shelf components with a custom 3D-printed housing. Full port ball valves are used to minimize pressure loss, as they do not restrict flow. With a single PWM command from the ground system, both the fuel and oxidizer valves are opened fully, and remain open during and after the burn; the thrust terminates when propellant is depleted. Leaving the valves open after the burn allows the nitrous vapor remaining inside the tank to dissipate, and ensures no pressure or propellant remains in the system aside from a small residual volume of fuel in the downcomer.

As an alternative to servo-actuated ball valves, the main valves may be Half Cat style pneumatic poppet valves. These will not be described in detail here since they are not recommended, but there is literature available on the HCR website regarding the design and function of these custom valves.

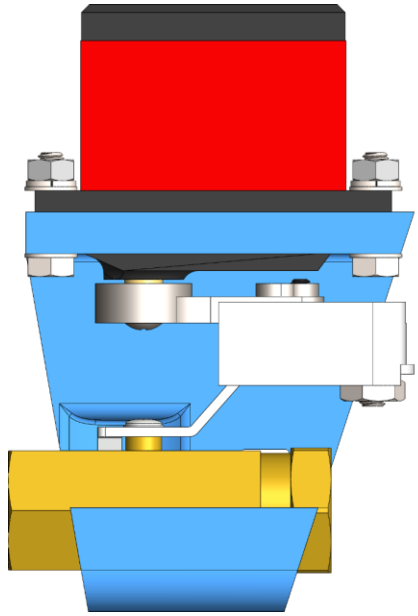

Figure 1.10: Servo-actuated main propellant ball valve (housing highlighted in blue for contrast)

Feed Lines

> Oxidizer and fuel shall flow from the Propellant Tank to the Thrust Chamber Assembly through either flexible stainless steel-braided PTFE hose or flexible nylon tubing rated to a minimum of 500 psi.

Due to the imprecise nature of the rocket and its components, the tubes (also called feed lines) connecting each part must be flexible. The main two kinds of tubing typically used are high-pressure nylon and stainless steel-braided PTFE. High-pressure nylon tubing is quite cheap and easy to cut to length, which makes it ideal for longer and less critical fluid lines. Braided PTFE hose with a 37° flared connection is very easy to attach and remove, but these are more expensive and only available in pre-determined lengths. PTFE hoses generally have thinner walls and larger inside diameters than high-pressure nylon tubing for a given outer diameter, allowing higher flow rates and lower pressure loss. Hydraulic hoses, which may be cheaper, are acceptable for fuel lines, but these should be avoided for oxidizer since the rubber liner could potentially be impregnated with nitrous oxide.

It is often the case that some tubing and many of the fittings used on Half Cat type rockets will not be explicitly rated to the maximum expected operating pressures that are possible with saturated N_2O. However, supplier ratings typically come with large safety factors built in and are acceptable to use for higher pressures **so long as they are pressurized only when personnel are at a safe distance from the system.** This is of critical importance – see Section 1.4 for more detail. PTFE-lined stainless steel-braided hoses are commonly available with ratings of 1500 - 3000 psi, which makes them an ideal choice for the connection from ground supply bottle to remotely operated fill valve.

Quick Disconnect

> Oxidizer shall flow from the Ground Support Equipment to the Propellant Tank through a Flange-Clip Quick Disconnect, which shall consist of a male fitting, female fitting, and clip. Either the female (recommended) or male fitting shall be integrated to the vehicle and the other fitting shall be integrated to the ground-side oxidizer fill line.
>
> The vehicle-side fitting shall be made from any alloy of aluminum or brass, and the ground-side fitting shall be made from any alloy of aluminum, brass, steel, or stainless steel. The male fitting shall seal to the female fitting with an elastomeric O-ring(s). Both the male and female fittings shall include flanges at the mating interface.
>
> The clip shall be made of any metal or plastic material, slide freely over the flanges of the mated male and female fittings, and include a tie-down point.

Quick disconnects (QDs) are a specialized type of fitting that can be rapidly mechanically disengaged, without the need to unscrew threads. The use of a QD on the nitrous fill line allows it to cleanly separate from the rocket at liftoff, preventing damage to the rocket and ground system that can result from a still-connected line being pulled taut and breaking under thrust load.

The standard liquid rocket design uses a **Flange-Clip QD**, developed by Half Cat Rocketry specifically for this application. The Flange-Clip QD is a completely passive device that uses the motion of the rocket itself to disengage the coupling, which then separates from pressure blowoff load. This eliminates the need for an active mechanism such as a pneumatic piston or electromechanical actuator, with the added benefit of simplifying the countdown and launch procedure. The assembly consists of two custom flanged fittings (one male and one female) and a U-shaped clip that fits over the flanges. The fittings seal to one another via a small O-ring installed on the male half. Each fitting also has a 1/8 NPT port, allowing standard COTS fittings to connect the QD to the rocket's tank and the fill line on the GSE.

As shown in Fig. 1.11, the two halves of the flange-clip QD are coupled together before launch by the clip, which reacts against the axial force exerted by the pressure in the nitrous fill line during and after oxidizer loading. This force is relatively low (on the order of 50 lbf) due to the small area that the pressure acts on, and the clip – which is typically made of 3D-printed plastic – is more than capable of withstanding it. The clip is tied down to the launchpad or otherwise secured to the ground using a strong, heat resistant tether such as Kevlar cord. When the rocket takes off, the fill line and QD fittings move upward while the clip remains stationary, pulling the flanged fittings out of the clip. At this point, the flanged fittings are axially unrestrained and separate nearly instantaneously from the internal pressure blowoff force.

Slack in the clip tether should be kept to a minimum so that the QD separates in the first 2-3 inches of the rocket's motion, with at least two feet of slack remaining in the fill line. Too short a fill line (or too long a clip tether) can result in tension on the fill line damaging the male fitting or causing it to bind in the bore of the female fitting, preventing separation even after the clip is disengaged. It is critical that the strength of the tether is sufficient to resist the frictional force between the clip and fitting flanges, with a dynamic amplification factor of at least 2. Plastic zip ties should never be used to connect the clip to the tether, as they are prone to snapping well below their rated breaking force.

It should be noted that there are also a wide variety of COTS quick disconnect fittings available, most of which use some version of a ball lock mechanism and are intended for pneumatic or hydraulic systems. However, such devices do not lend themselves well to the type of passive actuation

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described above; they have a high risk of jamming under sudden shock load, especially when the force is not perfectly axial. The flange-clip QD was created in response to failures of an earlier design that used an off-the-shelf QD fitting with a tether attached to the sleeve that releases the ball lock. Despite apparently successful testing of the system both by yanking on the tether and manually sliding the rocket up the launch rail, the QD failed to disconnect during liftoff on multiple launches due to the much higher force and acceleration imparted by the rocket's thrust, breaking the tether and fill line and leaving a still-connected portion of the GSE trailing behind the rocket.

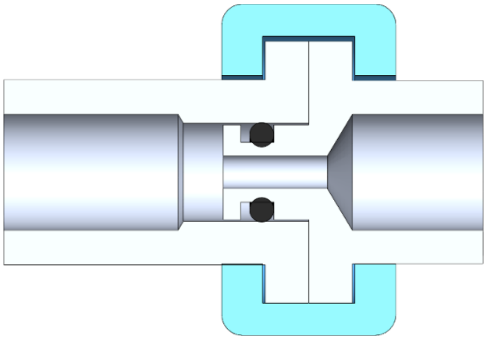

Figure 1.11: Flange-Clip QD (clip highlighted in blue for contrast)

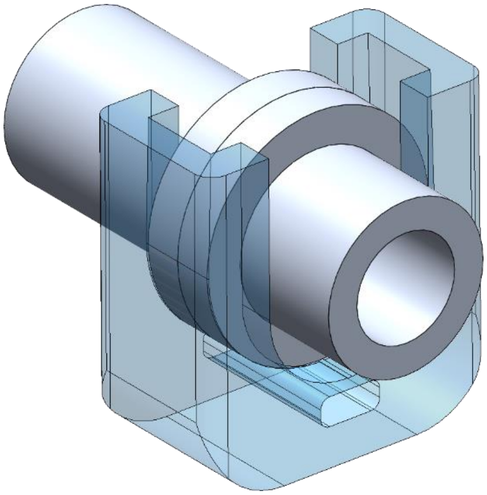

Figure 1.12: Flange-Clip QD (clip highlighted in blue for contrast)

Figure 1.13: Unsuccessful QD mechanism. The printed sleeve holds onto the release ring so that the QD can be pulled out, however in practice the shock load of launch prevented the QD from disconnecting and broke the tether.

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1.3.5 Interfaces

> The Thrust Chamber Assembly shall be connected to the Propellant Tank by a Thrust Structure composed of no fewer than three rigid members, fabricated from aluminum angle, T-bar, square or rectangular tube, U-channel, or similar extruded profile.
>
> Each member of the Thrust Structure must be fastened to both the Propellant Tank and Thrust Chamber Assembly at two locations (four total locations), which are separated by a minimum of one half of the outside diameter of the tank. Fasteners which apply axial preload shall be used for these connections, such as screws/bolts (recommended) or rivets; pins shall not be used.
>
> The Thrust Structure may be fastened directly to the outer diameter of the Propellant Tank and Thrust Chamber Assembly, or may use intermediate brackets or spacers to provide coplanar mating surfaces between components of different diameters.
>
> Fins shall be fastened to the rigid members comprising the Thrust Structure by screws/bolts (recommended) or rivets.
>
> The Airframe shall interface to the forward end of the tank assembly by sliding over the interface ring and/or a portion of the Propellant Tank itself. The Airframe shall be fastened to the tank assembly by no fewer than three radial fasteners, which thread into the interface ring or nuts installed against the inner diameter thereof (recommended).
>
> The Recovery Harness and/or any components in the primary load path of parachute deployment shock shall be anchored either directly or indirectly to the forward Propellant Tank bulkhead by means of fasteners that are either threaded into or pass through the bulkhead, without permitting leakage of propellant. The Recovery Harness and/or any components in the primary load path of parachute deployment shock shall not be anchored solely to the Airframe, and shall not be anchored solely or primarily with adhesive.

One of the key elements to ensuring flight worthiness of the Half Cat standard liquid rocket design is the manner in which the components are reliably and securely mated together. The first structural interface is between the propellant tank and the combustion chamber: These two are connected by a rigid external thrust structure, typically a set of aluminum angle brackets on which the fins are attached. The structure uses **2x2 attachment**, where both ends are connected at two points. This makes alignment of the tank and chamber a non-issue because neither end can freely rotate. Note in Fig. 1.14 how both tank and chamber are fastened to the angle brackets with two screws – all degrees of freedom are fixed, thus, assuming the brackets are straight, both components are held in-line with each other without requiring precise hole tolerances.

The thrust structure, externally bolted-on, can be easily removed and replaced if required. The angle brackets also provide a mounting point for fins, which can likewise be easily removed and replaced. Note in Fig. 1.14 how a fin can be unobtrusively attached to the angle bracket. Fins can be rapidly swapped out for a different design, or a backup spare in case of damage. One other benefit to this type of design (exoskeletal) is that it leaves plenty of unobstructed volume for components inside the plumbing section, whereas a structure within the rather limited circular cross section of the propellant tank (endoskeletal) can be excessively difficult to work around.

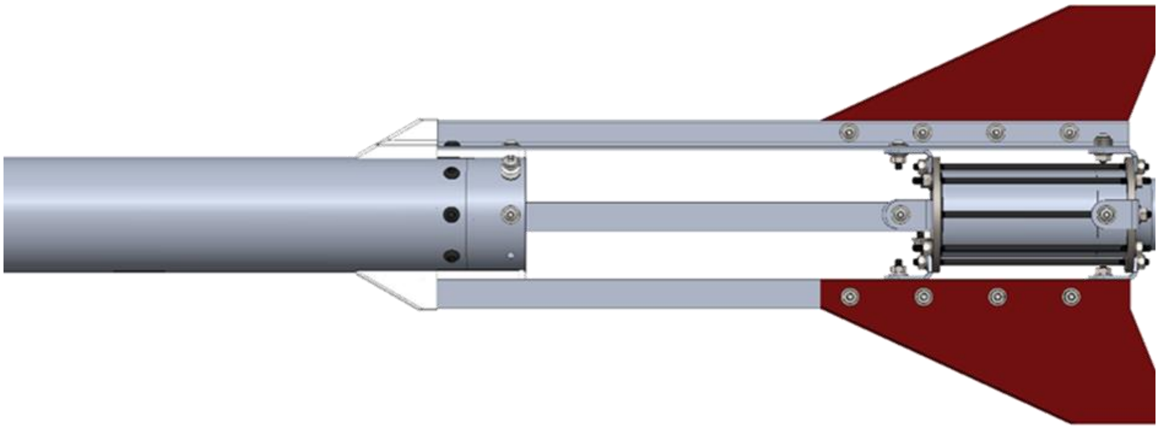

Figure 1.14: 2x2 attachment between thrust chamber assembly and propellant tank, with attached fins (valves and plumbing omitted)

The second critical interface is between the propellant tank and the airframe at the forward end of the rocket. **Clean airframe mating** is the idea that the rest of a high-power rocket, which includes body tubes, nose cone, electronics bay, and recovery system, can be cleanly mounted to the front of the liquid propulsion system without the need for additional structural components between the two. In the standard design, the forward retaining ring of the propellant tank extends from the tank casing and includes fastener holes to attach an airframe tube.

A recovery bulkhead with a U-bolt is connected to the forward tank bulkhead by two threaded rods. The rods may interface with the tank bulkhead in one of two ways: directly, by threading into blind holes in a sufficiently thick bulkhead, or indirectly, by using coupling nuts with screws that pass through the tank bulkhead and are sealed to prevent fuel leakage. The latter method is shown in Fig. 1.15. Shock cord can be anchored to the U-bolt to transfer load from the parachutes, and the airframe is easily removed for servicing with the recovery bulkhead remaining attached to the tank assembly.

In essence, the standard liquid rocket can be thought of as an independent propulsion system attached to a high-power rocket airframe and recovery system. With only slight modification, most high-power rocket airframes can be converted to for use with a liquid bipropellant motor using this method.

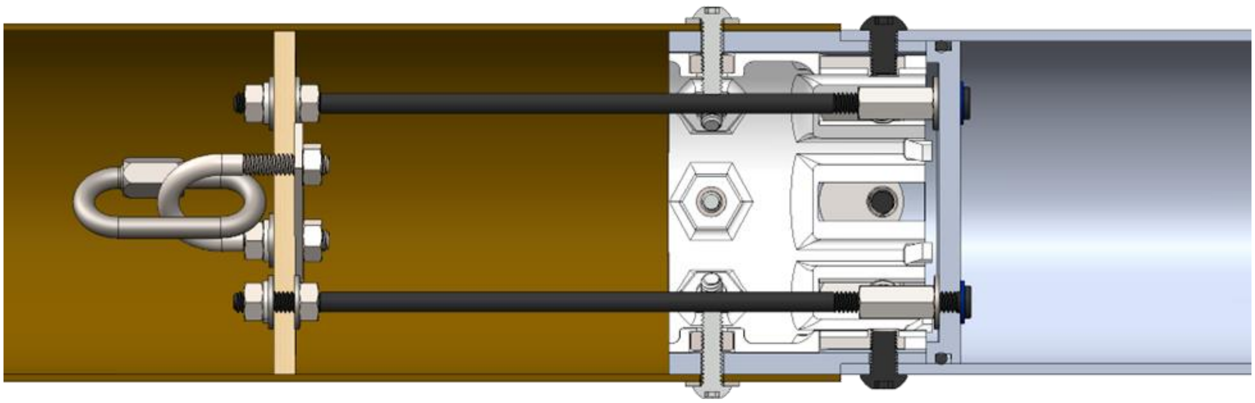

Figure 1.15: Clean airframe mating between fuel tank bulkhead and lower airframe tube, including recovery bulkhead for shock cord attachment (fuel valve and plumbing omitted)

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1.3.6 O-Rings and Gland Design

The most common kind of seal used between components in standard liquid rockets is the O-ring, so named for being a ring-shaped seal with a circular (O-shaped) cross-section. Typical O-rings are made of an elastomer material and form a seal by deforming inside a groove. The default standard for O-rings and O-ring gland design is the Parker O-Ring Handbook, but it comes with some caveats. It must be understood that the Parker guide is made for seals that are up to industry specifications, able to withstand potentially millions of cycles across wide temperature and pressure ranges. Designing to Parker specifications, however, can make assembly, servicing, and cost for a low-stakes amateur project far more burdensome than they need to be. Half Cat Rocketry has demonstrated on many occasions that "improper" O-ring gland design can work just as well for the purposes of an amateur liquid rocket. It should also be noted that the focus of this subsection is exclusively on radial O-ring seals (a.k.a. piston seal), where a round part with on O-ring installed on the exterior is pushed into a round bore. Face seal O-rings, which seal between the flat faces of two parts, are not used in standard Half Cat liquid rockets.

Function

The main principle to understand about O-rings is that they require compression, or "squeeze," to work properly, so that the elastomer flows into the microscopic surface imperfections under the pressure of installation. In practical terms, this means that the gland must be shallow enough for part of the O-ring to be protruding past the outer radius of the part it is installed on and make contact with the inner radius of the part it is being installed into. The other important parameters for an O-ring are stretch (how much its diameter increases when installed in the gland compared to the relaxed state) and gland fill (how much of the gland is filled once installed into the bore). As with squeeze, Half Cat Rocketry has demonstrated the acceptable range for these characteristics to be far wider than usually specified.

Material

There a wide variety of materials which O-rings can be made from, each with different characteristics. Most available materials are more exotic and niche than required for amateur liquid rockets, and costlier. **Buna-N** (a.k.a. NBR or nitrile rubber), is among the most common and least expensive material. It is also compatible with all commonly used materials, although it exhibits severe swelling after exposure to gasoline (even in very small concentrations, such as the 2% present in E98) and should be replaced after use if exposure occurs. **Silicone rubber** is slightly costlier than Buna-N, but its softness makes silicone O-rings easier to install. It is also compatible with all commonly used materials, although it exhibits severe swelling after exposure to gasoline and should be replaced after use if exposure occurs. **Viton** is a fluorinated silicone rubber, making it more compatible with oxidizers; however, compatibility with nitrous oxide in this specific context is not a concern, and it has never been the cause of failure for any Half Cat type rocket. Viton is more expensive and very similar in physical characteristics to Buna-N.

> **Note: Oxidizer compatibility on the rocket itself is not a requirement because personnel will never be near incompatible materials when oxidizer is present. See Section 1.4 for detailed safety information regarding nitrous oxide bipropellant rockets.**

Lubrication

It is necessary to apply grease to an O-ring to aid installation and prevent damage. Lubrication also helps the O-rings on the tank piston slide smoothly and prevent sticking during operation. A general rule of thumb is that any grease will work once, although it may cause the O-ring to swell or disintegrate over time. **Silicone grease** is a common option, although it has not been typically used by Half Cat Rocketry. Silicone grease should be avoided if using silicone O-rings. **Red lithium grease** (specifically Lucas Oil Red "N" Tacky #2) is the standard recommendation for its extremely low cost and higher viscosity, which make it easy to scoop and spread. As strange as it may seem to use literal axle grease in a bipropellant rocket motor, this lubricant has a long and successful heritage in

Half Cat type rockets. White lithium grease is similarly inexpensive and widely available. The white color comes from the inclusion of very small aluminum oxide particles, which do not meaningfully impact its lubrication properties. Super Lube is a brand name synthetic grease that contains microscopic PTFE particles. It is slightly more expensive than lithium grease, but works well for all types of O-rings. It is commonly used in amateur rocketry due to its inclusion in Aerotech reloadable solid motor kits. **Krytox** is an oxygen-compatible grease which is somewhat more expensive – the same note about oxidizer compatibility (and why it is unnecessary) applies to lubricants. If oxidizer compatible lubricant is mandated by a third party, such as a university advisor, **Tribolube** may be used in place of Krytox at lower cost.

When applying lubrication to O-rings, use a liberal amount of grease to ensure that they install smoothly. It never hurts to add more grease, especially with cheap greases.

O-Ring Damage and Re-Use

In typical amateur liquid rocket applications, O-rings rarely if ever need to be replaced. On parts which remain installed, O-ring life should be indefinite within the scope of this guide. The most common places where O-rings may need to be serviced are the forward tank bulkhead and tank piston, both exposed to fuel and un-installed regularly. If O-rings are not swelled, such that they still fit into their groove nicely, they may be re-lubricated and re-installed. If an O-ring is damaged, it should be replaced or else may leak when pressurized. Minor damage such as small surface nicks may be acceptable, but tears, slices, rips, and other large damage are likely to cause failure and warrant replacement.

Note: an exception to the above applies to O-rings that are used to seal combustion chambers in locations other than adjacent to the injector fuel manifold, such as on a nozzle or nozzle carrier sealing to a case or ablative liner. Such locations are likely to exceed the melting temperature of any elastomeric material, requiring replacement of the O-ring after each firing; an O-ring that melts during firing will usually maintain its sealing effectiveness for the duration of the burn, but should be replaced immediately thereafter. The Mojave Sphinx design does not include any O-rings that are expected to melt during normal operation.

O-Ring Glands

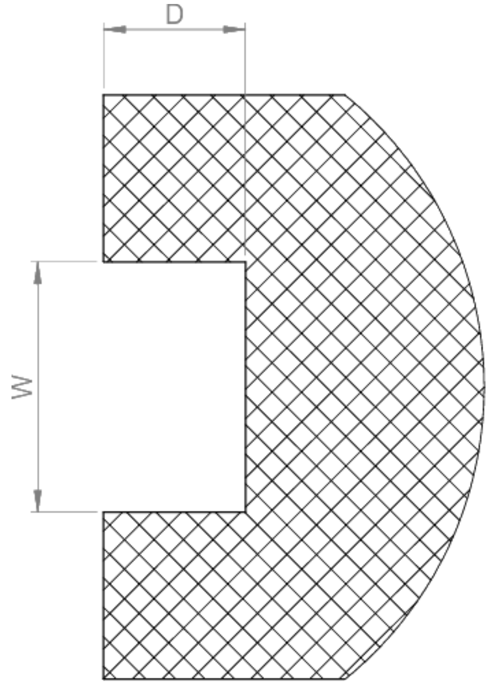
The source found to be most useful for amateur liquid rockets is the Marco Rubber Static O-Ring Design Chart, which is provided for reference in Appendix H. This reference has been used successfully in every Half Cat Rocketry project, and it has been found that the gland sizes can be safely increased even further than Marco Rubber specifies. To this end, provided below is a simplified chart for sizing O-ring glands.

It is recommended to leave at least .100" of length on either side of the O-ring groove whenever possible. This avoids a thin lip that is easily damaged, and in some applications provides axial distance margin before the O-ring protrudes past the end of the bore.

Note: The Marco Rubber O-Ring gland dimension chart will work as-is, but Table 1.2 offers more lenient dimensions, and the resulting gland will make installation easier without compromising seal integrity.

Procedure for designing a radial O-ring seal in standard amateur liquid rocket applications:

1. Find the inner diameter of the bore.
2. Select an O-ring cross-section. As a general rule, this should be the largest cross section for which a groove will reasonably fit in the length/thickness of the part.
3. Reference the Marco Rubber chart found in Appendix H.
4. Follow the column for E (O.D. Sealing Type Bore Diameter) down until the matching bore diameter is found in the appropriate cross-section, denoted by the leading number in the three number dash code. The dash code (e.g., -123) is the O-ring size.
5. Reference Table 1.2 below.
6. Find the row for the corresponding series number, and size the gland from the outer diameter of the part the O-ring will be installed on.



AS 568A Series	O-Ring Cross-Section (Inches)		Gland Width (W) (Inches)		Gland Depth (D) (Inches)	
	NOM	TOL ±	NOM	TOL ±	NOM	TOL ±
-0XX	0.070	0.003	0.100	0.005	0.054	0.004
-1XX	0.103	0.004	0.148	0.006	0.085	0.004
-2XX	0.139	0.004	0.196	0.007	0.115	0.004
-3XX	0.210	0.005	0.291	0.008	0.175	0.005
-4XX	0.275	0.006	0.387	0.010	0.231	0.005

Table 1.2: O-Ring Gland Size Chart

1.3.7 Port and Fitting Types

The topic of fittings is surprisingly heated in some engineering circles, as there are differing opinions on the use and proper occasions for various types of fittings. Discussion in this section will be limited to the relevant points required to understand and construct a simple amateur liquid rocket.

Pressure Ports

Simply put, a pressure port is a pressure-sealed passage into or out of a part – what that means in this context is that a pressure port is a hole with a fitting installed. For amateur liquid rockets, there are two main ways to seal a pressure port in a component: NPT and boss port. Both have their uses, advantages, and disadvantages.

NPT

National Pipe Taper (NPT) is a standard for tapered threads which seal by deformation. They form a conical profile as shown in Figure 1.16.

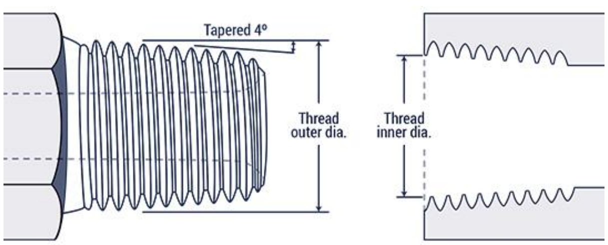


Figure 1.16: NPT male fitting and female port

NPT fittings have a reputation for being bad or difficult to use, which is often due to either a misapplication of NPT or a misunderstanding of the requirements in using it. There are a number of key advantages which make it ideal for amateur liquid rockets:

- Low cost and widely available with a large variety of form factors and a useful range of sizes
- Easy installation and low sensitivity to variation in installation torque and thread engagement, allowing controlled clocking when necessary
- Ports can be easily tapped into soft metals by hand using common and inexpensive tools that do not require high precision or rigid workholding (for 3/8NPT and smaller)
- Ability to withstand and seal at a wide range of temperatures

There are also distinct disadvantages which limit its usage:

- Limited number of removal and re-installation cycles (clocked fittings should not be removed and re-installed)
- Lack of deterministic indicators of leak-tightness without conducting pressurized leak checks
- Less precise clocking control than swivel-type straight thread fittings with a jam nut and O-ring
- Large sizes (1/2 NPT and above) can be challenging to hand-tap without sturdy workholding

The fact that NPT is so dominant in fitting catalogues makes it the default choice for pressure ports. NPT is also highly advantageous for building fitting trees because it goes together with Lego-like qualities: Tees, crosses, elbows, connectors, and reducers can be combined in many ways and branch out to line connections or adapt between two otherwise incompatible fittings. It has been the case at many (possibly a majority of) Half Cat Rocketry operations that the day has been saved by having a large collection of various NPT fittings to make, repair, or rework a connection.

In most applications, a few wraps of PTFE tape should be applied to the male threads of an NPT fitting prior to installation. This reduces friction against the threads of the female port and can act as a secondary sealant by helping to fill any remaining space between the threads.

Because NPT threads create a seal through deformation of the thread material rather than compression of an elastomeric or metallic seal, they are capable of sealing across a relatively wide range of torque and thread engagement, making them insensitive to variability in installation. This also allows NPT fittings to be installed in a specific rotational position (often called "clocking"), because the range of thread engagement across which an NPT fitting can seal encompasses more than one full rotation. Once the fitting reaches the minimum engagement required to seal, it can be tightened further by at least one full turn until clocked in the desired orientation, without detrimental effect. NPT fittings and threaded ports made from softer materials such as brass and aluminum are more forgiving in this regard than harder materials such as steel or stainless steel, which is also prone to galling. Stainless steel fittings are not recommended for amateur liquid rockets following the standard design discussed in this document, but can be used if no other options are available. When both the male and female threads are made from stainless steel, nickel-bearing PTFE tape should be used to prevent galling.

In summary, NPT is a convenient pressure port connection that has the advantage of cost and ubiquity for the size of liquid rocket that most amateurs and students will build. There are challenges to using NPT, but it remains the most advantageous option for creating a pressure-sealed connection in a machined component. A chart of NPT thread dimensions is provided for reference in Appendix G.

NPT Size	Depth of Fitting in Port in CAD (in.)
1/16	0.200
1/8	0.200
1/4	0.250
3/8	0.280
1/2	0.360

Table 1.3: Recommended NPT depths in CAD

Straight Thread / Boss Ports

Boss ports are a broad class of sealing types which have straight threads and compress a sealing element between a fitting and the part it is threading into as shown in Figs. 1.17 and 1.19. The most common standards for boss ports found in the context of liquid rockets are BSPP, AS5202, and SAE J1926-1.

BSPP

The most suitable type of straight thread fitting for low-cost amateur rocketry applications is BSPP (British Standard Pipe Parallel). These fittings are somewhat less available in the United States than NPT. However, they are much less expensive than other types of straight thread fittings due to their use in plumbing applications, similarly to NPT. BSPP fittings have straight threads with either an O-ring or bonded sealing washer (elastomer gasket molded or adhered onto a metal washer) that is compressed between the underside of the fitting hex and the flat surface surrounding the port. In some cases, a copper washer may be used as a gasket; though capable of withstanding higher temperatures than elastomers, copper washers are less effective at creating a leak-tight seal, more sensitive to surface finish on the fitting and ported surface, and require higher installation torque.

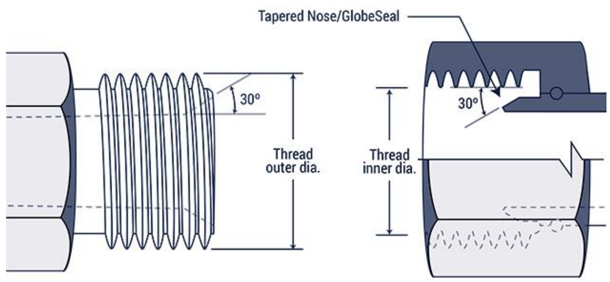


Figure 1.17: BSPP fitting and port

No specialized seal gland geometry is used for BSPP; this greatly simplifies machining the ports, as they are simply straight thread tapped holes. A milled spot face around the port of at least the diameter of the sealing washer is recommended to provide a smoother sealing surface, but is often not required when using an elastomer gasket, especially if the ported surface is already machined rather than raw stock. If needed, the area surrounding the port can be polished by hand using fine sandpaper or abrasive finishing pads (such as ScotchBrite brand).

BSPT

BSPT (British Standard Pipe Taper) is – as the name implies – not a straight thread fitting type, however male BSPT fittings can be installed into BSPP female ports, using PTFE tape in the same manner as NPT rather than an O-ring to create a seal. The thread pitch of BSPP and BSPT fittings are the same, however BSPP male fittings are not compatible with BSPT female ports. While BSPT is not generally recommended for standard liquid rockets due to lower availability, it has virtually all of the same characteristics as NPT.

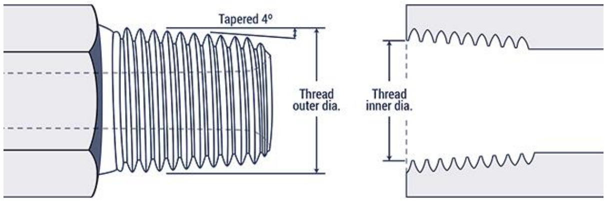


Figure 1.18: BSPT male fitting and female port

AS5202

In professional aerospace applications, AS5202 ports are the predominant method of connecting tube fittings to machined components. These ports use UNF straight threads and have a tightly-controlled seal gland geometry compatible with with AS568 O-rings, as well as metallic K-seals for high-temperature and cryogenic applications. Machining AS5202 ports requires an expensive specialized porting tool, which cuts the seal gland geometry with the required surface finish, and in some cases also reams the hole to the precise tap drill diameter. AS5202-compatible fittings can adapt to most common types of metallic tube connections (i.e., flared and compression), and are typically made from 300-series stainless steel. Cost can range from tens to hundreds of dollars per fitting depending on the type and supplier. When operating on a limited budget, AS5202 ports and corresponding AS-specification fittings are not recommended for student- or amateur-built standard liquid rockets, unless supplied free or deeply discounted by a sponsor.

SAE J1926-1

Automotive and industrial applications often use SAE J1926-1 boss ports. These ports are very similar to AS5202 and also accept a range of UNF-thread fittings, however the sealing feature is compatible only with elastomer O-rings. A specialized porting tool is also required for SAE J1926-1, although these are less expensive and more common than those for AS5202.

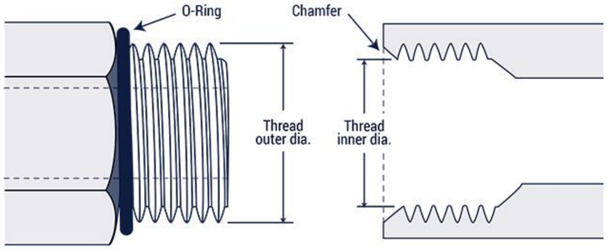


Figure 1.19: J1926-1 straight thread O-ring boss fitting and port. AS5202 fittings and ports look very similar.

Straight thread boss ports have a few beneficial aspects for amateur liquid rockets:

- Effectively unlimited removal and re-installation cycles
- Compression of O-ring provides a more deterministic indicator of leak-tightness upon installation
- Swivel-type fittings using a jam nut offer precise clocking control
- Some types of straight thread ports (BSPP) can be tapped into soft metals by hand using common and inexpensive tools that do not require high precision or rigid workholding

However, it comes with downsides that typically make it a non-starter in the design phase:

- Less common (in the United States) than NPT (typically more expensive and fewer varieties available)
- Often available only in steel or stainless steel, driving higher costs

- Some types (AS5202, SAE J1926-1) require specialized porting tools, and cannot be created from a drilled pilot hole by hand

The biggest reason that boss ports are not used more on Half Cat type rockets is the lack of vast, inexpensive catalogues of fittings in every form factor as is the case with NPT. The second biggest reason is that boss ports cannot be clocked as easily as NPT; boss ports have a very limited range of motion once they are tight enough to seal reliably.

One unconventional use of the boss port fitting concept which shows up occasionally is the bolt passthrough on a tank bulkhead. See Fig. 1.15 and note how the two screws anchoring the recovery bulkhead pass through the forward bulkhead with an elastomer seal under the screw head. In the Mojave Sphinx design they are retained with nuts, but in some cases may be threaded into the bulkhead itself, in the same manner as a boss port fitting. This is an easy, reliable way to add fastener passthroughs to flat surfaces with only a tapped hole.

Tube Connections

By comparison, there are many options for connecting pressurized fluid lines. The types which are usually found in amateur liquid rockets broadly include compression fittings, flared fittings, and push-to-connect fittings.

It is important to understand that tube connections and pressure ports are two very different concepts! A single fitting may have different connection styles. In fact, fittings in this context are usually connecting between a tube and a pressure port and will have a different fitting standard on each end. *Tube connections are not the same as pressure ports!* For example: If someone says that their rocket uses NPT, they likely mean that the pressure ports in their machined components are NPT tapped holes. This says nothing about the tubes connections, which could be any one of several different types.

Compression

Compression fittings operate by compressing a ferrule onto the fitting with a nut. The ferrule deforms inwards, gripping the tube to form a seal and resist blowout under pressure. Compression fittings are quite common and therefore inexpensive. Their biggest advantage is that the tube does not need to be flared, and thus can be any length cut from standard tube stock (nylon, aluminum, copper, or stainless steel). However, one downside of compression fittings is a dubious torque spec, usually specified on a turn-basis (i.e., one and a quarter turns past hand-tight), which makes them less reliable for high-stress applications. This was most spectacularly the case in the first static fire of Full Cat, where a tube in the fuel feed system was ejected from a compression fitting due to insufficient retention by the ferrule.

The ferrule will be made of different materials depending on the tubing type; for nylon tubing, a PTFE or acetal ferrule should be used; for aluminum, copper, or brass tubing, a brass ferrule should be used; stainless steel ferrules should only be used with stainless steel tubing, which is not recommended for standard liquid rockets.

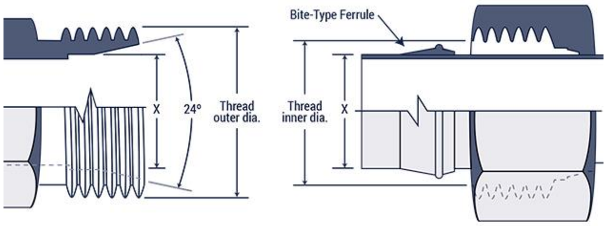


Figure 1.20: Compression fitting, ferrule, and nut

SwageLok, Yor-Lok, and other similar brands are a specialized type of compression fitting. They work in a very similar manner, but are often far more expensive and typically only used for metal tubing

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37° Flare

37-degree flare fittings are perhaps the most ubiquitous type of tube connections in professional aerospace applications, as well as the high-performance automotive world and industrial hydraulic systems. They are generally available in two varieties: AN (Air Force-Navy Aeronautical Standard) and JIC (Joint Industry Council). The two are functionally identical for the purposes of amateur liquid rocketry, with the only differentiator being that AN uses more precise Class 3 "medium fit" threads, while JIC uses more loosely controlled Class 2 "free fit" threads, and are generally less expensive than AN.

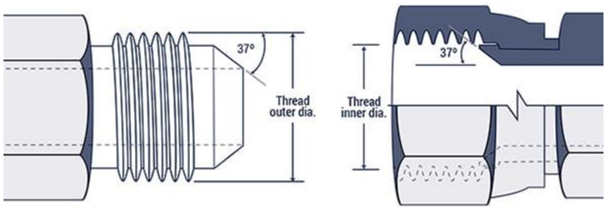

Figure 1.21: 37° flared fitting and port

These connections use a pair of male and female conical metal surfaces, which have a 37-degree half angle (measured from the centerline) and are pressed against one another by the preload from a threaded nut (commonly called a B-nut). The conical profile results in an annular contact line with sufficiently high contact stress to microscopically deform the surfaces. When the female side of the connection is a flared tube, a machined sleeve is placed between the flared end of the tube and the inside of the B-nut to reduce friction and distribute load, similarly to a washer in a bolted connection. Female flared fittings, such as those on flex hoses, typically integrate the flare and sleeve into a single machined part.

Both aluminum and stainless steel tubing can be used with 37-degree flare fittings, with the use of a flaring tool to deform the ends of the tube without cracking. Flaring tools compatible with stainless steel tubing are much more expensive than those suitable for aluminum. A tube bending tool is also required if using metal tubing in any other situation than a straight run.

Due to the difficulty of creating precise bends and the relatively high cost of flaring and bending tools, rigid metal tubing is not recommended for standard liquid rockets, except for straight runs for the portion of a fuel downcomer that is exposed to free stream flow during flight. In this context compression fittings are recommended, but flared connections may be used if desired.

In contrast to rigid metal tubing, flex hoses using 37-degree fittings are quite useful and accessible to the amateur liquid rocket builder, as discussed in Section 1.2.4. Such flex hoses comprise much of the fluid system in the Mojave Sphinx rocket and Ground Support Equipment design due to their reliability and ease of use. Flared fittings are indefinitely reusable, unless regularly over-torqued to the point of yielding.

Flared fittings may be tightened according to a torque specification (many of which are available online) or based on the number of turns past the initial increase in resistance when all surfaces become clamped, however most sizes below ½" will seal at any reasonable value of "wrench tight."

45-Degree Flare

45-degree flare fittings are not recommended for use in standard liquid rockets. They are primarily found in refrigeration and air conditioning contexts, and while their function is virtually identical to 37-degree flare fittings, they are less commonly available. 45-degree and 37-degree fittings are not considered to be compatible with one another, however a seal can be achieved between mismatched flare angles with sufficient torque, which will usually yield one or both of the fittings.

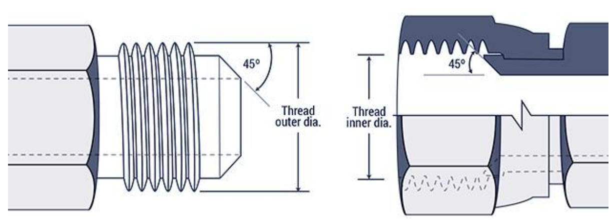

Figure 1.22: 45° flared fitting and port

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Push-to-Connect

Push-to-Connect (PTC) fittings seal by pushing the tube past an O-ring that is pre-installed in the fitting. The tube is retained by a ring of metal teeth that prevent reverse movement. Like compression fittings, the tube does not need to be flared; however, PTC fittings only work with flexible tubing made from nylon or similar polymers, as they rely on the softness of the material for the metal teeth inside the fitting to establish a grip on the tube. Another advantage of these fittings is that the tube can be rotated in place after installation, since the seal is not dependent on axial compression (which prevents movement).

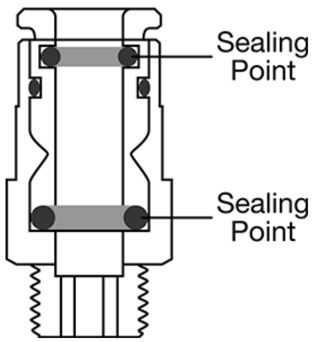

Figure 1.23: Push-to-Connect fitting. Tube not pictured.

To remove the tube from a PTC fitting, a release ring on the outer face is depressed to push the internal teeth away from the tube. The fittings are indefinitely reusable, although the plastic tubing may eventually wear out from repeated removal and reinsertion.

Fitting Material

Brass is the default fitting material for the standard liquid rocket architecture. Most NPT fittings are available in brass (bare or nickel plated), as well as mild steel, stainless steel, and sometimes aluminum.

Brass possesses sufficient corrosion resistance to ensure that surface oxidation is not problematic, and its softness makes fittings more forgiving with regard to installation torque of NPT fittings, which is especially advantageous for controlling clocking. The relative softness also reduces wear on tapped ports in aluminum tank bulkheads and injectors when removed and reinstalled. Aluminum has similar characteristics with much lower density than brass, but is less durable due to its slightly lower yield strength and hardness (when comparing grades from which fittings are commonly made). Additionally, aluminum is not suitable for hot gas connections such as igniters and chamber pressure sense ports; brass is preferred for these applications, followed by stainless steel only when necessary.

Mild steel and stainless steel should be avoided when interfacing with aluminum or copper machined parts, as the harder fitting threads will increase wear on the tapped port when removed and reinstalled. Mild steel also suffers from poor corrosion resistance in humid environments.

Galvanic Corrosion

Galvanic corrosion is often cited as a major potential issue when fittings and the ports into which they are installed are made from dissimilar metals. The two materials can form a galvanic couple, which can result in corrosion when exposed to moisture.

In practice, galvanic corrosion is rarely problematic for standard liquid rockets with a service life of less than two years. Even in humid environments such as Central Florida, the PTFE tape normally used on NPT threads is sufficient to mitigate galvanic corrosion between brass fittings and aluminum ports for a period of at least a year. In dry environments such as Southern California, galvanic corrosion can be considered a non-issue for standard liquid rockets.

Significant visible galvanic corrosion has been observed on a small number of occasions on Half Cat rockets when brass/aluminum interfaces have remained installed for greater than six months without any effort made to limit exposure to moisture. It has never resulted in the failure of a fitting or port. Even so, it is recommended to store standard liquid rocket systems in a climate controlled space whenever possible.

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1.3.8 HalfCatSim

HalfCatSim (HCS) is a simulation program written in Microsoft Excel specifically for the prediction of thrust curves from nitrous oxide liquid rocket motors using dual-acting vapor pressurization. It is a transient simulation, meaning that it calculates the changes in conditions across a series of timesteps spanning the duration of the burn, rather than producing a steady-state snapshot that predicts conditions only for one instantaneous point. This is an important distinction because self-pressurizing motors are never steady-state due to the decay in pressure over time, and a statepoint which provides acceptable results at the start of a burn may cause failure at the end (for example, an unusually low injector stiffness). The transient nature of HCS is also extremely useful for modeling flight performance of amateur liquid rockets, as the resulting thrust curve can be imported to analysis programs like OpenRocket and RASAero II.

HCS has been actively maintained and developed for several years, receiving regular updates that improve accuracy and usability. With a few empirical input values determined through testing, its calculated output matches Mojave Sphinx's static test data to within a few percent of the actual measured thrust and pressures. These empirical inputs can be generalized to similar systems utilizing the standard liquid rocket architecture, or determined through non-hotfire testing such as waterflows. The level of accuracy demonstrated by HCS makes it possible to design standard liquid rocket motors with high confidence in their performance metrics. Furthermore, it allows static testing to be skipped entirely – assuming a suitable launch site able to accommodate the minimum standoff distance or bunkers providing acceptable physical protection – if necessary due to limited resources. Establishing precedent for this practice, 1Cat/4 (50lbf), 3Cat/8 (80lbf), and Mojave Sphinx (250lbf) were all designed using HalfCatSim and successfully launched without first conducting a static test.

HCS includes a number of more advanced features for those who wish to be very detailed in predicting a thrust curve or are seeking to anchor the simulation to test data. Parameters like feed line and component pressure drops, CdA override, film coolant injection, and tank pressure decay control are all available, but not required for the basic design functionality.

Besides motor performance simulation, HCS includes calculator modules for three different types of pressure vessels. These can be used to find structural margin in propellant tanks and combustion chambers, which saves time and avoids risk of error in re-formulating the relevant solid mechanics equations from scratch. These modules are also useful for solid and hybrid motor casings, and have been successfully implemented on numerous occasions by members of the amateur rocketry community.

With HalfCatSim, liquid motors are far more accessible to students and hobbyists than ever before. Alongside resources such as this guidebook, it removes the requirement that anyone looking to build a liquid bipropellant rocket start entirely from scratch. Furthermore, it is free and open-source so that anyone may use it to design liquid motors or modify it to suit their needs.

1.4 Safety Hazards and Mitigation

Rockets are inherently dangerous, as they necessarily store large quantities of chemical energy within structures that are often designed with narrow margins to save weight. Liquid motors are no different than solids and hybrids in this matter. However, liquids do have different hazards that persons working on and around the system must be aware of. The most important safety measure, and usually the only one that matters, is **standoff distance**. While there are dangers for which being far away is not possible or not relevant, standoff distance is the only effective precaution against the most serious and lethally dangerous hazards. **There is no substitute for standing far away when operating the system.** In other words, *don't have people near it when it's hazardous!*

Oftentimes, the risk to hardware is conflated with the risk to people. The former is at the discretion of the hardware's owner, the latter is unacceptable. What this means is that often-quoted "safety measures" like fully pressure-rated parts, material compatibility, oxygen service cleaning, etc. are *optional* on the rocket. If personnel are standing near the system when it is pressurized or has oxidizer in it, when these would matter, *the situation has already gone wrong!* It will be stated repeatedly: **The only hazard mitigation that matters is keeping all persons clear of the system when N_2O is present anywhere other than the supply bottle.** There is only one exception to this rule, and that is the hose between the N_2O supply bottle and the remotely actuated fill valve. Since the supply bottle must be opened by hand, there will be N_2O present up to the fill valve. This hose should be kept to the absolute shortest length required to reach from the supply bottle fill valve (ideally only 12 inches or shorter), and no larger than ¼" nominal hose diameter, in order to minimize the volume pressurized with N_2O when the supply bottle is opened. In some cases, the fill valve can be mounted directly onto the supply bottle using a brass CGA fitting adapter. Hoses between the supply bottle and fill valve must be made entirely from oxidizer-compatible materials (i.e., PTFE, brass, and stainless steel) and must have a safe working pressure rating of at least 1000psi. (Manufacturer-rated working pressures include a large safety factor, typically 4X.) The remotely actuated fill valve is held to the same requirements; brass-bodied valves with a stainless steel ball and PTFE seats, such as those listed in the Mojave Sphinx GSE Bill of Materials, are commonly available. Furthermore, "whip checks" – also called hose whip restraints – are strongly recommended, to limit the ability of a failed or improperly connected hose to strike and injure nearby personnel. No other components beyond the hose and remote fill valve can be allowed to contact N_2O before all people have been removed from the area.

Are Liquid Rockets Extremely Dangerous?

Like all types of rockets, liquid bipropellant motors can cause harm if mistreated. However, they are not intrinsically more dangerous than other types of rockets – they are simply different. Solid rocket motors, although commonly used, are pre-mixed combustibles which can burn or explode due to stray sparks or electrical charges. Unlike solids, where an inadvertent initiation of the igniter during installation would light the propellant and cause catastrophic injuries, a standard liquid motor simply cannot be ignited by accident during transport, handling or pre-launch preparation; for one, its fuel is sealed away inside the tank, and secondly, no oxidizer is loaded.

If one was to stand near a solid rocket motor during operation, that would be extremely dangerous and a grave violation of every safety principle regarding rocketry. The same goes for hybrid and liquid rocket motors. There is no unique aspect of bipropellant systems that makes them fundamentally more dangerous. **No one can ever be near a rocket motor during operation.** It has been said and will be said repeatedly: *Distance is the only safety precaution that matters.* To approach a live rocket motor of any kind is dangerous.

The following is a discussion of potential safety hazards which may be present with liquid rockets, and mitigation strategies for each.

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1.4.1 High Pressure

High pressure is the most straightforward hazard of a rocket. High pressure can cause hardware to break, projecting shrapnel in any direction at high velocities. Pressure can also cause ordinary injuries purely from gas momentum, where escaping fluid acts like a knife or a bullet. Although it is mandatory that all personnel be cleared when the system is pressurized, it is likely that one will encounter small amounts of trapped pressure, such as between a closed supply bottle and its remotely actuated fill valve. In these situations, fittings may be slowly opened to relieve the pressure while keeping hands away from the escaping gas. If a valve is actuated to relieve the pressure, the line it eventually exits from may whip around if not secured ("whip-checked"). High pressure hazard can be mitigated by keeping all persons clear of the system when N_2O or other pressurized gas is present anywhere other than the supply bottle.

To prevent pressure from being trapped inside the oxidizer run tank, a static vent (i.e., a small hole, typically .020-.047" in diameter) must always be included at or near the top of the volume occupied by N_2O. The static vent serves other purposes besides safety, but that is its most important function: Even in the event of total control failure, the rocket will always depressurize itself given enough time because the static vent is a built-in leak. There should never be a need for firearms to be a part of safety procedures, as was the case at the 2018 Spaceport America Cup and 2024 FAR 51025 competition where at both events a hybrid rocket had to be shot to depressurize the sealed oxidizer tank.

1.4.2 Fire Hazard

Fire hazards are an intrinsic part of rocketry due to the use of flammable substances as fuel and igniters. Fires can occur when free fuel is ignited and spread rapidly if there is a puddle or leak present. Firefighting equipment, such as a Class B handheld extinguisher or a large bucket of water or sand, should always be kept on-hand in case a fire threatens personnel safety. Solvent fuel fires may damage hardware but are mostly benign - the biggest danger is the potential to start secondary fires of nearby equipment, structures, or vegetation. Fire hazards can be mitigated by keeping open flame, sparks, and other ignition sources away when handling fuel *especially* if there is a known spill or suspected leak. Whenever possible, fires should be allowed to burn themselves out with personnel at a safe distance unless the fire is very small and able to be safely extinguished.

1.4.3 Oxidizer Hazard

Oxidizer hazard is present due to N_2O, which splits into nitrogen and oxygen when it decomposes. This decomposition is thermally triggered, meaning that it will not decompose ordinarily unless exposed to a heat source. The main danger to be aware of is that N_2O will accelerate fires, so it should not be vented near hot parts, embers, sparks, or open flame. Although it may appear to act as an extinguisher due to how cold it can get, N_2O should **NEVER** be used to fight fires. Oxidizer hazard can be mitigated by keeping all persons clear of the system when N_2O is present anywhere other than the supply bottle.

1.4.4 N_2O Decomposition

Decomposition is the most critical and unique hazard of N_2O. When it reaches its decomposition temperature, N_2O splits into nitrogen and oxygen while releasing significant heat energy. This makes it an exothermic process. In addition to causing a rapid pressure spike if contained, the free hot oxygen will combust with most anything flammable - simultaneously creating an oxidizer hazard. The decomposition temperature is normally around 1000°F, but a catalyst such as fine metal particles and other contaminants can lower that threshold. Without a significant heat source like an open flame there is little risk of decomposition, but the potential for contact with catalysts and heat sources during normal operation of the rocket is precisely the reason that personnel must be kept away from the system when N_2O is outside the supply bottle.

A less intuitive source of heat is **adiabatic compression**, where N_2O is either compressed or slams into a stoppage with sufficient momentum to instantaneously raise the local temperature above the decomposition threshold. The most common place for this to happen is in a solenoid or other fast-acting poppet valve. All N_2O valves other than the supply bottle valve must be actuated remotely when there is N_2O present. Cavitating N_2O can also provide the requisite compression heating as bubbles of N_2O vapor collapse - N_2O pumps should **never** be used around personnel. Decomposition hazard can be mitigated by keeping all persons clear of the system when N_2O is present anywhere other than the supply bottle.

In addition to regular fire hazards, there is a secondary risk that a fire occurring around a vessel containing N_2O gas, even at ambient pressure, may cause a decomposition event. For this reason, no persons may approach a rocket, test setup, or any other N_2O tank for a **minimum of two minutes** following the last indication of fire or smoke unless it is thoroughly purged with an inert gas such as CO_2. The heating of residual N_2O vapor from a lingering fire inside the combustion chamber or anywhere in proximity to the rocket can cause a tank to explode long after the initiating event. It is especially important to recognize that unlike a normal high-power rocket being on fire, approaching an inflamed N_2O rocket is more hazardous than leaving it alone to burn itself out. If this presents a risk of igniting vegetation and starting a brush fire, emergency fire response should be available at the site.

1.4.5 BLEVE

Boiling **L**iquid **E**xpanding **V**apor **E**xplosion, **BLEVE**, refers to the situation in which a saturated liquid under pressure loses containment and rapidly flashes into gas, resulting in a vapor explosion. Although unlikely, a BLEVE can occur if the N_2O tank experiences a sudden large leak. A key point to note is that a BLEVE will almost certainly not be the primary hazardous event if one occurs, but it will increase damage to hardware and the projected distance of any thrown debris. For example, some mechanism that causes a bulkhead to tear out of an N_2O tank will have already critically damaged the system but will also result in a BLEVE as the N_2O rushes out. The main danger to be aware of is the potential for an explosive event which is beyond the energy release of an equivalently sized pressurized gas container. BLEVE hazard can be mitigated by keeping all persons clear of the system when N_2O is present anywhere other than the supply bottle.

1.4.6 Fuel-Air Explosion

A **fuel-air explosion** occurs when enough fuel vaporizes into a volume of air (containing oxygen) to reach the explosive threshold and ignites, resulting in a detonation. Unlike propane, which readily becomes a gas, alcohol and other room-temperature liquid solvent fuels evaporate quite slowly and are rapidly dispersed by ambient air movement. This makes solvent fuels generally immune to fuel-air explosive mixtures *under normal circumstances* unless they are purposely kept in a stagnant volume with the right oxygen concentration. As is good practice for solvent fuels, they should be handled in a ventilated area. The only real risk of a fuel-air explosion is when a gross leak of both fuel and N_2O gas occurs in a confined space near an ignition source, where the N_2O acts as the air. Fuel-air explosion hazard can be mitigated by handling fuel only in well-ventilated areas, such as near an open roll-up door or outside, and by keeping all persons clear of the system when N_2O is present anywhere other than the supply bottle.

1.4.7 Electrical Hazard

Danger exists with both high and low voltage **electrical sources**. The direct hazard of low voltages is typically a large battery, such as a 12V car battery, unintentionally shorting to itself and starting a fire. High voltages, such as those found in sparker systems, can cause electrical shocks, damage equipment, and start fires. Keep high-voltage devices powered down until needed, and always insulate exposed wires to prevent shorts. Keep E-matches and other electric initiators shunted (leads twisted together) until ready to make a connection to prevent accidental initiation by induced current or stray charges. Always spark-check electrical leads (by briefly touching the supply wires together) before connecting initiators to ensure that current is not flowing, which could cause an unintended pyrotechnic event.

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1.4.8 Burns

Components such as the thrust chamber assembly may be very hot after firing and can cause **burns** if touched before being allowed to cool down. If it is necessary to make contact, such as when recovering a rocket in the field, place the back of your hand about half an inch away from the surface to feel for radiant heat. If no radiant heat is felt, quick-touch feel parts (by touching for as little time as possible) to judge the temperature. In most cases, hot metal parts can be quickly cooled to safe temperatures by pouring a small amount of water over the surface.

Pyrotechnic ignition materials, including E-matches and solid propellant grains, also pose a risk of burns if mishandled. When connecting igniter electrical leads to the ground system wires, keep hands and other body parts clear of the nozzle, to avoid exposure to flame or hot gas if the pyrotechnic igniter is accidentally set off. As mentioned in the previous section, electrical leads should be spark-checked before connecting to prevent this from occurring.

1.4.9 Frostbite

On the flipside, parts that have recently been exposed to liquid N_2O may be very cold and can cause **frostbite**. Quick-touch feeling parts may also be used to test for cold. It is possible for liquid N_2O to leak out of fittings in a place where it could make contact with skin, particularly the fittings connecting N_2O supply bottle to hose and hose to fill valve. As previously mentioned, it is sometimes preferred to vent this hose by loosening a fitting. The rapid boiling of escaping liquid will absorb heat from anything it touches, which can cause frostbite. This hazard can be mitigated by keeping hands and exposed skin away from the fitting being loosened to avoid contact with liquid N_2O.

1.4.10 Fume Inhalation

Most liquid fuels are inherently volatile to some degree, meaning they constantly evaporate into air. The health effects of breathing a large volume of fumes varies by chemical, but typically results in headache, nausea, or respiratory irritation. In order for this to occur, the fumes must build up in a closed room – therefore, this hazard can be mitigated by only handling fuels in well-ventilated areas, such as near an open roll-up door or outside. As a general rule, personnel should avoid breathing in any airborne chemicals, which also include cleaning agents and rocket motor exhaust.

1.4.11 Asphyxiation

Commonly used gases like N_2O and CO_2 can rapidly displace air in a closed volume, like the inside of a room. Venting a large volume of non-air gas in a closed room may result in drowsiness, or at an extreme, asphyxiation due to lack of oxygen. This hazard can be mitigated by only working with compressed gases in well-ventilated area, such as near an open roll-up door or outside. If a gas bottle is actively leaking indoors, immediately remove personnel from the room and open a door or window if possible. Close the bottle or take it outside, and turn on any available fans to clear the contaminated air from the room.

A rare but occasional scenario can occur in which a gas bottle may inadvertently begin leaking: If a bottle has been in a relatively warm environment, and is then moved to a much colder environment, the thermal contraction of the hand valve may be sufficient to open a leak path. Most notably, this can occur when a bottle has been sitting outside on a hot day and then put into an air-conditioned car or room. Always ensure that bottle hand valves are fully tightened, and if leakage does occur then the same procedure as above should be followed to clear the air in the room.

1.4.12 Standoff Distances

Table 1.4 provides recommended minimum standoff distances by impulse class. Note that this distance extends in all directions from the rocket. These distances should be treated as a *minimum recommendation*, and also apply to occupied buildings and vehicles. Limited exceptions may be made on a case-by-case basis only when persons are behind adequate protection, such as the bunkers used at FAR and RRS.

Pressure relief devices, oxidizer service cleaning, "fail-safe" software, etc. are not an acceptable replacement for standoff distance. In fact, the presence of such "safety mitigations" can instill a false sense of security and invite complacency towards the still-present dangers of being near a pressurized tank containing oxidizer, fuel, and/or inert gas.

Motor Class	Min. Distance (feet)
A – G	200
H – I	250
J – K	350
L – M	500
N – O	750
Above O-Class	1000

Table 1.4: Minimum recommended safe standoff distances

Note: The above distances are based on the total stored energy in the propellant of a typical motor in each size class. These distance guidelines are based on those originally set forth by the Tripoli Rocketry Association (TRA) and were intended primarily to apply solid and hybrid motors, although the stored energy in liquid propellants is similar. Some edge cases unique to liquid propulsion may require modification of these guidelines (always in the direction of increased conservatism), such as extremely short-duration tests of very high-thrust liquid motors. If a test is planned to only partially deplete the propellant tanks, the standoff distance should be based on the maximum potential total impulse if all loaded propellant were to be consumed, regardless of the intended duration.

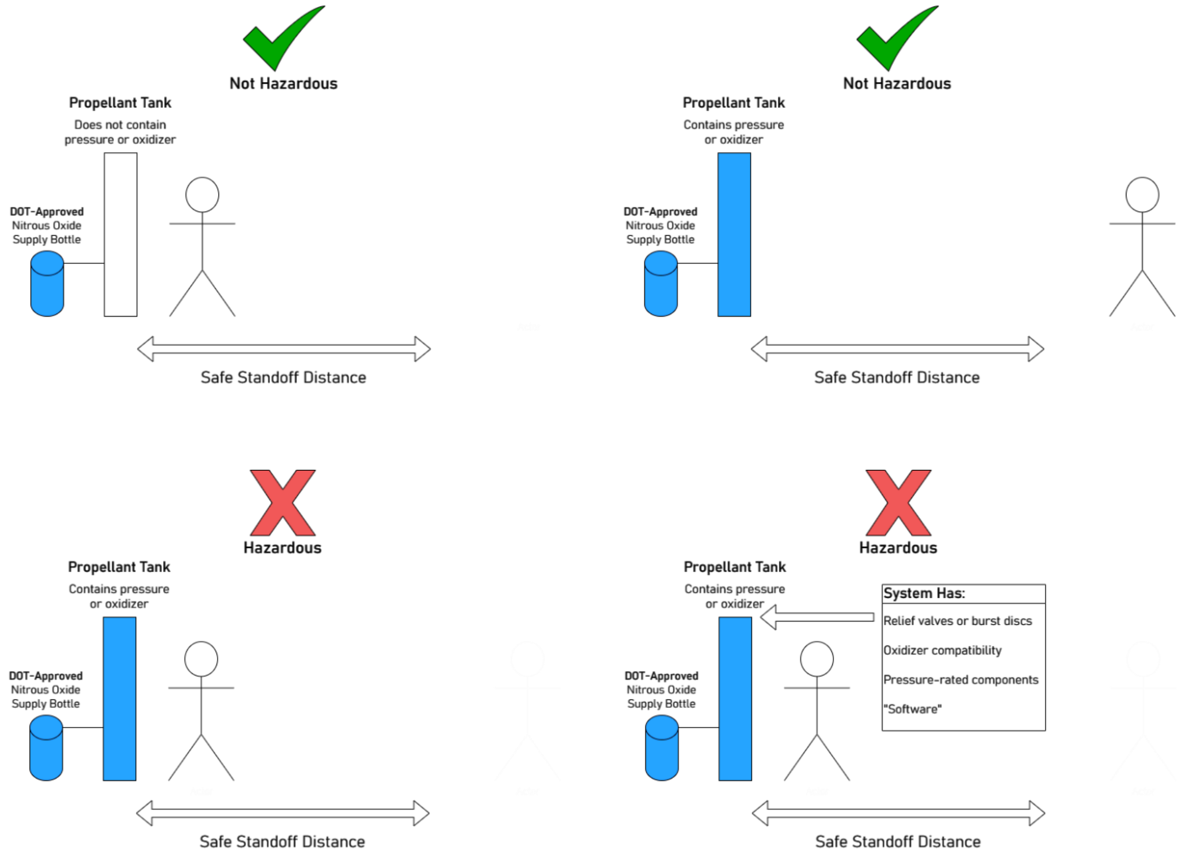

Figure 1.24: Hazardous and non-hazardous situations involving liquid rockets

1.5 Liquid Rocket Legality

Liquid bipropellant rockets are generally not a part of either of the major amateur rocketry organizations in the United States. At the time of publication, there are no commercially-produced liquid rocket motors certified for sale to consumers, and as such all liquids are classified as experimental. The National Association of Rocketry (NAR) does not allow testing or launching of experimental motors at their events, and the Tripoli Rocketry Association (TRA) safety code does not include liquid bipropellants among the permitted types of research (experimental) motors. The TRA safety code does include language indicating that liquid bipropellant projects may be approved to test or launch at a TRA-sanctioned event on a case-by-case basis after review, but no such project has thus far been approved at the time of writing.

1.5.1 Tribrid Motors

The only exceptions to the above are RATTworks' K350 and K600 tripropellant "tribrid" motors, which were the inspiration for the original Half Cat project. The tribrids were largely identical to any other rudimentary hybrid motor (such as those produced and sold by Contrail), having a solid fuel grain, floating injector bulkhead, and Urbanski-Colbourn valve to fill, inject, and ignite nitrous oxide. However, they had in addition a central, concentric fuel tank which began injecting fuel partway through the burn, at which point the motor switched from hybrid to tribrid mode until the solid fuel ran out and it became a pure bipropellant. As of 2024, the tribrid motors remain on the combined NAR/TRA certified rocket motors list and therefore are the only kind of liquid bipropellant rocket allowed at either NAR or TRA events; however, since RATTworks no longer produces the K350 or K600, these motors are effectively extinct.

1.5.2 Test and Launch Limitations

With this in mind, it is important to understand that any liquid bipropellant rocket, including Mojave Sphinx, cannot be flown or test fired at a NAR or TRA sanctioned event. Static test firings are a simpler matter to arrange, since it only requires an appropriate facility, approval of the landowner, and compliance with any local fire codes and regulations. A launch is not so simple; the FAA waivers granted to local club launches cannot be used for independent liquid launches. It is therefore necessary to obtain a separate FAA waiver for any rocket above Class 1 (FAA Class 1 rockets cannot have more than 125 grams of propellant) in addition to an appropriately large area of open land, approval of the landowner, and compliance with local fire codes and regulations.

Both the National Association of Rocketry and Friends of Amateur Rocketry provide instructions on their websites for completing the paperwork required to obtain an FAA waiver for a rocket launch (FAA Form 7711-2 with supplemental information per 14 CFR 101.29(a).) While not insurmountable, the barriers to launch are high enough that it is generally infeasible to launch a liquid bipropellant rocket outside of a few select locations.

1.5.3 Available Launch Sites

The two main organizations that support liquid bipropellant launches are **Friends of Amateur Rocketry** (FAR) and **Reaction Research Society** (RRS), both of which are located in the Mojave Desert, near Koehn Dry Lake, north of the town of Mojave, CA.

FAR

Friends of Amateur Rocketry is the most accessible launch site for liquid rockets; it hosts twice-monthly public launches on the first and third Saturday of each month with its own insurance and rules independent of both national organizations. Students, teams, and individuals interested in testing or launching at FAR need only provide notice through their online form, pay a small daily use fee to offset the operating cost of the on-site facilities, and sign a liability waiver. FAR hosts tests and launches of all sizes and types of amateur rockets. For launches of rockets using commercial motors, spectators observe at a safe distance, and those preparing their rockets may continue working. For tests and launch of experimental rockets (non-commercial motors or unconventional deployment systems), all attendees must take cover in the bunkers for protection against motor failure or ballistic return (when a rocket's recovery system completely fails and it goes down almost as fast as it went up). Bunker calls typically occur once every 1-2 hours, and it is important that everyone at FAR proceed to bunkers quickly so as to not delay operations. The bunkers are an example of adequately secure protection, and the usual safe standoff distances may be reduced because all persons are behind and below solid concrete walls.

RRS

Reaction Research Society was founded in 1947 and operates a site immediately adjacent to FAR on the north side. RRS's mission is rocket propulsion experimentation, education, and outreach, for which it has several test stands and launchpads to host rocket hot fires and launches. RRS does not have a regular public schedule of launch events but is very accommodating to individuals and teams, and the site can be available upon request for members who pay a modest annual fee. Some student teams choose to spend one or more weeks at the site preparing and conducting tests since it is less busy than the FAR site.

1.5.4 Looking Forward

In summary, liquid rockets are not presently permitted at any NAR or TRA sanctioned events but may be tested locally if arrangements are made. However, any launch attempt will need to be conducted at FAR or RRS in California. It is the hope of Half Cat Rocketry to eventually expand launch opportunities either through official certification of a liquid motor or special approval under the TRA safety code.

Readers of this guidebook can play an important role in the future acceptance of liquid rocket motors within national rocketry organizations by testing and launching Mojave Sphinx, gathering data, and continuing to build a record of safety and repeatability.

Section II – Mojave Sphinx

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2.1 Introduction

Oftentimes, the greatest difficulty in starting a liquid rocket project is *uncertainty* – not knowing what works and what doesn't, what the performance will be, how the rocket will actually be fabricated – and fear of unpredictable failures can be discouraging to the point of stopping a project before it even begins. In reality, many common sources of vague concern are trivial, and can be safely neglected. Nonetheless, without prior experience it can be very challenging to find the right path to a successful test fire or launch.

Mojave Sphinx is Half Cat Rocketry's answer to the "unknown unknowns" problem. Through years of building bipropellant rockets, and five distinct generations of major improvements, this design was settled upon as the ideal "kit" for newcomers to amateur liquid rockets. Mojave Sphinx provides a starting point in the form of a complete system that works reliably while providing opportunities for further optimization of its performance. The requisite simulation, construction, iteration, and flight testing has already been completed to say with confidence that the finished product will be successful. In addition, it has the benefit of optimization for production – not only is Mojave Sphinx more reliable, faster to recycle, and easier to maintain than earlier Half Cat rockets, it also takes substantially less time and money to produce from scratch. Extensive static and flight testing of the rocket (35 tests at the time of publication) has resulted in further adjustments to reduce cost and given insight into the required maintenance schedule and component life limits.

The rocket's size was chosen specifically to create a visually impressive vehicle. At 4 inches in diameter and standing 8 feet tall, it reaches a respectable apogee (5,000 to 10,000 feet). All parts and materials can be purchased for an amount well within most university teams' budgets, and fabrication requires only a modest amount of machining which can be accomplished in a few days if divided among multiple team members. Essentially, Mojave Sphinx was sized so that an individual or small team can build a liquid propulsion system cheaply, learn basic machine work, and come away with a large, unique-looking rocket that is fun to launch. While it is possible to make a standard liquid rocket at a smaller size, say 3-inch diameter, the rocket would be substantially smaller at only a marginally lower cost.

One of Half Cat Rocketry's goals is to change the commonly held perception that liquid rockets are prohibitively expensive, take years of work, and are incredibly difficult to get right. This section breaks down each subsystem into its major components to show how they go together, and to show that the completed vehicle is well within the capabilities of a moderately able amateur rocket builder. Mojave Sphinx, as with all Half Cat style rockets, is far simpler than one might imagine for a liquid-fueled system. In fact, one of its defining characteristics compared to both solid and hybrid motors is that is substantially cheaper to operate and much easier to reload after firing.

2.1.1 Key Specifications

These values are approximate due to variation in launch conditions, fuel blend, and injector design.

Mojave Sphinx	Nominal Specs
Rocket Diameter	4.0 inches
Overall Length	96 inches
Design Thrust	250 lbf
Chamber Pressure	250 psi
Burn Time	5 seconds
Total Impulse	5,000 Ns (95% L-Class)
Oxidizer	Nitrous Oxide
Fuel	Alcohol
Nominal O:F Ratio	2.1
Chamber Type	Heatsink
Maximum Altitude	**~10,000 ft**

Table 2.1: Mojave Sphinx key specifications

2.1.2 Cost Summary

The cost table below assumes that machining is done in-house, and does not include taxes. See Section 4 – Bill of Materials for a complete list of parts and prices. Consumables are priced for a total of three launches and based on prices in California at the time of writing, and do not include taxes. Note that the ground system need only be built once, and not at all if borrowed.

Mojave Sphinx	Cost Estimate
Propellant Tank	$222.94
Fluid System	$160.66
Propellant Valves	$155.78
Thrust Chamber	$223.10
Igniter Cartridge	$27.25
Airframe	$128.95
Recovery	$211.55
Consumables	$183.74
Ground System	$529.45
Total Cost	$1,843.42
Rocket Only Cost	**$1,130.23**

Table 2.2: Mojave Sphinx cost per category

2.1.3 Manufacturing Statistics

Listed below are the approximate machining times for each component of the rocket. They assume moderate proficiency with a manual lathe & mill, and may not be representative of all skill levels. Use of CNC machining rather than manual can reduce these estimates substantially.

Mojave Sphinx	Machining Time
Propellant Tank	8 hours
- *2x Bulkheads*	*1 hour (each)*
- *Piston*	*2 hours*
- *2x Collars*	*1 hour (each)*
- *Tube*	*2 hours*
Nozzle	2 hours
Throat Insert	1 hour
Injector	3 hours
Chamber	0.5 hours
Total Machining	**~15 hours**

Table 2.3: Mojave Sphinx machining time

2.1.4 Creation of Mojave Sphinx

Mojave Sphinx was initially conceived and its first iteration built in mid-2023. It was the first 5th-generation HCR vehicle, and as with all generations, its defining architecture change was a response to unsatisfactory elements in preceding rockets. Immediately before (and overlapping with) Mojave Sphinx were 3Cat/8 and Full Cat; both of those 4th-generation vehicles used polymer-seat pneumatic Half Cat valves, themselves a response to the shortcomings of O-rings as valve poppet seals. The change made in Mojave Sphinx was to replace the custom machined Half Cat valves with servo-actuated ball valves, like those which had been in use in the fill system since the beginning. This change was remarkable because it was the first time HCR architecture had made a move *away* from mechanical simplicity – the relatively bulky valves could never beat the light weight and low-part-count Half Cat valves, but they did offer something else: ease of use. The 5th generation of rocket was explicitly optimized for external parties to clone, and Mojave Sphinx is intended to be as user-friendly as possible toward first-time liquid rocket builders, especially with regard to the servo-actuated ball valves that are made of off-the-shelf components. Servo-actuated ball valves will not achieve the minimal size and form factor of Half Cat valves, but they trade a whole subset of the fluid system – the pneumatic lines – for a 3-pin plug that can be connected to the same controller as the rest of the launch system.

Mojave Sphinx is not one specific rocket, but a *type* of rocket. It is the first of Half Cat Rocketry's "production" designs, one created, documented, and released for others to build as a kit and improve upon. It is certain that modifications will be made by other teams, spawning further developments that become a part of future rockets. In many ways, Mojave Sphinx is the most important Half Cat vehicle yet made because it enables a pace of innovation beyond what HCR can achieve on its own and truly lowers the barrier to entry for liquid bipropellant rockets.

Figure 2.1: Mojave Sphinx, hardware

Figure 2.2: Mojave Sphinx, assembled

2.2 Design and Simulation

The rocket's major parameters were determined in HalfCatSim. Based on data gathered from several prior rocket motors, including Mojave Sphinx, it is a powerful tool for sizing all the parameters of a simple liquid rocket.

Mojave Sphinx was designed to produce about 250-300 lbf of thrust for five seconds. This is sufficient to produce a visually impressive launch where the rocket is easy to follow and burns until it is virtually out of sight. The nominal thrust-to-weight ratio is also high enough that it can safely launch in any normally acceptable wind conditions (up to 20 mph), and reaches a safe rail exit velocity even if the thrust is slightly knocked down by a poor-efficiency injector, low performing fuels (such as diesel), or cold temperatures. The nominal total impulse is very near the boundary between L- and M-class (~5000 Ns) and can fall into either designation depending on the hardware configuration – namely the efficiency of the injector – and temperature of the nitrous oxide, which determines both its pressure and density. By coincidence, thrust in pound-force and chamber pressure in PSI happen to be almost exactly the same magnitude (250-300), and trend closely together.

The HalfCatSim (v1.3.8) file to accompany this guidebook is available on the Half Cat Rocketry website and GitHub repository. Because the rocket has already been designed, it is not necessary to change most of the values; The most important parameter which may vary for an individual launch is the ambient temperature. For a simpler launch-day reference than altering the HCS file and re-running the resultant thrust curve through OpenRocket, a table of launch conditions vs. expected thrust, pressures, burn time, total impulse, and max altitude is provided in Table 2.6 (Section 2.5).

Although experimentation and customization are encouraged, it is recommended that first-time liquid projects should closely follow this guide to maximize probability of initial success. Building a "stock" Mojave Sphinx vehicle will develop an understanding of the driving factors behind each element of the design, which then enables modifications to be made without introducing new problems. The propellant tank length is the best candidate for customization, since that can be easily adjusted to add or subtract total impulse. The number and size of injector orifices is also readily modifiable, so long as the O:F ratio and chamber pressure are kept within approximately 15% of the original nominal values. A larger number of smaller orifices can noticeably improve performance; note that HCS does not account for the effects of orifice size on propellant mixing, and that the efficiency value must be estimated and updated manually. Nor does HCS account for the effect of increased chamber volume; the L* result is for informational purposes only. L* is a very "hand-wavey" metric for comparing different chamber designs, and online sources often give values far in excess of what is required for an amateur rocket motor. In practice, with all other inefficiencies accounted for, chamber size is one of the less-impactful parameters in a standard liquid rocket. The only meaningful rule of thumb determined by Half Cat Rocketry is that L* should be kept above 10" minimum, else there is a risk that the combustion chamber may ignite but fail to remain ignited.

A complete explanation of HalfCatSim's inner workings is beyond the scope of this guide, but the following is an overview of the relevant inputs and outputs, as a guide for those looking to customize Mojave Sphinx. Parameters not discussed should be left at their default values unless making major changes to the rocket or architecture.

Figs. 2.3 and 2.4 show the rocket's design, with its basic injector, at typical summer and winter temperatures. These are not the temperatures outside, but inside the propellant tank itself after the oxidizer fill sequence. See Section 2.5 for more information on the effect of temperature and strategies to regulate supply bottle temperature

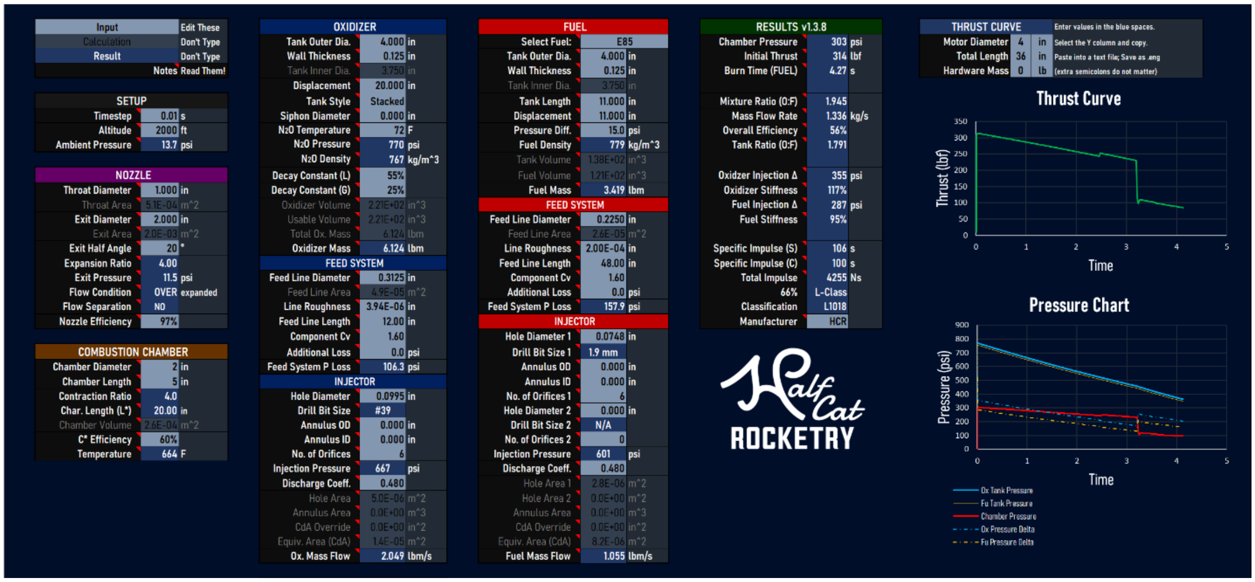

Figure 2.3: Mojave Sphinx HalfCatSim design, motor simulation with basic injector at typical summer temperature

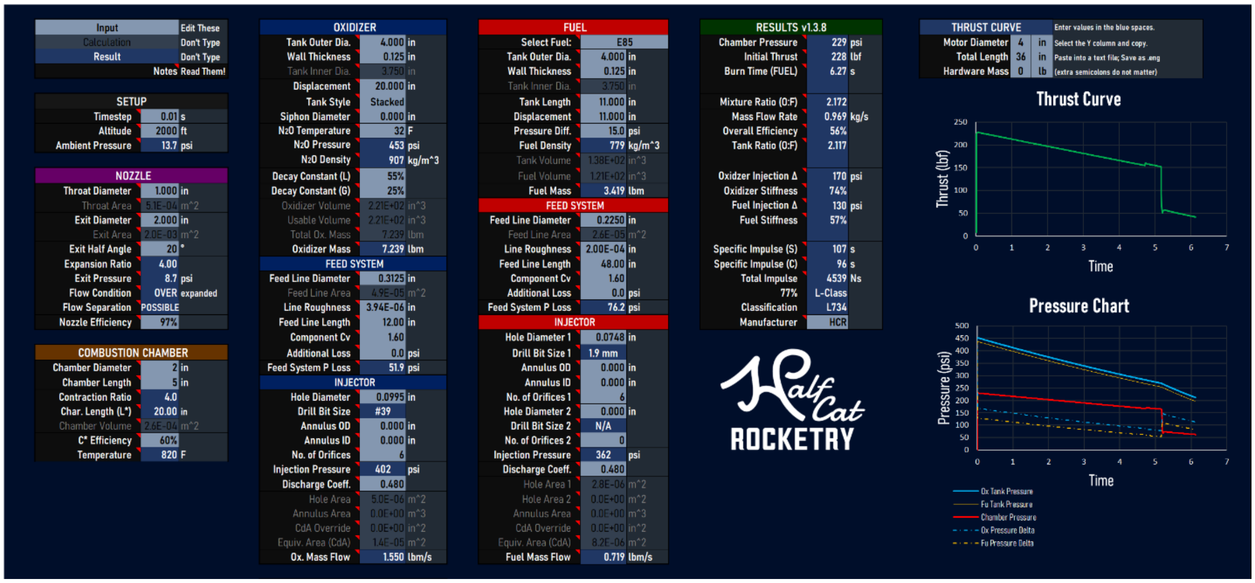

Figure 2.4: Mojave Sphinx HalfCatSim design, motor simulation with basic injector at typical winter temperature

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2.2.1 Setup

Timestep

Increasing or decreasing the time step can sometimes help resolve large oscillations in the thrust curve as well as some types of Excel errors that may appear in the Results block.

Altitude

Launch site altitude determines the ambient pressure, which in turn affects thrust due to the ratio with exhaust exit pressure.

2.2.2 Nozzle

Throat Diameter

Throat diameter (which is used to calculate throat area) is a critical dimension which determines chamber pressure. It is the smallest diameter of the nozzle, where the exhaust is choked at Mach 1.

Exit Diameter and Half Angle

The only thing nozzle exit diameter influences is the exit pressure of the exhaust. Typically there is a fairly wide range of exit diameters that will only affect thrust slightly. The exit half angle is the angle formed by the diverging cone and the centerline of the nozzle; larger values will be less efficient, but generally anything 20° or less will have negligible cosine losses. The exit diameter must always be greater than the throat diameter to prevent errors.

Flow Condition and Separation

Given the chamber pressure and expansion ratio, the exhaust will be either under or overexpanded for the ambient pressure. The only case where this matters is if it is grossly overexpanded, which can cause flow separation (HCS will warn that it is likely to occur if exit pressure is less than 40% of ambient).

Nozzle efficiency

This is the ratio of actual nozzle performance vs. theoretical, due to surface effects. 95-98% is usually a good approximation. This is also known as Cf (thrust coefficient) efficiency.

2.2.3 Combustion Chamber

Chamber Diameter and Length

These do not affect anything in the simulation but are used to calculate the chamber's characteristic length, or L*, which is chamber length multiplied by contraction ratio. Contraction ratio, the ratio between chamber and throat areas, determines the Mach number (i.e., velocity) of gas in the chamber. L* is therefore a proxy for residence time and can be used to compare chamber designs.

C* Efficiency

Also called ηc* (pronounced "eta-C-star"), this variable represents the combustion efficiency. It can vary greatly depending on injector and chamber design, but 70% is a good first guess for a run-of-the-mill standard liquid rocket design.

2.2.4 Oxidizer

Tank OD and Wall Thickness

These are simply the outer diameter and wall thickness of the oxidizer tank. Inner diameter is a calculated parameter because most tubing used as the tank will be specified by OD and wall.

Displacement

This is the length of the N_2O column which can be utilized during the burn. For a stacked tank, displacement can be thought of as the internal length of the oxidizer tank that is occupied by liquid N_2O from outlet (bottom) to static vent (top).

Tank Style

Mojave Sphinx is a stacked tank, where the fuel is located above the oxidizer. Concentric tanks are not relevant to this design.

N_2O Temperature

Since nitrous oxide is stored as a saturated liquid, its equilibrium pressure and liquid & gas density are a function of temperature. The liquid will chill somewhat as it fills from the supply bottle, so it is reasonable to assume a temperature 10-15° C colder than the launch site temperature.

Decay Constants

Self-pressurizing blowdown will cause tank pressure to decay over time to some percentage of initial pressure. These constants should be left as-is for Mojave Sphinx unless fine-tuning the simulation based on test data.

2.2.5 Fuel

Fuel Selection

Mojave Sphinx is designed for E85 (85% ethanol, 15% gasoline mixture available at some gas stations). However, the design is sufficiently robust that virtually any flammable liquid may be used, with varying levels of performance. Alcohols are preferred for ease of handling, but solvents such as acetone and most paint thinner or brush cleaner products will work reasonably well. The most common alternatives to E85 in Mojave Sphinx are isopropyl alcohol (99% recommended), purer forms of ethanol, and kerosene (Diesel #2, heating fuel, or any grade of jet aircraft fuel).

Tank OD and Wall Thickness

Similarly, these are the outer diameter and wall thickness of the fuel tank. Again, inner diameter is a calculated parameter.

Displacement

This is the length from the fuel-facing side of the piston to the bottom of the forward bulkhead. It is equal to full piston movement because fuel pressure drops to zero the moment that the piston contacts the forward end.

Pressure Difference

There is a slight sliding resistance on the piston due to friction from the O-rings. For Mojave Sphinx it can be conservatively assumed to be about 10 psi. Overestimation of pressure difference across the piston will cause the system to run more fuel-rich than predicted. While performance will be lower as a result, hardware will not be harmed by lower combustion temperatures. A more refined estimate can be obtained by measuring the force required to slide a piston with greased O-rings installed, and dividing by the internal cross sectional area of the fuel tank.

2.2.6 Feed System

Both the oxidizer and fuel feed system modules work the same way to calculate pressure loss through the plumbing. This module can be ignored if a known CdA of the system is available, but it is a useful tool for separating feed system pressure loss from the injector.

Feed Line Diameter

This is the inner diameter of the tube that carries propellant from the tank to the injector. It determines propellant velocity inside the line and is the most important factor in pressure loss.

Line Roughness

Surface roughness also has an impact on pressure loss. Typical roughness for different materials are given in the tooltip for this field in HalfCatSim.

Feed Line Length

Pressure loss is found on a per unit length basis, so it is directly proportional to line length.

Component Cv

Cv, or flow coefficient, describes pressure loss for a given flow rate. Every fluid component will have a Cv, usually given by the manufacturer or found by flow testing. Mojave Sphinx's propellant valves have a listed Cv of 1.6, for example.

Additional Loss

This parameter can be used to add in any other known pressure losses, which may come from sharp bends, valves, regenerative cooling passages, etc.

2.2.7 Injector

Both the oxidizer and fuel injector modules work the same. There are additional fields that will normally not be used for Mojave Sphinx – namely the annulus fields, and the second set of fuel orifices (which could be used for film cooling).

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Hole Diameter

This is the diameter of the drilled holes in the injector, through which propellant enters the chamber. It is selectable from a dropdown because there is a finite range of drill bit sizes available to choose from. Below the hole diameter is the corresponding drill bit required for that size.

Number of Orifices

The number of injection holes for fuel or oxidizer. If an annulus is present, it multiplies by that as well.

Discharge Coefficient

This can be purely the discharge coefficient of the orifices (the Cd), or a combined flow coefficient of the whole system, depending on whether the feed system pressure loss module is used.

CdA Override

This is purposely hidden, but it is an editable parameter. This can be replaced with an actual CdA found in testing to give the most accurate injection area based on real data.

2.2.8 Oxidizer Vent

The oxidizer vent module only has one editable parameter, hole diameter. This sizes the static vent and will give an estimate for fill time based on oxidizer temperature and tank size. Note that this is approximate; in reality, oxidizer fill tends to take longer than predicted because there is a non-negligible amount of time required to initially pressurize the tank.

2.2.9 Results

Chamber Pressure, Thrust, and Burn Time

Combustion chamber pressure is based on mass flow, throat area, and characteristic velocity (c*). Thrust is based on mass flow and effective exit velocity. Both of these values are displayed for the beginning of the burn, when all values are at the design point. The burn time is the length of time until one of the propellants is fully depleted, and the limiting reagent is displayed next to the time value.

Mixture Ratio, Mass Flow Rate, and Efficiency

Mass flow rate is the amount of mass passing through the system per second. The mixture ratio is the ratio of oxidizer to fuel mass flow rate (a.k.a. O:F ratio). Overall efficiency is the product of all other efficiencies to show how the complete motor performs compared to the perfect theoretical case. Tank O:F ratio is simply the ratio of the usable mass of oxidizer and fuel in the propellant tanks, to assist with determining the ideal displacement for each propellant. Maximum total impulse for a given system efficiency and combined tank volume is achieved when the tank O:F ratio closely matches the combustion chamber O:F ratio, so that both propellants are depleted nearly simultaneously.

Injection Pressure Delta and Stiffness

The pressure delta is the difference between feed pressure and chamber pressure, and it is an important metric because injection pressure must remain higher than the chamber. Injector stiffness is a measure of how much pressure budget the injector has compared to the chamber, given by the following formula:

$$Stiffness = \frac{Feed\ Pressure - Chamber\ Pressure}{Chamber\ Pressure}$$

Stiffnesses for both fuel and oxidizer should be kept to at least 30% to absorb random pressure fluctuations and off-nominal conditions. Higher stiffness provides more cushion with no significant adverse effects; a stiffness of 60%+ is generally recommended. The relevant pressures are plotted to provide a visual indication of how the system behaves. Note that the displayed value of stiffness is for the start of the burn, but will decline over time; reference the pressure chart to determine how low the pressure delta drops by the end. If stiffness become too low (<20%), HCS may stop working properly.

Specific and Total Impulse

Specific impulse (I_{sp}) is a measure of efficiency. HCS provides two Isp results: The Start (S) I_{sp} is measured at the start of the burn, consistent with other results above, and is equal to thrust divided by mass flow; the Cumulative (C) I_{sp} result measures efficiency of propellant utilization and is equal to total impulse divided by propellant weight. Total impulse is the integration of thrust over the whole burn time and is the basis for the letter-classification system of amateur rocket motors.

2.2.10 Graphs and Thrust Curve

Standard Half Cat type liquid rockets are usually simulated in OpenRocket and RASAero with the correct tank, fluid system, and chamber masses modeled as components in the program in order to more accurately reflect mass distribution (see Section 2.5); hardware mass should therefore be set to a negligible non-zero value (e.g., 0.01 lbs). The thrust curve can be saved in a format usable for simulation by selecting the column, copying and pasting into a text file, and saving as [Name].eng. Extra semicolons in the thrust curve file are not an issue.

The thrust curve and pressure chart are displayed in the program, adjacent to the results module. There are some quirks of the program which manifest here that users should be aware of:

- Sometimes, the curve will show a slight but noticeable step change in amplitude (see Fig. 2.5). This is normal, since HCS draws from a table of combustion properties for every 50 psi and 0.25 mixture ratio. Step changes occur when there is a shift across one of these boundaries.
- Pressure and thrust oscillations may occur in some edge cases, such as low stiffness. Too low of a stiffness may cause the calculations to rapidly bounce between high and low values, and often indicates an inadequate design which could cause instabilities in practice.

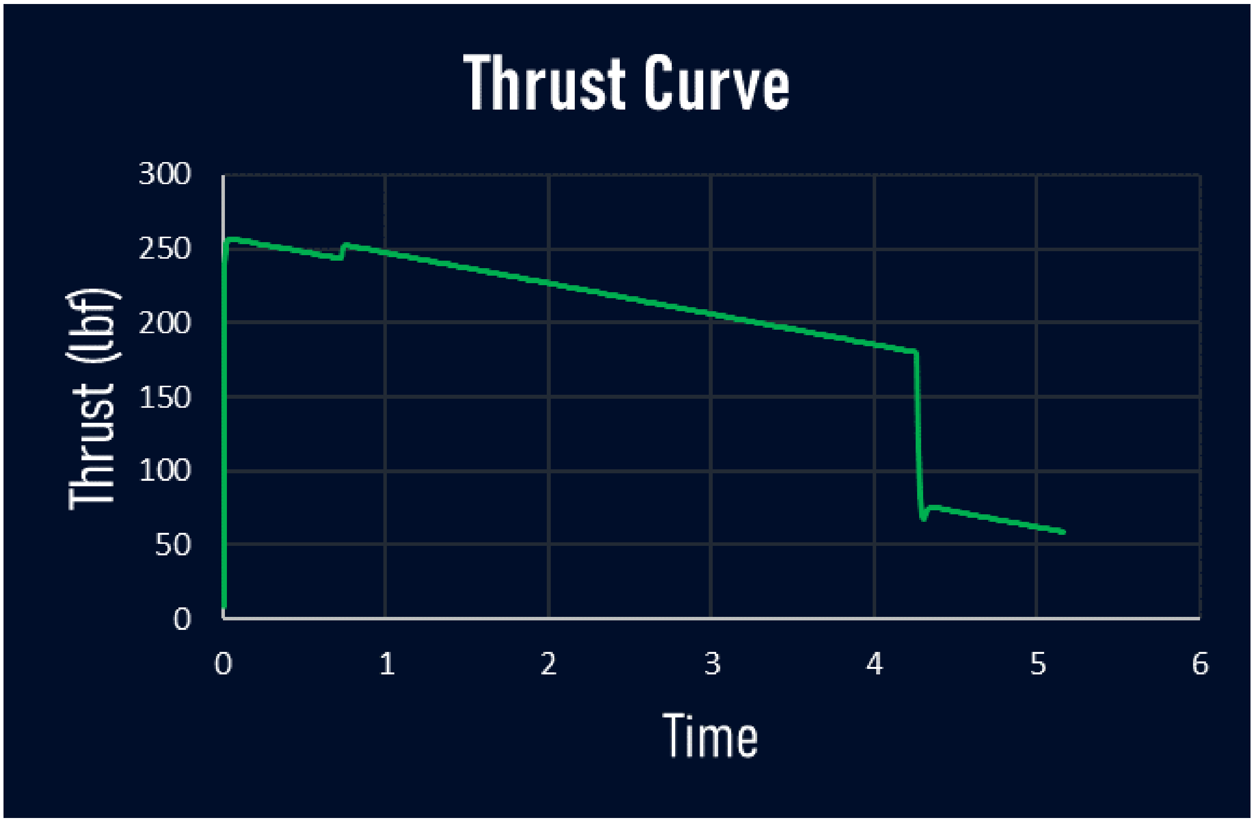

Figure 2.5: Mojave Sphinx HalfCatSim sample thrust curve, taken at an ambient air temperature of 60° F

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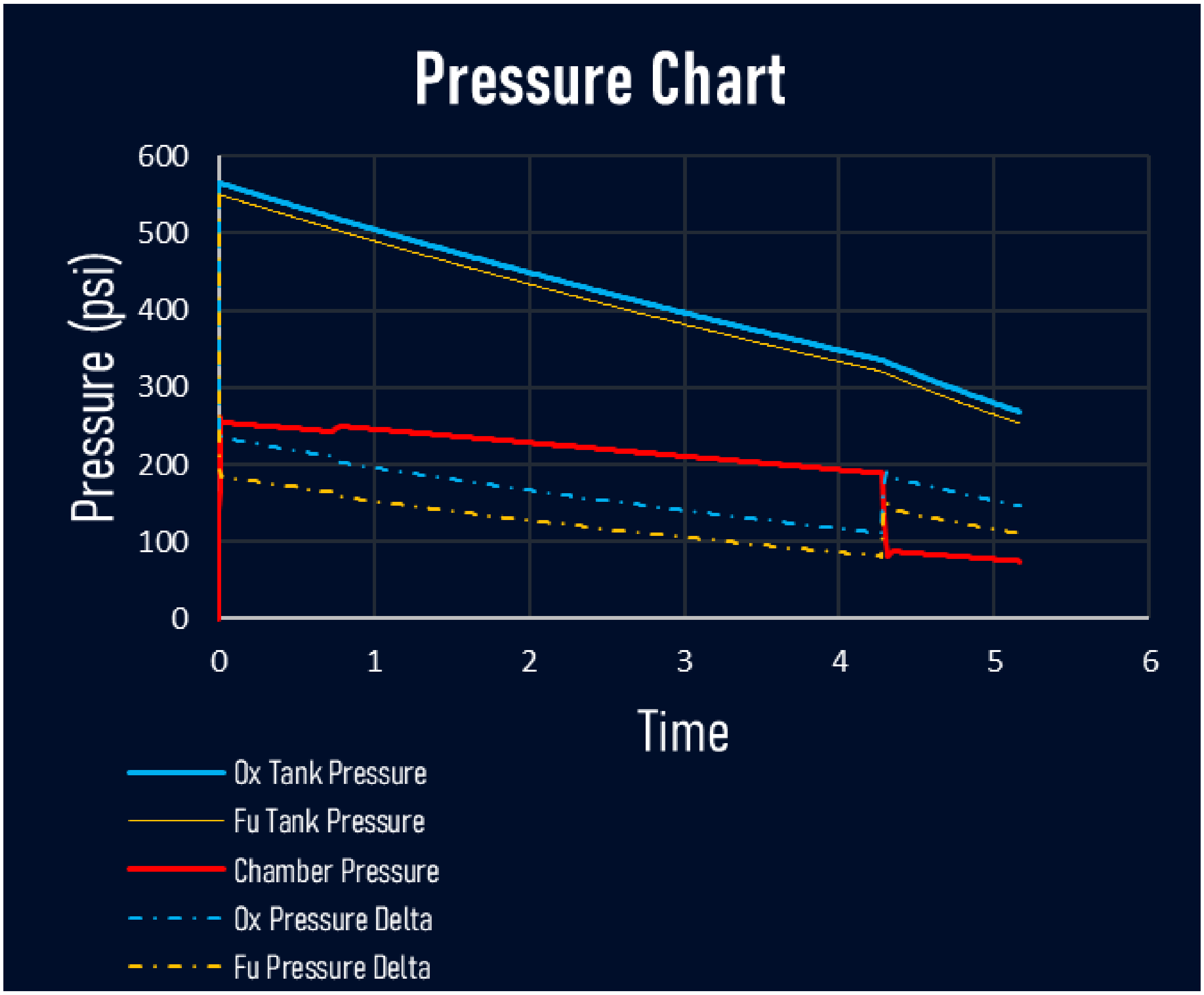

Figure 2.6: Mojave Sphinx HalfCatSim sample pressure chart, taken at an ambient air temperature of 60° F

2.3 Hardware

Mojave Sphinx is the design upon which the Half Cat Standard is based. This section follows from 1.2 and describes each component in more detail, with specifics relating to Mojave Sphinx that are not necessarily codified in the standard.

Like all standard liquid rockets, the use of the tank casing as the majority of the airframe – without an encapsulating airframe tube – makes this a "subminimum diameter" design. This is preferable for liquid rockets since it allows components (such as the fuel downcomer) to extend beyond the nominal diameter. Eliminating the requirement that the entire motor assembly slide inside a tube greatly simplifies integration, and permits direct attachment of the fins and thrust structure to the propulsion system while providing unobstructed access to the igniter cartridge and oxidizer fill QD. Furthermore, sub-minimum diameter rockets also achieve better performance because they omit the mass of an extra airframe tube, and can achieve minimal cross sectional area (when using an airframe tube with the same outer diameter as the tank). The design also gives Mojave Sphinx a unique visual style, especially if closeout panels are omitted and the (minimal) plumbing is exposed.

2.3.1 Propulsion System

The propulsion system consists primarily of two major subassemblies: the **propellant tank** and the **thrust chamber assembly** (TCA). Between these is the **plumbing** (or **fluid system**), which includes the feed lines, oxidizer fill system, and propellant valves, and the **thrust structure** in the form of external brackets. In the case of Mojave Sphinx, the propellant valves are mounted directly to the tank outlets for simplicity; however, for the sake of categorization they are counted as part of the plumbing.

2.3.2 Propellant Tank

The propellant tank of Mojave Sphinx is a sliding piston stacked tank, meaning that the fuel and oxidizer volumes are separated by the propellant piston which is free to move axially under the force exerted by the oxidizer pressure. The piston is installed into the forward end of the tank and pushed to a predetermined depth, and the space above it is filled with fuel.

Oxidizer fills from the bottom, and vents through a static vent hole drilled into the side of the tank just below the piston's starting position. During firing, oxidizer drains back out the bottom while fuel is pushed out the top by upwards motion of the piston and runs through an external downcomer to the combustion chamber.

Fig. 2.9 depicts an exploded view of the Mojave Sphinx propellant tank.

Tank Casing

This is the aluminum tube which forms the body of the tank and serves as part of the rocket's airframe. Eight equally spaced thru-holes are drilled at each end for the radial fasteners that secure the retaining rings and tank bulkheads. A very small (1 mm) hole is drilled in the side at the top of the oxidizer portion, which serves as the static vent.

Oxidizer Bulkhead

The oxidizer bulkhead seals the aft end of the oxidizer tank with a single O-ring, and includes the oxidizer fill and outlet ports. The fill port is the smaller of the two due to the lower flow rate required for tank fill, and is located near the edge to allow the fill QD to protrude slightly beyond the tank diameter, providing clearance for the QD flange clip. The larger outlet fitting is also off-center to accommodate the asymmetric valve assembly within the vehicle diameter.

Fuel Bulkhead

The fuel bulkhead seals the forward end of the tank with a single O-ring, and includes the fuel outlet port as well as two thru-holes for the fasteners that anchor the recovery system to the tank. The bolts installed in the thru-holes thread into coupling nuts placed on the exterior surface of the bulkhead, and rubber sealing washers under the heads prevent fuel leakage. Like the aft bulkhead, the forward bulkhead's tank outlet port is off-center due to the geometry of the servo-actuated ball valve assembly.

Retaining Rings

Each retaining ring holds in its respective bulkhead, transferring the pressure load into the casing wall through screws loaded in shear. The retaining rings also have a secondary purpose in attaching the airframe (fuel side) and thrust structure brackets (oxidizer side). The holes in these rings are thru-holes rather than tapped holes; the screws thread into nuts which are held in place on the inner diameter of the retaining ring by a 3D-printed plastic component. While the use of nuts adds a small amount of mass and cost compared to tapping the retaining ring itself (unless outsourcing machining, in which case cost is reduced), it eliminates 32 tapping operations (16 per ring) and replaces aluminum threads with more durable steel nuts that will not wear out from repeated removal and reinstallation of the fasteners. The nuts can also be easily replaced if stripped or cross-threaded.

Piston

The propellant piston keeps the fuel and oxidizer sealed from one another while physically transferring the force exerted by N_2O pressure to the fuel. It has two O-rings to keep the propellants separated and a 1/4-20 blind hole on the fuel side so that a bolt or threaded rod can be inserted to extract the piston from the forward end of the tank. The O-ring glands are sized the same as any other on the rocket, even though they are technically dynamic seals with linear motion during firing.

The friction of the piston O-rings installed in the tank is more than sufficient to keep the piston in place when unpressurized, even when fuel is loaded, such that there is no concern of the piston sliding out of place during handling or operations. It usually takes tens of pounds of force to move the piston (i.e., forcefully pushing on the piston with a ramrod to reset its position in the tank), which is much greater than the weight of the fuel.

The smaller-diameter portion that extends from the top face of the piston contacts the forward bulkhead when fuel is depleted, while providing clearance for the recovery-anchoring fastener heads that protrude from the bulkhead on the inside of the tank.

The piston length is approximately half of its diameter, which is sufficient to prevent it from binding in the tube.

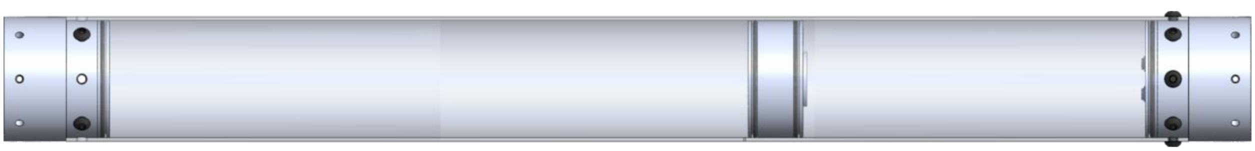

Figure 2.7: Side-view of Mojave Sphinx propellant tank

Figure 2.8: Section-view of Mojave Sphinx propellant tank

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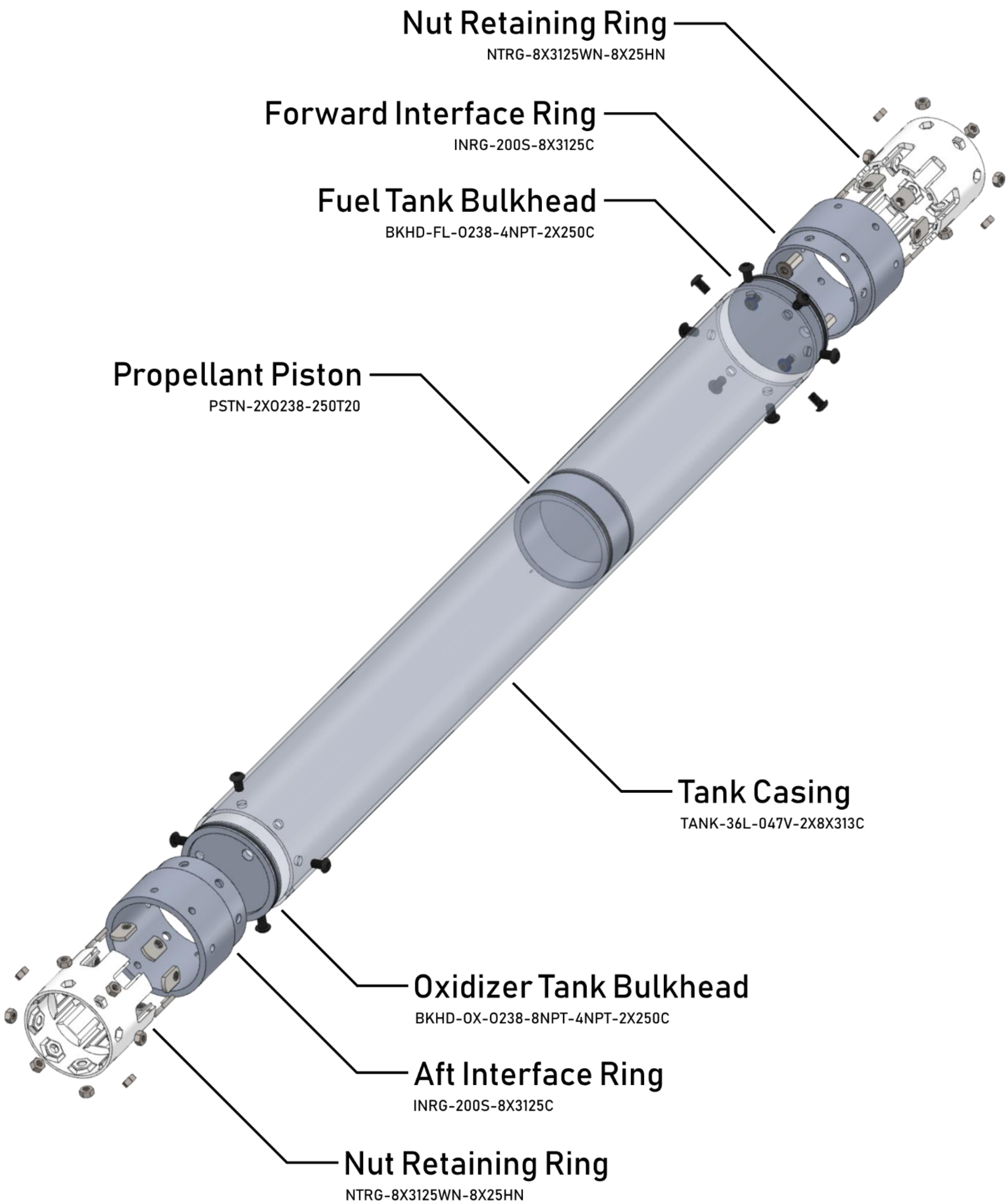

Figure 2.9: Exploded-view diagram of Mojave Sphinx propellant tank

2.3.3 Fluid System

Mojave Sphinx's fluid system is very simple for a liquid bipropellant rocket. Fig. 2.14 depicts the Piping and Instrumentation Diagram (P&ID) of Mojave Sphinx.

Unlike prior generations of Half Cat rockets, Mojave Sphinx uses servo-actuated ball valves rather than custom pneumatic Half Cat valves. This reduces the number of machined parts, and eliminates some potential points of failure (i.e., PTFE poppet seats which are very sensitive to FOD compared to ball valves). The fluid lines are standard PTFE-lined stainless flex hoses, which are available from McMaster-Carr (as well as many other industrial suppliers) and allow the joints to be easily connected and disconnected without requiring precise alignment.

Fig. 2.12 depicts an exploded view of the Mojave Sphinx fluid system.

Main Propellant Valves

The valves are responsible for preventing flow from the tank to the injector until commanded to open. They are assembled from an off-the-shelf ball valve, a servo designed for hobby applications, and two custom 3D printed plastic parts that connect them. The bracket is bolted to the housing of the servo and constrains the valve body, while the handle connector joins the servo horn to the handle of the ball valve to transmit rotation.

Fig. 2.10 depicts an exploded view of the servo-actuated ball valves.

Oxidizer Line

The oxidizer line transfers N_2O from the outlet of the oxidizer valve to the oxidizer inlet on the injector. It is a standard commercial off-the-shelf flex hose with brass 37-degree flare fittings. A stainless steel overbraid provides reinforcement for a PTFE liner that contains the high pressure fluid. Flexibility is critical, as not everything will line up perfectly due to manufacturing and installation tolerances that determine the position of the oxidizer valve.

Fuel Downcomer

In the stacked tank configuration used for Mojave Sphinx the fuel outlet is at the top of the tank, therefore a "downcomer" is necessary to route fuel down alongside the tank to the combustion chamber. This is the same type of PTFE-lined stainless flex hose as the oxidizer line, in a slightly smaller size due to the lower flow rate of fuel. An external tube parallel to the tank is much simpler than an internal downcomer within the tank, which would require an additional set of dynamic seals on the piston, increasing complexity and potential inter-propellant leak points. The drag created by the protruding fuel downcomer has a negligible impact on the performance of the vehicle.

Oxidizer Fill System

The onboard portion of Mojave Sphinx's oxidizer fill system is a very simple assembly consisting of two high pressure PTC fittings, a check valve, a short flexible nylon tube, and a simple flange-clip quick disconnect (QD or QDC). The QD is responsible for disconnecting the ground-side oxidizer fill line. It is a passive component that separates from pressure blow-off load when the tethered clip is removed as the rocket takes off.

Fig. 2.13 depicts an exploded view of the Mojave Sphinx quick disconnect.

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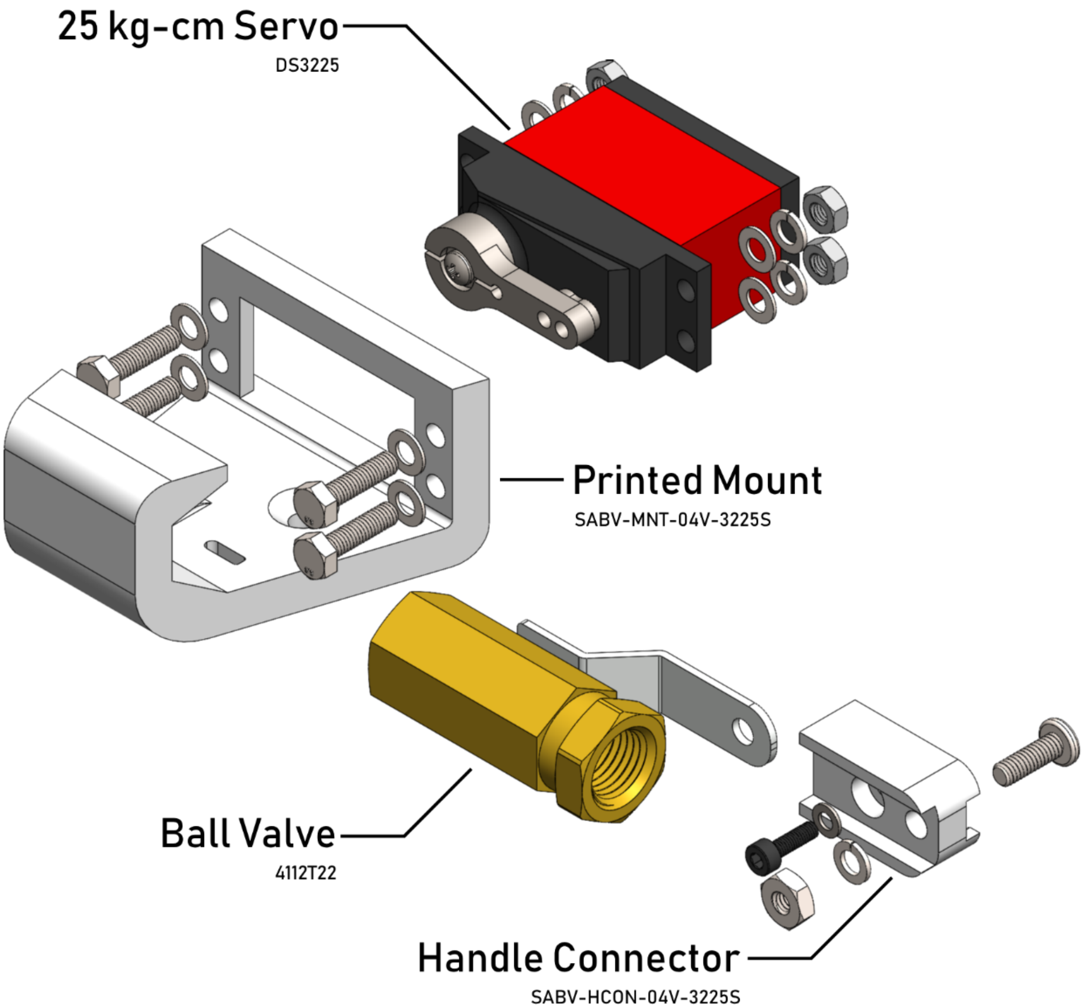

Figure 2.10: Exploded-view diagram of Mojave Sphinx main propellant valve (fuel and oxidizer valves identical)

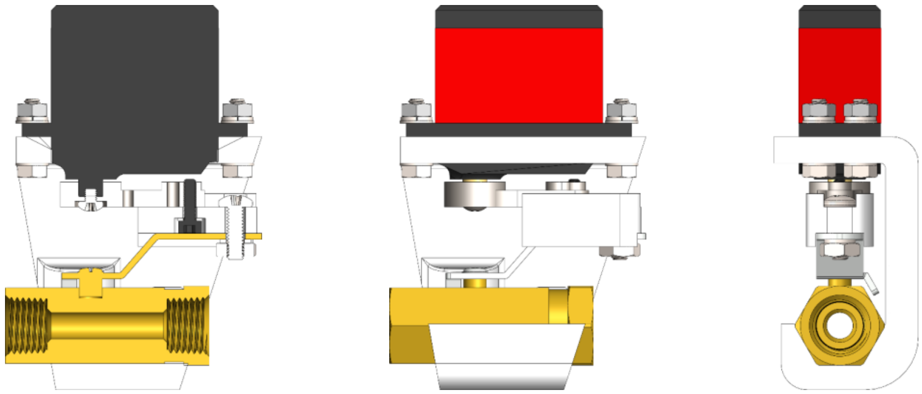

Figure 2.11: Views of main propellant valves in section plane of flow path (left), from the side (center), and into the axis of flow (right)

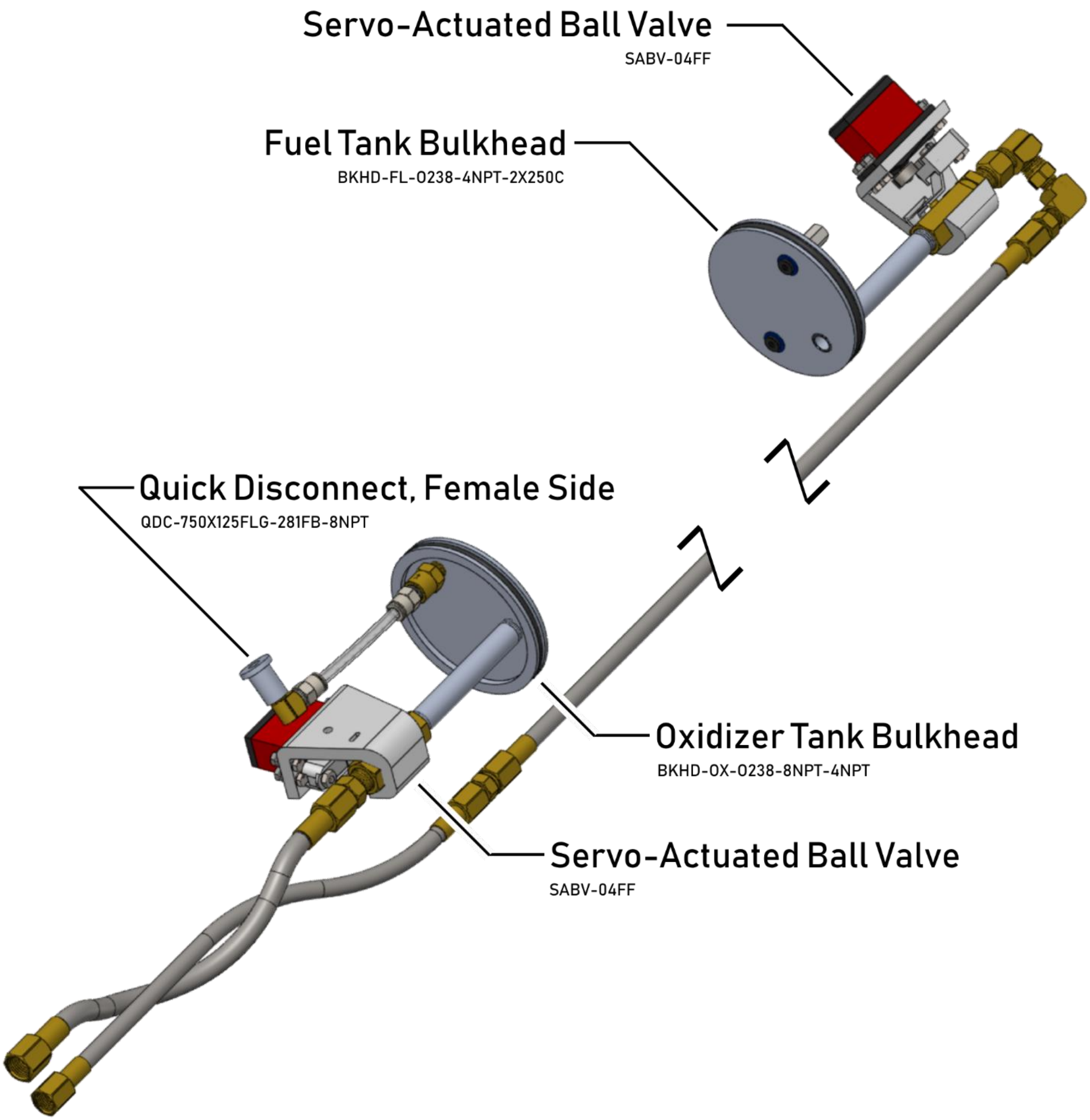

Figure 2.12: Isolated view of Mojave Sphinx fluid system (fuel downcomer truncated for clarity)

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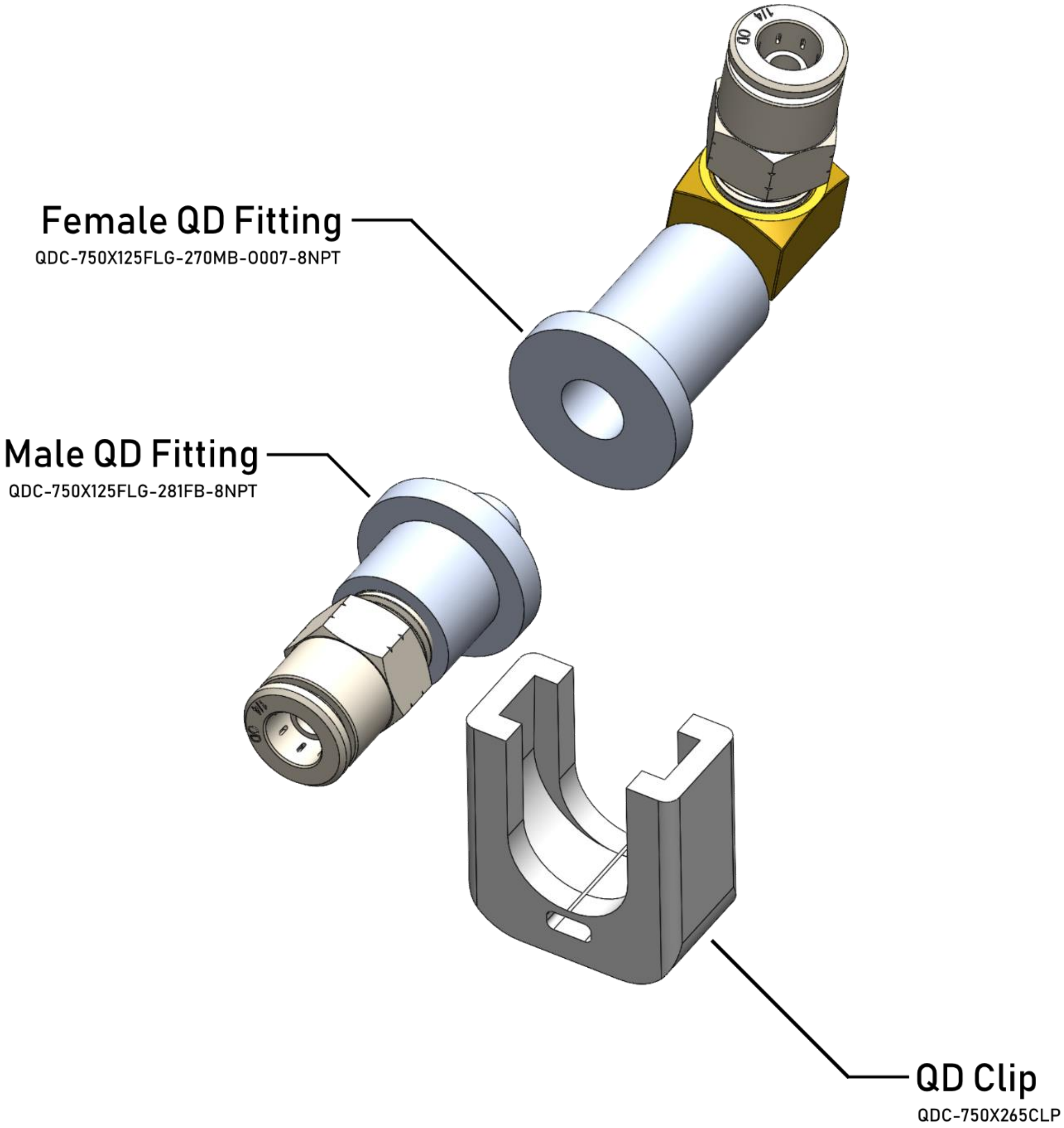

Figure 2.13: Exploded-view diagram of Mojave Sphinx quick disconnect

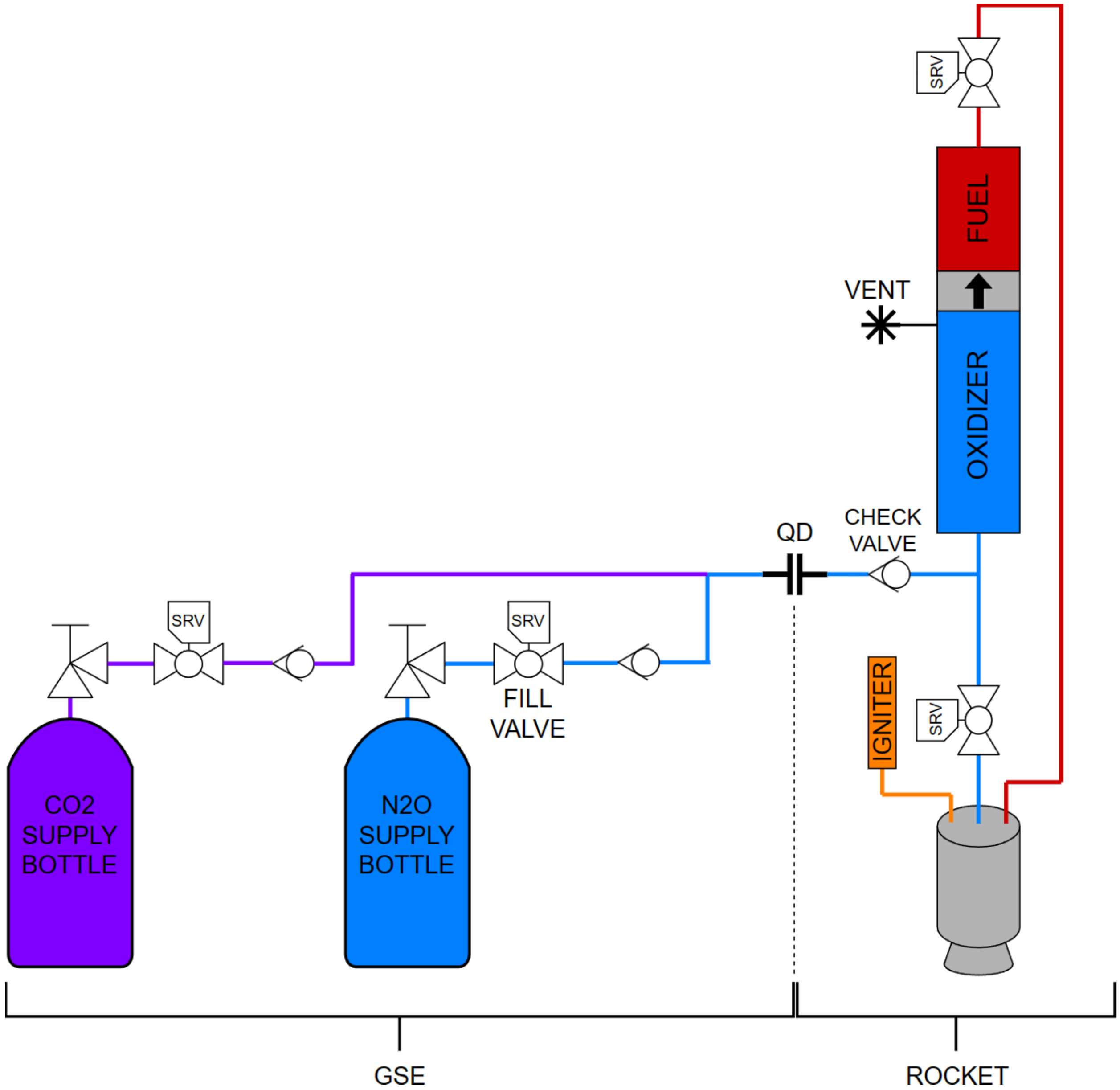

Figure 2.14: Mojave Sphinx and GSE P&ID, including optional CO_2 supply bottle (only used in static fire testing)

2.3.4 Thrust Chamber Assembly

Mojave Sphinx uses a heatsink TCA as described in Section 1.2.3 with a separate aluminum combustion chamber and nozzle, and a copper throat insert. The nozzle, chamber, and injector are held together by axial threaded rods with flange plates. The high thermal conductivity of the material transmits heat quickly enough that the surface exposed to combustion gas does not melt. The combustion temperature is low enough, and the burn time short enough, that the total absorbed heat does not raise the bulk temperature of the material above the point at which the majority of strength is lost. Although copper is a better material for a heat sink chamber due to its higher thermal conductivity and heat capacity, aluminum is sufficient for the majority of Mojave Sphinx's chamber and is much cheaper and lighter.

Fig. 2.17 depicts an exploded view of the Mojave Sphinx Thrust Chamber Assembly.

Chamber

The chamber portion of the TCA is a thick-walled aluminum cylinder with a larger-diameter bore at the forward end. This bore houses the injector, and forms the outer portion of the injector sealing surfaces. The chamber is sized such that it can be made from 3"-OD x 1/2"-wall extruded aluminum tube, with machining required only at the ends and injector bore. This greatly reduces the required amount of machining time and material removal compared to solid bar stock. The thick wall provides strength and thermal mass, as well as sufficient surface area for the gasket seal on the nozzle end.

Nozzle

The nozzle is also aluminum, machined from solid bar stock on a lathe (recommended) or mill. The contour is conical for manufacturing simplicity (bell nozzles are not possible with manual machining and require CNC). The converging cone uses a typical 45° half-angle. The diverging cone is at a 20° half-angle –slightly steeper than the typical 15°– which shortens nozzle overall length with little impact to efficiency. The nozzle has a cylindrical bore to accept the throat insert, with a shallow internal groove for the throat insert retaining spring.

Throat Insert

The throat insert is a small piece of copper that is set into the nozzle, and contains the actual nozzle throat as well as a portion of the converging and diverging cones. The copper throat insert was added to the design during development because it was observed that a single-piece aluminum nozzle was operating at the edge of survivability under nominal conditions, and could experience moderate to severe erosion under off-nominal conditions that increased O:F ratio, such as unusually low ambient temperatures. Copper's superior heat resistance ensures that it will survive any conditions that the motor can reasonably produce. The throat has a short straight section, the length of which is approximately one quarter of the throat diameter. This reduces both heat flux and sensitivity to manufacturing tolerances compared to a throat that comes to a point or radius at its minimum diameter. Medium-grit sandpaper or a small file can be used to (carefully) round the corners leading into and out of the straight section on a lathe.

The groove on the exterior of the nozzle insert is not an O-ring gland, but rather the location of the retaining spring. This toroidal spring is installed into the groove much like an O-ring, and is compressed radially when the throat insert is installed into the nozzle; it then expands slightly into the corresponding internal groove in the nozzle bore, providing semi-permanent retention of the throat insert. Unlike an O-ring, the spring survives the peak temperature at the nozzle/throat insert interface, and does not require regular replacement. The throat insert is "sealed" to the nozzle simply by the contact of the flat faces at the lower end under the force from chamber pressure. Any blow-by around the throat insert is minimal and does not affect the hardware or performance.

Gasket Seal

The gasket seal prevents hot gas from escaping at the interface between chamber and nozzle, which can cause damaging erosion and lead to a failure of the thrust chamber assembly. It is made from flexible graphite (often referred to by the brand name Grafoil). The gasket used in Mojave Sphinx has a very thin (~.006") layer of stainless steel foil in the middle, to provide resistance to cracking or tearing when handled. When the graphite is compressed between the chamber and nozzle it deforms into the microscopic surface imperfections to create a seal, similarly to an elastomer, although with less recovery from compression. For this reason, it is not recommended to reuse graphite gaskets. However, graphite is able to withstand the extreme temperatures of the combustion gas without melting or eroding, and the gasket does not need to be replaced unless the thrust chamber is disassembled for other reasons.

Flange Plates

The flange plates are flat metal rings with eight equally spaced holes for the chamber tie rods. The outer diameter of the Flange Plates matches that of the tank, and their inner diameter allows portions of the nozzle and injector to pass through them. The upper and lower Flange Plates are identical. The nuts and washers installed on the chamber tie rods at each end transfer preload from torque to the Flange Plates, which in turn compress the remainder of the Thrust Chamber Assembly. These parts are made from mild or carbon steel for stiffness, and can be laser- or waterjet-cut (or CNC milled) from plate stock.

Injector

Mojave Sphinx's injector is a style called a "scrintle," which a portmanteau of "screw" and "pintle." The biggest advantage of a scrintle is that all injection orifices can be drilled axially, which eliminates the need for fixturing the part at an angle during machining as would be required in an impinging doublet design. The other primary benefit is that scrintle (and other types of splashplate) injectors are relatively insensitive to the number and positional tolerance of injection orifices, particularly on the oxidizer side. Mojave Sphinx originally used an unlike impinging doublet injector, but this had very low performance compared to a scrintle injector with a similarly low number and large diameter of injection orifices. Oxidizer is injected onto the underside of the screw head, which diverts it radially outward to mix with the fuel streams. This provides respectable efficiency for an extremely simple design. The overall layout is still a groove-manifold injector, with a drilled hole for the oxidizer inlet and manifold, and a circumferential slot for distributing fuel to the injection orifices. The O-rings on either side of the fuel manifold groove prevent fuel from leaking into the chamber or out of the TCA to the surrounding environment.

In the Mojave Sphinx design, the injector also includes a groove near the top for an external snap ring, which is used to retain the injector. The snap ring is sandwiched between the upper flange plate and the forward end of the chamber, constraining axial movement in both directions. The use of a snap ring for this feature reduces the required diameter of aluminum bar stock from which the injector is machined.

Fig. 2.18 depicts four possible configurations of scrintle injector, each having varying levels of performance depending on the number and placement of fuel and oxidizer orifices.

Igniter

The igniter cartridge is assembled from standard brass and aluminum pipe fittings to reduce the number of custom machined parts, and contains the black powder solid motor (Estes A3) that provides the energy to initiate combustion of the liquid propellants. The flame produced by the solid propellant enters the chamber through a small hole in the injector face. A .136" (#29 drill size) hole is recommended; this results in a burn time of a little over one second, during which the propellant valves are opened. If the injector geometry permits, a larger hole may be used to increase this burn time by lowering the pressure within the igniter cartridge. However, with a properly executed startup sequence, a 1-second duration is sufficient for reliable ignition. Critically, the igniter pass-through hole in the injector must be large enough to permit the head of the e-match to be ejected without creating a blockage.

The black powder solid propellant is itself ignited by a standard electric match ("e-match") of the type used ubiquitously in high power rocketry. While often inadequate to ignite composite (APCP) solid propellants, e-matches do reliably ignite exposed black powder propellant grains. The clay nozzle of the Estes A3 igniter motor is removed using a drill bit until the face of the dark gray propellant grain is exposed. The ejection charge should also be removed from the igniter motor, although leaving it in is unlikely to have detrimental effects.

The e-match head is placed in contact with the aft face of the black powder grain, with 2-3 folds in the wire to hold it in place within the cartridge, preventing the e-match from being easily pulled out during handling. The e-match wires are passed through the igniter port and into the chamber, protruding out of the nozzle where they can be connected to the ground system's ignition circuit. The wires are ejected by igniter cartridge pressure upon ignition. At the forward end of the igniter cartridge, a wad of paper towel or similar sacrificial material is used to prevent the igniter motor from shifting forward, away from the e-match head. Detailed images of the igniter assembly process may be found in the pre-launch preparation procedures.

If static testing is to be conducted, the igniter cartridge provides a convenient location for a chamber pressure transducer, as it also functions as a thermal standoff tube. The igniter cartridge can be made considerably more compact by machining it with a single-piece aluminum body; this is left as an exercise for the reader.

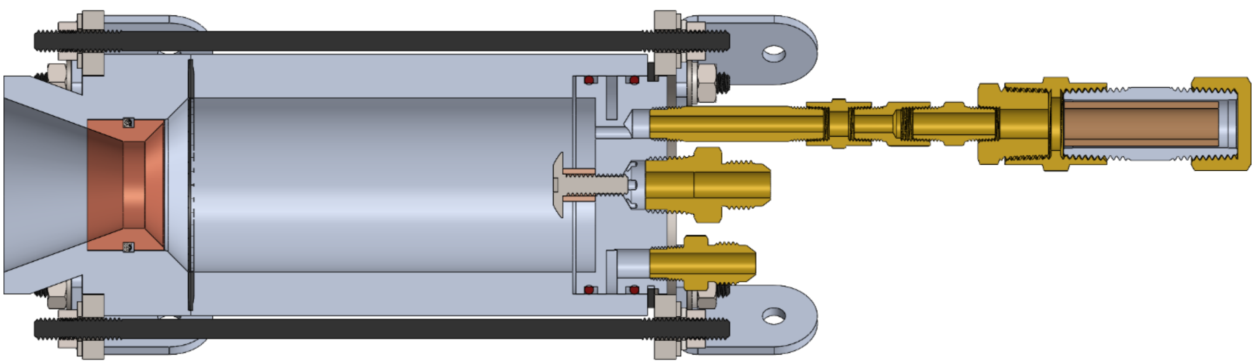

Figure 2.15: Section-view of Mojave Sphinx TCA (in-plane with propellant inlets and igniter cartridge)

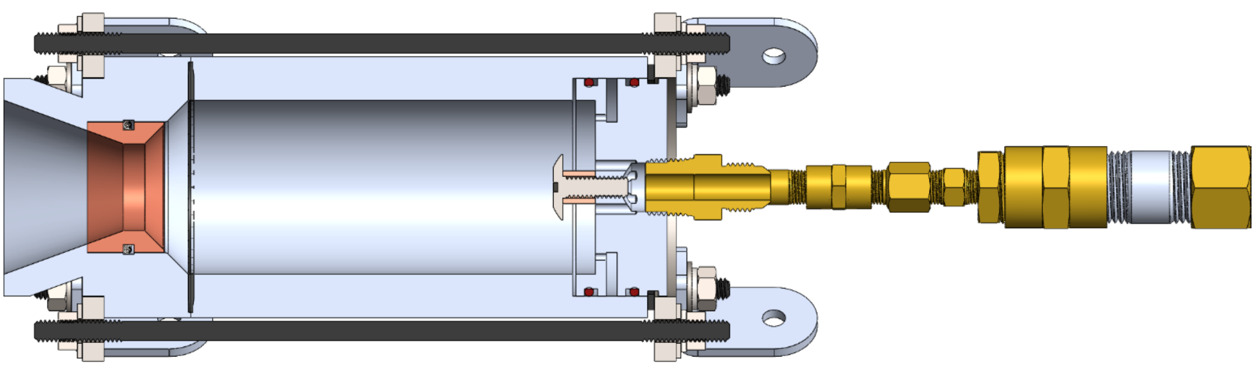

Figure 2.16: Section-view of Mojave Sphinx TCA (in-plane with injection orifices)

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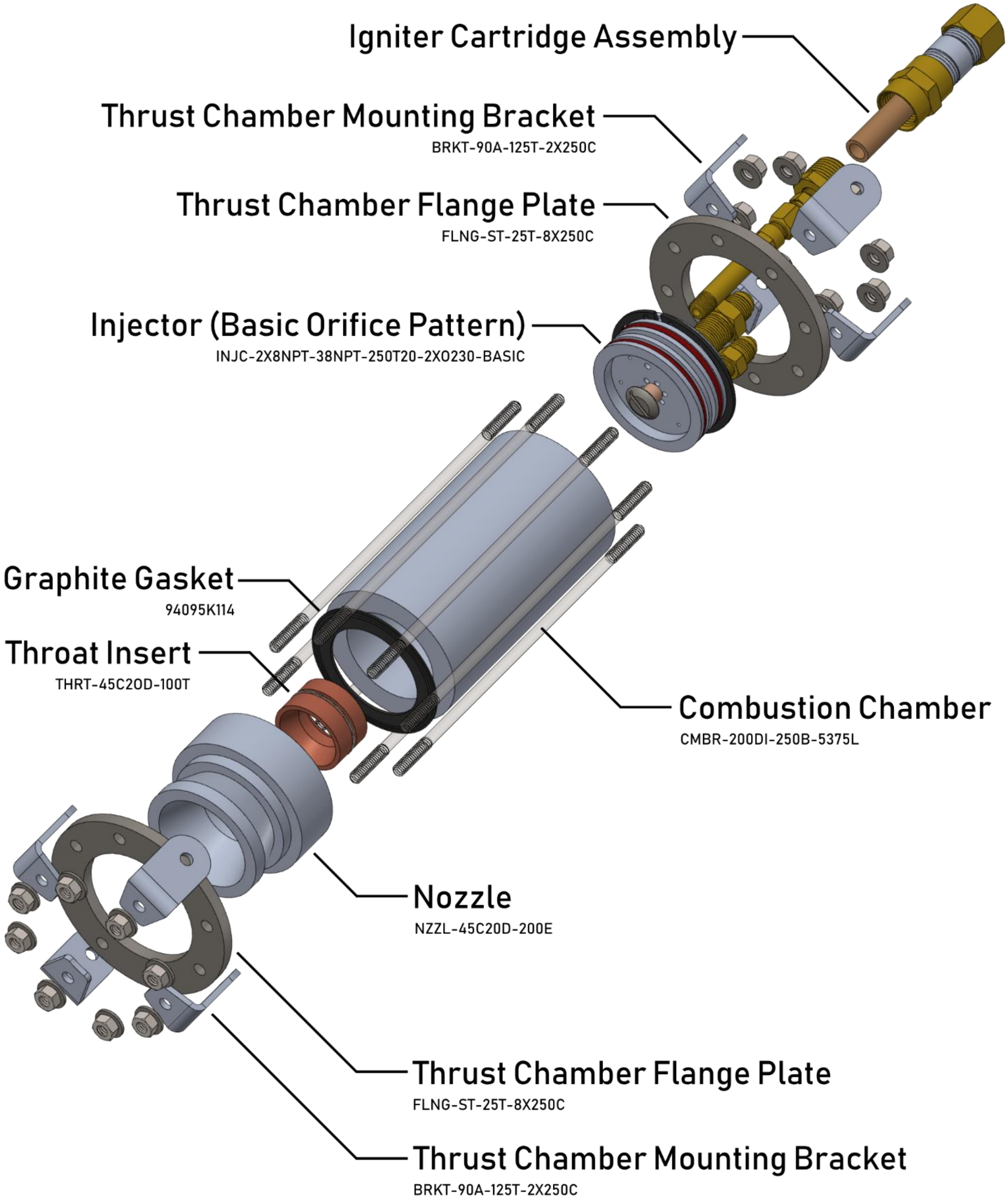

Figure 2.17: Exploded-view diagram of Mojave Sphinx TCA

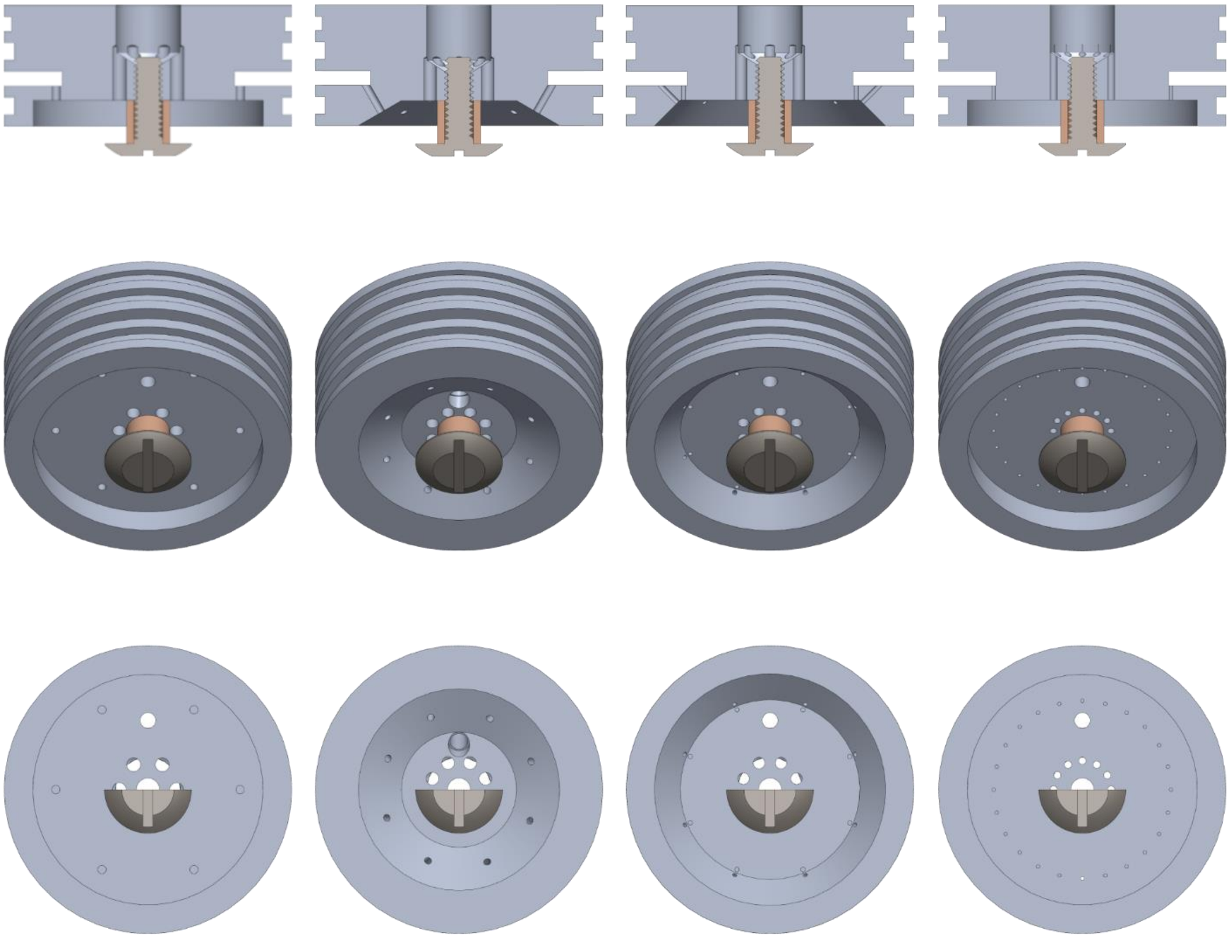

Figure 2.18: Examples of Mojave Sphinx scrintle injector geometries, in estimated order of increasing performance (left to right)

Injector	Oxidizer Orifices		Fuel Orifices		Mixture Ratio (Ambient Temp)	
BASIC-	Number	Diameter (in.)	Number	Diameter (in.)	40° F	90° F
6-6	6	0.0995	6	0.0748	2.191	1.900
8-8	8	0.0860	8	0.0635	2.241	1.944
8-16	8	0.0860	16	0.0465	2.144	1.858
12-12	12	0.0625	12	0.0472	2.112	1.848
12-24	12	0.0625	24	0.0310	2.371	2.069

Table 1.4: Mojave Sphinx basic injector options (not necessarily the same as those in Figure 2.18), with approximate mixture ratios

2.3.5 Propulsion Structural Attachment

Thrust Structure Brackets

The thrust structure brackets create a rigid connection between the thrust chamber and tank assemblies and provide a mounting point for fins. They are fabricated from 1" x 1" aluminum angle in 1/8" thickness, which provides a good balance between weight and sturdiness. One leg of the brackets lies tangent to the tank, which is easily fastened to the aft interface ring and thrust chamber brackets. Two bolted connection points on each end of each bracket facilitate alignment without requiring tight-tolerance holes. The other leg of the angle, which projects outward, allows fins to be simply and securely fastened to the structure with adequate rigidity. Since they are made of angle, rather than flat plate, the brackets have high stiffness in both axes, which makes them extremely sturdy against the relatively low thrust load from the motor and resistant to high-velocity landings. If bent or damaged, they can either be worked back into shape or replaced entirely.

Fins

The standard Mojave Sphinx fins are a basic tapered swept planform, cut from 1/4"-thick birch plywood. The sweep of the trailing edge allows the rocket to sit stably on its fins with the nozzle elevated slightly off the ground, which is convenient for fuel loading as well as storage or display. Four clearance holes in each fin are used to bolt them to the thrust structure brackets, which has the advantage of making them easily replaceable in the event of damage during transport or on a hard landing. The mounting location on the thrust structure brackets results in the fins being slightly offset from the centerline, and thus not perfectly radial to the tank. This does not negatively affect stability, nor does it induce excessive roll, as the fins are still radially symmetric. The leading edges are slightly beveled, albeit primarily for aesthetics– the performance benefit is marginal at the speeds Mojave Sphinx typically reaches, and is a much smaller factor than other sources of drag in this design. Plywood is an excellent fin material because it is low cost, easy to work with, and has high strength and stiffness to weight ratios, but many other materials are also suitable. The fins may be made from any sufficiently strong and stiff flat plate or sheet including aluminum, fiberglass and carbon fiber composites, and some plastics. The planform can be altered according to personal preference and/or to reduce drag, so long as the fins provide an acceptable center of pressure for aerodynamic stability.

Fig. 2.20 depicts an exploded view of a Mojave Sphinx fin bracket.

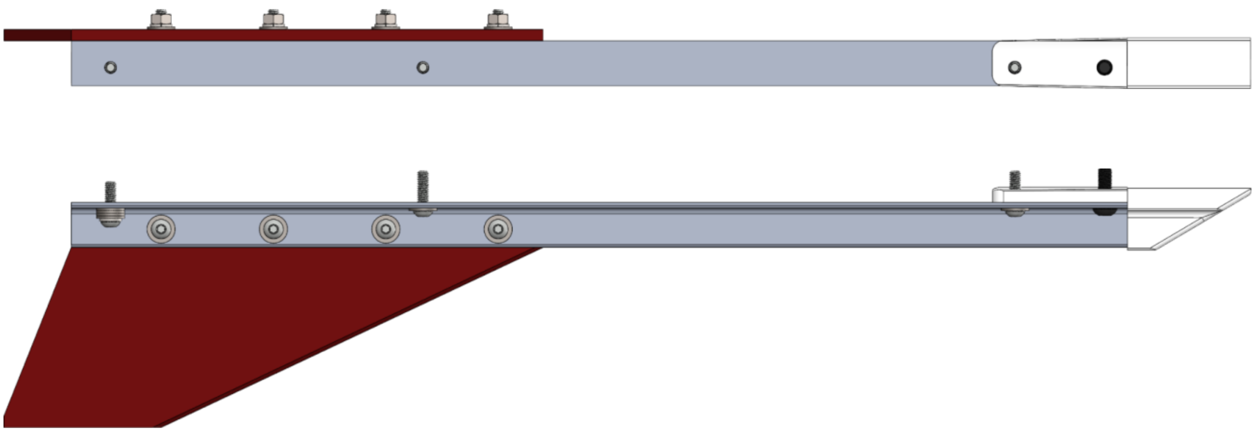

Figure 2.19: Side views of Mojave Sphinx fin bracket

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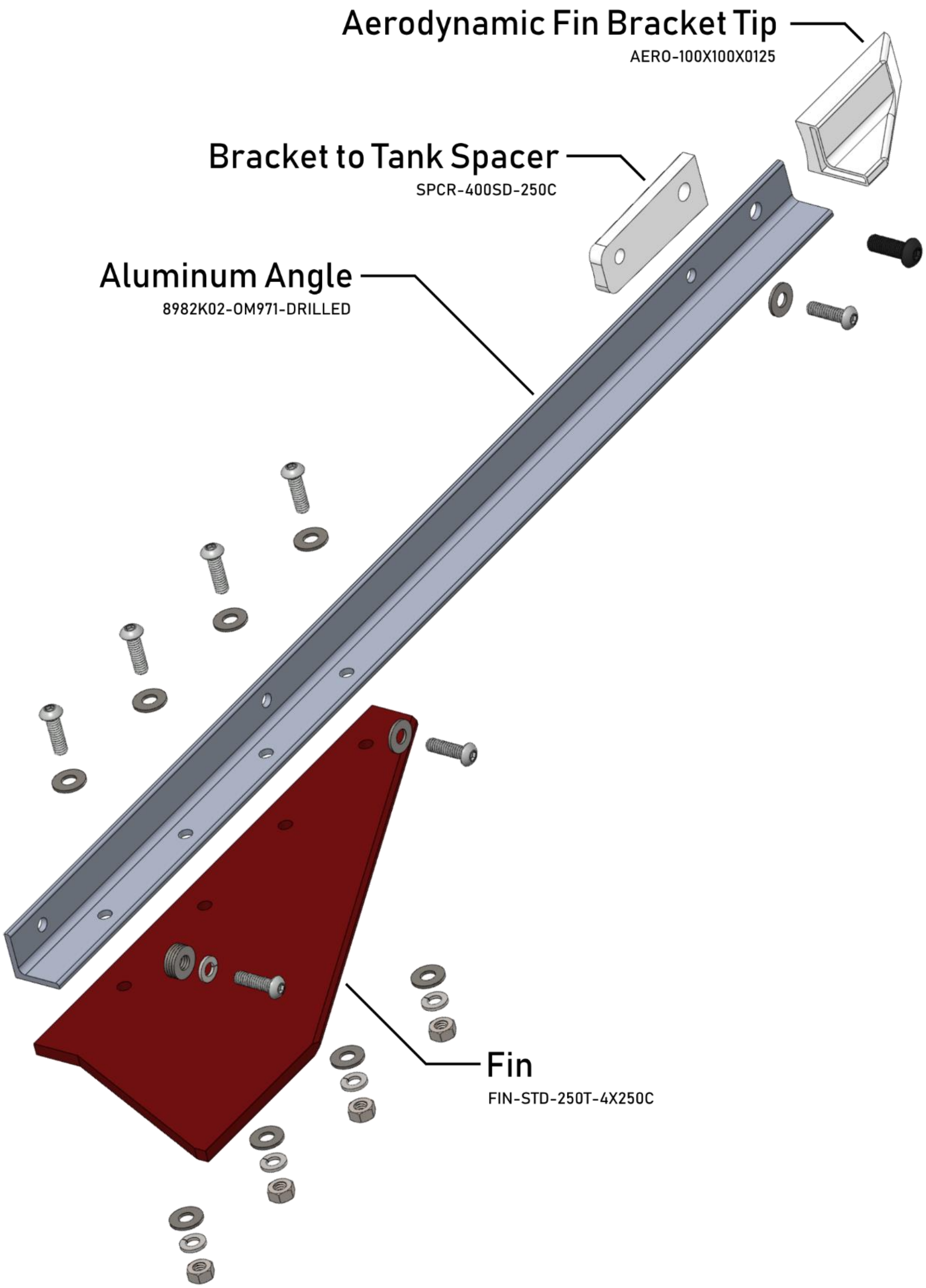

Figure 2.20: Exploded-view diagram of Mojave Sphinx fin bracket

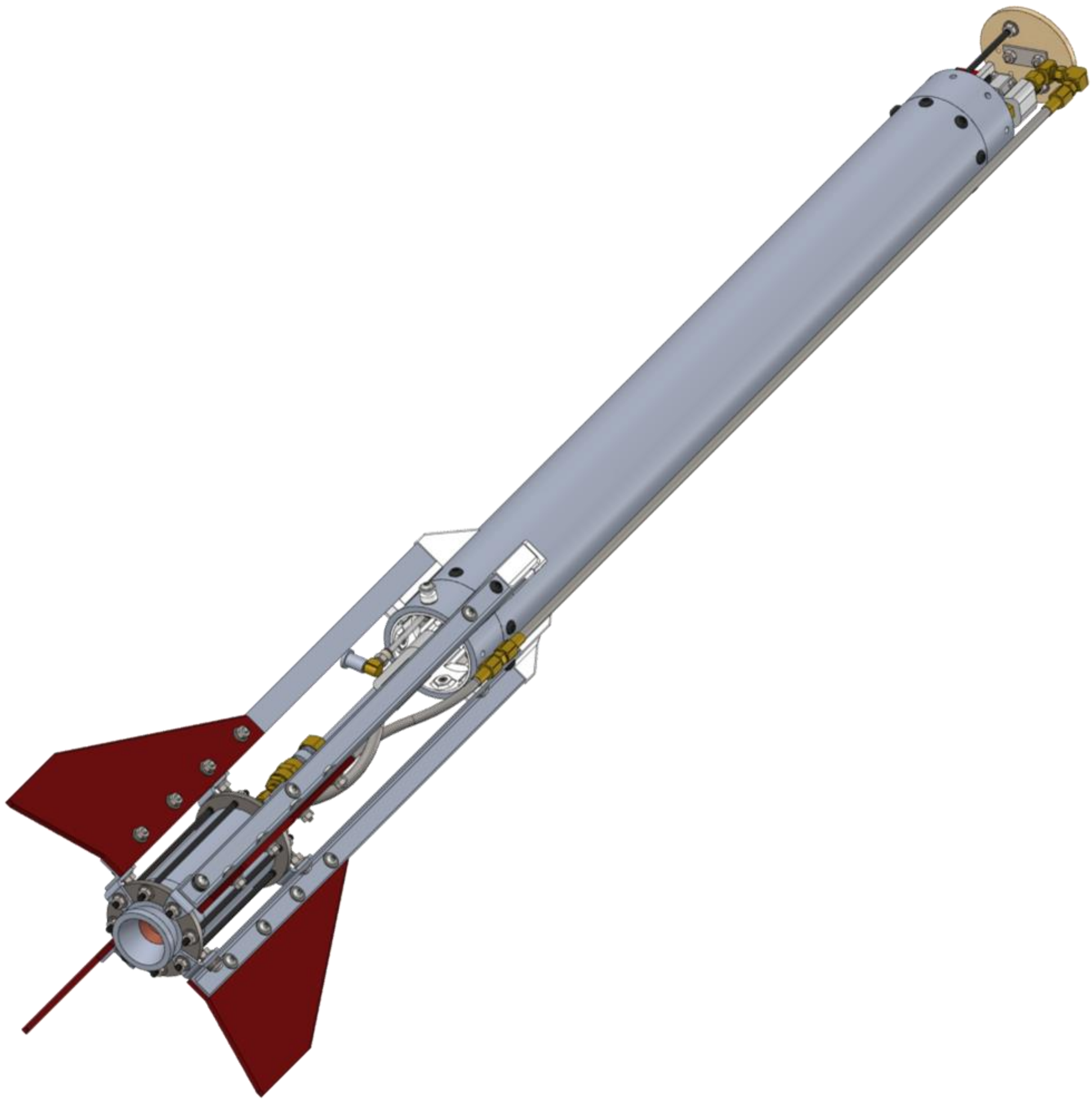

Figure 2.21: Mojave Sphinx integrated propulsion system

2.3.6 Airframe and Recovery System

The rest of Mojave Sphinx is a typical dual-deploy high power rocket, like any other that would be found at a NAR or TRA field. At apogee, the first ejection charge separates the rocket below the avbay, deploying the drogue parachute. At the programmed altitude of the altimeter, the second ejection charge separates the upper airframe from the avbay, deploying the main parachute.

The Mojave Sphinx airframe design uses a 3D-printed plastic coupler and nose cone, both of which are reinforced with threaded rods. Contrary to the often negative perception of 3D-printed structural components (airframe couplers in particular), they are more than sufficient because the threaded rods keep the layers in compression at all times, so they cannot split at the layer lines from tension caused by bending stresses. The use of reinforced 3D-printed parts keeps the airframe cost extremely low without sacrificing strength.

Fig. 2.22 depicts an exploded view of the Mojave Sphinx airframe and recovery system.

Avbay

The avionics bay, or *avbay*, houses the electronic components of the rocket's recovery system and serves as the coupler between upper and lower airframe tubes. As mentioned, the coupler is 3D-printed plastic reinforced with steel threaded rods. Plywood bulkheads close out the avionics bay on each end. Each bulkhead includes a U-bolt to which the shock cords are attached, and a 3D-printed centering feature ensures alignment with the coupler while providing a slot for shear pins and doubling as a convenient hole template if the bulkheads are made by hand (rather than laser- or router-cut). They are held in place by an additional pair of metal threaded rods, which transfer load from parachutes through the avbay assembly.

The altimeters mount to a flat rectangular piece of plywood, called the "sled." 3D-printed components facilitate attachment of the sled to two threaded rods which hold the bulkheads in place, and provide secure mounting for two 9-volt batteries that power the altimeters. Redundant altimeters, each with independent power supplies, wiring, and deployment charges, are strongly recommended to reduce the chance of a recovery failure.

Two holes in the coupler's thrust ring allow the altimeters' power wires to pass through to the outside, so that the electronics can be armed and disarmed externally. This is accomplished by twisting together the stripped ends of each pair of power wires, and wrapping with electrical tape. The spliced ends can then be tucked into the opposite hole, from which they are easily extracted upon recovery or a scrubbed launch attempt. This is a common method with a long history of use in high power rocketry, and is aptly referred to as "twist and tape." It provides the advantages of simplicity and reliability compared to the use of mechanical switches to control avionics power.

Dual deployment controllers use a small computer that measures altitude from the initial launch position, and fires the pyrotechnic deployment charges when it detects apogee (drogue charge) and a set altitude during descent (main charge). They also function as altimeters, recording the peak altitude of the rocket, and often other metrics such as maximum velocity. The Eggtimer Quark is recommended as it is an extremely economical option for a dual deployment controller/altimeter, which is soldered together from a simple kit by the user. Basic soldering abilities and testing of the assembled units prior to flight are required. Other options for reliable, pre-assembled dual deployment controllers with varying levels of features and cost include the PerfectFlite StratologgerCF, the Missileworks RRC2+, and MissileWorks RRC3.

Due to the safety-critical function of the dual deployment altimeters, scratch-built or self-programmed altimeters should NOT be relied upon for deployment of parachutes. Such devices should be flown only as passive instrumentation payloads without deployment charges connected to them, until thoroughly tested over many flights. Even then, a reliable commercial unit should always be present as a backup.

Fig. 2.25 depicts an exploded view of the Mojave Sphinx avbay.

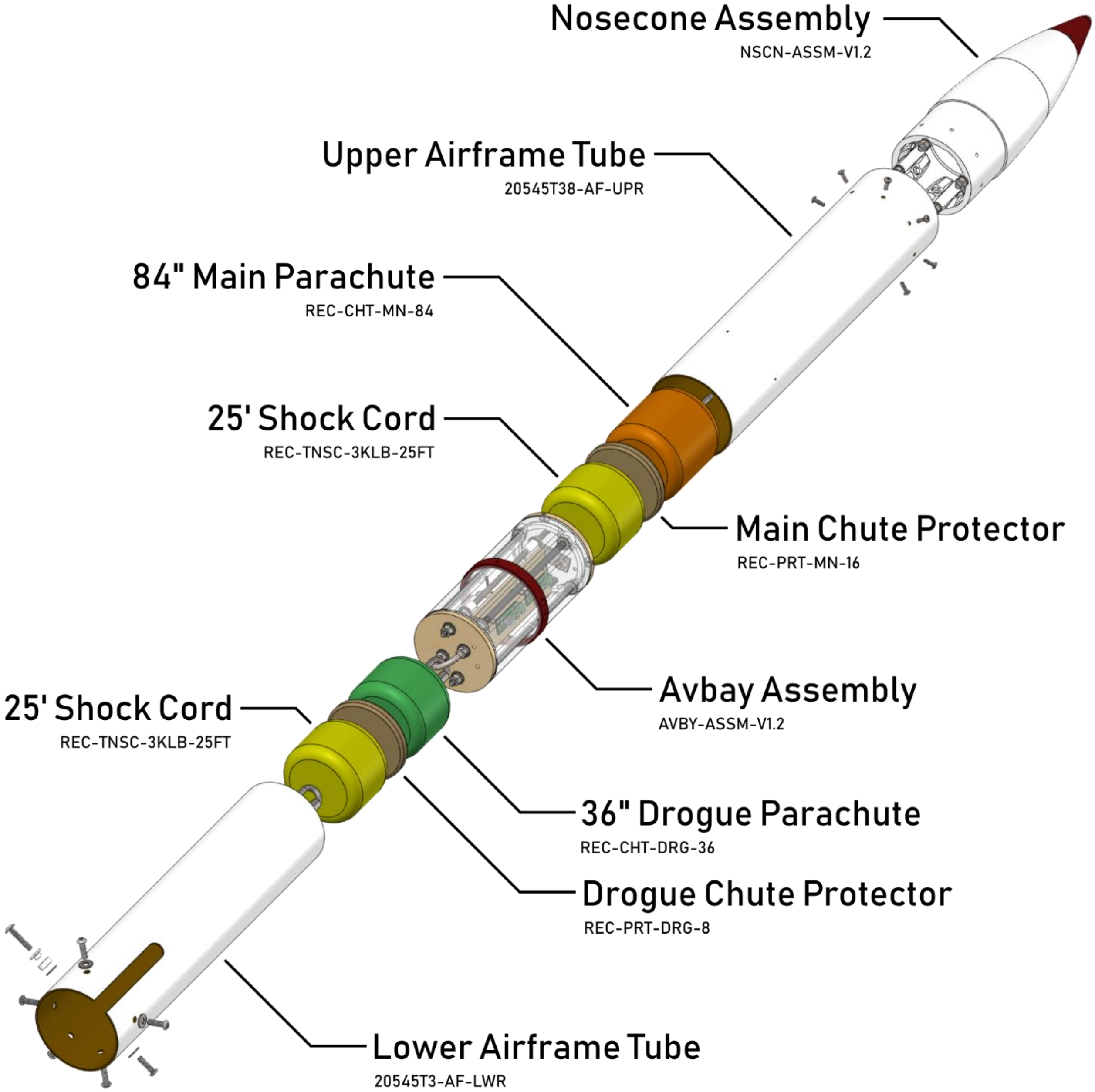

Figure 2.22: Exploded-view diagram of Mojave Sphinx airframe and recovery system

Figure 2.23: Side-view of Mojave Sphinx avbay

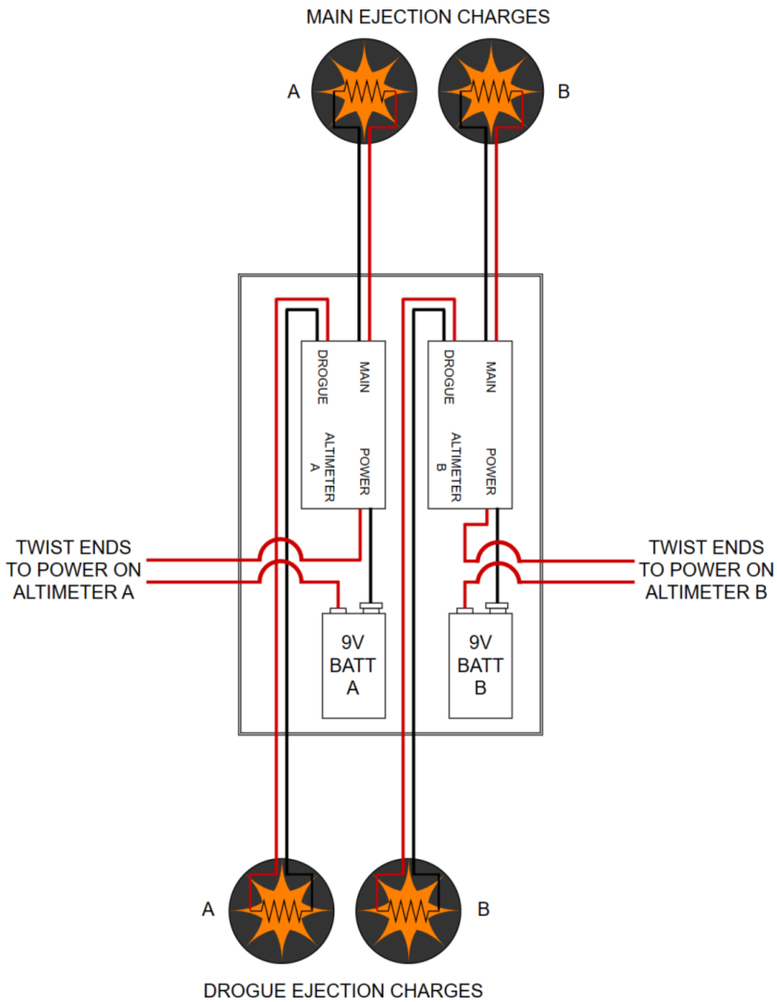

Figure 2.24: Avbay wiring diagram

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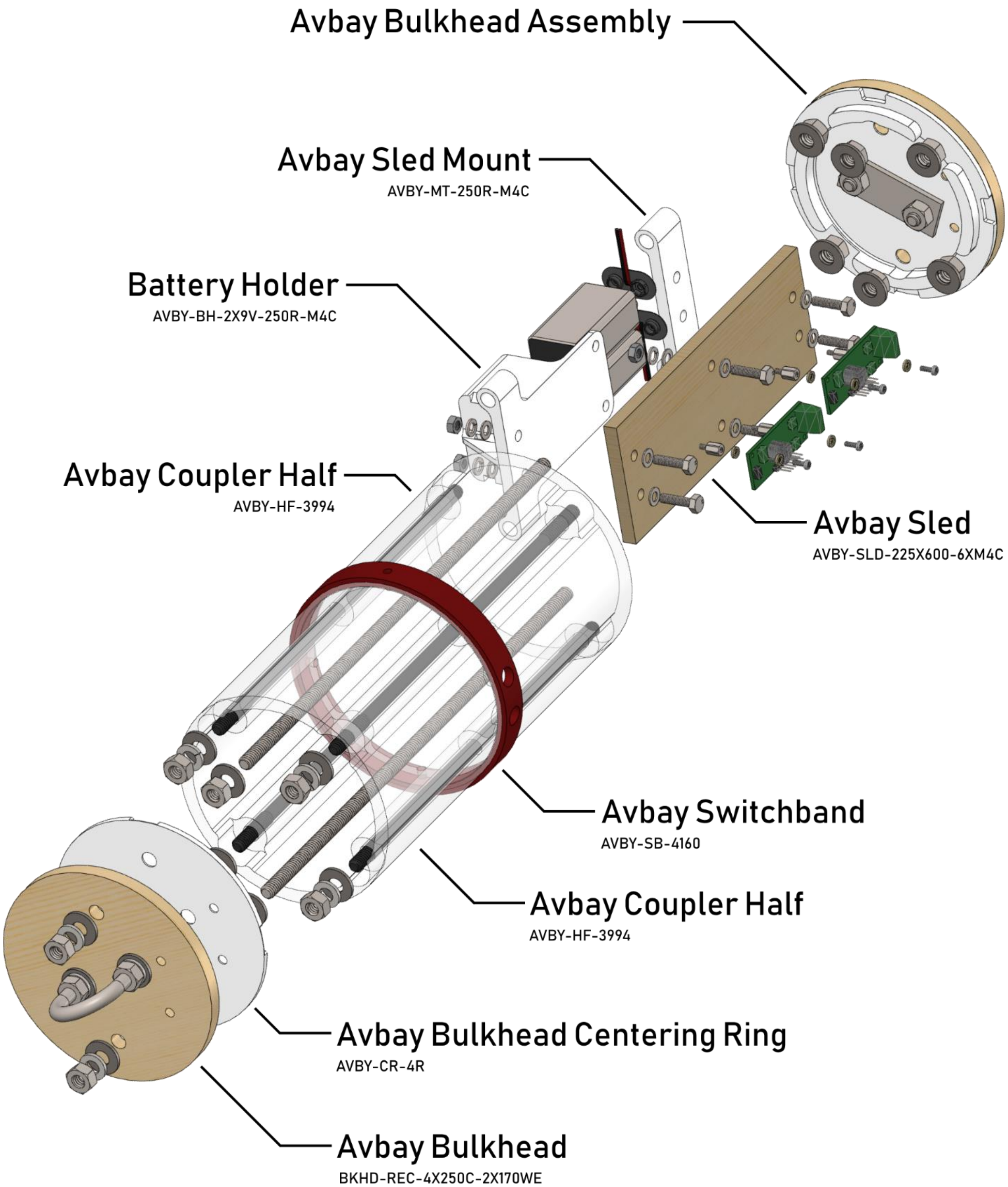

Figure 2.25: Exploded-view diagram of Mojave Sphinx avbay

Lower Airframe Tube

The lower airframe tube contains the drogue parachute and mates to the avbay coupler and the forward retaining ring of the motor. It is made from a cardboard mailing tube with a wall thickness of approximately .09 inches. Thinner-walled (~.06") tubes are less durable and not recommended, however thicker tubes with the same inner diameter may be used at the cost of slightly increased mass and drag. Radial holes are drilled at the aft end, and a slot cut for the fuel downcomer line. A 3D printed marking template ensures alignment of the holes and slot. Since this tube separates from the Avbay at apogee, this interface is friction fit by shimming the outer diameter of the Avbay/coupler with painters tape. There is no need for shear pins since it will not separate from drag or trapped pressure during ascent.

Upper Airframe Tube

The upper airframe tube contains the main parachute and mates to the avbay coupler and the nosecone. It is made from the same cardboard mailing tube as the lower airframe tube, with holes drilled radially at the forward end for screws that secure the nose cone. This tube is attached to the avbay with shear pins, small nylon screws which hold the airframe together during flight and tumbling after apogee but which break from the pressure of the main charge.

Nosecone

The nosecone closes off the forward end of the rocket with an aerodynamic contour. In Mojave Sphinx, it also provides extra volume for the shock cord to pack into. Like the avbay coupler, the nosecone is 3D-printed and held in compression by threaded rods. Unlike those used in the avbay, these threaded rods are made of nylon and therefore flexible – this allows them to bend to match the profile of the nosecone, which leaves most of the interior volume free while providing adequate structural reinforcement. The nose cone tip includes provisions for an eye bolt, which is used to secure the shock cord. The shank of the eye bolt passes through the nose cone tip and threads into a cap nut on the forward end, providing a durable rounded point. Fig. 2.28 depicts an exploded view of the Mojave Sphinx nose cone.

A forged eye bolt is used rather than the bent style, as the latter can be deformed by excessive or repeated shock loading from parachute deployment, potentially opening up far enough for the shock cord to slip out of the eye. Bent eye bolts that have been welded closed are also acceptable.

The nose cone tip is mounted to the lower portion of the nose cone assembly using four of the same nylon screws that serve as shear pins at the interface between Avbay and Upper Airframe Tube. Note that the nose cone tip has a much smaller internal cross-sectional area, therefore the force from pressure generated at ejection is much lower and will not shear the nylon screws.

Drogue Parachute

The drogue parachute ejects at apogee, when the rocket separates between the avbay coupler and lower airframe tube. Its purpose is to stabilize the vehicle's descent and slow it down enough that the main parachute will deploy successfully, but not so slow that the vehicle drifts away in the wind while descending to main charge altitude. Mojave Sphinx uses a 24-inch drogue parachute made of ripstop nylon, yielding a nominal descent rate of approximately 70 feet per second.

Main Parachute

The main parachute ejects at a pre-set altitude during descent, when the rocket separates between the avbay coupler and the upper airframe tube. Its purpose is to slow the vehicle down to a safe velocity for landing, so that ground impact will not cause damage. The main parachute is deployed only when close the ground (typically under 1000 feet), otherwise the rocket would be carried away by the wind. Mojave Sphinx has an 84-inch main parachute made of ripstop nylon, yielding a nominal descent rate of approximately 25 feet per second.

Shock Cord

The shock cord is the tether which connects all of the parts of the rocket after separation. Mojave Sphinx has two independent shock cords, which pass through the upper and lower airframe tubes to connect the propulsion system, avbay, and nose cone. Both are 24-foot lengths of 5/8-inch tubular nylon with a rated breaking strength of 3,000 lbf.

Shock cords should be made of flame-resistant material that can survive brief, repeated exposure to the hot combustion gas produced by the pyrotechnic ejection charges. Tubular nylon meets this requirement for approximately five ejections, but can be degraded over time until it fails well below its rated strength. For a rocket that will be flown multiple times, it is recommended to cover the segment of the shock cord that is adjacent to the ejection charges when the recovery system is packed with a more heat-resistant –or sacrificial– material. Aramid (Kevlar) sleeving is common for this application; however the simplest and lowest-cost solution is to wrap the affected area of the shock cord with masking tape, which is replaced after each flight or when it becomes scorched.

Kevlar cord or webbing can be used for the entirety of the shock cord, however it has significantly less elasticity than nylon. This means that shock loads are higher during separation events (specifically when the separated pieces reach the end of the cord's length and pull it taut), potentially leading to shock cord failure or damage to other components. If a Kevlar shock cord is used, it should be bundled into several sections each held together with a rubber band or single wrap of masking tape, to help dissipate energy more gradually as each bundle is pulled apart.

The shock cord is attached to the mounting points on the propulsion section, avbay coupler, and nose cone using quick links to allow easily separating and reconnecting each section of the rocket. The quick links may optionally be omitted in favor of tying the shock cord on directly, saving a small amount of mass and cost at the expense of convenience. Fig. 2.29 depicts an exploded view of the Mojave Sphinx forward bulkhead assembly's recovery mounting components.

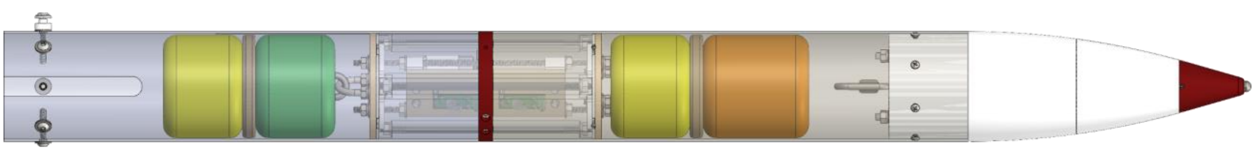

Figure 2.26: Side-view of Mojave Sphinx airframe (containing avbay and packed recovery system)

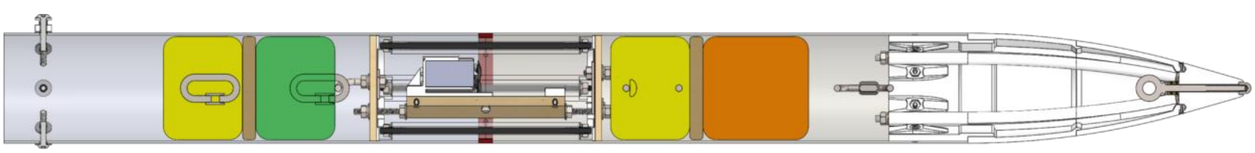

Figure 2.27: Section-view of Mojave Sphinx airframe (containing avbay and packed recovery system)

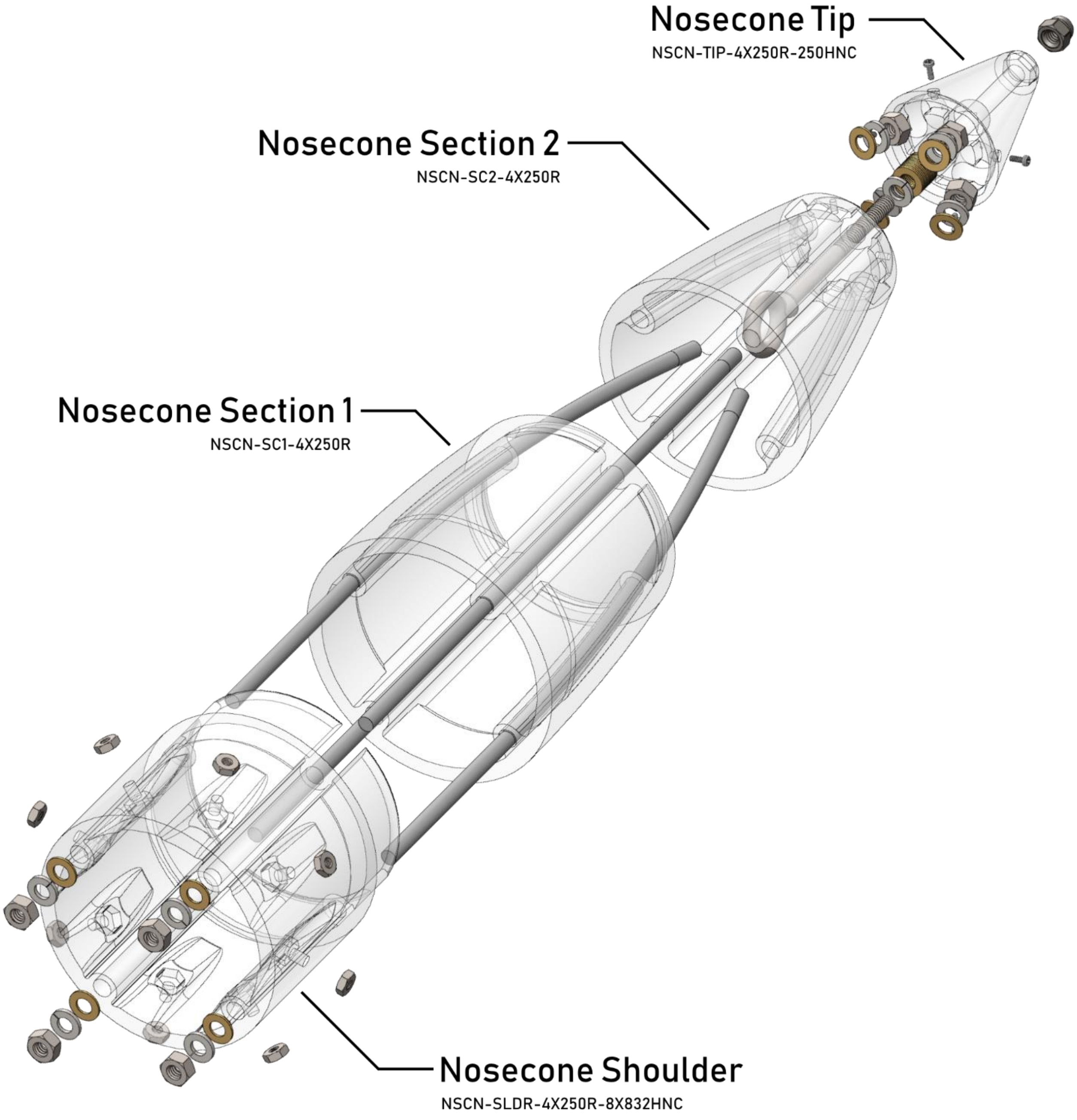

Figure 2.28: Exploded-view diagram of Mojave Sphinx nosecone assembly

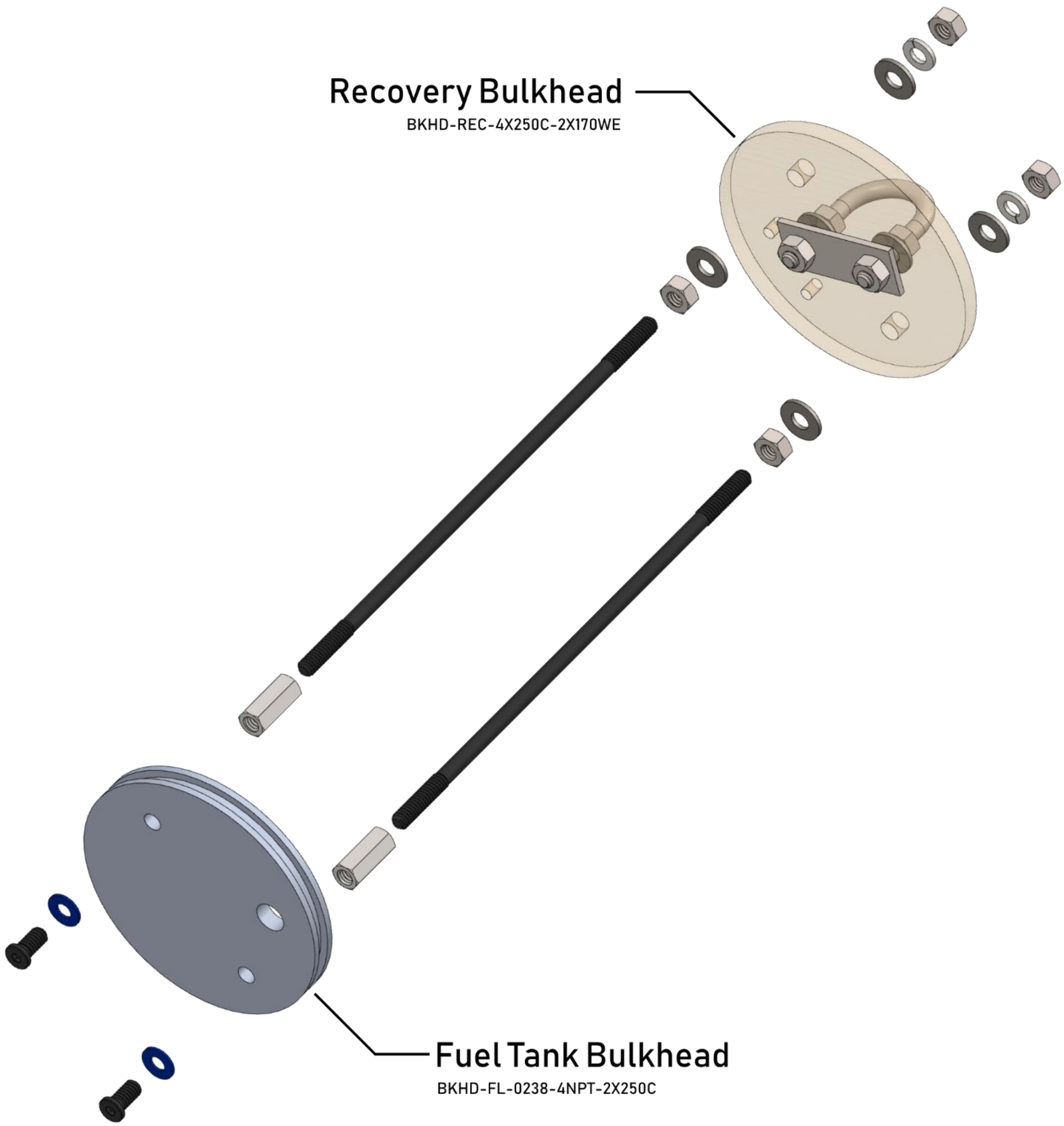

Figure 2.29: Exploded-view diagram of the Mojave Sphinx forward bulkhead assembly's recovery mounting components

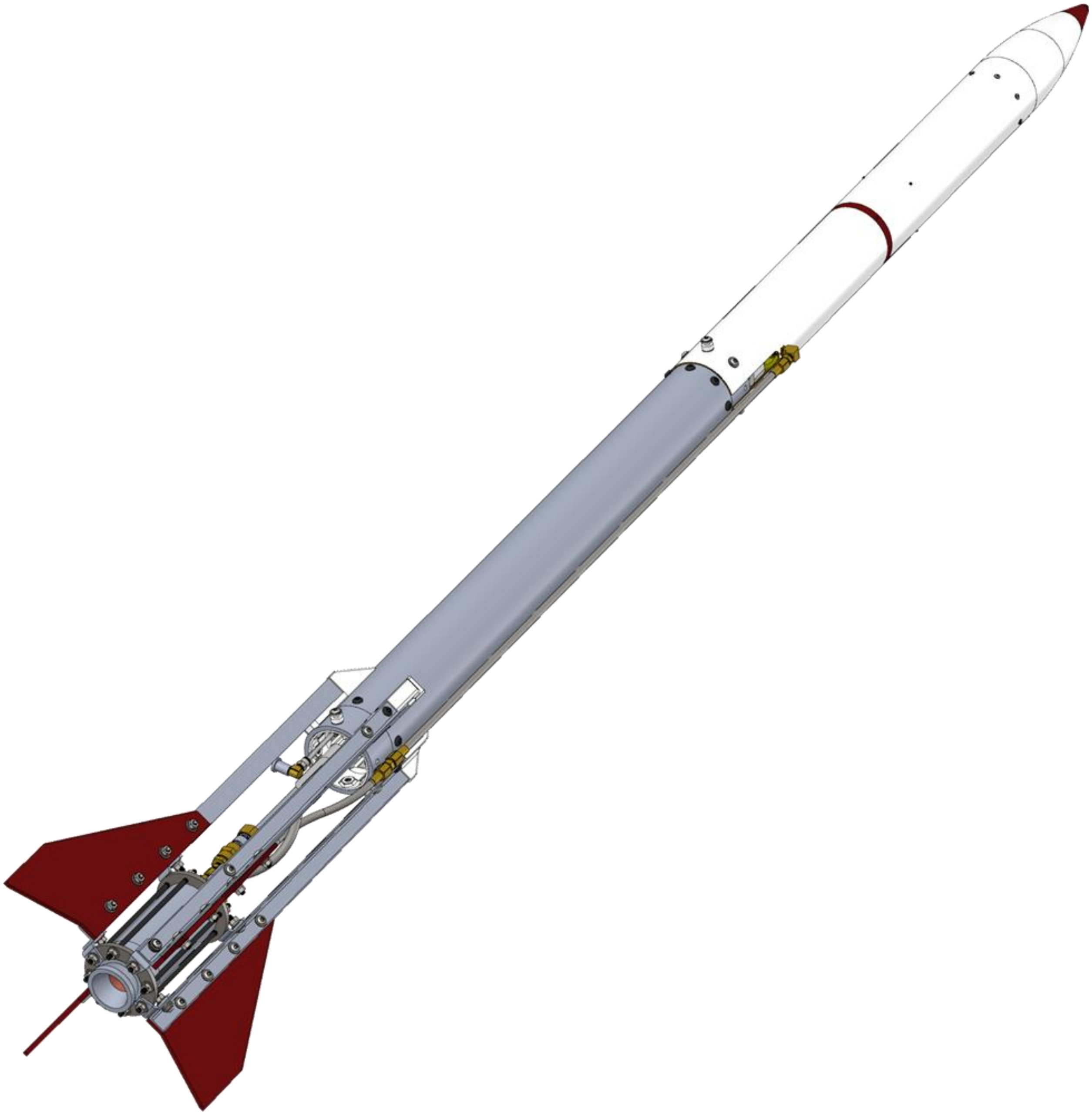

Figure 2.30: Mojave Sphinx complete vehicle

2.4 Structural Analysis

This section explains the basic principles and mathematics of analyzing the propellant tank and TCA. The propellant tank calculations shown here can also be found in the accompanying file HalfCatSim_v1.3.8_MojaveSphinx, in the Pressure Vessel tab.

The tank casing, bulkheads, combustion chamber, injector, and nozzle carrier are made of 6061-T6 aluminum, a very common grade with good mechanical properties (given below). Its properties can vary depending on the shape, manufacturer, and testing setup, and some sources may indicate higher strength than those listed below. Typical values are used:

6061-T6 Material Properties	
Yield Tensile Strength	40 ksi
Ultimate Tensile Strength	45 ksi
Yield Bearing Strength	56 ksi
Ultimate Bearing Strength	88 ksi
Shear Strength	30 ksi

Table 2.5: 6061-T6 aluminum material properties

Fasteners (bolts & screws) found on websites such as McMaster-Carr may be made from a variety of different steels and stainless steels. It is standard practice to use "Alloy Steel" with a tensile strength of at least 120 ksi, in which case the shear strength is approximately 72 ksi (found by multiplying tensile strength by 0.6). Mojave Sphinx uses 8x 5/16-24 button head hex drive screws for its propellant tank and 8x 1/4-20 threaded rod for its TCA. There are typically multiple coating options for fasteners; black oxide is almost always the cheapest and most ubiquitous, although corrodes more easily than other options if exposed to the elements or stored in a wet or humid environment. Functionally, there is no difference between coatings aside from relatively minor variation in corrosion resistance, and it is up to personal preference on price versus appearance – black oxide contrasts well with aluminum, whereas zinc plating matches and blends well with its silvery color.

Margin of Safety (MoS) is the ratio of material strength to stress, subtracted by 1 such that zero is exactly the zero-margin point, and any positive number means a positive margin of safety. In these calculations, no load factor (where the pre-calculation load is multiplied) or safety factor (where the post-calculation stress is multiplied) are applied. This is because it is more useful for amateur applications to see the raw margin and judge if this is acceptable, rather than shroud the result in load and safety factors that may not be consistent between calculations. MoS is found by:

$$\text{MoS} = \frac{\text{Strength}}{\text{Stress}} - 1$$

For Mojave Sphinx, only the yield margins will be examined because permanent deformation under normal operation is not considered acceptable. In all cases, the ultimate margin is higher than yield and thus does not drive the design. The tank of this rocket has already been designed and tested, but it is useful to see the math to understand the margins. Additionally, if weight optimizations are to be made (for example, by using a thinner-walled tank casing) the math will need to be checked again to ensure proper margins.

Since amateur rocketry is naturally a less rigorous field than professional engineering work, the equations presented here are fairly academic and a simplified look at what can be a very in-depth analysis. Margins of at least 0.3 are targeted so that any inaccuracies in analysis, imperfections in manufacturing, or variations in material properties can be comfortably ignored.

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2.4.1 Tank Hoop and Axial Stress

Hoop stress is the tensile stress developed in the tank wall in the tangential direction as a function of internal pressure pressing outward in all directions. For this calculation, we assume a cylindrical thin-walled pressure vessel. Outer diameter is used rather than mean diameter because it is a conservative assumption. Hoop stress is found by:

$$\sigma_h = \frac{P \cdot D}{2t}$$

$$\sigma_h = \frac{1000 \cdot 4}{2 \cdot 0.125}$$

$$\sigma_h = 16000\ psi$$

Where,

P ≡ Maximum expected tank pressure (psi)

D ≡ Outer diameter of tank (in.)

t ≡ Thickness of tank wall (in.)

Axial stress is the tensile stress developed in the tank wall parallel to the axis of the cylinder as a function of the internal pressure stretching the tank:

$$\sigma_a = \frac{P \cdot D}{4t}$$

$$\sigma_a = \frac{1000 \cdot 4}{4 \cdot 0.125}$$

$$\sigma_a = 8000\ psi$$

The margin to yield is then:

$$MoS_h = 1.50$$

$$MoS_a = 4.00$$

2.4.2 Tank Bolt Shear Failure

Bolt shear failure occurs when the fasteners holding the closure into the casing break in shear due to the force applied perpendicular to the axis of the fastener. First, find the force acting on each bolt assuming stress is equally distributed:

$$F_{bolt} = \frac{\frac{\pi}{4} {D_i}^2 P}{N}$$

$$F_{bolt} = \frac{\frac{\pi}{4} \cdot 3.75^2 \cdot 1000}{8}$$

$$F_{bolt} = 1381\ lbf$$

Where,

P ≡ Maximum expected tank pressure (psi)

N ≡ Number of fasteners

D_i ≡ Inner diameter of tank (in.)

Bolt shear stress is then found by:

$$\sigma_{bolt\ shear} = \frac{F_{bolt}}{\frac{\pi}{4} {D_{minor}}^2}$$

$$\sigma_{bolt\ shear} = \frac{1381}{\frac{\pi}{4} \cdot 0.2614^2}$$

$$\sigma_{bolt\ shear} = 25725\ psi$$

Where,

D_{minor} ≡ Minor diameter of fastener (in.)

The margin to yield is then:

$$MoS_{bolt\ shear} = 3.66$$

2.4.3 Tank Bolt Tear-Out

Bolt tear-out occurs when the fasteners tear through the end of the casing via shear failure of the casing material tangent to the holes. It is assumed that stress is evenly distributed among all fasteners. It is necessary to define the edge distance:

$$E_{min} = E - \frac{D_{hole}}{2}$$

$$E_{min} = 0.5 - \frac{0.328}{2}$$

$$E_{min} = 0.338\ in.$$

Where,

E ≡ Edge distance from center of bolt hole (in.)

D_{hole} ≡ Diameter of bolt hole (in.)

Bolt tear-out stress is then found by:

$$\sigma_{bolt\ tear\ out} = \frac{F_{bolt}}{E_{min} \cdot 2t}$$

$$\sigma_{bolt\ tear\ out} = \frac{1381}{0.338 \cdot 2 \cdot 0.125}$$

$$\sigma_{bolt\ tear\ out} = 16343\ psi$$

Where,

F_{bolt} ≡ Force on each fastener (lbf) [See 2.4.2]

t ≡ Thickness of tank wall (in.)

The margin to yield is then:

$$MoS_{bolt\ tear\ out} = 0.84$$

2.4.4 Tank Casing Tensile Failure

Casing tensile failure occurs when the portion of the casing between the fastener holes is stretched beyond its breaking point. It is a tensile failure that occurs between the centers of the fastener holes, where casing cross-sectional area is a minimum. It is found by:

$$\sigma_{tensile} = \frac{\frac{\pi}{4} {D_i}^2 P}{[\pi(D_o - t) - N \cdot D_{hole}]t}$$

$$\sigma_{tensile} = \frac{\frac{\pi}{4} 3.75^2 \cdot 1000}{[\pi(4 - 0.125) - 8 \cdot 0.328] \cdot 0.125}$$

$$\sigma_{tensile} = 9252\ psi$$

Where,

P ≡ Maximum expected tank pressure (psi)

N ≡ Number of fasteners

D_i ≡ Inner diameter of tank (in.)

D_o ≡ Outer diameter of tank (in.)

D_{major} ≡ Major diameter of fastener (in.)

t ≡ Thickness of tank wall (in.)

The margin to yield is then:

$$MoS_{tensile} = 3.32$$

2.4.5 Tank Bearing Failure

Bearing failure occurs when the force of the fasteners pushing against the edges of their holes causes the casing material to fail in compression, and is found by:

$$\sigma_{bearing} = \frac{F_{bolt}}{D_{major} \cdot t}$$

$$\sigma_{bearing} = \frac{1381}{0.313 \cdot 0.125}$$

$$\sigma_{bearing} = 35297\ psi$$

Where,

F_{bolt} ≡ Force on each fastener (lbf) [See 2.4.2]

D_{major} ≡ Major diameter of fastener (in.)

t ≡ Thickness of tank wall (in.)

The margin to yield is then:

$$MoS_{bearing} = 0.59$$

Bearing yield is the lowest MoS and thus the driving structural case. A margin of 0.59 means that the closure can theoretically survive 1.59 times the load before failure, corresponding to a tank pressure of 1590 psi. As mentioned before, this is not possible under normal circumstances due to the way saturated N_2O works. Therefore, the margin is acceptable.

2.4.6 TCA Clamping Force

The thrust chamber assembly must be clamped by the threaded rods with sufficient force to maintain compression of the graphite gasket when the chamber is pressurized. The required clamping force can be expressed as:

$$F_{clamp} = P_{gasket} \cdot A_{gasket} + P_c \cdot A_{chamber}$$

$$F_{clamp} = 4300 \cdot 3.927 + 300 \cdot 3.142$$

$$F_{clamp} = 18064\ lbf$$

Where,

P_{gasket} ≡ Pressure load on the gasket (psi) [4000-4500 psi recommended]

P_c ≡ Chamber Pressure (psi)

A_{gasket} ≡ Surface area of the gasket (in.^{2}).

$$A_{gasket} = \frac{\pi \cdot ({D_o}^2 - {D_i}^2)}{4}$$

$$A_{gasket} = \frac{\pi \cdot (3^2 - 2^2)}{4}$$

$$A_{gasket} = 3.927\ in^2$$

$A_{chamber}$ ≡ Internal cross-sectional area of the combustion chamber (in.^{2}).

$$A_{chamber} = \frac{\pi \cdot {D_i}^2}{4}$$

$$A_{chamber} = \frac{\pi \cdot 2^2}{4}$$

$$A_{chamber} = \pi\ in^2$$

Where,

D_o ≡ Outer diameter of combustion chamber (in.)

D_i ≡ Inner diameter of combustion chamber (in.)

The sum of the preload of the 8X threaded rods must be equal to or greater than the required clamping force. Torque required to achieve sufficient preload on each rod can be found by:

$$T = K_T \cdot D_{major} \cdot \frac{F_{clamp}}{N_{rods}}$$

$$T = 0.2 \cdot 0.25 \cdot \frac{18064}{8}$$

$$T = 113\ in \cdot lbf$$

Where,

K_T ≡ Nut factor, typically 0.15-0.2 for non-lubricated steel threads

D_{major} ≡ Major diameter of the tie rods

N_{rods} ≡ Number of threaded rods

While a torque wrench can be used to precisely meet the calculated value, tightening by hand is generally sufficient. The approximate applied torque can be found using a rough estimate of the force applied to a wrench of known length, and there is little consequence of over-torquing the chamber tie rods so long as it does not result in excessive deflection of the flange plates.

SCREWS - ENGLISH	
Link to companion guide on pressure vessel design	
Blue	User Inputs. Enter your values here.
Gray	Automatically Calculated Values. Don't type in these.
Yellow	Margin of Safety. All these should be above the minimum margin you have selected for your design. The lowest one determines your failure mode.

CASING		
Parameter		Units
Operating Pressure	1000	psi
Outside Diameter	4	in.
Wall Thickness	0.125	in.
Inside Diameter	3.75	in.

SCREWS		
Parameter		Units
# of Screws	8	
Thread	5/16-24	
Tap Drill	I	
Shear Strength	120000	psi
Center-Edge Distance	0.5	in.
Screw Hole Diameter	0.3125	in.

BEARING FAILURE		
Parameter		Units
Bearing Area	0.0	in^2
Bearing Stress	35343	psi
Bearing Failure MoS (Y)	0.6	
Bearing Failure MoS (U)	1.5	

SCREW SHEAR		
Parameter		Units
Force on Bulkhead	11045	lbf
Force on Each Screw	1381	lbf
Shear Stress in Screw	25725	psi
Screw Shear MoS	3.7	

Material Properties	6061-T6	
Parameter		Units
Tensile Strength(Yield)	40000	psi
Tensile Strength (Ultimate)	45000	psi
Bearing Strength (Yield)	56000	psi
Bearing Strength (Ultimate)	88000	psi
Shear Strength	30000	psi

CASING TENSILE FAILURE		
Parameter		Units
Minimum Tensile Area	1.2	in^2
Maximum Tensile Stress	9134	psi
Tensile Failure MoS (Y)	3.4	
Tensile Failure MoS (U)	3.9	

SCREW TEAR-OUT		
Parameter		Units
Effective Shear Area	0.1	in^2
Tear-out Stress	16065	psi
Screw Tear-out MoS	0.9	

MoS = (Material Strength ÷ Stress) - 1
Negative Margin of Safety means failure!

THRUST CHAMBER CLAMPING FORCE		
For flange plate retained chambers		
Gasket OD	3.000	in
Gasket ID	2.000	in
Number of chamber tie rods	8	
Gasket Compression	4300	psi
Chamber Pressure	300	psi
Load Factor	1	
Gasket Area	3.927	in^2
Required Clamping Force	18064	lbf
Required preload per rod	2258	lbf
Tie rod major diameter	0.250	in
Kt nut factor	0.200	
Torque required	113	in-lbf
	9.4	ft-lbf

Figure 2.31: Mojave Sphinx HalfCatSim design, pressure vessel

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2.5 Flight Analysis

OpenRocket

OpenRocket is the software tool of choice for predicting flight performance of Mojave Sphinx. It is a free, open-source program that uses a full 6-Degree of Freedom (6-DOF) model to simulate a rocket's trajectory.

The relevant inputs for Mojave Sphinx are the model itself and the thrust curve. The model is constructed in OpenRocket's "Rocket Design" tab; importing 3D models from a CAD program is not supported. Each component is added to the model tree, and the dimensions and masses populated to match those of the physical parts. An OpenRocket file containing a pre-defined model of the standard Mojave Sphinx design is available on the Half Cat Rocketry website.

The thrust curve is generated either by a HalfCatSim file or from empirically measured test data, and is added as a user-defined thrust curve in the OpenRocket Preferences window. It is recommended to set the loaded mass of the thrust curve file equal to the propellant mass, without including the mass of the hardware. Hardware mass is best represented by modeling each major subassembly as a component or mass object in OpenRocket, to achieve a realistic distribution of mass and resulting moment of inertia. The length of the motor in the thrust curve file should be set to the length of only the tank, as it represents only the propellant.

For a standard Mojave Sphinx without aerodynamic panels enclosing the thrust structure, the performance impact is typically a 15-20% reduction in apogee compared to an OpenRocket prediction where this section is modeled as a simple tube. The effects of airflow between the brackets on the Center of Pressure (CP) can be safely neglected, as this does not negatively affect ballistic stability; in reality, the CP may be shifted slightly aft by the increased drag from the low-pressure zone at the aft end of the propellant tank and stagnation of airflow against the forward end of the thrust structure. A more accurate apogee prediction may be obtained either by enclosing the thrust structure to increase similarity between the model and physical rocket, or by determining a more accurate drag coefficient (either empirically or analytically), which can be entered into OpenRocket as an override. An override value of approximately 1.720 (applied to all subcomponents) was found to result in close agreement between simulated and actual performance of the standard design without closeout panels. With the thrust structure roughly covered by aluminum tape spanning between the brackets, a Cd override of approximately 1.100 accounts for the remaining sources of parasitic drag such as fastener head protrusion.

Comprehensive documentation of OpenRocket's features may be found online in the form of a wiki as well as various tutorials.

RASAero II

For rockets expected to significantly exceed Mach 1, RASAero II will typically provide more accurate performance predictions, assuming sufficiently high-fidelity inputs. While somewhat less user-friendly, RASAero II offers improved aerodynamic and atmospheric modeling for high-velocity/high-altitude launches. Conveniently, parasitic drag sources may be accounted for by modeling them as "protuberances." Although it is not open-source, RASAero II is available to download for free, and is accompanied by a detailed user's guide.

RockSim

RockSim is a paid program with a nearly identical feature set to OpenRocket, and offers little to no advantage to justify its significant cost. The exception is if a Monte Carlo dispersion analysis is required to obtain a new FAA Certificate of Authorization (COA), in which case a monthly subscription for RockSim Pro may be worthwhile.

Custom Analysis Tools

Custom aerodynamic stability and performance prediction models coded using MATLAB, Python, or similar tools offer an excellent learning opportunity, but should always be validated against established programs like those mentioned above.

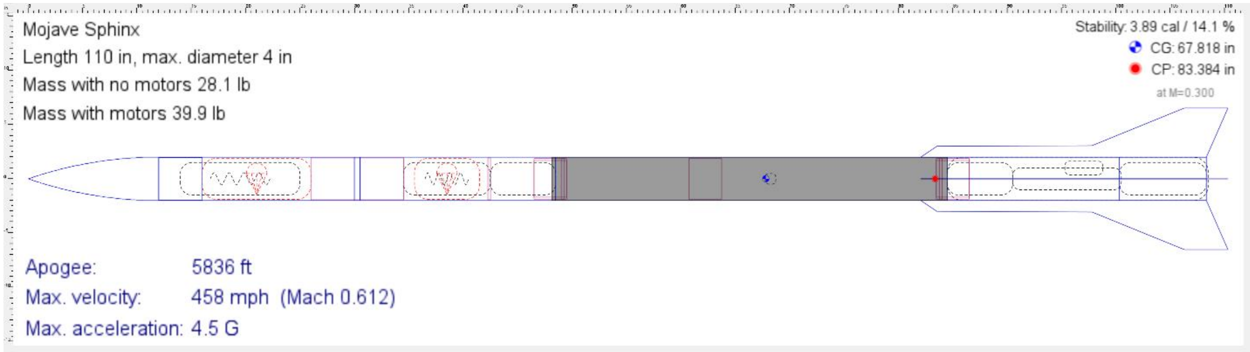

Figure 2.32: Mojave Sphinx OpenRocket model (text enlarged for readability)

Table 2.6 provides a reference for propulsion characteristics as a function of temperature, which dictates N_2O pressure and density. The given ambient temperatures are of the outside air, and not the temperature of oxidizer in the propellant tank. During the oxidizer fill, the liquid typically cools down to approximately 12° F colder than it was in the supply bottle, so that it reaches a correspondingly lower equilibrium pressure (12° F was determined empirically during Mojave Sphinx testing, and can vary depending on vent orifice and tank sizing). Additionally, temperatures listed are for bottles in shade – direct sunlight will raise the temperature and pressure further, sometimes significantly higher than air temperature. On hot days, bottles should be shielded from sunlight and/or cooled with ice or a wet towel; the latter was found to decrease bottle pressure by as much as 10 psi per minute when the towel was kept continuously soaked. On very cold days, sunlight can be used to keep pressure up. Regardless of the temperature, if a pressure gauge is present on the supply bottle or GSE, this should be used as a more accurate reading of oxidizer condition.

All values in Table 2.6 are for alcohol fuels (E85, isopropanol, etc.) using the BASIC-6-6 injector. If a hydrocarbon like diesel is used instead, multiply chamber pressure, thrust, total impulse, and altitude by 0.8 for a more accurate performance estimate. Fuel additives (see Section 2.6.3) have negligible effect on performance.

Ambient Temperature °F	P_{tank} psi	$P_{chamber}$ psi	Thrust lbf	Burn Time s	Total Impulse N•s	Altitude ft
All values are approximate						
<40	Not recommended – use bottle warmer					
40	425	220	220	5.9	5000	5800
50	500	240	240	5.2	4900	5700
60	575	260	270	4.7	4800	5500
70	650	280	290	4.2	4700	5400
80	725	300	320	3.9	4700	5400
90	825	310	320	3.5	4600	5300
100	925	330	340	3.3	4500	5100
110	1050	340	360	3.2	3900	4600
>110	Not recommended – cool bottle using ice or wet towel					

Table 2.6: Mojave Sphinx approximate performance numbers as function of ambient temperature

2.5.1 Impulse Adjustment

A unique feature of liquid bipropellant rockets is the ability to adjust burn time and total impulse independent of other performance metrics. Experimental solids can be adjusted by removing grains, but it also negatively impacts thrust and can only be done in increments of whole grains. Hybrid motors can be short-filled with less than a full load of oxidizer, but the fuel grain is still consumed; in addition, it presents a risk of ongoing fire as the partially-burnt grain continues to smolder in air and residual N_2O vapor. Liquid motors have no such limitations because the thrust profile will be identical at any fill level, up to the point of propellant depletion when the burn terminates.

There are several reasons one may wish to short-fill Mojave Sphinx: Altitude limitations, imposed either by the available FAA waiver or minimum cloud base; recovery considerations, since higher altitude often means a farther landing; and per-launch cost reduction, since a lighter fill will use less oxidizer (the most expensive consumable) if higher altitudes are not required or desired. To short-fill the rocket, the propellant piston may simply be pushed to a shallower depth in the fuel tank before loading fuel, and the oxidizer fill time should be reduced by the same proportion. Any excess fuel will simply be expelled through the chamber after oxidizer depletion.

2.5.2 Throttling

Because Mojave Sphinx's propellant valves are controlled by a PWM signal, it is possible to throttle them by changing the open position. The Cv curve for a full-port ball valve - in other words, the flow resistance as a function of position - is not very favorable for throttling, so it is difficult to achieve a precise setting. Although high fidelity throttling would require extensive flow testing or valves with more linear Cv curves, a single throttle point can be set fairly easily. In testing of the Mojave Sphinx prototype vehicle, the throttle setting partially closed the valves and produced roughly half of the nominal chamber pressure and thrust.

To throttle the valves, they must still be connected to power and PWM control. This means that it is not possible to throttle on a launch unless the valves are connected to an onboard computer rather than the ground system (which unplugs from the vehicle at launch). Low throttling at startup is not recommended because this may result in a slow, unstable rail exit, or it may not produce enough thrust to launch at all.

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2.6 Fuel Selection

Broadly speaking, there are two classes of fuels which can be used in Mojave Sphinx: **Organic solvents** and **hydrocarbons**. As a rule of thumb, Half Cat type rockets can successfully launch with just about any free-flowing liquid that is flammable in open air. In one memorable incident, a collection of solvents was taken up late on a FAR Saturday to refill the 1Cat/3 fuel tank for a last-minute test fire attempt (the motor did not ignite, but it would have if the igniter had been better than solid propellant shavings pushed through the throat). In another instance – a launch attempt of 1Cat/4 – spare isopropyl alcohol was accidentally left behind, forcing the rocket to fly under the power of the only solvent which could be found in the moment: acetone. In yet another case, 1Cat/4 was launched with Klean Strip paintbrush cleaner, for no other reason than because it was available. Undoubtedly, even more obscure fuels will be tried in the future.

Half Cat Rocketry often experiments with weird, unconventional, or inadvisable fuels – **this should not be taken as an endorsement of any particular fuel**. All others building liquid rockets are strongly advised to stick with recommended fuels for safety. Recommended fuels are listed in Table 2.7.

Gloves and eye protection should be worn at all times when handling any fuel. Always keep heat sources and open flame away from liquid fuels, and work in a well-ventilated area or outdoors to avoid fume inhalation. Always store fuel in secure, sealed containers away from heat or oxidizers.

2.6.1 Organic Solvents

Organic solvents are solvents which contain carbon and are typically represented by alcohols and ketones. A variety of organic solvents can be commonly found at home and hardware stores as disinfectants, paint removers, and surface cleaners. They are usually colorless, low-viscosity fluids with pungent odors. The biggest downside to organic solvents is that their fumes can cause harm if a great quantity is inhaled, so it is best to work with them outdoors or in a well-ventilated room.

Isopropanol

Isopropyl alcohol is the "classic" amateur liquid fuel. It is commonly referred to by the abbreviation IPA, or the names Isopropanol or 2-Propanol. It is among the best performing liquid fuels, possesses favorable cooling properties for regenerative chambers, and can be obtained at 99% purity very cheaply and easily. While not quite as cost-effective as "dirty" ethanol mixtures, it is very safe and can be used to clean parts and sanitize surfaces.

Ethanol

Pure ethanol has virtually identical properties to isopropanol, but it comes with one major downside: It is hard to find cheaply because it is taxed heavily for its use in alcoholic beverages. The next best option is a denatured ethanol, but these must be checked carefully because the additives can be hazardous and of wildly varying percentage (some denatured alcohols contain up to 50% methanol). For cost reasons, if pure ethanol is desired, then a mostly pure "dirty" mixture should be used. Dirty ethanols are mixtures that contain ethanol along with other flammable liquids, making them unsafe to drink and slightly less efficient than pure alcohol.

E98

E98 consists of (nominally) 98% ethanol and 2% gasoline, making it one of the purest dirty ethanols available. E98 can be found at racing shops for reasonable prices, making it only slightly less convenient to acquire than isopropanol or E85.

E85

First debuted in Mojave Sphinx's initial launch, E85 is the undisputed king of cheap fuels. Nominally consisting of 85% ethanol and 15% gasoline (although this can vary substantially depending on location and season), E85 can be pumped directly from many gas stations at a price comparable to regular gasoline. An inexpensive test kit or simply a graduated cylinder can be used to measure the ethanol content, by mixing the E85 with a small amount of water and observing the stratification between the gasoline and water/ethanol mixture. The gasoline content lowers performance slightly but it still behaves just like ethanol for the most part.

One minor safety concern for E85 compared to other solvent fuels is that the gasoline content gives it more flammable vapors than regular ethanol – it should go without saying that open flame and heat sources must be kept away from any fuel.

Methanol

Methanol should not be used. It has no real advantage in amateur liquid rockets, but it has the very real health hazard that it will cause sickness, blindness, and potentially death if inhaled or ingested. There are edge cases where the density and low ideal mixture ratio of methanol can be a benefit, but this is not the case most of the time. If methanol is used, personnel **must** wear protective equipment, including a respirator mask with an organic molecule filter cartridge.

Acetone

Acetone is the simplest ketone. It is a more powerful solvent than alcohol, and it is also slightly less efficient as a fuel. Acetone tends to swell O-rings and generally degrade the interior of fluid systems, so if used it should be flushed out as soon as possible with isopropanol, water, or another more benign fuel. There is no real reason to use acetone, unless it is the only solvent on hand or "just because."

Solvent Mixtures

There are a variety of products available from brands such as Klean Strip which are a mixture of other solvents. Paint thinner, lacquer thinner, brush cleaner, etc. will all work as fuel – however, it is important to look up and read the Safety Data Sheet (SDS) for a product to see if it contains methanol or other hazardous substances and take appropriate precautions.

2.6.2 Hydrocarbons

Hydrocarbons are organic compounds which contain only hydrogen and carbon. The most well-known hydrocarbons are the simple, short-chain molecules such as methane, propane, butane, etc. Oil refinement produces a plethora of long-chain molecules which are separated out by weight and classified under various names depending on the composition and average molecular weight.

The most famous hydrocarbon fuel for rockets is RP-1, a highly refined form of kerosene which has a long history of use in many launch vehicles. Because hydrocarbons contain no oxygen of their own, they have higher ideal mixture ratios than organic solvents. For rockets burning nitrous oxide, this means that the mixture ratio needs to be very high due to the relatively low oxygen content of N_2O. This is undesirable for a few reasons including increased cost and oxidizer feed system size. Realistically, organic solvents win out against hydrocarbons in amateur liquid rockets on every count.

The only reason hydrocarbons (namely diesel) are used in Mojave Sphinx is for the fiery, smokey exhaust plume that makes for a visual spectacle in launches.

Diesel

Like E85, diesel can be pumped cheaply from many gas stations. While not exactly the same mixture of hydrocarbons as "actual" kerosene, it is basically kerosene. Its performance is lower than alcohols because of its very high ideal mixture ratio, so diesel's only use is for show. Liquid hydrocarbons like diesel also have the downside that they don't evaporate the way organic solvents do, so it will coat anything it touches in an oily film (including the inside of the plumbing, the outside of the rocket if any spills, hands, tools, etc.). Any other form of kerosene can be substituted in place of diesel.

Jet-A

Jet fuel is another, more pure form of kerosene. Its performance, like any other hydrocarbon, will be low compared to alcohols, and it is not as simple to acquire as diesel. Jet-A was only used in Mojave Sphinx because it was available for free.

Gasoline

Pure gasoline should not be used. It has all the downsides of diesel but the added danger of volatility, meaning that it is always evaporating and creating noxious, flammable vapors.

WD-40

WD-40 was used as a fuel to prove the point that any flammable liquid will work in Mojave Sphinx. It is a proprietary mixture of hydrocarbons, which give it a similar look and performance to kerosene.

Other Light Oils

Although other hydrocarbons have yet to be tried at the time of writing, any light, relatively inviscid oil which burns in air should work as a fuel.

2.6.3 Fuel Additives & Custom Blends

All fuels used in Mojave Sphinx will burn with a natural light orange flame color, which may be indistinct depending on the ambient brightness; in full sunlight, the flame produced by most organic solvent fuels will be largely invisible. Metal salt additives can be used to create brighter and more unique flame colors, which make launches more exciting and visually impressive. All custom blends are typically a mixture of 2% by mass of solute in E85, but they can be made with any alcohol which will dissolve the additive. 2% is mostly arbitrary, but was chosen because it is low enough to be fully soluble in ethanol (or in a small amount of water) but enough to effectively change the flame color. The performance difference compared to unaltered fuel is negligible, and typically not possible to measure within the capabilities of amateur test setups. Higher or lower concentrations of additives may work just as well but have not been tried yet.

Meowjave Green [$B(OH)_3$]

Meowjave Green contains boric acid (also called orthoboric acid, and sometimes sold as roach killer), which delivers a bright green flame from the combustion of boron. It is named in homage to the Aerotech solid propellant *Mojave Green*.

CatPunRed [LiCl]

CatPunRed contains 2% by mass lithium chloride. Its name is the result of a social media suggestion, where the only requirement given was that it include a cat pun. CatPunRed burns a deep red due to the lithium content.

Garfield Gorange [$CaCl_2$]

Garfield Gorange contains calcium chloride, which results in a vibrant orange flame. While most fuels without additives will burn some shade of orange due to luminescence of carbon in the exhaust, standard liquid rocket motors will typically only produce a pale orange plume due to mediocre efficiency. However, the calcium content causes a much more pronounced orange color and makes the Mach diamonds highly visible. It also contrasts well with a blue sky background in photographs.

Tony Torange [NaBr]

Tony Torange was an attempt to make yellow flame with sodium bromide, but it burned a subdued orange instead. It is possible that a different concentration of the colorant, or in combination with other additives, may change the color to be more unique.

Meowrple [KI]

Meowrple contains potassium iodide dissolved in a small amount of water, since it will not readily dissolve in ethanol on its own. Potassium burns purple, although it is a paler color than other blends; in broad daylight, it may appear more white than purple. The additive is also more expensive, although this is relative since a Mojave Sphinx fuel load costs next to nothing.

Other Additives

There are other metal salts and compounds which may offer additional flame colors, but have not been tried yet. Some compounds, like strontium chloride (and potassium iodide), are soluble in a small amount of water, which can then be mixed into ethanol to add the colorant without affecting performance much. In the future, further additives (and mixtures of additives) will undoubtedly be tried in attempts to make other colors, such as blue.

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2.6.4 Fuel Summary

While Mojave Sphinx is truly a "flex fuel" rocket that will accept any flammable liquid, some are more preferable than others. Fuels that require special care to handle should be avoided. Table 2.7 summarizes all fuels which are advisable to use in Mojave Sphinx. Performance varies, and the difference is ultimately minor; although diesel is a relatively low-performing fuel, it will still power the rocket to roughly 80% of its achievable apogee compared to a better fuel such as pure alcohol.

The cost per flight can be found by simply dividing this value by two, as a standard Mojave Sphinx uses exactly half a gallon of fuel per firing. Prices listed are the approximate cost in California at the time of writing, and may not include taxes.

Fuel	Additive, 2% by Mass	Water	Gasoline	Plume Color	$/gal	$/Launch
Isopropanol		<1%		Orange	$30	$15
E98			<2%	Orange	$15	$7.50
E85			15%	Orange	$3	$1.50
Acetone				Orange	$30	$15
Diesel				Black/Yellow	$5	$2.50
Jet-A				Black/Yellow	$7	$3.50
WD-40				Black/Yellow	$30	$15
Meowjave Green	Boric Acid		0-15%	Green	$3	$1.50
CatPunRed	Lithium Chloride		0-15%	Deep Red	$10	$5
Garfield Gorange	Calcium Chloride		0-15%	Vivid Orange	$6	$3
Tony Torange	Sodium Bromide		0-15%	Orange	$6	$3
Meowrple	Potassium Iodide	1.5%	0-15%	Pale Purple	$9	$4.50

Table 2.7: Sphinx Drinks

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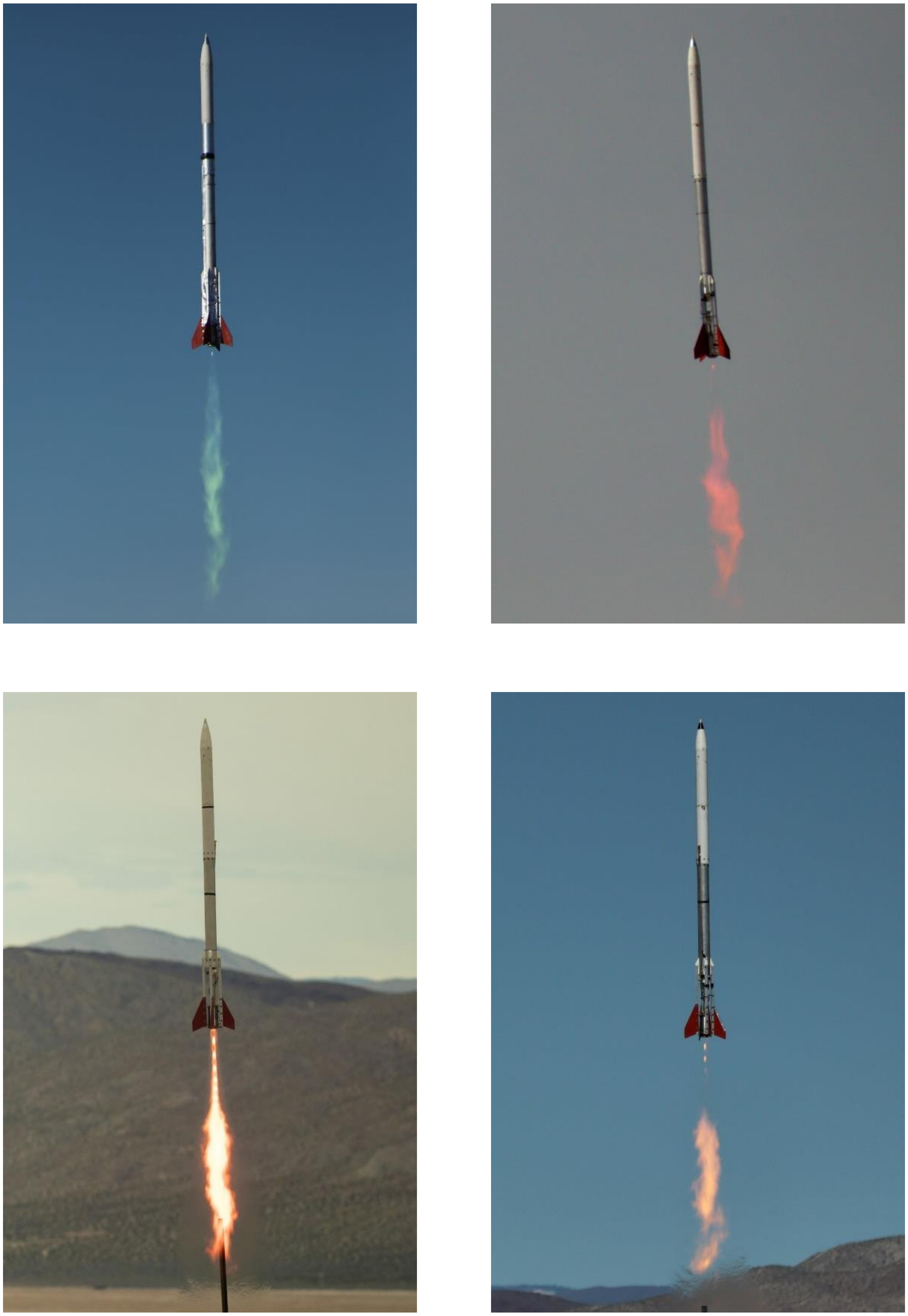

Figure 2.33: Left to right, top to bottom: Meowjave Green, CatPunRed, Garfield Gorange, Tony Torange

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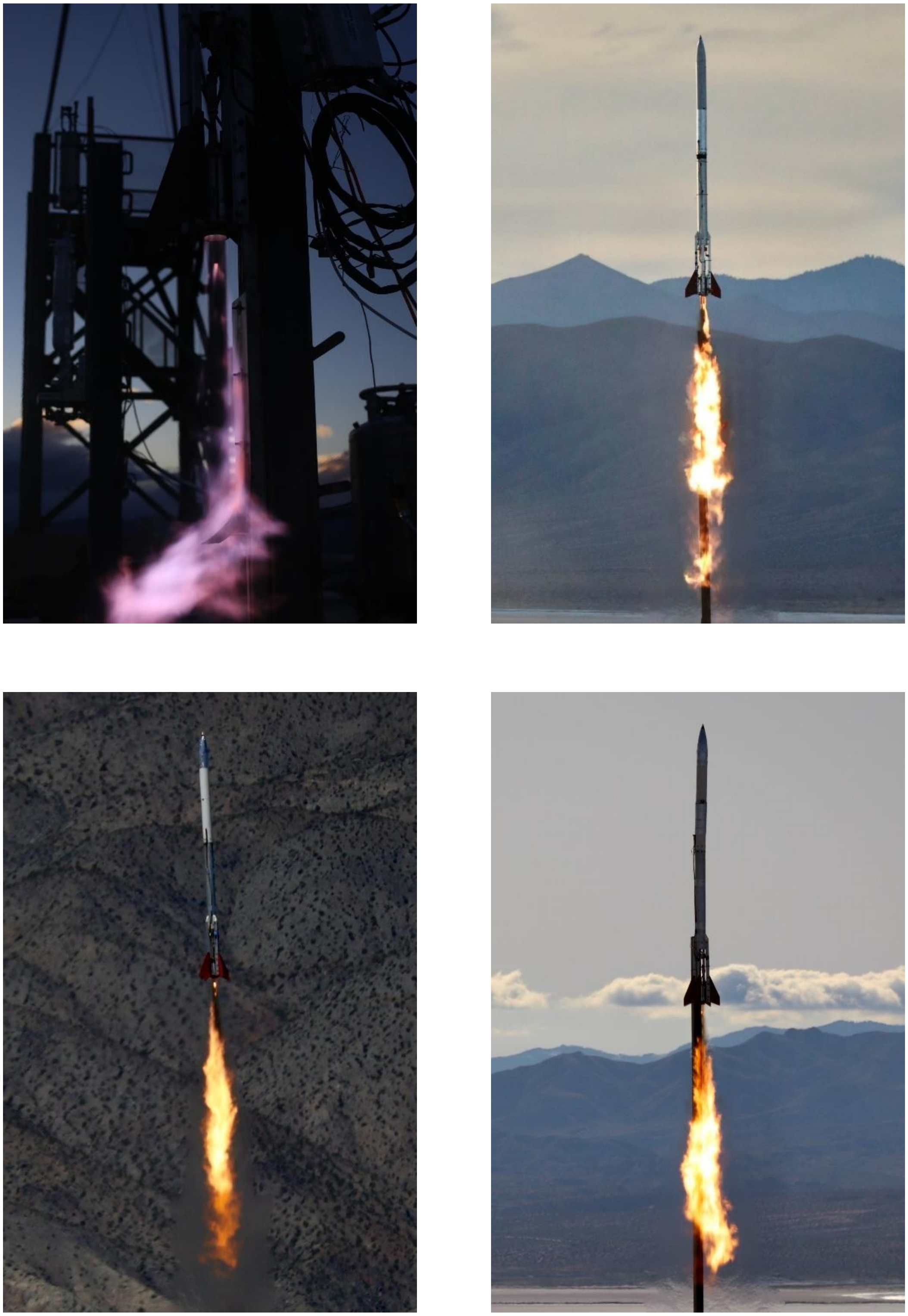


Figure 2.34: Left to right, top to bottom: Meowrple (static test at dusk), Diesel, WD-40, Jet-A

2.7 Maintenance Schedule

Mojave Sphinx is able to be fired and launched dozens of times without major refurbishment, however some minor components can be expected to degrade over time as a result of repeated cycles. This is primarily the case with parts that are repeatedly removed and reinstalled between firings, or are exposed to relatively extreme loading conditions during launch and recovery. Lack of maintenance does not necessarily lead directly to catastrophic failure, but in some cases may result in degraded performance. For example, a worn out oxidizer fill line tube may begin to leak at the push-to-connect fitting, which can result in a lower oxidizer fill level that reduces total impulse and apogee. In contrast, a worn out shock cord can snap during deployment, allowing the propulsion section to fall freely and impact the ground at high speed, suffering major damage. Table 2.9 lists parts that should be replaced on a regular basis, and the expected safe life span of each. An 'OR' statement should be treated as whichever condition comes first; for example, the QD fill tube wears out faster from launches because it may be jerked violently at takeoff and pull on the push-to-connect fittings as the QD clip disconnects.

These maintenance suggestions are based on data gathered from many firings of the Mojave Sphinx prototype, and should be sufficiently conservative estimates to keep the rocket in nominal operating condition. However, always use best judgment to refurbish or replace hardware as needed. Table 2.8 lists inspections which should conducted on the vehicle, and how often to perform each one. Some components' useful lifetimes are a function of time in addition to usage; for example, O-rings exposed to fuel will swell over time, so that they may be unusable even after only one cycle if the rocket has been sitting for more than a few days. More frequent maintenance is always beneficial, and it is generally advisable to replace parts when in doubt.

When conducting multiple flights within the same day, it is also advisable to have spare parts on hand to make repairs or replacements in the field if the rocket is damaged. Damage can occur even under mostly nominal conditions, such as a fin cracking on landing due to impact with a rock or other hard surface. Every part of Mojave Sphinx is designed to be individually replaceable, with the most easily damaged parts being the simplest to replace. Table 2.10 summarizes parts which should be kept on hand as spares.

Inspection	Perform After	Failure Mode Prevented
Check tightness of chamber threaded rods/nuts	Each firing	Hot gas leakage and erosion at chamber/nozzle joint
Verify fuel injector orifices are unobstructed	Each firing	Chamber hot spots or reduced performance due to clogged fuel orifices
Verify igniter pass-through hole is unobstructed and clear as needed	Each firing	Reduced igniter burn time or difficulty installing e-match as a consequence of soot buildup
Check tightness of fin fasteners	Each flight (or firing with fins installed)	Erratic trajectory due to excessive fin deflection in flight

Table 2.8: Recommended inspection schedule for Mojave Sphinx

Component	Replace After	Lack of Maintenance May Cause
Fuel Bulkhead O-Ring	3 firings	Fuel leakage out of tank
Propellant Piston O-Ring	3 firings	Difficulty pushing piston into fuel tank
QD Tube	5 firings	Oxidizer leakage out of tube Inability to full load tank
Shock Cord (if uninsulated)	5 launches	Airframe/propulsion separation on descent
Shock Cord (if insulated)	Tears or serious burns	Airframe/propulsion separation on descent
Graphite Gasket	TCA disassembly	Local melting due to hot gas leakage
TCA Flange Plates	Deformation prevents TCA assembly	Inability to re-assemble TCA

Table 2.9: Replacement schedule for Mojave Sphinx components

Component	Spares to Have	Likely Cause for Replacement
Fins	2	Hard landing
Parachutes (Drogue & Main)	1 each	Off-nominal deployment event
1/4" Nylon Tube	10 feet	Tube segment wearing out
Airframe Tubes	2	Hard landing or shock cord zipper damage
1/4-20 Fastening Hardware	10-20 of each type	Lost during vehicle recycle
O-Rings (all sizes used)	5+ each	Regular maintenance
Graphite Gasket	1	TCA disassembly
9V Altimeter Batteries	2	Installed batteries run out of charge (<8.2V)

Table 2.10: Spare Mojave Sphinx components recommended to be kept on-hand

Section III – Development History

3.1 Summary of Development

Though Half Cat Rocketry has built up sufficient design heritage to be confident in conducting a launch as a first test of a new rocket, static testing nonetheless remains an essential part of the development cycle. The data gathered in static testing allows verification of performance and refinements to flight simulation and HalfCatSim inputs. The large number of static tests conducted with Mojave Sphinx also served to identify and test the implementation of improvements to ease of operation, making the design as user-friendly as possible. Throughout the project – even during the writing of this guide – many small modifications were made to the system before the final configuration was frozen and released. Some of the data provided herein was collected from earlier versions of the Mojave Sphinx design and demonstrates how performance and simplicity can be improved through experimentation and iteration. The end result is the set of data and corresponding hardware described in Section 2.

In general, static tests and launches serve distinct purposes from one another. Static hot-fire tests gather performance data by measuring the key characteristics of the propulsion system, typically including thrust, chamber pressure, and tank pressure. From these values, total and specific impulse can be calculated and compared against predictions from simulation.

Launches, meanwhile, seek to demonstrate the ability of the system to function in the less forgiving environment of free flight, where stresses are less predictable and the consequences of failure are higher. They are also a greater operational challenge, in which the procedures used to prepare the vehicle and ground system are put to the ultimate test. Multiple rapidly successive flights can uncover difficulties in recycling the propulsion and recovery systems that are often not apparent until encountered in the field. In this area Mojave Sphinx has undergone substantial testing, with 18 launches at the time of writing, and up to four conducted within a single day.

Altimeters equipped with an accelerometer can provide a decent approximation of initial thrust and in some cases even be used to reconstruct an entire thrust curve, albeit with lower fidelity than direct measurement using a load cell on a test stand. Altitude and velocity data can help refine modeling of aerodynamic drag, but is ultimately less valuable to the design process than static performance data and operational learnings.

Mojave Sphinx **v1.0** was never static tested, and only launched one time. Despite its distinct appearance compared to later configurations, the v1.0 propulsion system was essentially the same as v1.1. The most notable structural difference is that its thrust chamber was mounted only at the forward end and projected fully aft of the fins, a feature shared with its predecessors, 2Cat/3 and 1Cat/4. This earlier layout reduces stability due to the large mass aft of the fins, and is prone to thrust chamber misalignment.

Mojave Sphinx **v1.1** incorporated the "2x2" style of thrust chamber mounting, along with an extended airframe housing a more traditional dual-deployment system. This configuration underwent two launches and three static tests, informing the design of a new iteration which would improve performance and alleviate pain points encountered during pre-test preparation and recycling of the system.

Mojave Sphinx **v1.2** rolled in the scrintle injector, which drastically improved performance over v.10 and v1.1. The higher combustion temperatures resulting from the improvement to mixing efficiency was observed to cause inconsistent throat erosion, occurring in some tests but not others and ranging widely in severity. This issue was remedied by the addition of a copper throat insert. Additionally, minor upgrades to most of the 3D printed components and the replacement of nylon tubing with braided flex hoses on v1.2 provide easier integration and more rapid turnaround times between successive tests or launches. The v1.2 configuration has accumulated 15 static tests and 15 launches at the time of writing.

3.2 Static Fires

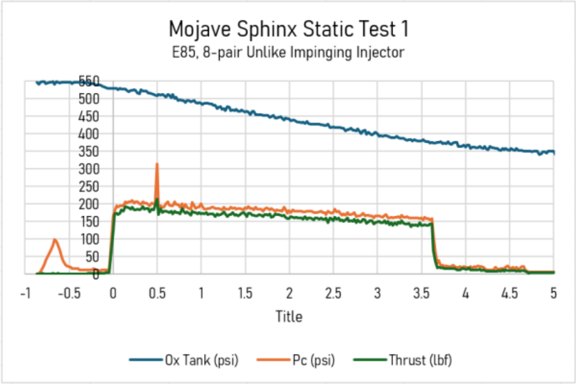
The test setup used for static fires of Mojave Sphinx is rudimentary but robust. The physical structure, nicknamed the "Cat Tower", is a strut channel (a.k.a. Unistrut) backbone with a crossbar at the top and flame deflector at the bottom. The crossbar is a short piece of strut channel bolted on with two custom gusset plates, and serves as the mounting location for the load cell that measures thrust. The flame deflector is a bent piece of 1/8"-thick stainless steel sheet, bolted through the slots in the backbone with a standard 45-degree strut channel bracket supporting it from beneath.

Along the length of the backbone are 3D-printed rocket holders which cradle the outer diameter of the propellant tank and slot securely into the strut channel. These holders have passthroughs for metal hose clamps which are tightened down onto the rocket. Since the thrust load is almost entirely axial into the crossbar, the strength of the printed plastic is sufficient, and the rocket holders allow movement in the axial direction so that they do not bind up and disturb the thrust measurement. Thrust is transferred to the load cell through an aluminum spacer block, which is fastened to the bottom of the load cell and contacts the edge of the forward retaining ring on the propellant tank. This interface is typically secured with zip tie, strong enough to hold the weight of the rocket hanging in tension but trivial to cut when the rocket needs to be removed.

See Appendix A for more information about static testing Mojave Sphinx.

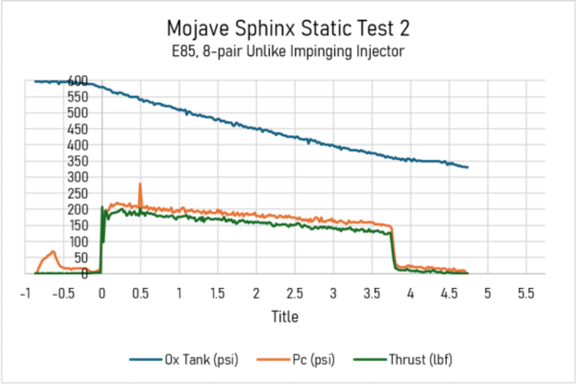
Figure 3.1: Mojave Sphinx in Cat Tower test stand, attached to the FAR medium I-beam

3.2.1 Test 1 | 2,716 N·s | 04 Nov 2023



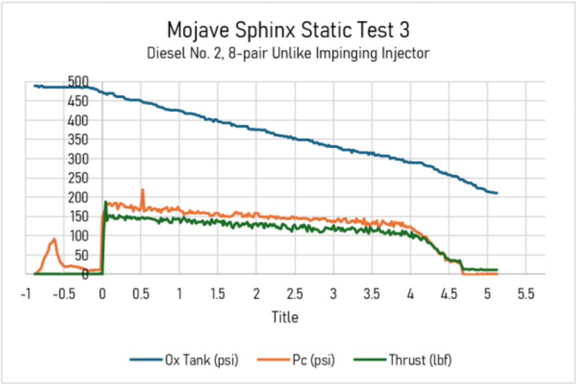
No anomalies or abnormal phenomena were observed in this first static test compared to the three launches that preceded it. This test did uncover that the performance of Mojave Sphinx v1.0 unlike impinging doublet injector was lower than predicted by approximately half, which was evidenced by the low apogees achieved thus far. White streaks visible in the almost completely transparent exhaust at the nozzle exit indicated the presence of uncombusted propellant, believed to be an undecomposed portion of the nitrous oxide that passed through the chamber without participating in the reaction.

3.2.2 Test 2 | 2,723 N·s | 04 Nov 2023



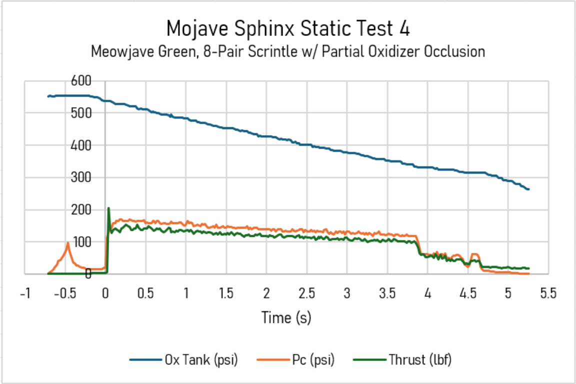
The data from the second static test was consistent with the first, and white streaks of uncombusted propellant were again visible exiting the nozzle within an almost invisible flame. The temperature-indicating sticker placed on the chamber reported a maximum external temperature of only 180°F, corroborating the theory that poor mixing efficiency was resulting in a relatively low chamber temperature.

3.2.3 Test 3 | 2,464 N·s | 04 Nov 2023



For the third test, the rocket was loaded with diesel fuel in an attempt to produce a brighter and more visible flame. Though partially successful in that regard, the inefficiency of the impinging injector produced a large volume of grayish-white smoke, attributed to the uncombusted portion of the fuel.

3.2.4 Test 4 | 2,429 N·s | 18 Nov 2023



For the fourth test, the injector was modified with a scrintle, by placing a countersunk head screw in the center of the ring of oxidizer orifices, partially occluding them. The hope was that this would improve atomization and mixing by deflecting some of the oxidizer outwards, leading to better performance. However, the thrust and total impulse were nearly identical to the previous tests, and it was concluded that partial deflection of the oxidizer streams was insufficient to prevent much of the nitrous from simply being ejected through the chamber.

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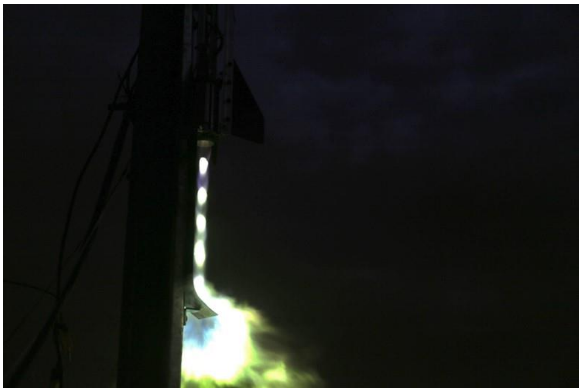
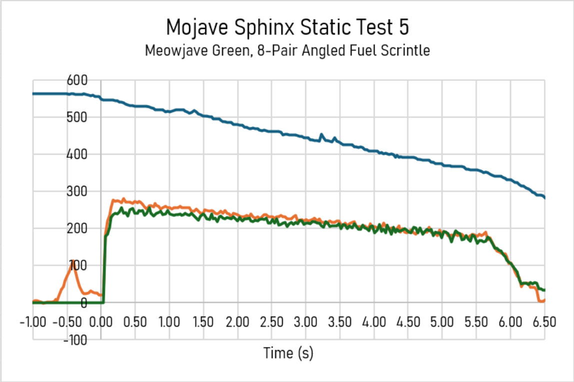
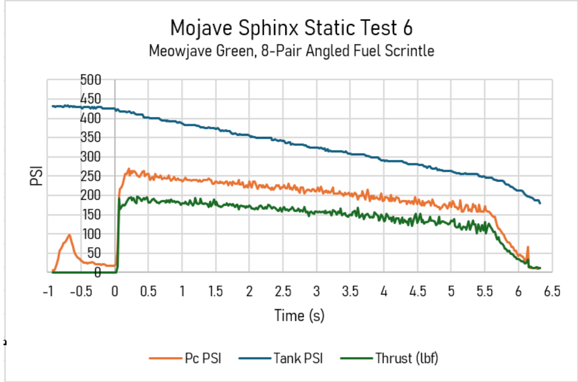
3.2.5 Test 5 | 6,080 N·s | 18 Nov 2023





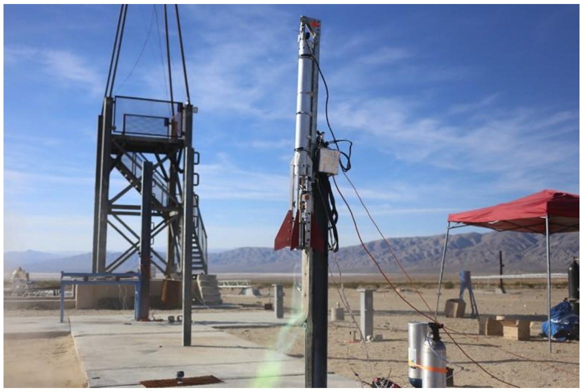
Following Test 4, an on-the-fly modification was made to the injector to increase radial deflection of the oxidizer. The scrintle was extracted and replaced with a button head screw and washer found in the FAR workshop, with the washer completely occluding the oxidizer orifices to ensure all flow was forced outwards to collide with the fuel streams. This simple change was an immediate success, doubling the thrust to approximately 300 lbf and producing distinct Mach diamonds in the late dusk, their vivid green color due to boric acid mixed into the fuel.

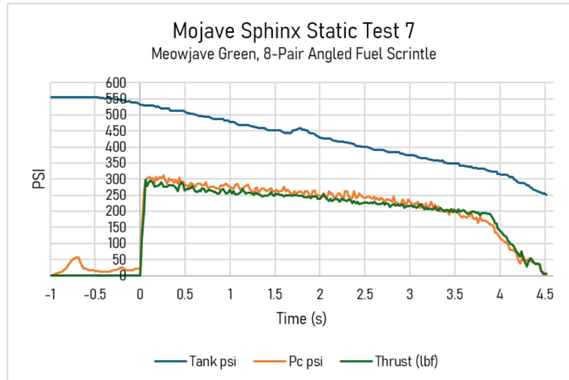
3.2.6 Test 6 | 4,077 N·s | 02 Dec 2023



Test 6 was essentially a repeat of Test 5, but with a wide-head screw replacing the button head screw and washer. The results were consistent, with identical performance adjusted for temperature conditions.

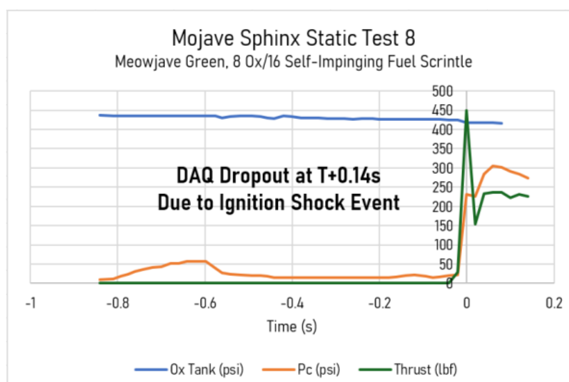
3.2.7 Test 7 | 4,362 N·s | 02 Dec 2023





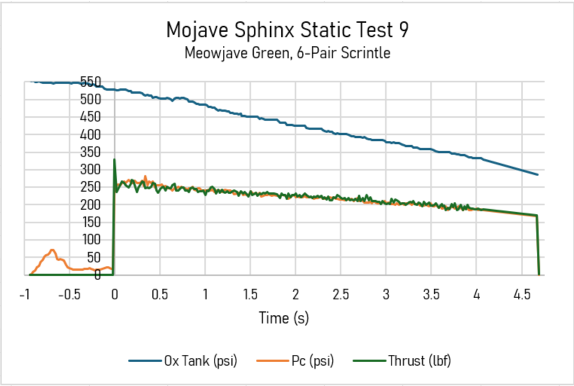
The launch following Test 6 and preceding Test 7 resulted in minor erosion of the aluminum nozzle throat, despite occurring on the same day under the same conditions and in an identical hardware configuration. Prior to Test 7, the thrust chamber assembly was swapped out for a spare unit. This test experienced much more severe nozzle erosion, in addition to a hot gas leak at the chamber-nozzle interface due to insufficient compression of the graphite gasket, although this is believed to be unrelated to the throat erosion. Notably, the structure of the exhaust plume was significantly different from previous tests, with a larger bubble-like shock pattern rather than small bright Mach diamonds. This suggests a higher than nominal OF ratio; further analysis indicated that low nitrous temperatures and higher than expected pressure drop in the fuel system could shift the OF as high as 2.6 (well above the nominal design point of 2.2).

3.2.8 Test 8 | 5,275 N·s | 16 Dec 2023



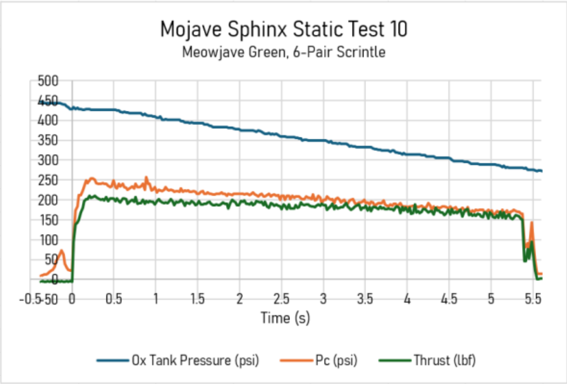
A new injector was made for Test 8 which lowered the mixture ratio closer to the original design point of 2.2. However, this test again showed severe melting of the aluminum throat. This may have been at least partially attributable to swelling and rolling of the tank piston O-rings –which had not been replaced for several firings– significantly increasing friction when under pressure, reducing the flow rate of fuel into the chamber.

3.2.9 Test 9 | 4,533 N-s | 16 Dec 2023



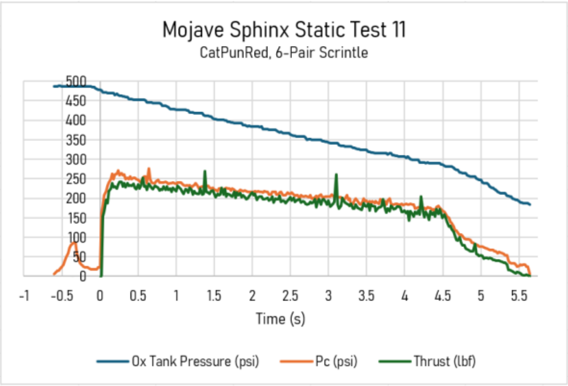
Prior to Test 9, the tank piston was removed and the O-rings replaced and re-lubricated. Performance was consistent with the previous four tests, and the throat only slightly eroded. This lent some credence to the tank piston O-ring theory, although a definitive root cause was never identified for why throat erosion had occurred on some tests but not others (much later, a more plausible theory was put forward that boric acid buildup in the fuel injector caused a mixture ratio shift – see Section 3.4).

3.2.10 Test 10 | 4,393 N-s | 17 Feb 2024



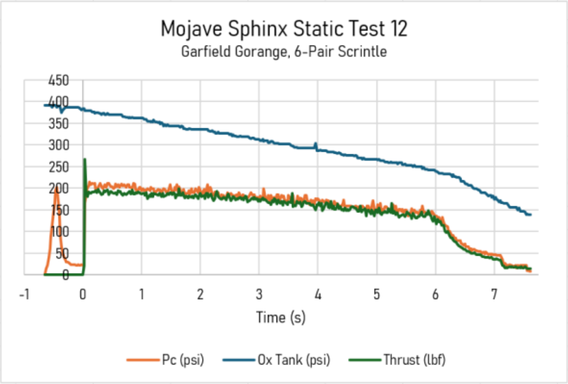
Test 10 was the first to use a copper throat insert, which was incorporated into the thrust chamber design to sidestep the issue of throat erosion. This test also gathered data on the final baseline injector for Mojave Sphinx v1.2, which is optimized for manufacturability at the expense of somewhat reduced performance (200-250 lbf). Test 10 performed nominally, with no erosion of the copper nozzle throat.

3.2.11 Test 11 | 4,231 N·s | 17 Feb 2024



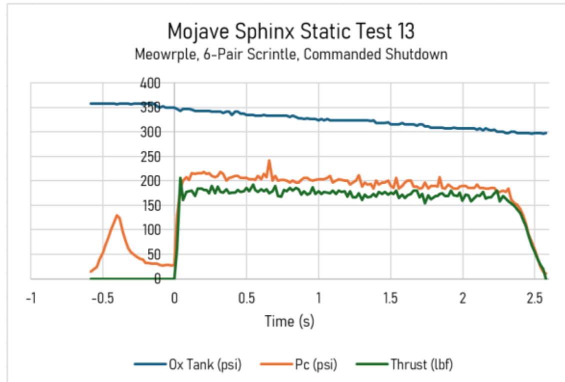
Test 11 demonstrated a new fuel blend, dubbed CatPunRed, consisting of E98 with 2% Lithium Chloride to produce a deep red flame color. The oxidizer was depleted slightly earlier than in Test 10, indicated by the transition from linear to exponential decay in oxidizer pressure with the start of gas blowdown. Although the rocket was filled for the same duration as previous tests (60 seconds), the oxidizer tank was not fully loaded due to a combination of a partially depleted supply bottle and a leak in the fill system that was discovered after the fact.

3.2.12 Test 12 | 4,852 N·s | 02 Mar 2024



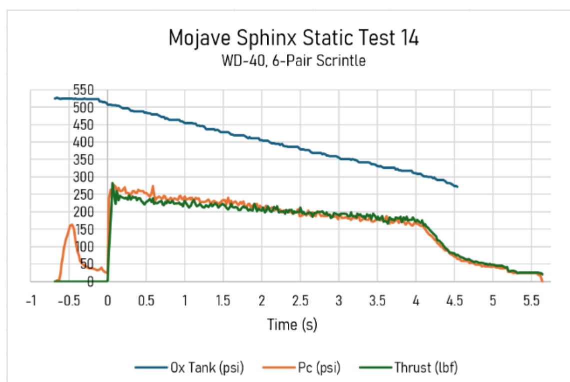
Test 12 debuted another visually spectacular fuel blend, named Garfield Gorange (E85 + 2% Calcium Chloride). Performance was nominal, and the CaCl produced a vibrant orange flame that accentuated the Mach diamonds in the exhaust. Prior to this test, an attempt was made to ignite the motor using only a glow plug made for diesel tractor engines, with the tip extending into the chamber from the injector face. However, the glow plug did not provide sufficient thermal energy to begin nitrous decomposition and combustion, and the chamber was swapped back to the standard design with a solid motor cartridge igniter for Test 12.

3.2.13 Test 13 | 1,889 N·s | 02 Mar 2024



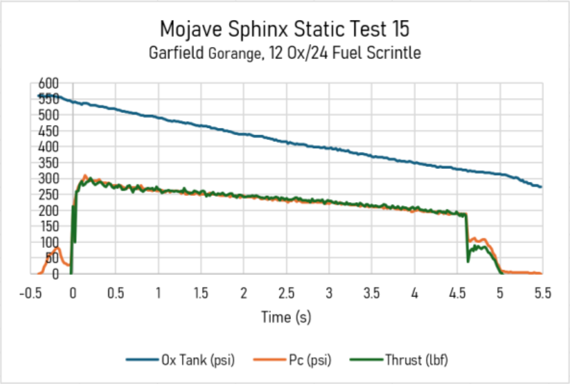
Test 13 introduced Meowrple (E98 + Potassium Iodide), creating a purple-hued flame reminiscent of methane-oxygen engines. This test was also the first demonstration of a commanded shutdown– the valves were closed three seconds after ignition, rather than allowing the propellant to deplete. A few seconds later, the valves were re-opened and the remaining propellant was dumped through the chamber, which was not sufficiently hot to cause reignition.

3.2.14 Test 14 | 4,175 N·s | 20 Apr 2024



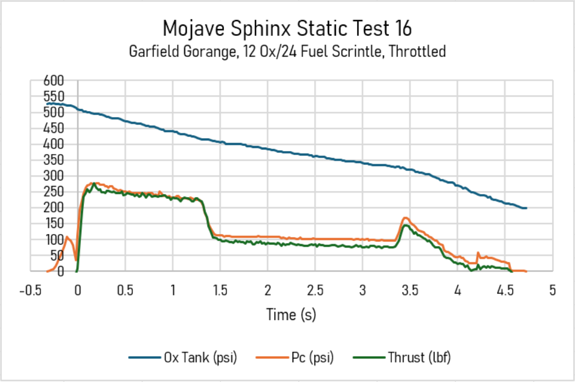
Test 14 marked the second firing of Mojave Sphinx to use WD-40 as fuel, the first being Launch 12. Initial thrust was in-family with previous tests using the basic 6-pair scrintle injector, however total impulse was reduced somewhat by significant erosion of the copper nozzle throat insert for the first time in the 8 firings since its introduction. Very minor localized erosion had been noted following launch 14 and had spread to a larger area after launch 15, though it manifested primarily as increased roughness with negligible impact on throat area. This roughness causes a dramatic increase in heat transfer from the exhaust, leading to the exponentially worse erosion in Test 14, after which replacement was required. This suggests a finite lifespan of the copper insert, particularly when using hotter-burning hydrocarbon fuels.

3.2.15 Test 15 | 4,992 N·s | 04 May 2024



Test 15 was a nominal firing of the higher-performing basic injector, using Garfield Gorange fuel, and it was the first of five static tests that day.

3.2.16 Test 16 | 2,466 N·s | 04 May 2024



Test 16 was the first throttle test, where the propellant valves were partially closed for a portion of the burn. This showed that it was possible to get a mostly flat thrust curve during throttle-down from a self-pressurized, otherwise passively operating liquid motor, with no detrimental effects aside from a slight loss of efficiency. The throttle was commanded back to full open just prior to propellant depletion.

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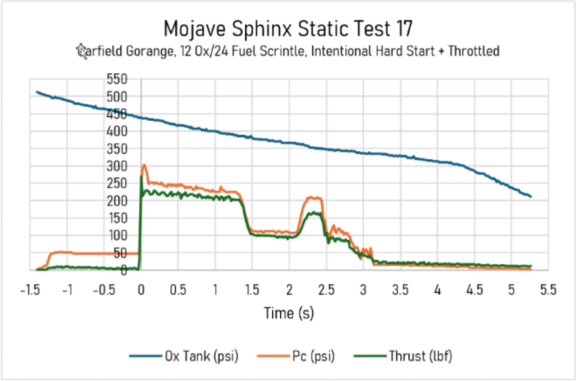
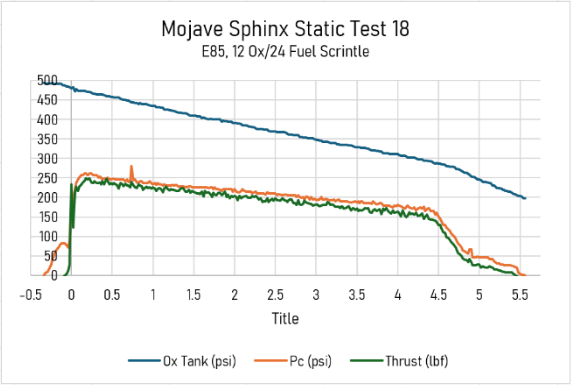
3.2.17 Test 17 | 2,258 N·s | 04 May 2024



Test 17, an intentional hard-start test, aimed to prove that the chamber would not take damage in the case that the igniter fired late. In this test, the propellant valves were opened and allowed to develop full flow before the igniter was triggered. After a short delay while the igniter started, combustion initiated and caused a brief spike in chamber pressure. No damage was observed in the chamber, and no fires were started externally (some fuel, aerosolized during the initial dump, can be seen rapidly flaming off in a few frames of video). After startup, the motor was briefly throttled down and brought back up again. Several observers believed that there had been an issue in this test due to the strange sequence, but all was nominal.

3.2.18 Test 18 | 4,118 N·s | 04 May 2024



Test 18 was a nominal firing, where the fuel was pure E85 without additives so that the natural flame color could be observed. Additionally, the ejection charge of the Estes A3-4 igniter motor was left intact to see what effect the brief pressure spike would have on the combustion chamber; only a puff of smoke was observed in the exhaust.

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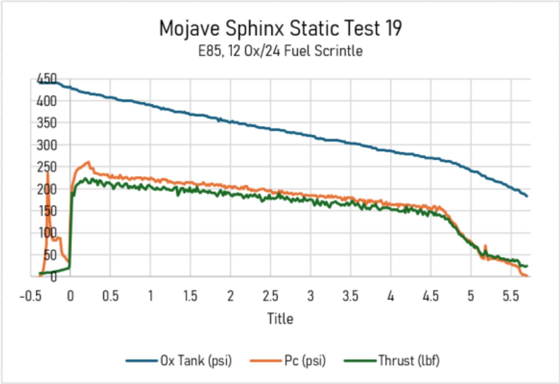
3.2.19 Test 19 | 4,046 N·s | 04 May 2024



Test 19 was a repeat of Test 18, but with the ejection charge removed as normally done. More performance and pressure data were gathered along with further operational heritage.

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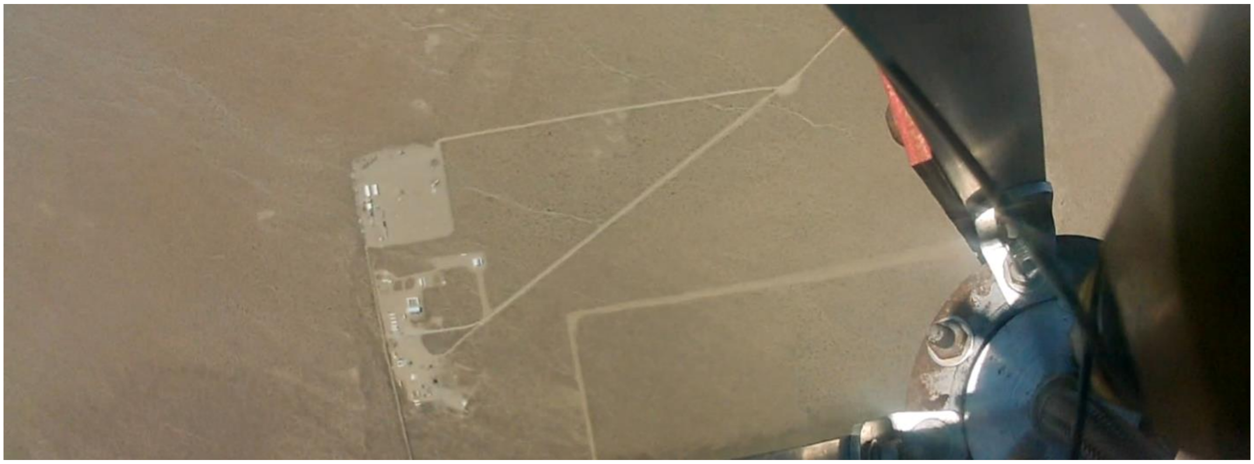
3.3 Launches

Launching is the most exciting part of a rocket project, and it is ultimately the goal of Half Cat Rocketry. Without launches, the cost and complexity reductions merely lead to an interesting benchtop demonstration of propulsion principles. The system truly shines out in the field: At the time of writing, no other liquid rocket is able to launch as fast, as often, or as cheaply as Mojave Sphinx. In fact, this rocket routinely outpaces commercial solid motors – partly due to not requiring any motor rebuild after firing, and partly because it has never had an ignition failure. The cost factor by itself is a strong argument compared to solid motors, since this is an L- or M-class rocket launched for $55 per flight (at the time of writing, a comparable Aerotech reload would cost about $380, before considering shipping, handling, and the price of the casing hardware).

All Mojave Sphinx launches are conducted at FAR from one of the 20-foot launch rails, which are 1.5" T-slot aluminum extrusion (a.k.a. 8020-brand 1515 extrusion). Launch control is handled from either the launch table by FAR's Mission Control container or a nearby bunker that provides visibility to the launchpad. Each launch, with temperature variation and venting losses considered, uses up to 10 lbs of N_2O. Therefore, a 10-lb supply bottle provides one "shot" and a 20-lb bottle two shots of oxidizer. Sometimes, two bottles with individually less than 10 lbs are connected in parallel to provide a full shot for a launch attempt. The fuel for any particular launch is usually selected day-of, depending on expectations for the number of launches to be conducted. A non-insignificant purpose of Mojave Sphinx launches is to spread the word of simple but effective liquid bipropellant rockets by prominently demonstrating efficient launch operations, fuel flexibility, and rapid turnaround time.

Mojave Sphinx launches are a crowd-pleaser at FAR because liquid rocket launches are still relatively rare, and Mojave Sphinx takes off with a sight and sound that is hard to find in a solid rocket: The flame may be bright red, green, or orange and totally without smoke, a stark contrast to the clear blue sky, with a satisfying rumble; or, the plume may be a brilliant yellow shrouded in dark smoke, with a loud crackle reminiscent of Falcon 9 and Atlas 5 orbital launches. Excitement is always guaranteed, and it often leaves newcomers to FAR with the reaction, *"Wow! That was a liquid rocket?"*

Mojave Sphinx will continue development in the future, and visitors to FAR will be able to witness launches of either the prototype vehicle or a newer build of the same design. It is the hope of Half Cat Rocketry that this guide inspires the creation of both "clones," those built directly from the guidebook, and "inspirations," rockets derived from the design which improve upon it or try out new techniques and technologies. In any scenario, it will be a great achievement for the work done on Mojave Sphinx to improve the number of liquid rocket projects and make them a regular feature of launch events.



3.3.1 Launch 1 | 2,589 feet | 15 Jul 2023

The first launch took place on a hot day in mid July, with nitrous tank pressures of over 1,000psi shortening the burn time to about 3 seconds. This was the first firing of Mojave Sphinx, before any static testing had been conducted; it was also the only firing of the original v1.0 configuration. Despite the low performance of the original 8-pair unlike-impinging injector, the rocket successfully lifted off the pad, a string of faint orange mach diamonds from the unmodified E85 visible in its exhaust. Unfortunately, the ejection charges failed to separate the airframe. The rocket fell and impacted sideways, incurring moderate damage to the airframe and plumbing. All major components survived and were reused in the subsequent v1.1 configuration.

3.3.2 Launch 2 | 3,595 feet | 07 Oct 2023

The second launch achieved similar performance of the propulsion system to the first, but reached a higher apogee with the longer yet lighter-weight v1.1 airframe. Though the recovery system deployed nominally, one of the plywood fins was damaged on landing. This provided the first of several demonstrations of how easily this type of rocket can be refurbished by rapidly replacing a component in the field.

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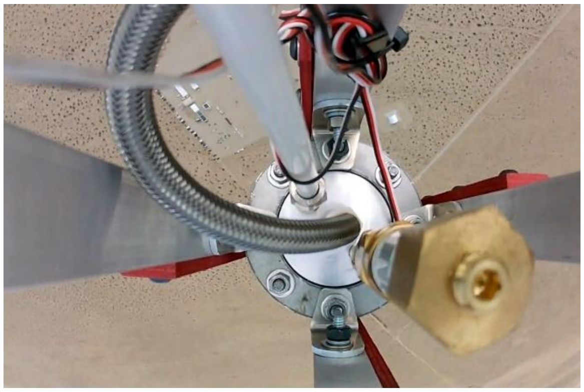
3.3.3 Launch 3 | 1,800 feet | 18 Nov 2023



The third launch occurred between Test 4 and Test 5, and was the last firing before the injector performance was dramatically improved. Ground winds of just under 20mph caused the rocket to weathercock significantly. Despite the low apogee, a unique view was captured from inside the base of the rocket thanks to an onboard camera fastened to the primary structure.

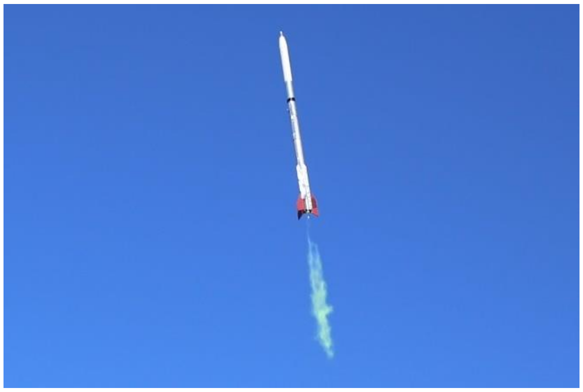
3.3.4 Launch 4 | 6,181 feet | 02 Dec 2023

Following the modification of the injector to the higher-performing scrintle configuration, Mojave Sphinx took off with a bright green plume thanks to the addition of boric acid to the fuel. The roughly-doubling of the total impulse afforded a much higher apogee as well, demonstrating the potential of the Mojave Sphinx design to deliver competitive performance.

3.3.5 Launch 5 | 1,200 feet | 16 Dec 2023

The fifth launch was performed with diesel (kerosene) for a bright and smokey plume effect. A combination of the lower performance of diesel as a fuel, high roll rates induced by an externally-mounted camera, and a relatively loose fit between the avbay coupler and airframe caused the vehicle to begin tumbling partway through the burn, shortly after which it coasted to a reduced apogee and successfully deployed its recovery system. The aforementioned camera captured an excellent view of the exhaust just inches from the nozzle exit.

3.3.6 Launch 6 | 6,359 feet | 06 Jan 2024



Launch 6 was the first of three launches conducted in a single day, and the first launch at FAR in 2024 – an auspicious start to the year, and a sign of many more nitrous-alcohol liquid bipropellant launches to come. This flight featured aerodynamic "panels" covering the gaps between thrust structure brackets, which were really just strips of aluminum tape. The reduction in drag as well as a slightly higher performing injector (8 oxidizer orifices with a scrintle and 8 self-impinging pairs of fuel orifices) yielded a modest improvement in apogee. A nominal recovery enabled the rocket to be rapidly recycled for the next launch.

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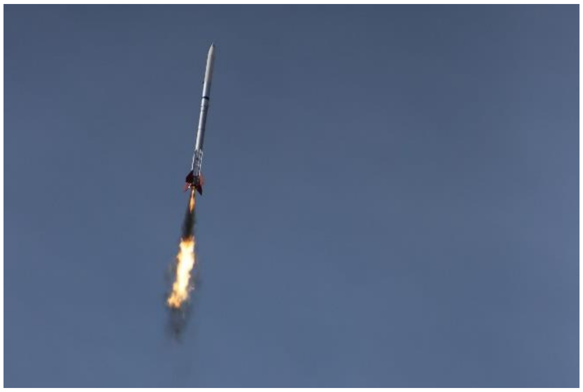
3.3.7 Launch 7 | 5,765 feet | 06 Jan 2024



For the second of three launches that day, Mojave Sphinx went up again on diesel. A small amount of Meowjave Green fuel was added to the fuel tank, floating on top of the kerosene thanks to its lower density and the immiscibility of the two liquids. This added a green tinge to the plume at startup, visible in some photographs. Without the issues present on Launch 5, the rocket flew stably to a respectable apogee, demonstrating the viability of diesel as a crowd-pleasing fuel choice.

3.3.8 Launch 8 | 6,453 feet | 06 Jan 2024

06 January 2024

Launch 8 marked the second occasion on which an amateur liquid rocket had flown three times in a single day, preceded by the much smaller 1Cat/4 in December of 2022. While the drogue deployed nominally at apogee, excessive spinning during descent led to a failed main deployment. Compounding this misfortune, the rocket impacted onto a large metal pole at the RRS site, crumpling the thrust structure and damaging the plumbing; the tank and chamber were unharmed. Repair required only the replacement of the aluminum angles and a plywood fin, a handful of new fittings, and a fresh cardboard airframe tube. This launch day demonstrated the rapid turnaround time possible with a simple liquid rocket architecture, as well as the advantages of using inexpensive and easily replaceable components.

3.3.9 Launch 9 | 5,285 feet | 17 Feb 2024

Launch 9 was the first flight with the simplified injector which is recommended as the baseline in this guide: a 6-pair scrintle with straight fuel orifices rather than angled. The rocket reached just over one mile in altitude, demonstrating an attractive balance between performance and manufacturing simplicity. The CatPunRed fuel blend burned with a clean red flame, clearly visible against a bright but hazy sky. Recovery was nominal, and the first use of a low-cost 7-foot main parachute fabricated from a lightweight hexagonal tent tarp.

3.3.10 Launch 10 | 6,850 feet | 16 Mar 2024

Launch 10 tested a higher-performing variant of the baseline injector, with 12 oxidizer orifices and 24 straight fuel orifices. The fuel blend used was Garfield Gorange, which made a spectacularly bright and well-defined orange flame. Both parachutes deployed, but the nylon shock cord snapped due to cumulative degradation from exposure to ejection charges without insulation. The propulsion section fell in a flat spin, suffering only minor damage on impact. Though an undesirable outcome, the shock cord failure served to inform improvements to the recommended maintenance schedule for a frequently-flown Mojave Sphinx.

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3.3.11 Launch 11 | 6,400 feet | 07 Apr 2024

Launch 11 debuted yet another fuel additive blend, dubbed Tony Torange. Thanks to ideal weather conditions, the simplified baseline (6-pair scrintle) injector lofted the rocket to nearly the same apogee as previous higher-performing variants. The drogue deployed nominally, but excessive friction from tape used to shim the coupler joint caused the airframe to bind, and the charges to blow out the forward end of the heavily-used cardboard airframe tube rather than ejecting the main parachute. After a quick replacement of one cracked fin, a sheared fitting on the oxidizer tank outlet, and the cardboard airframe tube, the rocket was prepped for its next flight.

3.3.12 Launch 12 | 5,800 feet | 07 Apr 2024

Launch 12 featured a long-planned and highly-anticipated fuel: WD-40. The beloved multi-purpose lubricant and corrosion inhibitor was poured straight from its (non-aerosol) 1-gallon can into the fuel tank of Mojave Sphinx. The spectacle of this unusual fueling process before a small crowd of onlookers garnered reactions ranging from delight to bemused skepticism, as well as outright befuddlement from some following along on social media. The flame produced was similar to that of diesel but surprisingly less sooty, and the apogee was almost identical to Launch 7. Recovery was nominal, and the rocket was immediately prepared for yet another launch.

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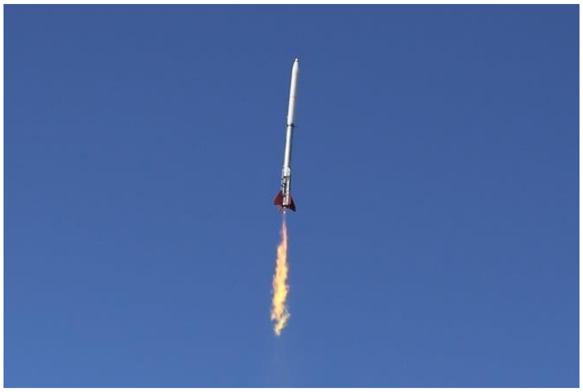
3.3.13 Launch 13 | 950 feet | 07 Apr 2024

Launch 13, as superstition would have it, involved an intriguing albeit relatively harmless anomaly. The ground support system had previously been configured to include an optional throttled state in which the valves would be commanded to open only about halfway, with the intent of testing this functionality in a static test. During the countdown for Launch 13, the controller was accidentally misconfigured, causing the rocket to start up in the throttled state. Upon ignition the rocket failed to lift off, as the throttled thrust was evidently less than the weight of the rocket combined with the friction of the rail guides. The vehicle operator recognized the error and was able to manually command the valves to fully open, as the vehicle was still connected to the GSE. At this point the rocket took off with about two seconds remaining in the burn, reaching a reduced apogee from which it was successfully recovered.

3.3.14 Launch 14 | 1,900 feet | 07 Apr 2024

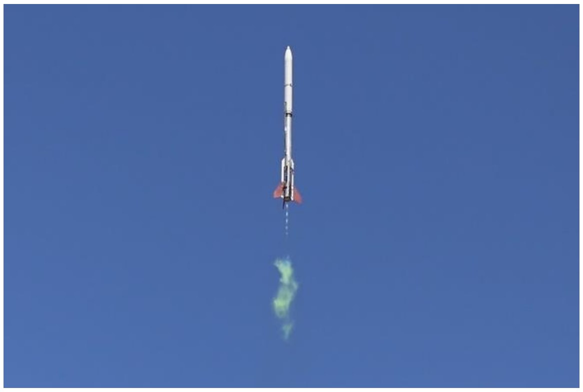
Launch 14 took place immediately following Launch 13, with a turnaround time of just 27 minutes from recovery to launch readiness. This was also the first time Mojave Sphinx had been fueled with Jet-A, which produced a moderately sooty orange flame very similar to WD-40. The airframe coupler joint was looser than usual due to minor damage to the cardboard tube; this caused significant corkscrewing similar to that seen on Launch 5, hence the low apogee. The rocket nonetheless held together and successfully deployed both parachutes, marking the first time that an amateur liquid rocket had completed four launches in a single day.

3.3.15 Launch 15 | 5,263 feet | 20 Apr 2024



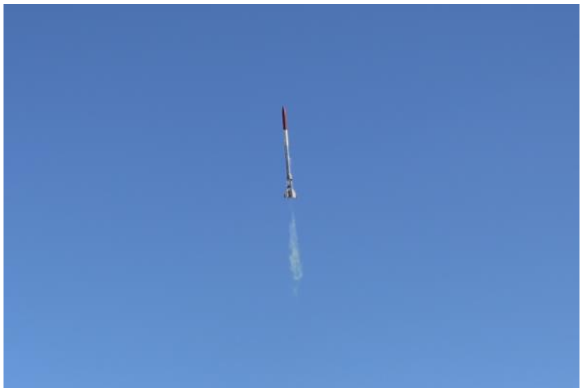
Launch 15 was performed with a mixture of Meowjave Green and Garfield Gorange fuel blends, in the hopes of creating a green and orange flame; as shown, the $CaCl_2$ overpowered the boric acid, resulting in a predominantly orange plume. The rocket reached a nominal apogee on the baseline injector (6-pair scrintle) and the recovery system deployed nominally.

3.3.16 Launch 16 | 3,600 feet | 18 May 2024



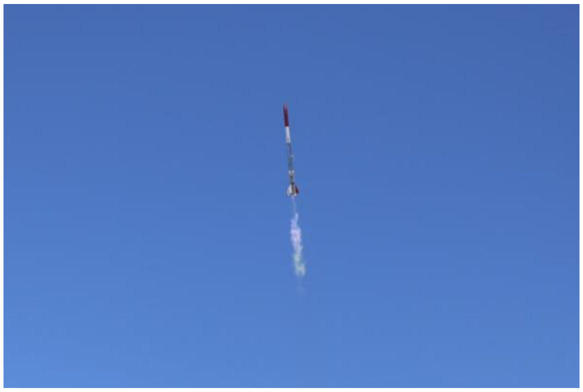
Launch 16 achieved a lower than typical apogee as a result of filling from a partially empty 10 lb nitrous supply tank. The ascent and recovery were otherwise nominal, with the Meowjave Green fuel producing distinct Mach diamonds and afterburning.

3.3.15 Launch 17 | 4,598 feet | 20 Jul 2024 [SN02]



This launch was an attempted drag race between Mojave Sphinx SN01 and SN02, which was christened *Half Cat Walking II* with special livery in homage to Half Cat Rocketry's first liquid rocket. Due to ongoing issues with the fuel feed system of *Mojave Sphinx* (see Section 3.4 – Excess Fuel Additive Impaction), that rocket did not achieve ignition, and afterward the fuel injection manifold was found to still be partially clogged with boric acid. The ascent of *Half Cat Walking II* was nominal, although the main parachute deployed at apogee. This was identified to be the result of improper shear pin slot sizing on the avbay coupler, and a correction was made to the model. The apogee, spot-on to the prediction of Table 2.6, was good confirmation of simulation accuracy (Table 2.6 was determined months before this flight).

3.3.16 Launch 18 | 1,363 feet | 20 Jul 2024 [SN02]



A second attempt of the drag race was made later in the same day as Launch 17, with the same result: No ignition of *Mojave Sphinx*, and a nominal liftoff of *Half Cat Walking II*, albeit with a short burn time and low apogee due to a partial oxidizer load. Upon drogue ejection, the rocket experienced a recovery system anomaly in which the plywood aft avbay bulkhead split along its plies. The propulsion section then separated from the airframe and main parachute, impacting tail-first under drogue. This failure mode had not occurred in any of the preceding 15 launches of *Mojave Sphinx* nor the previous launch of *Half Cat Walking II*, however the plywood used for this bulkhead was from an alternate source and may have been of lower quality. Regardless, the recommended material for the bulkheads was changed to aluminum to prevent recurrence.

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Additionally, upon recovering the airframe assembly one section of the nose cone was found to be severely deformed due to ambient temperatures in excess of 110°F and full sun. (see Section 3.4 – Heat Warpage of Printed Components). The ignition failure of *Mojave Sphinx* may be attributable to continued clogging of fuel orifices or other deviations from the nominal configuration described in this guidebook, as it had undergone substantial experimental modification to the thrust chamber assembly. Damage to the *Half Cat Walking II* propulsion section was limited to the fins, thrust structure brackets, and cardboard lower airframe tube, all of which are easily replaceable thanks to the modular design.

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3.4 Miscellaneous Observations

Half Cat Rocketry often deliberately pushes the envelope to find out just how much physical abuse a standard liquid rocket can take and still function. Such a punishing testing regimen (for example, several consecutive launches and/or static tests in the span of a few hours) demonstrates the rocket's ability to withstand less-than-gentle handling, as well as rapidly building up a substantial body of data on which to base recommendations such as the maintenance schedule in Section 2.7.

Throughout the development of Mojave Sphinx, the authors encountered a number of unusual scenarios resulting from the system's behavior under suboptimal conditions. These observations generally do not warrant a dedicated section of this guide or any specific design changes, but did inform some aspects of the operation and documentation of Mojave Sphinx. They are relayed here mainly as interesting anecdotes which may offer some insights to the reader.

3.4.1 Airframe Tube Life Limits

Mojave Sphinx SN01's lower airframe tube was damaged and replaced so many times in development that it may well be considered a consumable item. On average, each tube survived only about two launches before being bent or zippered, although this has been somewhat mitigated by improvements over the earlier recovery system. Fortunately, this component is very easy and inexpensive to fabricate, making it feasible to keep a stock of spares on hand.

Degradation of the lower airframe tube is a leading cause of "noodling," when the vehicle becomes slightly floppy due to creases, tears, or delamination of the cardboard reducing its stiffness. Tubes that have been mildly "crunkled" may be acceptable to re-fly, but usually result in increased corkscrewing of the vehicle in flight that can range from inconsequential to quite dramatic, depending on the degree of damage.

Lower airframe tube damage most often occurs during landings when the tube impacts the ground as the rocket tips over following the initial touchdown on the fins, even with nominal recovery system deployment. A violent parachute deployment caused by high winds or a non-bundled shock cord can have similar effects, as well as "zippering" the tube.

The upper airframe tube is far more resilient to damage because it descends only attached to the nosecone rather than being rigidly coupled to the heavy propulsion system, as is the case for the lower tube. The only instance of upper airframe tube damage occurred on that tube's tenth flight, when the main ejection charge blew out the side of the tube instead of separating it from the avbay. This was caused by a combination of tube fatigue and packing the main parachute compartment too tight.

3.4.2 Aerodynamic Limits

Mojave Sphinx normally flies with no panels over the plumbing, which negatively impacts its apogee but otherwise causes no issues. The vehicle also has a number of small components protruding into the airflow such as zip ties, fastener heads, the fuel downcomer, and often a radio tracking beacon affixed to the exterior of the thrust structure with tape. The off-axis drag from such small items is negligible, but larger asymmetric protuberances such as GoPro-style cameras can lead to significant precession.

Figure 3.2: GoPro-style camera mounted to Mojave Sphinx

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The phenomenon, combined with a slightly damaged lower airframe tube, contributed to the erratic flight path seen in Launch 5. Any similarly large cameras or other items attached to the exterior of the vehicle should be oriented such that they will not induce roll and should ideally be balanced out by an identical source of drag on the opposite side.

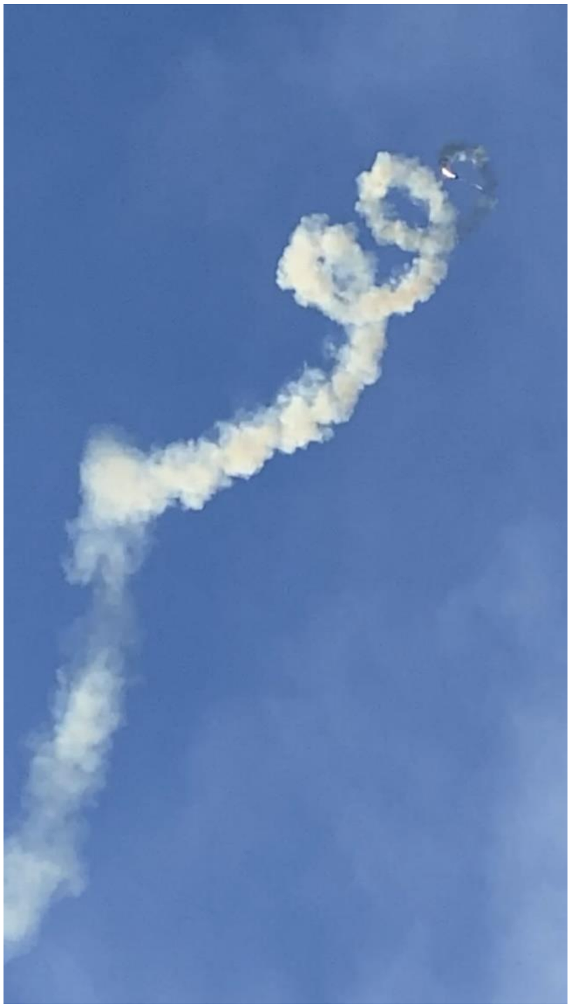

Figure 3.3: Mojave Sphinx Launch 5 erratic flight path

3.4.3 Piston O-Ring Interpropellant Leakage

As far back as the original Half Cat Walking liquid rocket, there was occasional evidence of slight leakage across the propellant piston O-ring seals. Potential minor cross-contamination between tanks has not caused issues thus far in over 50 tests and launches of nitrous liquid rockets; it is unlikely to lead to catastrophic failure due to the lack of ignition sources within the propellant tank and the high activation energy required for nitrous decomposition (although it should be noted that this energy threshold can be reduced by the presence of organic contaminants). Leakage past a piston O-ring was only positively confirmed on one occasion, while recycling Mojave Sphinx between its 18th and 19th static tests. The piston O-rings had not been replaced in five firings, and were visibly twisted from repeated cycling without relubrication. As the piston was extracted from the tank, a small amount of residual fuel was sprayed outward when the forward O-ring passed the edge of the tank bolt holes. The presence of trapped pressure in the (very small) volume between the piston O-rings indicated that nitrous had leaked past at least the lower O-ring. It was not conclusive whether fuel and/or nitrous had leaked past the upper O-ring as well, although it is likely given the state of the O-ring. In any case, there were no deleterious effects, and this scenario is easily avoided with proper servicing of the piston seals.

3.4.3 Excess Fuel Additive Impaction

On a flight attempt following Launch 16, the vehicle failed to flow fuel after the main valves were opened. The prior launch attempt had ended in a cold flow because a slightly mistimed controller sequence opened the main valves first, allowing the flowing propellant to blow the ignition leads off the e-match wires before the command was sent to fire the igniter.

It was initially theorized that the piston had somehow become stuck due to cumulative damage to the tank from a handful of hard landings, despite being subjected to over 6,000 lbf when pressurized. The piston clearance was modified, yet fuel once again failed to flow on the subsequent launch attempt. At this point, the fuel line was removed and the system inspected, revealing the true cause.

In the first two of these unsuccessful launch attempts, HCR was attempting to fire a "super green" fuel blend; an extra ~60g of boric acid had been shoveled into each fuel load and mixed in the rocket's open fuel tank to bring the concentration up to 6% for a brighter green color. It was obvious after the first attempt that such a high concentration of boric acid did not fully dissolve given the inadequate time and mixing, with a significant amount of particulate remaining in the fuel tank. What was only later discovered, however, was that a clump of undissolved boric acid granules had become impacted in the fuel injector inlet fitting, creating a >99% blockage that allowed virtually no fuel flow into the chamber. The blockage was removed using a pick, and the fuel line and injector manifold were flushed and purged using water and compressed air.

The takeaway is to avoid having undissolved excess fuel additives in the rocket's tank, as they may form blockages in the system. It is recommended to mix custom fuel blends in a separate container first, verifying that no powder remains in the bottom before it is loaded into the rocket.

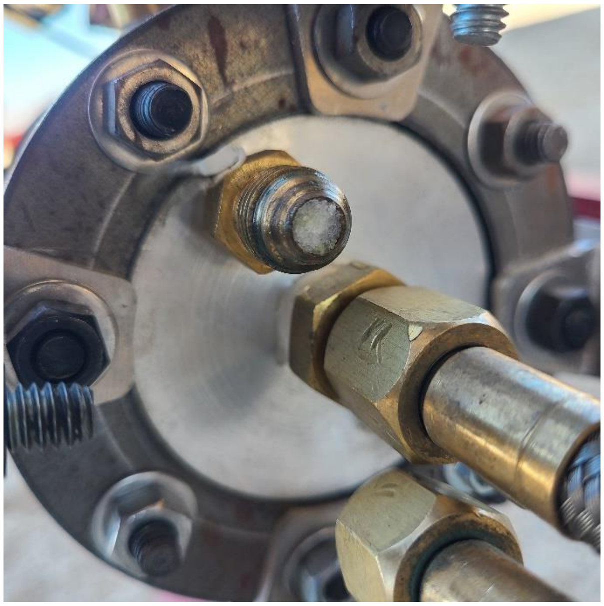

Figure 3.4: Fuel inlet to TCA, clogged with boric acid

3.4.4 Mixture Ratio Creep from Fuel Additive Buildup

On a handful of firings, throat erosion was observed with no immediately obvious cause, usually immediately following a nominal firing with no erosion on the same hardware under identical conditions. While not definitively proven, it is speculated that this may have resulted from buildup of crystalline fuel additives (typically boric acid or calcium chloride) in the fuel system, particularly the injector orifices, increasing the O:F ratio. This could be caused by the presence of undissolved excess additives or evaporation of residual fuel in the system leaving behind deposits. Similarly to the above, this can be largely avoided by ensuring all fuel additives are fully dissolved. As an extra precaution the fuel system can be flushed with water, E85, IPA, or ethanol without additives, however this is not usually necessary when the recommended additive concentrations are used. The current piston design included in this guide leaves a small residual volume in the fuel tank at the end of burn which helps prevent any slurry at the bottom of the tank from being injected into the fuel system, in addition to providing clearance for the recovery anchor screws.

3.4.5 Heat Warpage of Printed Parts

Plastic 3D printed parts are used extensively in the Mojave Sphinx design, and many tests and launches have taken place in high ambient temperatures (above 100F) and in direct sunlight. Overture brand white PLA+ filament was used exclusively for all printed parts on both SN01 and SN02 as well as the GSE. At the time of writing, no failures have resulted from softening of 3D printed parts, and only one case of detrimental warpage of any Mojave Sphinx component has been observed: the SN02 nose cone upon recovery from Launch 18 was found to be severely distorted. It should be noted that this nose cone was painted a dark satin red, rather than the typical bare white filament of the other parts, and that this launch took place on an exceptionally hot day at FAR. The deformation is believed to have occurred either in flight or upon contacting the ground tip-first under the main parachute, as the liftoff photo shows a nominal smooth surface. White

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filament or paint is strongly recommended to reduce solar heating, especially if using PLA or PLA+. Use of more heat-resistant materials such as PETG or ABS will reduce the risk of warping, but is not required. While typical ambient temperatures at FAR/RRS are acceptable, a Mojave Sphinx or printed components thereof should never be left in a hot car, which can easily exceed the glass transition temperatures of most filaments.

Figure 3.5: Warped PLA+ nose cone

Section IV – Bill of Materials

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4.1 Summary

This section presents the complete Bill of Materials (BOM) for Mojave Sphinx. Included are both COTS components such as fittings and fasteners, and stock material for the 3D printed and machined custom components. If printing and/or machining are outsourced to an online service, these stock materials do not also need to be purchased. Some parts are recommended to be produced by metal laser cutting (SendCutSend) but could also be produced by other means such as waterjet cutting or machining; since outsourcing is recommended for these parts, stock material is not listed in the BOM. See Appendices C, D and E for a complete list of 3D printed, laser cut, and machined parts.

Each unique *item* is listed only once in this section, even if it is used in multiple parts of the rocket. For example, if a QTY 100 box of fasteners is listed in one subsection, but not all are used, it will not appear again in later subsections which use fasteners from the same box. However, if, for example, a threaded rod is purchased in individual quantities (rather than a multi-pack), the quantity needed in each subsection is listed in that subsection. In this way, the BOM lists all items which need to be purchased, without repeats. It is therefore recommended to use this section to track procurement rather than the BOM tables at the beginning of each operation of the Vehicle Assembly Procedures (Section V), as many items are repeated in multiple operations.

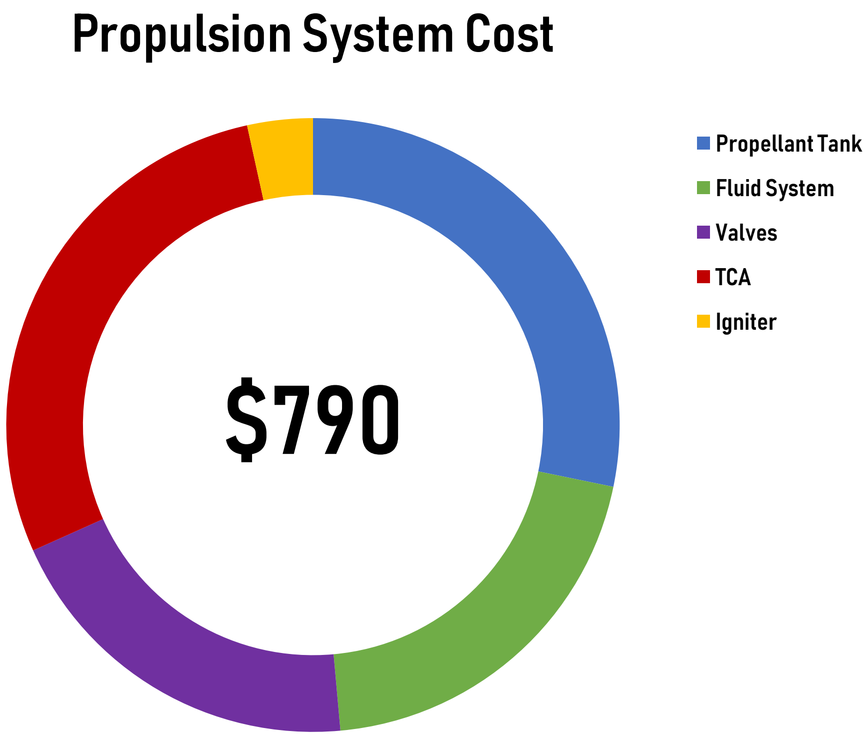
While the majority of COTS items are sourced from McMaster-Carr for the sake of convenience and quality assurance, equivalent – and in some cases identical – products may be available at a lower price from other suppliers. Additionally, part numbers, names, descriptions, and availability may change following the publication of this document. When making any substitutions, it is left to the reader to identify a suitable replacement with similar specifications. Most components are not sensitive to minute details so long as the important characteristics (i.e., thread size, ability to withstand pressure, etc.) are compatible with the rest of the system.

Note that this BOM comprises only the rocket; the ground support system's Bill of Materials is presented separately in Section VI.

The vehicle parts are subdivided into a few major subsystems: Propellant tank, fluid system, thrust chamber assembly, igniter, valves, airframe, and recovery. Each subsection has two tables: a description table, which contains information on each component, its quantity, and unit/total price, and a procurement table, which provides the vendor/description (if applicable) and part number. Some line items have alternate, usually higher price sources (e.g. 1a, 1b, etc.) in case the primary vendor is out of stock. Prices do not include tax or shipping, which will vary depending on location. Links to specific product pages are provided where appropriate; some vendors, such as Amazon, often have multiple identical products for sale from different suppliers, in which case the intended product description is provided so that the reader can locate that item on the website. Certain common items (e.g., batteries) are simply listed as "Retail" and may be acquired at any typical retail store. The authors would like to apologize in advance for any difficulty in sourcing parts from Amazon, since the website is poorly designed and filled with nearly identical listings that may not be the same from one day to the next. Unfortunately, it is often the most accessible and lowest-cost source for electronic items (such as servos) that ship from within the United States. Please see Appendix F for a list of parts organized by vendor, as well as direct Amazon links.

For completeness, all part numbers used in the construction of the vehicle are included; Parts made from other purchased items (for example, printed components) appear with a line item cost of $0.00.

4.2 Propulsion System



4.2.1 Propellant Tank

Line	Item	Unit Price	QTY	Cost	Context
1	6061 Aluminum Round 4"D X 1/2"L	$14.95	2	$29.90	Tank Bulkheads
2	6061 Aluminum Round 4"D X 3"L	$22.26	1	$22.26	Tank Piston
3	6061 Aluminum Tube 4"D X 1/8"W X 36"L	$85.38	1	$85.38	Tank Casing
4	6061 Aluminum Tube 4"OD X 1/2"W X 3"L	$10.37	2	$20.74	Bolted Tank Rings
5	-238 Buna-N O-Rings (Pack of 50)	$16.14	1	$16.14	Tank/Piston Seals
6	5/16-24 X 1/2" Button Head Screw (Pack of 25)	$7.57	1	$7.57	Tank Bolts
7	5/16-24 Offset Narrow Base Weld Nut (Pack of 25)	$9.21	1	$9.21	Tank Bolt Nuts
8	1/4-20 X 7/8 Button Head Hex Drive Screws (Pack of 50)	$9.30	1	$9.30	Fwd Bulkhead Recovery Anchors, Fin Brackets, Airframe
9	1/4-20 Coupling Nut	$0.39	2	$0.78	Fwd Bulkhead Recovery Anchors
10	Sealing Washers for 1/4" Screw, 0.5" OD (Pack of 10)	$7.49	1	$7.49	Fwd Bulkhead Recovery Anchors
11	Ultra-Low-Profile Socket Head Screw Alloy Steel, 1/4"-20 Thread Size, 1/2" Long	$4.93	2	$9.86	Propellant Piston Extraction
12	Spacer, for 5/16", 5/8" OD x 1/2" Long	$4.31	1	$4.31	Bushing for Tank Drill Jig
13	Propellant Tank Casing	$0.00	1	$0.00	Machined
14	Fuel Tank Bulkhead	$0.00	1	$0.00	Machined
15	Oxidizer Tank Bulkhead	$0.00	1	$0.00	Machined
16	Propellant Piston	$0.00	1	$0.00	Machined
17	Interface Ring	$0.00	2	$0.00	Machined
18	Nut Retaining Ring	$0.00	2	$0.00	Printed
19	Propellant Tank Drill Jig	$0.00	1	$0.00	Printed
		Subtotal		**$222.94**	

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Line	Part Number	Vendor Description	Source
1	1610T37-1610T134	Multipurpose 6061 Aluminum 4" Diameter (1/2 in)	https://www.mcmaster.com/1610T37-1610T134/
2	1610T37-1610T33	Multipurpose 6061 Aluminum 4" Diameter (3 in)	https://www.mcmaster.com/1610T37-1610T33/
3	9056K42-9056K423	Multipurpose 6061 Aluminum Round Tube 1/8" Wall Thickness, 4" OD (3 ft)	https://www.mcmaster.com/9056K42-9056K423/
4	7392T17-7392T173	Multipurpose 6061 Aluminum Round Tube 1/4" Wall Thickness, 4" OD (3 in)	https://www.mcmaster.com/7392T17-7392T173/
5	9452K226	Oil-Resistant Buna-N O-Ring 1/8 Fractional Width, Dash Number 238	https://www.mcmaster.com/9452K226/
6	91255A378	Button Head Hex Drive Screw Black-Oxide Alloy Steel, 5/16"-24 Thread, 1/2" Long	https://www.mcmaster.com/91255A378/
7	94579A550	Steel Offset-Barrel Narrow-Base Weld Nut 5/16"-24 Thread Size	https://www.mcmaster.com/94579A550/
8	91306A279	Button Head Hex Drive Screws Zinc-Plated Alloy Steel, 1/4"-20 Thread, 7/8" Long	https://www.mcmaster.com/91306A279/
9	90264A435	Zinc-Plated Steel Coupling Nut Low-Strength, 1/4"-20 Thread Size	https://www.mcmaster.com/90264A435/
10	91367A952	Chemical-Resistant Fluorosilicone Sealing Washer for 1/4" Screw Size,.230" ID,.5" OD,.052" to .072" Thick	https://www.mcmaster.com/91367A952/
11	90357A013	Ultra-Low-Profile Socket Head Screw Alloy Steel, 1/4"-20 Thread Size, 1/2" Long	https://www.mcmaster.com/90357A013/
12	93320A215	Polished Unthreaded Spacers 5/8" OD, 1/2" Long, for 5/16" Screw Size	https://www.mcmaster.com/93320A215/
13	TANK-36L-047V2X8X313C	-	Made from 9056K423
14	BKHD-FL-0238-4NPT2X250C	-	Made from 1610T134
15	BKHD-OX-0238-8NPT4NPT	-	Made from 1610T134
16	PSTN-2X0238-250T20	-	Made from 1610T33
17	INRG-200S-8X3125C8X250C	-	Made from 7392T173
18	NTRG-45C20D-200E	-	Made from printer filament
19	DRLJG-TANK-8X6250D-BSHNG	-	Made from printer filament

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4.2.2 Fluid System

Line	Item	Unit Price	QTY	Cost	Context
1	Aluminum Pipe Nipple, 1/4NPT, 4"L	$5.09	2	$10.18	Tank outlets to valves
2	Brass High Pressure Elbow Fitting, M/F, 1/4NPT	$2.94	2	$5.88	Fuel valve outlet
3	High-Pressure Brass Straight Reducer, 1/4 x 1/8 NPT Male	$2.64	1	$2.64	Fuel valve outlet
4	High-Pressure Brass Elbow Connector, 1/8 NPT Female	$3.31	1	$3.31	Fuel valve outlet
5	37 Degree Flared Adapter for 5/16" Tube OD, 1/8 Pipe Size	$5.38	1	$5.38	Fuel valve outlet
6	High-Pressure Braided Chemical Hose with Fittings Brass 1/2"-20 Thread Size Flare UNF Female, 3/8" OD - 42"	$30.36	1	$30.36	Fuel Line 42" Section
7	High-Pressure Braided Chemical Hose with Fittings Brass 1/2"-20 Thread Size Flare UNF Female, 3/8" OD - 14"	$19.32	1	$19.32	Fuel Line 14" Section
8	High-Pressure Braided Chemical Hose with Fittings Brass 9/16"-18 Thread Size Flare UNF Female, 7/16" OD – 12"	$27.61	1	$27.61	Ox Line
9	37 Degree Flared Straight Connector for 5/16" Tube OD, 1-3/8" Long	$4.47	1	$4.47	Fuel Line Union
10	37 Degree Flared Adapter for 3/8" Tube OD x 1/4 NPT Male	$3.65	1	$3.65	Ox Valve Outlet
11	Nylon Tubing, 1/4" OD, 800PSI, 10ft	$11.50	1	$11.50	Fill tube
12	Check Valve, 1/8NPT Female/Male, Brass	$15.00	1	$15.00	Fill
13	Elbow, 1/8NPT, Male/Female, Brass	$2.16	1	$2.16	Fill check to QD
14	Push to Connect Fitting, 1/4" Tube X 1/8NPT	$3.95	2	$7.90	Fill check to QD
15	3/4" X 6" 6061-T6 Round Bar	$4.39	1	$4.39	QD Stock Material
16	-007 Buna-N O-rings (Pack of 100)	$4.25	1	$4.25	QD Seal
17	High Pressure Brass Straight adapter, 1/4NPT Female x Male	$2.66	1	$2.66	Fuel valve outler spacer
18	Quick Disconnect, ¾" x ⅛" Flange, 9/32" Female Bore, 1/8 NPT	$0.00	1	$0.00	Machined
19	Quick Disconnect, ¾" x ⅛" Flange, .270 Male Barb, -007 O-Ring Gland	$0.00	1	$0.00	Machined
20	Quick Disconnect Clip, for ¾" x ⅛" Flange	$0.00	1	$0.00	Printed
		Subtotal		**$160.66**	

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Line	Part Number	Vendor Description	Source
1	44665K137	Standard-Wall Aluminum Pipe Nipple Threaded on Both Ends, 1/4 NPT, 4" Long	https://www.mcmaster.com/44665K137/
2	50785K43	High-Pressure Brass Pipe Fitting 90 Degree Elbow Adapter, 1/4 NPT Female x Male	https://www.mcmaster.com/50785K43/
3	5485K31	High-Pressure Brass Pipe Fitting Straight Reducer, 1/4 x 1/8 NPT Male	https://www.mcmaster.com/5485K31/
4	50785K35	High-Pressure Brass Pipe Fitting 90 Degree Elbow Connector, 1/8 NPT Female	https://www.mcmaster.com/50785K35/
5	50675K435	37 Degree Flared Fitting for Copper Tubing Straight Adapter for 5/16" Tube OD, 1/8 Pipe Size	https://www.mcmaster.com/50675K435/
6	4468K858	High-Pressure Braided Chemical Hose with Fittings Brass 1/2"-20 Thread Size Flare UNF Female, 3/8" OD (42 in)	https://www.mcmaster.com/4468K812-4468K858/
7	4468K031	High-Pressure Braided Chemical Hose with Fittings Brass 1/2"-20 Thread Size Flare UNF Female, 3/8" OD (14 in)	https://www.mcmaster.com/4468K812-4468K031/
8	4468K865	High-Pressure Braided Chemical Hose with Fittings Brass 9/16"-18 Thread Size Flare UNF Female, 7/16" OD (12 in)	https://www.mcmaster.com/4468K813-4468K865/
9	50675K135	37 Degree Flared Fitting for Copper Tubing Straight Connector for 5/16" Tube OD, 1-3/8" Long	https://www.mcmaster.com/50675K135/
10	50675K163	37 Degree Flared Fitting for Copper Tubing Adapter for 3/8" Tube OD x 1/4 NPT Male	https://www.mcmaster.com/50675K163/
11	9685T3	High-Pressure Hard Plastic Tubing for Air&Water Nylon, Semi-Clear White, 0.15" ID, 1/4" OD (10 ft)	https://www.mcmaster.com/9685T3/
12	7768K21	Brass Threaded Check Valve with Brass Piston, 1/8 NPT Female x NPT Male	https://www.mcmaster.com/7768K21/
13	50785K41	High-Pressure Brass Pipe Fitting 90 Degree Elbow Adapter, 1/8 NPT Female x Male	https://www.mcmaster.com/50785K41/
14	9396T31	High-Pressure Push-to-Connect Tube Fitting for Air and Water, Adapter, 1/4" Tube OD x 1/8 NPTF Male	https://www.mcmaster.com/9396T31/
15	8974K299	Multipurpose 6061 Aluminum 3/4" Diameter (1/2 ft)	https://www.mcmaster.com/8974K11-8974K299/
16	9452K15	Oil-Resistant Buna-N O-Ring 1/16 Fractional Width, Dash Number 007	https://www.mcmaster.com/9452K15/
17	50785K27	High-Pressure Brass Pipe Fitting Straight Adapter with Hex Body, 1/4 NPT Female x Male	https://www.mcmaster.com/50785K27/
18	QDC-750X125FLG-281FB8NPT	-	Made from 8974K299
19	QDC-750x125FLG-270MB-0007	-	Made from 8974K299
20	QDC-750X250CLP	-	Made from printer filament

4.2.3 Valves

Line	Item	Unit Price	QTY	Cost	Context
1	25kg Servo w/ 25T Servo Horn (Pack of 2)	$28.99	1	$28.99	Fuel/Ox valve actuators
2	Compact High Pressure Ball Valve, 1/4NPT	$17.26	2	$34.52	Fuel/Ox Valves
3	8-32 Hex Nut, Low Strength (Pack of 100)	$2.02	1	$2.02	Valve Handle Screw
4	M4X0.7 Hex Nut, Low Strength (Pack of 100)	$1.90	1	$1.90	Servo mount screws
5	8-32 X 1/2"L Screw, Zinc Plated Steel (Pack of 100)	$3.98	1	$3.98	Valve Handle Screw
6	M4X0.7 X 16mm Hex Head Screws, 18-8SS (Pack of 100)	$10.56	1	$10.56	Servo mount screws, Avbay Sled
7	M4 Washer, 8mm OD, 18-8SS (Pack of 100)	$3.43	1	$3.43	Servo mount screws
8	M4 Split Lock Washer, 18-8SS (Pack of 100)	$1.94	1	$1.94	Servo mount screws
9	M3 Flat Washer, 18-8SS, 7mm OD (Pack of 100)	$2.19	1	$2.19	Servo Horn Connector
10	M3x0.5 10mm Low Profile Socket Head Screw, 18-8SS (Pack of 25)	$2.28	1	$2.28	Servo Horn Connector
11	3-pin Servo Extension Cables, 1m (Pack of 10)	$9.99	1	$9.99	Servo wires
12	3-Pin Servo Y-Harness	$7.99	1	$7.99	Optional; can make by splcing extensions
13	PLA+ 3D Printer Filament, White, 2kg (Or Equivalent)	$45.99	1	$45.99	Valve actuator housings (NOTE: <1kg required for Valves; Also used on Airframe)
14	Servo Valve Mount	$0.00	1	$0.00	Printed
15	Servo Valve Handle Connector	$0.00	1	$0.00	Printed
		Subtotal		**$155.78**	

Line	Part Number	Vendor Description	Source
1	DS3225	2Pack 25KG High Torque RC Servo Waterproof servo Compatible with 1/6, 1/8, 1/10, 1/12 RC Car, Full Metal Gear Steering Servo with 25T Servo Horn (270°)	https://www.amazon.com/
2	4112T22	Compact High-Pressure Brass Ball Valve with Lever Handle, 1/4 NPT Female	https://www.mcmaster.com/4112T22/
3	90480A009	Low-Strength Steel Hex Nut Zinc-Plated, 8-32 Thread Size	https://www.mcmaster.com/90480A009/
4	90591A141	Zinc-Plated Steel Hex Nut Low-Strength, M4 x 0.7 mm Thread	https://www.mcmaster.com/90591A141/
5	90272A194	Zinc-Plated Steel Pan Head Phillips Screw 8-32 Thread, 1/2" Long	https://www.mcmaster.com/90272A194/
6	91280A044	Medium-Strength Class 8.8 Steel Hex Head Screw M4 x 0.70 mm Thread, 16 mm Long	https://www.mcmaster.com/91280A044/
7	98689A113	General Purpose 18-8 Stainless Steel Washer for M4 Screw Size, 4.300 mm ID, 8 mm OD	https://www.mcmaster.com/98689A113/
8	92148A160	18-8 Stainless Steel Split Lock Washer for M4 Screw Size, Standard, 4.4 mm ID, 7.6 mm OD	https://www.mcmaster.com/92148A160/
9	93475A210	18-8 Stainless Steel Washer for M3 Screw Size, 3.2 mm ID, 7 mm OD	https://www.mcmaster.com/93475A210/
10	92855A310	18-8 Stainless Steel Low-Profile Socket Head Screws with Hex Drive, M3 x 0.5 mm Thread, 10 mm Long	https://www.mcmaster.com/92855A310/
11	SRV-3PIN-1MXT	YXQ 1M Servo Extension Cable 3 Pin Male to Female Lead Wire for RC Airplane (10Pcs)	https://www.amazon.com/
12	SRV-Y-HRNS	5 Pcs JR/Futaba Style Servo 1 to 2 Y Harness Leads Splitter Cable Male to Female Extension Lead Wire for RC Models Airplane 7cm	https://www.amazon.com/
13	N/A	OVERTURE PLA Plus (PLA+) Filament 1.75mm PLA Professional Toughness Enhanced PLA Roll, Cardboard Spool, Premium PLA 2kg(4.4lbs), Dimensional Accuracy Probability +/- 0.02mm (White 2-Pack)	https://www.amazon.com/
14	SABV-MOUNT-V2	-	Made from printer filament
15	SABV-HCON-V2	-	Made from printer filament

4.2.4 Thrust Chamber Assembly

Line	Item	Unit Price	QTY	Cost	Context
1	6061 Aluminum Round 3"D X 6"L	$23.23	1	$23.23	Nozzle and injector stock
2	6061 Aluminum Tube 3"D X 1/2"W X 6"L	$37.00	1	$37.00	Chamber Tube
3	110 Copper Round Bar 1-1/2" Diameter 2" Long	$18.88	1	$18.88	Nozzle Throat Insert
4	37 Degree Flared Adapter for 5/16" Tube OD, 1/8 Pipe Size	$5.38	1	$5.38	Fuel Inlet
5	37 Degree Flared Adapter for 3/8" Tube OD x 3/8 NPT Male	$5.18	1	$5.18	Ox Inlet
6	-141 Silicone O-rings (Pack of 10)	$10.17	1	$10.17	Injector Seals
7	Inverted External Retaining Ring for 2.5" OD	$1.18	1	$1.18	Injector Flange
8	Graphite Pipe Gasket, Size 1	$2.83	2	$5.66	Chamber/nozzle seal
9	Flange Plate, Thrust Chamber, Steel, 1/4"	$9.28	2	$18.56	Chamber flanges
10	Bracket, Thrust Chamber Mounting, Aluminum, 1/8"	$5.18	8	$41.44	Chamber attachment to fin brackets
11	1/4 Washers 5/8" OD 18-8SS (Pack of 100)	$5.50	2	$11.00	Chamber tie rods, fins, avbay
12	Split Lock Washer for 1/4 Screw Size (Pack of 100)	$3.02	1	$3.02	Chamber tie rods, fins, avbay
13	1/4-20 Medium Strength Hex Nuts (Pack of 100)	$7.08	1	$7.08	Chamber tie rods, fins, avbay
14	1/4-20 x 8"L Black Oxide Threaded on Both Ends Stud	$2.59	8	$20.72	Chamber tie rods (NOTE: Add'l qty on Airframe)
15	Low-Profile Ultra-Wd Truss Head Slotted Screw 1/4"-20 Thread, 3/4" Long	$8.32	1	$8.32	Scrintle Screw
16	High-Temperature Dry-Running 841 Bronze Sleeve Bearing for 1/4" Shaft Diameter and 3/8" Housing ID, 3/8" Long	$0.97	1	$0.97	Scrintle Sleeve
17	Garter Spring Hard Drawn Steel, 1.529" OD, 1.341" ID	$5.31	1	$5.31	Nozzle Insert Retainer
18	Injector, Basic Orifice Pattern	$0.00	1	$0.00	Machined
19	Nozzle, for Throat Insert	$0.00	1	$0.00	Machined
20	Combustion Chamber	$0.00	1	$0.00	Machined
21	Throat Insert, Spring Retained	$0.00	1	$0.00	Machined
		Subtotal		**$223.10**	

Line	Part Number	Vendor Description	Source
1	61ARB3	6061 Aluminum Round Bar (Size: 3 in, Length: 6 in)	https://www.midweststeelsupply.com/store/6061aluminumroundbar
1a	1610T41	Multipurpose 6061 Aluminum 3" Diameter (1/2 ft)	https://www.mcmaster.com/8974K82-1610T41/
2	61ARDT3500	6061 Aluminum Round Bar (Size: 3 X 1/2 in, Length: 6 in)	https://www.midweststeelsupply.com/store/6061aluminumroundtube
2a	1610T42	Multipurpose 6061 Aluminum 3-1/2" Diameter (1/2)	https://www.mcmaster.com/8974K88-1610T42/
3	CRB112	110 Copper Round Bar (Size: 1-1/2 in, Length: 2 in)	https://www.midweststeelsupply.com/store/110copperroundbar
3a	9103K93	Multipurpose 110 Copper Disc 1-1/2" Diameter (2 in)	https://www.mcmaster.com/9103K9-9103K93/
4	50675K435	37 Degree Flared Fitting for Copper Tubing Straight Adapter for 5/16" Tube OD, 1/8 Pipe Size	https://www.mcmaster.com/50675K435/
5	50675K164	37 Degree Flared Fitting for Copper Tubing Adapter for 3/8" Tube OD x 3/8 NPT Male	https://www.mcmaster.com/50675K164/
6	9396K79	High-Temperature High-Purity Silicone O-Ring 3/32 Fractional Width, Dash Number 141	https://www.mcmaster.com/9396K79/
7	90213A101	Inverted External Retaining Ring for 2-1/2" OD, Black-Phosphate 1060-1090 Spring Steel	https://www.mcmaster.com/90213A101/
8	94095K114	High-Temperature Graphite Gasket for ANSI Class 600, for Pipe Size 1, 1-5/16" ID	https://www.mcmaster.com/94095K114/
9	FLNG-ST-25T-8X250C	-	https://sendcutsend.com/
10	BRKT-90A-125T-2X250C	-	https://sendcutsend.com/
11	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD	https://www.mcmaster.com/92141A029/
12	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD	https://www.mcmaster.com/91102A750/
13	95505A601	Medium-Strength Steel Hex Nut Grade 5, 1/4"-20 Thread Size	https://www.mcmaster.com/95505A601/
14	90281A102	Black-Oxide Steel Threaded on Both Ends Stud 1/4"-20 Thread Size, 8" Long, 1" Long Threads	https://www.mcmaster.com/90281A102/
15	90015A410	Low-Profile Ultra-Wd Truss Head Slotted Screw 1/4"-20 Thread, 3/4" Long	https://www.mcmaster.com/90015A410/
16	9368T14	High-Temperature Dry-Running 841 Bronze Sleeve Bearing for 1/4" Shaft Diameter and 3/8" Housing ID, 3/8" Long	https://www.mcmaster.com/9368T14/
17	8284N57	Garter Spring Hard Drawn Steel, 1.529" OD, 1.341" ID	https://www.mcmaster.com/8284N57/
18	INJC-2X8NPT-38NPT-250T20-2X0230-BASIC	-	Made from 61ARB3
19	NZZL-45C20D-200E	-	Made from 61ARB3
20	CMBR-200DI-250B-525L	-	Made from 61ARDT3500
21	THRT-45C20D-100T	-	Made from CRB112

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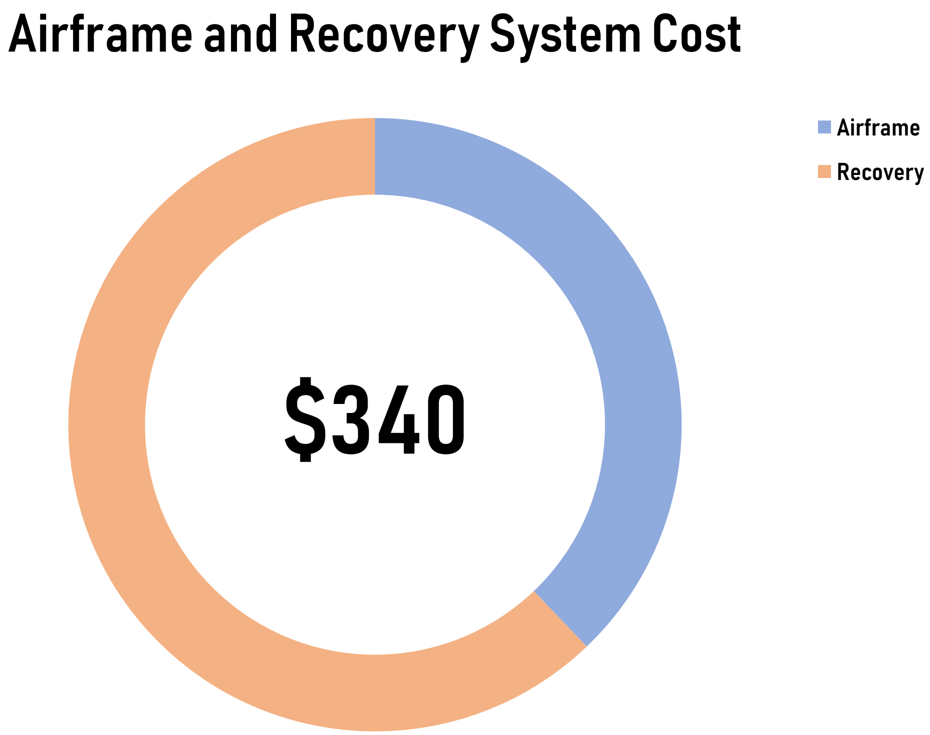
4.2.5 Igniter

Line	Item	Unit Price	QTY	Cost	Context
1	Thick-Wall Pipe Nipple, 1/2NPT X 2"L, Aluminum	$8.28	1	$8.28	Cartridge body
2	1/2NPT Cap, Brass	$2.96	1	$2.96	Cartridge cap
3	1/2NPT Coupling, Brass	$4.05	1	$4.05	Cartridge body
4	NPT Bushing, 1/2 Male X 1/8 Female, Brass	$4.72	1	$4.72	Cartridge bottom
5	Pipe Nipple, 1/8NPT X 2"L, Brass	$2.78	1	$2.78	Cartridge outlet
6	High-Pressure Brass Pipe Fitting Straight Adapter with Hex Body, 1/8 NPT Female x Male	$1.40	1	$1.40	Cartridge outlet
7	High-Pressure Brass Pipe Straight Connector, 1/8 NPT Male	$1.60	1	$1.60	Cartridge outlet
8	High-Pressure Brass Straight Connector with Hex Body, 1/8 NPT Female	$1.46	1	$1.46	Igniter inlet
		Subtotal		**$27.25**	

Line	Part Number	Vendor Description	Source
1	2155K18	Thick-Wall Aluminum Pipe Nipple Threaded on Both Ends, 1/2 Pipe Size, 2" Long	https://www.mcmaster.com/2155K18/
2	50785K164	High-Pressure Brass Pipe Fitting Cap, 1/2 NPT Female	https://www.mcmaster.com/50785K164/
3	50785K94	High-Pressure Brass Pipe Fitting Straight Connector, 1/2 NPT Female	https://www.mcmaster.com/50785K94/
4	4429K421	Low-Pressure Brass Threaded Pipe Fitting Bushing Adapter with Hex Body, 1/2 Male x 1/8 Female NPT	https://www.mcmaster.com/4429K421/
5	50785K171	High-Pressure Brass Pipe Fitting Nipple, Threaded on Both Ends, 1/8 Pipe Size, 2" Long	https://www.mcmaster.com/50785K171/
6	50785K25	High-Pressure Brass Pipe Fitting Straight Adapter with Hex Body, 1/8 NPT Female x Male	https://www.mcmaster.com/50785K25/
7	5485K21	High-Pressure Brass Pipe Fitting Straight Connector, 1/8 NPT Male	https://www.mcmaster.com/5485K21/
8	50785K91	High-Pressure Brass Pipe Fitting Straight Connector with Hex Body, 1/8 NPT Female	https://www.mcmaster.com/50785K91/

4.3 Airframe and Recovery System



4.3.1 Airframe

Line	Item	Unit Price	QTY	Cost	Context
1	Nose Cone Shoulder, 4X 1/4" Rod Sleeves, for 8X 8-32 Hex Nuts with Clearance Holes	$0.00	1	$0.00	3D Printed from filament on Valves BOM
2	Nose Cone, Section 1, 4X 1/4" Rod Sleeves	$0.00	1	$0.00	3D Printed from filament on Valves BOM
3	Nose Cone, Section 2, 4X 1/4" Rod Sleeves	$0.00	1	$0.00	3D Printed from filament on Valves BOM
4	Nose Cone, Tip, 4X 1/4" Rod Sleeves, 1/4" Clearance Hole with Hex Nut Capture	$0.00	1	$0.00	3D Printed from filament on Valves BOM
5	1/4-20 Nylon Threaded Rod, 24"L	$6.35	2	$12.70	Nose Cone Tension Rods
6	Cadmium-Plated Steel MIL. Spec. Washer for 1/4" Screw Size, NAS 1149-F0432P	$5.21	1	$5.21	Nose Cone Tension Rods
7	Galvanized Steel Eyebolt with Nut and with Shoulder, for Lifting, 1/4"-20 Thread Size, 1-1/2" Thread Length, 3" Shank	$5.54	1	$5.54	Nose Cone Recovery Anchor
8	316 Stainless Steel Cap Nut, 1/4"-20 Thread Size	$2.99	1	$2.99	Nose Cone Eyebolt Nut
9	Airframe - 4" Mailing Tube, 36"L	$8.60	1	$8.60	.08" Wall Cardboard, White
10	Avionics Bay Coupler, Half, 3.994" OD, Printed	$0.00	1	$0.00	3D Printed from filament on Valves BOM
11	Avionics Bay Switch Band, 4.16" OD, Printed	$0.00	1	$0.00	3D Printed from filament on Valves BOM
12	1/4-20 x 8"L Black Oxide Threaded on Both Ends Stud	$2.59	6	$15.54	Coupler tension rods, Recovery Bulkhead Studs (Note: Add'l QTY on Chamber)
13	U-Bolt with Mounting Plate, Galvanized, 1/4"-20 Thread Size, 1" ID	$1.31	3	$3.93	Shock Cord Anchor Point
14	1/4-20 X 10"L Threaded Rod, B7 Medium Strength	$3.60	2	$7.20	Avbay rods
15	Aluminum Angle, 1" X 1" X 1/8" X 24"L	$7.59	4	$30.36	Fin brackets
16	Spacer, Fin Bracket to Tank	$0.00	4	$0.00	3D Printed from filament on Valves BOM
17	1/4" x 12" x 24" Birch Plywood	$18.48	1	$18.48	Fins
18	5/16-24 X 7/8" Button Head Screws (Pack of 10)	$4.17	1	$4.17	Fin Bracket Attachment to Tank
19	Aluminum Foil Tape, Acrylic Adhesive, 2" Wide, 15 Feet Length, 0.005" Thick	$7.79	1	$7.79	Coupler Shimming
20	18-8 Stainless Steel Flanged Button Head Screw, 1/4"-20 Thread, 1-1/4" Long (Pack of 5)	$6.44	1	$6.44	Rail Button Screws

Line	Item	Unit Price	QTY	Cost	Context
21	Rail Button, 1515, Printed, Part A	$0.00	2	$0.00	3D Printed from filament on Valves BOM
22	Rail Button, 1515, Printed, Part B	$0.00	2	$0.00	3D Printed from filament on Valves BOM
23	Lower Airframe Template	$0.00	1	$0.00	Printed
24	Upper Airframe Template	$0.00	1	$0.00	Printed
25	Upper Airframe Backing Plug	$0.00	1	$0.00	Printed
26	Fin Bracket Template, Aft	$0.00	1	$0.00	Printed
27	Fin Bracket Template, Forward	$0.00	1	$0.00	Printed
		Subtotal		**$128.95**	

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Line	Part Number	Vendor Description	Source
1	NSCN-SLDR-4X250R8X832HNC	-	Printed
2	NSCN-SC1-4X250R	-	Printed
3	NSCN-SC2-4X250R	-	Printed
4	NSCN-TIP-4X250R250HNC	-	Printed
5	98831A028	Nylon Threaded Rod 1/4"-20 Thread Size, 2 Feet Long (White)	https://www.mcmaster.com/98831A360-98831A028/
6	95229A420	Cadmium-Plated Steel MIL. Spec. Washer for 1/4" Screw Size, NAS 1149-F0432P	https://www.mcmaster.com/95229A420/
7	3018T23	Galvanized Steel Eyebolt with Nut and with Shoulder for Lifting, 1/4"-20 Thread Size, 1-1/2" Thread Length, 3" Shank	https://www.mcmaster.com/3018T23/
8	92994A029	316 Stainless Steel Cap Nut Super-Corrosion-Resistant, 1/4"-20 Thread Size	https://www.mcmaster.com/92994A029/
9	20545T38	Round Shipping Tube with Press-on End Caps, 4" ID, 36" Inside Length	https://www.mcmaster.com/20545T38/
10	AVBY-HF-3994	-	Printed
11	AVBY-SB-4160	-	Printed
12	90281A102	Black-Oxide Steel Threaded on Both Ends Stud 1/4"-20 Thread Size, 8" Long, 1" Long Threads	https://www.mcmaster.com/90281A102/
13	3043T643	U-Bolt with Mounting Plate, Zinc-Plated Steel, 1/4"-20 Thread Size, 1" ID	https://www.mcmaster.com/3043T643/
14	92580A328	Grade B7 Medium-Strength Steel Threaded Rod 1/4"-20 Thread Size, 10" Long	https://www.mcmaster.com/92580A328/
15	89822K402	Multipurpose 6061 Aluminum 90 Degree Angle with Round Edge, 1/8" Thickness, 1" High x 1" Wide Outside	https://www.mcmaster.com/8982K4-8982K402/
16	SPCR-400SD-250C0313C	-	Printed
17	1125T412	Marine-Grade Plywood Sheet 12" x 24" x 1/4"	https://www.mcmaster.com/1125T412/
18	91255A839	Button Head Hex Drive Screw Black-Oxide Alloy Steel, 5/16"-24 Thread, 7/8" Long	https://www.mcmaster.com/91255A839/
19	7631A82	Foil HVAC Tape Acrylic Adhesive, 2" Wide, 15 Feet Length, 0.005" Overall Thickness	https://www.mcmaster.com/7631A82/
20	97654A620	18-8 Stainless Steel Flanged Button Head Screw 1/4"-20 Thread, 1-1/4" Long	https://www.mcmaster.com/97654A620/
21	RLBTN-A-1515-250C	-	Made from printer filament
22	RLBTN-B-1515-250C	-	Made from printer filament
23	TMPLT-AF-LWR-416	-	Made from printer filament
24	TMPLT-AF-UPR-416	-	Made from printer filament
25	PLG-DRIL-AF-UPR-416	-	Made from printer filament
26	TMPLT-FIN-BRKT-1X1-AFT	-	Made from printer filament
27	TMPLT-FIN-BRKT-1X1-FWD	-	Made from printer filament

4.3.2 Recovery System

Line	Item	Unit Price	QTY	Cost	Context
1	Eggtimer Quark Dual Deploy Altimeter Kit	$20.00	2	$40.00	Deployment controller
2	7.2ft Hexagonal Tent Tarp, Main Chute Canopy	$24.99	1	$24.99	Alternate main chute canopy (saves $55.94)
3	250lb Kevlar Cord, 100ft	$13.95	1	$13.95	Main chute canopy shroud lines
4	Drogue Parachute, 36” Diameter	$20.00	1	$20.00	Drogue chute
5	Tubular Nylon Shock Cord, 3000lbf Breaking Strength	$0.55	50	$27.50	Shock cord
6	Parachute Protector, Nomex, 16 X 16”	$9.50	2	$19.00	Main and Drogue Chute Protector
7	Avionics Bay Sled, Plywood, 2.25” X 6.00”, 6X M4 Clearance Holes	$0.00	1	$0.00	Avbay sled
8	Bulkhead, Recovery/Avionics Bay, 3.99” OD, 4X 1/4" Clearance Holes	$6.78	3	$20.34	Avbay bulkheads, recovery bulkhead
9	Avionics Bay Bulkhead Centering Ring, for 4-Rod Coupler	$0.00	2	$0.00	Avbay centering rings
10	Avionics Bay Sled Mount, for .25” Rods, M4 Clearance Holes	$0.00	1	$0.00	Avbay sled mount
11	Avionics Bay Battery Holder, 2X 9V Batteries, for .25” Rods, M4 Clearance Holes	$0.00	1	$0.00	Avbay battery holder
12	Hex Standoffs, 2-56, Aluminum	$0.52	4	$2.08	Altimeter mounting
13	Nylon Washers, #2 Screw Size	$3.97	1	$3.97	Altimeter Insulation
14	Nylon Pan Head Screws, Phillips, 2-56 Thread, 1/4" Long	$8.43	1	$8.43	Altimeter mounting, Shear Pins, Nose Cone
15	9V Battery Connector	$1.21	2	$2.42	Altimeter Power
16	9V Alkaline Batteries (Pack of 2)	$8.00	1	$8.00	Altimeter Power
17	Quick Link 1400lb Capacity	$2.97	4	$11.88	Shock cord attachment
18	20GA Silicone Coated Wire, Red & Black, 10ft Each	$8.99	1	$8.99	Avbay wiring
		Subtotal		**$211.55**	

Line	Part Number	Vendor Description	Source
1	EGTMR-QRK	Eggtimer Quark Deployment Controller	http://eggtimerrocketry.com/home/altimeters-av-bay/
1a	SLCF	StratologgerCF Altimeter	https://www.perfectflitedirect.com/stratologger cf-altimeter/
1b	RRC3+	RRC3+ Altimeter	https://www.missileworks.com/rrc3
2	CNPY-CHT-86IN	Hikeman Hexagonal Tent Footprint,1-4 Person Ultralight Waterproof Tent Tarp Ground Sheet Mat with 6 Tent Stakes for Camping Hiking Picnic Backpacking (Medium)	https://www.amazon.com/
3	CRD-KVLR-250LB	emma kites 100% Kevlar Braided String Utility Cord Abrasion Flame Resistant, Tactical Survival Fishing Assist Cord Model Rocket Paracord Trip Line Camping Cordage	https://www.amazon.com/
4	REC-CHT-DRG-36	36in Topflight Chute	https://www.csrocketry.com/recovery-supplies/top-flight-recovery/standard-parachutes/36in-topflight-chute.html
4a	PAR-36	36in Topflight Chute	http://www.topflightrecoveryllc.com/page1.html
5	REC-TNSC-3KLB	5/8" Yellow Tubular Nylon (50 ft)	https://www.csrocketry.com/recovery-supplies/hardware-and-shock-chord/kevlar-and-nylon-shock-chord/5/8-yellow-tubular-nylon.html
5b	WSR-NYL-BWT-058-HOG	5/8 Inch BlueWater Tubular Nylon Hot Orange (50 ft)	https://www.strapworks.com/58-inch-blue-water-tubular-hot-orange
6	REC-PRT-16	16" SkyAngle Chute Protector	https://www.csrocketry.com/recovery-supplies/skyangle/protectors/16-skyangle-chute-protector.html
6a	FCP-18x18"	18" FIREWALL Parachute and Shock Cord Protectors	http://www.topflightrecoveryllc.com/page3.html
7	AVBY-SLD-225X600-6XM4C	-	Made from printer filament + plywood
8	BKHD-REC-399-250C-2X170WE	-	https://sendcutsend.com/
9	AVBY-CR-4R	-	Made from printer filament
10	AVBY-MT-250R-M4C	-	Made from printer filament
11	AVBY-BH-2X9V250R-M4C	-	Made from printer filament
12	93505A211	Male-Female Threaded Hex Standoff Aluminum, 3/16" Hex Size, 1/4" Long, 2-56 Thread Size	https://www.mcmaster.com/93505A211/
13	91755A200	Self-Retaining Washer for # 2 & M2 Size, 0.115" ID, 0.203" OD, 0.022"-0.042" Thick	https://www.mcmaster.com/91755A152-91755A200/
14	94735A707	Nylon Pan Head Screws Phillips, 2-56 Thread, 1/4" Long	https://www.mcmaster.com/93135A013/
15	7712K511	Battery Holder 1 9V Battery, T-Shape with Single Layout, 1.04" Long	https://www.mcmaster.com/7712K511/
16	9V-BATT	9 Volt Battery	Retail Store
17	8947T26	Oval-Shaped Threaded Connecting Link Type 316 Stainless Steel, 1/4" Thickness, 5/16" Opening, Not for Lifting	https://www.mcmaster.com/8947T26/
18	20GA-RBP	20 Gauge Wire 20 feet Silicone Wire Soft and Flexible Tinned Copper Wire High Temperature Resistance 10 ft Black and 10 ft Red Stranded Wire for 3D Printer, Test Leads, RC Applications	https://www.amazon.com/

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4.4 Consumables

Line	Item	Unit Price	QTY	Cost	Context
1	Nitrous Oxide	$5.50	20	$110.00	Oxidizer
2	E85	$3.09	2	$6.18	Fuel
3	A3-4T (4-pack)	$10.00	1	$10.00	Igniter
4	MJG Firewire E-matches (Pack of 20)	$15.00	1	$15.00	Igniter, Ejection Charges
5	Black Powder, 4F, 1lb	$33.00	1	$33.00	Ejection charges
6	Nitrile Gloves (Pack of 20)	$7.90	1	$7.90	Glove Fingers Used for Ejection Charges
7	Vinyl Electrical Tape, 3/4" X 60ft	$1.66	1	$1.66	Ejection Charges and wire splices
		Subtotal		**$183.74**	

Line	Part Number	Vendor Description	Source
1	N/A	-	Racing shop
2	N/A	-	Gas station
3	A3-4T	-	Retail hobby store
4	1834	Firewire Electric Match Bundle of 20	https://www.csrocketry.com/recovery-supplies/ejection-supplies/firewire-electric-match.html
4a	395157029341	100pcs/11.81in Electric Connecting Wire for Firework Firing System Match Igniter	https://www.ebay.com/
5	1318	Goex 4F Black Powder (1 lb)	https://www.csrocketry.com/recovery-supplies/ejection-supplies/black-powder.html
5a	N/A	Pyrodex FFFG Equivalent Powder	https://shop.hodgdon.com/pyrodex-p-pistol-powder/
6	52555T644	Disposable Nitrile Gloves Textured, 4 Mil Thick (Large)	https://www.mcmaster.com/52555T64-52555T644/
7	7619A11	Electrical Tape 3/4" Wide, 60 Feet Long, Black	https://www.mcmaster.com/7619A11/

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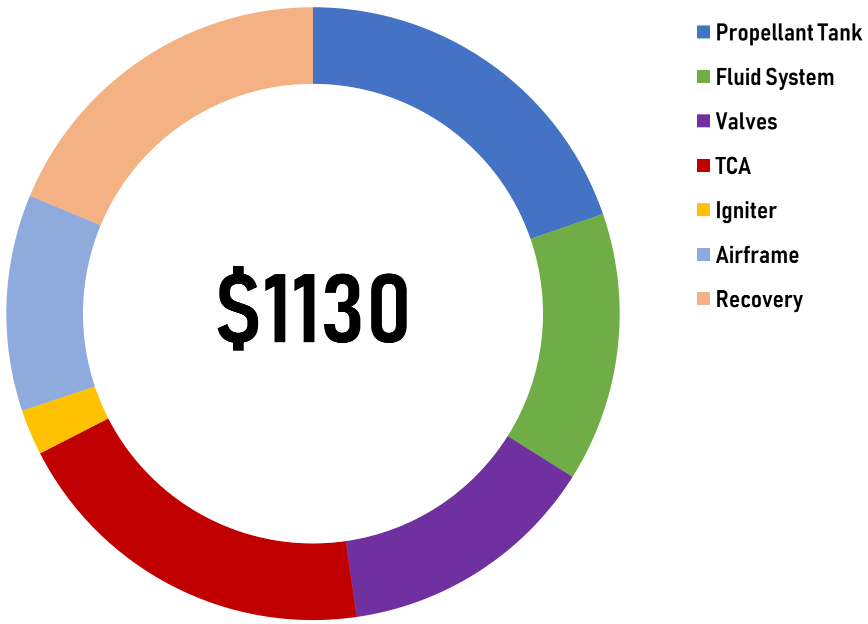
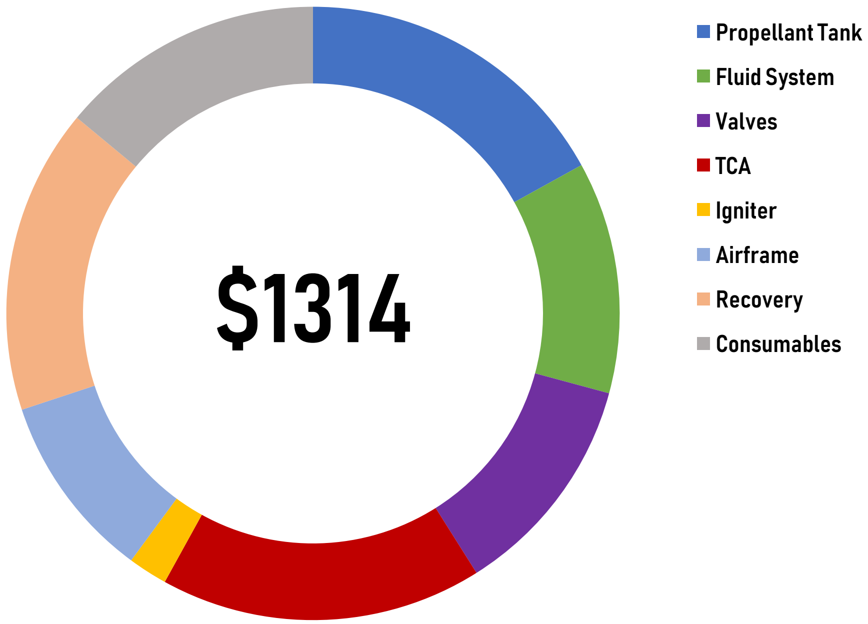
Vehicle Build Cost



Build and Launch Cost



Section V – Vehicle Assembly Procedures

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Required Tools

Wrenches

QTY	Tool
1	3/16
2	7/16
1	1/2
1	9/16
1	5/8
1	11/16
1	3/4
2	7mm
1	Strap wrench accommodating 2.5-3.75" diameter

Note: Standard fixed wrenches of each listed hex size with one open and one closed end are sufficient to perform all assembly. Adjustable wrenches may be substituted, but will incur varying degrees of difficulty based on the clearance at each location. Sockets may improve ease of assembly, but are not required.

Hex Keys

QTY	Tool
1	1/8
1	5/32
1	3/16
1	2mm

Note: Standard L-shaped hex keys are sufficient. Driver bits may be used in combination with a power drill for some steps to reduce assembly time, however this increases the risk of damage from excessive torque.

Screwdrivers

QTY	Tool
1	#1 Phillips
1	#2 Phillips

Cutting Tools

QTY	Tool
1	Razor Knife
1	Flush Cutters or Scissors
1	Fine-Toothed Saw (Optional)

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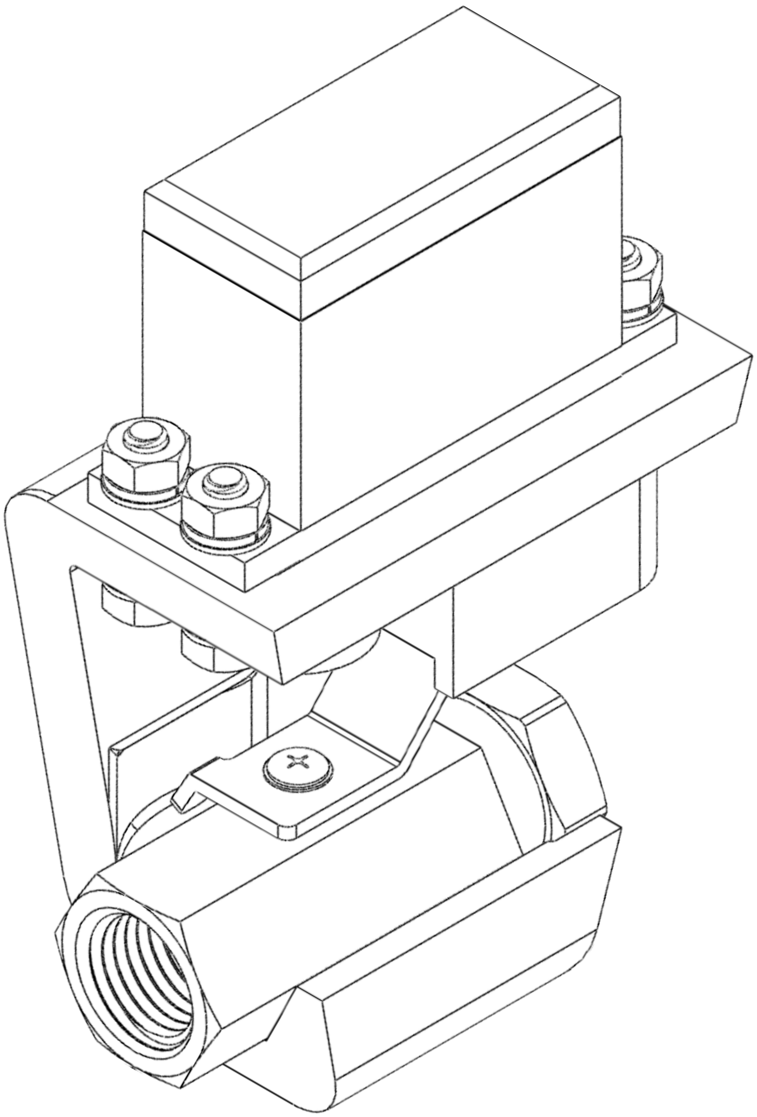
Drill Bits

QTY	Tool
1	1.2mm
1	#50
1	3/16
1	9/32
1	17/64 or H
1	21/64 or Q
1	11/32

Miscellaneous

QTY	Tool
1	Needle Nose Pliers
1	Channel Lock Pliers or Vise Grips
1	Large External Snap Ring Pliers
1	1lb Deadblow Hammer
1	Flat File
1	Automatic Center Punch
1	Wire Stripper/Cutter
1	Measuring Tape
1	Pencil or fine-tip marker
1	1" PVC pipe or Wooden Dowel
1	Countersink or Deburring Knife
1	Medium-Grit Sandpaper (Optional)

OP 1: Assemble Servo-Actuated Ball Valves



OP 1: Assemble Servo-Actuated Ball Valves

Gather the following:

QTY	Part Number	Description
2	SABV-MOUNT-V2	Servo Valve Mount V2.STL
2	SABV-HCON-V2	Servo Valve Handle Connector V2.STL
-	N/A	3D Printer Filament (PLA+, PETG, or ABS recommended)
2	4112T22	Compact High Pressure Brass Ball Valve
2	DS3225	25kg Servo with 25T Servo Horn
2	93475A210	M3 Flat Washer 7mm OD
2	92855A310	M3x0.5 10mm Long 18-8 Low-Profile Socket Head Screw
2	90272A194	#8-32 Pan Head Screw, 1/2" Length
2	90480A009	#8-32 Hex Nut, Zinc Plated, Low Strength Steel
2	-	Nylon Zip Tie, 0.188-inch width
8	92180A044	Medium-Strength Class 8.8 Steel Hex Head Screw M4 x 0.70 mm Thread, 16 mm Long
8	90591A141	M4x0.7 Metric Hex Nuts
8	98689A113	M4 Flat Washers
8	92148A160	M4 Split Lock Washers

Note: All steps in this OP will be performed twice to build two identical valve assemblies. The quantities listed are for two complete assemblies.

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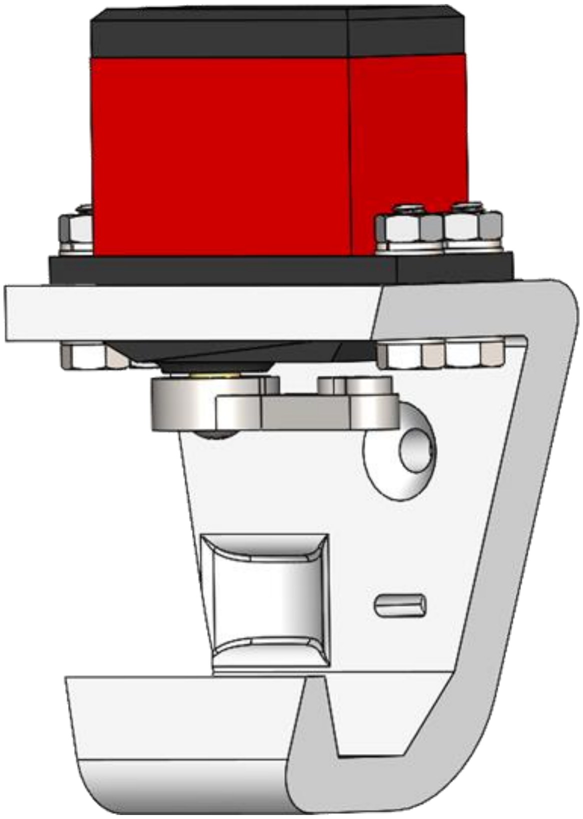
OP 1: Assemble Servo-Actuated Ball Valves

1. Ensure that the servo horn is installed on the servo in the correct orientation. Connect the servo to whatever device you will be controlling it from, and verify that the servo horn points in the correct direction when the servo is commanded to both the valve open and valve closed states. Secure the servo horn to the spur gear using the M3 phillips head screw included with the servo.

   Note: If this screw is lost or damaged, it may be replaced with PN 92000A76.

2. Install the DS3225 Servo into the Servo Valve Mount using QTY 4 91280A044 M4 hex head screws, QTY 8 98689A113 flat washers, QTY 4 92148A160 lock washers, and QTY 4 90591A141 nuts as shown.

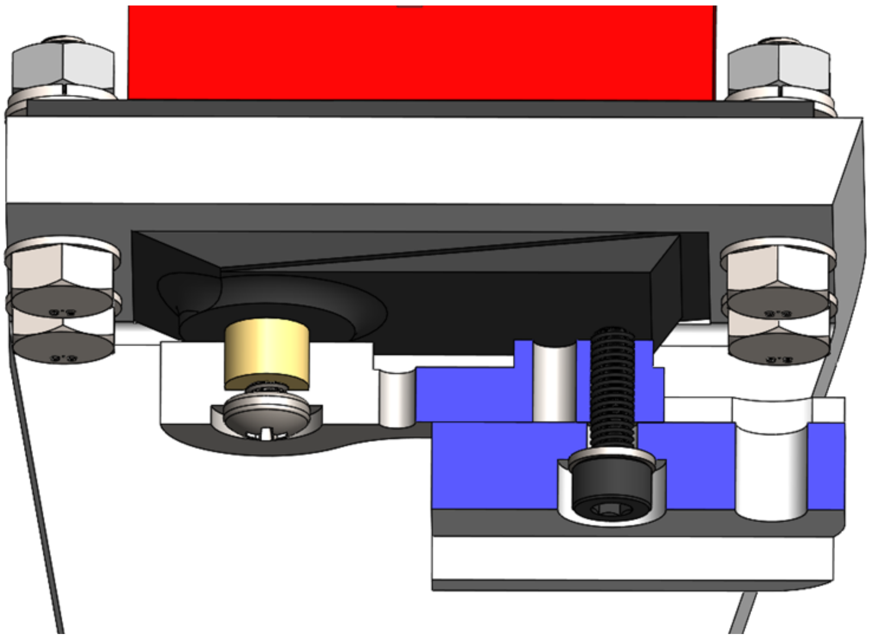
   Note: The 2X screws closest to the back of the mount should be fully tightened prior to installing the outer 2X fasteners. Socket head screws (PN 90128A215) may be substituted to remove this dependency; hex cap screws were selected to permit the use of an adjustable wrench, without requiring a metric hex key.



OP 1: Assemble Servo-Actuated Ball Valves

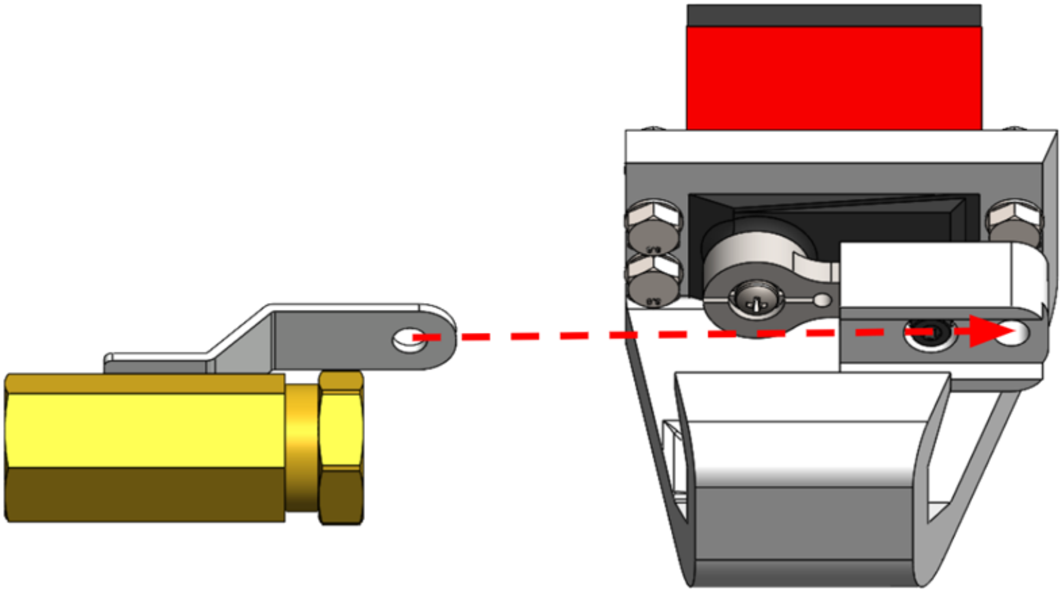
3. Move the servo horn so it points out from the Servo Valve Mount (Valve Closed position). Mount the Servo Valve Handle Connector onto the Servo horn as shown, using the M3 Socket Head Cap Screw and washer installed in the threaded hole closest to the end of the servo horn.

   Note: Servo horn and servo valve handle connector shown sectioned for visibility. Section cut surfaces are highlighted in blue.



OP 1: Assemble Servo-Actuated Ball Valves

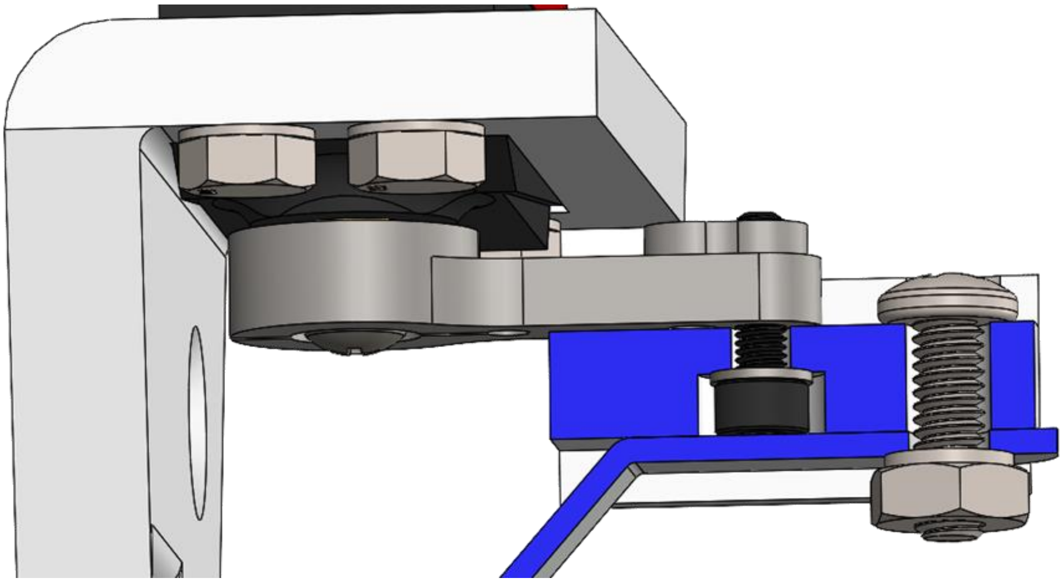
4. Move the servo horn back to the Valve Open position, parallel to the back face of the Servo Valve Mount. Then insert the 4112T22 ball valve into the mount, so that the handle slides into the Servo Valve Handle Connector and the indicated holes are aligned.



OP 1: Assemble Servo-Actuated Ball Valves

5. Move the servo horn and valve handle to the valve closed position, and install QTY 1 90272A194 screw with QTY 1 92148A160 lock washer and QTY 1 90480A009 nut through the Servo Valve Handle Connector and ball valve handle. The screw should fit through the existing hole in the valve handle. If it does not, drill as necessary to achieve a clearance fit.

   Note: Valve handle and servo valve handle connector shown sectioned for visibility. Section cut surfaces are highlighted in blue.



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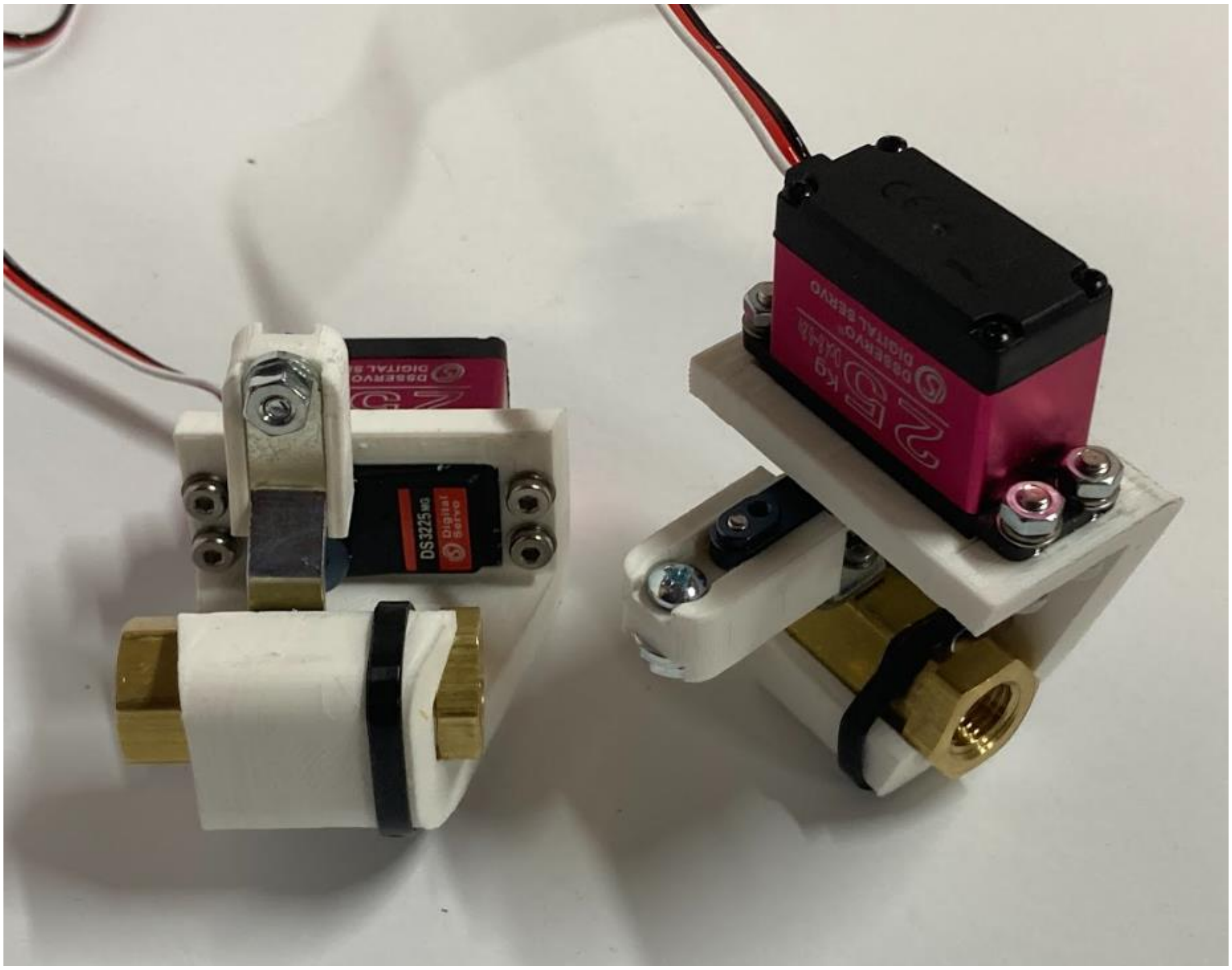
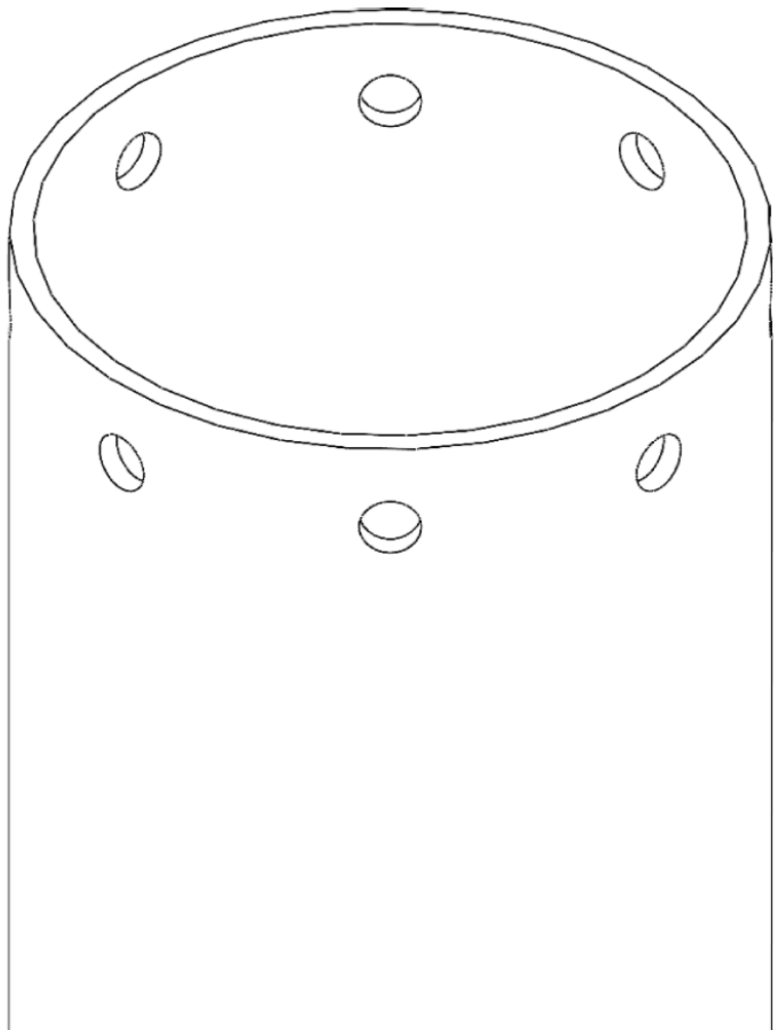
OP 1: Assemble Servo-Actuated Ball Valves

6. Complete the assembly by securing the valve in place with a nylon zip tie as shown in the photo. The zip tie should pass through the small rectangular slot in the Servo Valve Mount. Note that while the zip tie is not critical to the function of the valve, it reduces movement of the valve body during actuation.

7. Bag and label the completed servo-actuated ball valve assemblies with PN SABV-04FF and set aside for integration on a later step.



OP 2: Drill Tank Tube



OP 2: Drill Tank Tube

Gather the following:

QTY	Part Number	Description
1	9056K423	6061-T6 Aluminum Tube, 4" OD, ⅛" Wall, 36" Long
2	-	Tank Drill Jig, 8X 5/16" Holes

Note: A vertical mill with indexing head may be used in place of the printed drill jigs; this is recommended if available.

1. Ensure that the tank tube ends are cut square to within approximately +/-.020. This can be checked by wrapping a strip of paper around the tube and aligning the edge to create a straight line along the surface of cylinder. If needed, use a file or trim off a short section of the tube (<.25") with a hacksaw or bandsaw to square the ends.

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OP 2: Drill Tank Tube

2. Install the 2X tank drill jigs onto the ends of the tubes by pressing them on until the end of the tube contacts the lip of the jig. Ensure that the drill jig is snug on the tube and cannot slide or rotate. Secure using tape if necessary.

   Optional: Mark each of the hole locations using a marker or automatic center punch. A center punch will help keep the tip of the drill in place when starting the hole.

3. Drill 8X holes using an 11/32" drill bit in each end of the tank tube, using the jig to align the drill bit. Be careful not to allow the drill bit to strike the inside surface on the far side of the tube.

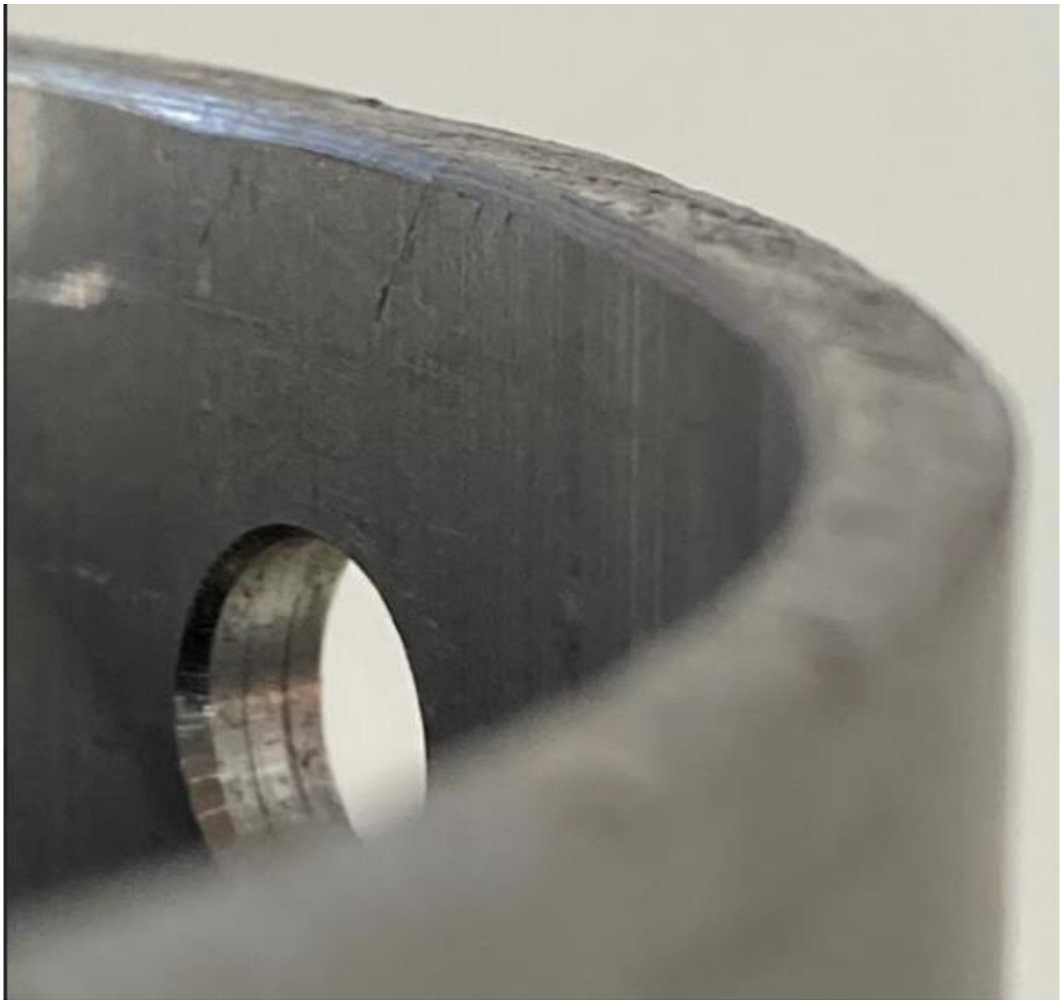
   A drill press is recommended, however a hand drill may be used if desired.

   A drill stop may be used to prevent the bit from striking the inner wall on the far side of the tank, but is not required.

OP 2: Drill Tank Tube

4. Debur the edges of the holes on the inside of the tube, to ensure that sharp edges or burrs will not damage O-rings when inserting the piston and bulkhead. A reversible countersink such as the Noga RC2000 is recommended, however any standard countersink tool may be used to break the interior edges by hand. If sandpaper or abrasive pads are used, ensure all motion is circumferential; axial motion will increase the likelihood of leakage by creating scratches perpendicular to the seal.

5. Debur the interior edges of both ends of the tank using a deburring knife or fine rounded file. This will reduce risk of damage to seals and improve ease of inserting the piston and bulkhead.



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OP 2: Drill Tank Tube

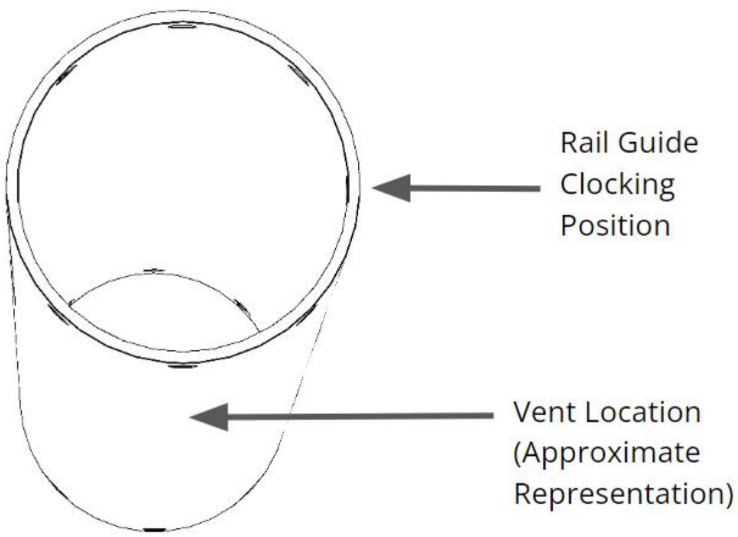
6. Measure 14.25 inches from one end of the tank, in line with one set of tank bolt holes. Mark this location using a permanent marker.

7. At the marked location, drill a 1.2mm diameter hole through the wall of the tank to create the nitrous static vent orifice.

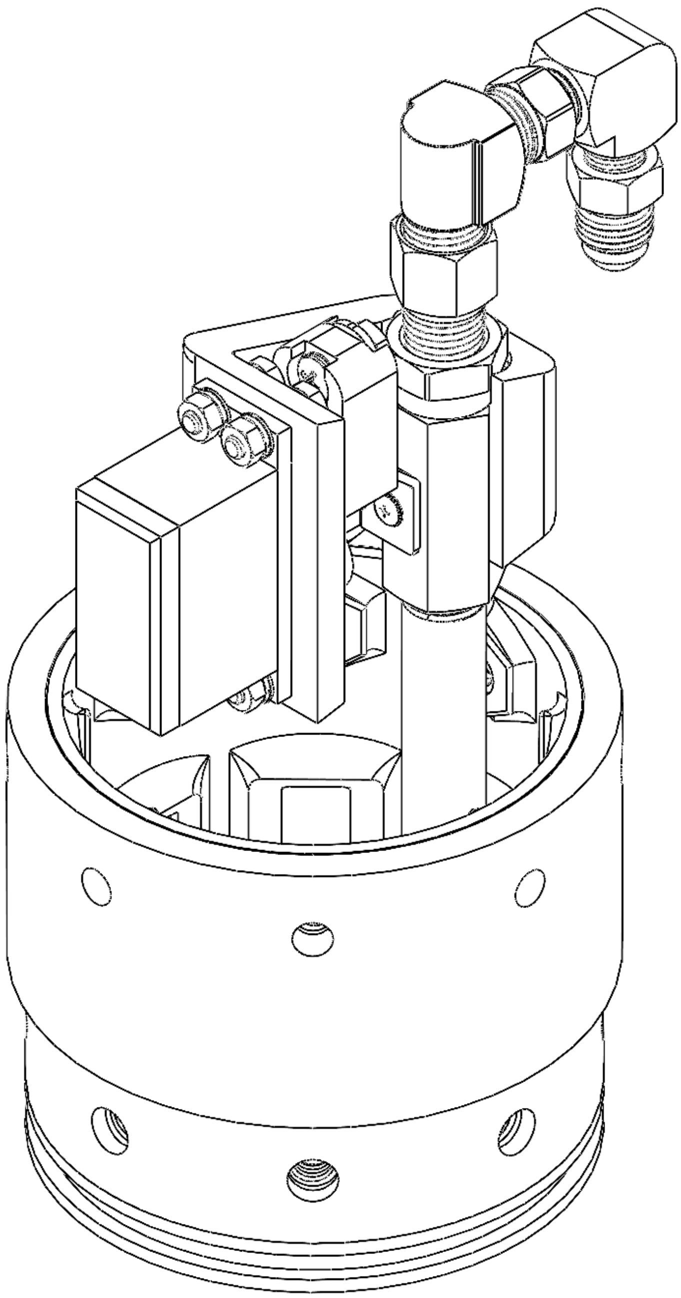
An automatic center punch may be used prior to drilling to help prevent the drill bit from walking.

To assist in identifying the vent location, mark as shown using a permanent marker or paint pen.

8. Mark a line between one pair of bolt holes 90 degrees from the location of the vent, and label with "RAIL GUIDES." This will ensure that the vent points to one side of the rail for maximum visibility.



OP 3: Fuel Bulkhead Subassembly



OP 3: Fuel Bulkhead Subassembly

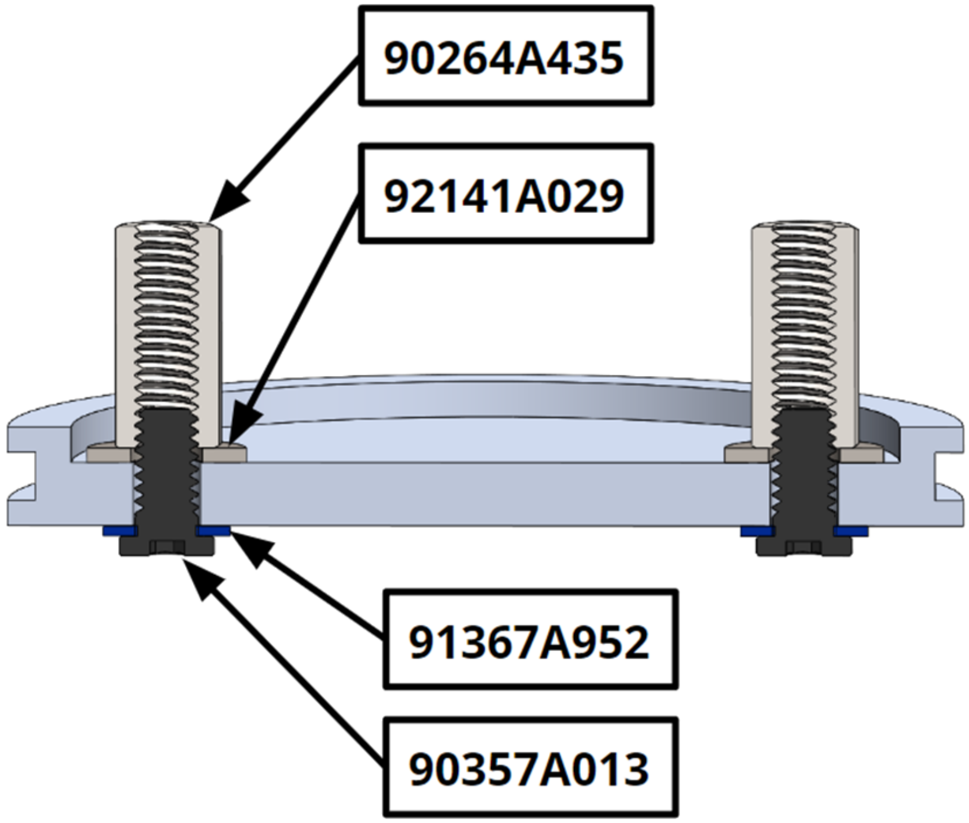
Gather the following:

QTY	Part Number	Description
1	SABV-04FF	Servo-Actuated Ball Valve Assembly, 1/4NPT Female
1	BKHD-FL-0238-4NPT-2X250C	Fuel Tank Bulkhead, -238 O-ring Gland, 1/4NPT Port, 2X ¼" Clearance Holes
1	INRG-200S-8X3125C-8X250C	Tank Interface Ring, 3.75" Diameter, 8X 5/16" & ¼" Clearance Holes
1	NTRG-8X3125WN-8X25HN	Nut Ring, Printed, for 8X 5/16" Weld Nuts & ¼" Hex Nuts
8	94579A550	Steel Offset-Barrel Narrow-Base Weld Nut, 5/16"-24 Thread Size
8	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
2	90357A013	Ultra-Low-Profile Socket Head Screw Alloy Steel, 1/4"-20 Thread Size, 1/2" Long
2	91367A952	Chemical-Resistant Fluorosilicone Sealing Washer for 1/4" Screw Size
2	90264A435	Zinc-Plated Steel Coupling Nut, Low-Strength, 1/4"-20 Thread Size
2	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
1	44665K137	Aluminum Pipe Nipple, 1/4NPT, 4" Lg
1	50785K43	Brass High Pressure Elbow Fitting, M/F, 1/4NPT
1	5485K31	High-Pressure Brass Straight Reducer, 1/4 x 1/8 NPT Male
1	50785K35	High-Pressure Brass Elbow Connector, 1/8 NPT Female
1	50675K435	37 Degree Flared Adapter for 5/16" Tube OD, 1/8 NPT Male
1	50785K27	High-Pressure Brass Straight adapter, 1/4NPT Female x Male
-	-	PTFE Thread Sealant Tape

OP 3: Fuel Bulkhead Subassembly

1. Install QTY 2 90357A013 ultra-low profile socket head screws with QTY 2 91367A952 sealing washers under the heads of the screws (one per screw) into the FBKHD-D375-0238-4NPT fuel bulkhead as shown. Thread screws into QTY 2 90264A435 coupling nuts, with QTY 2 92141A029 washers between the coupling nuts and bulkheads. Tighten screws until snug, then ½ additional turn.

   Note: Excessive torque may cause sealing washers to be extruded.



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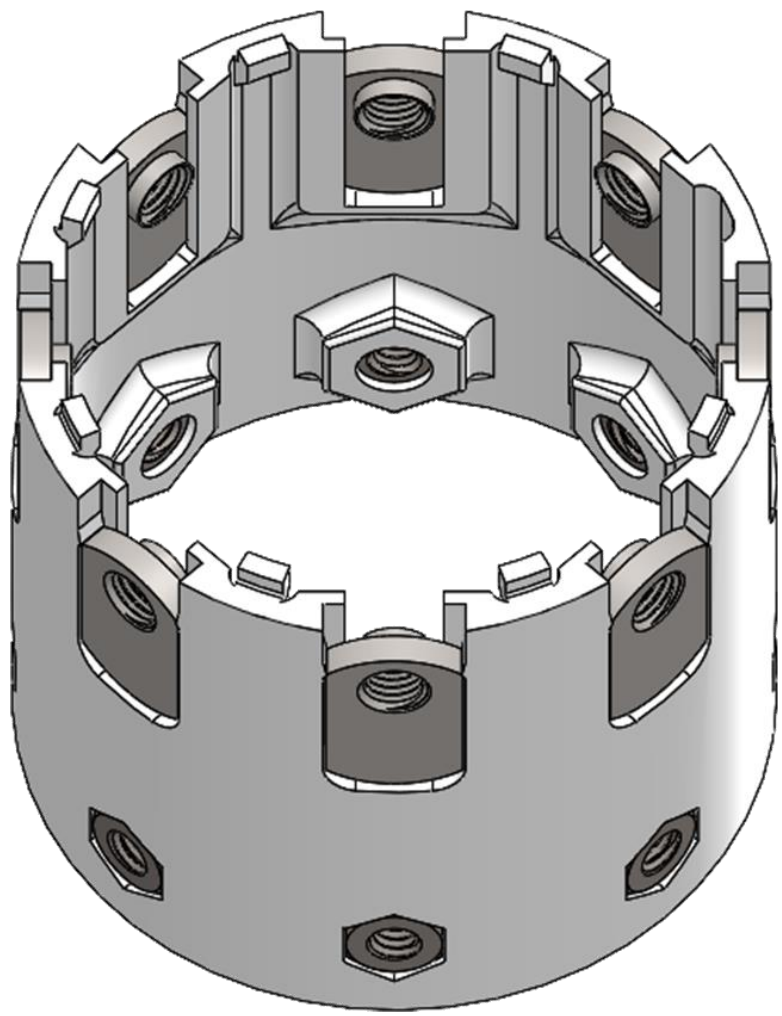
OP 3: Fuel Bulkhead Subassembly

2. Place QTY 8 94579A550 5/16-24 weld nuts and QTY 8 95505A601 1/4-20 hex nuts into QTY 1 NTRG-3125WN-25HN-8X printed nut ring as shown.

   A strip of scotch tape or similar may be used to retain the nuts prior to insertion into the machined integration ring. Note that adhesive should not be used to bond the nuts in place. They must be free to float within their cutouts to accommodate any hole misalignment. Tape may be used to cover the edges of the hex nuts (do not cover holes).



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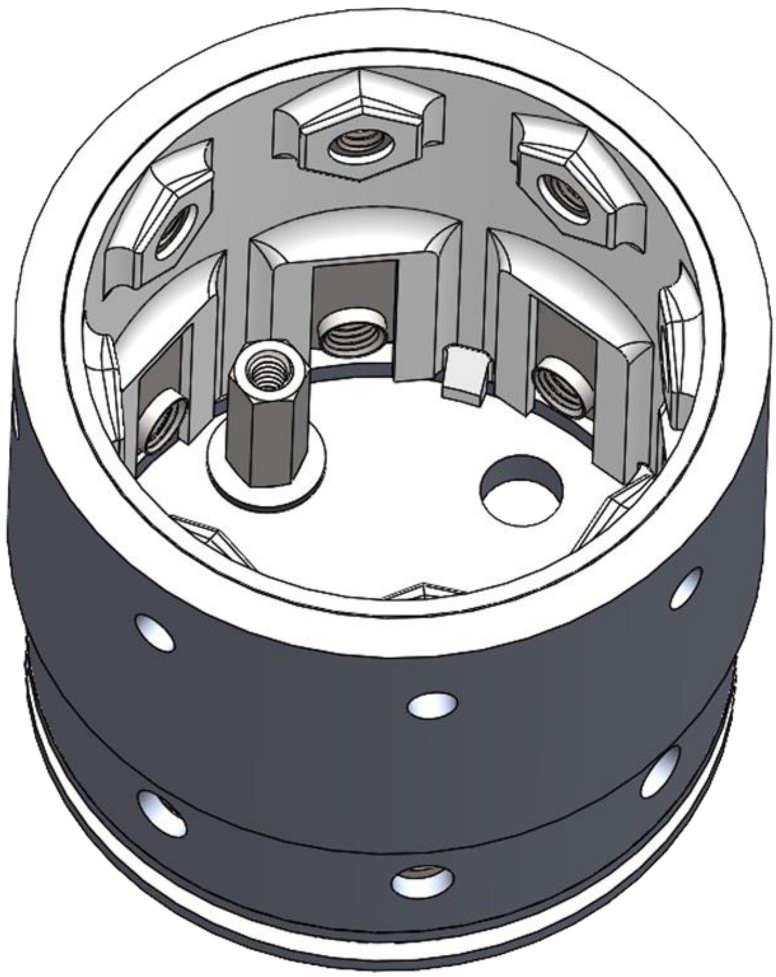
OP 3: Fuel Bulkhead Subassembly

3. Place QTY 1 Tank Interface Ring onto the outer face of the bulkhead as shown.

   Note: The interface ring MUST be installed prior to integrating the valve assembly onto the bulkhead.

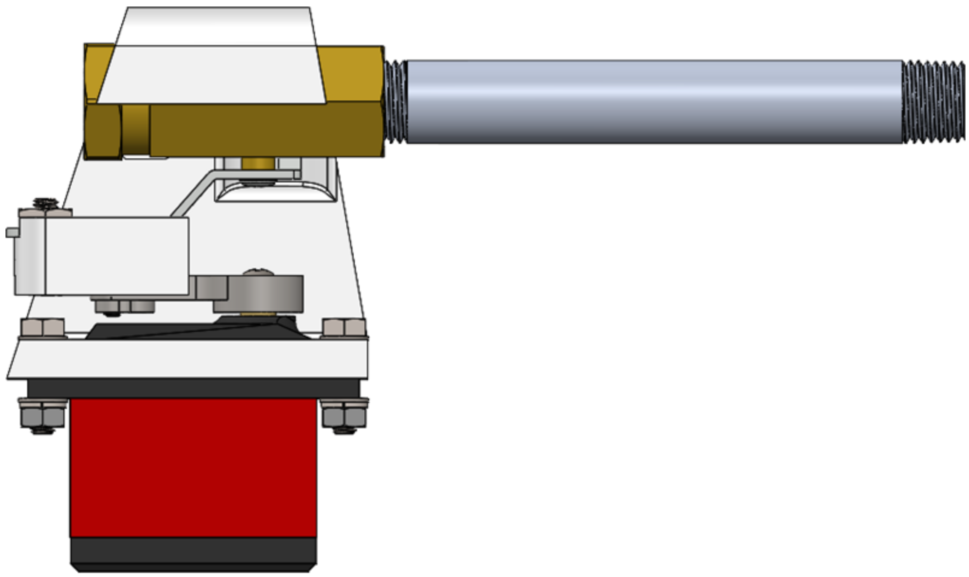
4. Insert the fully populated nut ring into QTY 1 INRG-375-3125C-250C-8X tank interface ring as shown. The 5/16-24 weld nuts should align with the larger holes on the smaller diameter portion of the interface ring.

   Note: The location of the "missing" centering tab does not matter for the fuel bulkhead subassembly.



OP 3: Fuel Bulkhead Subassembly

5. Apply 2-3 clockwise wraps of PTFE tape to both ends of QTY 1 44665K122 Aluminum Pipe Nipple, and thread one end into port of QTY 1 SABV-14NPT-FF as shown. Note the orientation of the valve bracket. Only tighten the pipe nipple to hand-tight at this time.



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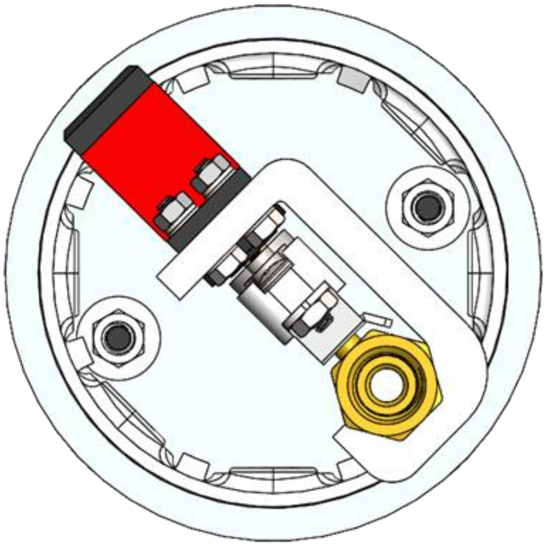
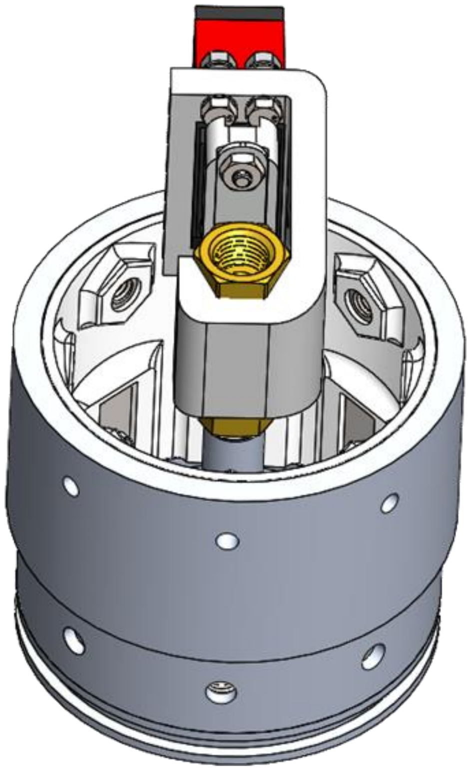
OP 3: Fuel Bulkhead Subassembly

6. Thread the other end of the 44665K122 Aluminum Pipe Nipple into the offset 1/4 NPT port on the FBKHD-D375-0238-4NPT bulkhead. Tighten until snug, then rotate no more than one full turn until the valve assembly aligns with the diameter of the bulkhead.





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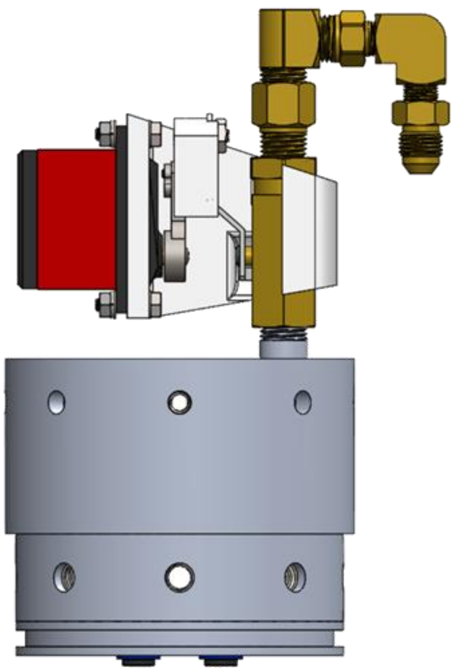
OP 3: Fuel Bulkhead Subassembly

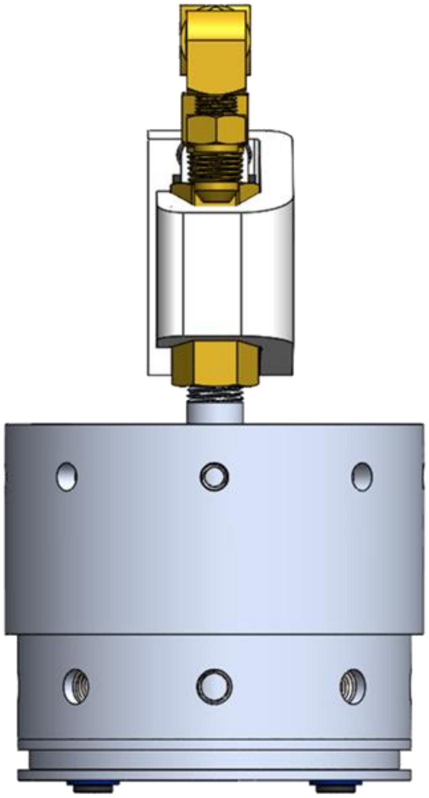
7. Install QTY 1 50785K27 straight adapter, QTY 1 50785K43 male/female elbow fitting, QTY 1 5485K31 reducing adapter, QTY 1 50785K35 female elbow fitting, and QTY 1 50675K435 flared fitting adapter.

   Apply 2-3 wraps of PTFE tape onto each set of male threads before installation.

   When installing elbow fittings, tighten until snug, then no more than one full turn until the fitting is pointed in the correct direction.

   Note: The purpose of the 50785K27 straight adapter fitting is to prevent excess slack length in the fuel downcomer line.





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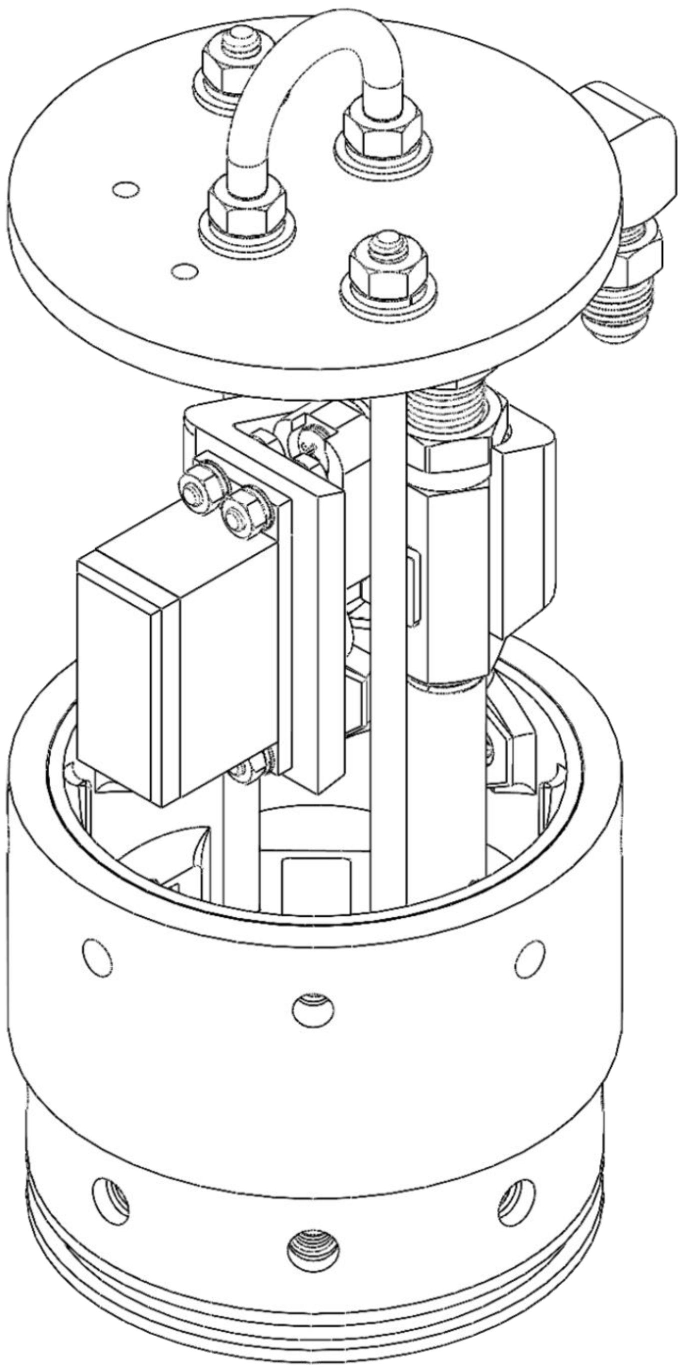
OP 4: Recovery Bulkhead Integration



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OP 4: Recovery Bulkhead Integration

Gather the following:

QTY	Part Number	Description
2	91025A568	Black-Oxide Steel Threaded Stud, 1/4"-20 Thread Size, 7" Long
6	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
6	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
4	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
1	3043T643	U-Bolt with Mounting Plate, Zinc-Plated Steel, 1/4"-20 Thread Size, 1" ID
1	BKHD-REC-4X250C-2X170WE	Bulkhead, Recovery/Avionics Bay, 4X 1/4" Clearance Holes, 2X .170" Wire Exit Holes

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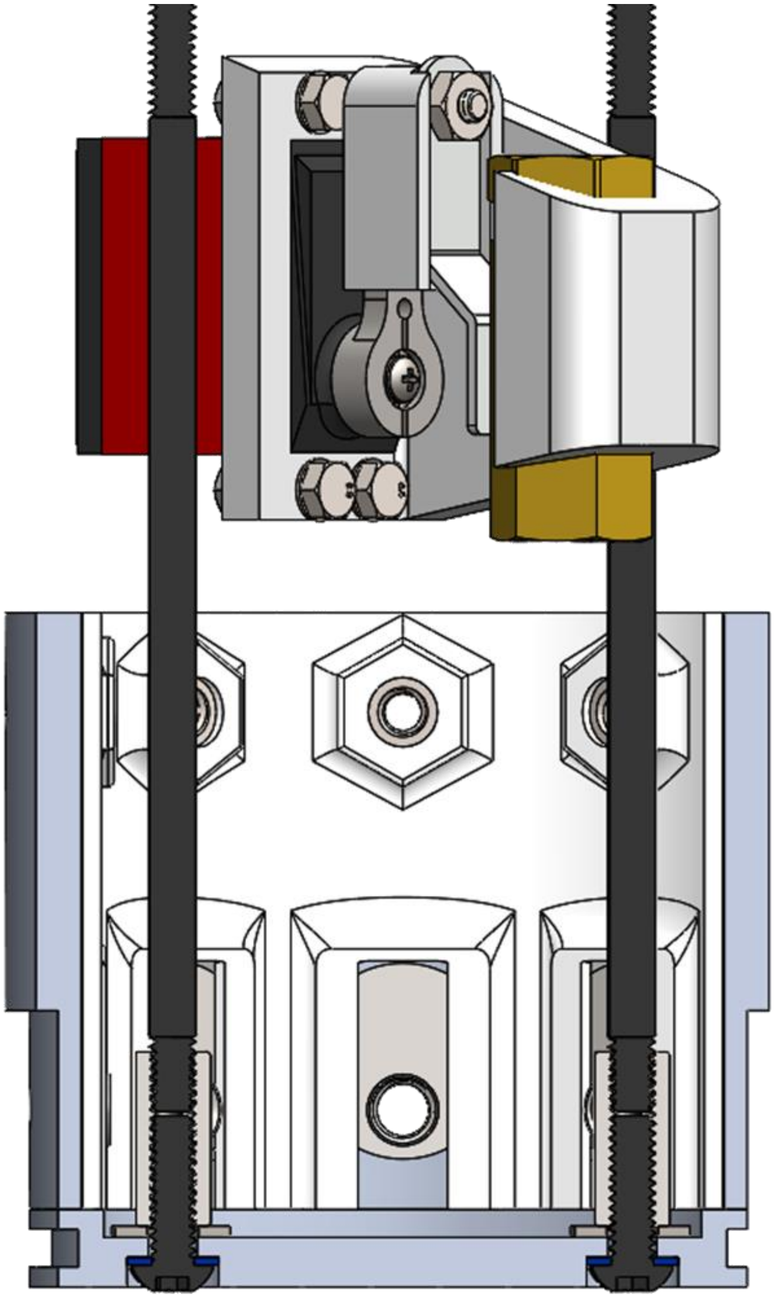
OP 4: Recovery Bulkhead Integration

1. Thread QTY 2 91025A568 studs into the coupling nuts until they contact the ends of the screws installed through the forward bulkhead or reach the ends of the stud threads. Tighten to hand-tight; hardware installed in a later step will prevent rotation.



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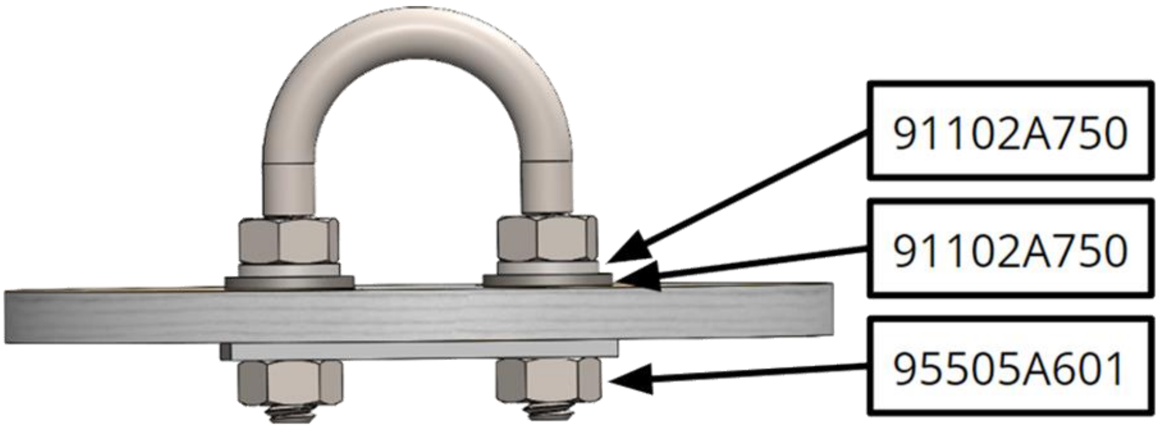
OP 4: Recovery Bulkhead Integration

2. Remove the hex nuts and mounting plate included with the 3043T643 U-bolt, then thread the included hex nuts all the way to the end of the thread, tightening until snug. Place QTY 2 91102A750 split lock washers and QTY 2 92141A029 flat washers onto the ends of the U-bolt, then insert the U-bolt into the holes in the recovery bulkhead. Secure with the included mounting plate and QTY 2 95505A601 hex nuts. Tighten both hex nuts approximately 1/4 turn past full compression of the lock washers.



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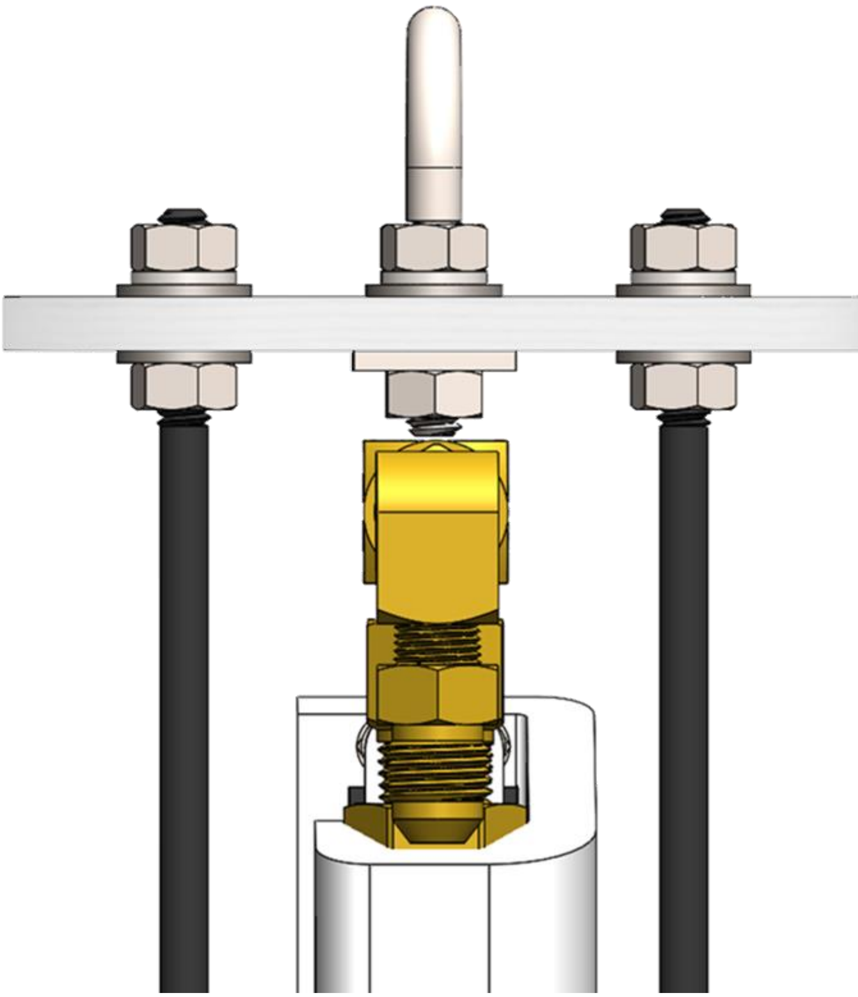
OP 4: Recovery Bulkhead Integration

3. Thread QTY 2 95505A601 hex nuts about ¾" onto the threaded studs, and place QTY 2 92141A029 flat washers on top of the nuts. Place the recovery bulkhead with U-bolt onto the threaded studs, and secure with an additional QTY 2 95505A601 hex nuts, QTY 2 92141A029 flat washers, and QTY 2 91102A750 split lock washers as shown. Tighten the hex nuts on each stud approximately 1/4 turn past full compression of the lock washers.



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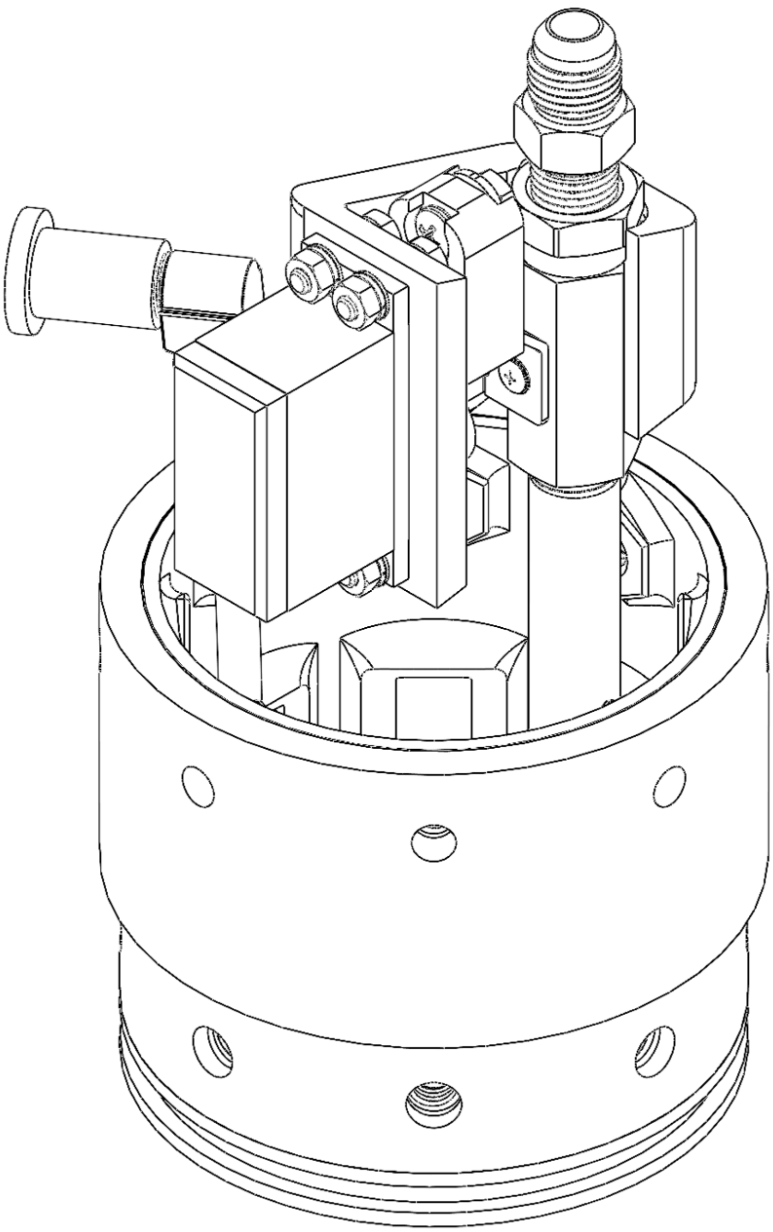
OP 5: Oxidizer Bulkhead Subassembly



OP 5: Oxidizer Bulkhead Subassembly

Gather the following:

QTY	Part Number	Description
1	SABV-14NPT-FF	Servo-Actuated Ball Valve Assembly, 1/4NPT Female
1	BKHD-OX-0238-8NPT-4NPT	Oxidizer Tank Bulkhead, 3.75" Diameter, -238 O-ring Gland, 1/8NPT & 1/4NPT Ports
1	INRG-200S-8X3125C-8X250C	Tank Interface Ring, 2" Shoulder Length, 8X 5/16" & ¼" Clearance Holes
1	NTRG-8X3125WN-8X25HN	Nut Ring, Printed, for 8X 5/16" Weld Nuts & ¼" Hex Nuts
8	94579A550	Steel Offset-Barrel Narrow-Base Weld Nut, 5/16"-24 Thread Size
8	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
1	44665K137	Aluminum Pipe Nipple, 1/4NPT, 4" Lg
1	50675K163	37 Degree Flared Adapter for 3/8" Tube OD x 1/4 NPT Male
1	7768K21	Brass Threaded Check Valve, 1/8 NPT Female x NPT Male
2	9396T31	High-Pressure Push-to-Connect Tube Fitting, 1/4" Tube OD x 1/8 NPTF Male
1	50785K41	High-Pressure Brass Pipe Fitting 90 Degree Elbow Adapter, 1/8 NPT Female x Male
3.75 in.	9685T3	High-Pressure Hard Nylon Plastic Tubing, 0.15" ID, 1/4" OD
1	QDC-750x125FLG-281FB-8NPT	Quick Disconnect, ¾" x ⅛" Flange, 9/32" Female Bore, 1/8 NPT
-	-	PTFE Thread Sealant Tape

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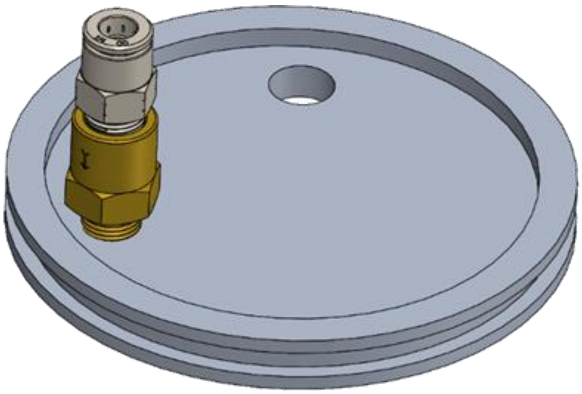
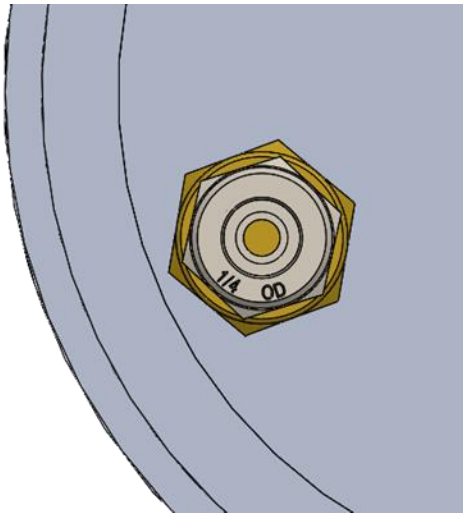
OP 5: Oxidizer Bulkhead Subassembly

1. Apply 2-3 clockwise wraps of PTFE tape to the male threads of QTY 1 9396T31 high-pressure push-to-connect fitting (1/8 NPT) and QTY 1 7768K21 brass check valve. Thread the push-to-connect fitting into the check valve, and tighten until snug. Then, thread the check valve into the 1/8 NPT port on the OBKHD-D375-0238-4NPT oxidizer tank bulkhead and tighten until snug. Once snug, continue to tighten the check valve until one corner of the check valve points radially outward (<1/6 turn required). This will ensure sufficient clearance to the nut retaining ring.

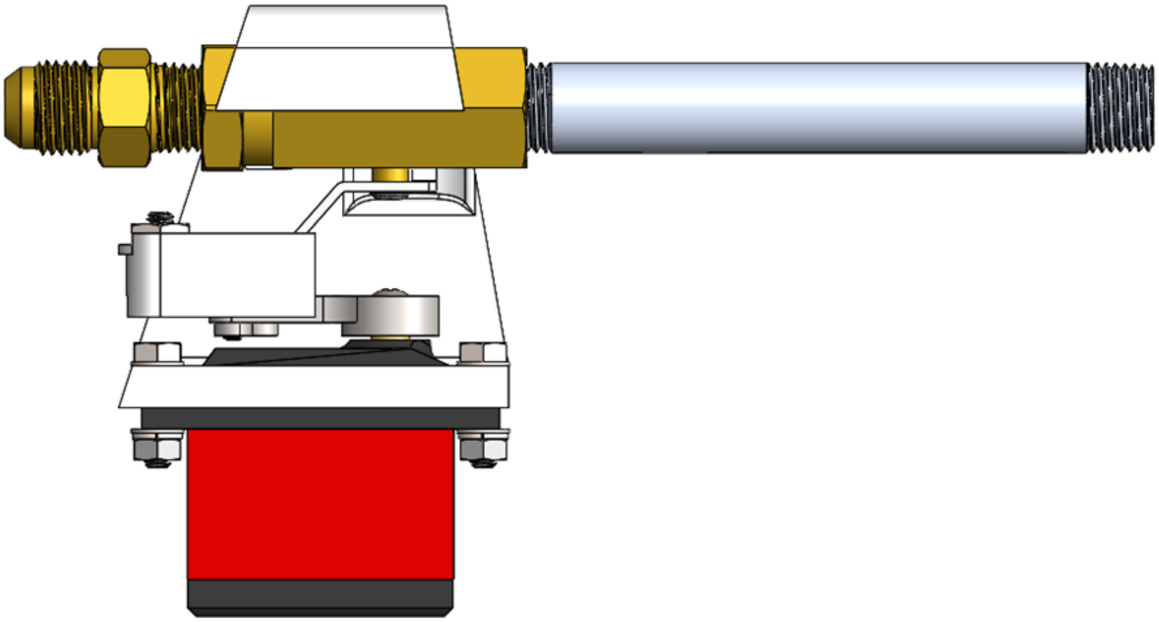




OP 5: Oxidizer Bulkhead Subassembly

2. Apply 2-3 clockwise wraps of PTFE tape to both ends of QTY 1 44665K122 Aluminum Pipe Nipple, and thread one end into port of QTY 1 SABV-14NPT-FF valve as shown. Note the orientation of the valve bracket. Only tighten the pipe nipple to hand-tight at this time.

3. Apply 2-3 clockwise wraps of PTFE tape to the threads of of QTY 1 50675K163 37 degree flared adapter fitting and thread into the other side of the SABV-14NPT-FF valve as shown. Note the orientation of the valve bracket. Tighten the fitting until snug, 1-3 turns from finger tight.



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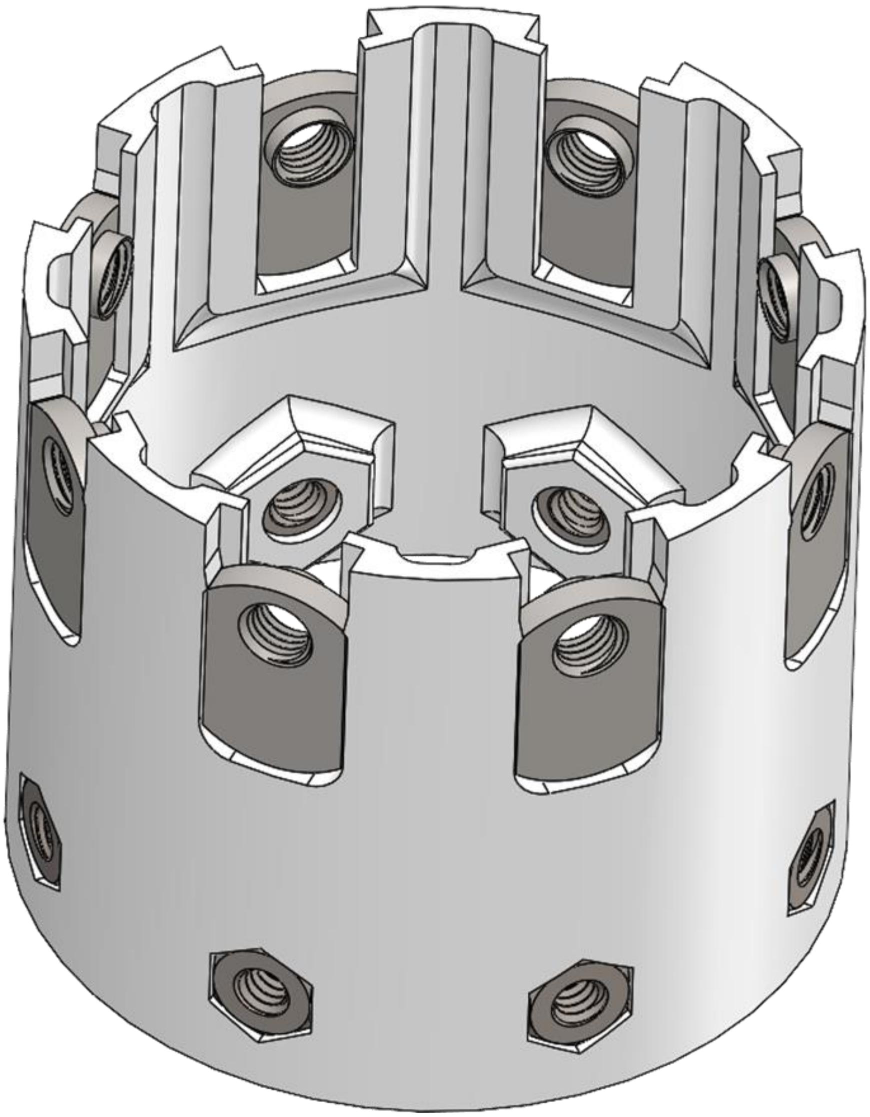
OP 5: Oxidizer Bulkhead Subassembly

4. Place QTY 8 94579A550 5/16-24 weld nuts and QTY 8 95505A601 1/4-20 hex nuts into QTY 1 NTRG-3125WN-25HN-8X printed nut ring as shown.

   A strip of scotch tape or similar may be used to retain the nuts prior to insertion into the machined integration ring. Note that adhesive should not be used to bond the nuts in place. They must be free to float within their cutouts to accommodate any hole misalignment.

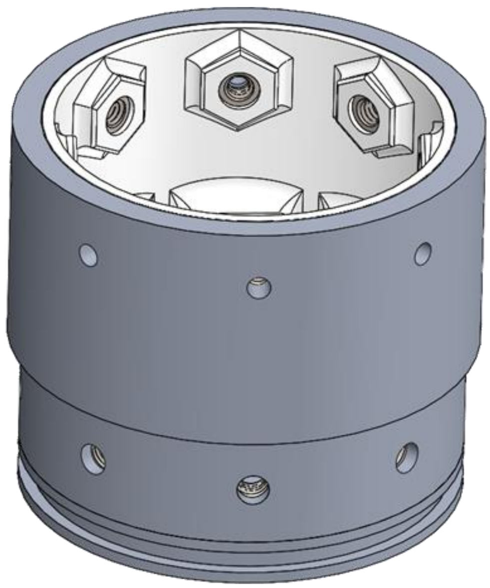


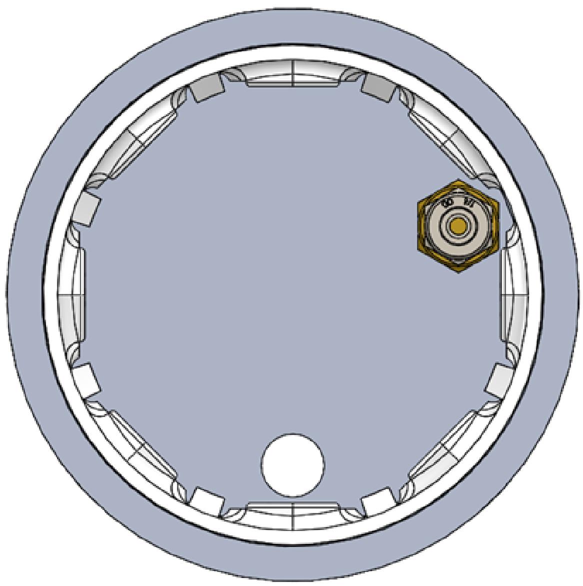
OP 5: Oxidizer Bulkhead Subassembly

5. Place QTY 1 Tank Interface Ring onto the outer face of the bulkhead as shown.

   Note: the interface ring MUST be installed prior to integrating the valve assembly onto the bulkhead.

6. Insert the fully populated nut ring into QTY 1 INRG-375-3125C-250C-8X tank interface ring as shown. The 5/16-24 weld nuts should align with the larger holes on the smaller diameter portion of the interface ring. Align the nut ring and interface ring so that the oxidizer fill check valve aligns with the section that does NOT have a centering tab, as shown.





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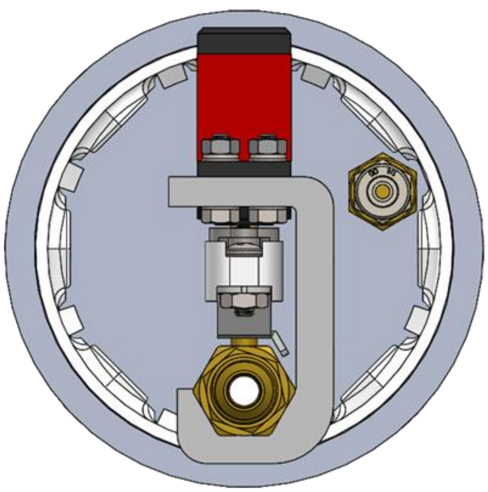
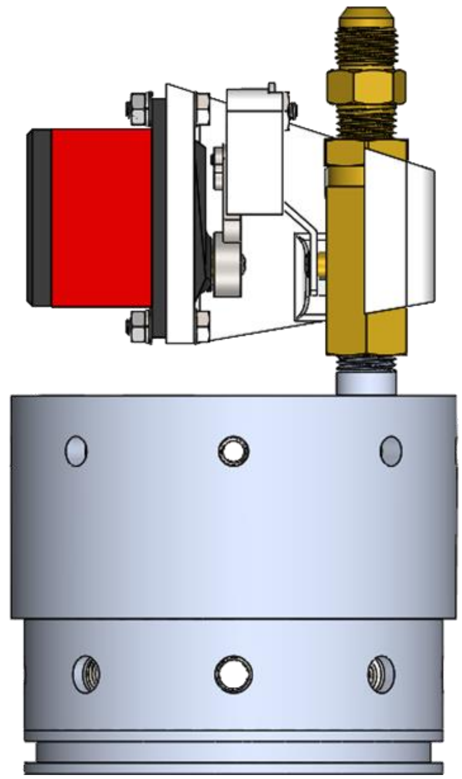
OP 5: Oxidizer Bulkhead Subassembly

7. Thread the aluminum pipe nipple connected to the oxidizer valve into the 1/4 NPT port on the OBKHD-D375-0238-4NPT oxidizer tank bulkhead. Tighten until snug, then rotate no more than one full turn until the valve assembly aligns with the diameter of the bulkhead as shown.





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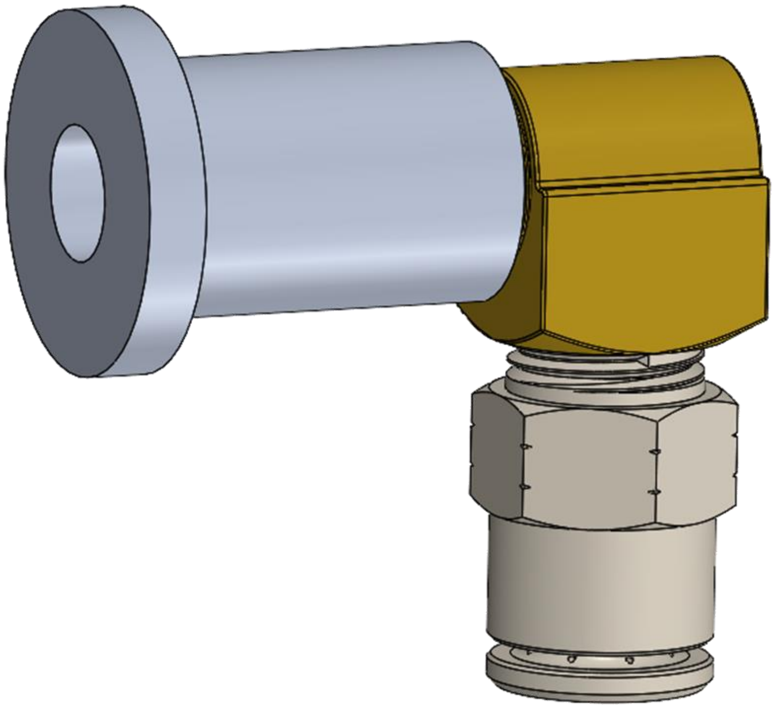
OP 5: Oxidizer Bulkhead Subassembly

8. Apply 2-3 clockwise wraps of PTFE tape to the threads of QTY 1 50785K41 brass elbow fitting and QTY 1 9396T31 push-to-connect fitting. Assemble the two fittings and QTY 1 QDC-750x125FLG-281FB-8NPT QD fitting as shown, tightening all threads until snug, 1-3 turns past finger tight.



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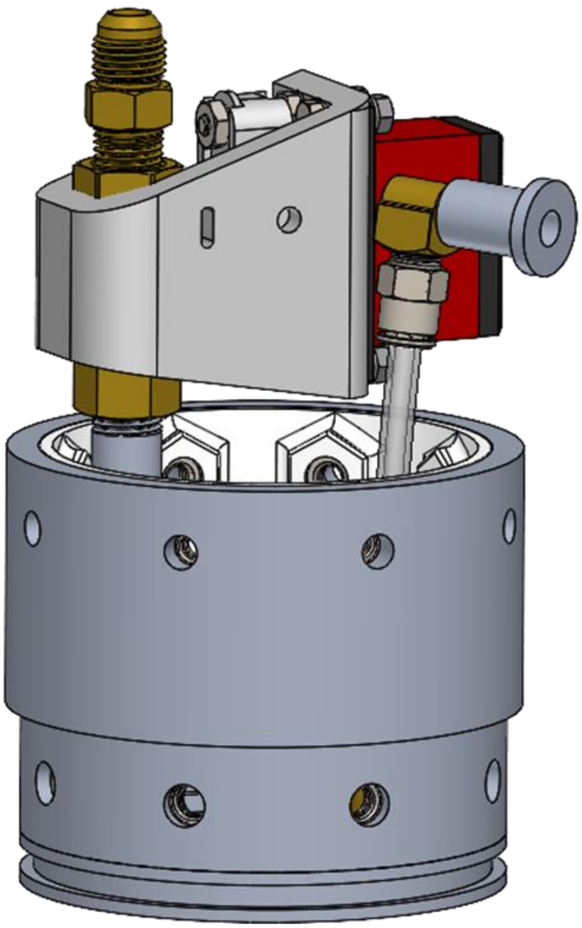
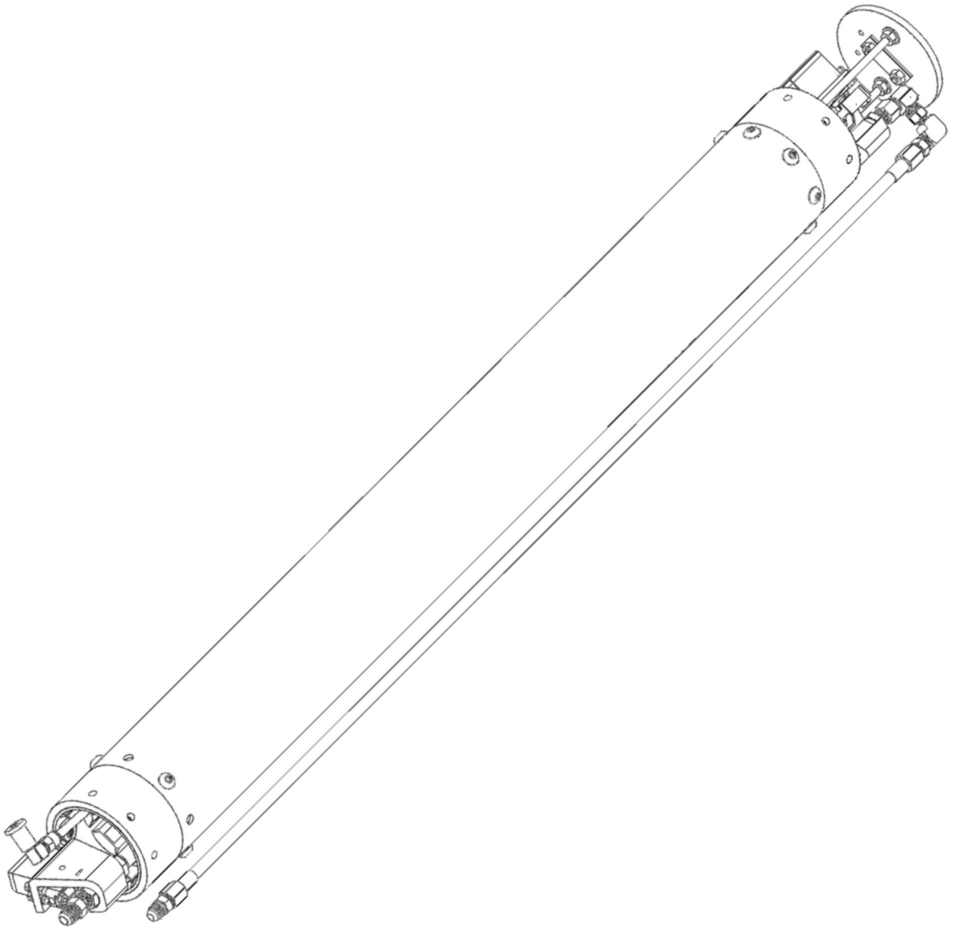
OP 5: Oxidizer Bulkhead Subassembly

9. Cut a section of 9685T3 tubing 3.625-3.875 inches long. Mark the tube at 0.56 inches from each end using a permanent marker.

10. Insert one end of the tube into the push-to-connect fitting on the oxidizer fill check valve, until the mark aligns with the top face of the fitting, or the tube is fully seated. Then, connect the push-to-connect fitting on the QD assembly to the other end of the tube, inserting the tube up to the mark, or until fully seated.



OP 6: Tank Assembly



OP 6: Tank Assembly

Gather the following:

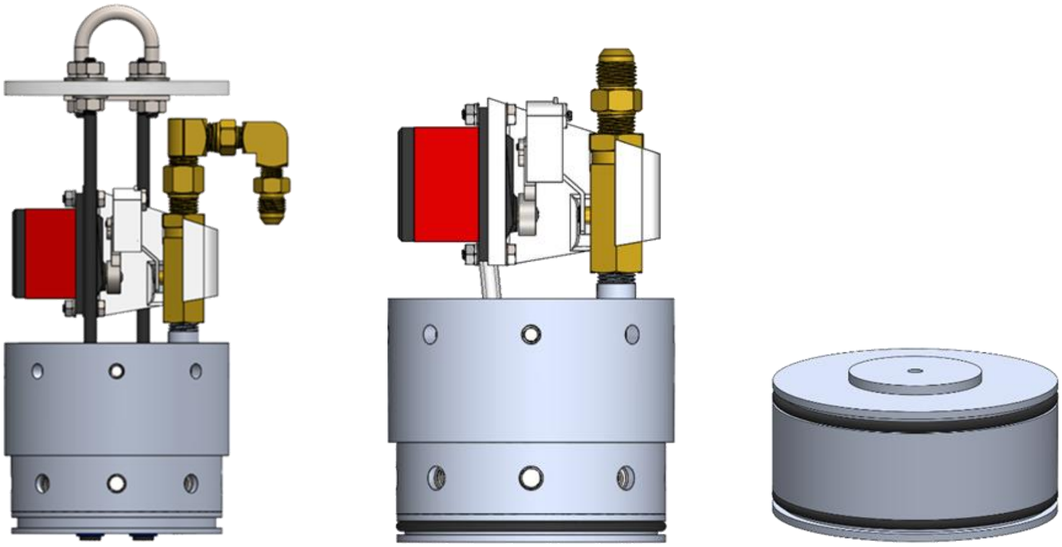
QTY	Part Number	Description
1	-	Fuel Bulkhead Subassembly
1	-	Oxidizer Bulkhead Subassembly
1	TANK-36L-047V-2X8X313C	Tank Tube, Drilled, 36″ Long, 1.2mm (.047″) Vent, 8X 5/16″ Clearance Holes Per End
1	PSTN-2XO238-250T20	Piston, 2X -238 O-Ring Glands, ¼-20 Tapped Hole
4	9452K226	-238 Buna-N O-ring
12	9255A378	Button Head Hex Drive Screw, Black-Oxide Alloy Steel, 5/16"-24 Thread, 1/2" Long
1	4468K858	High-Pressure Braided Chemical Hose with Fittings Brass 1/2"-20 Thread Size Flare UNF Female, 3/8" OD - 42"
1	50675K135	37 Degree Flared Straight Connector for 5/16" Tube OD, 1-3/8" Long

OP 6: Tank Assembly

1. Apply a liberal amount of grease to the QTY 5 -230 Buna-N O-rings. Set aside on a clean surface.

2. Install QTY 1 -230 Buna-N O-ring into the O-ring glands on each of the QTY 2 Bulkhead Subassemblies.

3. Install QTY 2 -230 Buna-N O-rings onto the fuel tank piston.



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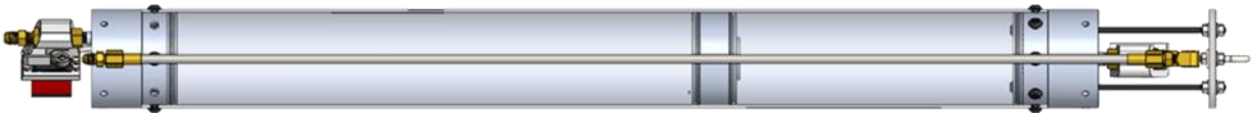
OP 6: Tank Assembly

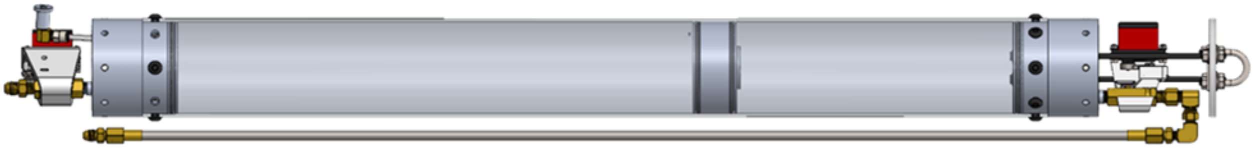
Reference the images below for the following steps on this operation.



Fuel Line Raceway Side

-90 Degrees from Fuel Line Raceway

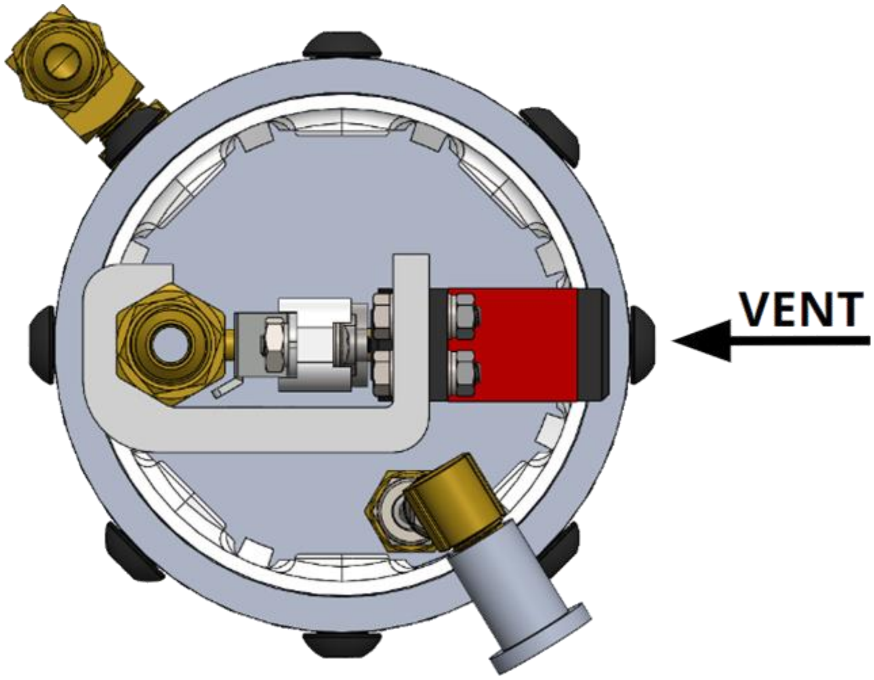
QD and Vent Side: 180 Degrees from Fuel Line Raceway



Rail Guide Side: +90 degrees from Fuel Line Raceway

OP 6: Tank Assembly

Reference the images below for the following steps on this operation.



Relative Clocking of Fuel Line Raceway, Oxidizer Valve, Vent, and QD

OP 6: Tank Assembly

4. Insert the piston with O-rings into the tank. The face of the piston with the ¼-20 threaded extraction hole should face towards the forward end where the fuel bulkhead will be inserted; this is the end closest to the vent orifice. Take care not to damage the O-rings; apply slow, even pressure to compress the seals into the tube. Using a marked piece of PVC pipe, push the piston down until the top face sits 12.125-12.25 inches from the end of the tube.

5. Insert the oxidizer bulkhead/valve subassembly into the aft end of the tank (farthest from the vent orifice). Note the orientation relative to the designated rail guide position.Take care not to damage the O-ring; apply slow, even pressure to compress the seal into the tube.

   Use the tank interface ring to ensure that the bulkhead is seated at the correct depth. Align the bolt holes in the interface ring to the tank bolt holes. If the ring and tank were match drilled, ensure the clocking marks are aligned.

6. Insert the fuel bulkhead/valve subassembly into the forward end of the tank. Note the orientation relative to the designated rail guide position. Take care not to damage the O-ring; apply slow, even pressure to compress the seal into the tube.

   Use the tank interface ring to ensure that the bulkhead is seated at the correct depth. Align the bolt holes in the interface ring to the tank bolt holes. If the ring and tank were match drilled, ensure the clocking marks are aligned.

OP 6: Tank Assembly

7. Install QTY 8 91255A378 screws through the tank and retaining ring bolt holes at the forward end (Fuel Valve side), threading into the weld nuts in the nut retaining ring. Insert all screws before tightening to allow freedom of movement for alignment. Once all 8X screws are engaged in the threads, tighten to snug using a 3/16" hex key. These fasteners are loaded primarily in shear, and do not need to be extremely tight.

8. Install QTY 4 91255A378 screws through the tank and retaining ring bolt holes at the aft end (Oxidizer Valve side), threading into the weld nuts in the nut retaining ring. Skip every other hole, and ensure that the screw locations are aligned relative to the valve and rail guide positions as shown in the reference images. The remaining bolt holes will be used to secure the thrust structure to the tank at a later time. Leave all 4X screws on this end slightly loose.

   CAUTION: *The tank cannot be pressurized until all 8X screws are installed. If the tank is to be pressure tested prior to integration of the fin bracket/thrust structure assembly, install an additional 4X 91255A378 screws and tighten all screws to snug.*

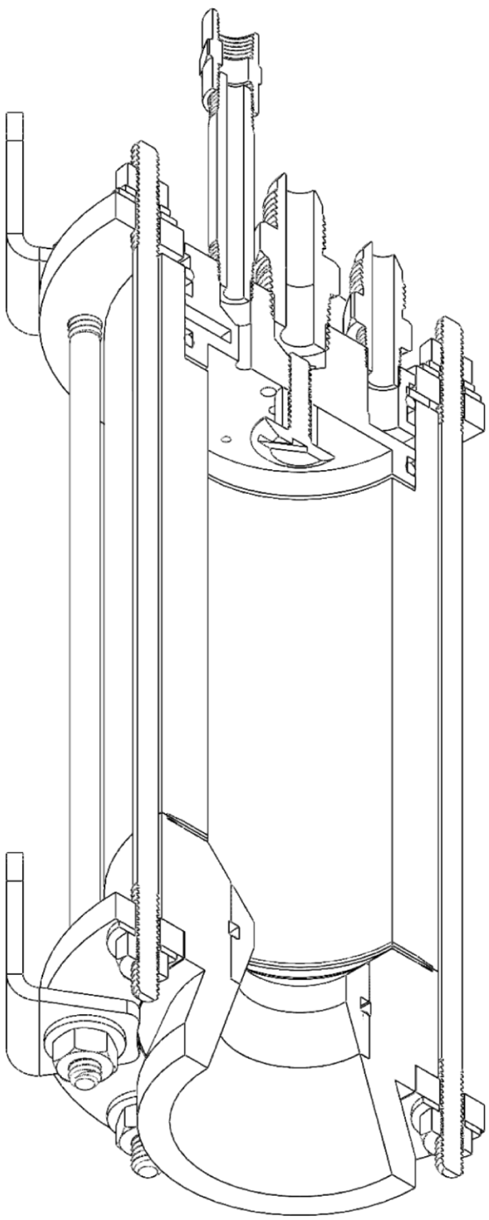
OP 6: Tank Assembly

9. Install QTY 1 50675K135 flared union fitting into one end of QTY 1 4468K858 hose. Tighten to wrench tight (approx. 80 ft-lbs).

10. Connect the other end of QTY 1 4468K858 hose to the flared fitting on the outlet of the fuel valve, located at the forward end of the tank. Tighten to wrench tight (approx. 100-150 in-lbs).

    The fuel line may be secured to the tank using zip ties and/or tape as desired. A strip of aluminum tape running lengthwise is recommended. Do not fully cover the fuel line with tape at this time, as the fuel valve servo wire must also be secured in a similar manner.

OP 7: Thrust Chamber Assembly



OP 7: Thrust Chamber Assembly

Gather the following:

QTY	Part Number	Description
1	NZZL-45C20D-200E	Nozzle, 45/20 Degree, 3.00" OD, 2.00" Exit, Bored for Throat Insert
1	THRT-45C20D-100T	Throat Insert, 45/20 Degree, 1.00" Throat
1	CMBR-200DI-250B-5375L	Combustion Chamber, 2.00" ID, 2.50" Injector Bore, 5.375" Long, MS V1.2
1	INJC-2X8NPT-38NPT-250T20-2XO230-BASIC	Injector, 2X 1/8NPT ports, 1X 3/8NPT Port, ¼-20 Tapped Hole, 2X -141 O-ring Glands, Basic Orifice Pattern
1	50675K164	37 Degree Flared Adapter for 3/8" Tube OD x 3/8 NPT Male
1	50675K435	37 Degree Flared Adapter for 5/16" Tube OD, 1/8 Pipe Size
1	50785K171	High-Pressure Brass Pipe Nipple, 1/8 Pipe Size, 2" Long
1	50785K91	High-Pressure Brass Straight Connector with Hex Body, 1/8 NPT Female
2	9396K79	High-Temperature High-Purity Silicone O-Ring, Dash Number 141
1	90213A101	Inverted External Retaining Ring for 2.5" OD, Black-Phosphate 1060-1090 Spring Steel
1	94095K114	High-Temperature Graphite Gasket for ANSI Class 600, for Pipe Size 1, 1-5/16" ID
2	FLNG-ST-25T-8X250C	Chamber Flange, Steel, .25" Thick, 8X 1/4" Clearance Holes, MS V1.2
8	BRKT-90A-125T-2X250C	Bracket, Thrust Chamber Mounting, 90-degree Angle, 1/8" Thick Aluminum, 2X 1/4" Clearance Holes, MS V1.2
16	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
16	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
8	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
8	90281A102	Black-Oxide Steel Threaded on Both Ends Stud, 1/4"-20 Thread Size, 8" Long, 1" Long Threads
1	90015A410	Low-Profile Ultra-Wd Truss Head Slotted Screw 1/4"-20 Thread, 3/4" Long
1	9368T14	High-Temperature Dry-Running 841 Bronze Sleeve Bearing for 1/4" Shaft Diameter and 3/8" Housing ID, 3/8" Long
1	8284N57	Garter Spring Hard Drawn Steel, 1.529" OD, 1.341" ID
-	N/A	PTFE Tape
-	N/A	O-ring Grease

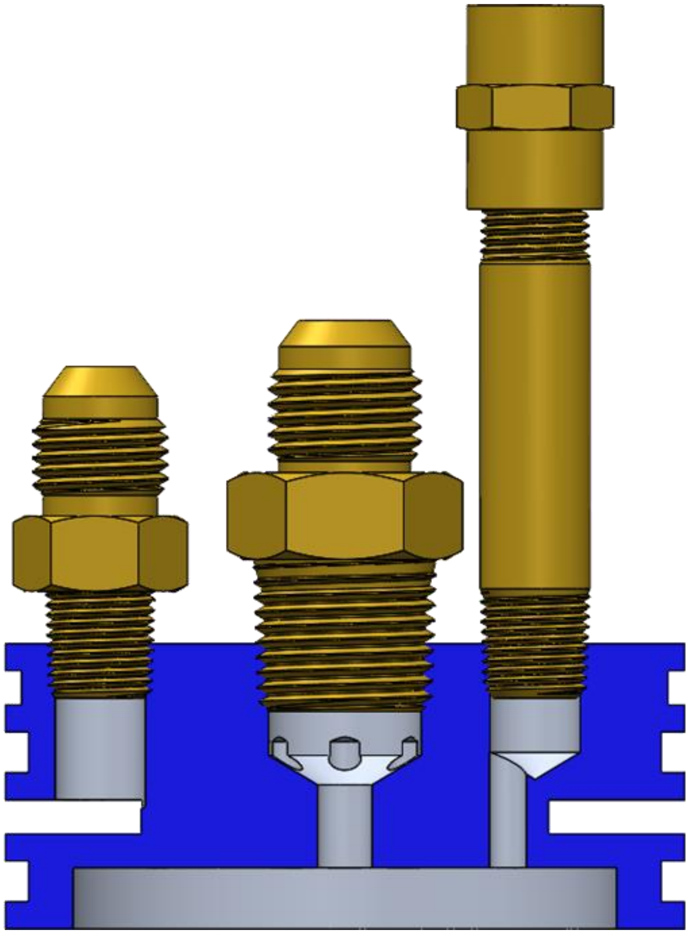
OP 7: Thrust Chamber Assembly

1. Apply 2-3 clockwise wraps of PTFE tape to the male threads of QTY 1 50675K164 and QTY 1 50675K435 flared adapter fittings and both ends QTY 1 50785K171 pipe nipple. Install the fittings into the injector ports as shown, with QTY 1 50785K91 installed on the upper end of the pipe nipple. Tighten all fittings to snug, 1-3 turns past finger-tight. A strap wrench is recommended to grip the injector while installing fittings.

   Install the 50675K164 fitting into the center port (oxidizer inlet) first, to allow for tool access. A thin-walled socket may also be used to remove dependency on order of installation.

   Pliers or vise-grips should be used to install the 50785K171 pipe nipple. Marring of the surface is acceptable and non-detrimental.

   Note: Injector sectioned to show port geometry. Section cut faces are highlighted in blue.



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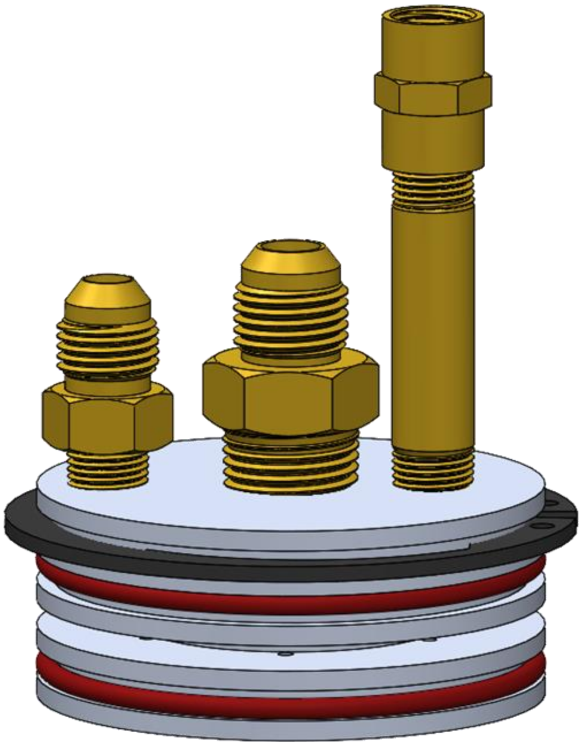
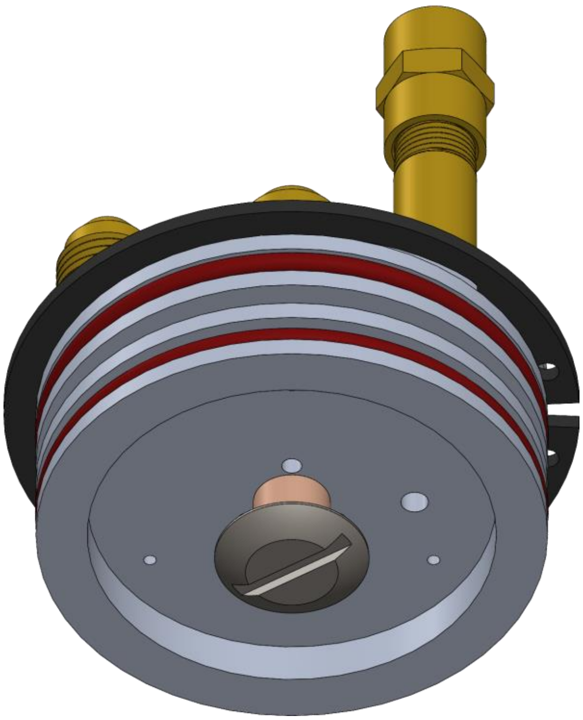
OP 7: Thrust Chamber Assembly

2. Install QTY 1 97633A450 external retaining ring into the upper-most groove on the injector as shown. Ensure that the ring is fully seated into the groove. The clocking of the retaining ring does not matter.

3. Install QTY 1 9368T14 bronze sleeve bearing and QTY 1 90015A410 truss head slotted screw as shown. Tighten firmly, ensuring that the bearing is compressed to the injector face.

4. Liberally grease QTY 2 9396K79 -141 high-temperature O-rings, and install into the O-ring glands on the injector as shown. The deepest groove (2nd from the injector face) is the fuel manifold; do NOT install an O-ring in this groove.





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OP 7: Thrust Chamber Assembly

5. Install the injector assembly into the larger bore in the combustion chamber. Take care not to damage the O-rings; apply slow, even pressure to compress the seal into the bore.

   When the injector is fully seated, the external retaining ring should contact the forward face of the combustion chamber. A small gap is acceptable at this time, as the injector will be drawn in by the tie-rods on a later step.

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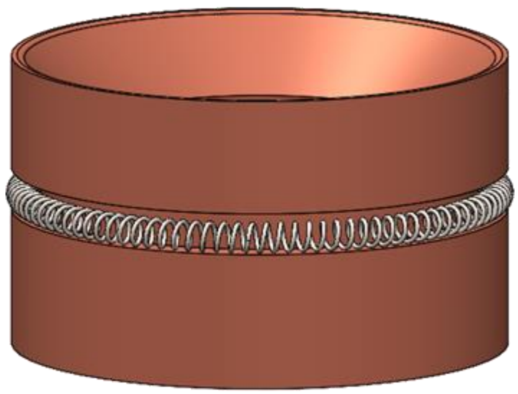
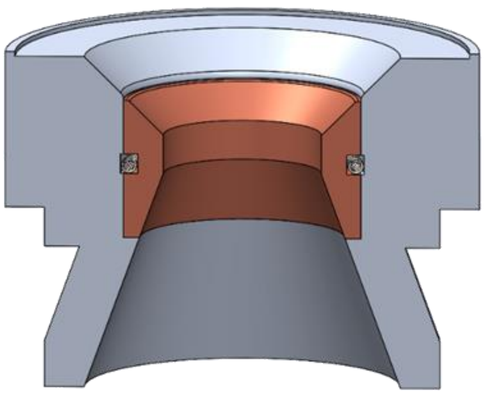
OP 7: Thrust Chamber Assembly

6. Place QTY 1 8284N57 spring into the groove of QTY 1 THRT-45C20D-100T nozzle throat insert.

7. Coat the outside of the throat insert, including the spring, in a thin layer of grease, then install the insert into the nozzle as shown in the section view. A wooden dowel or plastic rod may be used to press or mallet the insert into the bore until the spring seats in the retaining groove. The spring prevents the nozzle throat insert from becoming easily dislodged and falling into the chamber during handling.

   Note that the nozzle throat insert does not have a soft seal; the compressive load against the bottom face of the nozzle bore generated by chamber pressure is sufficient to minimize blow-by, without requiring a gasket or O-ring.



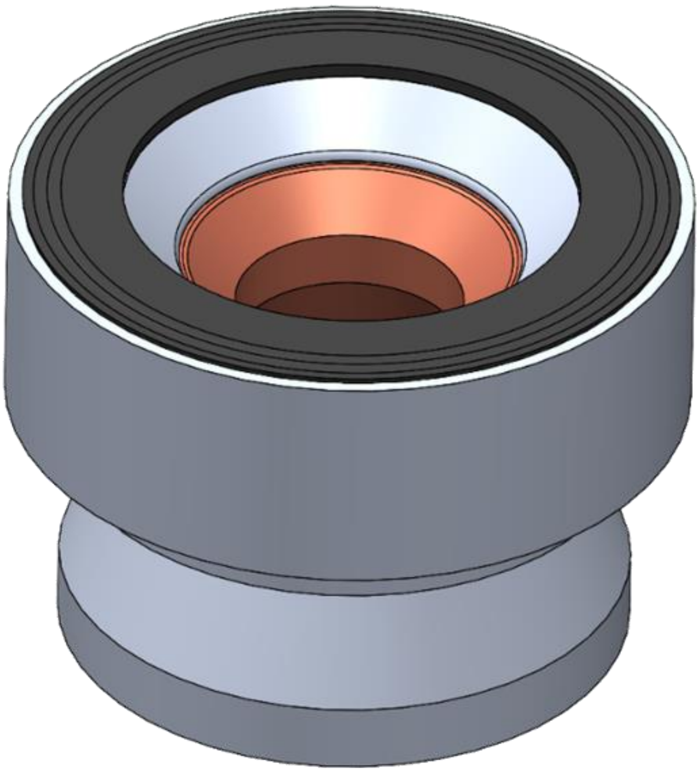


OP 7: Thrust Chamber Assembly

8. Using a razor knife, trim the inner edge of the 94095K114 graphite gasket to an approximately 2-inch inner diameter. A high degree of precision is not required, so long as there is at least 3/8" of width remaining on all sides of the gasket. Slight protrusion into the combustion chamber is non-detrimental.

   Once trimmed, place the gasket onto the flat face of the nozzle as shown.

   Note: There is a thin layer of stainless steel foil in the middle of the gasket, however it can be cut easily with a sharp blade.



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OP 7: Thrust Chamber Assembly

9. Place QTY 1 FLNG-ST-25T-8X250C flange over the external retaining on the injector. Place the second flange around the nozzle, and stack the injector/chamber on top of the nozzle and gasket as shown.

   Tip: use a strip of aluminum tape to hold the nozzle concentric to the chamber (not shown).

10. Thread QTY 4 95505A601 hex nuts onto QTY 4 90281A102 threaded studs with approximately .28" of thread protruding. Place QTY 1 91102A750 split lock washers onto each rod underneath the nuts, followed by QTY 1 92141A029 flat washer on each rod. Then, insert the rods through the upper flange as shown.

    Note the location of the flange holes and rods relative to the injector fittings. Two holes must align with the fuel inlet and igniter port, and the rods should be installed the positions shown, adjacent to and +/-90 degrees from the injector fittings.

11. Place QTY 1 92141A029 flat washer and QTY 1 95505A601 hex nut onto the lower end of each rod to retain the lower flange. Thread the nuts on until the flange is seated against the nozzle, with approximately equal thread protrusion on each end of the rod. Tighten the nuts to snug; they will be fully tightened on a later step.

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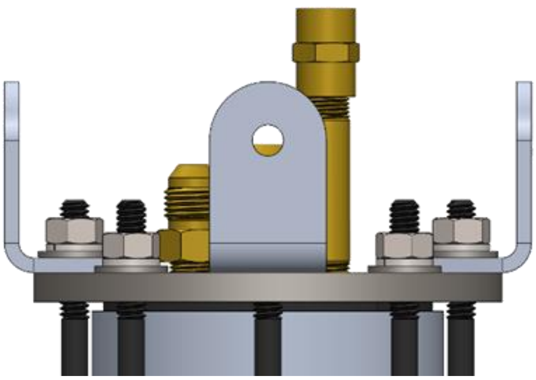
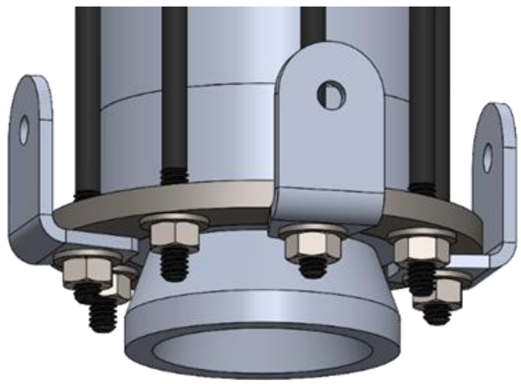
OP 7: Thrust Chamber Assembly

12. Thread QTY 4 95505A601 hex nuts onto QTY 4 90281A102 threaded studs with approximately .15" of thread protruding. Place QTY 1 91102A750 split lock washer onto each rod underneath the nuts, followed by QTY 1 92141A029 flat washer on each rod.

    Then, place QTY 1 BRKT-90A-125T-2X250C brackets onto each rod, with the longer tab extending vertically upward. Insert the rods through the unoccupied holes in both flanges.

    Place an additional QTY 4 QTY 4 BRKT-90A-125T-2X250C brackets onto the rods at the aft end of the chamber assembly, in the same orientation. Secure with an additional QTY 4 95505A601 hex nuts and QTY 4 92141A029 flat washers to complete the assembly as shown. Lock washers are not required on the aft end.





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OP 7: Thrust Chamber Assembly

13. Tighten the nuts on all 8 rods until the lock washers are fully compressed, then approximately ¼ additional turn. Ensure roughly equal thread protrusion on both ends of each rod.

    Note: It is recommended to tighten the nuts in a star pattern. After tightening all 8X nuts, repeat the pattern as needed until all nuts are found to remain tight. Some visible deflection of the FLNG-ST-25T-8X250C flange plates is normal, and does not indicate a problem.

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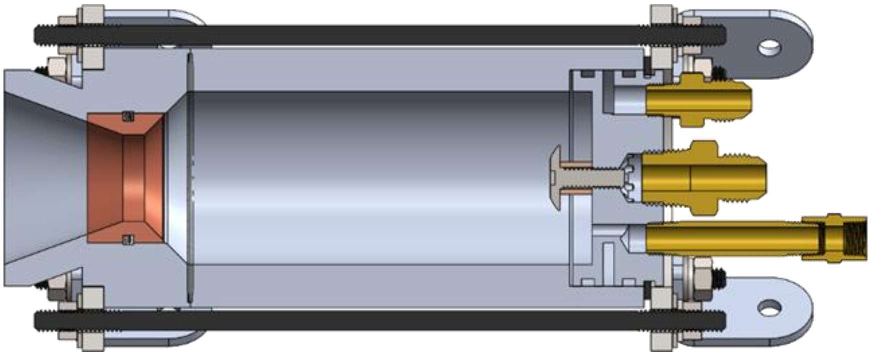
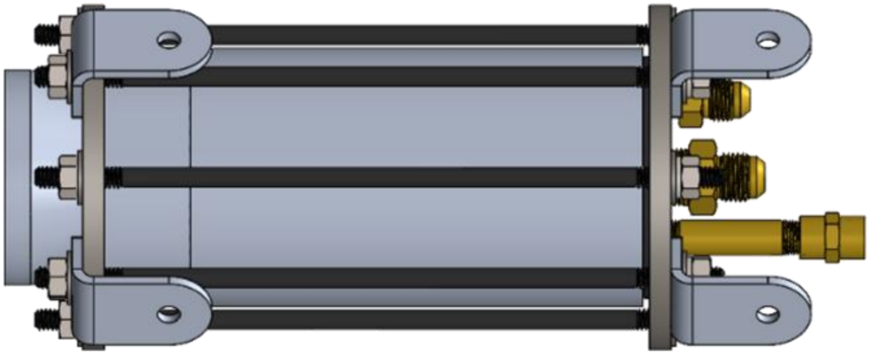
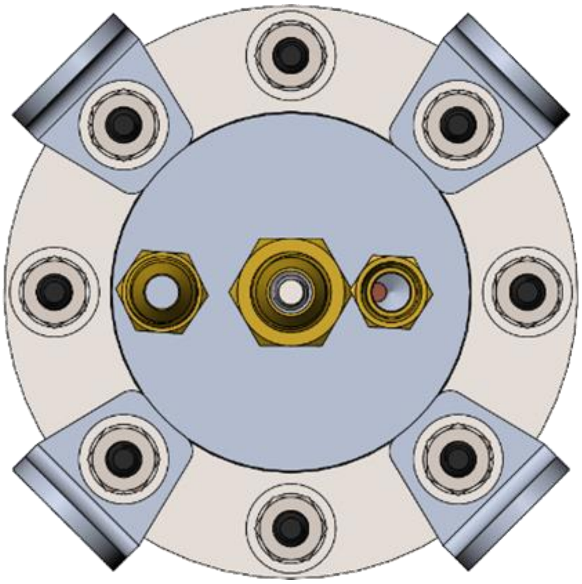
OP 7: Thrust Chamber Assembly

Reference the images below for the configuration of the complete thrust chamber assembly.







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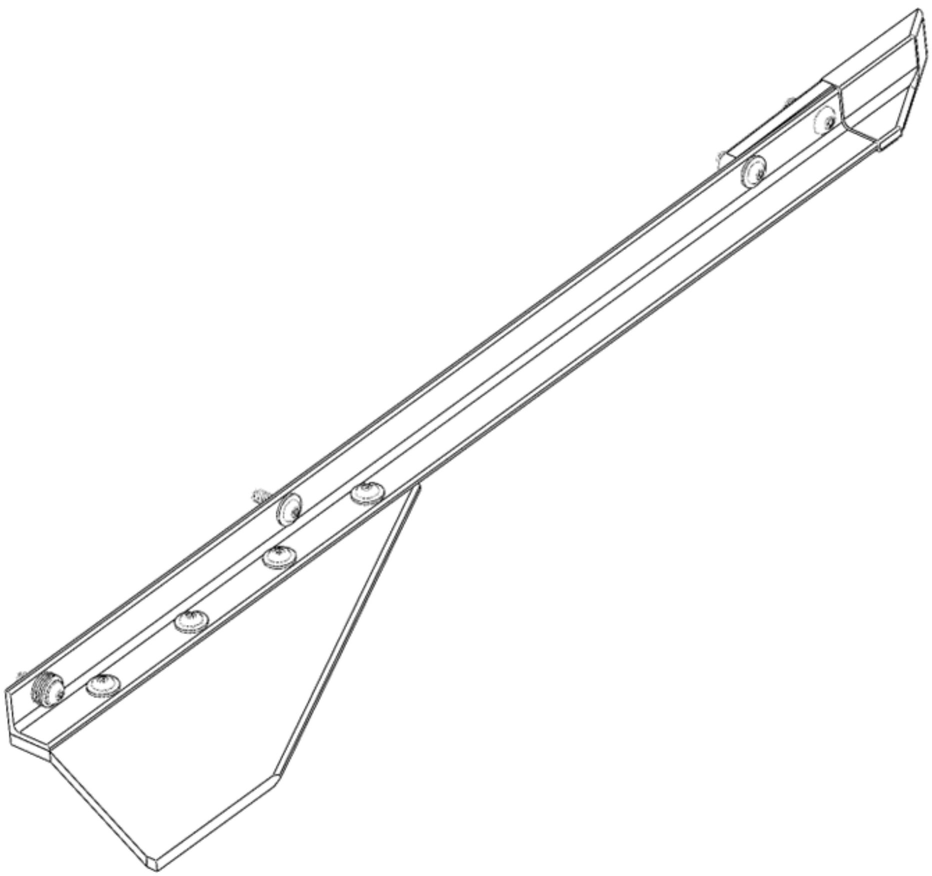
OP 8: Fin Bracket Subassemblies



OP 8: Fin Bracket Subassemblies

Gather the following:

QTY	Part Number	Description
4	8982K402-OM971	1" X 1" X .125" 6061-T6 Al Angle 24" Long, Online Metals Part No. 971
4	FIN-STD-250T-4X250C	Fin, Standard Profile, Plywood, 1/4" Thick, 4X 1/4" Clearance Holes* *(Or alternative/custom fins)
16	91306A279	Button Head Hex Drive Screw, Zinc-Plated Alloy Steel, 1/4"-20 Thread, 7/8" Long
32	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
16	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
16	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
4	AERO-100X100X0125	Aerodynamic Fin Bracket Tip, for 1.00 X 1.00 X .125 Aluminum Angle (Optional)
1	TMPLT-FIN-BRKT-1X1-AFT	Fin Bracket Drill Jig, Aft
1	TMPLT-FIN-BRKT-1X1-FWD	Fin Bracket Drill Jig, Fwd

Note: All steps in this OP will be performed four times to build four identical fin bracket assemblies. The quantities listed are for four complete assemblies.

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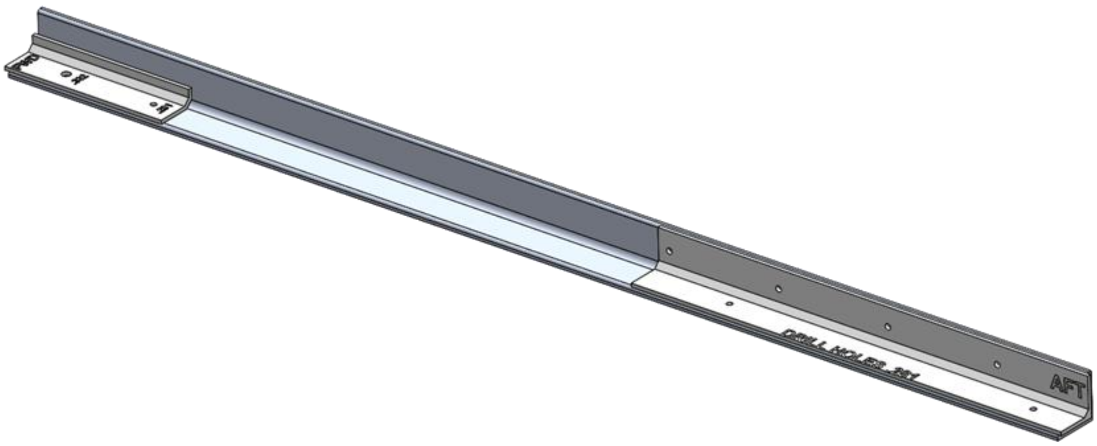
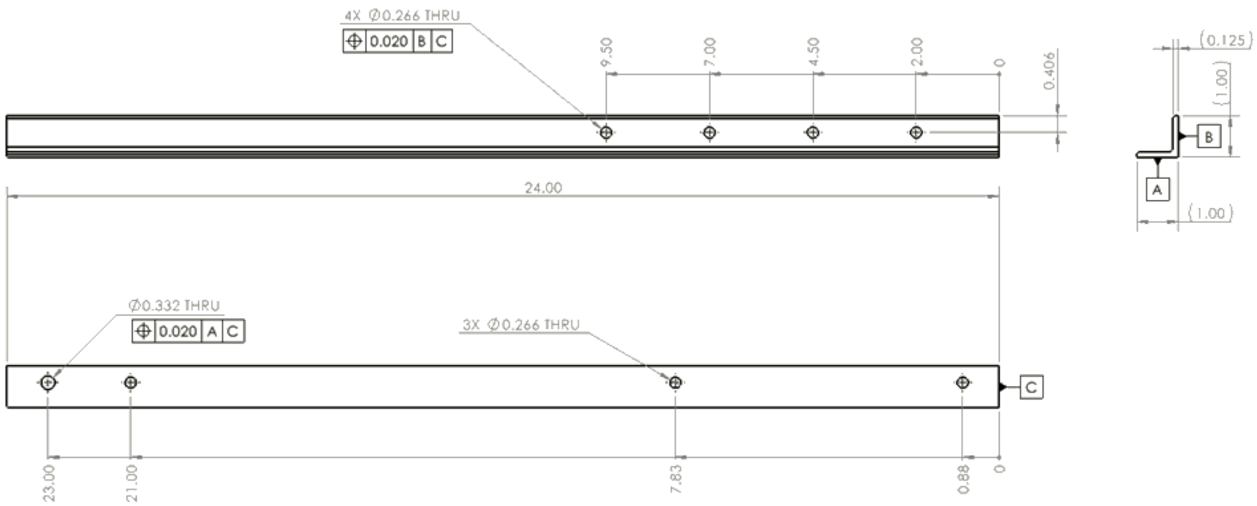
OP 8: Fin Bracket Subassemblies

1. Drill 1X .332" and 7X .281" holes in QTY 4 pieces of 1"X1"X.125" aluminum angle. The 3D printed templates may be used to mark the hole locations. If the templates are not used, refer to the drawing below. A drill press or mill is recommended. If using a drill press or hand drill, use an automatic center punch at each hole location prior to drilling to help prevent the bit from walking.





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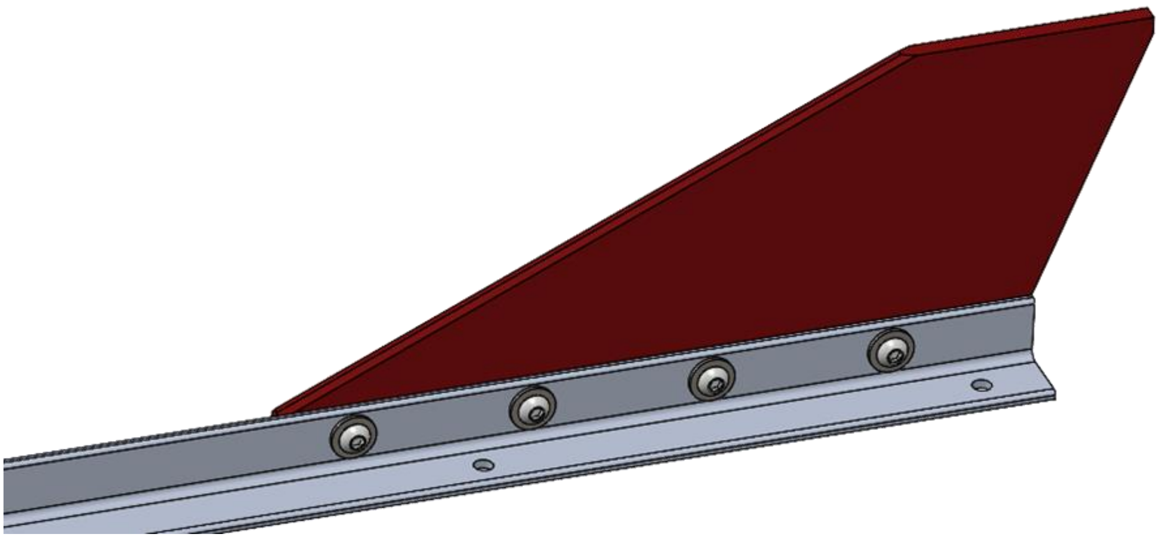
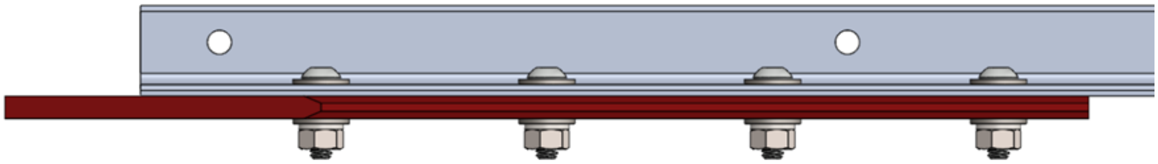
OP 8: Fin Bracket Subassemblies

2. Mount QTY 4 FIN-STD-250T-4X250C Fins (or alternate/custom fins) to the drilled aluminum angle brackets using QTY 4 91306A279 screws, QTY 8 92141A029 flat washers, QTY 4 91102A750, and QTY 4 95505A601 hex nuts per fin, as shown below. Tighten 16X screws approximately 1/4 turn past full compression of the lock washer.





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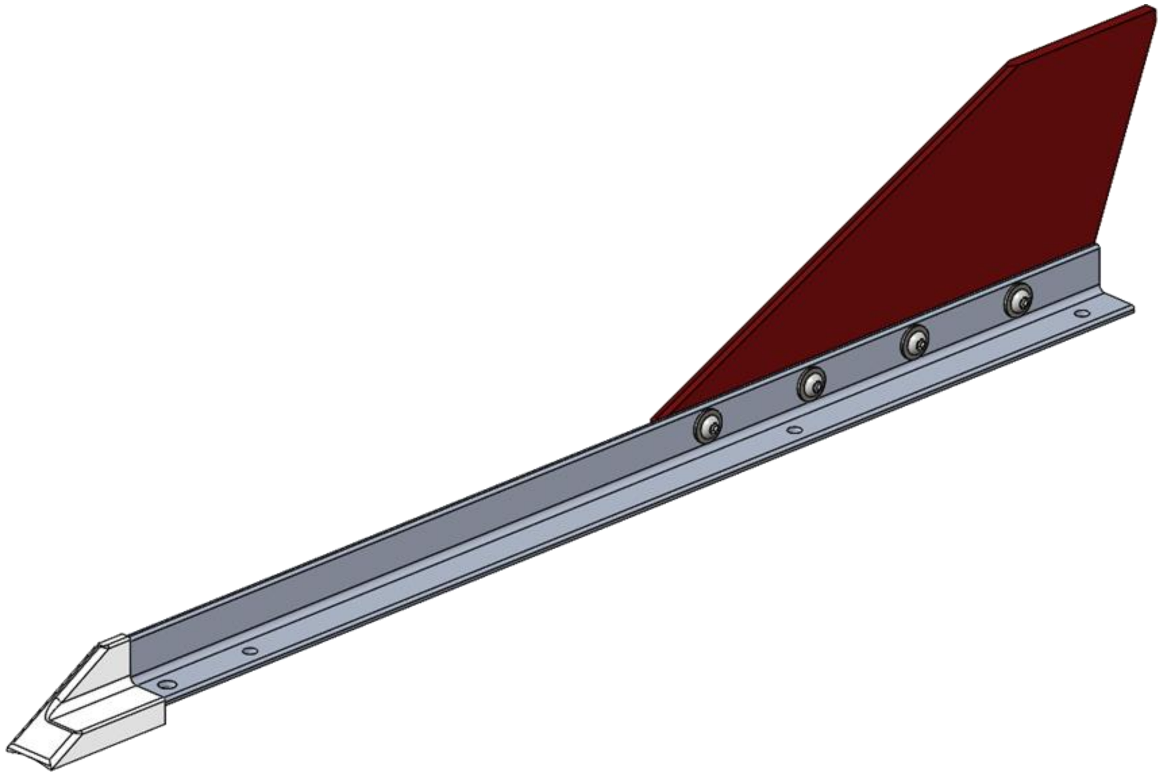
OP 8: Fin Bracket Subassemblies

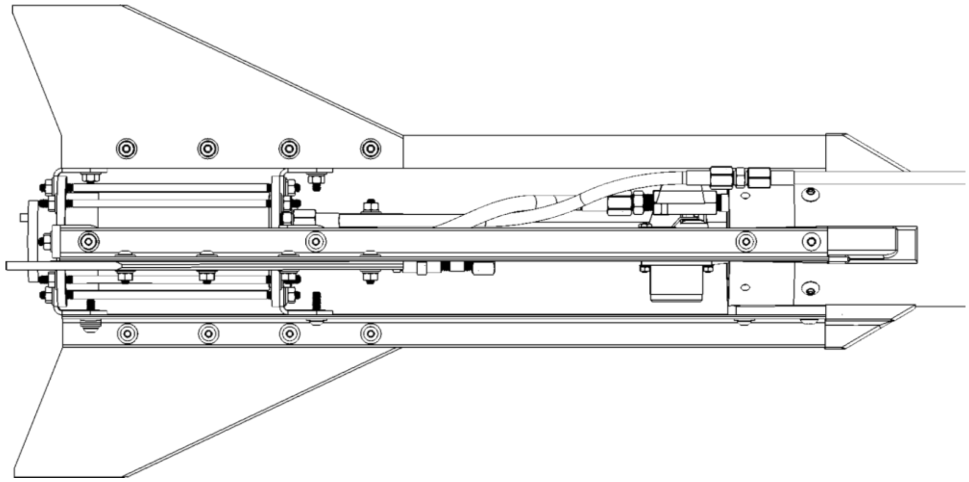
3. Optional: If the leading edges of the aluminum angle fin brackets have not been tapered, install QTY 4 AERO-1X1X125-TIP printed aerodynamic bracket tips onto the aluminum angle as shown.

   Deburr the edges of the aluminum angle with a deburring knife or file prior to installation

   The printed aerodynamic bracket tips are designed to be a press fit, however tolerances of both printed parts and aluminum angle may vary. If loose, they may be bonded on using an adhesive suitable for non-porous materials, such as epoxy. If tight, installation may be aided by beveling the edges of the aluminum angle using a file, or carefully warming the aluminum angle and/or printed part using a heat gun to soften the printed plastic.



OP 9: Thrust Structure & Feedline Integration



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OP 9: Thrust Structure & Feedline Integration

Gather the following:

QTY	Part Number	Description
1	-	Thrust Chamber Assembly
1	-	Propellant Tank Assembly
4	-	Fin Bracket Assembly
4	SPCR-400SD-250C0313C	Spacer, Fin Bracket to Tank
8	91306A279	Button Head Hex Drive Screw, Zinc-Plated Alloy Steel, 1/4"-20 Thread, 7/8" Long
4	91255A839	Button Head Hex Drive Screw, Black-Oxide Alloy Steel, 5/16"-24 Thread, 7/8" Long
32	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
16	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
16	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
1	4468K031	High-Pressure Braided Chemical Hose with Fittings Brass 1/2"-20 Thread Size Flare UNF Female, 3/8" OD - 14"
1	4468K865	High-Pressure Braided Chemical Hose with Fittings Brass 9/16"-18 Thread Size Flare UNF Female, 7/16" OD
1	SRV-Y-HRNS	Servo Y-Harness, 3-Pin
1	SRV-3PIN-1MXT	Servo Extension Cable, 3-Pin, 1m

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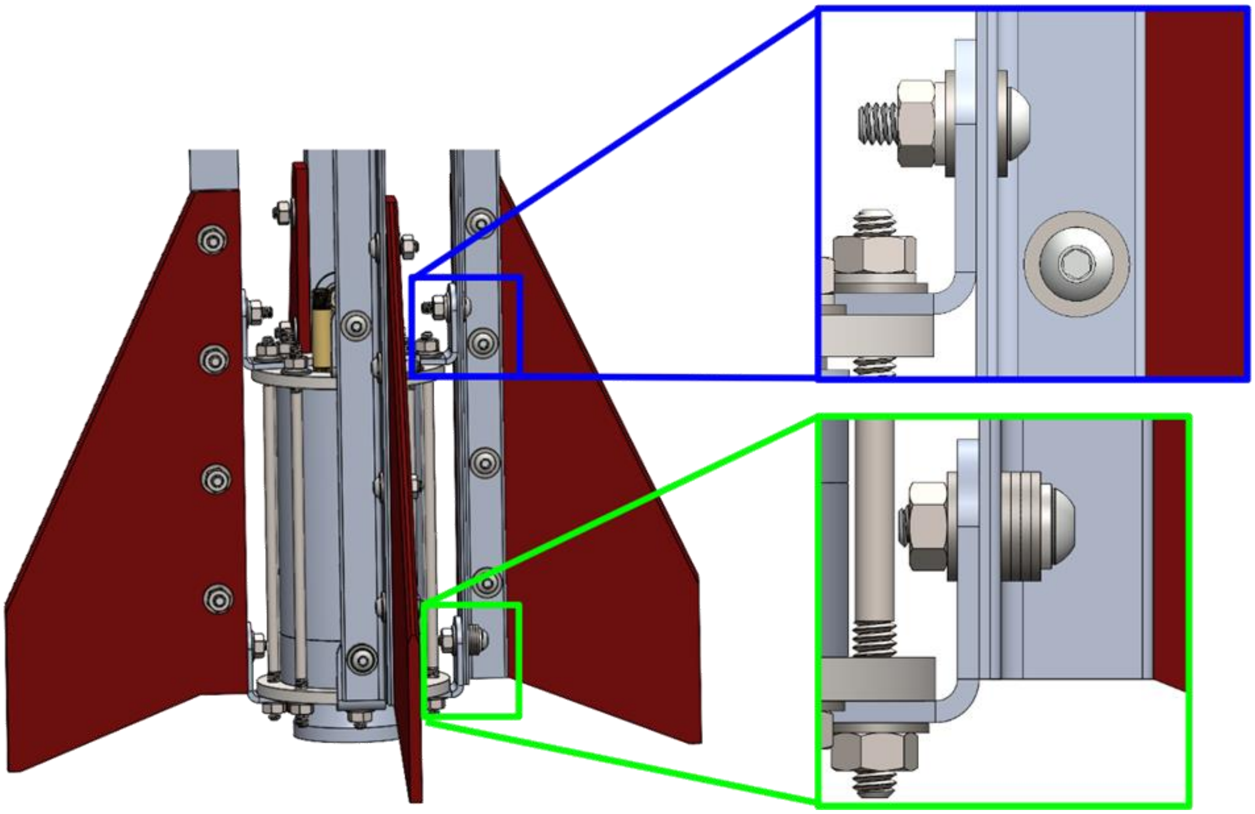
OP 9: Thrust Structure & Feedline Integration

Reference the images below for the following steps on this operation.



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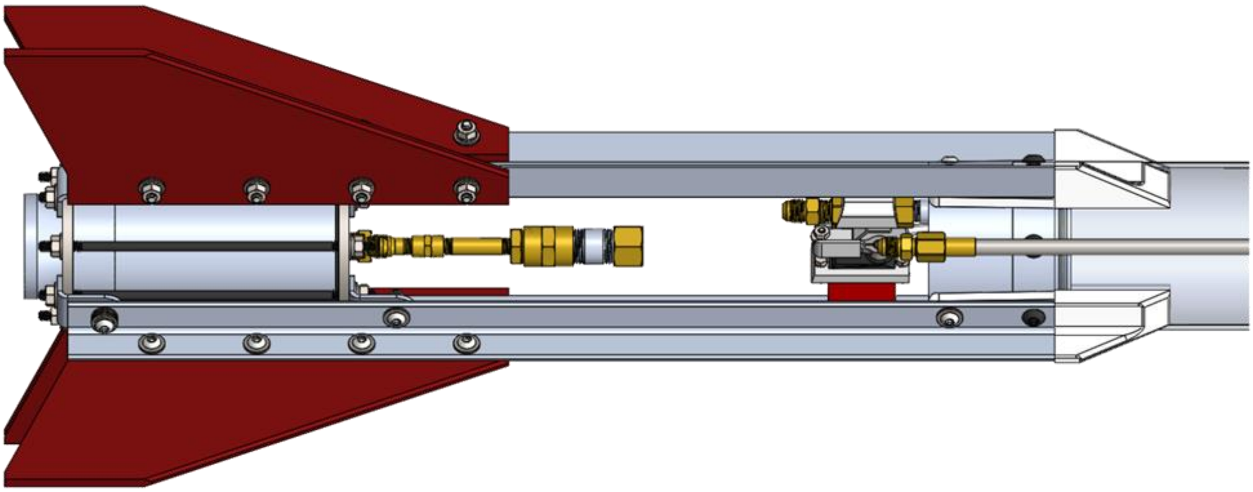
OP 9: Thrust Structure & Feedline Integration

1. Connect the QTY 4 Fin Subassemblies to the thrust chamber mounting brackets as shown. Use QTY 1 91306A279 screw with QTY 2 92141A029 flat washers, QTY 1 91102A750 lock washer, and QTY 1 95505A601 hex nut at each of the upper thrust chamber brackets.

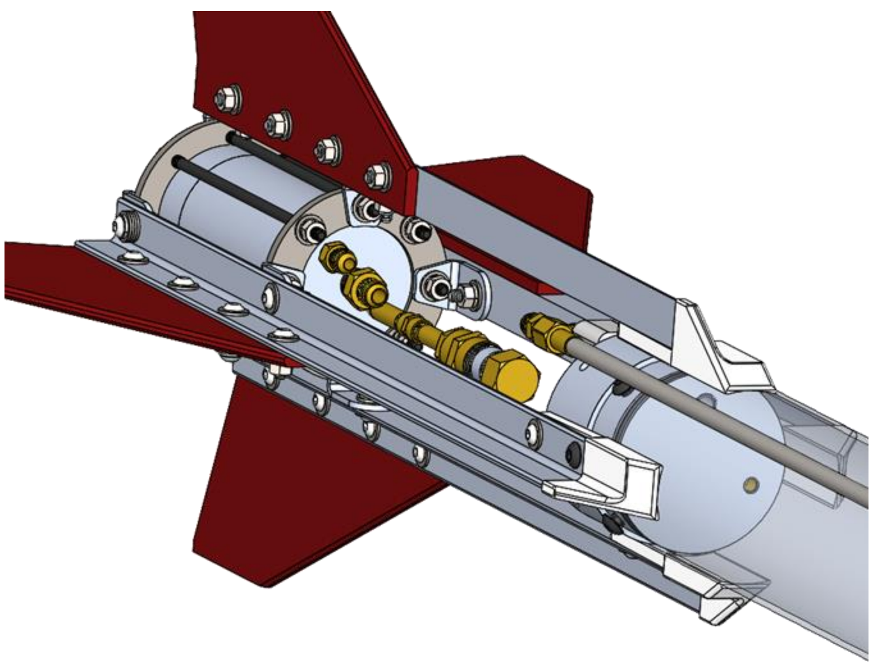
2. On the lower thrust chamber brackets, stack QTY 1 91102A750 lock washer followed by QTY 4 92141A029 flat washers under the head of the screw, then insert the screw through aligned holes in the aluminum angle fin bracket and the thrust chamber mounting bracket. Place an additional QTY 1 92141A029 flat washer onto the screw on the back side of the thrust chamber bracket, then secure with QTY 1 95505A601 hex nut.

OP 9: Thrust Structure & Feedline Integration

Reference the images below for the following steps on this operation.



Note orientation of thrust chamber/injector fittings relative to oxidizer valve.



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OP 9: Thrust Structure & Feedline Integration

3. Connect one end of QTY 1 4468K865 hose to the outlet fitting on the oxidizer valve. Tighten to wrench tight (approx. 250-300 in-lbf).

   Note: Be sure to back up the oxidizer valve outlet fitting to prevent torquing the valve assembly itself.

4. Align the thrust chamber and fin brackets relative to the tank assembly as shown; the fuel inlet fitting on the injector should be on the same side as the fuel line downcomer previously installed on the tank.

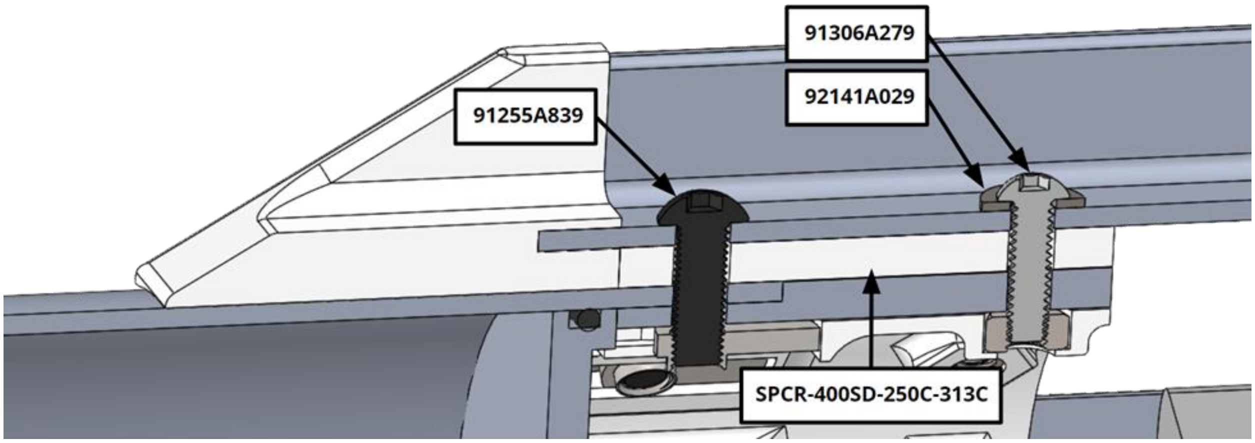
5. Align the holes in the fin brackets with the corresponding 5/16" and 1/4" holes in the tank and interface ring, then slide QTY 1 SPCR-400SD-250C-313C spacer between the fin bracket and tank.

6. As each spacer is inserted, install QTY 1 91306A279 screw with QTY 1 92141A029 washer into each of the 1/4" holes, and QTY 1 91255A839 screw into each of the 5/16" holes. Thread the screws into the nuts captured in the nut retaining ring, and tighten all 4X 91306A279 and 4X 91255A839 screws to snug.

   Caution: Excessive torque may damage the printed nut retaining ring.

OP 9: Thrust Structure & Feedline Integration

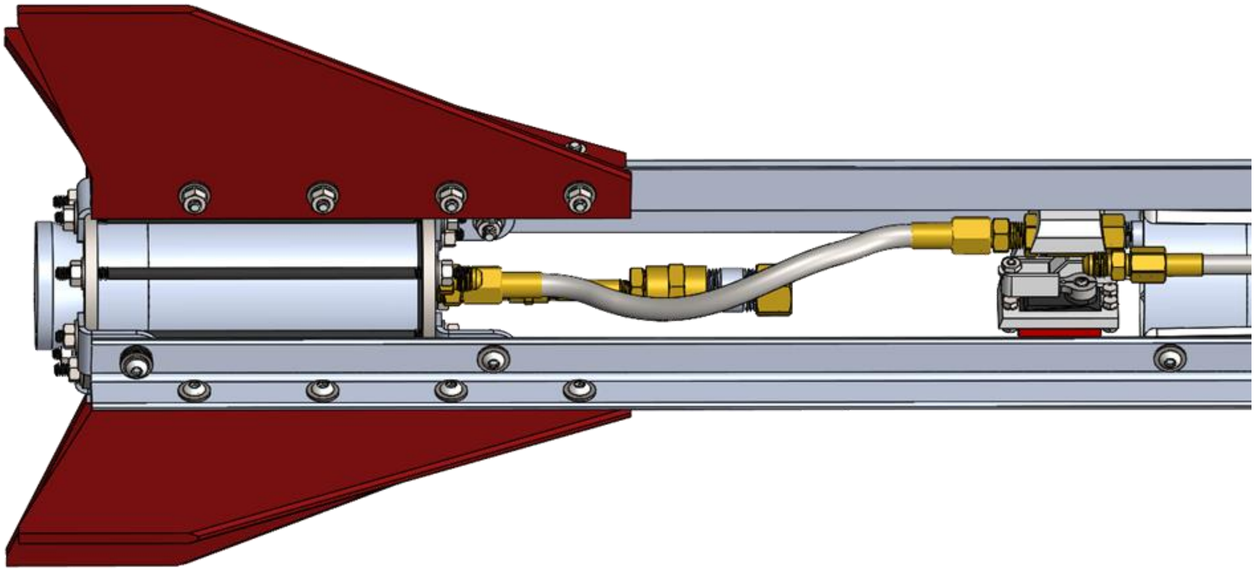
Reference the image below for the following step on this operation.



OP 9: Thrust Structure & Feedline Integration

7. Connect the free end of the 4468K865 hose to the oxidizer inlet fitting on the injector. Torque to moderately tight (approx. 250-300 in-lbf).

   Route the line approximately as shown, forming a loose spiral to take up the excess length.



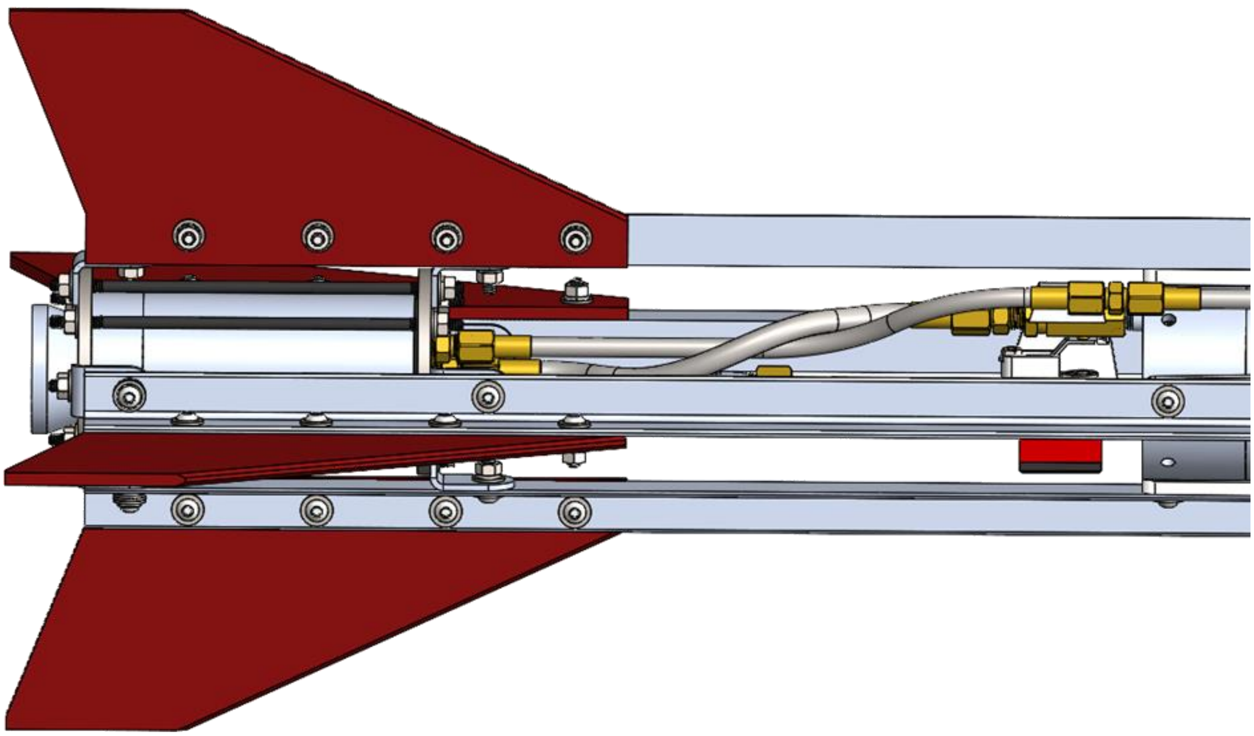
OP 9: Thrust Structure & Feedline Integration

8. Connect one end of QTY 1 4468K031 hose to the union fitting on the fuel line downcomer installed on the tank assembly. Torque to wrench tight (approximately 100-150 in-lbf).

9. Connect the other end of QTY 1 4468K031 hose to the fuel inlet fitting on the injector. Torque to wrench tight (approximately 100-150 in-lbf).

   Route approximately as shown, tucking behind the oxidizer line.

10. Once the feedlines are fully installed, plug the fuel valve servo lead into the female end of the SRV-3PIN-1MXT servo extension cable. Route the extension down the side of the tank alongside the fuel downcomer, securing it to the fuel hose with 3-4 zip ties or loops of tape. Plug the other end of the servo extension and the oxidizer valve servo lead into the SRV-Y-HRNS servo Y-harness. Secure all connections using electrical tape to prevent them from being accidentally unplugged during handling. Bundle up any excess wire length and secure to one of the thrust structure brackets using tape and/or zip ties, with the male end of the Y-harness free.



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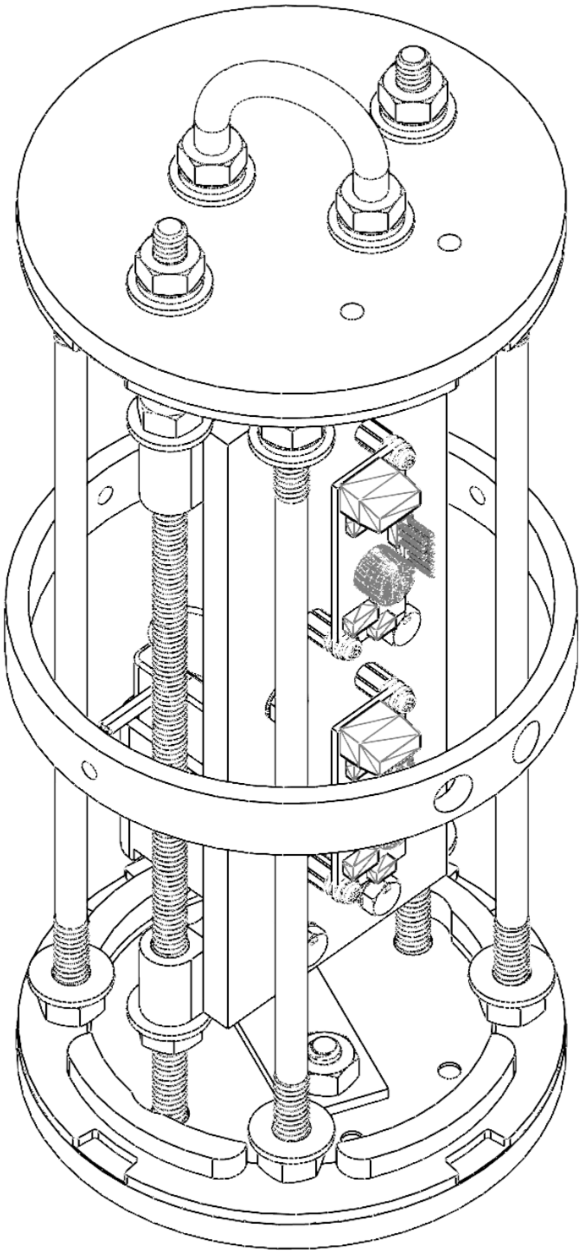
OP 10: Avionics Bay Assembly



OP 10: Avionics Bay Assembly

Gather the following:

QTY	Part Number	Description
2	AVBY-HF-3994	Avionics Bay Coupler, Half, 3.994" OD, Printed
1	AVBY-SB-4160	Avionics Bay Switch Band, 4.16" OD, Printed
20	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
20	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
16	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
4	90281A102	Black-Oxide Steel Threaded on Both Ends Stud, 1/4"-20 Thread Size, 8" Long, 1" Long Threads
2	92580A328	Grade B7 Medium-Strength Steel Threaded Rod
2	3043T643	U-Bolt with Mounting Plate, Zinc-Plated Steel, 1/4"-20 Thread Size, 1" ID
2	AVBY-CR-4R	Avionics Bay Bulkhead Centering Ring, for 4-Rod Coupler
2	BKHD-PLY-399-250C-4X	Bulkhead, Plywood, Recovery/Avionics Bay, 3.99" OD, 4X 1/4" Clearance Holes
1	AVBY-SLD-225X600-6XM4C	Avionics Bay Sled, Plywood, 2.25" X 6.00", 6X M4 Clearance Holes
1	AVBY-MT-250R-M4C	Avionics Bay Sled Mount, for .25" Rods, M4 Clearance Holes
1	AVBY-BH-2X9V-250R-M4C	Avionics Bay Battery Holder, 2X 9V Batteries, for .25" Rods, M4 Clearance Holes
6	92180A044	Medium-Strength Class 8.8 Steel Hex Head Screw, M4 x 0.70 mm Thread, 16 mm Long
12	98689A113	General Purpose 18-8 Stainless Steel Washer for M4 Screw Size, 4.300 mm ID, 8 mm OD
6	92148A160	18-8 Stainless Steel Split Lock Washer for M4 Screw Size, Standard, 4.4 mm ID, 7.6 mm OD
6	90591A141	Zinc-Plated Steel Hex Nut, Low-Strength, M4 x 0.7 mm Thread
4	93505A211	Male-Female Threaded Hex Standoff, Aluminum, 3/16" Hex Size, 1/4" Long, 2-56 Thread Size
4	90604A303	Pan Head Combination Phillips/Slotted Screws, 18-8 Stainless Steel, 2-56 Thread Size, 1/4" Long
8	91755A152	Self-Retaining Washer for # 2 & M2 Size, 0.115" ID, 0.203" OD, 0.022"-0.042" Thick
2	EGTMR-QRK	Eggtimer Rocketry Quark Dual Deployment Altimeter, Assembled
2	7712K511	Battery Holder, 1 9V Battery, T-Shape with Single Layout, 1.04" Long
6 ft	16GA-RBP	20 Gauge Stranded Wire, Red/Black Pair, Silicone Coated
2	71295K64	Cable Tie, Standard, 9" Long
2	9V-BATT	9 Alkaline Battery

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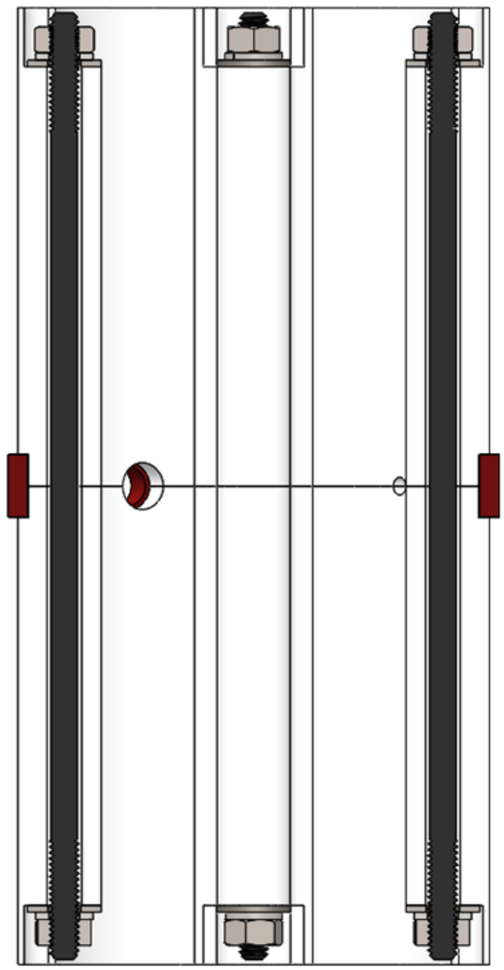
OP 10: Avionics Bay Assembly

1. Assemble QTY 2 AVBY-HF-3992 avionics bay coupler halves and and QTY 1 AVBY-SB-4160 avionics bay switch band as shown. Thread QTY 1 95505A601 hex nut with QTY 1 91102A750 lock washer and QTY 1 92141A029 flat washer onto one end of each of the QTY 4 90281A102 threaded rods, then insert the rods through the sleeves of the printed coupler components. Secure each rod with an additional QTY 1 92141A029 flat washer, QTY 1 91102A750 lock washer, and QTY 1 95505A601 hex nut.

   Ensure equal thread protrusion such that the rods do not extend past the end of the coupler. Tighten the nuts on all 4X rods only until the lock washers are fully compressed to flat. Excessive torque may damage the printed components.

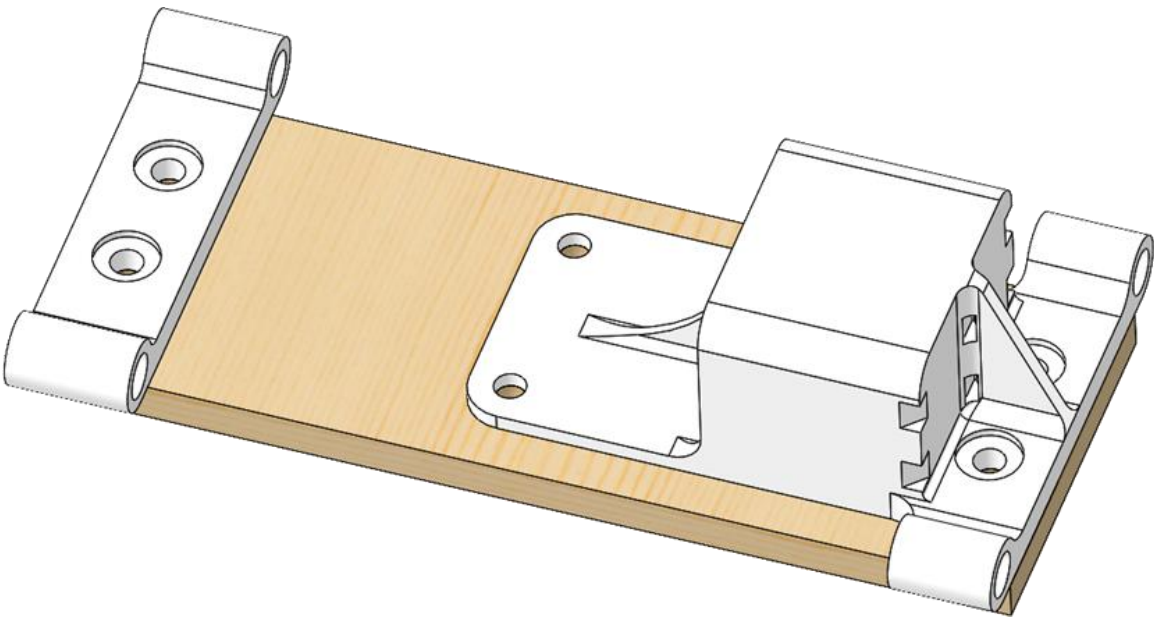


OP 10: Avionics Bay Assembly

2. If the AVBY-PLY-SL-225X600 avionics bay sled has not been prefabricated, cut a 2.25" x 6" rectangle from 1/4" plywood.

3. Place the AVBY-MT-250R-M4C avionics bay sled mount and AVBY-BH-2X9V-250R-M4C battery holder onto the plywood sled as shown, and mark the position of 6X holes using the printed parts. Remove printed parts and drill holes using a #16 or similarly-sized drill bit to create clearance holes suitable for M4 fasteners.

   It is recommended to insert QTY 2 92580A328 threaded rods through the sleeves to ensure alignment prior to drilling mounting holes



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OP 10: Avionics Bay Assembly

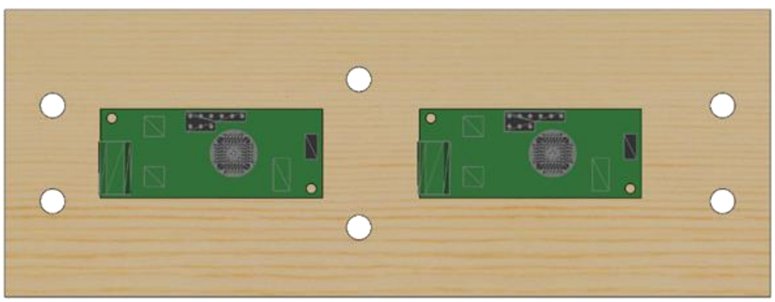
4. Place QTY 2 Eggtimer Quark altimeters, assembled per the manufacturer's directions, on the avionics bay sled as shown. The exact position is not critical, however the terminal blocks should be approximately centered on the sled to ensure sufficient clearance to the coupler reinforcing rods.

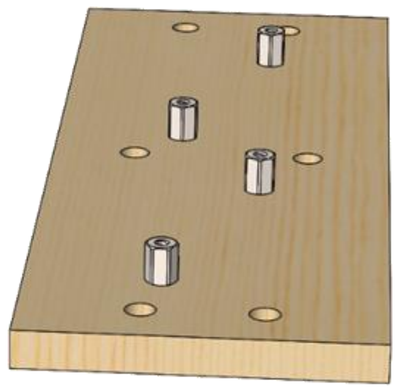
   Mark the hole positions using a fine point pen or mechanical pencil, then remove the altimeters and drill 4X holes with a #50 drill bit (2-56 tap drill size).

5. Thread QTY 4 93505A211 hex standoffs into the holes in the plywood sled. Once fully seated, back off the standoffs 2-4 turns, apply a small dab of cyanoacrylate (superglue) gel or other suitable adhesive, then re-engage threads fully.

   It is not necessary to tap the holes; the standoffs will cut their own threads due to the softness of the plywood.

   The 90604A303 screws may be temporarily threaded into the standoffs to allow a phillips screwdriver to be used for installation of the standoffs into the sled. Hold the standoffs with a 3/16" wrench or pliers while removing the screws.





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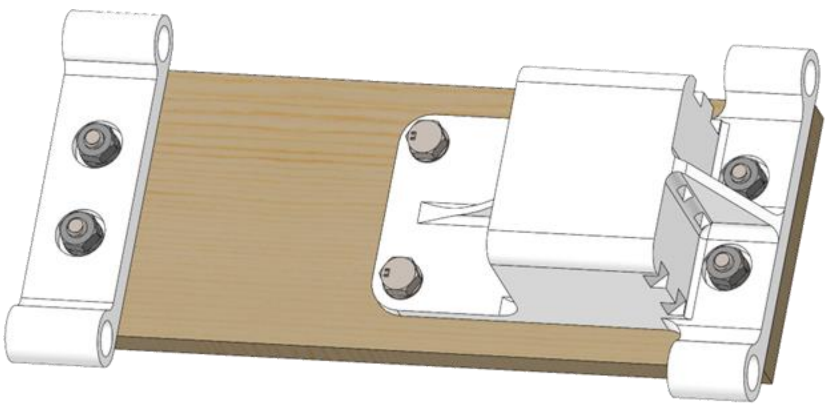
OP 10: Avionics Bay Assembly

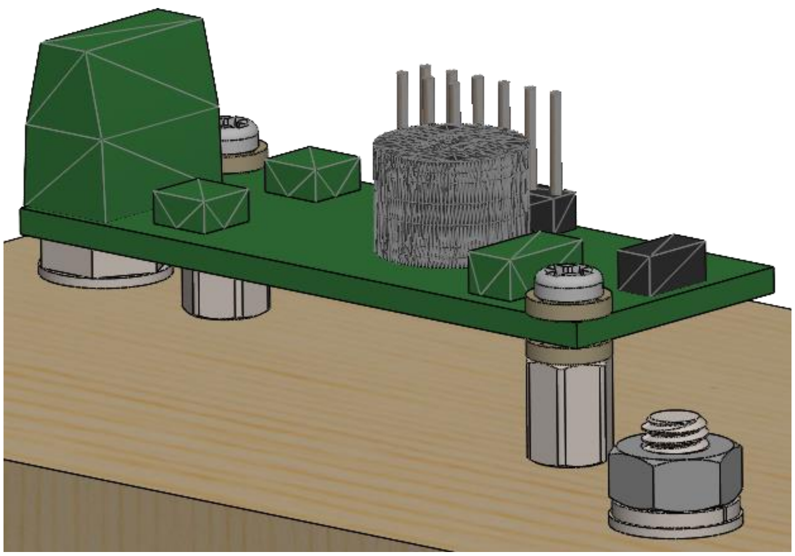
6. Mount the AVBY-MT-250R-M4C avionics bay sled mount and AVBY-BH-2X9V-250R-M4C battery holder onto the plywood sled as shown, using QTY 6 92180A044 M4 hex head screws, QTY 12 98689A113 M4 flat washers, QTY 6 92148A160 M4 split lock washers, and QTY 6 90591A141 M4 hex nuts.

   Tighten all fasteners approximately 1/4 turn past full compression of the lock washer.

7. Mount the QTY 2 Eggtimer Quark altimeters onto the hex standoffs using QTY 4 90604A303 2-56 screws and QTY 8 91755A152 plastic washers as shown. Each hole on the altimeter boards should have a plastic washer on each side to protect against the risk of electrical shorts.

   Tighten the screws only to snug using a small phillips screwdriver.





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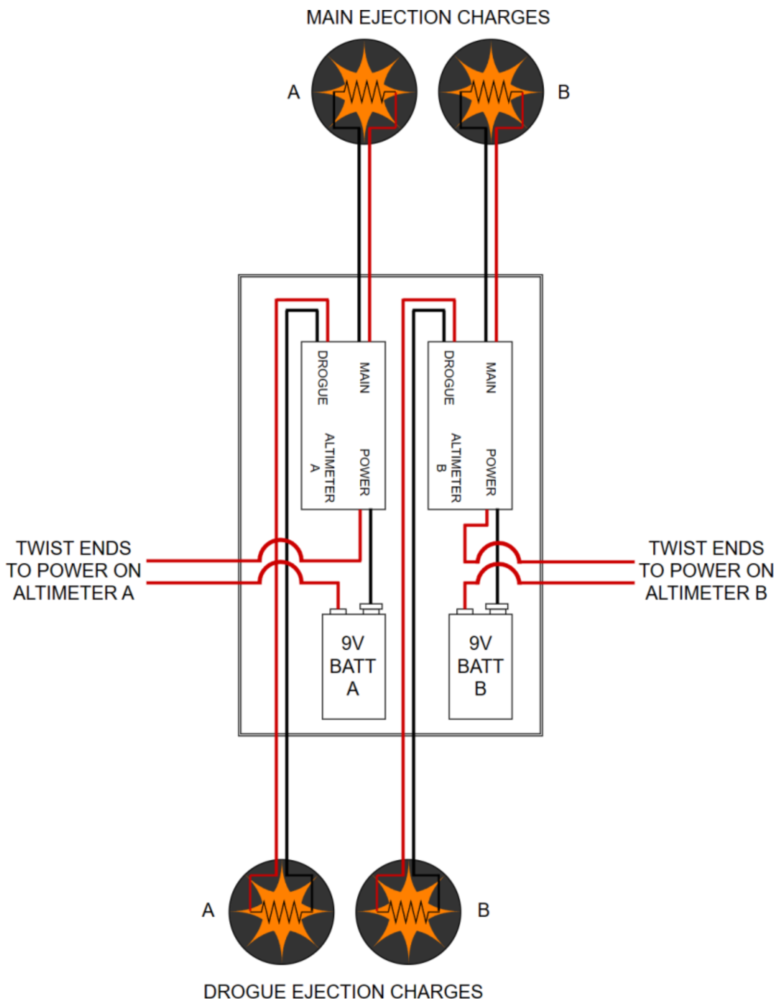
OP 10: Avionics Bay Assembly

Reference the image below for a generic wiring diagram of the avionics bay.



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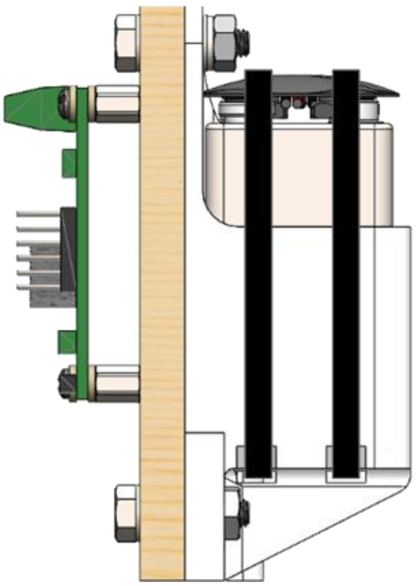
OP 10: Avionics Bay Assembly

8. Connect wiring to the QTY 2 Eggtimer Quark altimeters per the manufacturer's directions, using 20GA-RBP 20 Gauge Stranded Wire, Red/Black Pair, Silicone Coated and QTY 2 7712K511 9V battery connectors or equivalents. Each altimeter should have two wires for the drogue charge, two wires for the main charge, and two wires for connecting/disconnecting power externally. Mark the wires to differentiate between main and drogue on each altimeter.

   Note that the Mojave Sphinx V1.2 avionics bay is designed for "twist and tape" style power connection/disconnection, in which a pair of wires with stripped ends are twisted together to supply power and wrapped with electrical tape to secure the connection. To disconnect power from the altimeters, the electrical tape is removed and the wires are separated and insulated. These wires should be long enough to be inserted through the 2X large holes in the avionics bay switch band prior to installing the avionics bay sled (~10")

   The "twist and tape" power wires should NOT be pushed inside the avionics bay, as this will make them inaccessible should power need to be disconnected after an aborted launch. The wires will not be harmed by protruding 2-4" out of the rocket during flight, so long as they are securely twisted and wrapped in electrical tape.

9. Install QTY 2 9V batteries into the battery holder as shown. Snap the 7712K511 battery connectors onto the terminals of each battery (ensuring that power is disconnected from the altimeter), then secure the batteries with QTY 2 zip ties routed through the slots/notches on the battery holder and over the tops of both battery connectors.



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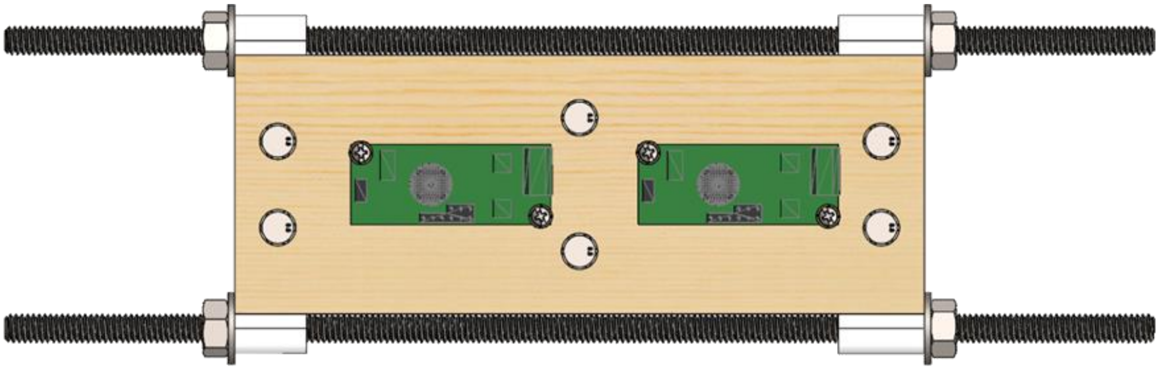
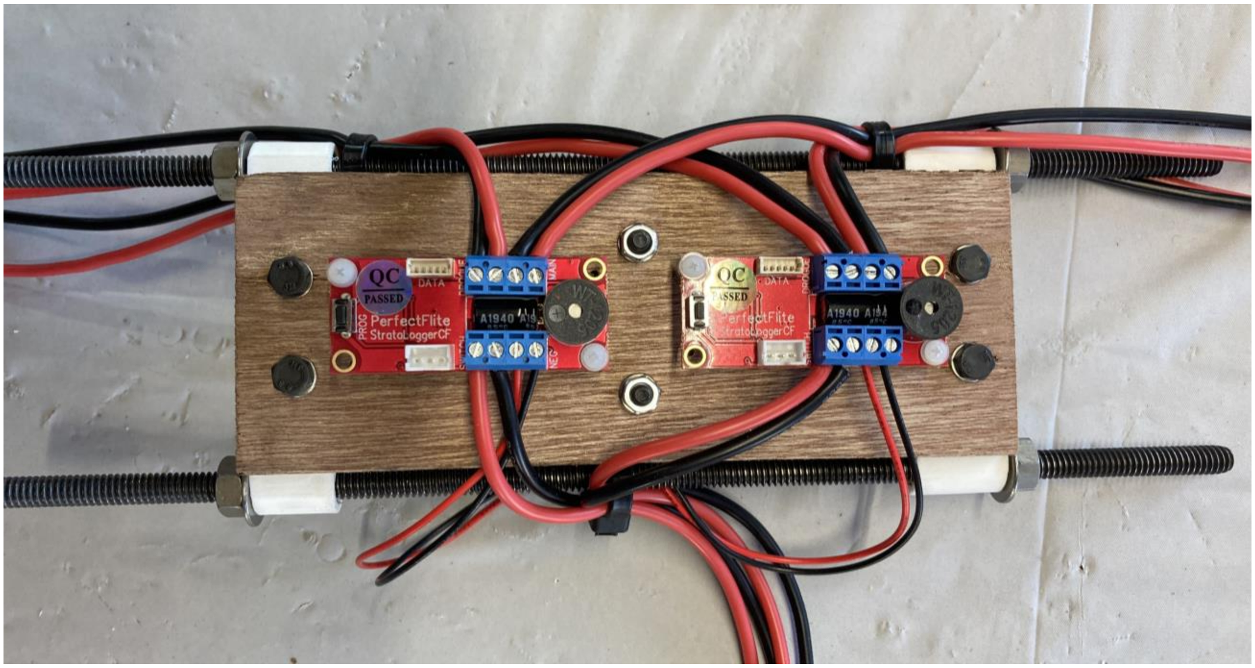
OP 10: Avionics Bay Assembly

10. Insert QTY 2 92580A328 threaded rods through the sleeves of the avionics bay sled assembly, with equal protrusion of the rods from each end. Place QTY 1 92141A029 flat washer followed by QTY 1 95505A601 hex nut onto each end of each rod to secure the avbay sled assembly in place on the rods as shown.

    Tighten only to finger-tight, or lightly snug using a wrench. Excessive torque may damage the printed components.

    Note: Wiring is omitted from the reference image. It is recommended to strain relieve wires using zip ties as shown in the reference photo below. Altimeters shown are the StratologgerCF.





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OP 10: Avionics Bay Assembly

11. Remove the hex nuts and mounting plate included with the 3043T643 U-bolt, then thread the included hex nuts all the way to the end of the thread, tightening until snug. Place QTY 2 91102A750 split lock washers and QTY 2 92141A029 flat washers onto the ends of the U-bolt, then insert the U-bolt into the holes in the avionics bay bulkhead and centering ring. Secure with the included mounting plate and QTY 2 95505A601 hex nuts. Tighten both hex nuts approximately 1/4 turn past full compression of the lock washers.

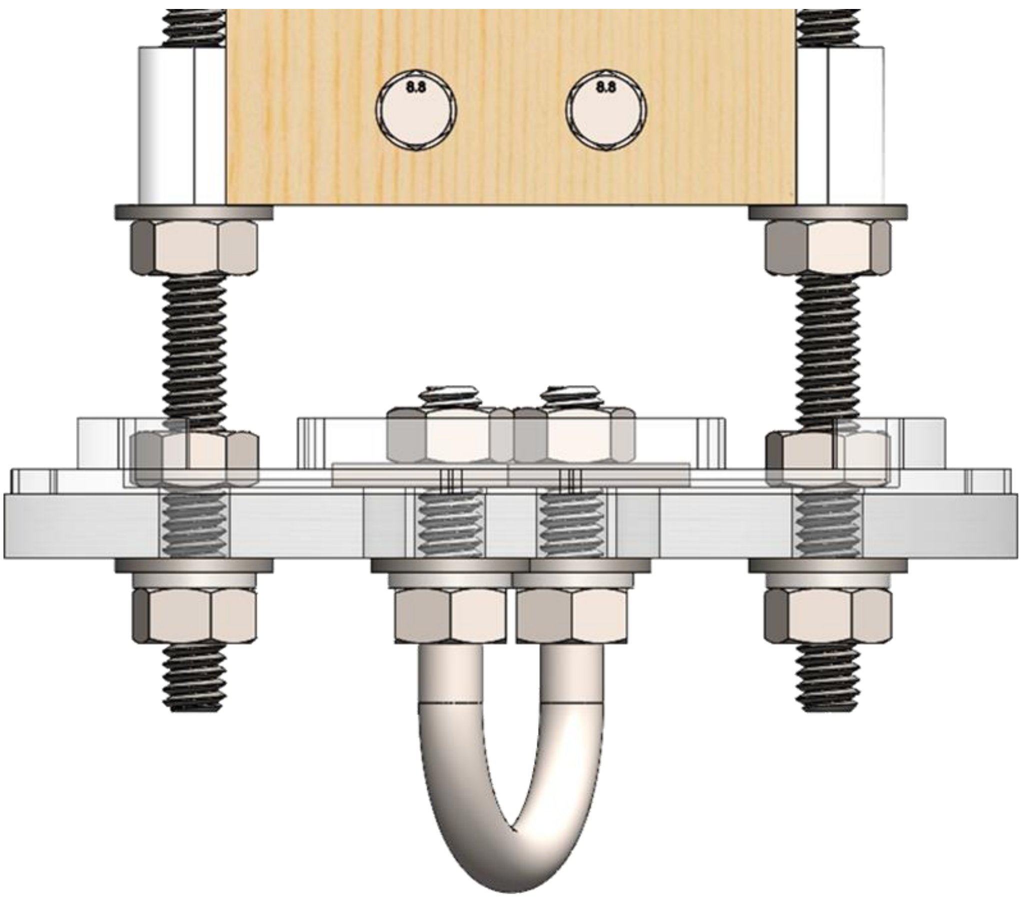
OP 10: Avionics Bay Assembly

12. Thread QTY 1 95505A601 hex nut approximately .875" onto the lower end of each of the avionics bay sled threaded rods.

    Then insert the rods on through the holes on the avionics bay bulkheads as shown.

    Install QTY 1 92141A029 flat washer followed by QTY 1 91102A750 split lock washer and QTY 1 95505A601 hex nut onto each rod. Tighten the hex nuts on each rod against each other until the lock washers are fully compressed to secure the bulkhead in place on the threaded rods. The rods should protrude approximately .25-.30" from the outer hex nuts.

    Mark this bulkhead with "AFT" using a permanent marker, and insert the 2X pairs of drogue charge wires from the altimeters through the wire exit holes.



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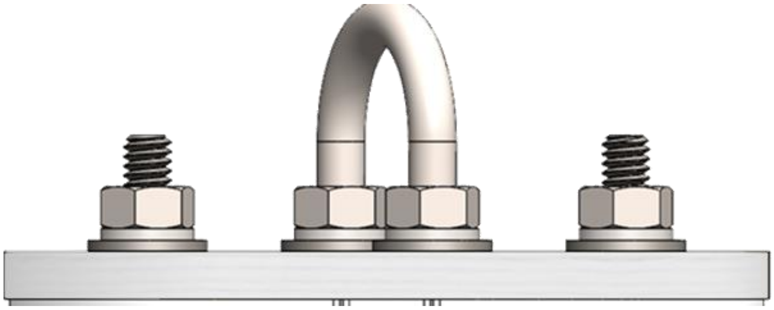
OP 10: Avionics Bay Assembly

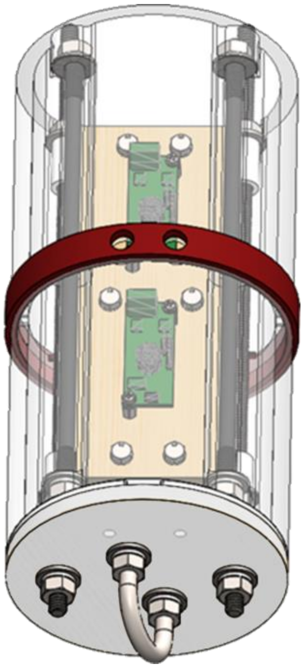
13. Install the avionics bay sled with attached bulkhead into the avionics bay coupler in the orientation shown. During (or prior to) installing the sled, feed each pair of the "twist and tape" altimeter power switch wires through the large holes in the avionics bay switch band from the inside.

    A piece of masking or electrical tape may be placed onto each pair of altimeter power wires to prevent the ends of the wires from accidentally slipping back into the avionics bay.

14. Place the second avionics bay bulkhead over the protruding ends of the threaded rods and secure with QTY 2 92141A029 flat washers, QTY 2 91102A750 split lock washers, and QTY 2 95505A601 hex nuts.

    Tighten the hex nuts just until the lock washers are fully compressed.





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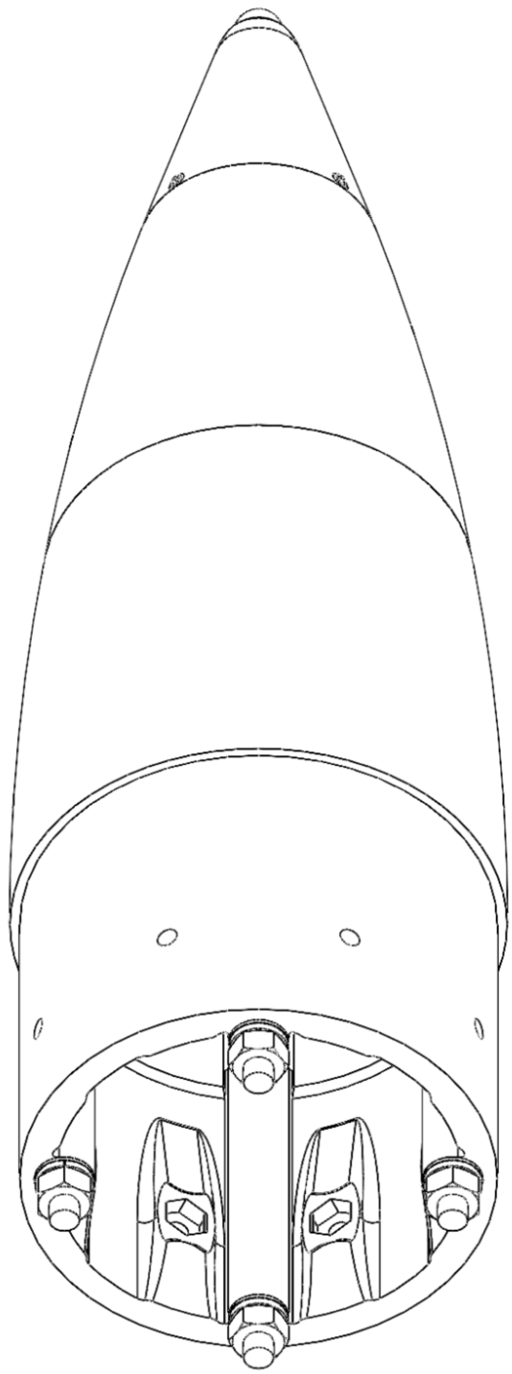
OP 11: Nose Cone Assembly



OP 11: Nose Cone Assembly

Gather the following:

QTY	Part Number	Description
1	NSCN-SLDR-4X250R-8X832HNC	Nose Cone Shoulder, 4X 1/4" Rod Sleeves, for 8X 8-32 Hex Nuts with Clearance Holes
1	NSCN-SC1-4X250R	Nose Cone, Section 1, 4X 1/4" Rod Sleeves
1	NSCN-SC2-4X250R	Nose Cone, Section 2, 4X 1/4" Rod Sleeves
1	NSCN-TIP-4X250R-250HNC	Nose Cone, Tip, 4X 1/4" Rod Sleeves, 1/4" Clearance Hole with Hex Nut Capture
2	98831A028	1/4-20 Nylon Threaded Rod, 24"
8	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
9	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
8	95229A420	Cadmium-Plated Steel MIL. Spec. Washer for 1/4" Screw Size, NAS 1149-F0432P
8	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
4	93135A013	Nylon Pan Head Screws, Phillips, 2-56 Thread, 1/4" Long
1	3018T23	Galvanized Steel Eyebolt with Nut and with Shoulder, for Lifting, 1/4"-20 Thread Size, 1-1/2" Thread Length, 3" Shank
1	92994A029	316 Stainless Steel Cap Nut, 1/4"-20 Thread Size
8	90480A009	#8-32 Hex Nut, Zinc Plated, Low Strength Steel
24 in.	TNSC-3KLB	Tubular Nylon Shock Cord, 3000lbf Breaking Strength

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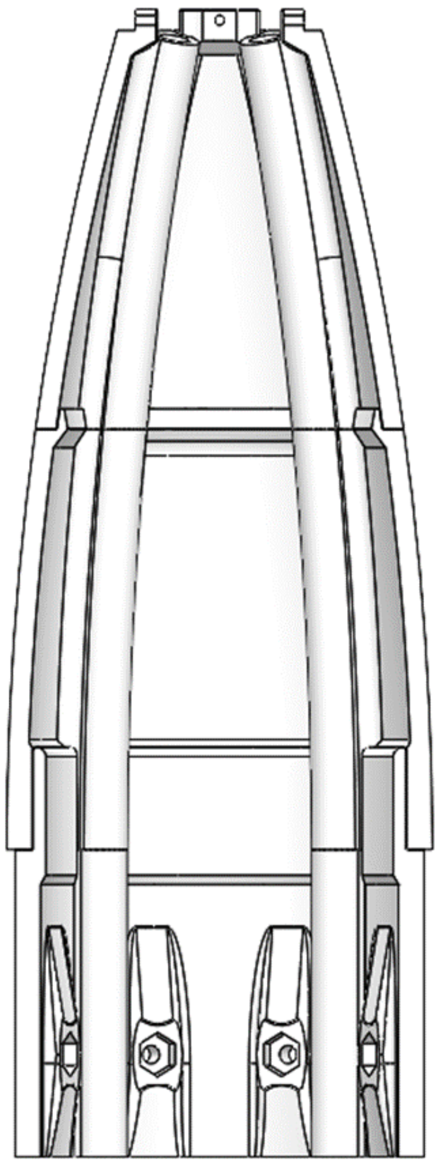
OP 11: Nose Cone Assembly

1. Cut QTY 2 98831A028 Nylon Threaded Rods into equal lengths of 12 inches each, for a total of four pieces.

2. Stack QTY 1 NSCN-SLDR-4X250R-8X832HNC Nose Cone Shoulder, QTY 1 NSCN-SC1-4X250R Nose Cone Section 1, and QTY 1 NSCN-SC2-4X250R Nose Cone Section 2 as shown.



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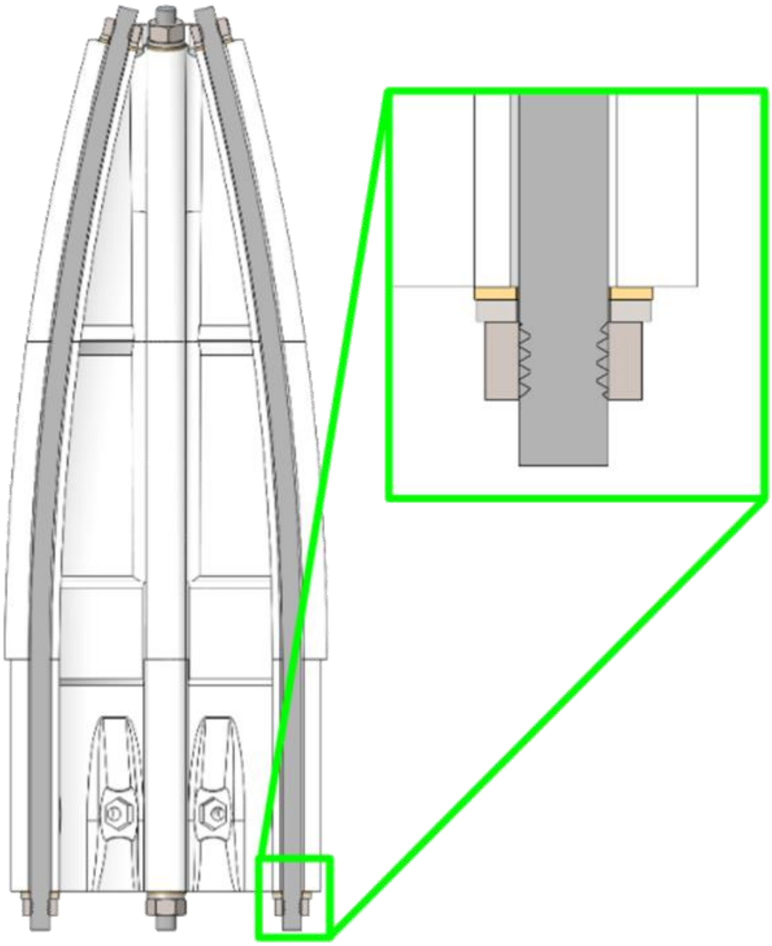
OP 11: Nose Cone Assembly

3. Insert QTY 4 12-inch sections of 98831A028 Nylon Threaded Rod into the sleeves into the sleeves of the printed nose cone components as shown, with approximately .50" protrusion from the bottom of the nose cone shoulder.

4. Install QTY 1 95505A601 hex nut with QTY 1 91102A750 lock washer and QTY 1 95229A420 flat washer onto each end of each nylon threaded rod, with approximately equal thread protrusion from each nut. Tighten the 4X nuts on the bottom of the nose cone shoulder just until the lock washers are fully compressed.

   CAUTION: Excessive torque may strip the threads of the nylon threaded rods.

   Note: Excessive thread protrusion will interfere with the nose cone tip installed on a later step.



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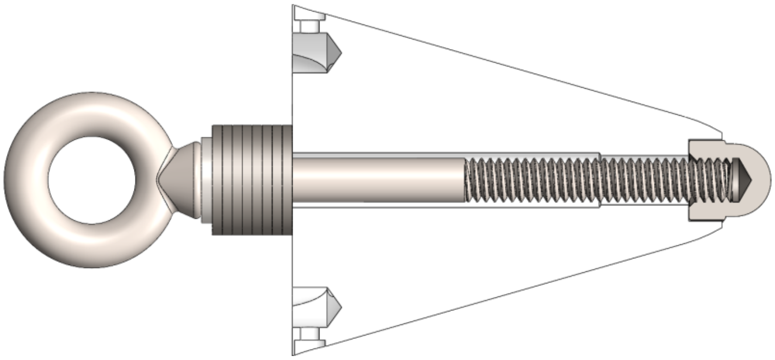
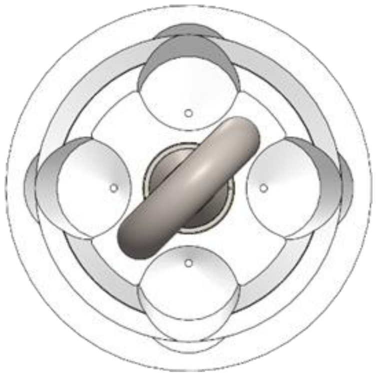
OP 11: Nose Cone Assembly

5. Place QTY 1 91102A750 lock washer and QTY 8 92141A029 washers onto the shank of QTY 1 3018T23 eye bolt. Then, insert QTY 1 92994A029 cap nut into the hex on the NSCN-TIP-4X250R-250HNC nose cone tip, and thread the eye bolt with washers into the cap nut until snug, ensuring that the eye is oriented between the counterbores as shown. Washers may be added or subtracted as needed.

   Note: The eye bolt is prevented from rotating by other features within the nose cone assembly, and does not need to be especially tight. Excessive torque may damage the hex on the printed nose cone tip.





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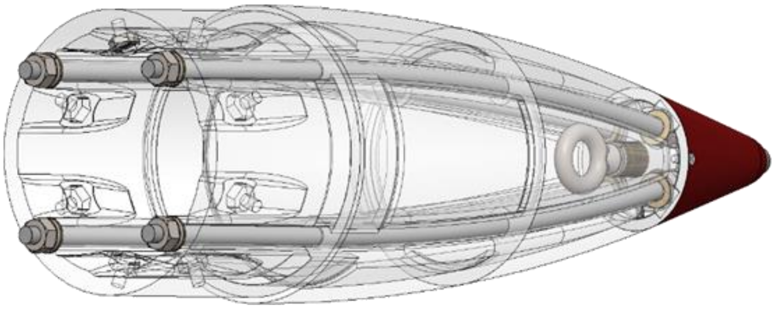
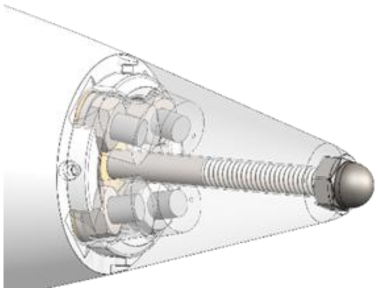
OP 11: Nose Cone Assembly

6. Tie one end of a 24" section of TNSC-3KLB shock cord to the eye bolt using a non-slip loop knot. The loop should be large enough that the body of the knot sits 2-3 inches behind the eye bolt when pulled taut. Ensure the knot is sufficiently compact to fit through the opening in the NSCN-SC2-4X250R nose cone section.

7. Place the nose cone tip with eye bolt onto the lower portion of the nose cone assembly, aligning the tabs and slots so that the tension rods and nuts sit within the counterbores.





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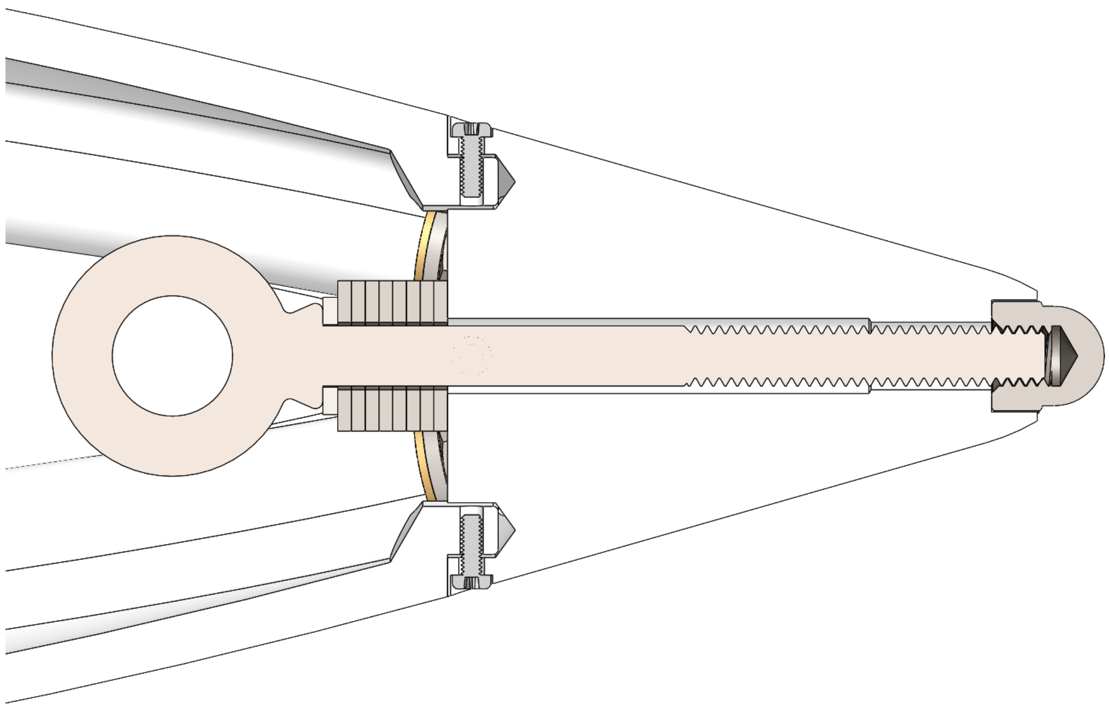
OP 11: Nose Cone Assembly

8. Secure the nose cone tip to Section 2 of the nose cone using QTY 4 93135A013 nylon screws as shown.

   Note: The screw holes are nominally an interference fit to allow the screw to be pushed or threaded in without tapping the hole, and retained by friction. If the screws fit loosely in the holes, adhesive may be used. If the holes are too small to install the screws, they may be drilled as needed, and optionally tapped with a #2-56 thread on the NSCN-SC2-4X250R tabs.



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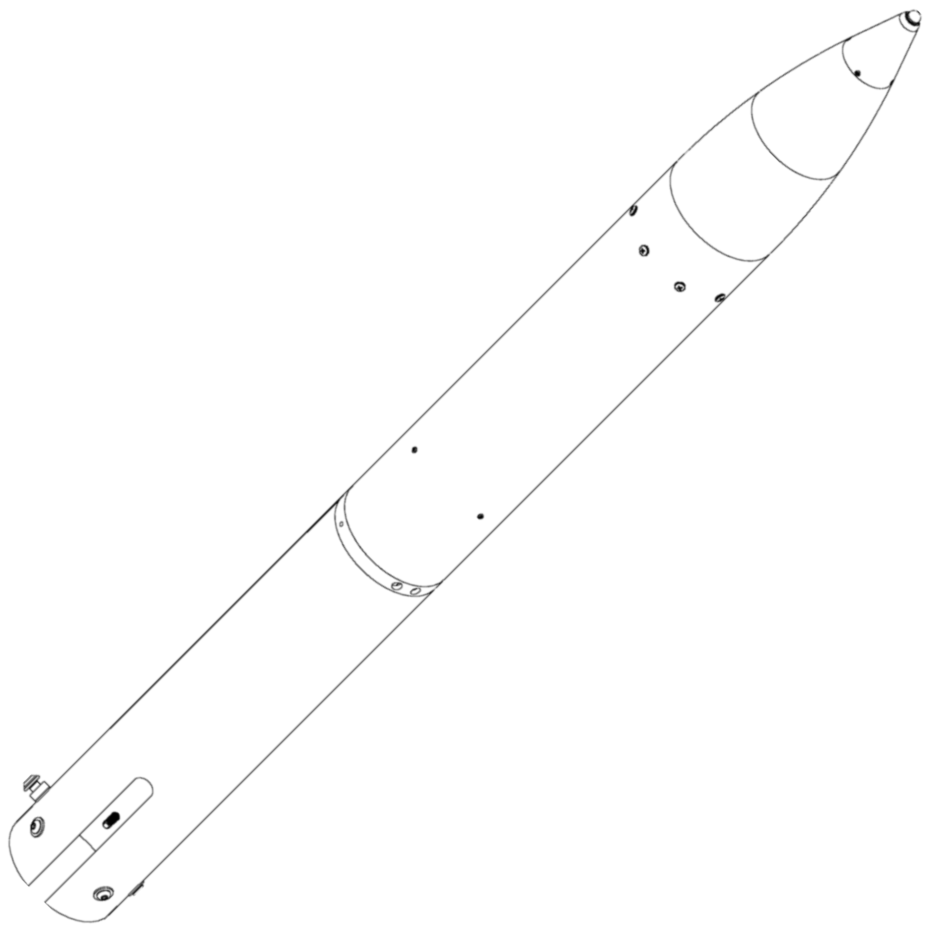
OP 11: Nose Cone Assembly

9. Place QTY 8 90480A009 hex nuts into the hexagonal cutouts on the interior of the nose cone shoulder. The nuts should snap in past the retention tabs with moderate force.

   Note: If the nuts cannot be pushed past the retention tabs, lightly shave down the tips of the tabs using a razor blade. If the tolerances are too loose for the nuts to be adequately retained, a small strip of 7631A82 aluminum foil tape or similar can be placed over each hexagonal cutout.

10. Tie the protruding section of shock cord into a second non-slip loop knot, so that the loop hangs out of the nose cone shoulder.

OP 12: Airframe Fabrication



OP 12: Airframe Fabrication

Gather the following:

QTY	Part Number	Description
1	20545T38	Round Shipping Tube, Cardboard, 4" ID, 36" Length
-	TMPLT-AF-LWR-416	Template, Hole and Slot Marking, Lower Airframe Tube
-	PLG-DRL-AF-LWR-416	Backing Plug, Sacrificial, for Lower Airframe Tube Drilling
-	TMPLT-AF-UPR-416	Template, Hole Marking, Upper Airframe Tube
-	PLG-DRL-AF-UPR1-416	Backing Plug, Sacrificial, for Upper Airframe Tube Drilling

Note: Alternate shipping tubes may be used so long as they are 4" inner diameter. However, thin walled mailing tubes (~.062" thick) are not recommended, as they are prone to damage and will increase the risk of structural failure in flight. The recommended tube has a wall thickness of approximately .080"; .125" and .250" heavy duty shipping tubes are acceptable, at the cost of increased weight and drag. Using an alternate tube with a larger OD will also require modifying the printed hole and slot marking templates.

OP 12: Airframe Fabrication

1. Cut QTY 1 20545T38 shipping tube into two pieces of equal length (18 inches each). Designate one as the upper airframe tube (20545T38-AF-UPR) and one as the lower airframe tube (20545T38-AF-LWR). Ensure the cut end is flat and clean.

2. Use the TMPLT-AF-LWR-416 template to mark the positions of the airframe mounting bolt holes and fuel line slot on the lower airframe tube. Then, insert the PLG-DRL-AF-LWR sacrificial backing plug into the tube so that it sits flush with the end at which the holes are to be drilled. This prevents or reduces delamination of the cardboard layers during drilling.

   Note: The plug is intentionally oversized to preload against the inside of the tube.

3. Using a 9/32" drill bit, drill 7X holes in the airframe tube in the locations marked using the template. Once all holes are drilled, remove and discard the sacrificial backing plug.

4. Cut the slot along the templated line using a razor blade and/or a very fine toothed saw.

   Tip: It is recommended –but not required– to reinforce the edges of the slot, holes, and tube ends using a thin cyanoacrylate glue or epoxy that will soak into the cardboard.

5. Optional step: cover the lower airframe tube with aluminum tape in lengthwise strips with approximately ¼" of overlap. Burnish the tape down with a flexible plastic card to remove wrinkles.

   Note: This is primarily for visual effect, and provides minimal if any structural reinforcement.

6. Use the TMPLT-AF-UPR1-416 template to mark the positions of the nose cone screw holes on the forward end the upper airframe tube. Then, insert the PLG-DRL-AF-UPR1 sacrificial backing plug into the tube so that it sits flush with the end at which the holes are to be drilled. This prevents or reduces delamination of the cardboard layers during drilling.

   Note: The plug is intentionally oversized to preload against the inside of the tube.

OP 12: Airframe Fabrication

7. Using a 3/16" drill bit, drill 8X holes in the airframe tube in the locations marked using the template. Once all holes are drilled, remove and discard the sacrificial backing plug.

8. Use the TMPLT-AF-UPR2-416 template to mark the positions of the shear pin holes on the aft end of the upper airframe tube.

   Note: A sacrificial backing plug is not required due to the small diameter of these holes. Using a Number 50 (.070") drill bit, drill 4X holes in the airframe tube in the locations marked using the template. Once all holes are drilled, use sandpaper and/or a razor blade to clean up any raised material on the inside of the tube.

   Note: The holes are intentionally undersized to allow press-fitting the shear pins through the cardboard.

9. Verify alignment of the lower airframe mounting bolt holes by sliding the 20545T38-AF-LWR airframe tube over the upper tank interface ring. Ensure that 7X 91306A279 screws are able to be installed simultaneously into the nuts retained in the interface ring. No screw is installed in the hole that aligns with the fuel line slot.

10. Verify alignment of the upper airframe nose cone screw holes by inserting the nose cone assembly into the forward end of the upper airframe tube and installing 8X 90272A194 screws into the nuts retained in the nose cone shoulder.

11. Verify alignment of the upper airframe tube shear pin holes by sliding the upper airframe tube onto the forward end of the avionics bay coupler, so that the 4X shear pin holes are positioned over the shear pin slots in the avionics bay bulkhead as shown. Install 4X 93135A013 nylon screws into the shear pin holes by press fitting, or turning with a screwdriver, although the cardboard holes are not intended to be threaded.

    Note: If needed, the shear pins may be retained for flight using a small patch of tape over the head.

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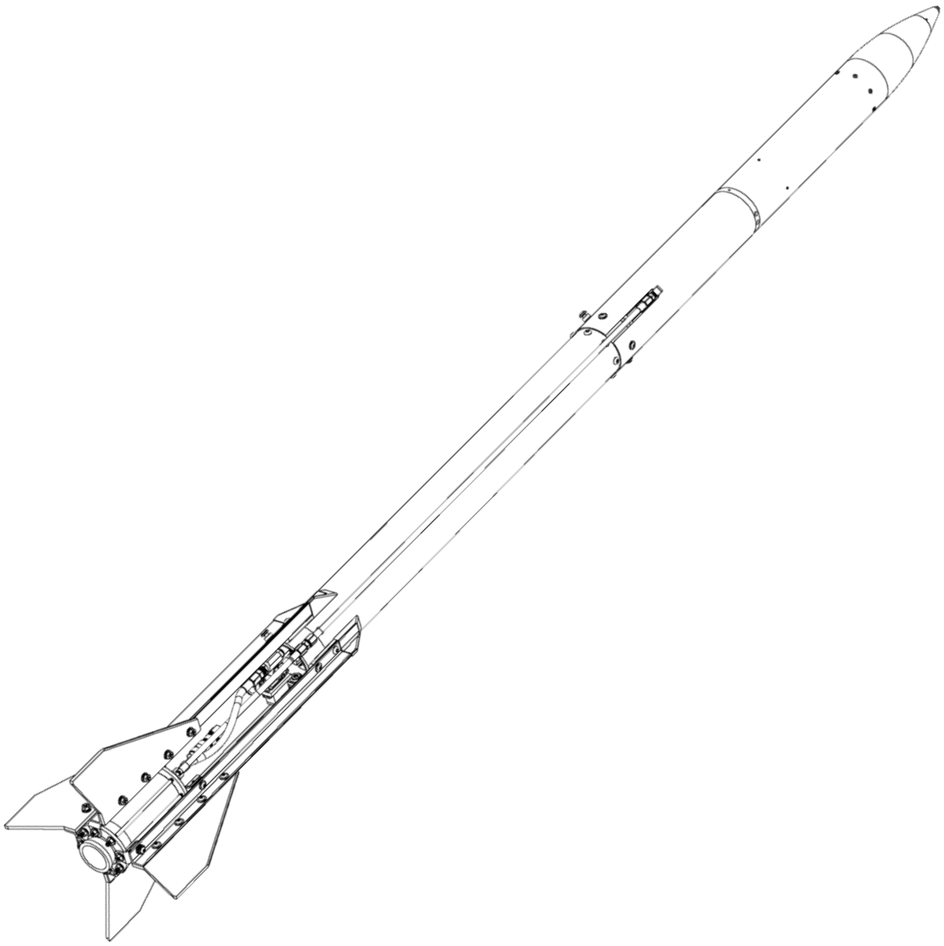
OP 13: Recovery System & Airframe Integration



OP 13: Recovery System & Airframe Integration

Gather the following:

QTY	Part Number	Description
48 ft	REC-TNSC-3KLB	Tubular Nylon Shock Cord, 3000lbf Breaking Strength
1	CNPY-CHT-86IN	7.2ft Hexagonal Tent Tarp, Main Chute Canopy
84 ft	CRD-KVLR-250LB	Kevlar Cord, 250lb breaking strength
2	REC-PRT-16	Parachute Protector, Nomex, 16 X 16"
1	REC-CHT-DRG-36	Drogue Parachute, 36" Diameter
4	8947T26	Quick Link, 1400lb Rating, 316SS
8	90272A194	#8-32 Screws, ½" Long, Phillips Pan Head
2	97654A620	Flange Head Screw, ¼-20, 1 ¼" Long
2	92141A029	Flat Washer for ¼" Screw Size
2	RLBTN-A-1515-250C	Rail Button, 1515, Printed, Part A
2	RLBTN-B-1515-250C	Rail Button, 1515, Printed, Part B

OP 13: Recovery System & Airframe Integration

Note: Skip steps 1-3 if using a COTS parachute.

1. Cut 3 sections of CRD-KVLR-250LB Kevlar cord, each approximately 28 feet in length. Ensure all pieces are consistent in length to within +/-3 inches. These will form the shroud lines for the main parachute.

2. Tie the ends of each piece of Kevlar cord to the loops sewn onto the corners of the hexagonal tarp, with minimal excess length after the knot. Ensure the ends of each section of cord are tied to adjacent loops, rather than spanning across the canopy to the loop on the opposite side. Any type of knot may be used; a non-slip loop knot is recommended.

3. Gather the Kevlar cords from the middle of each section. Allow the canopy to bunch into a triangle, so that the sewn loops onto which the shroud lines are tied all align with each other. This will ensure the around lines are equal in length. Once the sewn loops are aligned, tie a loop at the midsection of the bundled shroud lines using an overhand knot. This will be used to connect the shroud lines to the shock cord via a quick link.

4. Cut the remaining 48ft of shock cord into two equal lengths of 24 ft each.

5. Designate one section of shock cord as the main recovery harness, and one section as the drogue recovery harness.

6. On the main recovery harness, tie a loop approximately 6 to 8 feet from one end, using an overhand knot on a doubled section of cord. Alternate methods such as a Rigger's Loop Knot or Alpine Butterfly may also be used if desired. This loop will be used to connect the main parachute.

7. Connect the end of the main recovery harness closest to the loop to the short section of shock cord on the nose cone assembly by tying a non-slip loop knot, with the loop passing through the existing non-slip loop knot on the nose cone.

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OP 13: Recovery System & Airframe Integration

8. Pass the other end of the main recovery harness through the 20545T38-AF-UPR airframe tube, and tie a second non-slip loop knot on the end of the harness. Connect this non-slip loop knot to the U-bolt on the forward end of the Avionics Bay Coupler assembly with QTY 1 8947T26 quick link. Close the quick link and tighten hand tight. A wrench may be used, but is not required.

9. Tie a non-slip loop knot on each end of the drogue recovery harness.

10. Connect one end of the drogue recovery harness to the U-bolt on the recovery bulkhead on the tank assembly with QTY 1 8947T26 quick link. Close the quick link and tighten hand tight. A wrench may be used, but is not required.

11. Connect the other end of the drogue recovery harness to U-bolt on the lower end of the Avionics Bay Coupler assembly with QTY 1 8947T26 quick link. Do not close the quick link at this time.

12. Tie the center of the shroud lines on the REC-CHT-DRG-36 drogue parachute into a 2-3-inch diameter loop using an overhand knot. Then, place this loop onto the 8947T26 quick link on the drogue recovery harness, where it connects to the Avionics Bay Coupler.

13. Place the reinforced slit of QTY 1 REC-PRT-16 parachute protector onto the 8947T26 quick link on the drogue recovery harness, where it connects to the Avionics Bay Coupler. Close the quick link and tighten hand tight. A wrench may be used, but is not required.

14. Using QTY 1 8947T26 quick link, connect the loop at the base of the main parachute shroud lines to the loop on the main recovery harness, 6-8 feet from the nose cone end. Do not close the quick link at this time.

15. Place the the reinforced slit of QTY 1 REC-PRT-16 parachute protector onto the 8947T26 quick link at the base of the main parachute shroud lines, where it connects to the main recovery harness. Close the quick link and tighten hand tight. A wrench may be used, but is not required.

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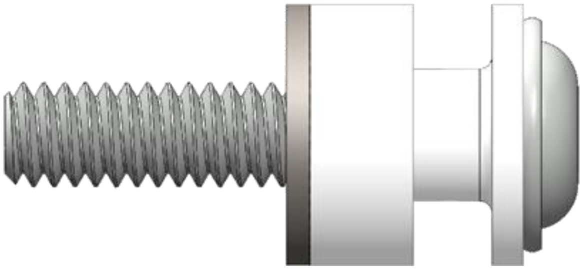
OP 13: Recovery System & Airframe Integration

16. Install the Nose Cone Assembly into the forward end of the 20545T38-AF-UPR airframe tube, and secure with QTY 8 90272A194 screws, threaded into the nuts in the nose cone shoulder.

17. Mount the lower airframe tube onto the forward tank interface ring using QTY 6 91306A279 screws and QTY 6 92141A029 washers in the locations shown. Tighten to snug using a 5/32" hex key.
18. *Note: excessive torque may damage the printed nut retaining ring.*

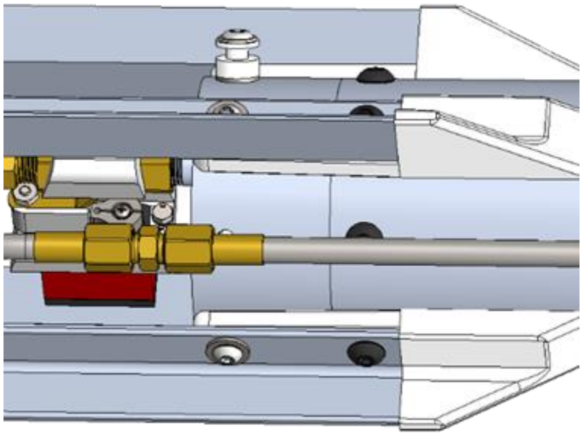
19. Place QTY 2 RLBTN-A-1515-250C, QTY 2 RLBTN-B-1515-250C, and QTY 2 92141A029 washers onto QTY 2 97654A620 screws (one of each per screw) as shown to form a rail button assembly.

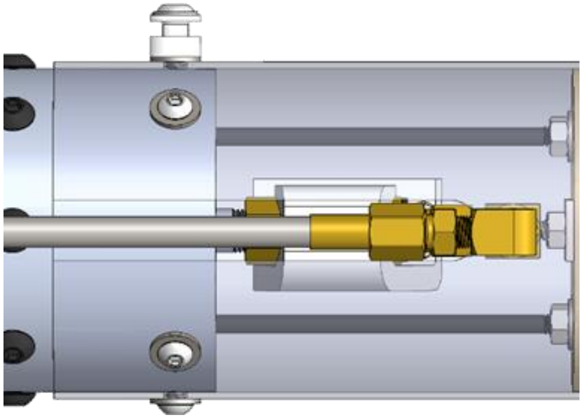


OP 13: Recovery System & Airframe Integration

12. Install one rail button assembly into the unoccupied hole/nut on the forward tank interface ring where shown, 90 degrees from the fuel line. Tighten to very slightly snug, so that the rail button can rotate with minor resistance. It does not need to spin freely.

13. Install the second rail button assembly into the hole/nut on the lower tank interface ring where shown, 90 degrees from the fuel line (aligned with the upper rail button). Tighten to very slightly snug, so that the rail button can rotate with minor resistance. It does not need to spin freely.





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Section VI – Ground Support Equipment

6.1 GSE Overview

Ground Support Equipment, or **GSE**, is a critical part of any rocket system. The launch vehicle may be the most interesting part, but it simply does not function without GSE.

For solid rockets, GSE can be as simple as a switch that fires an igniter. For UC-valve hybrids, where the igniter also acts as the main oxidizer valve, it must also be capable of loading oxidizer into the motor. For Mojave Sphinx and all standard liquid rockets, it must also be able to open the main propellant valves to start the flow of fuel and oxidizer, separate from the ignition command. Furthermore, since any operation in which N_2O is present outside the supply bottle is hazardous to personnel, all such activities must be performed at a safe distance. This requires a remotely-controlled fluid handling system which is both safe and economical, so as to not dwarf the cost of the rocket itself.

The purpose of the GSE is to:

1. Control flow of N_2O from a supply bottle
2. Provide ignition power
3. Issue a valve-open command
4. Dump N_2O rapidly to safe the vehicle

For rockets with pneumatic Half Cat valves, the valve-open command may be a trigger for a pyrotechnic device, such as a line cutter that severs and vents a pneumatic pressure supply tube. In any standard liquid rocket, the oxidizer dump may be the same command as the normal valve-open, only without triggering the igniter, and may involve dumping both propellants. Only in the unlikely event of complete power loss during fill should the static vent be relied upon to fully empty the oxidizer tank, as this can take upwards of an hour depending on tank and vent sizes. The remote control system described in this guide is configured so that a loss of communication with the GSE will automatically open the vehicle propellant valves, returning the system to a safe state.

The GSE can be divided into two major subsystems: The fill system and the control system. The fill system is a simple plumbing assembly consisting of a supply bottle connection, a fill valve, and a QD connection. The control system is taken straight from a much more well-developed and commercially available field – hobby R/C aircraft. R/C plane transmitters and receivers make for affordable and reliable wireless control systems that do not require a Ham license or any programming, beyond configuring the existing firmware through a user interface. Furthermore, modern 2.4gHz radio protocols are robust to interference due to the use of an Automatic Frequency Hopping Digital System (AFHDS). The control system consists of a transmitter, receiver, battery, voltage regulator, and electrical relay. Below is a basic electrical schematic of the GSE:

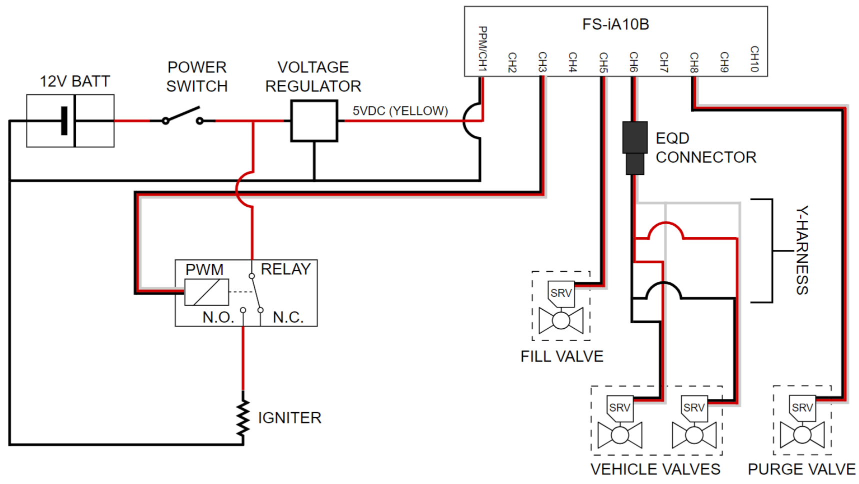

Figure 6.1: GSE electrical schematic

6.2 GSE Bill of Materials

Line	Item	Unit Price	QTY	Cost	Context
1	FlySky FS-I6X Transmitter w/ iA10B Receiver	$59.99	1	$59.99	Controller
2	Toggle Switch Guards (Pack of 6)	$8.49	1	$8.49	Switch covers
3	12V 160 CCA AGM Battery	$49.99	1	$49.99	Electrical connections
4	20GA Silicone Coated Wire, Red & Black, 10ft Each	$0.00	1	$0.00	Leftover from avbay
5	Relay Module, PWM Controlled, 10A 30V	$11.99	1	$11.99	Ignition switch
6	12V to 5V Voltage Regulator	$12.99	1	$12.99	Battery to receiver
7	GSW-17-SPST Toggle Switch with Screw Terminals	$5.99	1	$5.99	GSE Power Switch
8	Straight-Blade Receptacle with Screw Terminals, 5-15 NEMA, Side Terminal	$3.36	1	$3.36	Electrical outlets
9	Nylon Wall Plate for NEMA Outlets	$0.73	1	$0.73	outler cover; can also print version with labels
10	3-pin Servo Extension Cables, 1m (Pack of 10)	$0.00	1	$0.00	Leftovers from Valves
11	21 Inch Steel Toolbox, Voyager, HFT	$29.99	1	$29.99	GSE Enclosure
12	1/4-20 x 2" Eye Bolt	$2.87	2	$5.74	Battery Restraints
13	25kg Servo w/ 25T Servo Horn	$17.89	1	$17.89	Valve Actuator
14	Compact High Pressure Ball Valve, 1/4NPT	$17.26	1	$17.26	Ox FIll Valve
15	20lb Nitrous Tank	$197.00	1	$197.00	INCLUDES APPROX SHIPPING COST
16	Brass Nipple, Wrench Tighten, CGA 326, 1/4 NPT Male	$8.49	1	$8.49	Nitrous tank adapter
17	Brass Female CGA 326 Nut for High-Pressure Nipple Hose Fitting for Compressed Gas	$5.90	1	$5.90	Nitrous tank adapter
18	High-Pressure Braided Chemical Hose with Fittings Brass 7/16"-20 Thread Size Flare UNF Female, 5/16" OD – 14"	$16.14	1	$16.14	Tank to Valve Hose
19	37 Degree Flared Adapter for 1/4" Tube OD x 1/4 NPT Male	$3.71	2	$7.42	Tank outlet and valve inlet
20	High-Pressure Brass Straight Connector, 1/4 NPT Female	$1.78	1	$1.78	Tank adapter to flare fitting

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Line	Item	Unit Price	QTY	Cost	Context
21	High-Pressure Brass Through-Wall Straight Connector, 1/4 NPT Female	$9.63	1	$9.63	Fill Bulkhead Fitting
22	3/4-16 Hex Nut, 18-8 Black Oxide	$1.79	1	$1.79	Bulkhead Fitting spacer nut
23	High-Pressure Brass Right-Angle Tee Adapter, 1/4 NPT Female x Male	$5.71	1	$5.71	Nitrous Gauge tee
24	High-Pressure Brass Straight Connector, 1/4NPT Male	$2.67	1	$2.67	Gauge Tee to valve
25	High-Pressure Push to Connect, 1/4 Tube OD, 1/4NPT Male	$3.84	1	$3.84	Valve to fill line
26	High-Pressure Push to Connect, 1/4 Tube OD, 1/8NPT Male	$3.95	2	$7.90	Fill line bulkhead
27	High-Pressure Brass Through-Wall Straight Connector, 1/8 NPT Female	$6.97	1	$6.97	Fill line bulkhead fitting
28	Pressure Gauge with Steel Case, 1/4 NPT Male Center Back Connection, 2" Dial, 0-2000 PSI	$15.85	1	$15.85	Supply pressure
29	8-32 X 1/2"L Screw, Zinc Plated Steel (Pack of 100)	$0.00	1	$0.00	Leftovers from Valves (handle connector screw)
30	8-32 Hex Nut, Low Strength (Pack of 100)	$0.00	1	$0.00	Leftovers from Valves (handle connector screw)
31	M4 Washer, 8mm OD, 18-8SS (Pack of 100)	$0.00	1	$0.00	Leftovers from Valves (servo mounting)
32	M4 Split Lock Washer, 18-8SS (Pack of 100)	$0.00	1	$0.00	Leftovers from Valves (servo mounting)
33	250lb Kevlar Cord, 100ft	$13.95	1	$13.95	QD Clip Tether / Shroud lines for tent tarp chute)
34	Nylon Tubing, 1/4" OD, 800PSI, 10ft	$0.00	1	$0.00	Leftover from Fluid System Components
35	PLA+ 3D Printer Filament, White, 2kg (Or Equivalent)	$0.00	1	$0.00	Leftover from Valves (valve actuator housing)
36	Servo Valve Mount	$0.00	1	$0.00	Printed
37	Servo Valve Handle Connector	$0.00	1	$0.00	Printed
		Subtotal		**$529.45**	

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Line	Part Number	Vendor Description	Source
1	DTUS_FSI6X_10CH	FLYSKY FS-i6X 10CH 2.4GHz RC Transmitter Controller/W iA10B Receiver Upgrade Cable for RC Helicopter Plane Quadcopter Glider	https://www.amazon.com/
2	AZ18080602-03	Antrader Plastic 12mm Mount Dia. Toggle Switch Cover Dustproof Safety Waterproof Safety Flip Cover Cap Red 6-Pack	https://www.amazon.com/
3	62586	THUNDERBOLT MAGNUM 12V 160 CCA AGM Battery	https://www.harborfreight.com/12v-160-cca-agm-battery-62586.html
4	20GA-RBP	20 Gauge Wire 20 feet Silicone Wire Soft and Flexible Tinned Copper Wire High Temperature Resistance 10 ft Black and 10 ft Red Stranded Wire for 3D Printer, Test Leads,RC Applications	https://www.amazon.com/
5	LCATMC1569	LICHIFIT High Voltage 1CH PWM RC Aircraft Remote Control Signal Relay Switch K1 Navigation Light Controller	https://www.amazon.com/
6	090600AFA	DROK 12v to 5v Volt Converter, DC 8-35V to 5V 3A 15W Voltage Regulator Board Power Supply Module, 9V 12V 24V Waterproof Car Volt Step Down Buck Converter	https://www.amazon.com/
7	GSW-17	Gardner Bender GSW-17 Electrical Toggle Switch, SPST, ON-OFF, 6 A/120V AC, Screw Terminal	https://www.amazon.com/
8	7159K3	Straight-Blade Receptacle with Screw Terminals, 5-15 NEMA, Side Terminal	https://www.mcmaster.com/7159K3/
9	7526K23	Nylon Wall Plate for NEMA Outlet, for 1 Device	https://www.mcmaster.com/7526K53/
10	YXQ	YXQ 1M Servo Extension Cable 3 Pin Male to Female Lead Wire for RC Airplane (10Pcs)	https://www.amazon.com/
11	91111	VOYAGER 21 in. Steel Toolbox	https://www.harborfreight.com/steel-toolbox-91111.html
12	9489T519	Routing Eyebolt with Nut - Not for Lifting 316 Stainless Steel with Bent-Closed Eye, 1/4"-20 Thread, 2" Shank	https://www.mcmaster.com/9489T519/
13	DS3225	20KG Steering Servo, RC Servo with Full Metal Gear and 25T Servo Horn (180°)	https://www.amazon.com/
14	4112T22	Compact High-Pressure Brass Ball Valve with Lever Handle, 1/4 NPT Female	https://www.mcmaster.com/4112T22/
15	20LBALVLV-326	NEW 20 LB ALUMINUM N2O CYLINDER WITH HANDLE	https://gascylindersource.com/shop/nitrous-oxide-cylinders/20-lb-aluminum-n2o-cylinder-with-handle/
16	79215A673	Hose Fitting for Compressed Gas Brass Nipple, Wrench Tighten, CGA 326, 1/4 NPT Male	https://www.mcmaster.com/79215A673/
17	79215A672	Brass Female CGA 326 Nut for High-Pressure Nipple Hose Fitting for Compressed Gas	https://www.mcmaster.com/79215A672/
18	4468K811	High-Pressure Braided Chemical Hose with Fittings Brass 7/16"-20 Thread Size Flare UNF Female, 5/16" OD (14 in)	https://www.mcmaster.com/4468K811-4468K041/
19	50675K162	37 Degree Flared Fitting for Copper Tubing Adapter for 1/4" Tube OD x 1/4 NPT Male	https://www.mcmaster.com/50675K162/
20	50785K92	High-Pressure Brass Pipe Fitting Straight Connector, 1/4 NPT Female	https://www.mcmaster.com/50785K92/

Line	Part Number	Vendor Description	Source
21	50785K273	High-Pressure Brass Pipe Fitting Through-Wall Straight Connector, 1/4 NPT Female	https://www.mcmaster.com/50785K273/
22	97149A370	18-8 Stainless Steel Hex Nut Black-Oxide, 3/4"-16 Thread Size	https://www.mcmaster.com/97149A370/
23	50785K222	High-Pressure Brass Pipe Fitting Right-Angle Tee Adapter, 1/4 NPT Female x Male	https://www.mcmaster.com/50785K222/
24	5485K22	High-Pressure Brass Pipe Fitting Straight Connector, 1/4 NPT Male	https://www.mcmaster.com/5485K22/
25	9396T32	High-Pressure Push-to-Connect Tube Fitting for Air and Water, Adapter, 1/4" Tube OD x 1/4 NPTF Male	https://www.mcmaster.com/9396T32/
26	9396T31	High-Pressure Push-to-Connect Tube Fitting for Air and Water, Adapter, 1/4" Tube OD x 1/8 NPTF Male	https://www.mcmaster.com/9396T31/
27	50785K272	High-Pressure Brass Pipe Fitting Through-Wall Straight Connector, 1/8 NPT Female	https://www.mcmaster.com/50785K272/
28	3846K8	Single Scale Pressure Gauge with Steel Case 1/4 NPT Male Center Back Connection, 2" Dial (0 to 2,000 psi)	https://www.mcmaster.com/3846K8-3846K93/
29	90272A194	Zinc-Plated Steel Pan Head Phillips Screw 8-32 Thread, 1/2" Long	https://www.mcmaster.com/90272A194/
30	90480A009	Low-Strength Steel Hex Nut Zinc-Plated, 8-32 Thread Size	https://www.mcmaster.com/90480A009/
31	98689A113	General Purpose 18-8 Stainless Steel Washer for M4 Screw Size, 4.300 mm ID, 8 mm OD	https://www.mcmaster.com/98689A113/
32	92148A160	18-8 Stainless Steel Split Lock Washer for M4 Screw Size, Standard, 4.4 mm ID, 7.6 mm OD	https://www.mcmaster.com/92148A160/
33	EK5580	emma kites 100% Kevlar Braided String Utility Cord Abrasion Flame Resistant, Tactical Survival Fishing Assist Cord Model Rocket Paracord Trip Line Camping Cordage	https://www.amazon.com/
34	9685T3	High-Pressure Hard Plastic Tubing for Air&Water Nylon, Semi-Clear White, 0.15" ID, 1/4" OD (10 ft)	https://www.mcmaster.com/9685T3/
35	N/A	OVERTURE PLA Plus (PLA+) Filament 1.75mm PLA Professional Toughness Enhanced PLA Roll, Cardboard Spool, Premium PLA 2kg(4.4lbs), Dimensional Accuracy Probability +/- 0.02mm (White 2-Pack)	https://www.amazon.com/
36	SABV-MOUNT-V2	-	Made from printer filament
37	SABV-HCON-V2	-	Made from printer filament

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6.3 GSE Assembly Procedures

The GSE presented in this section is constructed within a metal toolbox, which provides a durable housing that protects the system from exposure to the rocket's exhaust and can conveniently also store the tools needed to recycle the rocket between launches. The integrated packaging of the entire system including fill, control electronics, power, and optional CO_2 purge (used for static testing only) requires minimal on-site setup time and is well suited for long term use. If project budget is a limiting factor and only a small number of launches are planned, the GSE can be simplified at the expense of reduced ease of use by eliminating the toolbox and accompanying fittings and fasteners.

OP 1: Assemble Servo-Actuated Ball Valves (GSE)

Gather the following (per valve):

QTY	Part Number	Description
1	SABV-MOUNT-V2	Servo Valve Mount V2.STL
1	SABV-HCON-V2	Servo Valve Handle Connector V2.STL
-	N/A	3D Printer Filament (PLA+, PETG, or ABS recommended)
1	4112T22	Compact High Pressure Brass Ball Valve
1	DS3225	25kg Servo with 25T Servo Horn
1	93475A210	M3 Flat Washer 7mm OD
1	92855A310	M3x0.5 10mm Long 18-8 Low-Profile Socket Head Screw
1	90272A194	#8-32 Pan Head Screw, 1/2" Length
1	90480A009	#8-32 Hex Nut, Zinc Plated, Low Strength Steel
1	-	Nylon Zip Tie, 0.188-inch width
4	92180A044	Medium-Strength Class 8.8 Steel Hex Head Screw M4 x 0.70 mm Thread, 16 mm Long
4	90591A141	M4x0.7 Metric Hex Nuts
4	98689A113	M4 Flat Washers
4	92148A160	M4 Split Lock Washers

The SABV-04FF servo-actuated ball valve assemblies used in the GSE are identical to those used as the fuel and oxidizer valves on the vehicle Refer to Section 5 Op 1 for detailed instructions.

If constructing Fill Only GSE, only QTY 1 SABV-04FF is required. If a CO_2 purge valve for static testing is desired, build QTY 2 SABV-04FF.

OP 2: Assemble Fill System

Gather the following:

QTY	Part Number	Description
1	SABV-04FF	Servo-Actuated Ball Valve Assembly
1	79215A673	CGA 326 to 1/4NPT Adapter, Brass
1	79215A672	CGA 326 Female Nut, Brass
1	50785K92	High-Pressure Brass Straight Connector, 1/4 NPT Female
2	50675K162	37 Degree Flared Adapter for 1/4" Tube OD x 1/4 NPT Male
1	4468K811	High-Pressure Braided Chemical Hose with Fittings Brass 7/16"-20 Thread Size Flare UNF Female, 5/16" OD
1	50785K273	High-Pressure Brass Through-Wall Straight Connector, 1/4 NPT Female
1	97149A370	3/4-16 Hex Nut, 18-8 Black Oxide
1	50785K222	High-Pressure Brass Right-Angle Tee Adapter, 1/4 NPT Female x Male
1	3846K93	Pressure Gauge with Steel Case, 1/4 NPT Male Center Back Connection, 2" Dial, 0-2000 PSI
1	5485K22	High-Pressure Brass Straight Connector, 1/4NPT Male
1	9396T32	High-Pressure Push to Connect, 1/4 Tube OD, 1/4NPT Male
2	9396T31	High-Pressure Push to Connect, 1/4 Tube OD, 1/8NPT Male
1	50785K272	High-Pressure Brass Through-Wall Straight Connector, 1/8 NPT Female

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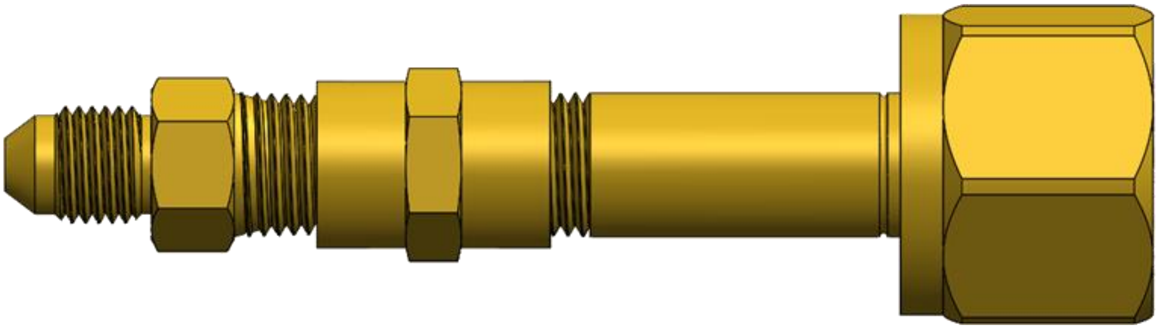
OP 2: Assemble Fill System

1. Slide QTY 1 79215A672 CGA 326 nut over QTY 1 79215A673 CGA 326 adapter nipple, so that the threads cover the rounded nub.

2. Apply 2-2 wraps of PTFE tape to QTY 179215A673 adapter nipple and QTY 1 50675K162 37 degree flared adapter fitting. Connect the flared adapter fitting to the CGA adapter nipple using QTY 1 50785K92 female straight connector as shown. Tighten all fittings to snug, 1-3 turns past hand tight.



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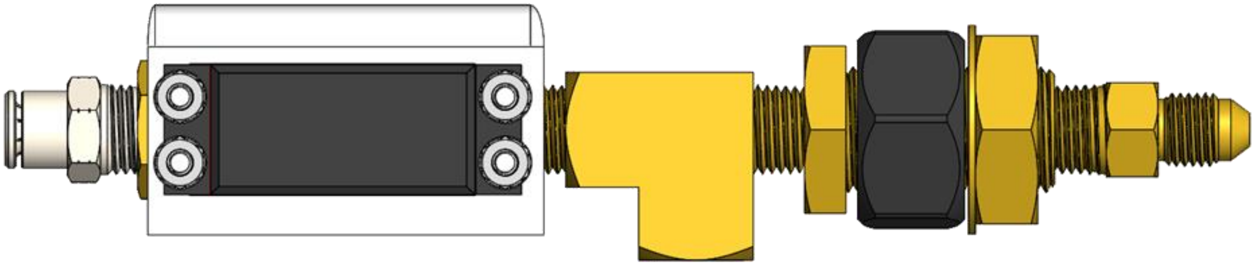
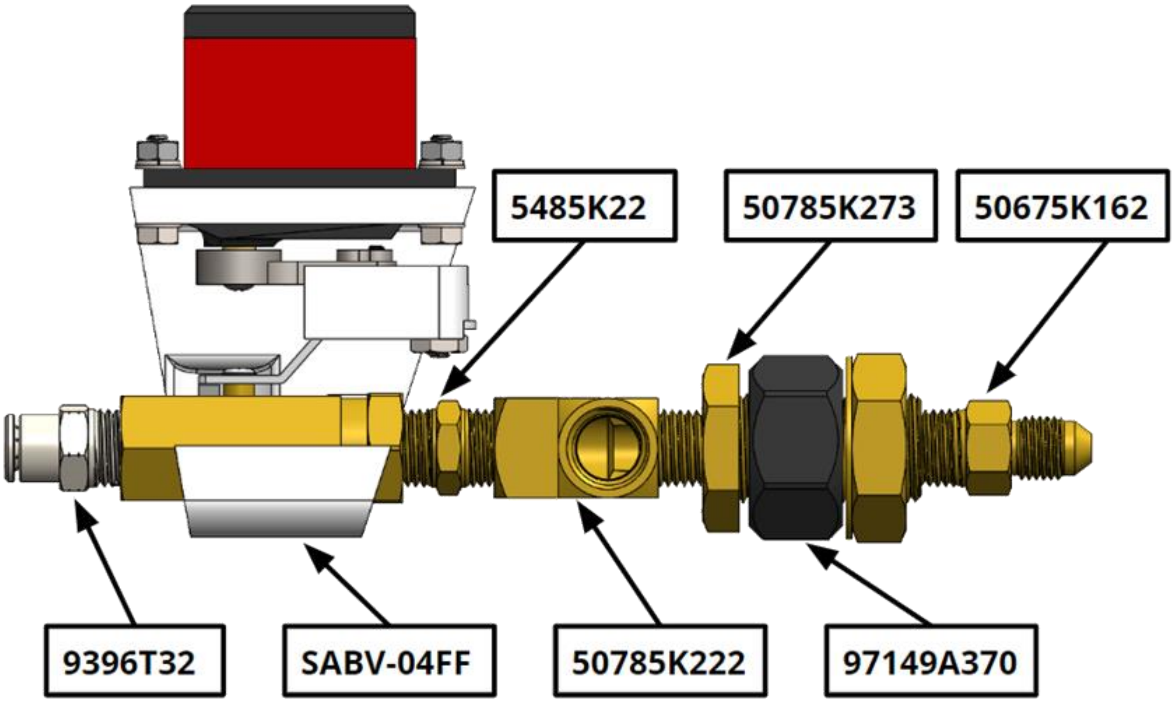
OP 2: Assemble Fill System

3. Apply 2-3 wraps of PTFE tape to the male threads on QTY 1 50675K162 37 degree flared adapter, QTY 1 50785K222 tee, QTY 1 50785K273 male straight connector, and QTY 1 9396T32 push-to-connect fitting. Assemble with QTY 1 50785K273 through-wall fitting and QTY 1 SABV-04FF as shown. Tighten all fittings to snug, 1-3 turns past hand tight. Ensure the 50785K222 tee is clocked as shown.

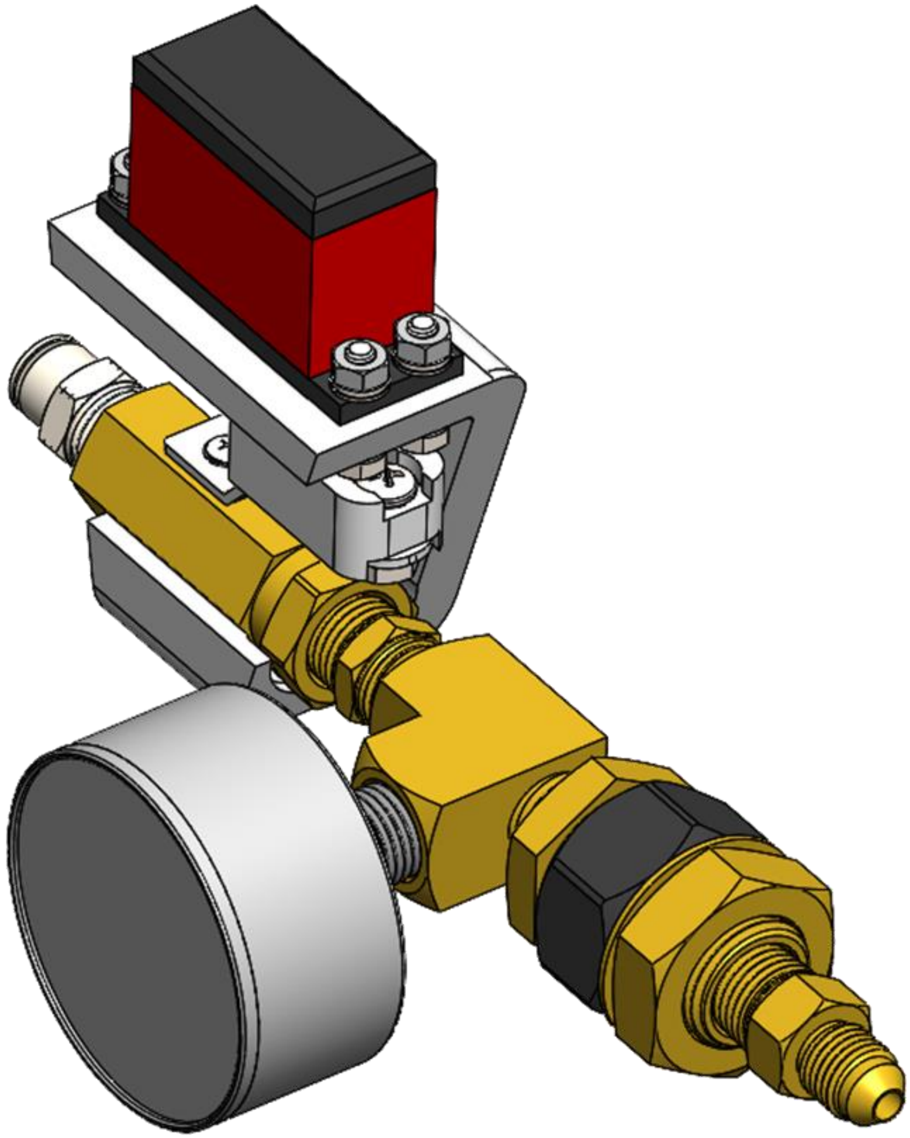
4. Thread the 97149A370 hex nut onto the 50785K273 through-wall fitting until there is approximately one thread between the nut and fixed hex portion of the fitting, then loose-install the included brass jam nut and toothed washer.





OP 2: Assemble Fill System

5. Install QTY 1 3846K93 gauge into the side port on the 50785K222 tee, with 2-3 wraps of PTFE tape applied to the threads. Tighten until snug, clocked so that the gauge scale is horizontal for readability.



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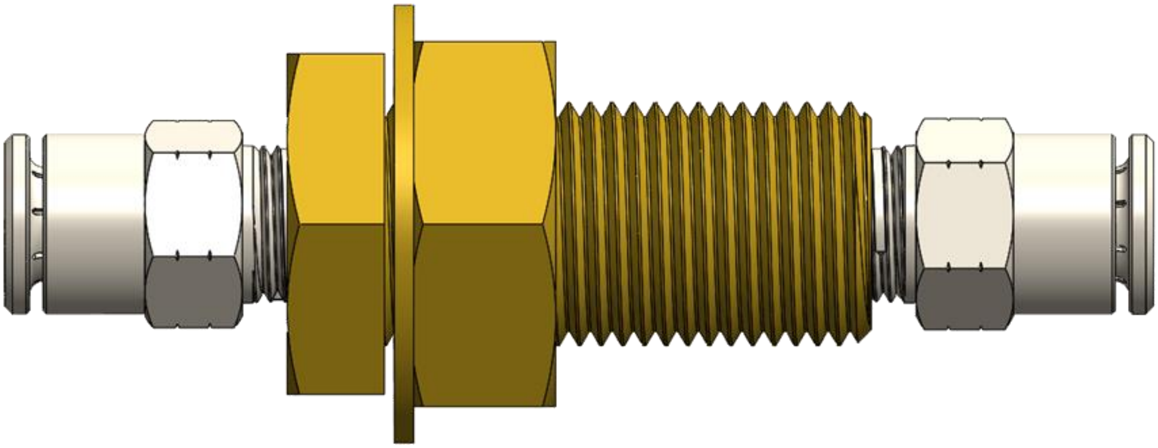
OP 2: Assemble Fill System

6. Apply 2-3 wraps of PTFE tape to QTY 1 9396T31 push-to-connect fittings and install into each end of QTY 1 50785K272 through-wall fitting as shown to form the fill line bulkhead assembly. Tighten all fittings to snug, 1-3 turns past hand tight.



OP 3: Assemble Purge System (Optional)

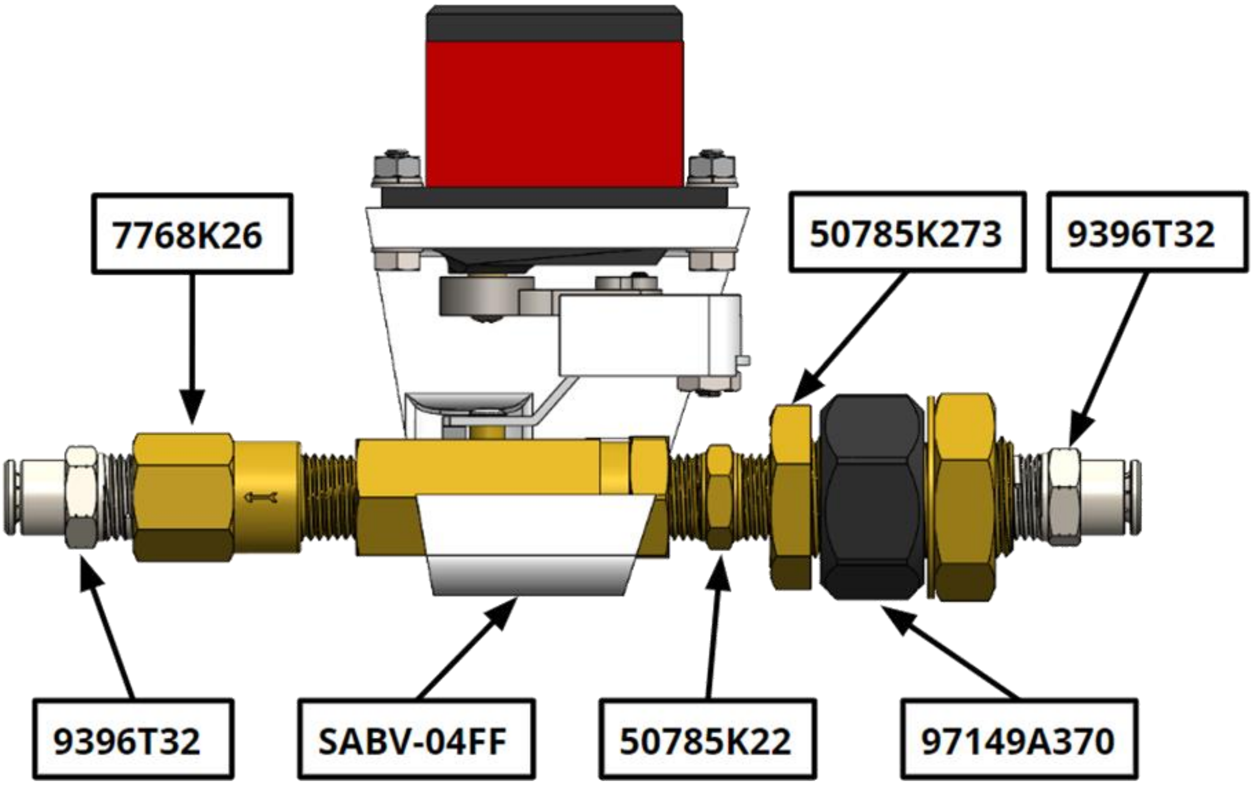
Gather the following:

QTY	Part Number	Description
1	SABV-04FF	Servo-Actuated Ball Valve Assembly
1	50785K92	High-Pressure Brass Straight Connector, 1/4 NPT Female
1	50785K273	High-Pressure Brass Through-Wall Straight Connector, 1/4 NPT Female
1	97149A370	3/4-16 Hex Nut, 18-8 Black Oxide
1	5485K22	High-Pressure Brass Straight Connector, 1/4NPT Male
2	9396T32	High-Pressure Push to Connect, 1/4 Tube OD, 1/4NPT Male
2	7768K26	Brass Threaded Check Valve, 1/4 NPT Male x NPT Female

OP 3: Assemble Purge System (Optional)

1. Apply 2-3 wraps of PTFE tape to the male threads of QTY 2 9396T32 push-to-connect fittings, QTY 1 5485K22 male straight connector, and QTY 1 7768K26 check valve. Assemble with QTY 1 50785K273 through-wall connector and QTY 1 SABV-04FF valve as shown. Tighten all fittings to snug, 1-3 turns past hand tight.

2. Thread the 97149A370 hex nut onto the 50785K273 through-wall fitting until there is approximately one thread between the nut and fixed hex portion of the fitting, then loose-install the included brass jam nut and toothed washer.



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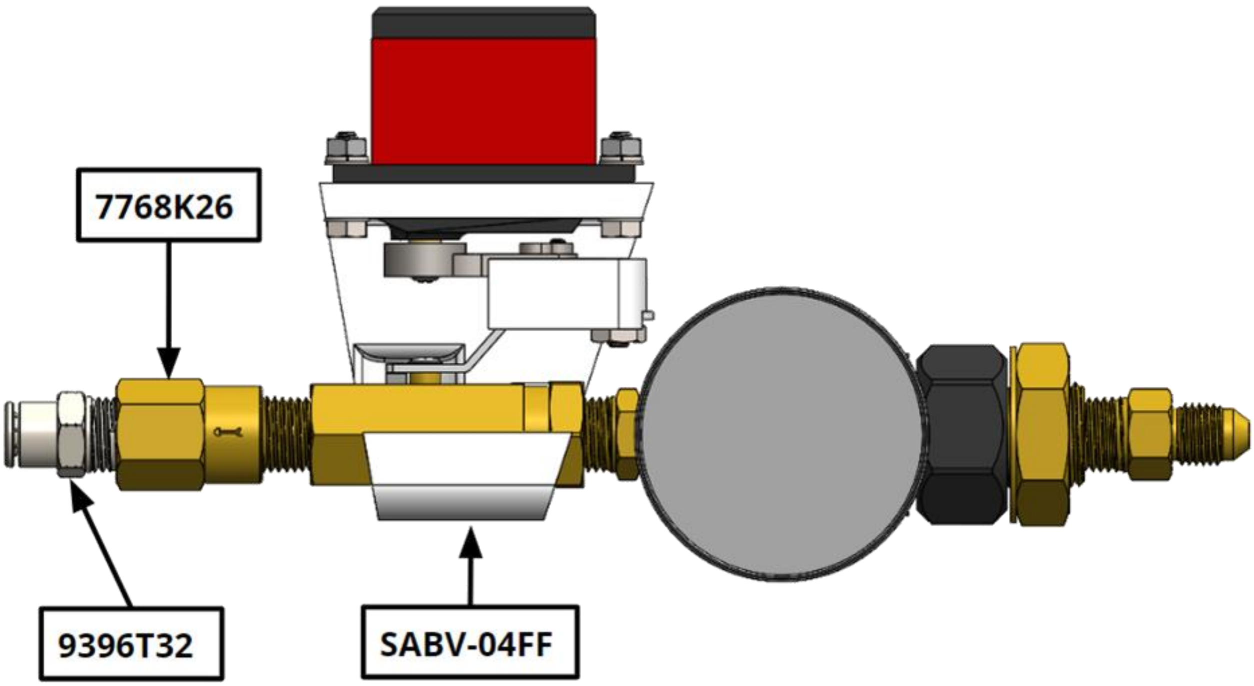
OP 3: Assemble Purge System (Optional)

3. If already installed, remove QTY 1 9396T32 push-to-connect fitting from the fill assembly. Install QTY 1 7768K26 check valve into the SABV-04FF outlet, then reinstall QTY 1 9396T32 into the check valve outlet as shown. Apply 2-3 fresh wraps of PTFE tape to each fitting prior to installation.

   Note: This check valve is only required if a purge valve is also present; it prevents cross-contamination between the CO_2 and N_2O supply tanks in the event that both valves are accidentally commanded open at the same time with the tanks at slightly different pressures. If a purge valve is not included, no check valves are needed on the fill system.



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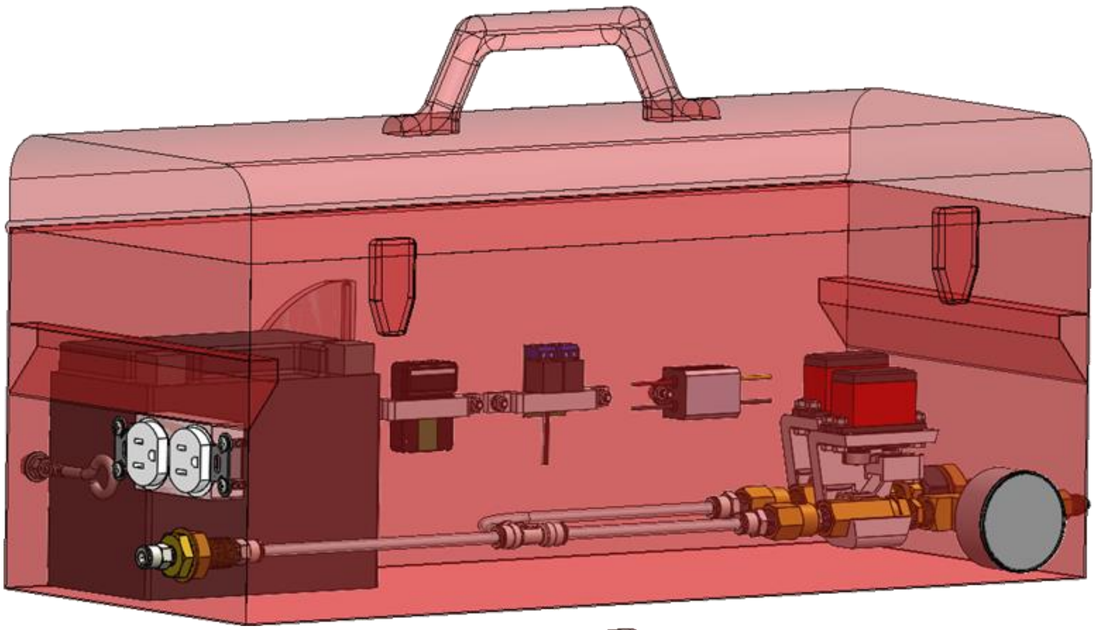
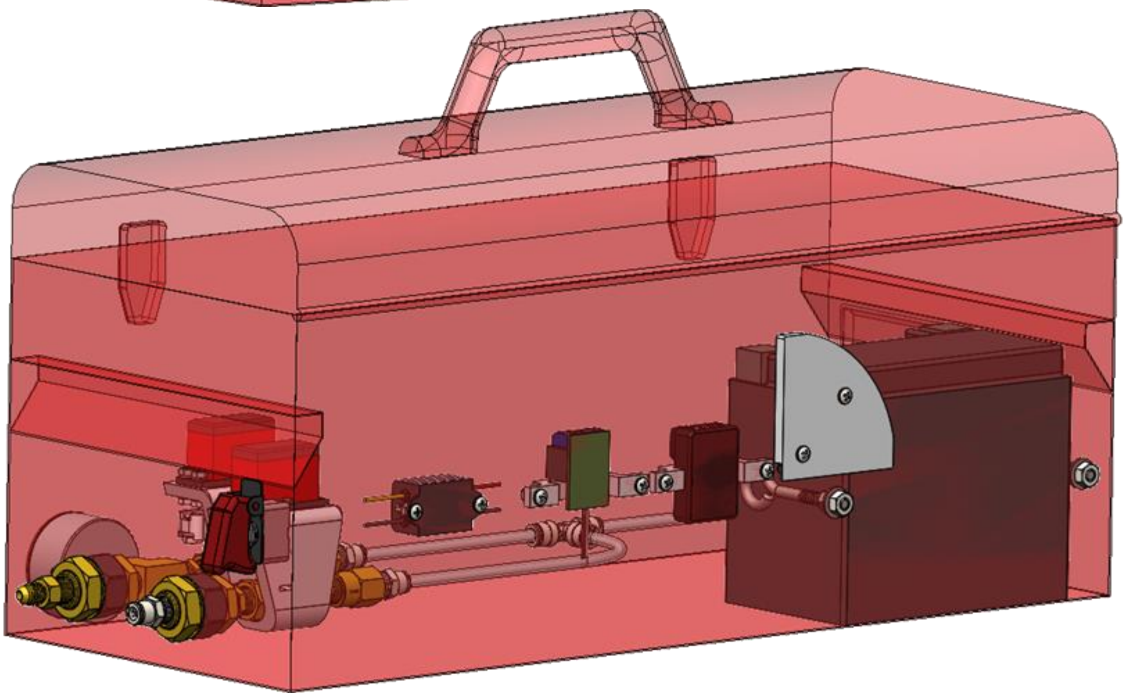
OP 4: Prepare Toolbox Enclosure

Gather the following:

QTY	Part Number	Description
1	91111	21-Inch Steel Toolbox, Voyager, HFT

Refer to the images below for the context of each hole created on this operation.





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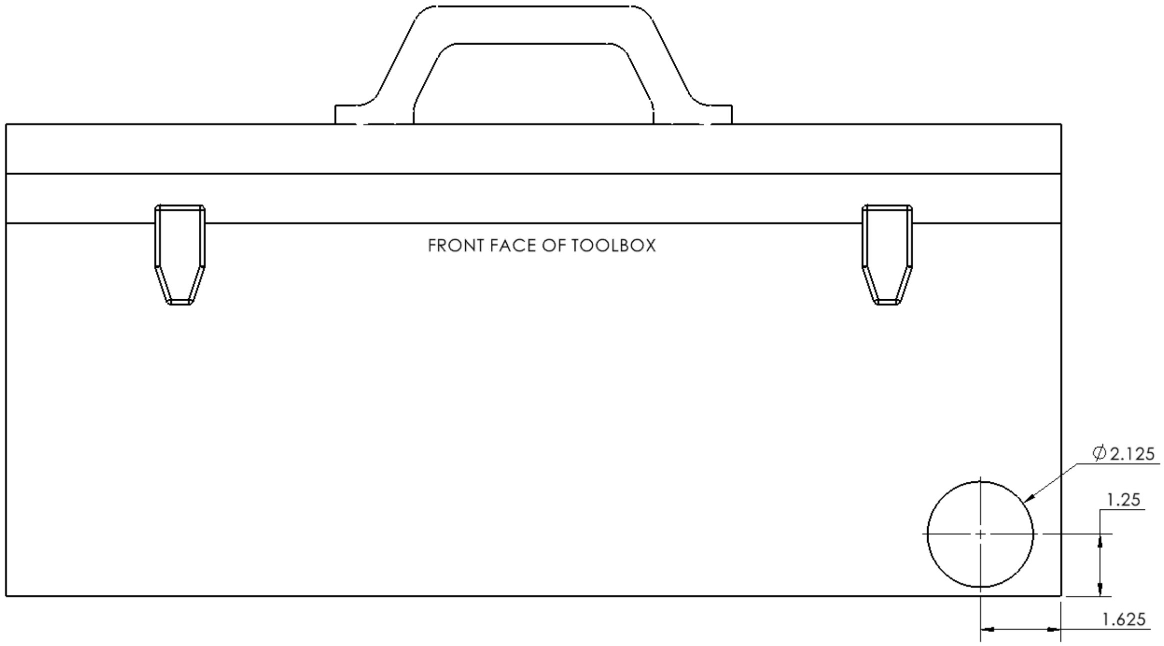
OP 4: Prepare Toolbox Enclosure

1. Using a hole saw, cut a 2 1/8-inch-diameter hole where shown on the front face of the 91111 21-Inch Voyager HFT toolbox.



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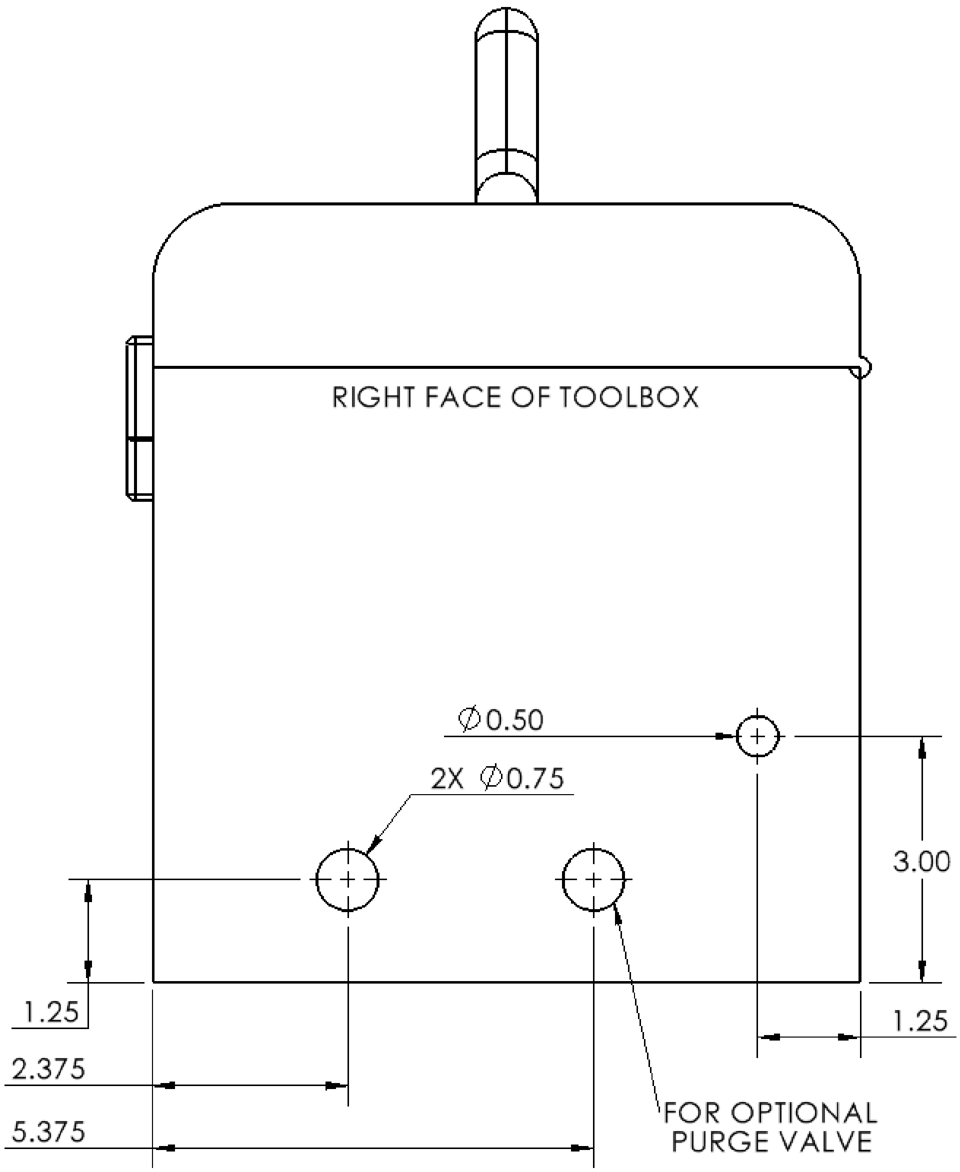
OP 4: Prepare Toolbox Enclosure

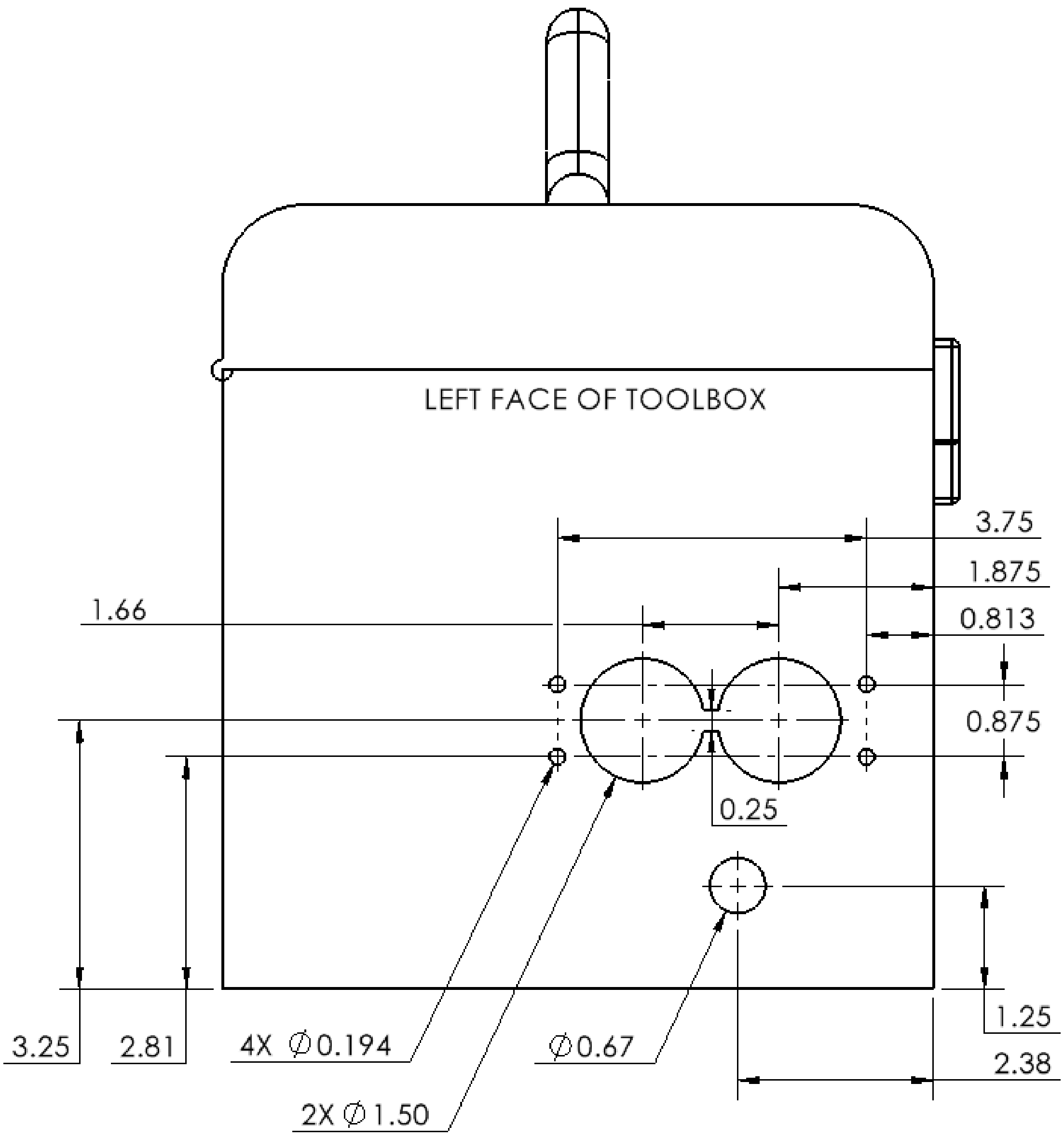
2. Drill the holes as shown in the side of the toolbox that is on the right when facing the front (where the latches are located). Note: if no purge valve is to be included, only the left-most of the two 3/4-inch holes is needed.



OP 4: Prepare Toolbox Enclosure

3. Drill the holes as shown in the side of the toolbox that is on the left when facing the front (where the latches are located). Use a hole saw for the 1.5-inch holes, and cut an approximately 1/4-inch side slot between them using a hacksaw.

   Note: The imperfect alignment of the 1.5-inch holes with the NEMA electrical outlets is intentional to avoid overlap between the holes, which can cause the hole saw blade to bind.



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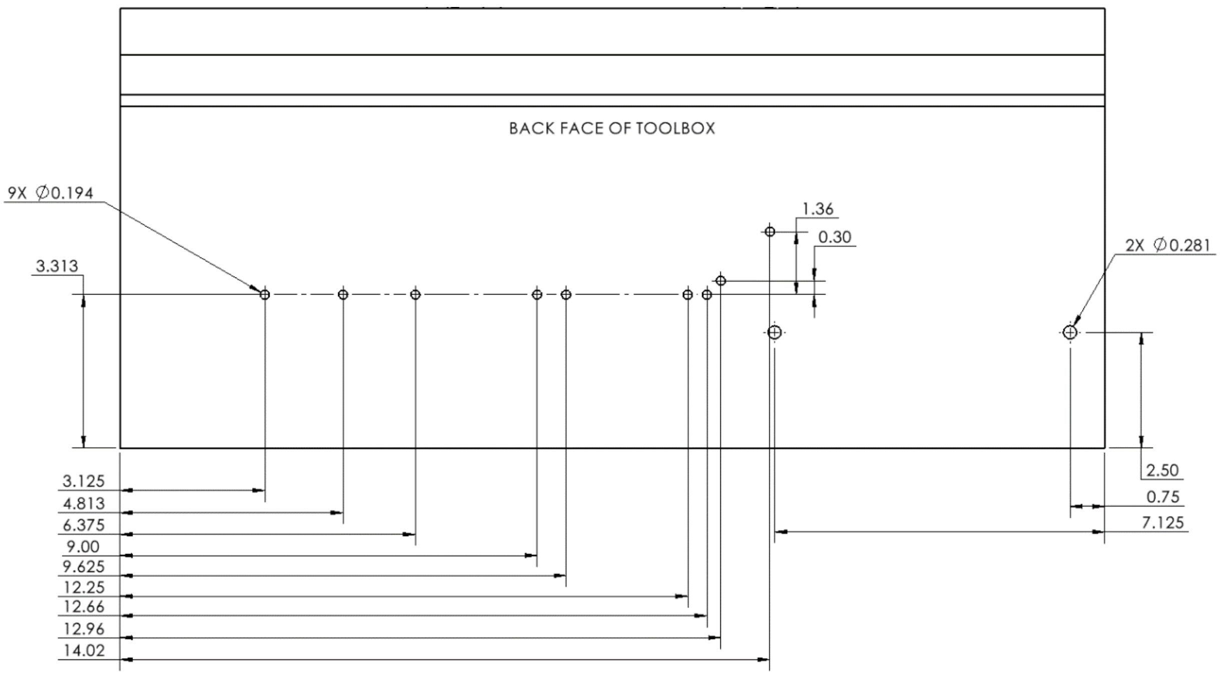
OP 4: Prepare Toolbox Enclosure

4. Drill the holes as shown in the back side of the toolbox.



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OP 5: Fluid System Integration

Gather the following:

QTY	Part Number	Description
1	-	Fill Valve Assembly
1	-	Fill Line Bulkhead Assembly
As Needed	9685T3	Nylon Tubing, 1/4" OD, 800PSI, 10ft

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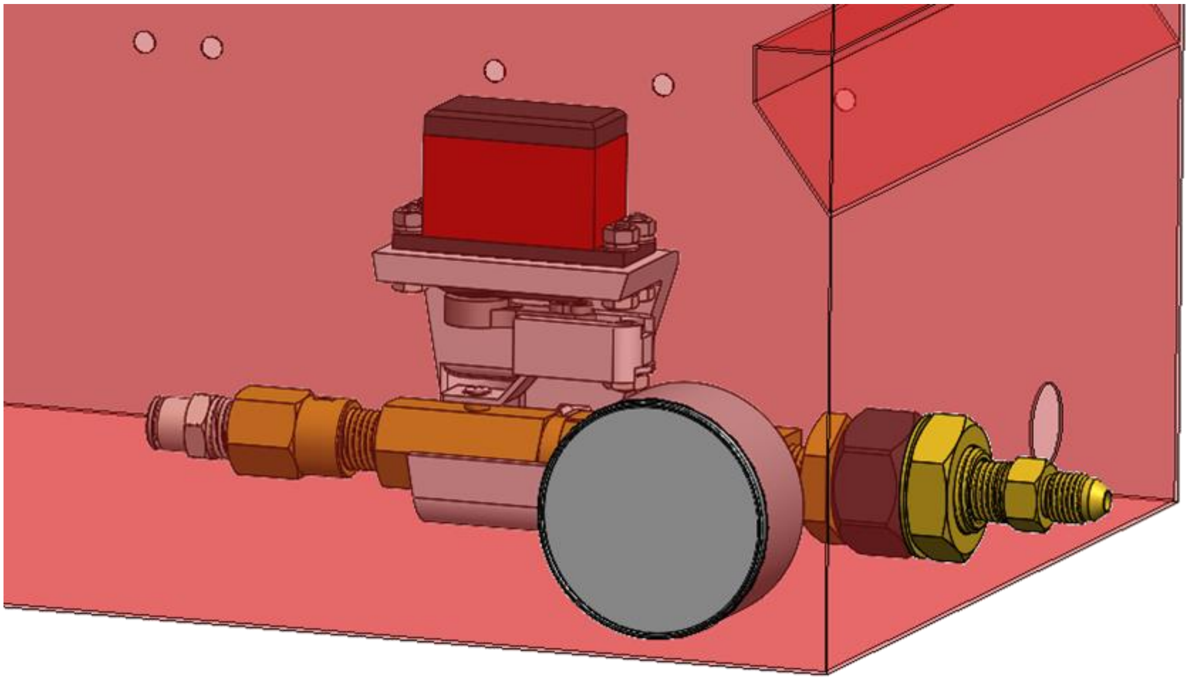
OP 5: Fluid System Integration

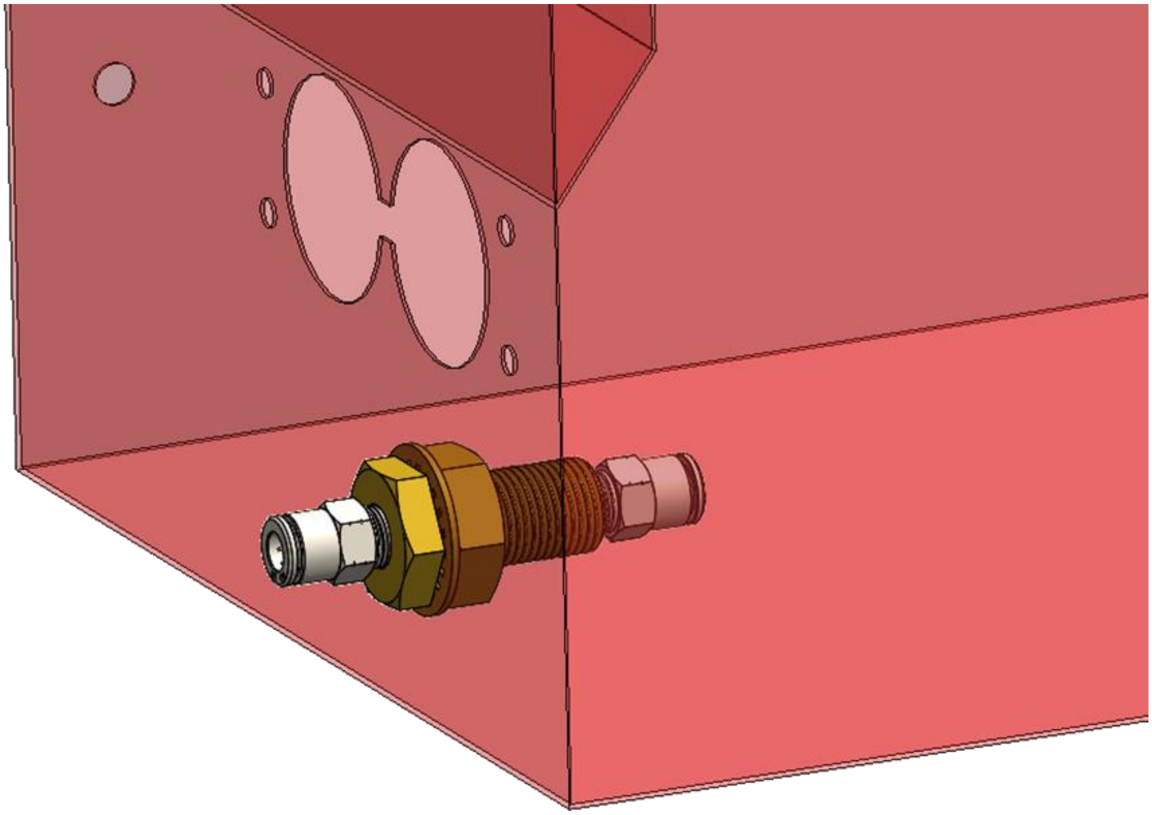
1. Remove the brass nut and toothed washer from the 50785K273 through-wall fitting on the fill valve assembly. Pass the fitting through the 0.75" hole in toolbox where shown, then re-install the toothed washer and brass nut. The 97149A370 hex nut should contact the inside of the toolbox. Ensure the gauge is aligned with the hole in the front face of the toolbox, then tighten the brass nut against the 97149A370 hex nut to clamp the assembly in place.

   Note: The configuration shown includes the check valve on the fill valve assembly, which is only required if a purge valve for static testing is also included in the system.



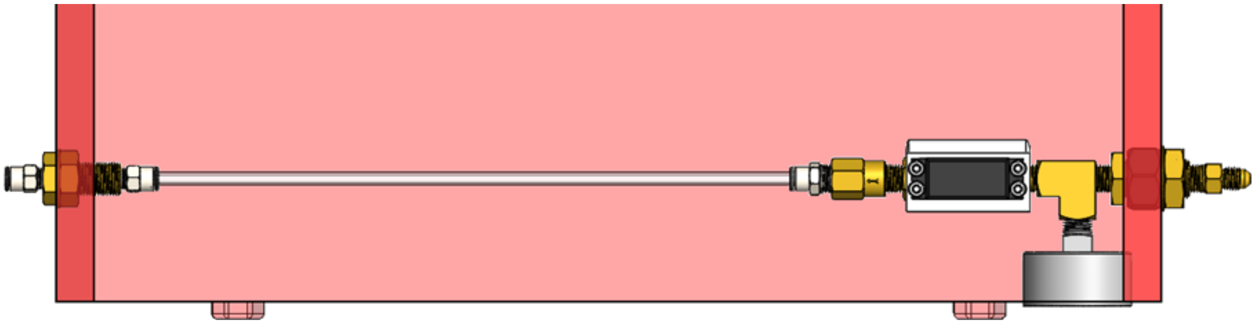
OP 5: Fluid System Integration

2. Remove the brass nut and toothed washer from the 50785K273 through-wall fitting on the fill line bulkhead assembly and install into 0.67" the hole on the left side of the toolbox as shown. Re-install the nut and washer onto the threaded portion that projects into the toolbox, and tighten to clamp the assembly in place.



OP 5: Fluid System Integration

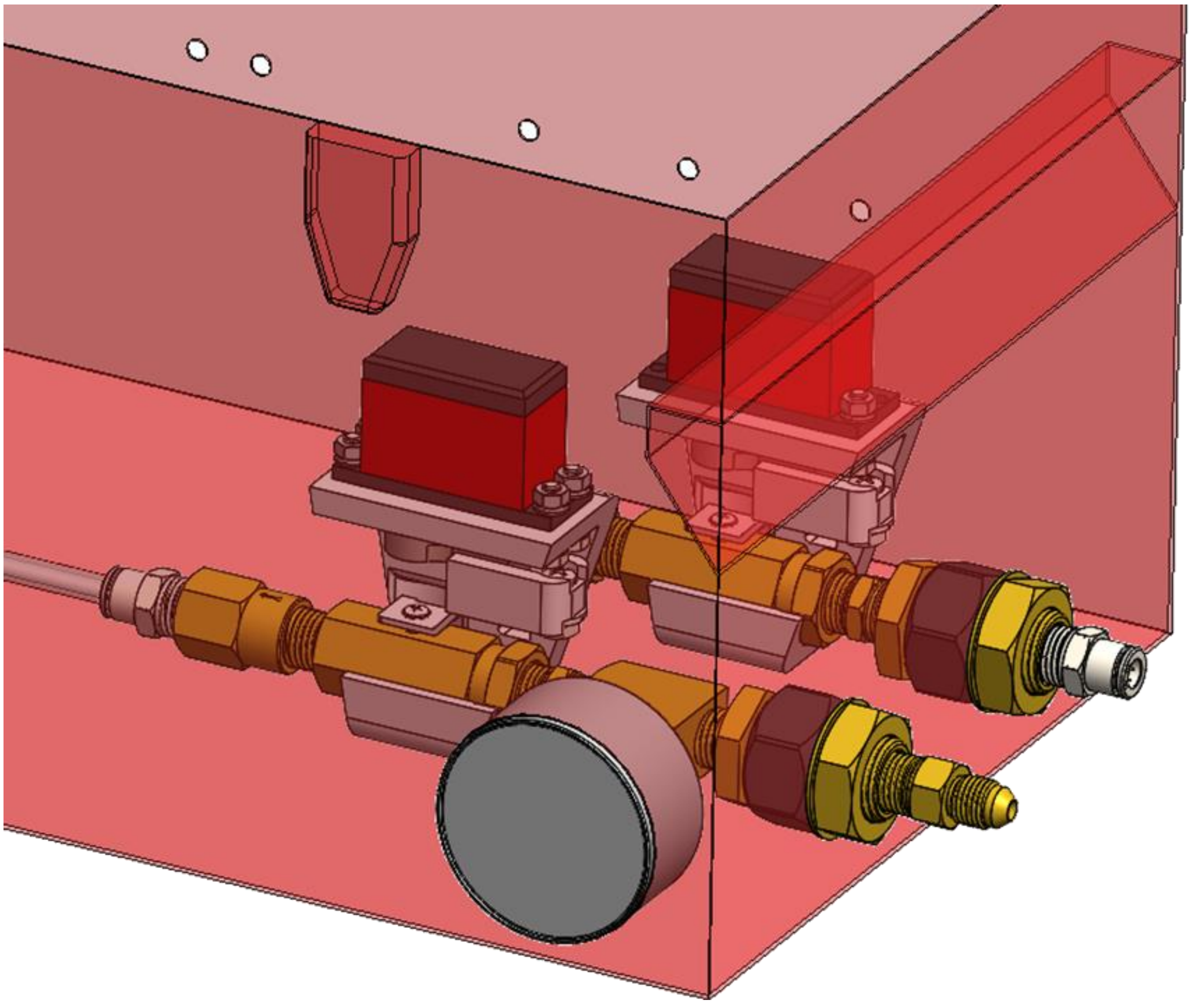
3. Cut a section of 9685T3 tubing approximately 13.5 inches in length. Insert one end into the 9696T32 push-to-connect fitting on the fill valve assembly, and the other end into the fill line bulkhead assembly as shown. Some slack in the line will aid in installation; it will not be perfectly straight as depicted in the CAD model.



OP 5: Fluid System Integration

4. The following steps are required ONLY if a purge valve is to be included in the system. If only a fill valve is installed, proceed to the next operation.

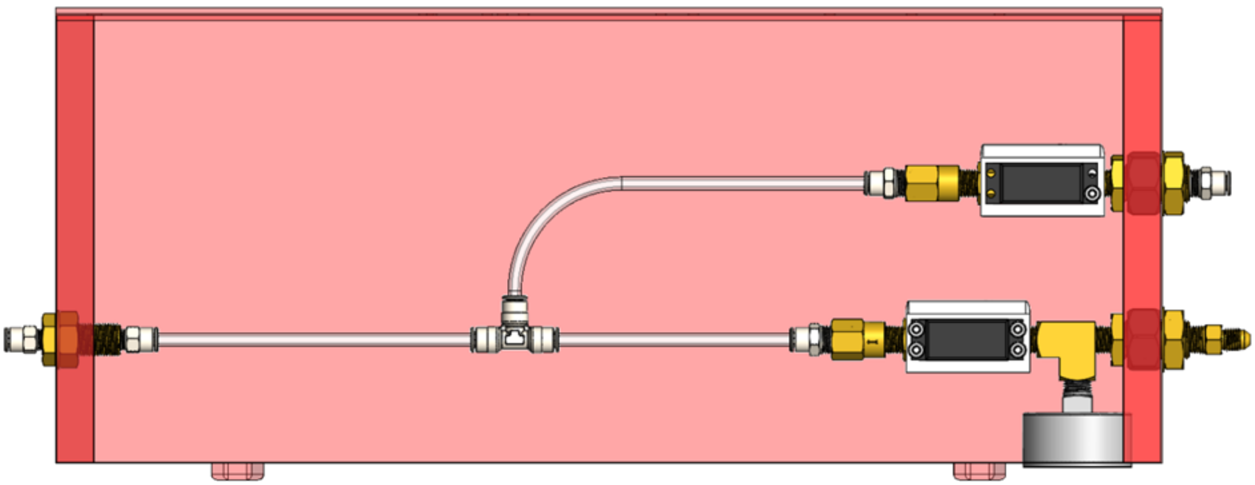
5. Install the purge valve into the second 0.75" hole in the right face of the toolbox as shown. The 97149A370 hex nut should contact the inner face of the toolbox, with the brass nut and toothed washer on the outside, as on the fill valve assembly. Ensure the valve is oriented vertically with the servo on top, then tighten the two nuts against one another to clamp the assembly in place.



OP 5: Fluid System Integration

6. Cut the 9685T3 fill tube approximately 4.5 inches from the fill valve assembly, and insert QTY 1 9396T61 push-to-connect tee as shown. If needed, a short section of tube may be removed to reduce excess slack length.

7. Cut a section of 9685T3 tubing approximately 8 inches long. Insert one end into the 9396T32 fitting on the purge valve assembly, and the other end into the branch of the 9396T61 tee as shown.



OP 6: Electrical System Integration

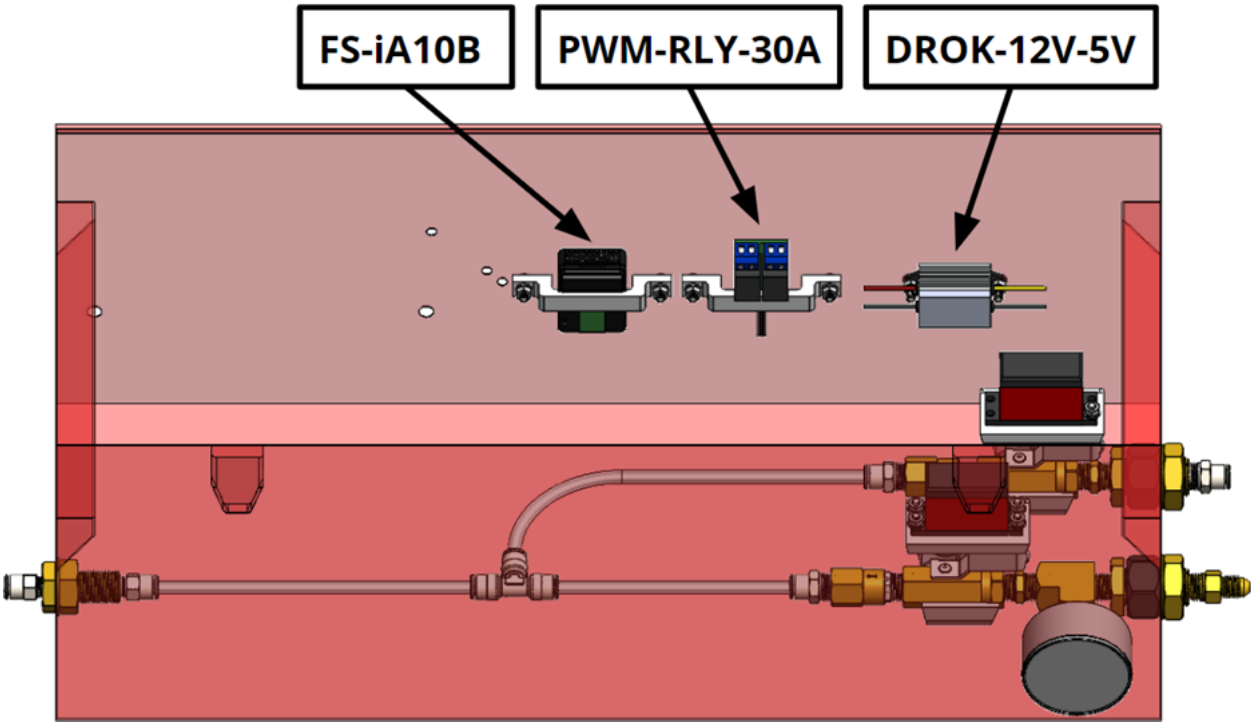
Gather the following:

QTY	Part Number	Description
1	FS-iA10B	FlySky 10ch 2.4gHz Receiver
1	DROK-12V-5V	12V to 5V adapter
1	PWM-RLY-10A	PWM-Controlled Relay Module, 30A, 12VDC
2	BRKT-EGSE-2X8C	Bracket, Electronics Mounting, GSE, 2X #8 Clearance Holes
1	CVR-ANT-2X8C	Cover, Receiver Antennas, GSE, 2X #8 Clearance Holes
12	9027A194	8-32 X 1/2"L Screw, Zinc Plated Steel
12	98689A113	M4 Washer, 8mm OD, 18-8SS
12	92148A160	M4 Split Lock Washer, 18-8SS
12	90480A009	8-32 Hex Nut, Low Strength Steel
2	9489T519	1/4-20 x 2" Eye Bolt
2	92141A029	18-8 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD
2	91102A750	Zinc-Plated Steel Split Lock Washer for 1/4" Screw Size, 0.26" ID, 0.487" OD
2	95505A601	Medium-Strength Steel Hex Nut, Grade 5, 1/4"-20 Thread Size
1	GSW-17-SPST	Toggle Switch, SPST
1	TGL-GRD-12MM	Toggle Switch Guard, 12mm Hole
1	7159K91	5-15 NEMA Electrical Outlet
1	7526K53	Nylon Wall Plate
1	SRV-3PIN-1MXT	Servo Extension Cable, 3-Pin, 1m
2	ZIP-TIE-188W	Nylon Zip Tie, .188" width
As needed	20GA-RBP	20 Gauge Stranded Wire, Red/Black Pair, Silicone Coated

OP 6: Electrical System Integration

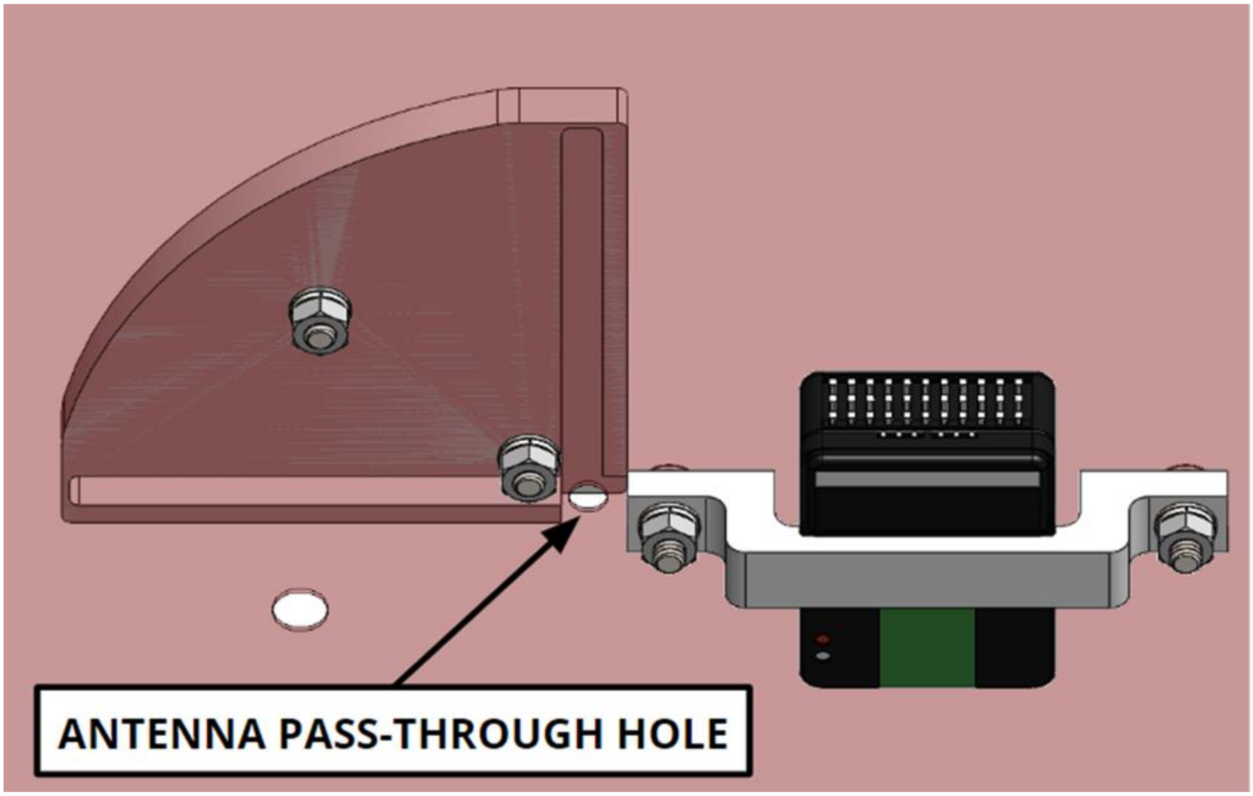
1. Mount the FS-iA10B receiver and PWM-RLY-30A relay module onto the inside of the back face of the toolbox as shown, using QTY 2 BRKT-EGSE-2X8C electronics mounting brackets. Secure the mounting brackets and DROK-12V-5V voltage regulator using QTY 6 9027A194 8-32 screws with 98689A113 flat washers, 92148A160 lock washers, and 90480A009 hex nuts.

   Note: M4 flat and lock washers are used with the #8 screws to reduce unique parts and cost; these components are common with the Servo Actuated Ball Valve assemblies. Additional flat washers may be placed under the heads of the screws if desired, but are not required. The PWM-RLY-30A module may differ slightly in appearance from the CAD model.



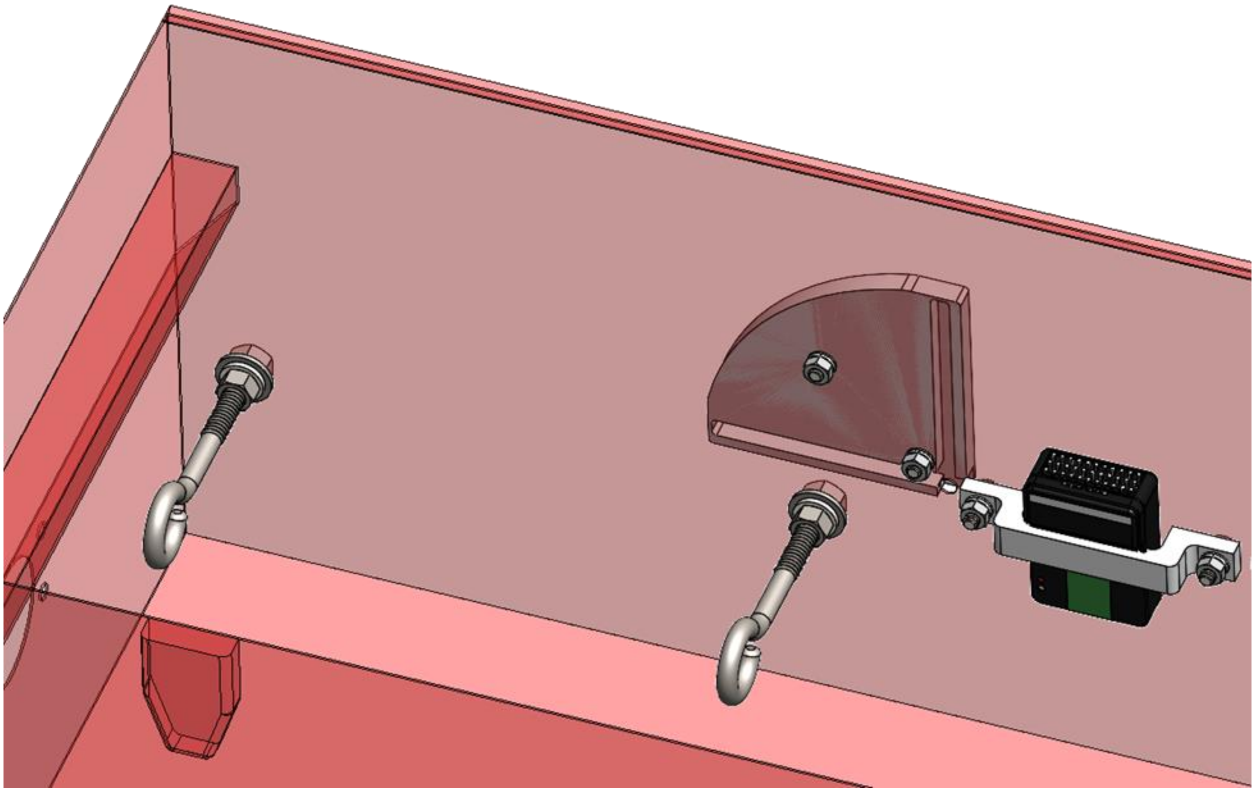
OP 6: Electrical System Integration

2. Pass the FS-iA10B antennas through the indicated hole and lay them into the slots in the CVR-ANT-2X8C antenna cover. Secure the antenna cover to the outer back face of the toolbox using QTY 2 9027A194 8-32 screws with 98689A113 flat washers, 92148A160 lock washers, and 90480A009 hex nuts.



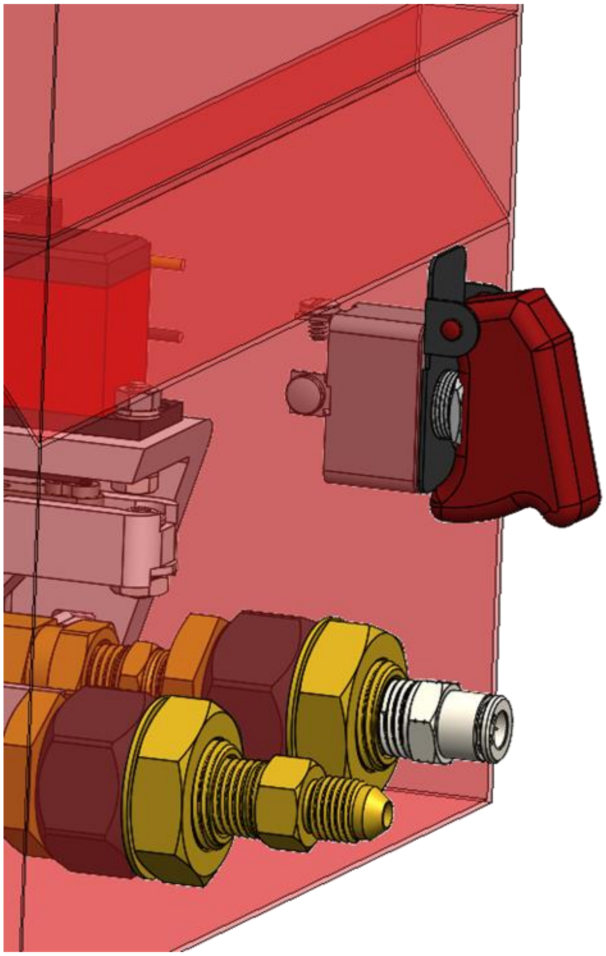
OP 6: Electrical System Integration

3. Install QTY 2 9489T519 eye bolts into the 1/4" clearance holes in the back face of the toolbox as shown, protecting inward with the eyes oriented vertically. Secure using the included hex nuts and QTY 2 92141A029 flat washers, QTY 2 91102A750 lock washers, and QTY 2 95505A601 nuts. These eye bolts will be used to secure the 12V battery on a later step.



OP 6: Electrical System Integration

4. Install QTY 1 GSW-17-SPST toggle switch with QTY 1 TGL-GRD-12MM into the ½" hole on the right side of the toolbox as shown. Orient the switch so that the toggle is angled downward in the off position, when it is covered by the toggle guard.



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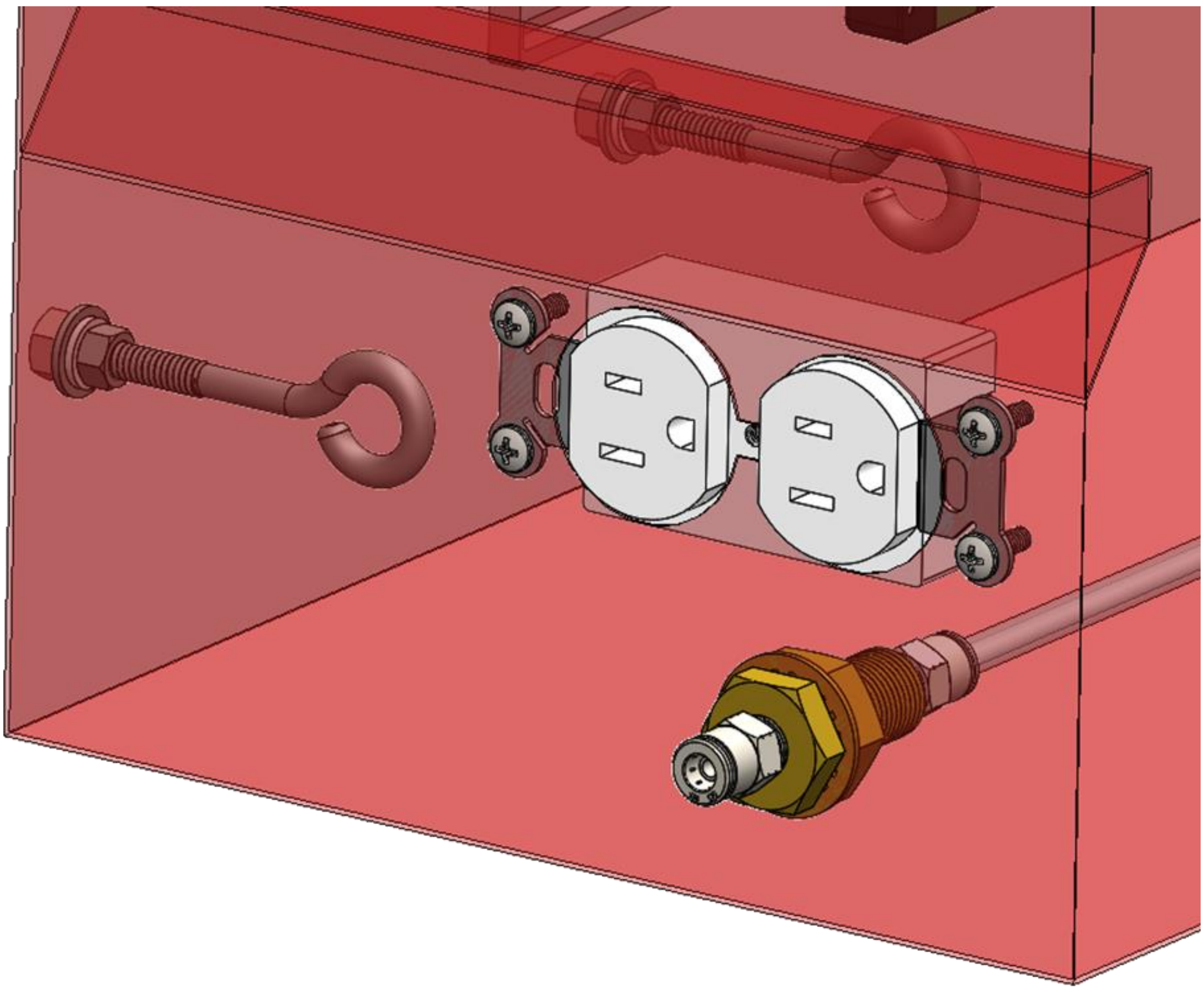
OP 6: Electrical System Integration

5. Using needle nose pliers, break off the small metal tab on the side of the 7159K91 outlet that connects the two receptacles. This will electrically isolate the two plugs from one another.

OP 6: Electrical System Integration

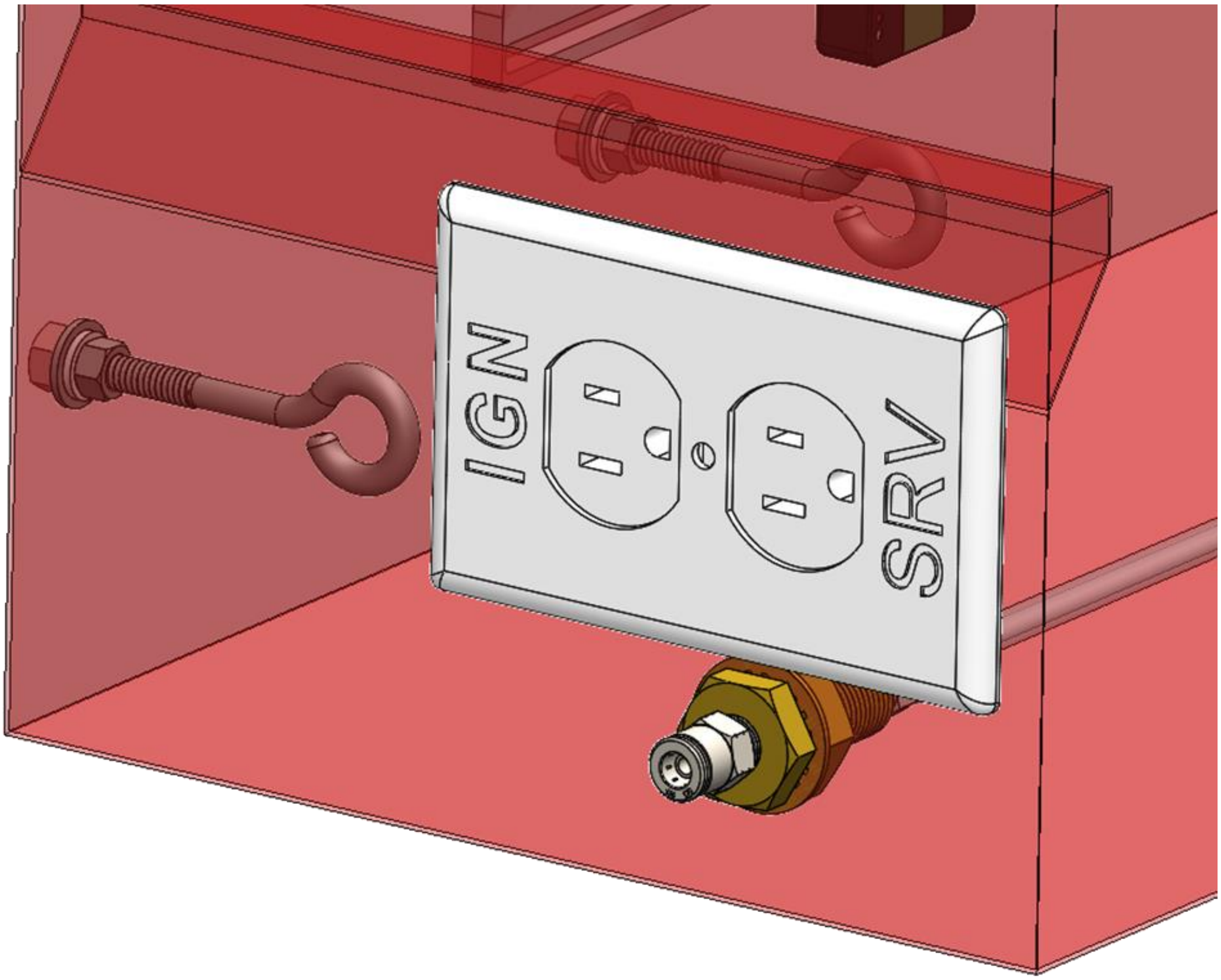
6. Install QTY 1 7159K91 electrical outlet onto the inner left face of the toolbox as shown, using QTY 4 9027A194 8-32 screws with 98689A113 flat washers, 92148A160 lock washers, and 90480A009 hex nuts.



OP 6: Electrical System Integration

7. Install the 7526K53 wall plate over the outlet using the included mounting screw (not shown). Label the outlets with "IGN" and "SRV" as shown to designate the igniter and servo outputs.

   Alternatively, the CAD part model may be 3D printed with engraved text. A 6-32 x 1/2" screw is required for mounting the plate to the receptacle.



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OP 6: Electrical System Integration

8. Cut the female (larger) plug off of QTY 1 SRV-3PIN-1M servo extension cable and strip approximately 0.5" of each wire. Connect the wires to the screw terminals on the electrical receptacle closest to the front of the toolbox as shown (indicated by SRV). This will be the Vehicle Valves cable which connects to the rocket.

   White wire: Connect to the screw terminal for the longer of the two slots

   Red Wire: Connect to the screw terminal for the shorter of the two slots

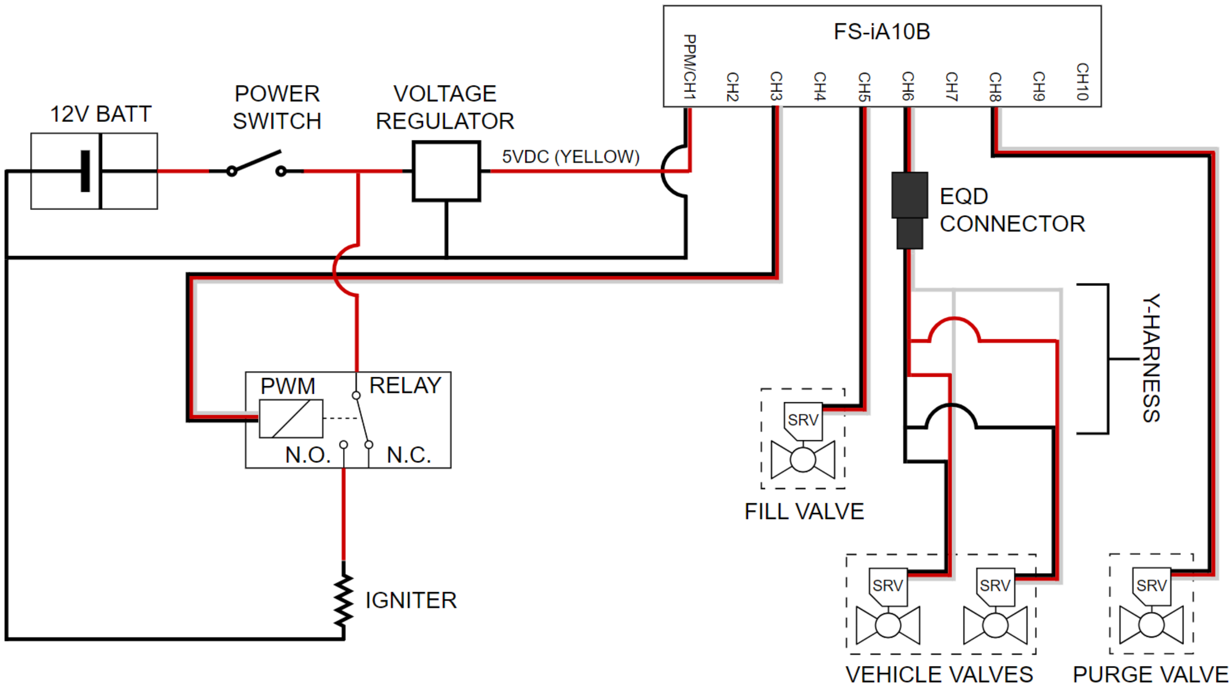
   Black Wire: Connect to the terminal for the ground pin (ensure the grounds of the two plugs are isolated by breaking off the tab on the side of the receptacle, as previously described).

9. Connect the servo leads to the FS-iA10B receiver as shown in the schematic below:

   Fill Valve to Ch5

   Vehicle Valves servo extension to Ch6

   Purge Valve to Ch8



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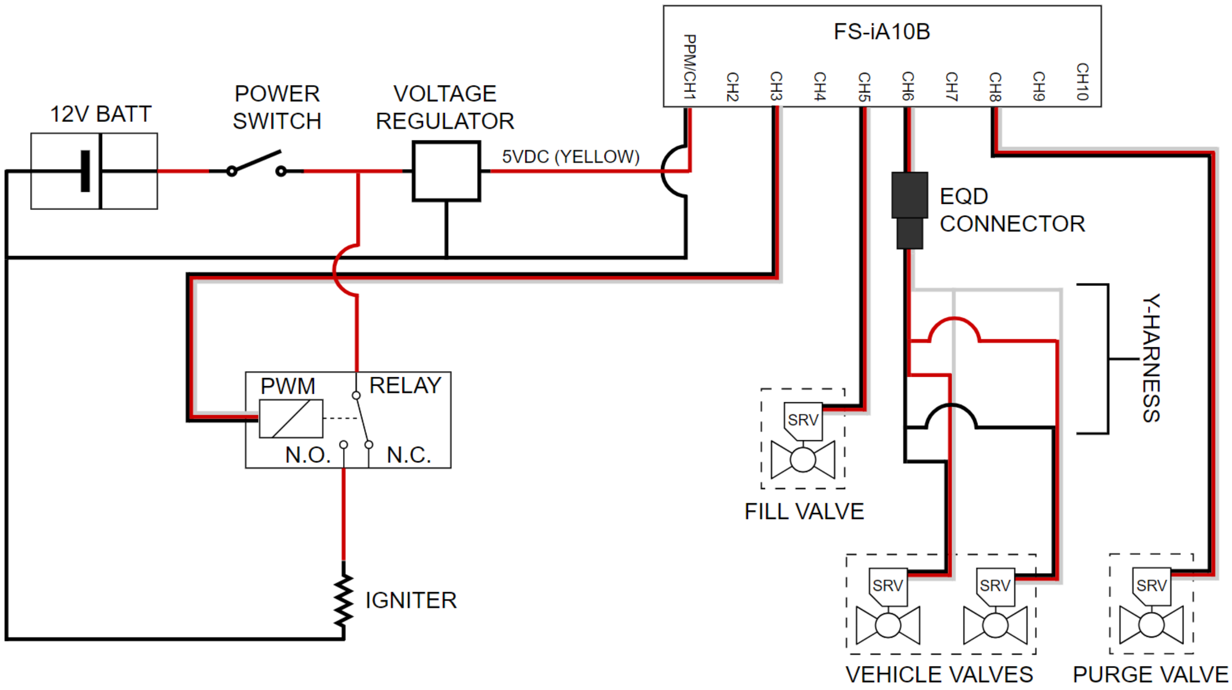
OP 6: Electrical System Integration

10. Connect the 3-pin cable from the PWM-controlled relay module to Ch3 as shown in the schematic.



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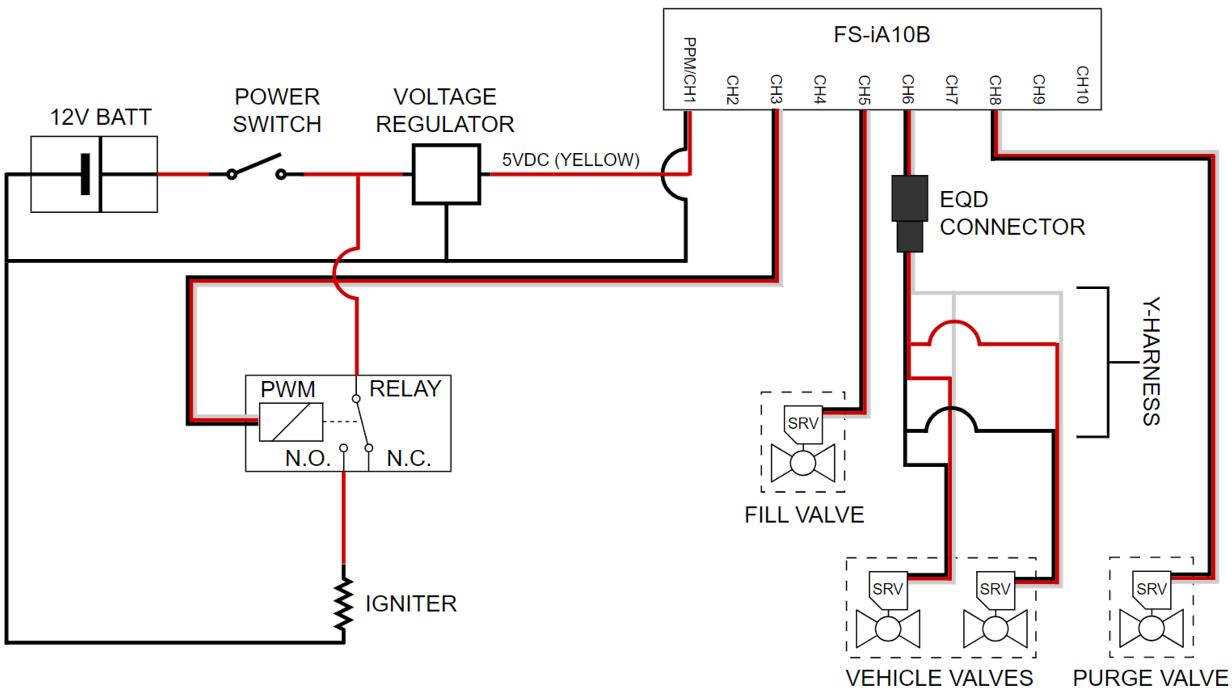
OP 6: Electrical System Integration

11. Using the 20GA stranded wire, connect the power switch, voltage regulator, and relay module as shown in the schematic. The 12V positive wire from the relay should be connected to the screw terminal for the longer of the two slots and the battery ground should be connected to the screw terminal for the shorter slot on the second electrical outlet. This will be used to supply power to the igniter.

12. Cut off the male (smaller) plug from QTY 1 SRV-3PIN-1M servo extension cable and strip approximately 0.5" of the red and black wires. The white wire will not be used. Splice the red wire to the positive 5V output (yellow wire) from the DROK-12V-5V voltage regulator, and the black wire to the negative (black) 5V output. Splices should be tightly twisted and insulated with electrical tape or heat shrink tubing. Soldering the splices is recommended but not required; crimp-on ring terminals connected with a screw may also be used if desired for greater modularity. Connect the 3-pin plug from the voltage regulator to Ch1/PPM on the FS-iA10B. This will provide power to the receiver and servos.

    Note: DO NOT connect to the battery until all wiring is complete.



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OP 6: Electrical System Integration

13. Place the battery between the two eye bolts and secure with 2-3 nylon zip ties, looped through the eyes and across the front of the battery.

14. With the power switch in the off position, connect the wires to the battery terminals as shown in the schematic.

15. Bundle wires together and onto fill line tubing for tidiness and strain relief as needed, using zip ties and/or electrical tape.

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OP 7: Fabricate Cables and Fill Line

Gather the following:

QTY	Part Number	Description
2	16-3-10FTXT	10 ft. x 16/3 Gauge Indoor/Outdoor Extension Cord
1	SRV-3PIN-1MXT	Servo Extension Cable, 3-Pin, 1m
1	ALG-CLP-INS	Alligator Electrical Clip, Insulated
As Needed	9685T3	Nylon Tubing, 1/4" OD, 800PSI
1	QDC-750x125FLG-270MB-0007	Quick Disconnect, ¾" x ⅛" Flange, .270 Male Barb, -007 O-Ring Gland
1	9452K15	-007 Buna-N O-ring
1	9396T31	Push to Connect Fitting, 1/4" Tube X 1/8NPT
As Needed	N/A	PTFE Tape

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OP 7: Fabricate Servo and Ignition Cables

1. Cut the female end off of QTY 2 16-3-10FTXT extension cord, and strip approximately 1 inch of each wire.

2. Cut the male end off of QTY 1 SRV-3PIN-1MXT servo extension cable, and strip approximately 1 inch of each wire.

3. Splice the servo extension wires onto the wires of one of the extension cords as follows:

- Red wire on servo extension to black wire on extension cord
- White wire on servo extension to white wire on extension cord
- Black wire on servo extension to green wire on extension cord.

Splices should be tightly twisted and insulated with electrical tape or heat shrink tubing. Soldering the splices is recommended but not required.

4. Crimp QTY 2 insulated alligator clips onto the black and white wires of the second extension cord (one clip per wire). This provides an easy method of connecting to the igniter e-match wires. The alligator clips may optionally be omitted in favor of splicing the stripped ends onto the e-match during pre-launch setup. The green wire is not used on the ignition cable and should be cut flush with the end of the outer insulation jacket.

   *CAUTION: **NEVER** plug the ignition or servo cables into a live 120V wall outlet. Doing so creates EXTREME DANGER of electrocution and/or fire.*

   Ensure that the servo wire is ONLY plugged into the SRV outlet on the GSE box. Plugging the servo lead into the IGN outlet may damage the servos.

5. Cut a section of 9685T3 nylon tubing about 6 feet in length. This will serve as the fill line from the GSE to the rocket.

6. Apply 2-3 wraps of PTFE tape to the male threads of QTY 1 9396T31 PTC fitting and install into the port of QTY 1 QDC-750x125FLG-270MB-0007 male QD fitting.

7. Firmly push one end of the 9685T3 tube into the PTC fitting until it is fully seated.

8. Install QTY 1 9452K15 O-ring onto the male barb of the QD fitting. The seal may be lightly greased if necessary to aid in installation. The QD O-ring generally will last for many uses, and must only be replaced if visibly damaged.

OP 8: Transmitter Setup & Firmware Configuration

Gather the following:

QTY	Part Number	Description
1	FS-i6X	Flysky 10CH 2.4GHz RC Transmitter Controller
1	-	GSE System
1	-	Rocket or spare servo
4	TGL-GRD-12MM	Toggle Switch Guard, 12mm Hole
4	92295A100	Thread-Forming Screws for Plastic, Number 4 Size, 1/4" Long

OP 8: Transmitter Firmware Configuration

Install Toggle Switch Covers

The FS-i6X transmitter's switches do not have sufficient thread length to permit installing the switch covers under the jam nut; instead, they are attached using screws. Adhesive may also be used to help bond on the switch covers, but is not recommended as the sole attachment method. It is recommended to remove the back half of the transmitter casing while drilling the switch cover mounting screw holes to verify that the hole drilling does not damage the switches or wiring.

20. Drill a ⅛" hole in the lower right corner of the metal base of QTY 4 TGL-GRD-12MM switch covers as shown.
21. Place the switch covers over the four toggle switches and mark the location of the holes on the transmitter casing.
22. Using a #37 (.104") drill bit, drill a hole in each of the marked locations adjacent to the switches on the transmitter housing. Take care not to damage the switches or wires
23. Install the switch covers onto the transmitter using QTY 4 92295A100 screws.

    Note: The corner of the switch cover on the right-most position may need to be bent upwards slightly with pliers.
24. Label (or engrave) the switch covers per the following:
    a. Switch A (Left-most): PRG (if purge functionality is included in the system)
    b. Switch B (Second from left): FILL
    c. Switch C (Third from left): IGN
    d. Switch D (Right-most): SRV

Note: Only 3X covers (shown) are required if purge functionality is not included in the system.

OP 8: Transmitter Firmware Configuration

Enable all 10 channels

1. Turn the transmitter on; all switches must be in the UP position and the left (throttle) stick all the way down for the transmitter to boot up. This is a safety feature intended to prevent accidentally powering the motor of a model airplane.
2. Hold OK -> MENU -> System Setup -> OK
3. Use the DOWN button to navigate to Aux Switches at the bottom of the list and press OK
4. Press OK until the arrow appears next to Ch: 6
5. Press the UP button until Ch: 10
6. Hold CANCEL to save the setting. A higher-pitched beep will be emitted and the menu will return to the previous level. Press OK again to return to the main MENU screen.

Assign channels to switches

1. DOWN -> Functions Setup -> OK
2. DOWN until Aux. Channels -> OK
3. Channel 5: press DOWN until Source reads SwB -> OK
4. Channel 6: press DOWN until Source reads SwD -> OK
5. Channel 7: press OK to skip
6. Channel 8: Press DOWN until Source reads SwA
7. Hold CANCEL to save the settings. A higher-pitched beep will be emitted and the menu will return to the previous level.

OP 8: Transmitter Firmware Configuration

Assign igniter channel and set left stick lockout

The igniter relay is connected to the throttle channel (Ch3), so that the left stick must be up in order to energize the igniter circuit. This serves as a safety lockout secondary to the switch cover. The igniter relay may also be connected to another auxiliary channel (7, 9, or 10) assigned to Switch C; this is not recommended as it increases the risk of accidental igniter activation, although it removes the risk of a failed ignition resulting from the left stick being in an incorrect position.

1. In FUNCTIONS menu, press DOWN until Assign Switches -> OK
2. Fly mode None -> press OK to skip
3. Idle mode None -> press OK to skip
4. Thro. Hold -> DOWN until SwC
5. Hold CANCEL to save the setting. A higher-pitched beep will be emitted and the menu will return to the previous level.
6. Depending on the type of relay module used (i.e., two-channel vs single channel), there may be a minimum PWM value to avoid having one channel energized. If this is the case navigate to Throttle Hold in the FUNCTIONS menu. Press UP to set Hold to On -> OK -> Up to set value so that the both channels of the relay (if using a dual-channel module) are off when the left stick is all the way down.
7. Hold CANCEL to save the setting. A higher-pitched beep will be emitted and the menu will return to the previous level.

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OP 8: Transmitter Firmware Configuration

Adjust servo endpoints

This step should be completed prior to initial assembly of the servo-actuated ball valves, to ensure that the servo horn is installed in the correct orientation. Adjusting the end points fine-tunes the position of the servo in the valve OPEN and valve CLOSED positions.

1. Ensure the transmitter is ON and all switches are in the DOWN position prior to bringing up power to the GSE.
2. Connect ONLY the FILL valve to servo to Ch5 on the FS-iA10B receiver. Disconnect any other servos from the receiver at this time. Ensure no pressure source is connected to the GSE fill or purge supply fittings.
3. In FUNCTIONS menu, navigate to End Points using DOWN -> OK
4. In End Points, press OK until the arrow appears next to the value on the right side of the row for Ch5. Adjust the end point UP or DOWN until the servo horn/valve handle are exactly perpendicular to the servo body/valve body. This is the valve CLOSED position.
5. Flip Switch B (second from the left) to the UP position to actuate the FILL valve to the OPEN position. Adjust the end point value UP or DOWN until the servo horn/valve handle are exactly parallel to the servo body/valve body. This is the valve OPEN position.
6. Hold CANCEL to save the setting. A higher-pitched beep will be emitted and the menu will return to the previous level.

Tip: If the servo is stalled against the valve actuator bracket, listen for an increase or decrease in the intensity of the high-pitched whine emitted by the servo while adjusting the endpoint values. Adjust in the direction that decreases the intensity of the noise until the servo horn begins to move away from the bracket. Avoid stalling the servo for long periods of time, as this may cause overheating or other damage. If the servo horn/valve handle is unable to reach the specified positions at the limits of the endpoint adjustment range, the servo horn must be removed and re-installed onto the spur gear in a different orientation.

OP 8: Transmitter Firmware Configuration

7. Connect the vehicle valves to Ch 6 on the FS-iA10B receiver. If setting the initial servo horn position, they may be connected individually. If fine-tuning the setting on an integrated vehicle, both valves should be connected simultaneously via the servo Y-harness, with the airframe removed to provide a clear view of the fuel valve.

8. Navigate to End Points in the FUNCTIONS menu -> OK

9. In End Points, press OK until the arrow appears next to the value on the right side of the row for Ch6. Adjust the end point UP or DOWN until the servo horns/valve handles are exactly perpendicular to the servo bodies/valve bodies. This is the valve CLOSED position.

   Note: A discrepancy of <5 degrees between the fuel and oxidizer valves is acceptable; the valves will still seal effectively as long as the ball fully contacts the seat without the port overlapping the seat's edge.

10. Flip Switch D (farthest right) to the UP position to actuate the VEHICLE valves to the OPEN position. Adjust the end point value UP or DOWN until the servo horn/valve handle are exactly parallel to the servo body/valve body. This is the valve OPEN position.

11. Hold CANCEL to save the setting. A higher-pitched beep will be emitted and the menu will return to the previous level.

12. If a purge valve is used on the GSE, connect the PURGE valve servo to Ch8 on the FS-iA10B receiver. Follow the same procedure as for the fill valve to adjust the end points. The purge channel (Ch8) is assigned to Switch A (first from the left)

OP 8: Transmitter Firmware Configuration

Verify channel mapping

This will ensure that each part of the system is responding correctly to control inputs from the transmitter

1. Verify that the FILL valve responds in the following manner:
    a. Switch B UP: FILL valve OPEN
    b. Switch B DOWN: FILL valve CLOSED
2. Verify that the VEHICLE valves respond in the following manner:
    a. Switch D UP: VEHICLE valves OPEN
    b. Switch D DOWN: VEHICLE valves CLOSED
3. Verify that the PURGE valve (if included) responds in the following manner:
    a. Switch A UP: PURGE valve OPEN
    b. Switch B DOWN: PURGE valve CLOSED
4. Verify that the IGNITER circuit responds in the following manner (via multimeter or spark checks)
    a. Switch C and Left Stick both fully DOWN: IGNITER circuit DE-ENERGIZED
    b. Switch C and Left Stick both fully UP: IGNITER circuit ENERGIZED
    c. Switch C UP and Left Stick fully DOWN: IGNITER circuit DE-ENERGIZED
    d. Switch C DOWN and Left Stick fully UP: IGNITER circuit DE-ENERGIZED

    Note: Switch C is the only 3-position switch on the FS-i6X transmitter. The middle position is effectively ignored; it should only be intentionally set to the fully up and fully down positions.

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OP 8: Transmitter Firmware Configuration

Configure receiver failsafes

The failsafe settings dictate how the receiver behaves if it loses connection with the transmitter for any reason. They must be configured to put the rocket and ground system in a safe state, with the fill and optional purge valves closed, the vehicle valves open so that no pressure remains inside the rocket, and the igniter circuit de-energized.

1. From home screen:

   Hold OK -> System Setup -> OK -> DOWN until RX Setup -> DOWN until Failsafe -> OK

2. Igniter failsafe: DOWN until arrow appears next to Channel 3 -> OK -> ensure left stick and Switch C (third from the left) are both all the way down -> UP to change OFF to ON -> Press OK

3. Fill failsafe: DOWN until arrow appears next to Channel 5 -> OK -> Switch B (second from the left) is DOWN (FILL valve CLOSED position) -> UP to change OFF to ON -> Press OK

4. Vehicle Valves failsafe: DOWN until arrow appears next to Channel 6 -> OK -> Switch D (farthest right) is UP (VEHICLE valves OPEN position) -> UP to change OFF to ON -> Press OK

5. Purge (if included) failsafe: DOWN until arrow appears next to Channel 8 -> OK -> Switch A (first from the left) is DOWN (PURGE valve CLOSED position) -> UP to change OFF to ON -> Press OK

6. Hold CANCEL to save the setting. A higher-pitched beep will be emitted and the menu will return to the previous level.

   IMPORTANT NOTE: *Failsafe settings are saved when holding CANCEL to exit the Failsafe menu and return to the RX Setup Menu. They are NOT saved when pressing OK to return from the individual channel failsafe setting screen to the Failsafes Menu.* ***ALWAYS*** *verify failsafe settings are set and saved correctly.*

7. To verify failsafes, ensure the FILL, PURGE, and VEHICLE valve servos as well as the igniter relay module are connected to the FS-iA10B receiver, no pressure supply is connected, and the GSE is powered on. Set the switches in the following positions:

   a. Switch A: UP to OPEN the PURGE valve

   b. Switch B: UP to OPEN the FILL valve

   c. Switch C AND Left Stick: fully UP to ENERGIZE igniter circuit (caution: ensure igniter leads are not connected to anything and are insulated from each other)

   d. Switch D: DOWN to CLOSE the VEHICLE valves

8. Turn the transmitter POWER switch OFF. Verify the system enters the following state:

   a. PURGE valve CLOSED

   b. FILL valve CLOSED

   c. IGNITER circuit DE-ENERGIZED (verify by multimeter or spark check)

   d. VEHICLE valves OPEN

Section VII – Launch Preparation and Procedures

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7.1 Vehicle Preparation

This section covers the preparation of the vehicle for static testing or launch. Recovery system packing is only required for launch. This procedure assumes that the rocket has been fully assembled per Section 5 and contains only the steps that must be repeated each time the rocket is recycled.

7.1.1 Fuel Loading

Caution: This procedure involves handling of fuel and O-ring grease. Ensure all personnel are equipped with safety glasses and nitrile gloves. Perform these steps outdoors or in a well-ventilated area with disposable shop towels or rags on hand to clean up any fuel spills.

1. Gather the following:
    a. 5/8" wrench (or adjustable)
    b. 9/16" wrench (or adjustable)
    c. 3/16" hex key or driver bit
    d. Optional: Battery powered drill with adjustable torque-limiting clutch
    e. Sturdy PVC pipe or wooden dowel with marking 12.25" from one end
    f. Safety glasses
    g. Nitrile gloves
    h. O-ring grease
    i. 1X -238 Buna-N O-rings (PN: 9452K226)
    j. Shop towels
    k. Approx. 1/2 gallon fuel (see section 2.6)
    l. If piston is to be removed (required every 3 firings or sooner):
    m. 1/4-20 bolt or threaded rod
    n. Vise-grip or large pliers
    o. 2X additional -238 Buna-N O-rings (PN: 9452K226)
2. Disconnect the fuel line from the flared fitting on the fuel valve outlet using the 5/8" and 9/16" wrenches.

Caution: Residual fuel may be present. Be prepared for a small amount of fuel to drip out of the fuel valve outlet and/or injector when the fuel line is disconnected.

3. Ensure the fuel valve is OPEN. If closed, it may be opened either using the GSE or by slowly and gently moving the valve handle/servo horn to the open position by hand. The servo must be disconnected from power to open manually. If the valve is closed, the forward tank bulkhead cannot be removed, as it will pull a vacuum.

4. Disconnect the fuel valve servo wire from the vehicle Y-harness at the 3-pin connector closest to the servo.
5. Remove the 8X 5/16" fasteners from the forward tank interface ring using the 3/16" hex key or driver bit and drill. Set aside for later reinstallation. A magnetic dish is recommended to prevent fasteners from being lost.
6. Remove the entire fuel bulkhead assembly from the tank by pulling on the U-bolt installed in the recovery bulkhead. The lower airframe tube may remain connected to the interface ring if installed. Note: When static testing without the recovery bulkhead, it is recommended to either re-install the recovery bulkhead or another pair of 1/4-20 threaded rods to remove the fuel bulkhead assembly by pulling on the coupling nuts. Removal by pulling on the valve assembly should be avoided, as it may damage the valve assembly and/or fuel tank outlet port/fitting.

Caution: Residual fuel will likely be present in the tank, even if some has already drained out of the valve outlet fittings and/or fuel line. It is recommended to remove the fuel bulkhead assembly with the rocket vertical or tilted upwards to prevent spillage.

Perform steps 7-11 only if the piston must be removed prior to the next firing. Servicing the piston seals is required every three firings. If the piston does not need to be removed, skip to step 12.

7. Insert a 1/4-20 bolt or threaded rod into the tapped blind hole in the center of the piston until it bottoms out. Tighten only to hand tight.
8. Pull the piston out of the forward end of the tank using the extraction bolt. A pair of vise-grips or pliers may be used to improve grip. The extraction fastener may now be removed from the piston.
9. Remove the 2X O-rings from the piston and discard. Clean any particulate or darkened grease from the O-ring grooves.
10. Coat 2X new -238 O-rings with grease and install into the grooves on the piston.
11. Re-install the piston into the tank with the 1/4-20 threaded blind hole facing the open forward end. Use even pressure to carefully push the O-rings past the tank edge and bolt holes. Verify that the piston extraction fastener has been removed before proceeding.
12. Push the piston down into the tank until the lower surface closest to the outer edge is 12.25 +0/-.25" from the forward end of the tank tube. A sturdy piece of PVC pipe or wooden dowel with a clearly visible marking is recommended. Caution: Do not apply more than 100lbf to the piston if the vehicle is resting on the plywood fins. If more force is required, place a wooden or concrete block under the nozzle to provide support without stressing the fins. No more than 150lbf should be required to install the piston to its final depth. DO NOT use a hammer or mallet to push the piston down. This may cause the piston to bind against the tank wall, preventing fuel flow when the valve is opened.
13. Verify that the nitrous tank static vent is unobstructed by poking a small piece of wire (such as from a spent e-match) at least 1/2" into the vent orifice. If the vent is found to be obstructed, pull the piston upwards using a long 1/4-20 threaded rod until the piston no longer blocks the vent. Blockage of the vent will prevent oxidizer loading.
14. Inspect the fuel bulkhead O-ring for damage or swelling to assess whether replacement is necessary. If so, remove and discard the O-ring, then grease and install 1X new -238 O-ring into the groove on the fuel bulkhead.

15. With the rocket vertical, pour approximately 1/2 gallon of fuel into the tank on top of the piston. Fuel may be pre-measured, or simply filled until the level reaches 1.25" from the end of the tank tube. Any excess fuel will be pushed out through the fuel valve when the fuel bulkhead assembly is reinstalled. Note: The nominal volume of the fuel tank is 120 cubic inches (.52 gal). A 1/2" variation in fuel tank length due to fill level and/or piston position will result in <5% variation in total impulse.

16. Insert the fuel bulkhead assembly into the forward end of the tank, ensuring proper orientation of the fuel valve outlet fitting and alignment of any clocking marks on the interface ring and tank. Use even pressure to carefully push the O-ring past the tank edge and bolt holes. Push down on the interface ring until it seats against the edge of the tank tube. Caution: any excess fuel will be pushed out through the fuel valve outlet. Use a shop towel or container against the outlet fitting to catch fuel spray.

17. Close the fuel valve either using the GSE or by slowly and gently moving the valve handle/servo horn to the closed position by hand. The servo must be disconnected from power to close manually.

    Note: At this point the fuel tank is fully sealed and the rocket may be returned to a horizontal orientation if desired.

18. Reinstall the 8X 5/16" fasteners into the forward tank retaining ring, threading them into the captive nuts. Leave fasteners loose until all 8X are installed, then tighten to snug.

19. Reconnect the fuel line hose to the flared fittings on the fuel valve outlet and tighten to snug.

20. Reconnect the fuel valve servo wire to the 3-pin extension from the vehicle Y-harness. Secure connector with 1-2 wraps of electrical or masking tape.

Fuel loading is now complete.

7.1.2 Igniter Installation

Caution: This procedure involves handling pyrotechnic materials. Safety glasses are required for all personnel in the vicinity. Face shields are recommended as an additional precaution for those directly handling pyrotechnic materials. These steps must be performed outdoors away from any other flammable materials and ignition sources.

1. Gather the following:
    a. 9/16" wrench (or adjustable)
    b. 15/16" wrench (or adjustable)
    c. Multimeter with continuity check function
    d. 3/8" drill bit
    e. Optional: battery operated drill
    f. Long (>6") hemostats
    g. 1X e-match (MJG FireWire or equivalent), at least 16" long
    h. 1X Estes A3-4T 13mm black powder rocket motor
    i. Grease

j. Shop towels

2. Disconnect the igniter cartridge assembly from the injector at the coupler fitting between the two pipe nipples where shown. Note: it is not recommended to disconnect the lower pipe nipple from the injector port, as this will result in wearing of the aluminum threads over time.

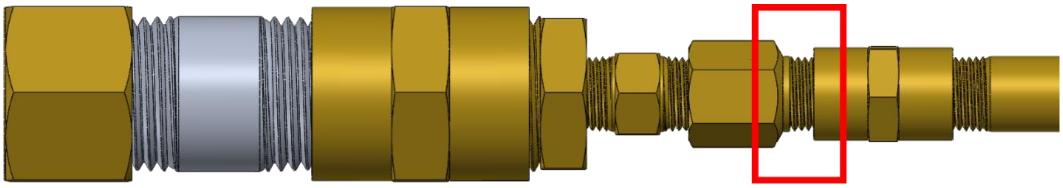

Figure 7.1: Cartridge igniter disconnection point

3. Remove the cap from the forward end of the igniter cartridge and set aside.

4. If the system has been previously fired, remove the spent igniter motor from the cartridge. Needle nose pliers, curved tweezers, or a hooked pick are recommended.

5. Inspect the igniter cartridge and injector for any blockage of the igniter flow path. Remove blockage if necessary using a stiff piece of wire or 1/8" tube brush. Note: blockages of less than 50% of the igniter inlet orifice area are acceptable so long as they do not prevent insertion of the e-match wires.

6. Prepare a new igniter motor by removing the clay nozzle from the Estes A3-4T using a 3/8" drill bit. This may be done by rotating the bit by hand, or using a battery powered drill at low speed. Drill until the dark gray propellant grain is exposed across the full diameter of the drill bit. A small amount of clay remaining on the outer edges is acceptable.

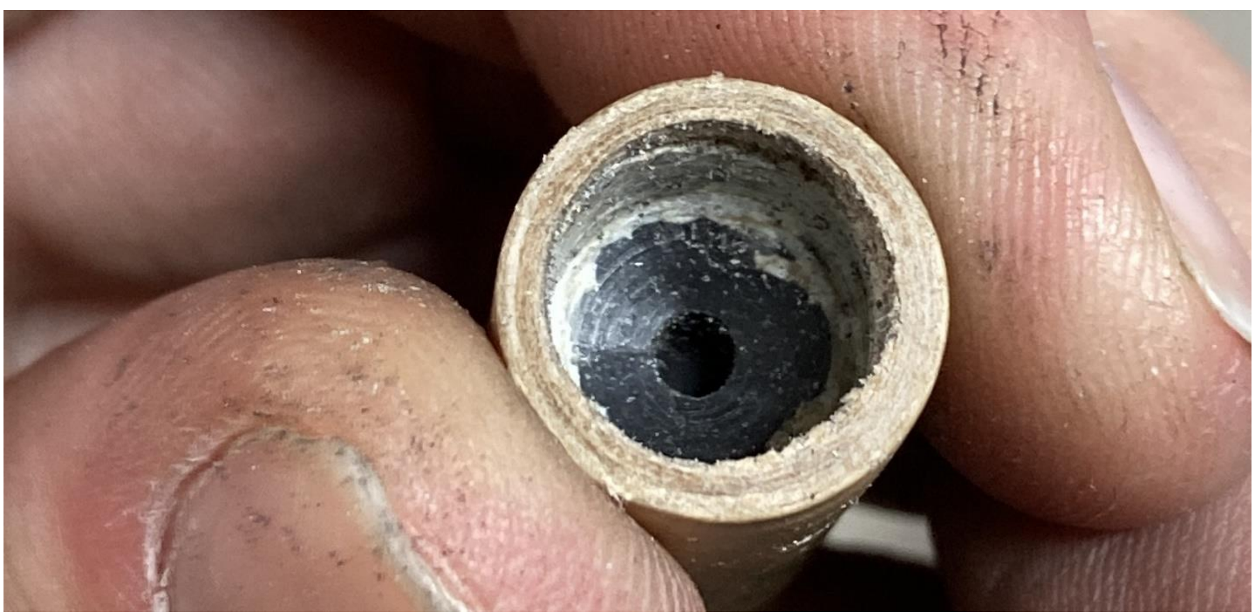

Figure 7.2: Estes A3 with clay nozzle removed (propellant grain exposed)

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7. Remove the ejection charge by drilling out the clay cap at the forward end of the A3-4T until the loose black powder charge is exposed. Most of the powder will simply fall out; remaining powder can be scraped out or left in place. Note: testing has demonstrated that there is no detrimental impact to leaving the ejection charge in place. Removal is recommended but not required.

8. Test a new e-match for continuity using a multimeter. If no continuity is indicated do not use the e-match, and replace it with one that does read continuity.

9. Shunt the e-match by twisting the exposed wire leads together. This will prevent accidental ignition from static discharge or other sources of current. Tightly twisting the first 3-5" of the e-match wire leads is recommended to aid in installation. The twisted wires may also be greased to slide more easily through the igniter flow path during installation.

10. Insert the wire lead end of the e-match into the igniter fittings on the injector as shown until the wires can be seen projecting into the chamber.

11. Position the igniter cartridge near the injector and insert the e-match head into the pipe nipple connected to the cartridge assembly as shown, until the e-match head and 3-4" of wire protrude from the forward end of the cartridge.

12. Thread the pipe nipple on the igniter cartridge into the coupler fitting on the chamber assembly as shown and tighten to snug. Note: testing has demonstrated that PTFE thread tape is not required for brass igniter fittings. Any resulting leakage is minimal and non-detrimental.

13. Fold the e-match wire 3-4 times approximately 1/2"below the head as shown. This will prevent the e-match from being accidentally pulled out during pre-launch handling, while still allowing it to be ejected during ignition.

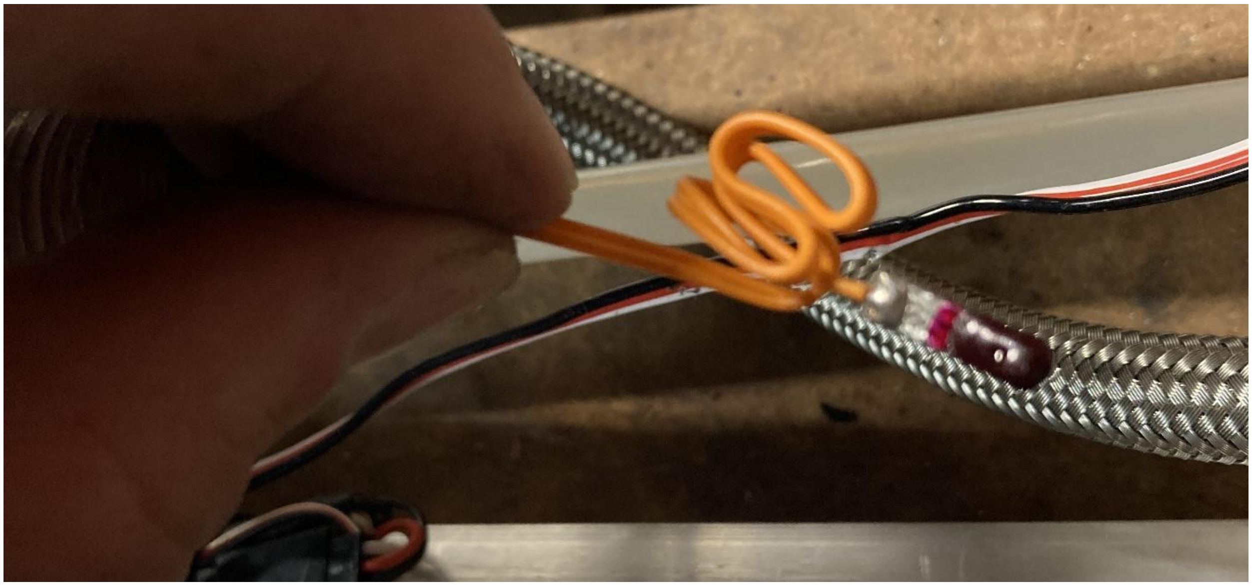

Figure 7.3: Folded e-match

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Figure 7.4: Folded e-match inside igniter cartridge

14. Place the cored end of the prepared Estes A3-4 igniter motor against the e-match head and gently push it into the cartridge, ensuring that the e-match head stays in contact with the propellant grain.
15. Insert a pair of long hemostats into the chamber through the nozzle throat and grip the e-match wire leads. Gently pull the wires through until the leads extend several inches out of the nozzle. Leave the stripped ends twisted together at this time to prevent accidental ignition from static discharge or other sources of current. Note: the bare wire ends may be partially untwisted to make it easier to fully separate them at the launch pad.
16. Place a small wad of shop towel or other springy material into the forward end of the igniter cartridge to fill the empty volume and maintain contact between the igniter motor and e-match head.
17. Reinstall the cap onto the forward end of the igniter cartridge and tighten to snug.

Igniter installation is now complete.

7.1.3 Recovery System Packing

Caution: This procedure involves handling pyrotechnic materials. Safety glasses are required for all personnel in the vicinity. Face shields are recommended as an additional precaution for those directly handling pyrotechnic materials. Gloves may also be used to prevent skin contact with Pyrodex powder.

Note: The recommended ejection charges are conservatively sized and when properly implemented will provide highly energetic separation of both the drogue and main. Ground testing is strongly recommended to verify and/or refine charge sizing, especially if any modifications have been made to the airframe *configuration or if alternative ejection charge materials such as 4F black powder are used. Many resources are available online to calculate an initial estimate for ejection charge sizes, however these are not a substitute for ground testing.*

1. Gather the following:
    a. Safety glasses
    b. Nitrile gloves
    c. Electrical tape
    d. Masking tape
    e. 4X e-matches (MJG FireWire or equivalent), at least 16" long
    f. FFFG (3F) Pyrodex powder
    g. Gram scale or 1/2 tsp measuring spoon
    h. Multimeter with continuity check function
    i. 4X 2-56 nylon screws (PN: 94735A707)

Prepare ejection charges:

2. Check continuity on 4X e-matches. If any e-matches do not indicate continuity, discard and replace with a new e-match that does. After checking continuity, shunt the bare wire leads by twisting them together to prevent accidental ignition from static discharge or other sources of current.
3. Cut 4X fingers off of a nitrile glove. These will be used to contain the ejection charges
4. Measure out either 8 grams or 1.5 teaspoons of 3F Pyrodex powder into each glove finger.
5. Insert the head of an e-match into the powder-filled glove finger, so that it is fully submerged in powder.
6. Twist the open end of the glove finger around the e-match wires, then wrap the entire charge tightly in 4-5 layers of electrical tape, slightly stretching the tape during wrapping to help compress the charge. The charges should be hard when complete and should not easily deform when pinched. There should be no excess volume inside the glove finger for powder to move around.
7. Before connecting any charges to the rocket's altimeters, verify acceptable battery voltage for both altimeter batteries. The acceptable voltage and method of verification will vary depending on the type of deployment controller used. Refer to the manufacturer's directions as needed. If necessary, replace or recharge batteries before continuing.
8. Connect the 4X completed ejection charges to the main and drogue deployment outputs for each altimeter. The recommended method is a Western Union splice, as shown below. Wrap all wire splices thoroughly with electrical tape. There should be one charge connected to each of the following:
    a. Altimeter A Main
    b. Altimeter A Drogue
    c. Altimeter B Main
    d. Altimeter B Drogue

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Refer to the generic avbay wiring diagram below.

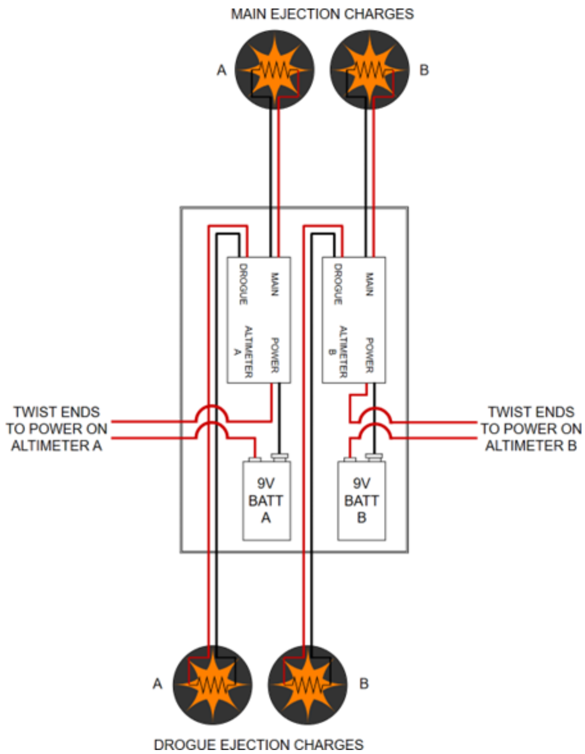

Figure 7.5: Avbay wiring diagram

Main Parachute Packing

Note: It is recommended to perform the following steps with at least two people.

9. Verify that the main recovery harness is securely connected to the nose cone and avbay assemblies before proceeding.

10. Gather the main parachute canopy from its center so that it forms a flat triangle on the work surface. Ensure the shroud line attachment points are roughly even with one another.

11. Fold the main parachute canopy into a strip approximately 8-10" wide, with the center of the canopy at one end and the shroud line attachment points at the other.

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Figure 7.6: Main parachute canopy, folded into strip

12. Z-fold the canopy so that each segment of the Z is approximately 1/3 of the canopy's radius.

Figure 7.7: Main parachute canopy, Z-folded

13. Tightly roll the Z-folded canopy starting from the end opposite the shroud lines. The resulting bundle should be approximately 3.5" in diameter. Do not wrap the shroud lines around the rolled canopy. The canopy must be held firmly to prevent it from unrolling before being packed into the airframe.

Figure 7.8: Main parachute canopy, rolled into bundle

14. Place the rolled canopy onto the Nomex main parachute protector, and lay the shroud lines alongside it in a zig-zag pattern. Then, wrap the canopy and shroud lines in the Nomex protector so that the canopy is fully covered. A "burrito-style" wrapping method is recommended.

Figure 7.9: Main parachute, laid on protector with shroud lines

Figure 7.10: Protector folded over main parachute

Figure 7.11: Main parachute bundle, wrapped in protector

15. Place the two main deployment charges into the upper airframe tube, initially positioning them several inches from the end of the tube.

16. Insert the Nomex-wrapped main parachute bundle into the upper airframe tube behind the ejection charges. Push the main parachute bundle into the upper airframe as far as possible with moderate force. Take care not to place strain on the ejection charge wire splices.

    Note: It is critical that the main parachute bundle is positioned between the ejection charges and the open end of the tube where the airframe will separate in flight. This allows the charges and airframe to function as a "parachute cannon" that can build up enough pressure to eject even a tightly packed bundle, rather than relying on the momentum of the airframe to extract the main parachute from the tube.

17. Bundle the main shock cord into 4-5 sections each containing about 6 feet of length. Wrap each bundle with 1-2 wraps of masking tape at a single point. This will help dissipate the shock of main parachute deployment as energy is expended to break the masking tape. Other types of tape should NOT be used; rubber bands are an acceptable substitute.

18. Pack the shock cord bundles into the upper airframe tube behind the main parachute, then insert the avbay coupler into the tube. The coupler should be a moderately snug fit that does not allow wobble of the airframe tube. Shim the outer surface of the coupler with masking or aluminum tape as necessary. Electrical tape should not be used.

19. Align the 4X shear pin holes in the upper airframe tube with the slots along the lower edge of the forward avbay bulkhead as shown. Then, insert a 2-56 nylon screw into each hole. The shear pin screws should be a press fit into the airframe holes, but a screwdriver may aid in installation. If the shear pins are loose enough that there is a risk of them falling out, a small patch of tape may be placed over the heads to retain them.

    Note: The shear pins should be included in ground testing of the main parachute ejection. This testing is important to verify that the shear pins break cleanly without bending or tearing the holes in the airframe tube, which can cause binding of the coupler and failure to deploy.

Main parachute packing is now complete.

Drogue Parachute Packing:

20. Verify that the drogue recovery harness is securely attached to the recovery bulkhead on the propulsion section and the avbay assembly before proceeding.

21. Fold the drogue parachute canopy in a similar fashion to the main. Due to the much smaller size of the drogue relative to the airframe tube, the packing method is less critical. Unlike the main, the shroud lines may be wrapped around the folded canopy for convenience.

22. Wrap the folded drogue parachute fully in the Nomex drogue parachute protector. A "burrito-style" wrapping method is recommended.

23. Place the 2X drogue ejection charges into the lower airframe tube, initially positioning them several inches from the end of the tube.

24. Insert the Nomex-wrapped main parachute bundle into the upper airframe tube behind the ejection charges. Push the main parachute bundle into the upper airframe as far as possible with moderate force. Take care not to place strain on the ejection charge wire splices. Note: because the drogue parachute fits much more loosely in the airframe tube, it is less critical that the lower airframe tube function as a

"parachute cannon." While the packing method described here is recommended, the momentum of the two sections of the rocket after deployment is generally sufficient to extract the drogue parachute.

25. Bundle the drogue shock cord into 4-5 sections each containing about 6 feet of length. Wrap each bundle with a single wrap of masking tape at a single point. This will help dissipate the shock of main parachute deployment as energy is expended to break the masking tape. Other types of tape should NOT be used; rubber bands are an acceptable substitute.

26. Pack the shock cord bundles into the lower airframe tube behind the drogue parachute, then insert the avbay coupler into the tube. The coupler should be a moderately snug fit that does not allow wobble of the airframe tube. Shim the outer surface of the coupler with masking or aluminum tape as necessary. Electrical tape should not be used.

    Note: It is recommended to mate the integrated upper airframe and avbay assembly to the lower airframe tube/propulsion section with the rocket standing vertical on its fins to aid in alignment.

Drogue parachute packing is now complete. The rocket is fully integrated and ready to carry to the launch pad.

7.2 GSE Setup

Mojave Sphinx's ground support equipment is very simple for a liquid rocket motor, and accordingly takes little time to set up. This procedure may be performed concurrently with Section 7.3 (Launchpad Operations), although it saves some time to have one team member set up the GSE while others finish preparing the vehicle for launch. This is especially true for sites where the launchpad(s) are located at a great distance from the preparation area and multiple trips are required to transport all equipment.

If using the "minimum viable GSE" setup, some steps in this section will not be applicable; make adjustments to the procedures as needed based on the features of the system being used. All functionality will remain the same regardless of GSE version.

7.2.1 Required Items

1. Gather the following and bring to the launchpad:
    a. Nitrous oxide supply bottle with adapter to -04 AN flare installed
    b. GSE box, also containing:
        i. Upstream fill line hose
        ii. Downstream fill line tube with male QD fitting
        iii. Servo cable
        iv. Ignition cable
        v. QD clip with pre-attached Kevlar tether
    c. Two 9/16" wrenches

       Note: One or both may be substituted with adjustable wrenches
    d. Ratchet strap (if using bottle without siphon tube)

       Note: The 20 lbm capacity bottle from Gas Cylinder Source recommended in Section 6.2 does not have a siphon tube and requires a ratchet strap. A bottle stand or other sturdy object to which the inverted bottle can be secured may also be required depending on the launch site; bottles can easily be secured to the launch pads in use as FAR.
    e. Transmitter for GSE control
    f. Fire extinguisher (if the site does not already have one near the pads)

7.2.2 Ground System Setup

2. Identify a suitable location to place the supply bottle adjacent to the launch rail. If the bottle has a siphon tube, it can simply sit on any reasonably flat surface. Bottles without a siphon tube must be inverted and secured to prevent tipping. The launch pad itself can often be used for this purpose (this applies to all

high-power launch pads at FAR), so long as the bottle will not be directly exposed to the rocket's exhaust (i.e., behind the launch rail, and away from the direction of the blast deflector).

3. Place the supply bottle down, and strap with ratchet strap until snug if inverted. Ensure the outlet adapter can be accessed to attach the supply hose and is pointed towards the GSE box, and that the handle can be reached to open and close the supply bottle's isolation valve.

   Note: If securing an inverted bottle to the structure of the launch pad itself, the rail may need to be lowered to load the rocket and raised back to vertical before the supply bottle can be strapped in its final position. In this case, defer this step until after the rocket has been loaded onto the rail and raised to vertical.

4. Identify a suitable location to place the GSE box adjacent to the launch rail. Ideally, this is a flat surface out of the way of the blast deflector, with as much of a clear line of sight to the launch table or control bunker as possible. Ensure the fill valve inlet is oriented such that the nitrous supply line can be easily routed from the bottle to the GSE box.
5. Retrieve the following items (storing/transporting inside the GSE box is recommended):
6. Upstream fill line hose
7. Downstream fill line tube with male QD fitting
8. Servo cable
9. Ignition cable
10. QD clip with pre-attached Kevlar tether
11. Thread the upstream fill line hose onto the oxidizer fill valve inlet on the GSE box, and onto the supply bottle outlet. Adjust their positions as necessary if the fill line does not easily reach.
12. Using an appropriate wrench, firmly tighten each B-nut on the upstream fill line hose while using a second wrench to back up the male flared fittings.
13. Pug the servo cable into the outlet marked with "SRV" on the GSE box.
14. Plug the ignition cable into the outlet marked with "IGN" on the GSE box.

    Note: Be sure that the cables are plugged into the correct outlets. Do NOT swap outlets; doing so will damage the servos in the vehicle's valve assemblies. It is recommended to obtain second-party verification that the cables are correctly configured before proceeding.

15. Insert the downstream fill line tube into the fluid outlet fitting on the GSE box. Push firmly to ensure that the push-to-connect fitting fully engages, and tug on the tubing to verify that it is properly retained by the internal teeth.
16. Place the end of the downstream fill line (with the male end of the quick disconnect) down in a safe spot so that it will not be accidentally damaged or exposed to dirt/debris before being connected to the vehicle.
17. Place the QD clip down in a safe spot so that it will not be stepped on or damaged.
18. Optional: The transmitter and GSE may now be turned on to perform initial functionality checkouts of the fill valve and ignition leads. These checkouts are also part of the launchpad operations in section 7.3 below.

19. Place the fire extinguisher about 20 feet away from the launchpad (if the site does not already have fire extinguishers on hand)

    *Note: **NEVER** approach a nitrous oxide tank which is on fire. This includes both the supply bottle and vehicle propellant tank. Whenever possible, launch pad fires should be allowed to burn themselves out with personnel at a safe distance, unless the fire is very small and able to be safely extinguished. Fires not involving a nitrous oxide tank, such as dry grass or other plant matter adjacent to the launchpad, should be responded to as usual per the launch site's fire response procedures.*

7.3 Launchpad Operations

The on-pad setup of Mojave Sphinx is similar to any other high-power rocket, with the exception of the oxidizer fill and vehicle valve connections. As with any amateur rocket, arming the vehicle is a hazardous operation and should not be performed until the launchpad is cleared of personnel who are not directly involved in the operation.

7.3.1 Rail Loading

1. Carry the fully packed and integrated vehicle to the launchpad.
2. If the launch rail is not already lowered, lower it to a horizontal position.
3. Load Mojave Sphinx onto the launch rail:
4. Slide the lower rail guide into the rail slot. Maintain the vehicle in an orientation colinear with the rail; excess torquing of the rail guide may cause damage to the guide, launch rail, or both.
5. Guide the vehicle down the rail until the upper rail guide slides into the rail slot. At this point the rail guides are able to support the full weight of the vehicle.
6. Slide the vehicle fully down the rail until it bottoms out on the rail stop. If there is no rail stop, a block of wood or similar may be used to stand the nozzle off from the blast deflector.
7. Raise the launch rail to a vertical position and lock its position if it has a locking feature. If the rail is angled, ensure that it is pointing away from the flight line. A launch angle of 2-5 degrees downrange is recommended.
8. Plug the male end of the quick disconnect (on the GSE side) into the female end (on the vehicle side).
9. Slide the QD clip over the mated quick disconnect, with the tether side facing toward the ground and the opening facing upwards. If the clip will not stay in place on it's own, a ¼-½" wide strip of masking tape placed over the clip's opening may be used to hold it in place without affecting its ability to separate.
10. Tie the clip tether to the launchpad or other secure object. The tether should ideally be slightly taut or have minimal slack such that the clip will be disengaged within the first 2-3 inches of the rocket's motion.
11. Plug the 3-pin servo cable into the vehicle valve servo wire, observing that all wire colors match. Some 3-pin cables may have a different wire color scheme:
    a. **WHITE = YELLOW**
    b. **RED = RED**
    c. **BLACK = BROWN**
12. Tape, tie, or zip-tie the servo cable to the launchpad or other secure object so that it will be unplugged from the Y-harness connector on the vehicle when the vehicle departs the rail.

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7.3.2 GSE Startup and Checkouts

Power on Transmitter & GSE

Caution: The transmitter must be booted up before supplying power to the GSE.

1. Flip all switches on the transmitter to the **UP** position, ensure the **LEFT** stick is fully **DOWN** and slide the transmitter power switch to **ON**.
2. After the transmitter has booted up, flip all switches to the **DOWN** position and close the switch covers.
3. Flip the GSE box power switch to **ON**. Verify that the transmitter has established a connection with the receiver after a few seconds.
4. If the system has been pressurized since the most recent time that the upstream fill line hose was connected, verify that the upstream fill line between the supply bottle and fill valve has been vented.
5. Manually confirm that the oxidizer supply bottle hand valve is closed. Failure to comply with this step may lead to unsafe pressurization of the rocket in close proximity to personnel.
6. **Manually confirm again that the oxidizer supply bottle hand valve is closed.**
    a. A second party verification is strongly recommended, especially with an inverted bottle where the direction of valve rotation appears reversed.
7. Flip the **FILL** switch **UP** to open the fill valve. Visually confirm that it has opened.
8. Flip the **FILL** switch **DOWN** to close the fill valve. Visually confirm that it has closed.
9. Flip the **SRV** switch **UP** to open the vehicle valves. Confirm that both have opened.
10. Flip the **SRV** switch **DOWN** to close the vehicle valves. Confirm that both have closed.

    Note: Visual observation of the fuel valve may be difficult or impossible on the launch pad with the airframe installed. It is recommended to perform this checkout at least once prior to airframe integration with visual confirmation of nominal fuel valve actuation. When fully integrated on the launch pad, auditory confirmation by listening for the sound of the servo is acceptable. Personnel performing this check must be familiar with the sound characteristic of a nominal valve actuation.

11. Perform a spark check:
    a. With **IGN** switch **DOWN**, briefly touch the ignition leads together to confirm that they **do not** spark.
    b. Flip the **IGN** switch **FULL UP**.
    c. **Briefly** touch the ignition leads together to confirm that they spark.
    d. Flip the **IGN** switch **FULL DOWN**.
    e. **Briefly** touch the ignition leads together to confirm that they **do not** spark.

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7.3.3 Vehicle Arming

Operations may only proceed when a launch window is imminent. Do not arm the rocket before a launch window is certain and all personnel will be immediately vacating the launchpad area.

Caution! Eye protection is required for all personnel at or near the pad during this operation. Live pyrotechnic charges can present a hazard in the event of misconfiguration or malfunction of the deployment controllers.

1. Turn on the **primary** deployment controller by twisting its power wires together. Ensure a minimum of five full twists of the wires. Wrap the connection with electrical tape to cover all exposed wire.
2. Turn on the **secondary** deployment controller by twisting its power wires together. Ensure a minimum of five full twists of the wires. Wrap the connection with electrical tape to cover all exposed wire.
3. Confirm that both deployment controllers read continuity of both drogue and main ejection charges.

Confirm that the Operator has physical possession of the GSE control transmitter and that all switch covers are closed before proceeding.

4. After touching the ignition leads together to confirm **no spark**, connect one clip of the ignition leads to each leg of the igniter wire.
   a. Ensure the leads and/or alligator clips cannot contact each other or any conductive surface such as the launch rail. Insulate igniter leads with electrical tape as required.

WARNING: The igniter is now armed.

5. Wait until all other personnel are walking away from the pad to a safe distance or bunker.
   a. This includes unrelated personnel at other launch pads on the range who may pass near the launch pad on their way to the observation area.
6. Start any cameras or other data collection devices at the pad.
7. Fully open the oxidizer supply bottle hand valve.
   a. Note: it is recommended to back off the valve approximately 1/4 turn from fully open so that the handle rotates easily. This prevents a full-open bottle from being mistaken for closed.

WARNING: The oxidizer fill system is now armed.

8. Proceed calmly from the pad to the launch control center.

7.4 Launch Procedure

Launching Mojave Sphinx is best done with a two-person team, a **Director** and an **Operator**. If necessary, one person can perform both roles to launch the rocket solo. More than two people are not required, and any additional team members should not be involved in the fill and launch operation; this may hamper clear and concise communication between the director and operator, or with the Launch Control Officer (**LCO**) and Range Safety Officer (**RSO**).

7.4.1 Procedure Review

Unlike what may be expected from a "traditional" amateur liquid rocket, the load-and-go launch procedure is a short, fast-paced sequence. It is quite simple to execute, but must be carried out with confidence to avoid wasting oxidizer or creating confusion during launch operations. Both the Director and operator (which may be the same person) should review the following steps to understand their roles.

Basically, read this whole section first before performing the actual fill and fire procedures. When the time comes to launch the rocket, the director and operator should already know what to do without needing to reference the guidebook.

7.4.2 Fill Criteria

Before proceeding to launch operations, decide on the criteria for concluding oxidizer fill. Typically, fill is concluded when either:

- [Time] has elapsed.
- The static vent begins visibly expelling liquid nitrous oxide.

Fill time for Mojave Sphinx is usually around 60 seconds, plus or minus 10 seconds depending on ambient temperature. Any change to the tank volume or static vent orifice size will change fill time. Whatever the case may be, predetermine the fill criteria and stick to those condition(s).

If determining fill based on visual observation of liquid exiting the vent, ensure the vent is oriented perpendicular to the observer. Liquid venting will present as a sudden and distinct change in the appearance of the vent, with an opaque, well-defined plume rather than a translucent wisp. The GSE fill valve should be closed immediately upon observation of liquid venting, to avoid wasting excess oxidizer.

If operating the rocket from the recommended standoff distance rather than a protected bunker closer to the pad at FAR or RRS, a time-based fill criteria is recommended as the venting may not be easily visible. Otherwise, an exception may be made to the recommendation that only two people be involved in the fill and launch operation, with a third person viewing the rocket through binoculars or a spotting scope with the sole responsibility of calling out when liquid venting is observed. The authority to call out liquid venting should rest solely with one individual, to avoid a split decision that may cause confusion or hesitation in entering the terminal count.

Figure 7.12: Comparison of Mojave Sphinx gas (left) and liquid (right) venting. In this camera view taken from approximately 270 feet away, note how the static vent plume changes from barely visible to a substantial cloud of vapor.

7.4.3 Holding After Oxidizer Fill

In the event that the 5-second launch countdown cannot commence immediately following completion of oxidizer fill (for example, due to a range violation by an aircraft or other vehicle), the rocket may be allowed to hold on the pad for up to 30 seconds. If launch does not occur within 30 seconds of closing the fill valve, either:

- Reopen the fill valve for 5-10 seconds to increase the pressure in the tank
- Abort the launch by opening the vehicle valves **without** firing the igniter, which will safely dump all propellant

A standard Mojave Sphinx tank loses approximately 4.5 psi per second from venting after the fill valve is closed. It is not recommended to proceed to ignition with a tank pressure lower than 400 psi, although tank pressure is not typically measured when launching. On a hot day, the actual allowable hold time before crossing this threshold may be longer than 30 seconds, however it is a reasonable rule of thumb under a typical range of conditions.

7.4.4 LCO Coordination

Inform the LCO that the rocket is ready to begin fill operations. Communicate the following:

- The fill and ignition system is controlled entirely from the R/C transmitter. It does not require the club to push any buttons on their launch controller.
- Nitrous fill will take about 60 seconds.
- After fill is completed, the LCO should give a prompt 5-second countdown.

There may be multiple rockets launching in the same window. Only proceed once a positive go-ahead has been given by the LCO to begin filling oxidizer.

Operations may only proceed when all personnel are at a safe standoff distance or inside of bunkers. Do not begin filling the rocket if there are any personnel within the safe standoff distance.

7.4.5 Load and Go

Note: The time counter on a phone video may be used to conveniently keep track of fill time elapsed.

1. **OPERATOR** Push the **LEFT** stick **FULL UP** while calling out **"Stick up."**
2. **OPERATOR** Flip the **FILL** switch **UP** while calling out **"Fill valve open."**
3. **DIRECTOR** Note fill start time on time counter.
4. **DIRECTOR** Call out fill time elapsed and remaining every 15 seconds.
5. **DIRECTOR** When the fill criteria has been met, call out "**Fill complete."**
6. **OPERATOR** Flip the **FILL** switch **DOWN** while calling out **"Fill valve close."**
7. **DIRECTOR** Confidently call out **"Ready for 5-count."**
8. **DIRECTOR** Confirm acknowledgment by the LCO.
9. Wait for the LCO or RSO to do a range check and begin countdown.
10. Wait for the countdown to finish.
11. **OPERATOR** Flip the **IGN** and **SRV** switches **FULL UP**.
12. The rocket will either launch or dump its propellants.
13. **OPERATOR** After launch or dump is complete, flip all switches **DOWN** and close all covers.

Note: With receiver failsafes set properly, turning off the transmitter will do the same as Step 13.

7.4.6 Flight Observation

Once the rocket has launched, it will proceed exactly as any other high-power rocket. Mojave Sphinx has no onboard control for its propulsion system and will burn until fuel depletion.

Visually track the vehicle as it ascends ("keep eyes on the rocket"). If personnel are inside of bunkers, this may not be possible until the RSO has given permission to exit.

Note: Because liquid propulsion systems do not generally produce a smoke trail after burnout, it may be difficult to visually track the vehicle through its entire flight profile, especially if the sun is in an unfavorable position or if there is partial cloud cover below the apogee altitude.

Confirm that the vehicle has successfully fired its apogee deployment charge and separated into two segments connected by shock cord. If this is not confirmed, make the RSO aware of a possible ballistic return and ensure that all persons are inside of bunkers if available.

Note: It has been observed that Mojave Sphinx, and other Half Cat style rockets with unshrouded thrust structures have a tendency to fall sideways after apogee if the drogue fails to deploy. The Mojave Sphinx prototype, on one occasion, experienced a complete deployment failure yet descended in a horizontal orientation until impact, slowing its fall nearly as its drogue parachute would have. On another occasion, the propulsion system separated from the parachutes due to shock cord damage and descended horizontally on its own. Although this is a seemingly consistent characteristic of this style of design, it should not be *considered a safe descent mode. Always treat an unseparated rocket as a heads-up event that can pose a risk to people and property in the vicinity.*

Visually track the vehicle as it descends ("keep eyes on the rocket"). Be aware that the LCO may launch other rockets while Mojave Sphinx descends under parachute.

Watch for firing of the main deployment charge. Altitude is difficult to judge by eye; depending on the deployment controller's setting (typically around 1000 feet), the vehicle may appear to be closer to the ground than it truly is.

Once the main parachute has deployed, the vehicle will slow to its final descent velocity. If the main parachute does not deploy, note that it will be moving considerably faster at touchdown.

If wind conditions have brought the vehicle back toward the flight line, make sure all persons are aware that there is an incoming rocket. Even at a "safe" nominal descent rate, collision of the rocket under parachutes with a person, structure, or vehicle has the potential to cause harm. If it appears that the rocket will land in close proximity to people, loudly announce "heads up" to draw the attention of anyone near the landing area.

Take note of the line-of-sight to the rocket's touchdown. If it is far away, it will be helpful to note which distant landmarks it appears to be in line with, so that a vector can be drawn to its location. A compass reading can also be used for this purpose. These measures are recommended even if the rocket is equipped with a GPS or radio tracking device, in the event that the tracker loses power on landing or otherwise malfunctions.

7.5 Launchpad Shutdown

It is important to shut down the pad promptly after firing because the oxidizer supply bottle is still open at this point. This presents a potential hazard to persons nearby in the event that the fill valve is accidentally opened, which can cause the fill line to whip violently.

Only cross the flight line after the RSO has given explicit permission or declared that the range is clear.

If the rocket is still on the pad after an oxidizer fill of any duration, refer to 7.5.2 (Aborted Firing). Do NOT approach the rocket without completing a safety walk.

7.5.1 Nominal Pad Shutdown

1. After the RSO has given permission or declared all-clear, calmly proceed toward the launchpad.
2. Stop about 20 feet away and listen for any hissing sounds. Politely ask others around to remain quiet for a moment if necessary.
3. If hissing sounds can be heard, attempt to identify the location(s) and stay clear. Hissing indicates a leak, which may be caused by a burst line, damaged fill valve, or loose fitting.
4. If the rocket has left the pad, leaks are only a minor hazard and will be stopped when the supply bottle is closed.
5. Approach the pad and fully close the oxidizer supply bottle hand valve. If there were leaks present, step away and wait for them to subside.
6. Vent the upstream fill line:
    a. Physically confirm that the oxidizer supply bottle is closed.
    b. Place the end of the fill line on the ground and secure it by standing on it ("whip-checking") with the QD fitting protruding slightly out from under the sole of the shoe. Ask others to step back a few feet.

    Note: The thrust force produced by the pressure and effective orifice area of the ¼" fill line and QD fitting is sufficiently low that it can be secured in this manner without risk of injury. This does not necessarily apply to venting pressurized lines in all situations, especially those with larger diameters and/or containing higher pressures. If desired, the fill line may be secured in an alternative manner such as a clamp or very short tether to a fixed or heavy object. In this case all personnel should stand clear by at least twice the length of the fill line in case the restraining device fails..

    c. Call out "Venting!"
    d. Open the fill valve to vent the upstream fill line. There will be a brief, loud hissing.

    Note: If the fill valve fully opens and the hissing does not stop within two seconds, close the fill valve and ensure that the supply bottle is fully closed.

   e. Alternatively, the upstream fill line may be vented by cracking the fitting connecting the line to the bottle. Use a wrench to loosen the fitting until hissing can be heard, slowly loosening it more as the hissing dies down, until pressure has fully vented. The fitting may then be re-torqued or removed.

7. Turn off the GSE by flipping the box power switch to **OFF**.
8. Turn off the transmitter by sliding the power switch to **OFF**.
9. The launchpad is now safe.

7.5.2 Aborted Firing

If the fill valve was opened at any point with the fill line connected to the rocket, there is a risk that the vehicle tank may still contain pressure. As part of the load-and-go procedure, the vehicle valves should have been opened to fully expel all propellant even if ignition did not occur. However, if the vehicle valves could not be opened for any reason, the oxidizer tank must be allowed to fully depressurize via the static vent.

If the vehicle valves were opened to expel propellants:

1. Follow procedure **7.5.1** (Nominal Pad Shutdown).
2. Disconnect ignition leads from igniter wires and twist the igniter wires together.

   *Note: Opening the main propellant valves will dump both oxidizer and fuel. Be mindful of expelled fuel on and around the pad area. **NEVER** bring a heat source, sparks, or open flame near liquid fuels. If the fuel was a hydrocarbon such as diesel, it will not evaporate and should be mopped up with rags or oil absorbent mats and disposed of in an environmentally responsible manner.*

   *Note: **NEVER** approach a nitrous oxide tank which is on fire. This includes both the supply bottle and vehicle propellant tank. Whenever possible, fires should be allowed to burn themselves out with personnel at a safe distance unless the fire is very small and able to be safely extinguished.*

If the vehicle valves were not opened to expel propellants:

The propellant tank may be partially or completely filled with oxidizer. The oxidizer tank check valve prevents backflow out of the tank – so if the vehicle valves cannot be opened, the only other way to offload oxidizer is through the static vent.

The static vent ensures that the tank cannot hold pressure indefinitely, however it takes a considerable amount of time for a full load of liquid nitrous to boil off through the vent. For a standard Mojave Sphinx tank, this is estimated to take 1-1.5 hours.

Fortunately, there is an extremely low probability of the system losing power or connection to the vehicle valves between the start of oxidizer loading and ignition. This has never occurred in over 50 firings of Half Cat style rockets at the time of writing, demonstrating the robustness and reliability of the GSE described in this guide. Additionally, a loss of communication between the transmitter and GSE will automatically safe the system with properly configured receiver failsafes.

It is important to understand that because the valves on the rocket are identical to those used on the ground system, and all valves are controlled by the same system, dumping propellant via the onboard vehicle valves is no less reliable than a dedicated dump valve on the ground system would be.

In the event that the vehicle valves are unable to be opened for any reason after any amount of oxidizer was loaded, follow the steps below.

1. Note the approximate time when oxidizer fill concluded. Wait at least one hour if the tank was completely filled. If the tank was only partially filled prior to aborting or a failed launch attempt, this may be reduced according to the percentage of the nominal fill duration completed.
2. After the RSO has given permission to proceed downrange, calmly and slowly walk toward the launchpad.
3. Stop about **100 feet away** and listen for any hissing sounds. Politely ask others around to remain quiet for a moment if necessary.
    a. If there is liquid oxidizer present in the propellant tank, a hissing sound should be audible from the static vent. It is helpful to approach the rocket from the side with the static vent in case of ambient noise making it difficult to hear from the opposite side.
4. If static vent hissing is audible, do not approach further. Return to the safe standoff distance or bunker and wait for the hissing to die down. Depending on fill level, vent orifice size, and ambient temperature, this may take anywhere from a few minutes to over an hour.
    a. During this time, **DO NOT** turn the transmitter off and back on; booting up the transmitter requires the switches to be in the UP position, which will energize the igniter circuit and command the valves open, which could result in accidental ignition and launch if the system were to spontaneously regain functionality. If at least three attempts to remotely open the vehicle valves are unsuccessful, it is recommended to turn the transmitter off and leave it off until the vehicle and pad are completely safed.
    b. Personnel MUST NOT approach closer than 100 feet until no hissing sound can be observed at that distance.
5. Once static vent hissing is no longer audible from a 100-foot distance, cautiously proceed toward the pad.
6. Stop about **50 feet away** and listen for any hissing sounds. All personnel should remain quiet for a few moments to provide an opportunity to listen for any continuing venting.
7. If static vent hissing is audible, do not approach further and wait for the hissing to die down.
8. Once static vent hissing is no longer audible from a 50-foot distance, cautiously proceed toward the pad.
9. Stop about **20 feet away** and listen for any hissing sounds. All personnel should remain quiet for a few moments to provide an opportunity to listen for any continuing venting.
10. If static vent hissing is audible, do not approach further and wait for the hissing to die down.
11. Once static vent hissing is no longer audible from a 20-foot distance, cautiously proceed toward the pad.
12. If there is still quiet hissing only audible within **10 feet**, give the propellant tank 5 additional minutes to vent or until hissing has ceased entirely.
13. When no hissing is audible from the static vent, follow procedure **7.5.1** (Nominal Pad Shutdown) beginning with closing of the oxidizer supply bottle hand valve.
14. After the oxidizer supply tank has been closed, disconnect ignition leads from igniter wires and twist the igniter wires together.

7.5.3 Vehicle Shutdown

This procedure only applies in the event that the vehicle was not launched and remains on the pad.

Caution! Eye protection is required for all personnel at the pad when deployment controllers with pyrotechnic charges are armed.

1. Turn off all deployment controllers to disarm the pyrotechnic charges. Insulate the altimeter power leads to prevent accidental re-arming.
2. It is recommended to command the vehicle valves into the closed position so that fuel does not leak when bringing the vehicle horizontal.
   a. Always be mindful of the possibility of fuel dripping from the nozzle, even with the fuel valve fully closed.
3. The vehicle may now be removed from the launch rail and prepared for another attempt.

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7.6 Recovery

After launch, Mojave Sphinx is recovered like any other high-power rocket. No pressure remains in the tank or feed system because the valves stay open, and all propellants are fully expended (save for a small amount of residual fuel that may drip from the chamber). The only significant hazard to be aware of is that the thrust chamber assembly will remain quite hot for several minutes after firing; while the chamber's peak external temperature is typically lower than some commercial solid motor casings, its substantial thermal mass retains heat for longer. Conversely, the propellant tank will be cold from the rapid expansion of the nitrous, but warms up quickly in the sun.

Be mindful of the potential for extreme component temperatures if the vehicle is recovered shortly after landing. It is strongly recommended to travel to the landing site with at least two people (buddy system). Personnel engaged in recovery must be dressed appropriately for the weather and carry plenty of water – this is especially critical at desert launch sites in the summer months, when severe dehydration and heat exhaustion can set in quickly. and exercise caution regarding natural hazards such as rough terrain or venomous wildlife.

After the vehicle has landed, await instructions from the RSO. When the RSO gives permission to enter the range, proceed in the direction the vehicle was last seen.

Note: If a radio beacon or GPS tracker is installed, follow the signal. If no electronic tracking device is installed, it is helpful to draw a vector from the observer's position on the flight line to a distant landmark in line with the rocket's last sighted position.

Exercise caution regarding natural hazards such as rough terrain or venomous wildlife; it is strongly recommended to travel to the landing site with at least two people (buddy system). Personnel engaged in recovery must be dressed appropriately for the weather and carry plenty of water. This is especially critical at desert launch sites in the summer months; when temperatures exceed 110° F, the danger posed by severe dehydration and rapid-onset heat exhaustion cannot be overstated.

Upon locating the vehicle, document its condition with photos before it is disturbed. This may be helpful for identifying landing damage or diagnosing other anomalies at a later time.

Optional: If the deployment controllers report the recorded apogee via a series of audible beeps, listen for the result. A video recording may be helpful and provides a crude form of data backup.

Carefully untuck the two pairs of avbay power wires and untwist the splices to turn off the deployment controllers. Insulate the leads with electrical tape, if possible, to prevent them from turning back on from accidental contact.

Optional: Stuff the parachute, chute protectors, and shock cord back into the tubes and slide the vehicle back together so that it may be more easily carried as a single piece. A tote bag is also a convenient means of bundling up parachutes and shack cords for transport. Carry the rocket back to the flight line. Once returned, it may be prepared for another launch.

Section VIII – Appendices

Appendix A: Static Testing of Mojave Sphinx

Static testing of a standard or only slightly modified Mojave Sphinx is not a prerequisite for launch. The prototype vehicle has undergone an extensive battery of testing, as described in Section 3; the results gathered across a wide range of conditions demonstrate that the motor is capable of operating reliably within the bounds set forth in Table 2.6. Furthermore, the HalfCatSim design spreadsheet, which has been anchored using actual test data, allows the motor to be simulated with sufficient accuracy to omit static testing even if the performance parameters have been modified within reason. The core concept of Mojave Sphinx is to provide a liquid motor design which is known to work and can proceed directly to flight.

Nonetheless, there are legitimate and compelling reasons why one may choose to static test the propulsion system: new injector designs, increased tank lengths/burn times, and reduced structural margin for mass savings, to name a few. Another possibility is that teams unable to travel to FAR due to distance or resource limitations may still be able to fire the motor locally, providing a satisfying conclusion to a liquid bipropellant rocket project even without a launch. Whatever the case may be, there are situations in which static testing is desirable. This guidebook focuses on launching and therefore does not go into great detail about static testing, but the following information is provided to convey a general methodology for static testing Mojave Sphinx and similar rockets.

A test stand can be divided into two distinct parts: the physical structure and the data acquisition (DAQ) system. Half Cat Rocketry's test stand structure is very straightforward – described in Section 3.2, it is constructed primarily of metal strut channel. The motor hangs from a load cell, secured to holders that cradle the tank and allow it to slide axially along the strut channel backbone. Any similar type of structure will work just as well, so long as the propellant tank is oriented mostly vertical (since oxidizer drains from the aft end of the tank) and the motor's only degree of freedom is movement in the axial direction (into the load cell). Most load cells deflect only a few thousandths of an inch, but more axial freedom is often helpful for installing and removing the motor from the test stand. While it is not strictly necessary for the thrust chamber to be vertical (down-firing), there is usually no reason for it to be horizontal; Half Cat Rocketry's philosophy for testing standard liquid rockets has always been to fire them in the flight configuration, including the thrust structure and chamber orientation. This is both a better test of the rocket's ability to fly successfully and less effort, as no additional structure or fixturing for mounting the thrust chamber is required beyond what is already part of the rocket.

Data collection can be implemented in many ways, but at the core of any system is a computer of some type, commonly referred to as a DAQ, which collects and stores sensor readings. The simplest option is an Arduino board with a basic code to read analog voltage inputs from sensors, convert them to measurement values, and write the data to an SD card or other memory device. Similar devices such as Raspberry Pi or other comparable single-board computers can also be used.

For a more "plug and play" solution including a basic GUI that does not require coding, LabJack products are favored by many for rocket motor testing. COTS DAQ systems are available from many vendors such as DATAQ Instruments, Omega, and National Instruments, roughly in order of increasing cost and decreasing user-friendliness.

The main types of sensors used in testing amateur rocket motors are load cells, pressure transducers (PTs), and thermocouples (TCs). Load cells and thermocouples generally require an amplifier, while PTs are commonly available with a 0.5-4.5V analog output. Sensors with a 4-20mA current output are often considered superior, but are more expensive and less straightforward to read.

Note: There are other common kinds of thermal probes, such as RTDs and thermistors, but for purposes of simplicity this section will only refer to thermocouples.

PTs come in many form factors, and can get expensive very quickly as accuracy or sampling rate increases. For the purposes of amateur rocketry, sampling rates of 100Hz are more than sufficient, and even as low as 20Hz may be satisfactory for the purposes of generating a thrust curve. A very common and inexpensive type of PT with a 0.5-4.5V analog voltage output is shown in Fig. A.1, which typically has male 1/8 NPT threads that can be adapted to many locations on Mojave Sphinx. They are available in a variety of pressure ranges as high as 1600 psi and can usually be found for around $25 from retailers on Amazon, eBay, or AliExpress.

Figure A.1: Generic pressure transducer

TCs, similarly, have a wide range of available form factors, the most useful of which are a sealed stainless steel probe that can be installed into a bored-through compression fitting for fluid measurement, and flat rings that can be attached to surfaces with a screw. There are several different types of TCs classified by letter (B, C, E, J, K, N, R, S, T); K-type are the most suitable for the temperature ranges encountered in standard liquid rockets. It should be noted that the combustion chamber temperature typically exceeds the range of any common sensor, precluding direct measurement. Temperature readings are significantly less important than pressure, but can be interesting for applications like the exterior wall of the thrust chamber. Fig. A.2 shows a relatively economical K-type TC with stainless steel probe from McMaster-Carr. Thermocouples cannot be read directly by most low-cost DAQ systems, but inexpensive amplifier carts that output a 0.5-4.5V analog signal are readily available and simple to implement. TCs can be easily calibrated using ice water at 0°C and boiling water at 100°C.

Figure A.2: Bendable thermocouple probe

Load cells are used to measure the thrust of the motor. S-type load cells (Fig. A.3) are recommended for ease of integration, and can read in both tension and compression. With some test setups and careful calibration, they can sometimes also be used to measure the mass of propellant in the tank before firing, however it is not recommended to use this as a fill criteria rather than time or visible liquid venting. The reading can be tared (zeroed out) with the motor hanging from the load cell before firing to accurately measure the force generated. Like TCs, load cells require an amplifier that is usually separate from the DAQ computer. Load cells are typically calibrated using a known mass or a hydraulic press with a force gauge (or pressure gauge and known area).

Figure A.3: S-type load cell

Sensor ranges should be selected to give significant margin above the maximum expected value, but not so much that the data is made noisy by the sensor's error, which is a percentage of its full scale. For example, a PT connected to the oxidizer tank or nitrous line could be reasonably expected to read up to about 1100 psi on the hottest days, therefore a 1600 psi range is appropriate. A PT reading chamber pressure through the igniter cartridge or a thermal standoff tapped directly into the injector or chamber wall might be expected to read around 500psi maximum, and could be rated for 750 or 1000 psi.

Oftentimes, DAQ or budget limitations mean that only a limited number of sensors can be implemented. Therefore, it is important to be strategic with sensor usage. For example, the reason that oxidizer *or* fuel tank pressure can be measured is because the sliding propellant piston ensures that both tanks are at nearly identical pressures. If only one PT can be used for some reason, chamber pressure is not typically the first choice – while chamber performance can be guessed at using HalfCatSim from tank pressure data, it is nearly impossible to know anything about performance if the tank pressure is unknown (flowmeters are seldom used, meaning that propellant flow rates must be derived from tank pressure data). That said, chamber pressure is an extremely important metric and every effort should be made to gather both tank and chamber pressure together. Load cell data is considered the most important for launch vehicles because at the end of the day it is thrust which determines the flight characteristics of the rocket. All other sensors can be neglected if the objective is purely to generate a thrust curve for launch. Note, however, that a lack of additional sensors will impose difficulty in diagnosing issues or extrapolating thrust data to other conditions.

The choice of sensors and locations is up to the team performing the static test, but for standard amateur liquid rockets there is a fairly common hierarchy of sensors:

- Load cell
- Oxidizer or fuel tank pressure
- Chamber pressure
- Oxidizer & fuel Injector inlet pressure
- Oxidizer fill line pressure
- Chamber exterior temperature
- Oxidizer & fuel injector inlet temperature

Some sensors may become more important depending on the vehicle design. For example, in a fluid system with little expected pressure loss, tank and injector inlet pressures will read nearly the same value and may not be important to gather separately. However, if the chamber is regeneratively cooled, knowledge of pressure loss through the cooling circuit is extremely valuable, as is temperature of the coolant at the injection manifold (after passing through the chamber wall).

One very simple and inexpensive way to gather temperature data is with single-use temperature stickers, available from McMaster-Carr (Fig. A.4). These stickers have boxes which turn black if exposed to their rated temperature, meaning that they will record the rough maximum wall temperature if placed on the exterior of the thrust chamber. This can be useful to determine if the chamber is operating near the limit of its thermal capabilities.

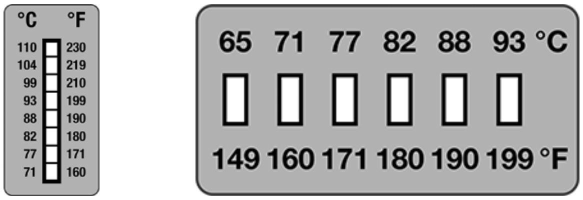

Figure A.4: Temperature stickers

In summary, there are many ways to go about testing Mojave Sphinx depending on objectives and the desired type and quality of data. It is possible to go without testing altogether, gather only the minimum required information, or instrument many parts of the motor, and this may be accomplished with any structural apparatus which supports the motor upright and only allows it to push into a load cell.

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Appendix B: Transporting Mojave Sphinx

In cases where air travel is required to reach FAR, RRS, or another launch site, Mojave Sphinx may be packed as checked luggage, so long as it does not contain any pyrotechnic materials (including igniter motors, e-matches, ejection charges, etc.) and has been cleaned of any residual liquid fuel. Any lithium batteries used to power onboard electronics must be removed as well, per FAA regulations. At least one tank bulkhead and the piston should be removed to allow for easy visual inspection inside the tube if necessary. It is also recommended to include a printed note – positioned so that it is the first thing seen when opening the suitcase or box – that states the following:

Attention TSA: This is an INERT model rocket. It contains NO HAZMAT of any kind.

While Mojave Sphinx technically falls under the definition of amateur high-power rocker rather than “model rocket,” the latter is a more universally understood concept and much less likely to alarm an inspecting agent.

Mojave Sphinx can be checked as luggage in a large suitcase, sturdy cardboard box, wooden crate, or heavy-duty shipping tube with rags, bubble wrap, or foam padding. The most secure option is a hard-sided rifle case, of which the Apache 9800 sold by Harbor Freight Tools is the most affordable version. The internal dimensions should be at least 50.375 x 13.625 x 5.125 inches. An example layout for packing a partially-disassembled Mojave Sphinx in such a case is shown below.

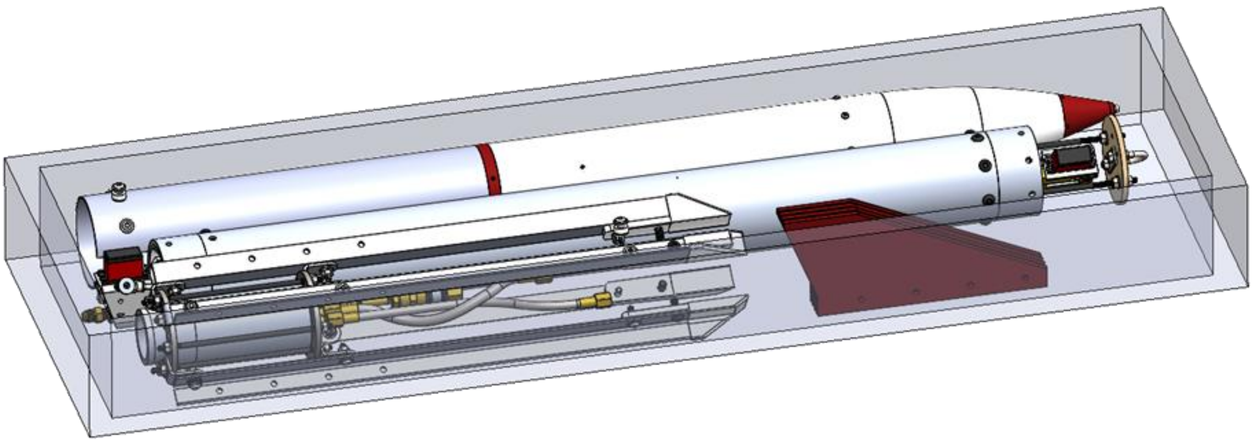

Figure B.1: Mojave Sphinx packaged in Apache 9800 rifle case

Standard liquid rockets have been transported as checked baggage in a similar manner on several occasions without issue. The GSE may be treated similarly; if using the standard toolbox-contained design it is recommended to place the toolbox inside another container with padding to protect it from dents; at a minimum, all protruding fittings should be temporarily removed and stored inside the box to prevent them from snagging or being damaged in handling.

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Appendix C: 3D Printed Components & Recommended Print Settings

All 3D printed components of Mojave Sphinx are available to download on both the Half Cat Rocketry GitHub repository and Thingiverse pages as STL, STEP, and SLDPRT files. The following is a list of parts which must be printed, as well as the quantities needed for a complete build.

Part Number	QTY	Description
SABV-MNT-04V-3225S	**2** (Vehicle) **1** (GSE, w/o Purge) **2** (GSE, w/ Purge)	Servo-Actuated Ball Valve Mount, Version 2
SABV-HCON-04V-3225S	**2** (Vehicle) **1** (GSE, w/o Purge) **2** (GSE, w/ Purge)	Servo-Actuated Ball Valve Handle Connector, Version 2
NSCN-SLDR-4X250R-8X832HNC	**1**	Nose Cone Shoulder, 4X 1/4" Rod Sleeves, for 8X 8-32 Hex Nuts with Clearance Holes
NSCN-SC1-4X250R	**1**	Nose Cone, Section 1, 4X 1/4" Rod Sleeves
NSCN-SC2-4X250R	**1**	Nose Cone, Section 2, 4X 1/4" Rod Sleeves
NSCN-TIP-4X250R-250HNC	**1**	Nose Cone, Tip, 4X 1/4" Rod Sleeves, 1/4" Clearance Hole with Hex Nut Capture
AVBY-HF-3994	**2**	Avionics Bay Coupler, Half, 3.994" OD, Printed
AVBY-CR-4R	**2**	Avionics Bay Bulkhead Centering Ring, for 4-Rod Coupler
AVBY-SB-4160	**1**	Avionics Bay Switch Band, 4.16" OD, Printed
AVBY-MT-250R-M4C	**1**	Avionics Bay Sled Mount, for .25" Rods, M4 Clearance Holes
AVBY-BH-2X9V-250R-M4C	**1**	Avionics Bay Battery Holder, 2X 9V Batteries, for .25" Rods, M4 Clearance Holes
NTRG-8X3125WN-8X25HN	**2**	Nut Ring, Printed, for 8X 5/16" Weld Nuts & 1/4" Hex Nuts
SPCR-400SD-250C-0313C	**4**	Spacer, Fin Bracket to Tank
AERO-100X100X0125	**4**	Aerodynamic Fin Bracket Tip, for 1.00 X 1.00 X .125 Aluminum Angle (Optional)
QDC-750X250CLP	**1** (Plus Spares)	Clip for 3/4" Flange-Clip Quick Disconnect
TMPLT-AF-LWR-416	**1**	Template, Hole and Slot Marking, Lower Airframe Tube
TMPLT-AF-UPR-416	**1**	Template, Hole Marking, Upper Airframe Tube
PLG-DRL-AF-UPR1-416	**1**	Backing Plug, Sacrificial, for Upper Airframe Tube Drilling
DRLJG-TANK-8X625OD-BSHNG	**1**	Propellant Tank Drill Jig
TMPLT-FIN-BRKT-1X1-AFT	**1**	Fin Bracket Template, Aft
TMPLT-FIN-BRKT-1X1-FWD	**1**	Fin Bracket Template, Forward

Table C.1: Mojave Sphinx 3D-printed components

All designs have been tested in PLA, and the servo actuated ball valve parts have been tested in PETG; ABS is expected to work as well. PETG or ABS is recommended for operating in high-temperature conditions, however PLA has been successfully used at 115°F ambient temperature and in direct sun.

All 3D printed parts used in Mojave Sphinx are designed to print on a consumer-grade FDM printer without supports, although some parts do require bridging. Parts may be printed in PLA, PLA+, PETG, or ABS. Testing was conducted primarily with PLA and PLA+ prints. Other materials such as sintered Nylon or high-strength resin may also be acceptable, however it is ultimately up to the reader to determine suitability of any particular material or process.

Recommended Print Settings

Printer used to develop settings: Creality Ender 5

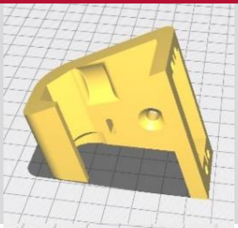
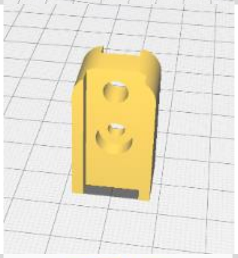
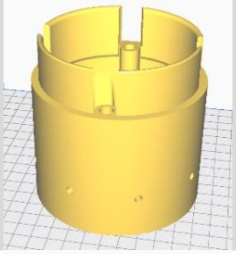
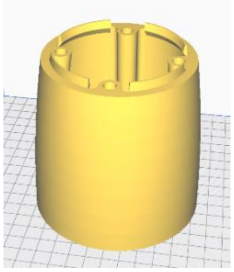
Setting	Value
Number of Walls/Perimeters	5
Infill	25%
Layer Height	0.1 mm – 0.3 mm

Table C.2: Recommended print settings for Mojave Sphinx components

The parts are designed to fit right out of the printer, but due to differences in calibration some light filing, sanding, or drilling may be required. Stringing or overprint should be removed prior to installation.

Print Orientation

Print components in the following orientations:

Part Number	Print Orientation
SABV-MNT-04V-3225S	
SABV-HCON-04V-3225S	
NSCN-SLDR-4X250R-8X832HNC	
NSCN-SC1-4X250R	

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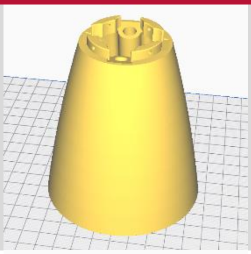
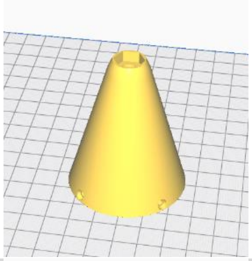
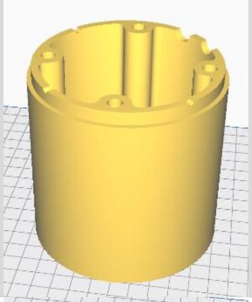
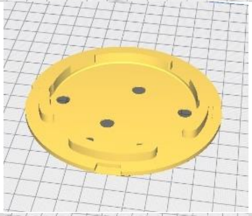
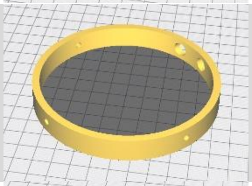
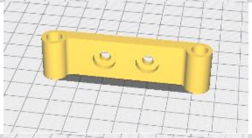
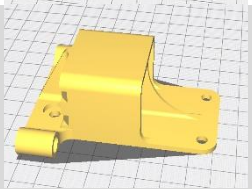
Part Number	Print Orientation
NSCN-SC2-4X250R	
NSCN-TIP-4X250R-250HNC	
AVBY-HF-3994	
AVBY-CR-4R	
AVBY-SB-4160	
AVBY-MT-250R-M4C	
AVBY-BH-2X9V-250R-M4C	

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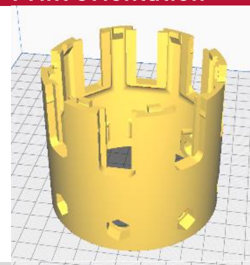
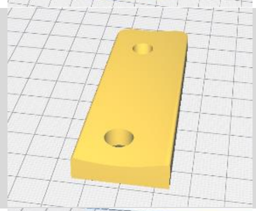
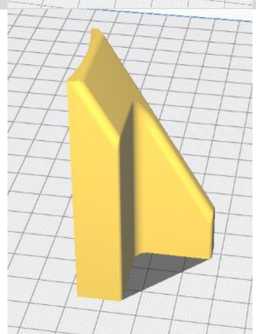
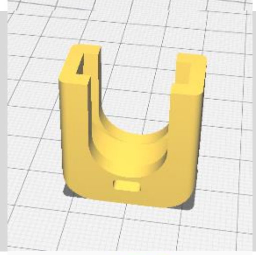
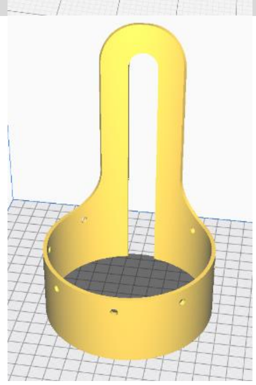
Part Number	Print Orientation
NTRG-8X3125WN-8X25HN	
SPCR-400SD-250C-0313C	
AERO-100X100X0125	
QDC-750X250CLP	
TMPLT-AF-LWR-416	

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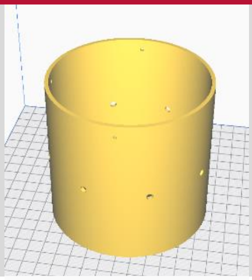
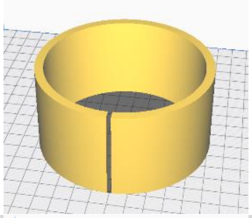
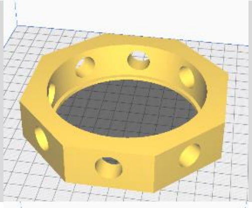
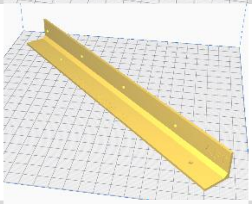
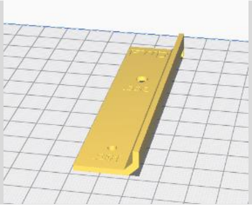
Part Number	Print Orientation
TMPLT-AF-UPR-416	
PLG-DRL-AF-UPR1-416	
DRLJG-TANK-8X625OD-BSHNG	
TMPLT-FIN-BRKT-1X1-AFT	
TMPLT-FIN-BRKT-1X1-FWD	

Table C.3: Print orientations for Mojave Sphinx components

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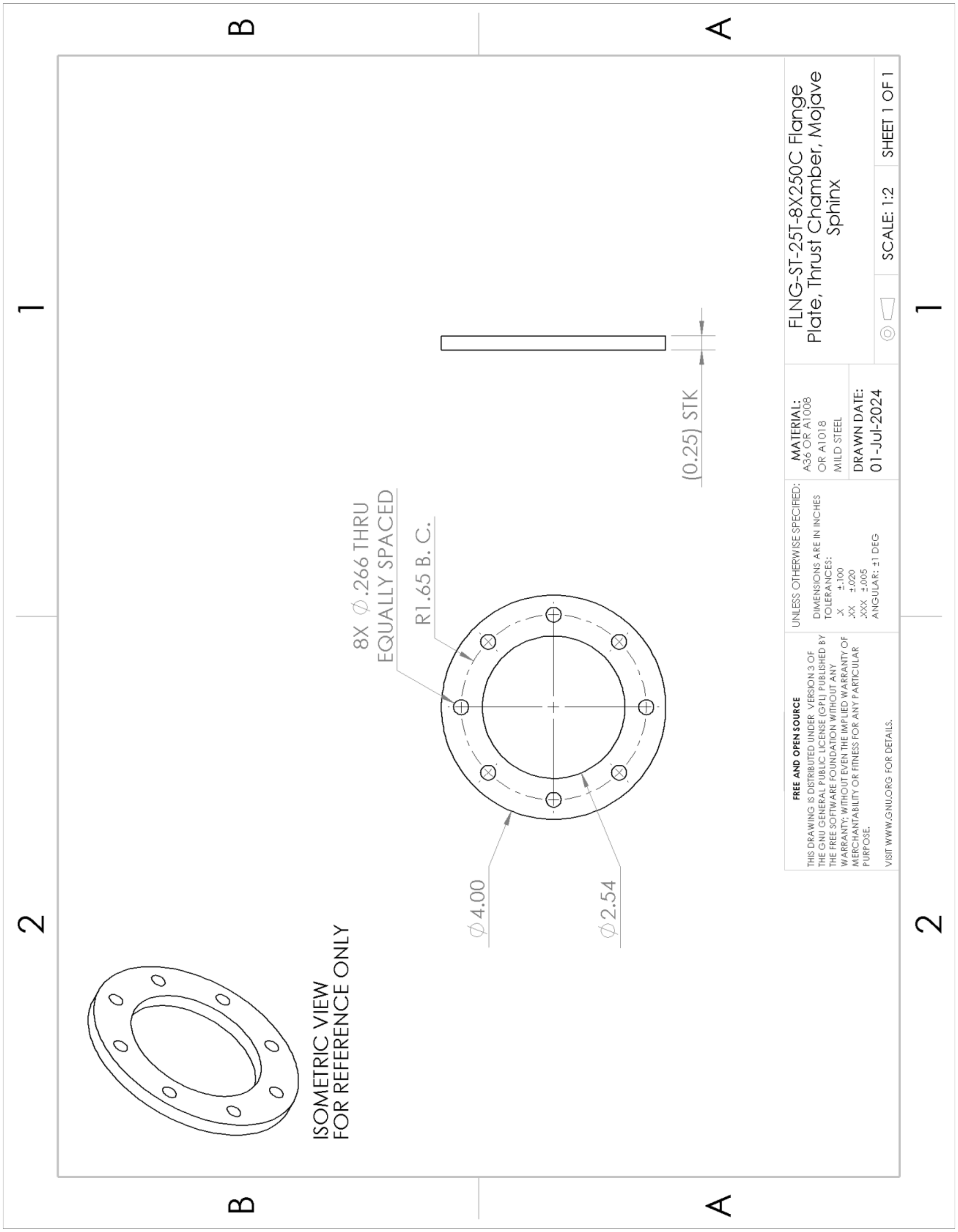
HalfCatRocketry.com
contact@halfcatrocketry.com

Appendix D: Laser-Cut Components & Part Drawings

All laser-cut components of Mojave Sphinx are available to download on the Half Cat Rocketry GitHub repository as STEP and SLDPRT files. The following is a list of parts which must be cut/bent, as well as the quantities needed for a complete build. It is recommended to order these parts through SendCutSend.

Part Number	QTY	Description
FLNG-ST-25T-8X250C	**2**	Flange Plate, Thrust Chamber, Mojave Sphinx
BRKT-90A-125T-2X250C	**8**	Bracket, Thrust Chamber Mounting, Mojave Sphinx
BKHD-REC-4X250C-2X170WE	**3**	Bulkhead, Recovery and Avionics Bay, Mojave Sphinx

Table D.1: Mojave Sphinx laser-cut components


FLNG-ST-25T-8X250C Flange Plate, Thrust Chamber, Mojave Sphinx
SCALE: 1:2
SHEET 1 OF 1
MATERIAL:
A36 OR A1008 OR A1018 MILD STEEL
DRAWN DATE:
01-Jul-2024
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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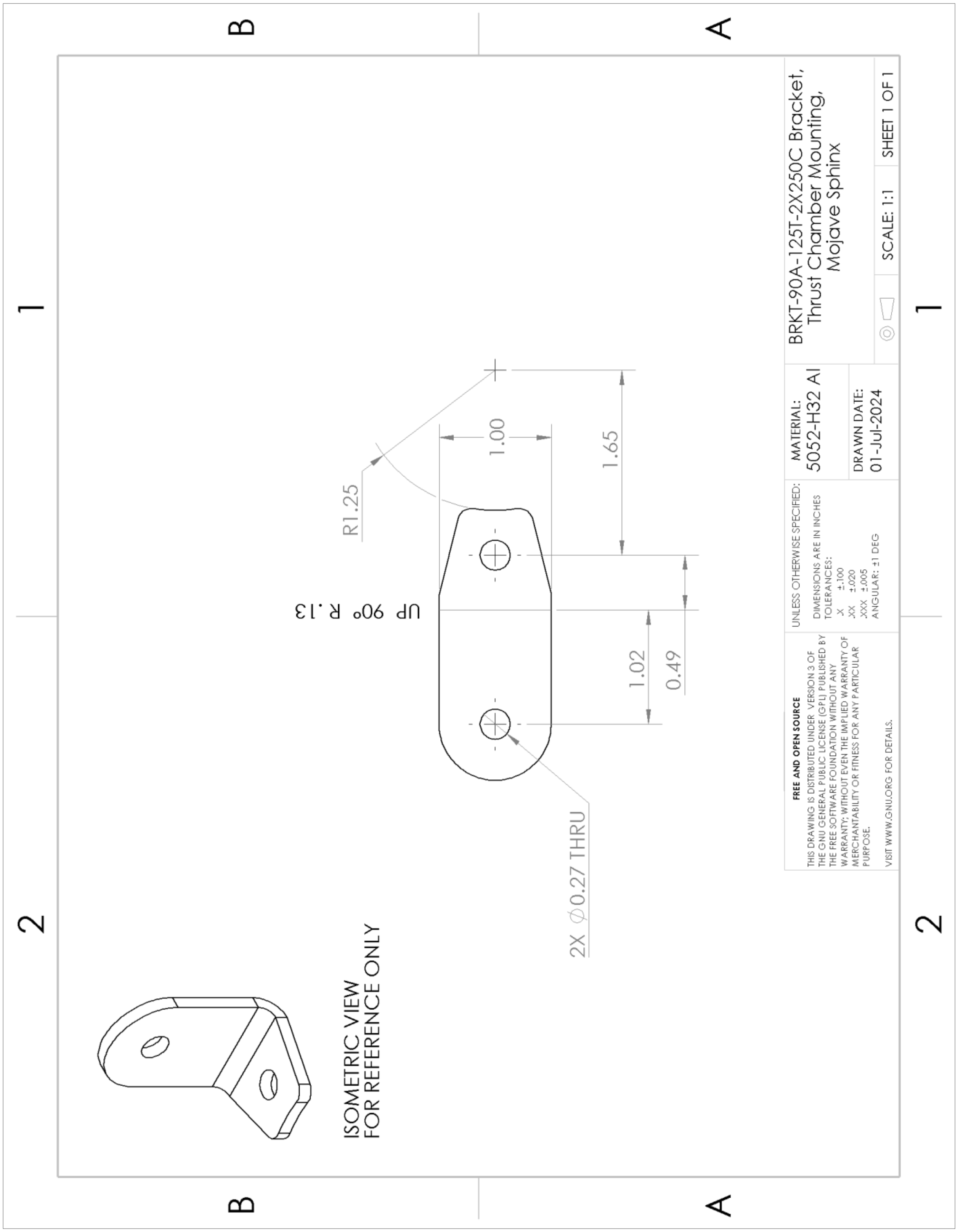
VISIT WWW.GNU.ORG FOR DETAILS.
8X ⌀.266 THRU
EQUALLY SPACED
R1.65 B. C.
(0.25) STK
⌀4.00
⌀2.54
ISOMETRIC VIEW
FOR REFERENCE ONLY


BRKT-90A-125T-2X250C Bracket,
Thrust Chamber Mounting,
Mojave Sphinx
MATERIAL:
5052-H32 Al
DRAWN DATE:
01-Jul-2024
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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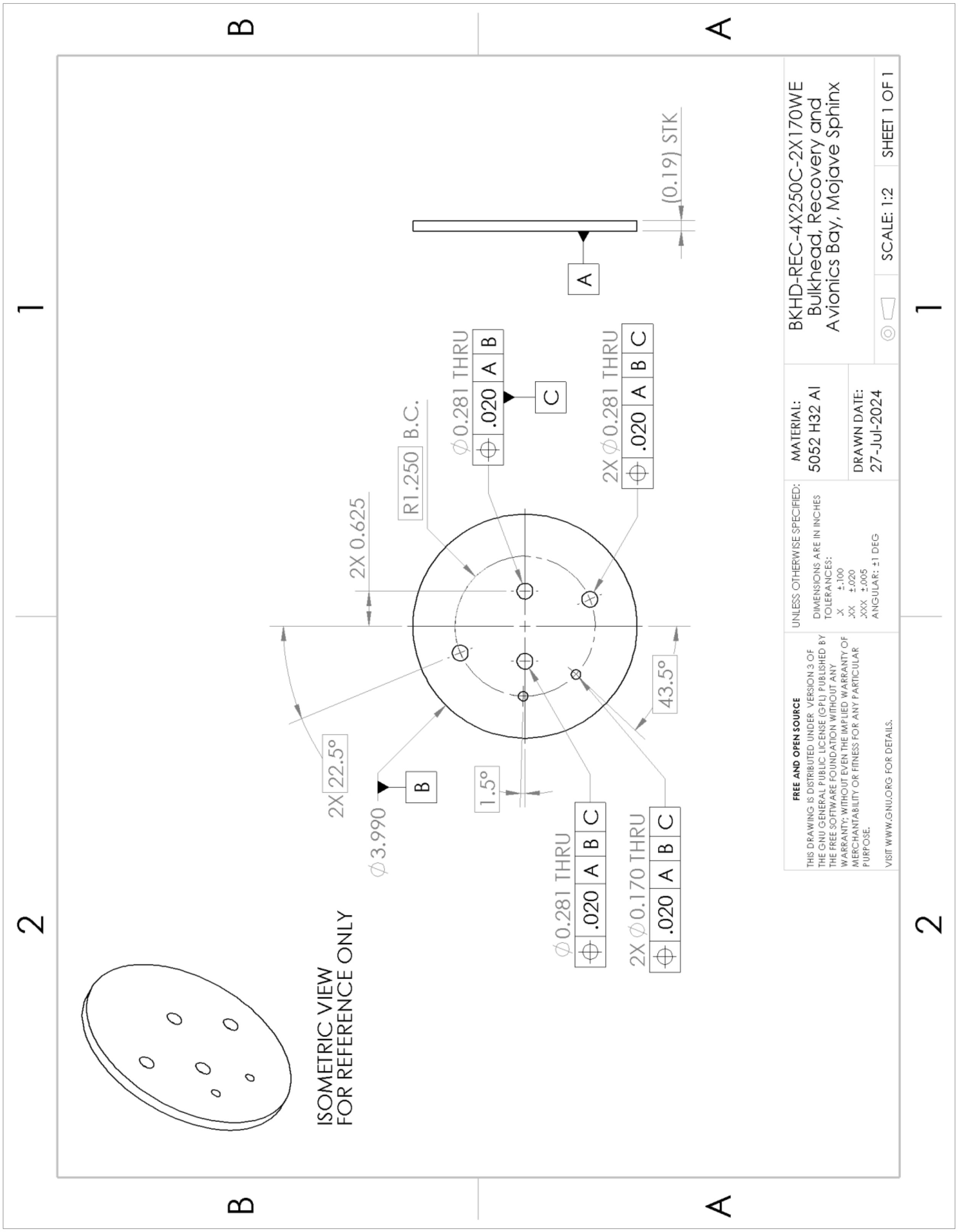
R1.25
1.00
1.65
UP 90° R.13
1.02
0.49
2X ⌀0.27 THRU
ISOMETRIC VIEW
FOR REFERENCE ONLY
A
B
1
2


ISOMETRIC VIEW
FOR REFERENCE ONLY
⌀3.990
2X 22.5°
2X 0.625
R1.250 B.C.
⌀0.281 THRU
.020 A B
2X ⌀0.281 THRU
.020 A B C
⌀0.281 THRU
.020 A B C
2X ⌀0.170 THRU
.020 A B C
1.5°
43.5°
(0.19) STK
A
B
C
BKHD-REC-4X250C-2X170WE
Bulkhead, Recovery and
Avionics Bay, Mojave Sphinx
MATERIAL:
5052 H32 Al
DRAWN DATE:
27-Jul-2024
SCALE: 1:2
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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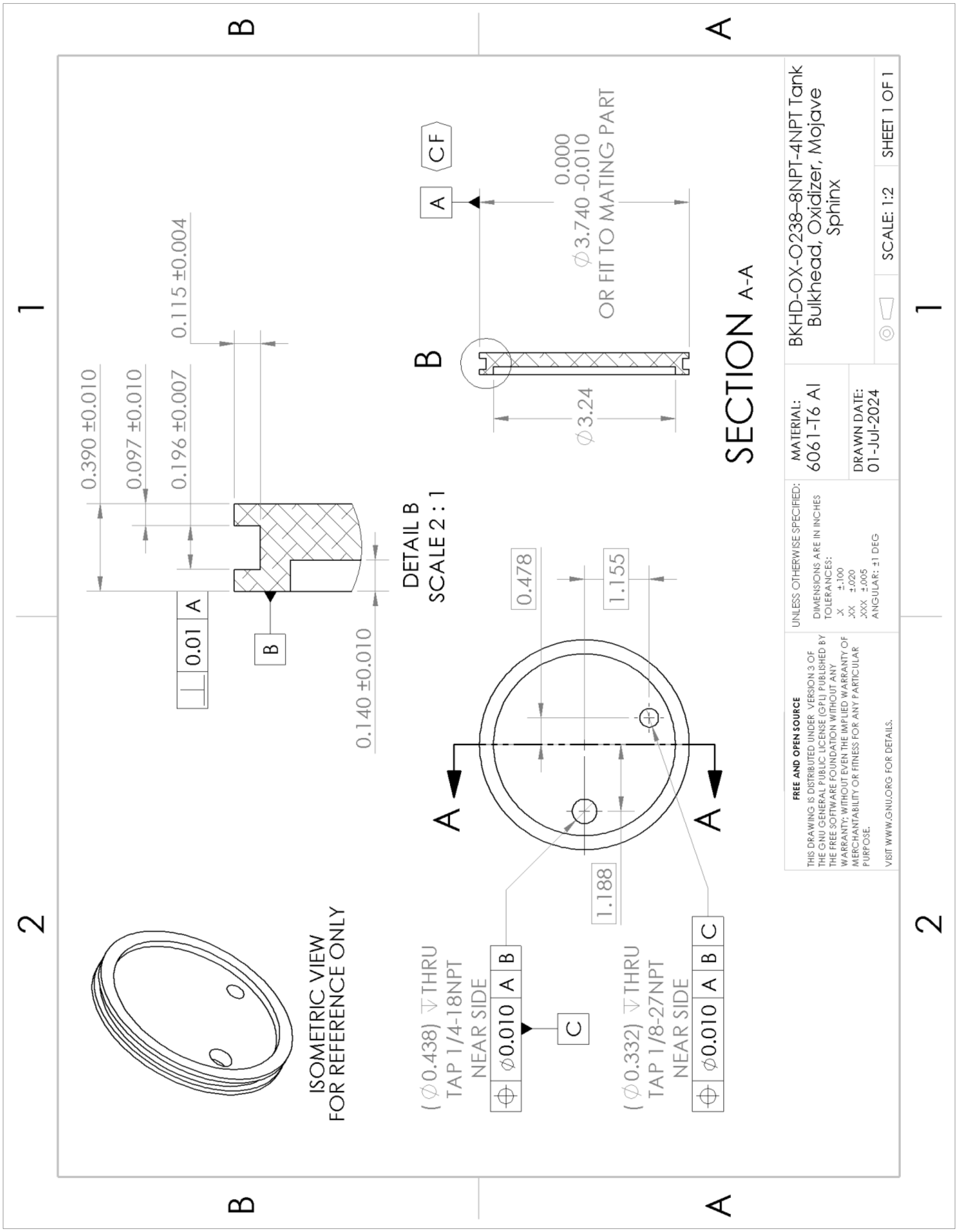
Appendix E: Machined Components & Part Drawings

All machined components of Mojave Sphinx are available to download on the Half Cat Rocketry GitHub repository as STEP and SLDPRT files. The following is a list of parts which must be cut/bent, as well as the quantities needed for a complete build. It is recommended to manufacture these parts in-house or through a local machine shop.

Part Number	QTY	Description
BKHD-OX-0238-8NPT-4NPT	1	Tank Bulkhead, Oxidizer, Mojave Sphinx
BKHD-FL-0238-4NPT-2X250C	1	Tank Bulkhead, Fuel, Mojave Sphinx
PSTN-2XO238-250T20	1	Propellant Piston, Mojave Sphinx
INRG-200S-8X3125C-8X250C	2	Interface Ring, Tank, Mojave Sphinx
CMBR-200DI-250B-525L	1	Combustion Chamber, Mojave Sphinx
NZZL-45C20D-200E	1	Nozzle, for Throat Insert, Mojave Sphinx
THRT-45C20D-100T	1	Throat Insert, Spring Retained, Mojave Sphinx
INJC-2X8NPT-38NPT-250T20-2XO230-BASIC	1	Injector, Basic Orifice Pattern, Mojave Sphinx
QDC-750X125FLG-281FB-8NPT	1	Quick Disconnect, Female, Mojave Sphinx
QDC-750X125FLG-270MB-0007-8NPT	1	Quick Disconnect, Male, Mojave Sphinx

Table E.1: Mojave Sphinx machined components



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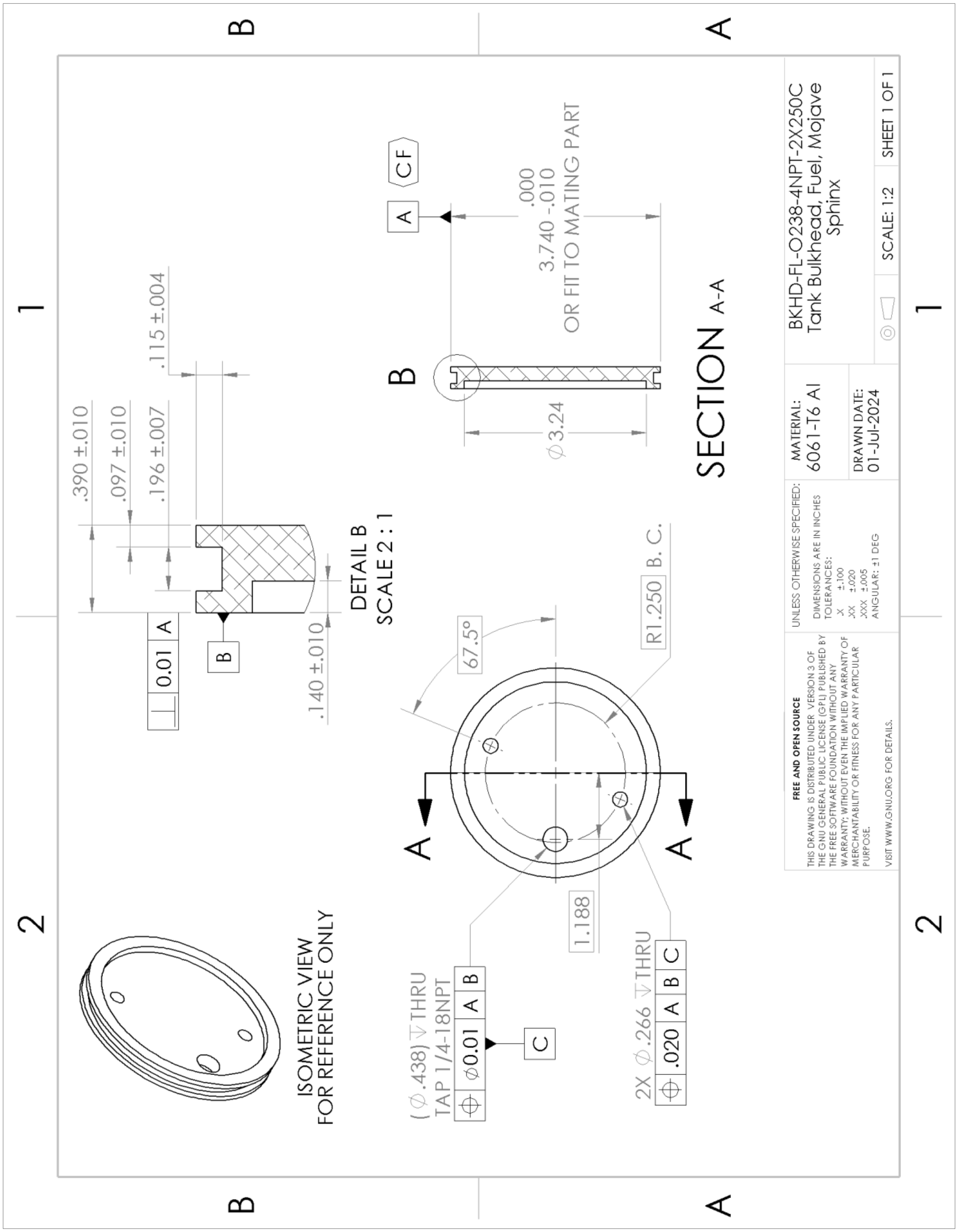
ISOMETRIC VIEW
FOR REFERENCE ONLY
DETAIL B
SCALE 2 : 1
.390 ±.010
.097 ±.010
.196 ±.007
.115 ±.004
.140 ±.010
0.01 A
B
SECTION A-A
Ø3.24
.000
3.740 -.010
OR FIT TO MATING PART
A
CF
67.5°
R1.250 B. C.
1.188
(Ø.438) THRU
TAP 1/4-18NPT
Ø0.01 A B
C
2X Ø.266 THRU
.020 A B C
BKHD-FL-O238-4NPT-2X250C
Tank Bulkhead, Fuel, Mojave Sphinx
MATERIAL:
6061-T6 Al
DRAWN DATE:
01-Jul-2024
SCALE: 1:2
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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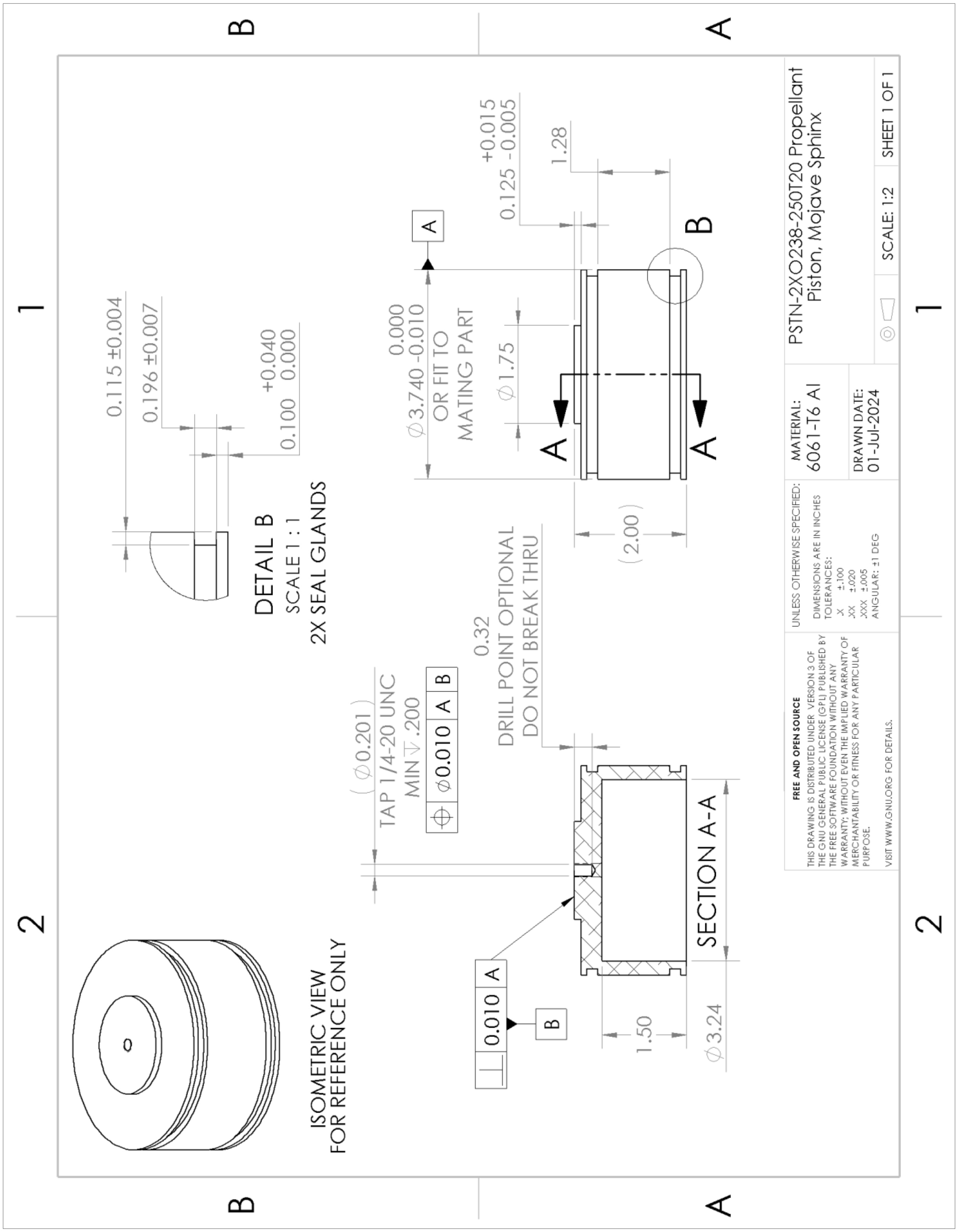
PSTN-2XO238-250T20 Propellant
Piston, Mojave Sphinx
SCALE: 1:2
SHEET 1 OF 1
MATERIAL:
6061-T6 Al
DRAWN DATE:
01-Jul-2024
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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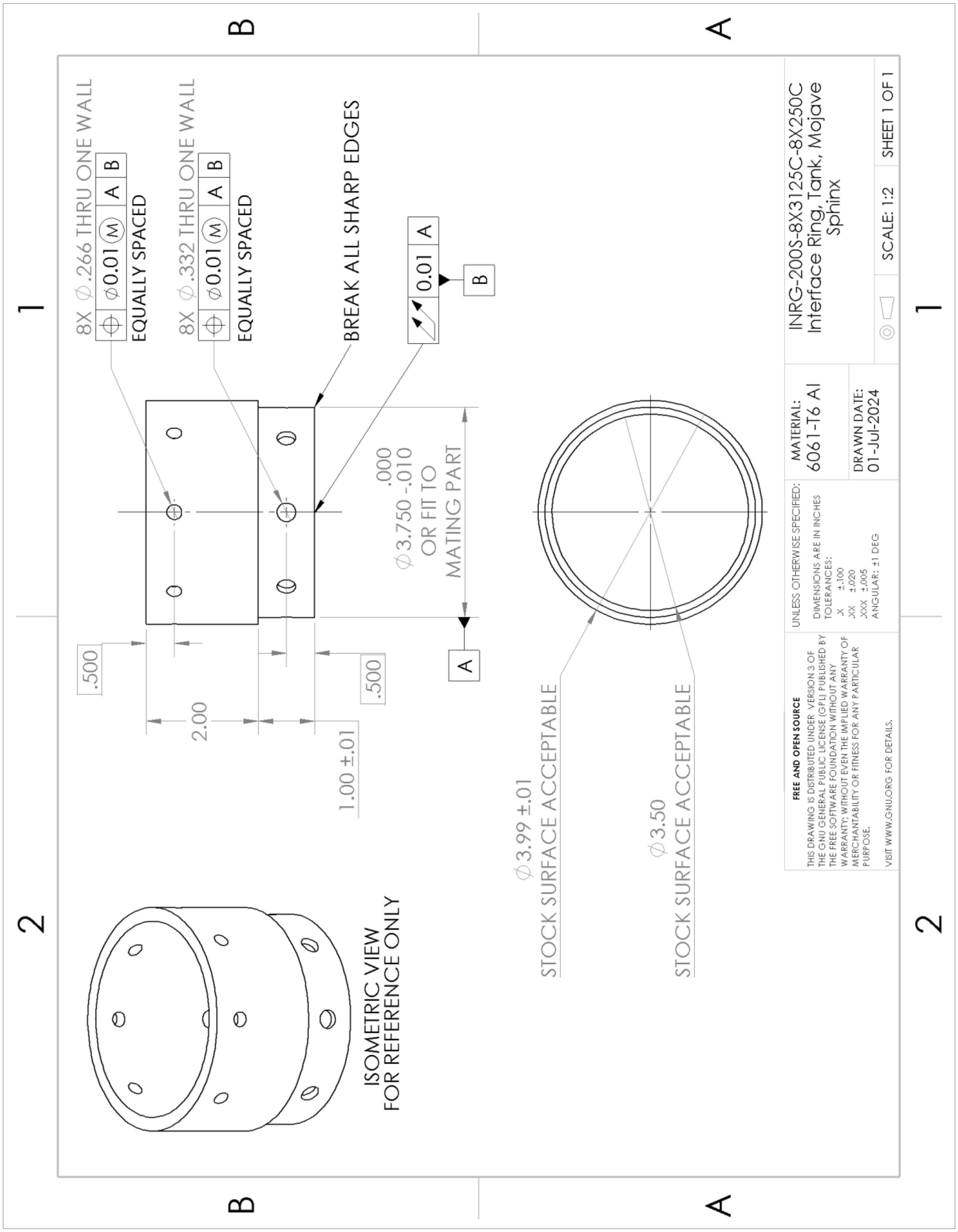
VISIT WWW.GNU.ORG FOR DETAILS.
DETAIL B
SCALE 1 : 1
2X SEAL GLANDS
0.115 ±0.004
0.196 ±0.007
0.100 +0.040 0.000
Ø3.740 0.000 -0.010
OR FIT TO
MATING PART
Ø1.75
0.125 +0.015 -0.005
1.28
(2.00)
SECTION A-A
0.32
DRILL POINT OPTIONAL
DO NOT BREAK THRU
(Ø0.201)
TAP 1/4-20 UNC
MIN .200
Ø0.010 A B
0.010 A
1.50
Ø3.24
ISOMETRIC VIEW
FOR REFERENCE ONLY


8X ⌀.266 THRU ONE WALL
⌀0.01 Ⓜ A B
EQUALLY SPACED
8X ⌀.332 THRU ONE WALL
⌀0.01 Ⓜ A B
EQUALLY SPACED
BREAK ALL SHARP EDGES
0.01 A
B
⌀3.750 .000 -.010
OR FIT TO
MATING PART
A
.500
2.00
1.00 ±.01
.500
⌀3.99 ±.01
STOCK SURFACE ACCEPTABLE
⌀3.50
STOCK SURFACE ACCEPTABLE
ISOMETRIC VIEW
FOR REFERENCE ONLY
INRG-200S-8X3125C-8X250C
Interface Ring, Tank, Mojave Sphinx
MATERIAL:
6061-T6 Al
DRAWN DATE:
01-Jul-2024
SCALE: 1:2
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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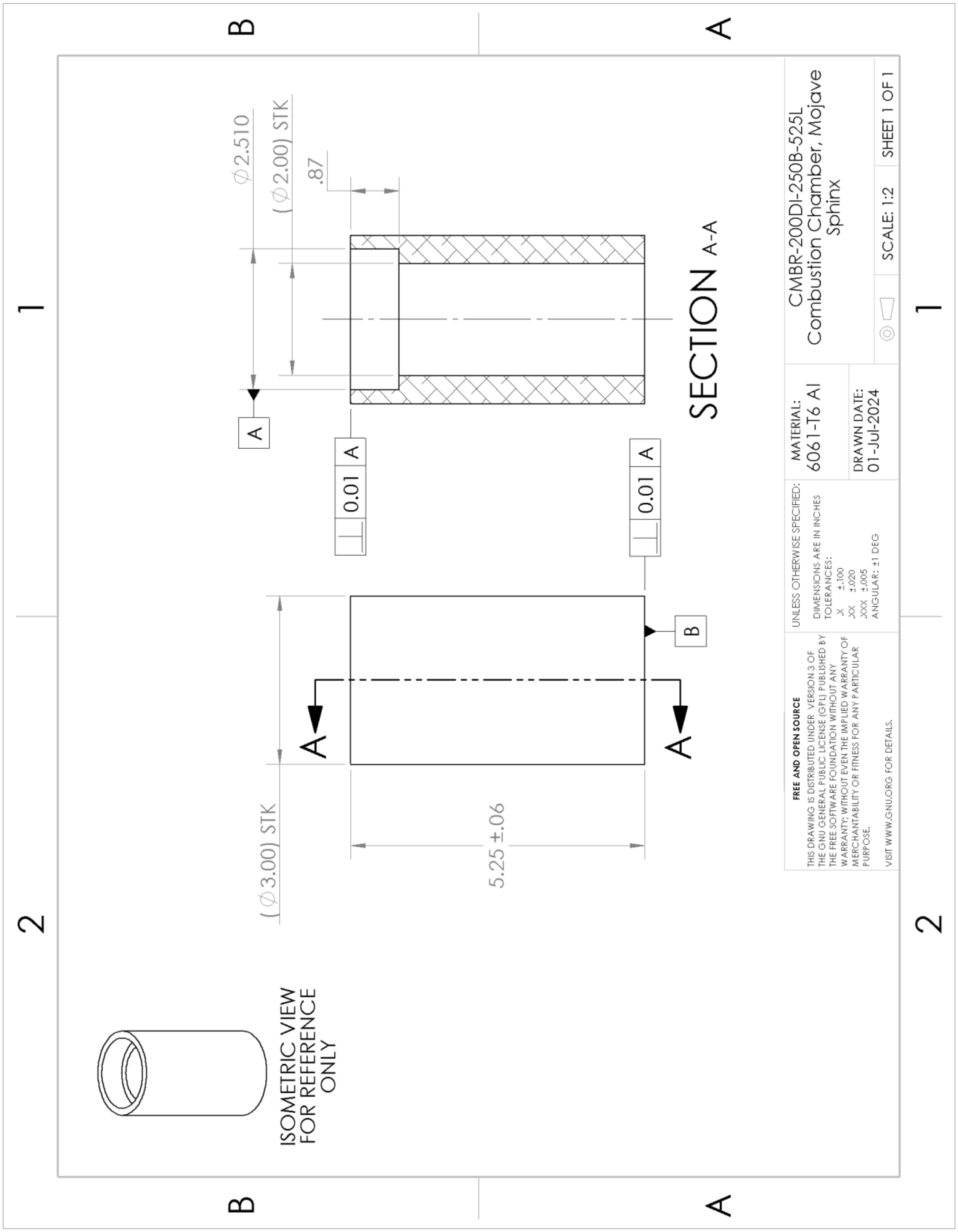

SECTION A-A
⌀2.510
(⌀2.00) STK
.87
(⌀3.00) STK
5.25 ±.06
0.01 A
A
B
ISOMETRIC VIEW FOR REFERENCE ONLY
CMBR-200DI-250B-525L Combustion Chamber, Mojave Sphinx
MATERIAL: 6061-T6 Al
DRAWN DATE: 01-Jul-2024
SCALE: 1:2
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: .X ±.100 .XX ±.020 .XXX ±.005 ANGULAR: ±1 DEG
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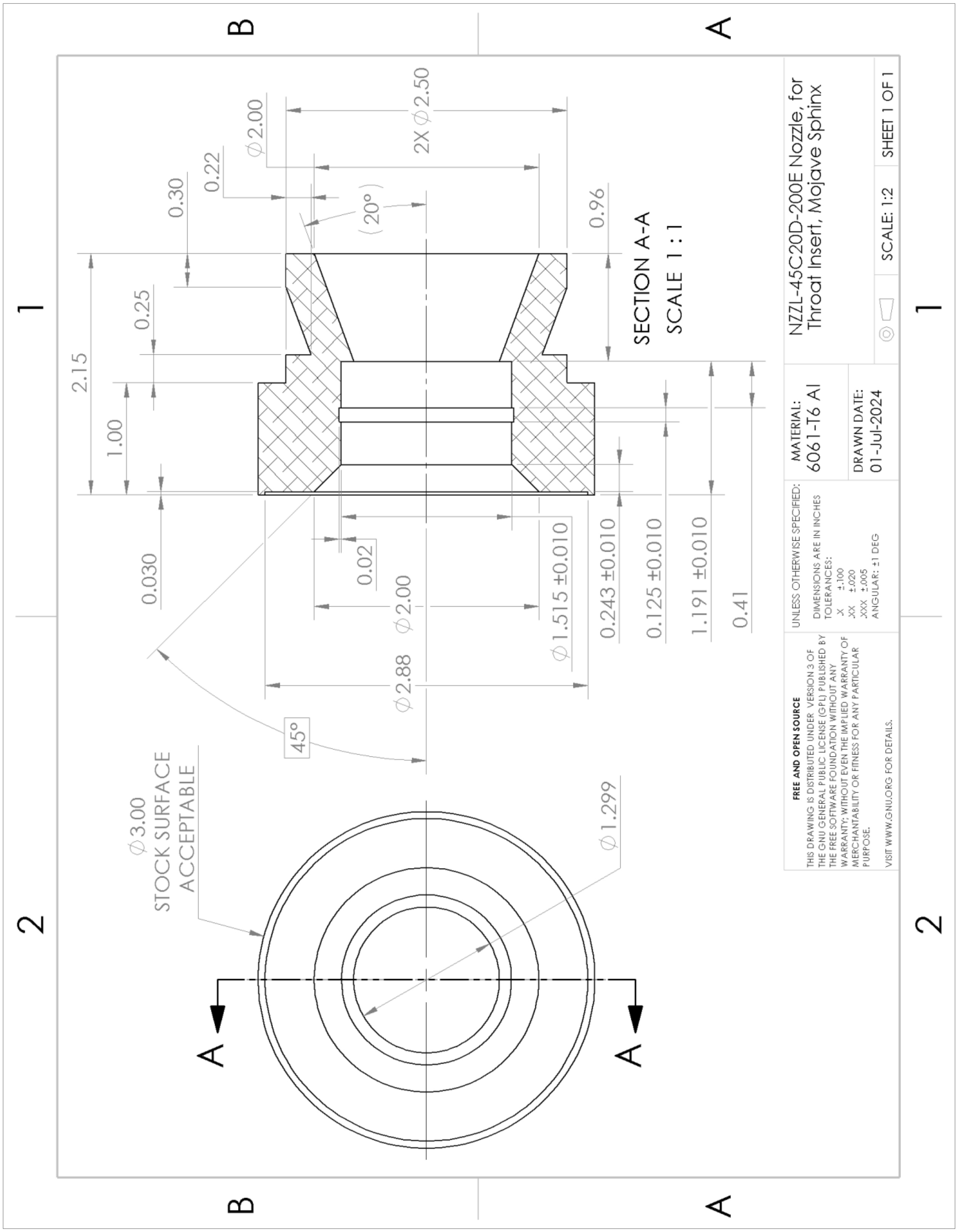

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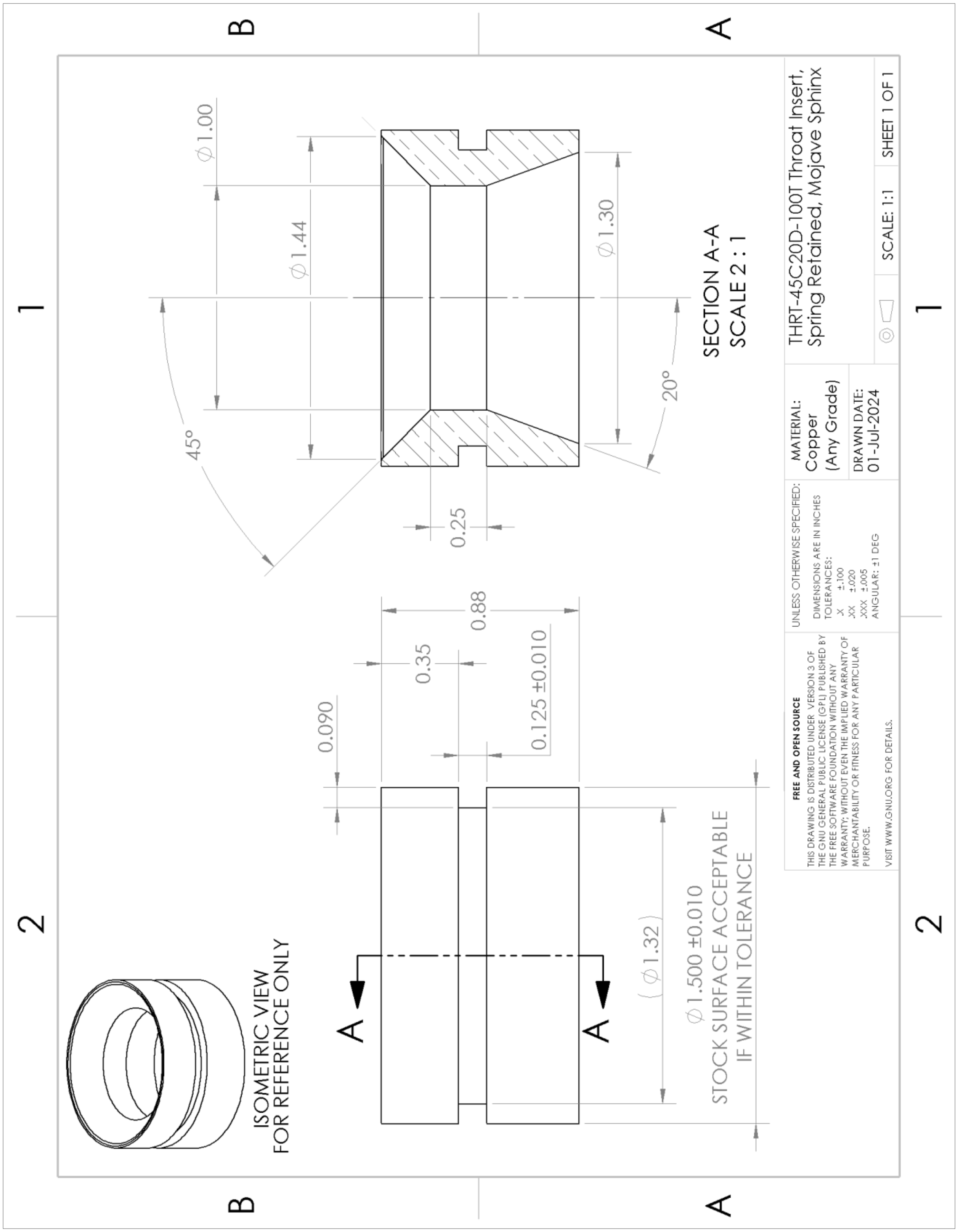
B
A
1
2
ISOMETRIC VIEW
FOR REFERENCE ONLY
SECTION A-A
SCALE 2 : 1
A
A
Ø1.00
Ø1.44
Ø1.30
45°
20°
0.25
0.88
0.35
0.090
0.125 ±0.010
(Ø1.32)
Ø1.500 ±0.010
STOCK SURFACE ACCEPTABLE
IF WITHIN TOLERANCE
THRT-45C20D-100T Throat Insert,
Spring Retained, Mojave Sphinx
MATERIAL:
Copper
(Any Grade)
DRAWN DATE:
01-Jul-2024
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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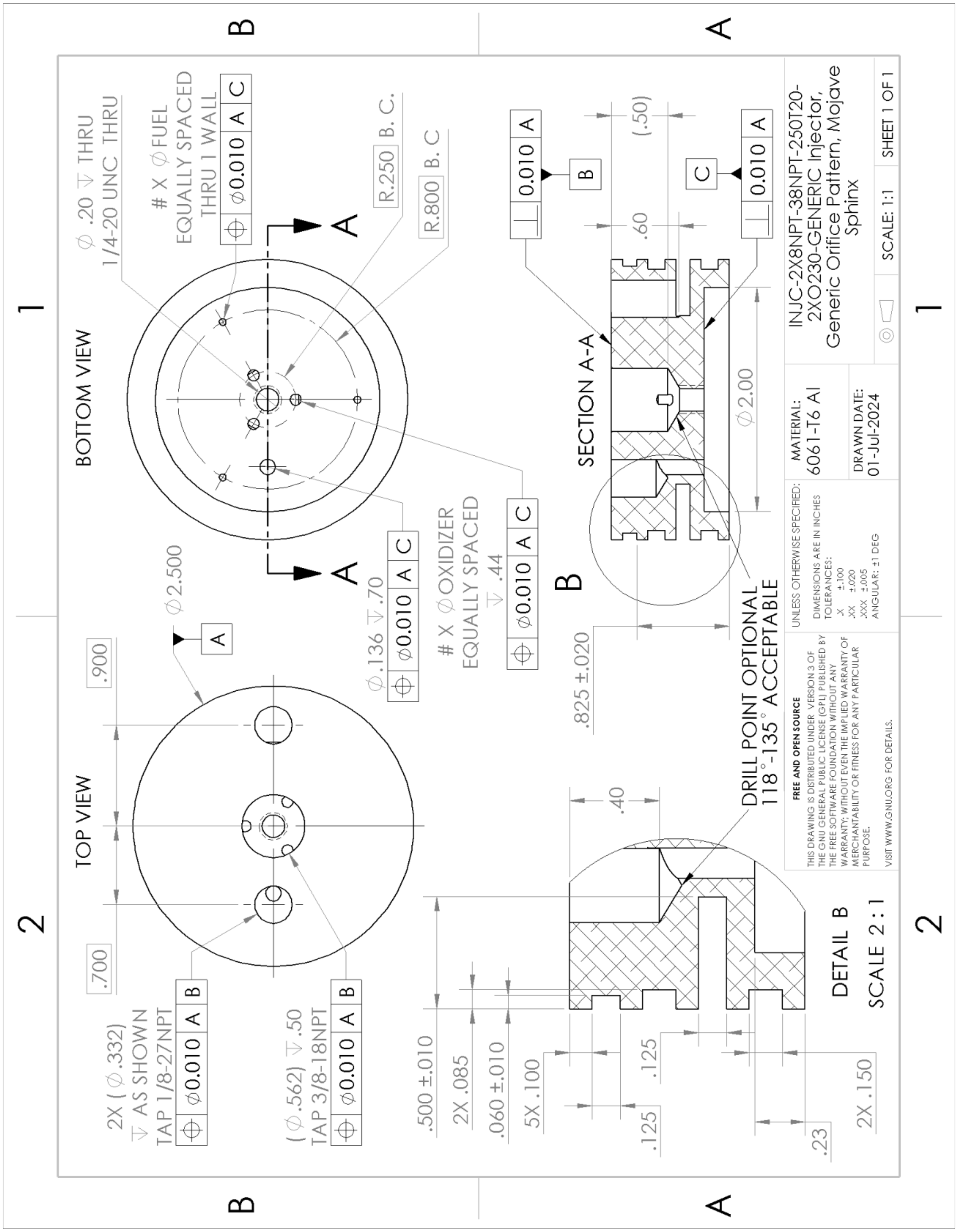
TOP VIEW
BOTTOM VIEW
SECTION A-A
DETAIL B
SCALE 2 : 1
2X (⌀.332)
AS SHOWN
TAP 1/8-27NPT
(⌀.562) ↧.50
TAP 3/8-18NPT
⌀ .20 ↧ THRU
1/4-20 UNC THRU
X ⌀ FUEL
EQUALLY SPACED
THRU 1 WALL
X ⌀ OXIDIZER
EQUALLY SPACED
↧ .44
⌀.136 ↧.70
⌀2.500
R.250 B. C.
R.800 B. C
⌀2.00
.825 ±.020
.500 ±.010
2X .085
.060 ±.010
5X .100
2X .150
DRILL POINT OPTIONAL
118°-135° ACCEPTABLE
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
MATERIAL:
6061-T6 AL
DRAWN DATE:
01-Jul-2024
INJC-2X8NPT-38NPT-250T20-2XO230-GENERIC Injector, Generic Orifice Pattern, Mojave Sphinx
SCALE: 1:1
SHEET 1 OF 1
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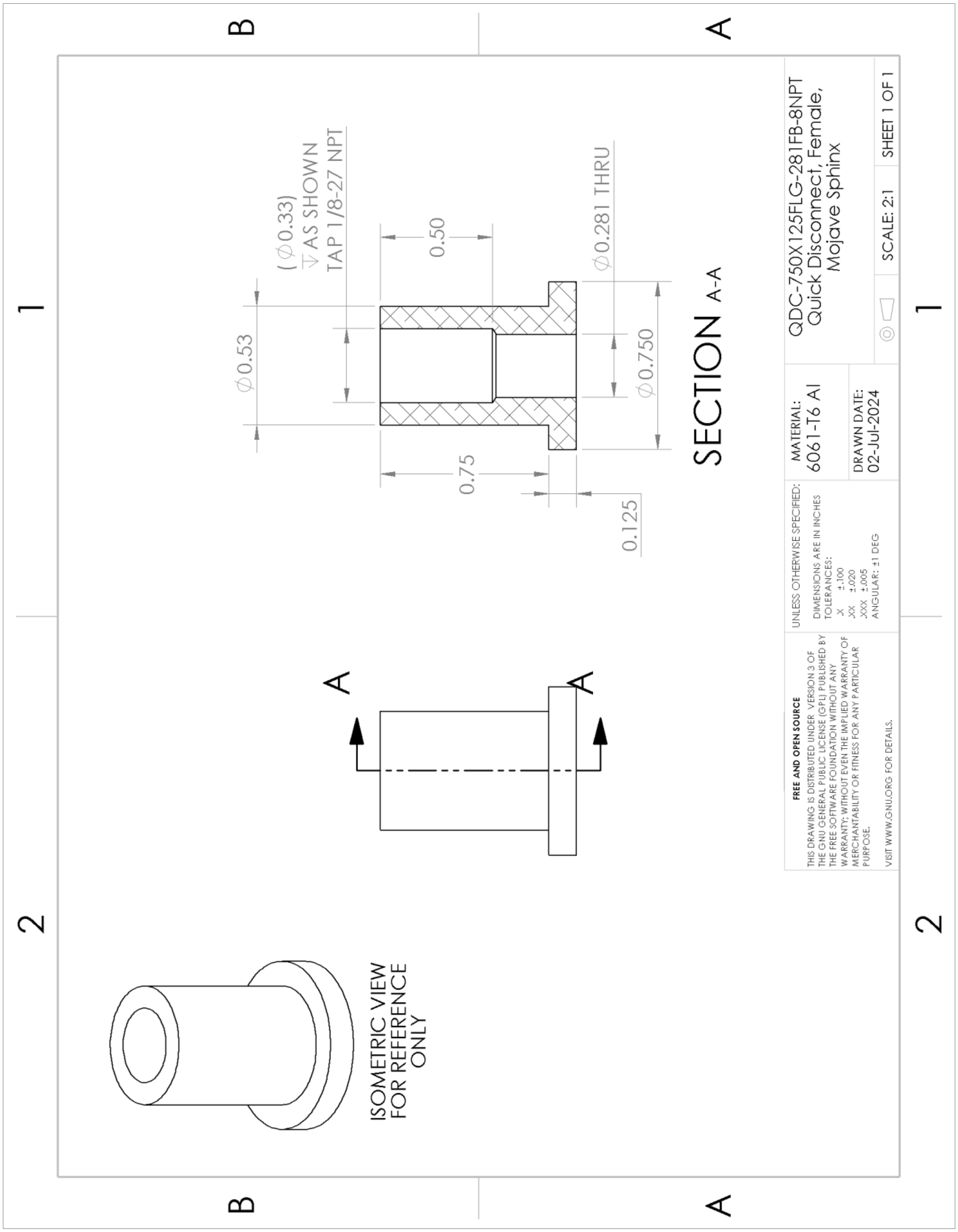

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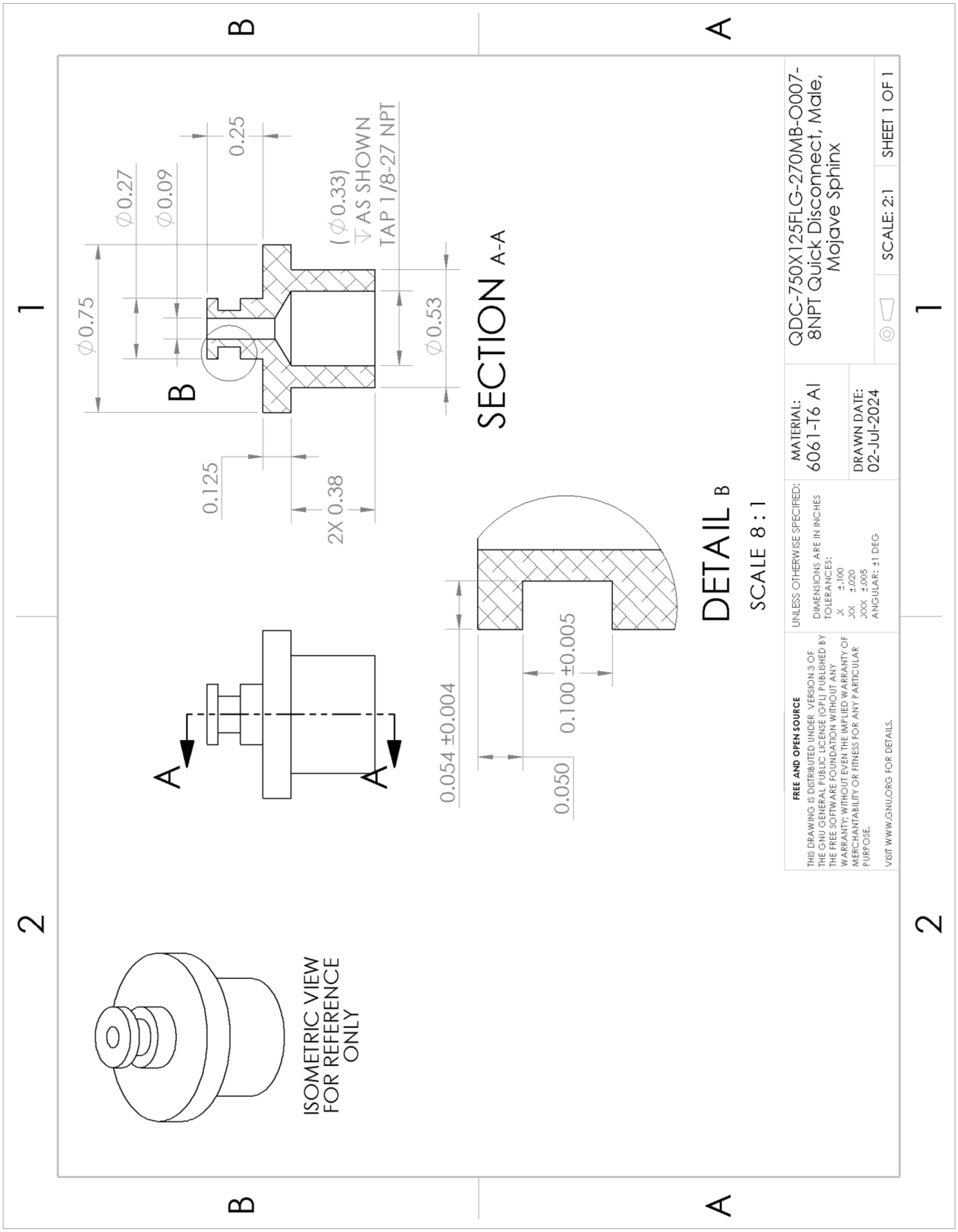
B
A
1
2
Ø0.75
Ø0.27
Ø0.09
0.25
(Ø0.33)
AS SHOWN
TAP 1/8-27 NPT
Ø0.53
B
0.125
2X 0.38
SECTION A-A
DETAIL B
SCALE 8 : 1
0.054 ±0.004
0.100 ±0.005
0.050
A
A
ISOMETRIC VIEW
FOR REFERENCE
ONLY
QDC-750X125FLG-270MB-O007-8NPT Quick Disconnect, Male, Mojave Sphinx
MATERIAL:
6061-T6 Al
DRAWN DATE:
02-Jul-2024
SCALE: 2:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.X ±.100
.XX ±.020
.XXX ±.005
ANGULAR: ±1 DEG
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Appendix F: Bill of Materials by Vendor

The tables in this section contain the same items as those in Sections 4 and 6.2 but rearranged into a more convenient format for ordering from each vendor, intended to be useful for ordering the entire rocket or GSE as a set. If ordering multiple rockets' worth of parts at one time, note that some items (fasteners, O-rings, etc.) come in multi-packs – review the material tables at the beginning of each operation in Sections 5 and 6.3 to determine if large packs can be re-used for multiple builds to save money.

For each vendor, the links are sorted in alphanumeric order. Additionally, GSE and consumable materials are listed in separate tables than the vehicle; if ordering vehicle/GSE/consumables together, ensure that any common items are properly accounted for. If items are out of stock, or a substitute is desired, see Sections 4 and 6.2 for possible alternate sources. Direct Amazon links are provided in these tables, but note that these may stop working in the future; refer to the part descriptions in Sections 4 and 6.2 to locate other sources.

Machined and laser-cut parts are not included; the drawings for these can be found in the preceding appendices. It is recommended that laser-cut parts be ordered through SendCutSend, and machined parts manufactured in-house. If outsourcing machined parts, there are a number of online services available in addition to any local shops willing to do small batches.

McMaster-Carr (Vehicle)

Line	QTY	Link
1	1	https://www.mcmaster.com/1125T412/
2	2	https://www.mcmaster.com/1610T37-1610T134/
3	1	https://www.mcmaster.com/1610T37-1610T33/
4	1	https://www.mcmaster.com/20545T38/
5	1	https://www.mcmaster.com/2155K18/
6	3	https://www.mcmaster.com/3043T643/
7	1	https://www.mcmaster.com/3018T23/
8	2	https://www.mcmaster.com/4112T22/
9	1	https://www.mcmaster.com/4429K421/
10	2	https://www.mcmaster.com/44665K137/
11	1	https://www.mcmaster.com/4468K812-4468K031/
12	1	https://www.mcmaster.com/4468K812-4468K858/
13	1	https://www.mcmaster.com/4468K813-4468K865/
14	1	https://www.mcmaster.com/50675K135/
15	1	https://www.mcmaster.com/50675K163/
16	1	https://www.mcmaster.com/50675K164/
17	2	https://www.mcmaster.com/50675K435/
18	1	https://www.mcmaster.com/50785K164/
19	1	https://www.mcmaster.com/50785K171/
20	1	https://www.mcmaster.com/50785K25/
21	1	https://www.mcmaster.com/50785K27/
22	1	https://www.mcmaster.com/50785K35/
23	1	https://www.mcmaster.com/50785K41/
24	2	https://www.mcmaster.com/50785K43/
25	1	https://www.mcmaster.com/50785K91/
26	1	https://www.mcmaster.com/50785K94/
27	1	https://www.mcmaster.com/5485K21/
28	1	https://www.mcmaster.com/5485K31/
29	2	https://www.mcmaster.com/7392T17-7392T173/
30	1	https://www.mcmaster.com/7631A82/
31	2	https://www.mcmaster.com/7712K511/
32	1	https://www.mcmaster.com/7768K21/
33	1	https://www.mcmaster.com/8284N57/
34	4	https://www.mcmaster.com/8947T26/
35	1	https://www.mcmaster.com/8974K11-8974K299/
36	4	https://www.mcmaster.com/8982K4-8982K402/
37	1	https://www.mcmaster.com/90015A410/
38	1	https://www.mcmaster.com/90213A101/
39	2	https://www.mcmaster.com/90264A435/
40	14	https://www.mcmaster.com/90281A102/

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Line	QTY	Link
41	2	https://www.mcmaster.com/90281A102/
42	1	https://www.mcmaster.com/90357A013/
43	1	https://www.mcmaster.com/90480A009/
44	1	https://www.mcmaster.com/9056K42-9056K423/
45	1	https://www.mcmaster.com/90591A141/
46	1	https://www.mcmaster.com/91102A750/
47	1	https://www.mcmaster.com/91255A378/
48	1	https://www.mcmaster.com/91255A839/
49	1	https://www.mcmaster.com/91280A044/
50	1	https://www.mcmaster.com/91306A279/
51	1	https://www.mcmaster.com/91367A952/
52	2	https://www.mcmaster.com/91755A152-91755A200/
53	1	https://www.mcmaster.com/92141A029/
54	2	https://www.mcmaster.com/92148A160/
55	1	https://www.mcmaster.com/92580A328/
56	1	https://www.mcmaster.com/92855A310/
57	1	https://www.mcmaster.com/92994A029/
58	1	https://www.mcmaster.com/93135A013/
59	1	https://www.mcmaster.com/93320A215/
60	4	https://www.mcmaster.com/93475A210/
61	1	https://www.mcmaster.com/93505A211/
62	1	https://www.mcmaster.com/9368T14/
63	2	https://www.mcmaster.com/9396K79/
64	2	https://www.mcmaster.com/9396T31/
65	1	https://www.mcmaster.com/94095K114/
66	1	https://www.mcmaster.com/9452K15/
67	1	https://www.mcmaster.com/9452K226/
68	1	https://www.mcmaster.com/94579A550/
69	1	https://www.mcmaster.com/95229A420/
70	1	https://www.mcmaster.com/95505A601/
71	1	https://www.mcmaster.com/9685T3/
72	1	https://www.mcmaster.com/97654A620/
73	2	https://www.mcmaster.com/98689A113/
74	8	https://www.mcmaster.com/98831A360-98831A028/

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Amazon (Vehicle)

Line	QTY	Link
1	1	https://www.amazon.com/dp/B08739MGPL/
2	1	https://www.amazon.com/dp/B09S35K5H4/
3	1	https://www.amazon.com/dp/B01850OT2G/
4	1	https://www.amazon.com/dp/B08RYV3SBP/
5	1	https://www.amazon.com/dp/B07PHDYZXN/
6	1	https://www.amazon.com/dp/B01AAX64EC/
7	1	https://www.amazon.com/dp/B01HLUZQ3M/

Midwest Steel Supply (Vehicle)

Line	QTY	Specification	Link
1	1	1-1/2" Diameter, 2" Long	https://www.midweststeelsupply.com/store/110copperroundbar
2	1	3" Diameter, 6"Long	https://www.midweststeelsupply.com/store/6061aluminumroundbar
3	1	3" Diameter, 1/2" Wall, 6" Long	https://www.midweststeelsupply.com/store/6061aluminumroundtube

Chris' Rocket Supplies (Vehicle)

Line	QTY	Link
1	50 ft	https://www.csrocketry.com/recovery-supplies/hardware-and-shock-chord/kevlar-and-nylon-shock-chord/5/8-yellow-tubular-nylon.html
2	2	https://www.csrocketry.com/recovery-supplies/skyangle/protectors/16-skyangle-chute-protector.html
3	1	https://www.csrocketry.com/recovery-supplies/top-flight-recovery/standard-parachutes/36in-topflight-chute.html

Eggtimer Rocketry (Vehicle)

Line	QTY	Link
1	2	http://eggtimerrocketry.com/home/altimeters-av-bay/

Miscellaneous (Vehicle)

Line	QTY	Specification	Source
1	1	9-Volt Alkaline Battery (Pack of 2)	Retail Store

McMaster-Carr (GSE)

Line	QTY	Link
1	1	https://www.mcmaster.com/3846K8-3846K93/
2	1	https://www.mcmaster.com/4112T22/
3	1	https://www.mcmaster.com/4468K811-4468K041/
4	2	https://www.mcmaster.com/50675K162/
5	1	https://www.mcmaster.com/50785K222/
6	1	https://www.mcmaster.com/50785K272/
7	1	https://www.mcmaster.com/50785K273/
8	1	https://www.mcmaster.com/50785K92/
9	1	https://www.mcmaster.com/5485K22/
10	1	https://www.mcmaster.com/7159K3/
11	1	https://www.mcmaster.com/7526K53/
12	1	https://www.mcmaster.com/79215A672/
13	1	https://www.mcmaster.com/79215A673/
14	1	https://www.mcmaster.com/90272A194/
15	1	https://www.mcmaster.com/90480A009/
16	1	https://www.mcmaster.com/92148A160/
17	2	https://www.mcmaster.com/9396T31/
18	1	https://www.mcmaster.com/9396T32/
19	2	https://www.mcmaster.com/9489T519/
20	1	https://www.mcmaster.com/9685T3/
21	1	https://www.mcmaster.com/97149A370/
22	1	https://www.mcmaster.com/98689A113/

Amazon (GSE)

Line	QTY	Link
1	1	https://www.amazon.com/dp/B07L2S38JT/
2	1	https://www.amazon.com/dp/B08Q3K92ZY/
3	1	https://www.amazon.com/dp/B07P663XJV/
4	1	https://www.amazon.com/dp/B01850OT2G/
5	1	https://www.amazon.com/dp/B00004WLKB/
6	1	https://www.amazon.com/dp/B09NR2NCPP/
7	1	https://www.amazon.com/dp/B07Z9YNP7S/
8	1	https://www.amazon.com/dp/B01HLUZQ3M/
9	1	https://www.amazon.com/dp/B01HLUZQ3M/

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Harbor Freight (GSE)

Line	QTY	Link
1	1	https://www.harborfreight.com/12v-160-cca-agm-battery-62586.html
2	1	https://www.harborfreight.com/steel-toolbox-91111.html

Gas Cylinder Source (GSE)

Line	QTY	Link
1	1	https://gascylindersource.com/shop/nitrous-oxide-cylinders/20-lb-aluminum-n2o-cylinder-with-handle/

Consumables

Line	QTY	Specification	Link/Source
1	1	Nitrile Gloves	https://www.mcmaster.com/52555T64/ or Retail Store
2	1	Vinyl Electrical Tape	https://www.mcmaster.com/7619A11/ or Retail Store
3	1		https://www.csrocketry.com/recovery-supplies/ejection-supplies/black-powder.html
4	1		https://www.csrocketry.com/recovery-supplies/ejection-supplies/firewire-electric-match.html
5	20 lb	Nitrous Oxide	Racing Shop
6	2 gal	E85	Gas Station
7	1	Estes A3-4T (4-pack)	Retail Hobby Store

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Appendix G: NPT Dimensions and Engagement Chart

National Standard Taper Pipe Thread (NPT) Thread Size Chart (Inches)

Nominal Pipe Size	Outside Diameter	Thread Density (TPI)	Thread Pitch	Hand Tight Engagement			Effective Thread	
				Length	Turns	Diameter	Length	Diameter
1/16	0.3125	27	0.03703704	0.16	4.32	0.28118	0.2611	0.2875
1/8	0.405	27	0.03703704	0.1615	4.36	0.3736	0.2639	0.38
1/4	0.54	18	0.05555555	0.2278	4.1	0.49163	0.4018	0.5025
3/8	0.675	18	0.05555555	0.24	4.32	0.62701	0.4078	0.6375
1/2	0.84	14	0.07142857	0.32	4.48	0.77843	0.5337	0.79178
3/4	1.05	14	0.07142857	0.339	4.75	0.98887	0.5457	1.00178
1	1.315	11+½	0.08695652	0.4	4.6	1.23863	0.6828	1.25631
1 1/4	1.66	11+½	0.08695652	0.42	4.83	1.58338	0.7068	1.60131
1 1/2	1.9	11+½	0.08695652	0.42	4.83	1.82234	0.7235	1.84131
2	2.375	11+½	0.08695652	0.436	5.01	2.29627	0.7565	2.3163
2 1/2	2.875	8	0.125	0.682	5.46	2.76216	1.1375	2.79063
3	3.5	8	0.125	0.766	6.13	3.3885	1.2	3.41563
3 1/2	4	8	0.125	0.821	6.57	3.88881	1.25	3.91563
4	4.5	8	0.125	0.844	6.75	4.38713	1.3	4.41563
5	5.563	8	0.125	0.937	7.5	5.44929	1.4063	5.47863
6	6.625	8	0.125	0.958	7.66	6.50597	1.5125	6.54063
8	8.625	8	0.125	1.063	8.5	8.50003	1.7125	8.54063
10	10.75	8	0.125	1.21	9.68	10.62094	1.925	10.66563
12	12.75	8	0.125	1.36	10.88	12.61781	2.125	12.66563
14	14	8	0.125	1.562	12.5	13.87263	2.25	13.91563
16	16	8	0.125	1.812	14.5	15.87575	2.45	15.91563
18	18	8	0.125	2	16	17.875	2.65	17.91563
20	20	8	0.125	2.125	17	19.87031	2.85	19.91563
24	24	8	0.125	2.375	19	23.86094	3.25	23.91563

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Appendix H: Marco Rubber Static O-Ring Gland Chart

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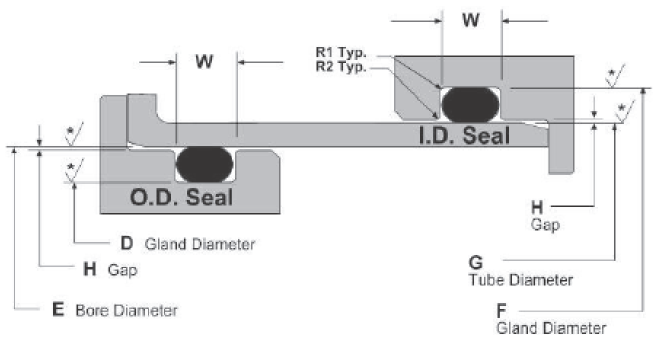
STATIC ROD AND PISTON GLAND INFORMATION

These types of glands are used in most common static radial applications



* Recommended surface finish: Ra 16 max. for gases and Ra 32 max. for fluids

STATIC O-RING GLAND WIDTH AND DEPTH AND DIAMETER DEFAULT RECOMMENDATIONS

AS 568A SERIES	O-RING CROSS-SECTION		GLAND WIDTH (W)		GAP (H)	GLAND CORNER RADII	
	NOM	TOL +/-	NOM	TOL +/-	MAX	(R1)	(R2)
-0XX	0.070	0.003	0.095	0.002	0.002	0.007	0.005
-1XX	0.103	0.004	0.142	0.003	0.002	0.007	0.005
-2XX	0.139	0.004	0.189	0.003	0.002	0.017	0.005
-3XX	0.210	0.005	0.283	0.003	0.003	0.027	0.005
-4XX	0.275	0.006	0.377	0.003	0.003	0.027	0.005

DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-005	0.070	0.003	0.101	0.005	0.137	0.000	0.002	0.237	0.212	0.000	0.002	0.112
-006	0.070	0.003	0.114	0.005	0.150	0.000	0.002	0.250	0.225	0.000	0.002	0.125
-007	0.070	0.003	0.145	0.005	0.181	0.000	0.002	0.281	0.256	0.000	0.002	0.156
-008	0.070	0.003	0.176	0.005	0.212	0.000	0.002	0.312	0.287	0.000	0.002	0.187
-009	0.070	0.003	0.208	0.005	0.243	0.000	0.002	0.343	0.318	0.000	0.002	0.218
-010	0.070	0.003	0.239	0.005	0.275	0.000	0.002	0.375	0.350	0.000	0.002	0.250
-011	0.070	0.003	0.301	0.005	0.337	0.000	0.002	0.437	0.412	0.000	0.002	0.312

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DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-012	0.070	0.003	0.364	0.005	0.400	0.000	0.002	0.500	0.475	0.000	0.002	0.375
-013	0.070	0.003	0.426	0.005	0.462	0.000	0.002	0.562	0.537	0.000	0.002	0.437
-014	0.070	0.003	0.489	0.005	0.525	0.000	0.002	0.625	0.600	0.000	0.002	0.500
-015	0.070	0.003	0.551	0.007	0.587	0.000	0.002	0.687	0.662	0.000	0.002	0.562
-016	0.070	0.003	0.614	0.009	0.650	0.000	0.002	0.750	0.725	0.000	0.002	0.625
-017	0.070	0.003	0.676	0.009	0.712	0.000	0.002	0.812	0.787	0.000	0.002	0.687
-018	0.070	0.003	0.739	0.009	0.775	0.000	0.002	0.875	0.850	0.000	0.002	0.750
-019	0.070	0.003	0.801	0.009	0.837	0.000	0.002	0.937	0.912	0.000	0.002	0.812
-020	0.070	0.003	0.864	0.009	0.900	0.000	0.002	1.000	0.975	0.000	0.002	0.875
-021	0.070	0.003	0.926	0.009	0.962	0.000	0.002	1.062	1.037	0.000	0.002	0.937
-022	0.070	0.003	0.989	0.010	1.025	0.000	0.002	1.125	1.100	0.000	0.002	1.000
-023	0.070	0.003	1.051	0.010	1.087	0.000	0.002	1.187	1.162	0.000	0.002	1.062
-024	0.070	0.003	1.114	0.010	1.150	0.000	0.002	1.250	1.225	0.000	0.002	1.125
-025	0.070	0.003	1.176	0.011	1.212	0.000	0.002	1.312	1.287	0.000	0.002	1.187
-026	0.070	0.003	1.239	0.011	1.275	0.000	0.002	1.375	1.350	0.000	0.002	1.250
-027	0.070	0.003	1.301	0.011	1.337	0.000	0.002	1.437	1.412	0.000	0.002	1.312
-028	0.070	0.003	1.364	0.013	1.400	0.000	0.002	1.500	1.475	0.000	0.002	1.375
-029	0.070	0.003	1.489	0.013	1.525	0.000	0.002	1.625	1.600	0.000	0.002	1.500
-030	0.070	0.003	1.614	0.013	1.650	0.000	0.002	1.750	1.725	0.000	0.002	1.625
-031	0.070	0.003	1.739	0.015	1.775	0.000	0.002	1.875	1.850	0.000	0.002	1.750
-032	0.070	0.003	1.864	0.015	1.900	0.000	0.002	2.000	1.975	0.000	0.002	1.875
-033	0.070	0.003	1.989	0.018	2.025	0.000	0.002	2.125	2.100	0.000	0.002	2.000
-034	0.070	0.003	2.114	0.018	2.150	0.000	0.002	2.250	2.225	0.000	0.002	2.125
-035	0.070	0.003	2.239	0.018	2.275	0.000	0.002	2.375	2.350	0.000	0.002	2.250
-036	0.070	0.003	2.364	0.018	2.400	0.000	0.002	2.500	2.475	0.000	0.002	2.375
-037	0.070	0.003	2.489	0.018	2.525	0.000	0.002	2.625	2.600	0.000	0.002	2.500
-038	0.070	0.003	2.614	0.020	2.650	0.000	0.002	2.750	2.725	0.000	0.002	2.625
-039	0.070	0.003	2.739	0.020	2.775	0.000	0.002	2.875	2.850	0.000	0.002	2.750
-040	0.070	0.003	2.864	0.020	2.900	0.000	0.002	3.000	2.975	0.000	0.002	2.875
-041	0.070	0.003	2.989	0.024	3.025	0.000	0.002	3.125	3.100	0.000	0.002	3.000
-042	0.070	0.003	3.239	0.024	3.275	0.000	0.002	3.375	3.350	0.000	0.002	3.250
-043	0.070	0.003	3.489	0.024	3.525	0.000	0.002	3.625	3.600	0.000	0.002	3.500
-044	0.070	0.003	3.739	0.027	3.775	0.000	0.002	3.875	3.850	0.000	0.002	3.750
-045	0.070	0.003	3.989	0.027	4.025	0.000	0.002	4.125	4.100	0.000	0.002	4.000

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DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-046	0.070	0.003	4.239	0.030	4.275	0.000	0.002	4.375	4.350	0.000	0.002	4.250
-047	0.070	0.003	4.489	0.030	4.525	0.000	0.002	4.625	4.600	0.000	0.002	4.500
-048	0.070	0.003	4.739	0.030	4.775	0.000	0.002	4.875	4.850	0.000	0.002	4.750
-049	0.070	0.003	4.989	0.037	5.025	0.000	0.002	5.125	5.100	0.000	0.002	5.000
-050	0.070	0.003	5.239	0.037	5.275	0.000	0.002	5.375	5.350	0.000	0.002	5.250
-102	0.103	0.003	0.049	0.005	0.085	0.000	0.002	0.247	0.224	0.000	0.002	0.062
-103	0.103	0.003	0.081	0.005	0.116	0.000	0.002	0.278	0.256	0.000	0.002	0.094
-104	0.103	0.003	0.112	0.005	0.148	0.000	0.002	0.310	0.287	0.000	0.002	0.125
-105	0.103	0.003	0.143	0.005	0.180	0.000	0.002	0.342	0.318	0.000	0.002	0.156
-106	0.103	0.003	0.174	0.005	0.212	0.000	0.002	0.374	0.349	0.000	0.002	0.187
-107	0.103	0.003	0.206	0.005	0.243	0.000	0.002	0.405	0.381	0.000	0.002	0.219
-108	0.103	0.003	0.237	0.005	0.275	0.000	0.002	0.437	0.412	0.000	0.002	0.250
-109	0.103	0.003	0.299	0.005	0.338	0.000	0.002	0.500	0.474	0.000	0.002	0.312
-110	0.103	0.003	0.362	0.005	0.400	0.000	0.002	0.562	0.537	0.000	0.002	0.375
-111	0.103	0.003	0.424	0.005	0.463	0.000	0.002	0.625	0.599	0.000	0.002	0.437
-112	0.103	0.003	0.487	0.005	0.525	0.000	0.002	0.687	0.662	0.000	0.002	0.500
-113	0.103	0.003	0.549	0.007	0.588	0.000	0.002	0.750	0.724	0.000	0.002	0.562
-114	0.103	0.003	0.612	0.009	0.650	0.000	0.002	0.812	0.787	0.000	0.002	0.625
-115	0.103	0.003	0.674	0.009	0.713	0.000	0.002	0.875	0.849	0.000	0.002	0.687
-116	0.103	0.003	0.737	0.009	0.775	0.000	0.002	0.937	0.912	0.000	0.002	0.750
-117	0.103	0.003	0.799	0.010	0.838	0.000	0.002	1.000	0.974	0.000	0.002	0.812
-118	0.103	0.003	0.862	0.010	0.900	0.000	0.002	1.062	1.037	0.000	0.002	0.875
-119	0.103	0.003	0.924	0.010	0.963	0.000	0.002	1.125	1.099	0.000	0.002	0.937
-120	0.103	0.003	0.987	0.010	1.025	0.000	0.002	1.187	1.162	0.000	0.002	1.000
-121	0.103	0.003	1.049	0.010	1.088	0.000	0.002	1.250	1.224	0.000	0.002	1.062
-122	0.103	0.003	1.112	0.010	1.150	0.000	0.002	1.312	1.287	0.000	0.002	1.125
-123	0.103	0.003	1.174	0.012	1.213	0.000	0.002	1.375	1.349	0.000	0.002	1.187
-124	0.103	0.003	1.237	0.012	1.275	0.000	0.002	1.437	1.412	0.000	0.002	1.250
-125	0.103	0.003	1.299	0.012	1.338	0.000	0.002	1.500	1.474	0.000	0.002	1.312
-126	0.103	0.003	1.362	0.012	1.400	0.000	0.002	1.562	1.537	0.000	0.002	1.375
-127	0.103	0.003	1.424	0.012	1.463	0.000	0.002	1.625	1.599	0.000	0.002	1.437
-128	0.103	0.003	1.487	0.012	1.525	0.000	0.002	1.687	1.662	0.000	0.002	1.500
-129	0.103	0.003	1.549	0.015	1.588	0.000	0.002	1.750	1.724	0.000	0.002	1.562
-130	0.103	0.003	1.612	0.015	1.650	0.000	0.002	1.812	1.787	0.000	0.002	1.625

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DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-131	0.103	0.003	1.674	0.015	1.713	0.000	0.002	1.875	1.849	0.000	0.002	1.687
-132	0.103	0.003	1.737	0.015	1.775	0.000	0.002	1.937	1.912	0.000	0.002	1.750
-133	0.103	0.003	1.799	0.015	1.838	0.000	0.002	2.000	1.974	0.000	0.002	1.812
-134	0.103	0.003	1.862	0.015	1.900	0.000	0.002	2.062	2.037	0.000	0.002	1.875
-135	0.103	0.003	1.925	0.017	1.963	0.000	0.002	2.123	2.099	0.000	0.002	1.937
-136	0.103	0.003	1.987	0.017	2.025	0.000	0.002	2.187	2.162	0.000	0.002	2.000
-137	0.103	0.003	2.050	0.017	2.088	0.000	0.002	2.250	2.224	0.000	0.002	2.062
-138	0.103	0.003	2.112	0.017	2.150	0.000	0.002	2.312	2.287	0.000	0.002	2.125
-139	0.103	0.003	2.175	0.017	2.213	0.000	0.002	2.375	2.349	0.000	0.002	2.187
-140	0.103	0.003	2.237	0.017	2.275	0.000	0.002	2.437	2.412	0.000	0.002	2.250
-141	0.103	0.003	2.300	0.020	2.338	0.000	0.002	2.500	2.474	0.000	0.002	2.312
-142	0.103	0.003	2.362	0.020	2.400	0.000	0.002	2.562	2.537	0.000	0.002	2.375
-143	0.103	0.003	2.425	0.020	2.463	0.000	0.002	2.625	2.599	0.000	0.002	2.437
-144	0.103	0.003	2.487	0.020	2.525	0.000	0.002	2.687	2.662	0.000	0.002	2.500
-145	0.103	0.003	2.550	0.020	2.588	0.000	0.002	2.750	2.724	0.000	0.002	2.562
-146	0.103	0.003	2.612	0.020	2.650	0.000	0.002	2.812	2.787	0.000	0.002	2.625
-147	0.103	0.003	2.675	0.022	2.713	0.000	0.002	2.875	2.849	0.000	0.002	2.687
-148	0.103	0.003	2.737	0.022	2.775	0.000	0.002	2.937	2.912	0.000	0.002	2.750
-149	0.103	0.003	2.800	0.022	2.838	0.000	0.002	3.000	2.974	0.000	0.002	2.812
-150	0.103	0.003	2.862	0.022	2.900	0.000	0.002	3.062	3.037	0.000	0.002	2.875
-151	0.103	0.003	2.987	0.024	3.025	0.000	0.002	3.187	3.162	0.000	0.002	3.000
-152	0.103	0.003	3.237	0.024	3.275	0.000	0.002	3.437	3.412	0.000	0.002	3.250
-153	0.103	0.003	3.487	0.024	3.525	0.000	0.002	3.687	3.662	0.000	0.002	3.500
-154	0.103	0.003	3.737	0.028	3.775	0.000	0.002	3.937	3.912	0.000	0.002	3.750
-155	0.103	0.003	3.987	0.028	4.025	0.000	0.002	4.187	4.162	0.000	0.002	4.000
-156	0.103	0.003	4.237	0.030	4.275	0.000	0.002	4.437	4.412	0.000	0.002	4.250
-157	0.103	0.003	4.487	0.030	4.525	0.000	0.002	4.687	4.662	0.000	0.002	4.500
-158	0.103	0.003	4.737	0.030	4.775	0.000	0.002	4.937	4.912	0.000	0.002	4.750
-159	0.103	0.003	4.987	0.035	5.025	0.000	0.002	5.187	5.162	0.000	0.002	5.000
-160	0.103	0.003	5.237	0.035	5.275	0.000	0.002	5.437	5.412	0.000	0.002	5.250
-161	0.103	0.003	5.487	0.035	5.525	0.000	0.002	5.687	5.662	0.000	0.002	5.500
-162	0.103	0.003	5.737	0.035	5.775	0.000	0.002	5.937	5.912	0.000	0.002	5.750
-163	0.103	0.003	5.987	0.035	6.025	0.000	0.002	6.187	6.162	0.000	0.002	6.000
-164	0.103	0.003	6.237	0.040	6.275	0.000	0.002	6.437	6.412	0.000	0.002	6.250

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DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-165	0.103	0.003	6.487	0.040	6.525	0.000	0.002	6.687	6.662	0.000	0.002	6.500
-166	0.103	0.003	6.737	0.040	6.775	0.000	0.002	6.937	6.912	0.000	0.002	6.750
-167	0.103	0.003	6.987	0.040	7.025	0.000	0.002	7.187	7.162	0.000	0.002	7.000
-168	0.103	0.003	7.237	0.045	7.275	0.000	0.002	7.437	7.412	0.000	0.002	7.250
-169	0.103	0.003	7.487	0.045	7.525	0.000	0.002	7.687	7.662	0.000	0.002	7.500
-170	0.103	0.003	7.737	0.045	7.775	0.000	0.002	7.937	7.912	0.000	0.002	7.750
-171	0.103	0.003	7.987	0.045	8.025	0.000	0.002	8.187	8.162	0.000	0.002	8.000
-172	0.103	0.003	8.237	0.050	8.275	0.000	0.002	8.437	8.412	0.000	0.002	8.250
-173	0.103	0.003	8.487	0.050	8.525	0.000	0.002	8.687	8.662	0.000	0.002	8.500
-174	0.103	0.003	8.737	0.050	8.775	0.000	0.002	8.937	8.912	0.000	0.002	8.750
-175	0.103	0.003	8.987	0.050	9.025	0.000	0.002	9.187	9.162	0.000	0.002	9.000
-176	0.103	0.003	9.237	0.055	9.275	0.000	0.002	9.437	9.412	0.000	0.002	9.250
-177	0.103	0.003	9.487	0.055	9.525	0.000	0.002	9.687	9.662	0.000	0.002	9.500
-178	0.103	0.003	9.737	0.055	9.775	0.000	0.002	9.937	9.912	0.000	0.002	9.750
-201	0.139	0.004	0.171	0.005	0.215	0.000	0.002	0.437	0.409	0.000	0.002	0.187
-202	0.139	0.004	0.234	0.005	0.278	0.000	0.002	0.500	0.472	0.000	0.002	0.250
-203	0.139	0.004	0.296	0.005	0.340	0.000	0.002	0.562	0.534	0.000	0.002	0.312
-204	0.139	0.004	0.359	0.005	0.403	0.000	0.002	0.625	0.597	0.000	0.002	0.375
-205	0.139	0.004	0.421	0.005	0.465	0.000	0.002	0.687	0.659	0.000	0.002	0.437
-206	0.139	0.004	0.484	0.005	0.528	0.000	0.002	0.750	0.722	0.000	0.002	0.500
-207	0.139	0.004	0.546	0.007	0.590	0.000	0.002	0.812	0.784	0.000	0.002	0.562
-208	0.139	0.004	0.609	0.009	0.653	0.000	0.002	0.875	0.847	0.000	0.002	0.625
-209	0.139	0.004	0.671	0.009	0.715	0.000	0.002	0.937	0.909	0.000	0.002	0.687
-210	0.139	0.004	0.734	0.010	0.778	0.000	0.002	1.000	0.972	0.000	0.002	0.750
-211	0.139	0.004	0.796	0.010	0.840	0.000	0.002	1.062	1.034	0.000	0.002	0.812
-212	0.139	0.004	0.859	0.010	0.903	0.000	0.002	1.125	1.097	0.000	0.002	0.875
-213	0.139	0.004	0.921	0.010	0.965	0.000	0.002	1.187	1.159	0.000	0.002	0.937
-214	0.139	0.004	0.984	0.010	1.028	0.000	0.002	1.250	1.222	0.000	0.002	1.000
-215	0.139	0.004	1.046	0.010	1.090	0.000	0.002	1.312	1.284	0.000	0.002	1.062
-216	0.139	0.004	1.109	0.012	1.153	0.000	0.002	1.375	1.347	0.000	0.002	1.125
-217	0.139	0.004	1.171	0.012	1.215	0.000	0.002	1.437	1.409	0.000	0.002	1.187
-218	0.139	0.004	1.234	0.012	1.278	0.000	0.002	1.500	1.472	0.000	0.002	1.250
-219	0.139	0.004	1.296	0.012	1.340	0.000	0.002	1.562	1.534	0.000	0.002	1.312
-220	0.139	0.004	1.359	0.012	1.403	0.000	0.002	1.625	1.597	0.000	0.002	1.375

DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-221	0.139	0.004	1.421	0.012	1.465	0.000	0.002	1.687	1.659	0.000	0.002	1.437
-222	0.139	0.004	1.484	0.015	1.528	0.000	0.002	1.750	1.722	0.000	0.002	1.500
-223	0.139	0.004	1.609	0.015	1.653	0.000	0.002	1.875	1.847	0.000	0.002	1.625
-224	0.139	0.004	1.734	0.015	1.778	0.000	0.002	2.000	1.972	0.000	0.002	1.750
-225	0.139	0.004	1.859	0.015	1.903	0.000	0.002	2.125	2.097	0.000	0.002	1.875
-226	0.139	0.004	1.984	0.018	2.028	0.000	0.002	2.250	2.222	0.000	0.002	2.000
-227	0.139	0.004	2.109	0.018	2.153	0.000	0.002	2.375	2.347	0.000	0.002	2.125
-228	0.139	0.004	2.234	0.020	2.278	0.000	0.002	2.500	2.472	0.000	0.002	2.250
-229	0.139	0.004	2.359	0.020	2.403	0.000	0.002	2.625	2.597	0.000	0.002	2.375
-230	0.139	0.004	2.484	0.020	2.528	0.000	0.002	2.750	2.722	0.000	0.002	2.500
-231	0.139	0.004	2.609	0.020	2.653	0.000	0.002	2.875	2.847	0.000	0.002	2.625
-232	0.139	0.004	2.734	0.024	2.778	0.000	0.002	3.000	2.972	0.000	0.002	2.750
-233	0.139	0.004	2.859	0.024	2.903	0.000	0.002	3.125	3.097	0.000	0.002	2.875
-234	0.139	0.004	2.984	0.024	3.028	0.000	0.002	3.250	3.222	0.000	0.002	3.000
-235	0.139	0.004	3.109	0.024	3.153	0.000	0.002	3.375	3.347	0.000	0.002	3.125
-236	0.139	0.004	3.234	0.024	3.278	0.000	0.002	3.500	3.472	0.000	0.002	3.250
-237	0.139	0.004	3.359	0.024	3.403	0.000	0.002	3.625	3.597	0.000	0.002	3.375
-238	0.139	0.004	3.484	0.024	3.528	0.000	0.002	3.750	3.722	0.000	0.002	3.500
-239	0.139	0.004	3.609	0.028	3.653	0.000	0.002	3.875	3.847	0.000	0.002	3.625
-240	0.139	0.004	3.734	0.028	3.778	0.000	0.002	4.000	3.972	0.000	0.002	3.750
-241	0.139	0.004	3.859	0.028	3.903	0.000	0.002	4.125	4.097	0.000	0.002	3.875
-242	0.139	0.004	3.984	0.028	4.028	0.000	0.002	4.250	4.222	0.000	0.002	4.000
-243	0.139	0.004	4.109	0.028	4.153	0.000	0.002	4.375	4.347	0.000	0.002	4.125
-244	0.139	0.004	4.234	0.030	4.278	0.000	0.002	4.500	4.472	0.000	0.002	4.250
-245	0.139	0.004	4.359	0.030	4.403	0.000	0.002	4.625	4.597	0.000	0.002	4.375
-246	0.139	0.004	4.484	0.030	4.528	0.000	0.002	4.750	4.722	0.000	0.002	4.500
-247	0.139	0.004	4.609	0.030	4.653	0.000	0.002	4.875	4.847	0.000	0.002	4.625
-248	0.139	0.004	4.734	0.030	4.778	0.000	0.002	5.000	4.972	0.000	0.002	4.750
-249	0.139	0.004	4.859	0.035	4.903	0.000	0.002	5.125	5.097	0.000	0.002	4.875
-250	0.139	0.004	4.984	0.035	5.028	0.000	0.002	5.250	5.222	0.000	0.002	5.000
-251	0.139	0.004	5.109	0.035	5.153	0.000	0.002	5.375	5.347	0.000	0.002	5.125
-252	0.139	0.004	5.234	0.035	5.278	0.000	0.002	5.500	5.472	0.000	0.002	5.250
-253	0.139	0.004	5.359	0.035	5.403	0.000	0.002	5.625	5.597	0.000	0.002	5.375
-254	0.139	0.004	5.484	0.035	5.528	0.000	0.002	5.750	5.722	0.000	0.002	5.500

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DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-255	0.139	0.004	5.609	0.035	5.653	0.000	0.002	5.875	5.847	0.000	0.002	5.625
-256	0.139	0.004	5.734	0.035	5.778	0.000	0.002	6.000	5.972	0.000	0.002	5.750
-257	0.139	0.004	5.859	0.035	5.903	0.000	0.002	6.125	6.097	0.000	0.002	5.875
-258	0.139	0.004	5.984	0.035	6.028	0.000	0.002	6.250	6.222	0.000	0.002	6.000
-259	0.139	0.004	6.234	0.040	6.278	0.000	0.002	6.500	6.472	0.000	0.002	6.250
-260	0.139	0.004	6.484	0.040	6.528	0.000	0.002	6.750	6.722	0.000	0.002	6.500
-261	0.139	0.004	6.734	0.040	6.778	0.000	0.002	7.000	6.972	0.000	0.002	6.750
-262	0.139	0.004	6.984	0.040	7.028	0.000	0.002	7.250	7.222	0.000	0.002	7.000
-263	0.139	0.004	7.234	0.045	7.278	0.000	0.002	7.500	7.472	0.000	0.002	7.250
-264	0.139	0.004	7.484	0.045	7.528	0.000	0.002	7.750	7.722	0.000	0.002	7.500
-265	0.139	0.004	7.734	0.045	7.778	0.000	0.002	8.000	7.972	0.000	0.002	7.750
-266	0.139	0.004	7.984	0.045	8.028	0.000	0.002	8.250	8.222	0.000	0.002	8.000
-267	0.139	0.004	8.234	0.050	8.278	0.000	0.002	8.500	8.472	0.000	0.002	8.250
-268	0.139	0.004	8.484	0.050	8.528	0.000	0.002	8.750	8.722	0.000	0.002	8.500
-269	0.139	0.004	8.734	0.050	8.778	0.000	0.002	9.000	8.972	0.000	0.002	8.750
-270	0.139	0.004	8.984	0.050	9.028	0.000	0.002	9.250	9.222	0.000	0.002	9.000
-271	0.139	0.004	9.234	0.055	9.278	0.000	0.002	9.500	9.472	0.000	0.002	9.250
-272	0.139	0.004	9.484	0.055	9.528	0.000	0.002	9.750	9.722	0.000	0.002	9.500
-273	0.139	0.004	9.734	0.055	9.778	0.000	0.002	10.000	9.972	0.000	0.002	9.750
-274	0.139	0.004	9.984	0.055	10.028	0.000	0.002	10.250	10.222	0.000	0.002	10.000
-275	0.139	0.004	10.484	0.055	10.528	0.000	0.002	10.750	10.722	0.000	0.002	10.500
-276	0.139	0.004	10.984	0.065	11.028	0.000	0.002	11.250	11.222	0.000	0.002	11.000
-277	0.139	0.004	11.484	0.065	11.528	0.000	0.002	11.750	11.722	0.000	0.002	11.500
-278	0.139	0.004	11.984	0.065	12.028	0.000	0.002	12.250	12.222	0.000	0.002	12.000
-279	0.139	0.004	12.984	0.065	13.028	0.000	0.002	13.250	13.222	0.000	0.002	13.000
-280	0.139	0.004	13.984	0.065	14.028	0.000	0.002	14.250	14.222	0.000	0.002	14.000
-281	0.139	0.004	14.984	0.065	15.028	0.000	0.002	15.250	15.222	0.000	0.002	15.000
-282	0.139	0.004	15.955	0.075	16.028	0.000	0.002	16.250	16.222	0.000	0.002	16.000
-283	0.139	0.004	16.955	0.080	17.028	0.000	0.002	17.250	17.222	0.000	0.002	17.000
-284	0.139	0.004	17.955	0.085	18.028	0.000	0.002	18.250	18.222	0.000	0.002	18.000
-309	0.210	0.005	0.412	0.005	0.472	0.000	0.004	0.812	0.777	0.000	0.004	0.437
-310	0.210	0.005	0.475	0.005	0.535	0.000	0.004	0.875	0.840	0.000	0.004	0.500
-311	0.210	0.005	0.537	0.007	0.597	0.000	0.004	0.937	0.902	0.000	0.004	0.562
-312	0.210	0.005	0.600	0.009	0.660	0.000	0.004	1.000	0.965	0.000	0.004	0.625

DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-313	0.210	0.005	0.662	0.009	0.722	0.000	0.004	1.062	1.027	0.000	0.004	0.687
-314	0.210	0.005	0.725	0.010	0.785	0.000	0.004	1.125	1.090	0.000	0.004	0.750
-315	0.210	0.005	0.787	0.010	0.847	0.000	0.004	1.187	1.152	0.000	0.004	0.812
-316	0.210	0.005	0.850	0.010	0.910	0.000	0.004	1.250	1.215	0.000	0.004	0.875
-317	0.210	0.005	0.912	0.010	0.972	0.000	0.004	1.312	1.277	0.000	0.004	0.937
-318	0.210	0.005	0.975	0.010	1.035	0.000	0.004	1.375	1.340	0.000	0.004	1.000
-319	0.210	0.005	1.037	0.010	1.097	0.000	0.004	1.437	1.402	0.000	0.004	1.062
-320	0.210	0.005	1.100	0.012	1.160	0.000	0.004	1.500	1.465	0.000	0.004	1.125
-321	0.210	0.005	1.162	0.012	1.222	0.000	0.004	1.562	1.527	0.000	0.004	1.187
-322	0.210	0.005	1.225	0.012	1.285	0.000	0.004	1.625	1.590	0.000	0.004	1.250
-323	0.210	0.005	1.287	0.012	1.347	0.000	0.004	1.687	1.652	0.000	0.004	1.312
-324	0.210	0.005	1.350	0.012	1.410	0.000	0.004	1.750	1.715	0.000	0.004	1.375
-325	0.210	0.005	1.475	0.015	1.535	0.000	0.004	1.875	1.840	0.000	0.004	1.500
-326	0.210	0.005	1.600	0.015	1.660	0.000	0.004	2.000	1.965	0.000	0.004	1.625
-327	0.210	0.005	1.725	0.015	1.785	0.000	0.004	2.125	2.090	0.000	0.004	1.750
-328	0.210	0.005	1.850	0.015	1.910	0.000	0.004	2.250	2.215	0.000	0.004	1.875
-329	0.210	0.005	1.975	0.018	2.035	0.000	0.004	2.375	2.340	0.000	0.004	2.000
-330	0.210	0.005	2.100	0.018	2.160	0.000	0.004	2.500	2.465	0.000	0.004	2.125
-331	0.210	0.005	2.225	0.018	2.285	0.000	0.004	2.625	2.590	0.000	0.004	2.250
-332	0.210	0.005	2.350	0.018	2.410	0.000	0.004	2.750	2.715	0.000	0.004	2.375
-333	0.210	0.005	2.475	0.020	2.535	0.000	0.004	2.875	2.840	0.000	0.004	2.500
-334	0.210	0.005	2.600	0.020	2.660	0.000	0.004	3.000	2.965	0.000	0.004	2.625
-335	0.210	0.005	2.725	0.020	2.785	0.000	0.004	3.125	3.090	0.000	0.004	2.750
-336	0.210	0.005	2.850	0.020	2.910	0.000	0.004	3.250	3.215	0.000	0.004	2.875
-337	0.210	0.005	2.975	0.024	3.035	0.000	0.004	3.375	3.340	0.000	0.004	3.000
-338	0.210	0.005	3.100	0.024	3.160	0.000	0.004	3.500	3.465	0.000	0.004	3.125
-339	0.210	0.005	3.225	0.024	3.285	0.000	0.004	3.625	3.590	0.000	0.004	3.250
-340	0.210	0.005	3.350	0.024	3.410	0.000	0.004	3.750	3.715	0.000	0.004	3.375
-341	0.210	0.005	3.475	0.024	3.535	0.000	0.004	3.875	3.840	0.000	0.004	3.500
-342	0.210	0.005	3.600	0.028	3.660	0.000	0.004	4.000	3.965	0.000	0.004	3.625
-343	0.210	0.005	3.725	0.028	3.785	0.000	0.004	4.125	4.090	0.000	0.004	3.750
-344	0.210	0.005	3.850	0.028	3.910	0.000	0.004	4.250	4.215	0.000	0.004	3.875
-345	0.210	0.005	3.975	0.028	4.035	0.000	0.004	4.375	4.340	0.000	0.004	4.000
-346	0.210	0.005	4.100	0.028	4.160	0.000	0.004	4.500	4.465	0.000	0.004	4.125

DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-347	0.210	0.005	4.225	0.030	4.285	0.000	0.004	4.625	4.590	0.000	0.004	4.250
-348	0.210	0.005	4.350	0.030	4.410	0.000	0.004	4.750	4.715	0.000	0.004	4.375
-349	0.210	0.005	4.475	0.030	4.535	0.000	0.004	4.875	4.840	0.000	0.004	4.500
-350	0.210	0.005	4.600	0.030	4.660	0.000	0.004	5.000	4.965	0.000	0.004	4.625
-351	0.210	0.005	4.725	0.030	4.785	0.000	0.004	5.125	5.090	0.000	0.004	4.750
-352	0.210	0.005	4.850	0.030	4.910	0.000	0.004	5.250	5.215	0.000	0.004	4.875
-353	0.210	0.005	4.975	0.037	5.035	0.000	0.004	5.375	5.340	0.000	0.004	5.000
-354	0.210	0.005	5.100	0.037	5.160	0.000	0.004	5.500	5.465	0.000	0.004	5.125
-355	0.210	0.005	5.225	0.037	5.285	0.000	0.004	5.625	5.590	0.000	0.004	5.250
-356	0.210	0.005	5.350	0.037	5.410	0.000	0.004	5.750	5.715	0.000	0.004	5.375
-357	0.210	0.005	5.475	0.037	5.535	0.000	0.004	5.875	5.840	0.000	0.004	5.500
-358	0.210	0.005	5.600	0.037	5.660	0.000	0.004	6.000	5.965	0.000	0.004	5.625
-359	0.210	0.005	5.725	0.037	5.785	0.000	0.004	6.125	6.090	0.000	0.004	5.750
-360	0.210	0.005	5.850	0.037	5.910	0.000	0.004	6.250	6.215	0.000	0.004	5.875
-361	0.210	0.005	5.975	0.037	6.035	0.000	0.004	6.375	6.340	0.000	0.004	6.000
-362	0.210	0.005	6.225	0.040	6.285	0.000	0.004	6.625	6.590	0.000	0.004	6.250
-363	0.210	0.005	6.475	0.040	6.535	0.000	0.004	6.875	6.840	0.000	0.004	6.500
-364	0.210	0.005	6.725	0.040	6.785	0.000	0.004	7.125	7.090	0.000	0.004	6.750
-365	0.210	0.005	6.975	0.040	7.035	0.000	0.004	7.375	7.340	0.000	0.004	7.000
-366	0.210	0.005	7.225	0.045	7.285	0.000	0.004	7.625	7.590	0.000	0.004	7.250
-367	0.210	0.005	7.475	0.045	7.535	0.000	0.004	7.875	7.840	0.000	0.004	7.500
-368	0.210	0.005	7.725	0.045	7.785	0.000	0.004	8.125	8.090	0.000	0.004	7.750
-369	0.210	0.005	7.975	0.045	8.035	0.000	0.004	8.375	8.340	0.000	0.004	8.000
-370	0.210	0.005	8.225	0.050	8.285	0.000	0.004	8.625	8.590	0.000	0.004	8.250
-371	0.210	0.005	8.475	0.050	8.535	0.000	0.004	8.875	8.840	0.000	0.004	8.500
-372	0.210	0.005	8.725	0.050	8.785	0.000	0.004	9.125	9.090	0.000	0.004	8.750
-373	0.210	0.005	8.975	0.050	9.035	0.000	0.004	9.375	9.340	0.000	0.004	9.000
-374	0.210	0.005	9.225	0.055	9.285	0.000	0.004	9.625	9.590	0.000	0.004	9.250
-375	0.210	0.005	9.475	0.055	9.535	0.000	0.004	9.875	9.840	0.000	0.004	9.500
-376	0.210	0.005	9.725	0.055	9.785	0.000	0.004	10.125	10.090	0.000	0.004	9.750
-377	0.210	0.005	9.975	0.055	10.035	0.000	0.004	10.375	10.340	0.000	0.004	10.000
-378	0.210	0.005	10.475	0.060	10.535	0.000	0.004	10.875	10.840	0.000	0.004	10.500
-379	0.210	0.005	10.975	0.060	11.035	0.000	0.004	11.375	11.340	0.000	0.004	11.000
-380	0.210	0.005	11.475	0.065	11.535	0.000	0.004	11.875	11.840	0.000	0.004	11.500

DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-381	0.210	0.005	11.975	0.065	12.035	0.000	0.004	12.375	12.340	0.000	0.004	12.000
-382	0.210	0.005	12.975	0.065	13.035	0.000	0.004	13.375	13.340	0.000	0.004	13.000
-383	0.210	0.005	13.975	0.070	14.035	0.000	0.004	14.375	14.340	0.000	0.004	14.000
-384	0.210	0.005	14.975	0.070	15.035	0.000	0.004	15.375	15.340	0.000	0.004	15.000
-385	0.210	0.005	15.955	0.075	16.035	0.000	0.004	16.375	16.340	0.000	0.004	16.000
-386	0.210	0.005	16.955	0.080	17.035	0.000	0.004	17.375	17.340	0.000	0.004	17.000
-387	0.210	0.005	17.955	0.085	18.035	0.000	0.004	18.375	18.340	0.000	0.004	18.000
-388	0.210	0.005	18.955	0.090	19.035	0.000	0.004	19.375	19.340	0.000	0.004	19.000
-389	0.210	0.005	19.955	0.095	20.035	0.000	0.004	20.375	20.340	0.000	0.004	20.000
-390	0.210	0.005	20.955	0.095	21.035	0.000	0.004	21.375	21.340	0.000	0.004	21.000
-391	0.210	0.005	21.995	0.100	22.035	0.000	0.004	22.375	22.340	0.000	0.004	22.000
-392	0.210	0.005	22.940	0.105	23.035	0.000	0.004	23.375	23.340	0.000	0.004	23.000
-393	0.210	0.005	23.940	0.110	24.035	0.000	0.004	24.375	24.340	0.000	0.004	24.000
-394	0.210	0.005	24.940	0.115	25.035	0.000	0.004	25.375	25.340	0.000	0.004	25.000
-395	0.210	0.005	25.940	0.120	26.035	0.000	0.004	26.375	26.340	0.000	0.004	26.000
-425	0.275	0.006	4.475	0.033	4.548	0.000	0.004	5.000	4.952	0.000	0.004	4.500
-426	0.275	0.006	4.600	0.033	4.673	0.000	0.004	5.125	5.077	0.000	0.004	4.625
-427	0.275	0.006	4.725	0.033	4.798	0.000	0.004	5.250	5.202	0.000	0.004	4.750
-428	0.275	0.006	4.850	0.033	4.923	0.000	0.004	5.375	5.327	0.000	0.004	4.875
-429	0.275	0.006	4.975	0.037	5.048	0.000	0.004	5.500	5.452	0.000	0.004	5.000
-430	0.275	0.006	5.100	0.037	5.173	0.000	0.004	5.625	5.577	0.000	0.004	5.125
-431	0.275	0.006	5.225	0.037	5.298	0.000	0.004	5.750	5.702	0.000	0.004	5.250
-432	0.275	0.006	5.350	0.037	5.423	0.000	0.004	5.875	5.827	0.000	0.004	5.375
-433	0.275	0.006	5.475	0.037	5.548	0.000	0.004	6.000	5.952	0.000	0.004	5.500
-434	0.275	0.006	5.600	0.037	5.673	0.000	0.004	6.125	6.077	0.000	0.004	5.625
-435	0.275	0.006	5.725	0.037	5.798	0.000	0.004	6.250	6.202	0.000	0.004	5.750
-436	0.275	0.006	5.850	0.037	5.923	0.000	0.004	6.375	6.327	0.000	0.004	5.875
-437	0.275	0.006	5.975	0.037	6.048	0.000	0.004	6.500	6.452	0.000	0.004	6.000
-438	0.275	0.006	6.225	0.040	6.298	0.000	0.004	6.750	6.702	0.000	0.004	6.250
-439	0.275	0.006	6.475	0.040	6.548	0.000	0.004	7.000	6.952	0.000	0.004	6.500
-440	0.275	0.006	6.725	0.040	6.798	0.000	0.004	7.250	7.202	0.000	0.004	6.750
-441	0.275	0.006	6.975	0.040	7.048	0.000	0.004	7.500	7.452	0.000	0.004	7.000
-442	0.275	0.006	7.225	0.045	7.298	0.000	0.004	7.750	7.702	0.000	0.004	7.250
-443	0.275	0.006	7.475	0.045	7.548	0.000	0.004	8.000	7.952	0.000	0.004	7.500

DASH SIZE	O-RING CROSS-SECTION		O-RING DIAMETER		O.D. SEALING TYPE GLAND DIAMETER (D)			O.D. SEALING TYPE BORE DIAMETER (E)	I.D. SEALING TYPE GLAND DIAMETER (F)			I.D. SEALING TYPE TUBE DIAMETER (G)
	NOM	TOL +/-	NOM	TOL +/-	DIA	TOL (+)	TOL (-)	+.002 / -.000	DIA	TOL (+)	TOL (-)	+.002 / -.000
-444	0.275	0.006	7.725	0.045	7.798	0.000	0.004	8.250	8.202	0.000	0.004	7.750
-445	0.275	0.006	7.975	0.045	8.048	0.000	0.004	8.500	8.452	0.000	0.004	8.000
-446	0.275	0.006	8.475	0.055	8.548	0.000	0.004	9.000	8.952	0.000	0.004	8.500
-447	0.275	0.006	8.975	0.055	9.048	0.000	0.004	9.500	9.452	0.000	0.004	9.000
-448	0.275	0.006	9.475	0.055	9.548	0.000	0.004	10.000	9.952	0.000	0.004	9.500
-449	0.275	0.006	9.975	0.055	10.048	0.000	0.004	10.500	10.452	0.000	0.004	10.000
-450	0.275	0.006	10.475	0.060	10.548	0.000	0.004	11.000	10.952	0.000	0.004	10.500
-451	0.275	0.006	10.975	0.060	11.048	0.000	0.004	11.500	11.452	0.000	0.004	11.000
-452	0.275	0.006	11.475	0.060	11.548	0.000	0.004	12.000	11.952	0.000	0.004	11.500
-453	0.275	0.006	11.975	0.060	12.048	0.000	0.004	12.500	12.452	0.000	0.004	12.000
-454	0.275	0.006	12.475	0.060	12.548	0.000	0.004	13.000	12.952	0.000	0.004	12.500
-455	0.275	0.006	12.975	0.060	13.048	0.000	0.004	13.500	13.452	0.000	0.004	13.000
-456	0.275	0.006	13.475	0.070	13.548	0.000	0.004	14.000	13.952	0.000	0.004	13.500
-457	0.275	0.006	13.975	0.070	14.048	0.000	0.004	14.500	14.452	0.000	0.004	14.000
-458	0.275	0.006	14.475	0.070	14.548	0.000	0.004	15.000	14.952	0.000	0.004	14.500
-459	0.275	0.006	14.975	0.070	15.048	0.000	0.004	15.500	15.452	0.000	0.004	15.000
-460	0.275	0.006	15.475	0.070	15.548	0.000	0.004	16.000	15.952	0.000	0.004	15.500
-461	0.275	0.006	15.955	0.075	16.048	0.000	0.004	16.500	16.452	0.000	0.004	16.000
-462	0.275	0.006	16.455	0.075	16.548	0.000	0.004	17.000	16.952	0.000	0.004	16.500
-463	0.275	0.006	16.955	0.080	17.048	0.000	0.004	17.500	17.452	0.000	0.004	17.000
-464	0.275	0.006	17.455	0.085	17.548	0.000	0.004	18.000	17.952	0.000	0.004	17.500
-465	0.275	0.006	17.955	0.085	18.048	0.000	0.004	18.500	18.452	0.000	0.004	18.000
-466	0.275	0.006	18.455	0.085	18.548	0.000	0.004	19.000	18.952	0.000	0.004	18.500
-467	0.275	0.006	18.955	0.090	19.048	0.000	0.004	19.500	19.452	0.000	0.004	19.000
-468	0.275	0.006	19.455	0.090	19.548	0.000	0.004	20.000	19.952	0.000	0.004	19.500
-469	0.275	0.006	19.955	0.095	20.048	0.000	0.004	20.500	20.452	0.000	0.004	20.000
-470	0.275	0.006	20.955	0.095	21.048	0.000	0.004	21.500	21.452	0.000	0.004	21.000
-471	0.275	0.006	21.955	0.100	22.048	0.000	0.004	22.500	22.452	0.000	0.004	22.000
-472	0.275	0.006	22.940	0.105	23.048	0.000	0.004	23.500	23.452	0.000	0.004	23.000
-473	0.275	0.006	23.940	0.110	24.048	0.000	0.004	24.500	24.452	0.000	0.004	24.000
-474	0.275	0.006	24.940	0.115	25.048	0.000	0.004	25.500	25.452	0.000	0.004	25.000
-475	0.275	0.006	25.940	0.120	26.048	0.000	0.004	26.500	26.452	0.000	0.004	26.000

Appendix J: Registered Mojave Sphinx Builds

SN	Name	Owner	Status
01	Mojave Sphinx	Half Cat Rocketry	Active
02	Half Cat Walking II	Half Cat Rocketry	Active

Half Cat Rocketry
HalfCatRocketry.com
contact@halfcatrocketry.com

Appendix K: License and Copyright Information

Link to Half Cat Rocketry Website

Link to GNU GPL Version 3 (HCR GitHub repository)

Link to GNU GPL Version 3 (Free Software Foundation)

Appendix L: References

The following is a list of publicly available references which were drawn upon to create this document. Citations are provided where possible; links are provided for web-hosted content. Both direct and Internet Archive links are included where possible, as a backup in the event that a website or link becomes non-functional. References are listed by section, but may apply to more than one section; they are included in the first section for which they are relevant.

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