Proposal for the Limited Allowance of N_2O/Alcohol Liquid Bipropellant Motors at Tripoli Research Events

Submitted to:	Submitted by:
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TRA Board of Directors	HalfCatRocketry.com

Date:

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Introduction

For many rocketry enthusiasts, liquid bipropellant engines represent the pinnacle of achievement in propulsion technology due to their prominence in orbital launch vehicles and importance to the aerospace industry from the beginning of the Space Age to the modern day. They also represent the biggest challenge to any experimenter in amateur propulsion. Liquid-propelled rocket projects tend to be the most highly regarded entries at events like Spaceport America Cup (IREC), and at independent launch sites such as Friends of Amateur Rocketry.

Functional amateur liquid motors are few and far between. Of those that achieve choked flow and qualify as a rocket engine – rather than a glorified flamethrower – most are consigned to life on a test stand and will never launch. Designing a flyable motor takes much more consideration for weight, packaging envelope, integration, and total impulse. If successful in these regards, launching a bipropellant rocket typically signifies the crowning achievement of a university team or independent amateur.

Currently, the Tripoli Research Safety Code prohibits liquid propellants under exclusion 5.2.1, which states:

> *With the exception of nitrous-oxide hybrid rocket motors, liquid rocket motors are generally prohibited at Tripoli Research Launches. BOD approval may be given for very well documented liquid motor projects. All such projects must be submitted to the TRC for review and recommendation to the BOD.*

We have not found evidence of any prior project being approved or even seriously proposed in the past; the handful of active liquid projects in existence either have the resources to source their own test site and insurance or operate at an unaffiliated location. To date, the “Half Cat” project stands out as perhaps the most detailed effort of any published amateur liquid motor. Thus, we believe that it meets the definition of “very well documented.”

The submitters of this proposal are the architects of Half Cat Rocketry, an organization dedicated to lowering the barrier to entry for liquid rocket engines. It is our belief that bipropellant motors can be safely brought into the realm of amateur experimental rocketry alongside solid and hybrid propulsion through radical design simplification and strict limitations on scope and operation.

Background of Experimenters

Austin Sennott is a rocket propulsion engineer from Florida. He graduated from the University of Central Florida in December 2020 with a degree in Aerospace Engineering and is employed on the Space Coast. Currently, he is Level 2 certified in high power rocketry and has been experimenting with solid, hybrid, and liquid propulsion since 2018.

LinkedIn

Charles Sharp is a Level 3 Certified member of both Tripoli and NAR, and is also employed as a rocket propulsion engineer on the Space Coast. In over 10 years of building rockets, he has gained expertise in all types of experimental rocket propulsion, including the first ever high-power rocket propelled by liquid CO2.

LinkedIn

Together they founded Half Cat Rocketry, named after the Half Cat liquid rocket engine which was developed between them from August to December of 2020. It was the first liquid engine ever manufactured and fired by students at UCF, and may be one of the only amateur bipropellant motors to be launched twice in one day. The driving reason behind creating a very low-cost system was and is that almost all of Half Cat Rocketry is personally funded. If you find the work presented here to be interesting, or wish to support the effort to create a cost-effective and open-source liquid rocket architecture, please consider making a donation to Half Cat Rocketry.

History of Bipropellant and Tripropellant Motors

The Reaction Research Society has been experimenting with liquid propellant rockets since as early as the 1940's, both in ground tests and flights. There are few good records of amateur projects throughout most of rocketry's history owing to the fact that prior to the internet, documentation was a task that required much more effort from the creator to write down and distribute – on top of the work for the project itself. Today, it is substantially easier to keep track of the field since everyone can now quickly snap a picture and upload it online.

In 1986, Dave Griffith began experimenting with simple liquid rockets. By 1996, he had switched from nitric acid to nitrous oxide as an oxidizer and created the first version of what would become the RATTworks architecture. During this time, Tom Mueller was building, firing, and flying his own liquid rockets and would ultimately end up recruited by Elon Musk as a founding employee of SpaceX in 2002.

RATTworks continued developing the "tribrid" motor, which was essentially a hybrid motor which also injected liquid alcohol fuel. This was done because the initial hybrid mode prevented a hard start, which is common in amateur engines. In 2010, the K350 was certified as a commercial motor and to this day remains one of only two liquid motors to ever receive certification by the national rocketry organizations (the other being the K600 tribrid).

There are a handful of other projects out there, the most notable being from university programs like MASA, Purdue Space Program, Space Concordia, Yellowjacket Space Program, SDSU Rocket Project, and several others. Truly amateur bipropellant engines are much harder to find, but occasionally they will launch at places like Friends of Amateur Rocketry and Reaction Research Society's Mojave Test Area. Revolution Aerospace was attempting to create an affordable, 3D printed, regeneratively cooled engine for the rocketry community as late as 2019, but is now defunct.

At the end of 2020, Half Cat appeared as the result of four months of work on our part. Half Cat is an oddity for its unique design that combines the best of mechanical simplicity with the freedom to create high-performance injectors and other features. It is also far and away one of the cheapest flyable amateur liquid engines in existence, and an incredibly robust design that can be launched, recovered, and re-launched rapidly.

Summary

The goal of this proposal is to gain Board of Director approval for the testing and launching of liquid rocket motors by the listed Tripoli members at officially sanctioned research events. The scope of these motors is restricted to an architecture consisting of (1) a propellant combination of nitrous oxide and alcohol, (2) pyrotechnically initiated valves, (3) a static vent which can never fail closed, and (4) the Tripoli Research Safety Code. The rest of this document will discuss the details of these points and provide supporting data for approval by the Board.

Specifics relating to performance or efficiency (e.g., injector design, mixing, feed system losses) will not be examined. While interesting, they are not relevant to this proposal, which is only intended to deal with the overall architecture and safety ramifications. Questions regarding these details may be directed to Half Cat Rocketry separate from the proposal.

Propellant Chemistry

Launching a liquid-fueled rocket requires a dense oxidizer to gain any appreciable amount of total impulse, and general sanity requires that it be compatible with human life. Together, these requirements eliminate gaseous oxidizers, acids, and most oxides of nitrogen. Of the two remaining options, N_2O and LOX, the latter has a variety of issues that make it difficult to work with at an amateur scale. N_2O has problems of its own, but its advantages make it the best choice for small liquid motors.

Nitrous Oxide (N_2O) is stored as a compressed, saturated liquid that, when heated, decomposes exothermically into nitrogen and oxygen. Its vapor pressure sits at an ideal spot for rocket engines (typically 500-1000 psi, depending on temperature), able to pressurize itself without the need for an auxiliary header gas.

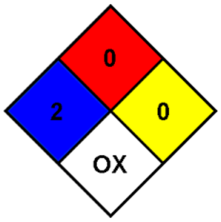
Fuels available for liquid engines are extremely diverse, but we have presently chosen to limit our engines to **isopropyl alcohol** (2-propanol), a common solvent found in high concentrations online and at hardware stores. Isopropanol is most well-known for being the active ingredient in many hand sanitizers. It is chemically stable and perfectly safe to handle, although it is accompanied by a mild health warning regarding excessive inhalation (see SDS in References). Isopropanol also has the convenient secondary usage as a cleaning agent for hardware.

Other alcohols may be substituted for isopropanol: ethanol is an even friendlier molecule, but more expensive due to taxes; methanol carries some potential performance benefits, but is slightly more hazardous. Proper safety protocols must be observed when handling any liquid fuels, or any rocket propellant altogether.

When N2O is thermally decomposed in the presence of alcohol, it combusts to produce a bright orange flame. The exhaust products consist of various gases including N_2, CO_2, H_2O, and others depending on the mixture ratio and efficiency. There are usually small amounts of gases like carbon monoxide (CO), but at the distance from spectator to engine the concentration is low enough to be completely negligible. Furthermore, the exhaust is far cleaner than solid rocket motors, which produce metal salts, soot, sulfur, and other heavy compounds that do not easily disperse in the atmosphere. In fact, it has been observed in the case of Half Cat that visible smoke production only results from ablated thermal liner. No hazard results from the combustion products of N2O and alcohol, and there are no concerns for bystanders besides a mildly unpleasant burning epoxy smell from the ablative liner.

Nitrous Oxide Safety

Although generally a friendly fluid, N_2O must be treated with respect. There are three main safety concerns associated with N_2O:



1. Compressed gas

2. Stored energy

3. Oxidizer

We will first address each point individually, and then in the context of rocket motors.

1) Any compressed fluid has the possibility of rapid expansion which can cause serious injury. Besides the force of the gas itself (which is often stored at 1000+ psi), if a gas bottle fails it usually does so catastrophically, releasing all of its contents instantaneously and fragmenting the container. The Department of Transportation requires that all commercial compressed gas cylinders be rated to very high safety factors and include a relief valve in case of overpressure. While risk can never be 100% eliminated, the DOT safety rating is treated as the highest standard.

2) As mentioned, nitrous oxide decomposes exothermically. This means that once a decomposition event begins, it rapidly spreads while adding energy. Inside of a contained pressure vessel this will become a detonation faster than human reflexes, so it is important to keep heat sources away while personnel are present. It should be noted that even in the presence of catalysts (which can lower the decomposition temperature), N_2O does not randomly explode; N_2O is commonly used in motorsports where it is subjected to much more extreme conditions without incident.

3) As an oxidizer, N_2O will accelerate fires and inflame substances which are not normally thought of as combustible. Care must be taken in considering what N_2O will come into contact with – the process of removing unwanted fuel residuals (where fuel is anything that easily burns) from equipment and hardware is referred to as oxygen cleaning, and it is done so that stray heat (especially as a result of adiabatic heating in valves and tube bends) does not ignite a fire where it is not desired.

Many rocketeers avoid nitrous oxide under the fairly legitimate impression that it can be scary (usually citing the 2007 Scaled Composites accident which killed three employees and injured three others) given the above concerns. However, we have never feared using N_2O because we respect its destructive capabilities and abide by one crucially important tenet above all else:

A system is safe when no personnel are ever in close proximity to any oxidizer, pressurized fluid, or energetic material capable of causing serious injury.

Since the liquid fuel is benign, and there are only small amounts of other stable energetic materials present (solid rocket propellants), the main safety hazard belongs to nitrous oxide. The principle spelled out above is applied by always evacuating the test or launch area to an appropriate safety distance before N_2O is ever allowed outside of its DOT-rated container, and keeping the area clear until all pressure has been relieved and no flames or embers are present. Only once there is no N_2O remaining outside of the DOT-rated vessel (save for residual wisps in plumbing at ambient pressure) and no energy source to start a decomposition event do we approach the system.

A common fallacy is believing that the same safety principles apply to *hardware*. Hardware, unlike human life, has *no intrinsic value*. Once the personnel safety tenet has been fulfilled, the risk to hardware is entirely at the discretion of its owner and his or her willingness to accept the destruction of the rocket, GSE, launchpad, or test stand. Put another way, oxygen cleaning and oxygen safety has no relevance to motor design and operation if people are never near the system when an oxidizer is present. It is only relevant to the parts in contact with nitrous oxide that a person will be around, and these parts – which must be properly rated well in excess of their maximum expected operating pressure – should be kept to an absolute bare minimum.

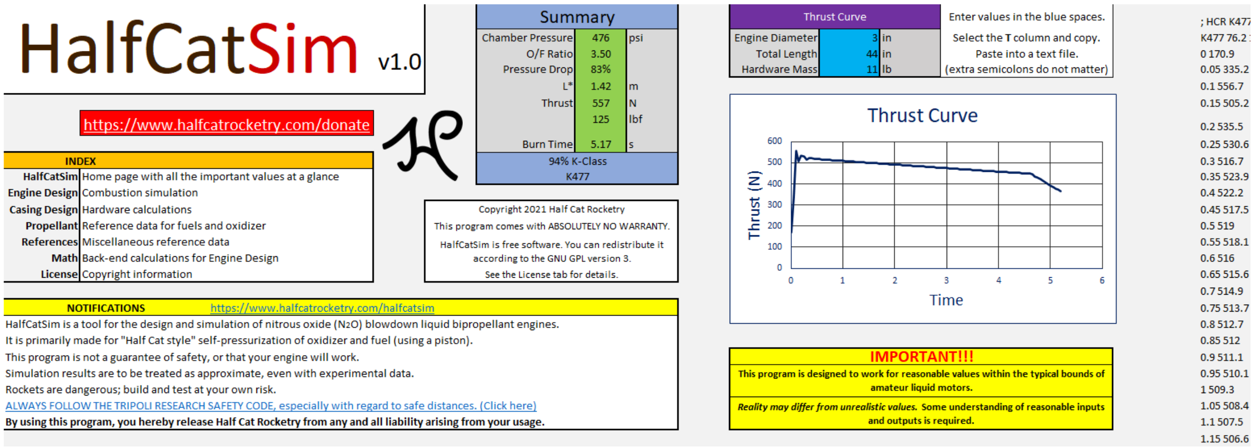
Following this guideline, along with general good practice and common sense, ensures that a rocketeer will never be in any greater danger than they are with standard solid motors. To this day, many hobbyists safely use nitrous oxide in hybrid rocket motors, and liquid engines can achieve an equivalent level of safety by following the same practices.

Mathematical Modeling

There are several simulators available for solid rocket motors, most notably BurnSim, OpenMotor, Richard Nakka's SRM.xls, and MotorSim. Similarly, there are a few hybrid simulators out there, including Aerocon Systems' Hybrid Design Program and Todd Moore's HDAS spreadsheet. Until August 2021, there did not exist an easily accessible and user-friendly liquid propellant simulation directly applicable to amateur motors. As discussed in the introduction, liquid projects are rare and those that take them on almost always build their own design tool as part of the process. The Half Cat engine was created the same way, however its simulation spreadsheet was intentionally developed to the point of public release so that other experimenters may use it to design their own N_2O/alcohol systems. This tool is called **HalfCatSim** and it is a crucial part of expanding access to bipropellant motors; an experimenter may know the theory, but have no way to correctly size an injector or nozzle. It can also serve as a sanity check for one's own calculations.

HalfCatSim works by taking all parameters of the engine and propellants as an input and running time-step based calculations as an output. The numerical data feeding the model is taken from NASA's Chemical Equilibrium with Analysis (CEA) and several of the variables have been refined based on test data from Half Cat. We use this tool to predict the performance of our engines and generate a close approximation of the expected thrust, total impulse, and burn time. HalfCatSim also includes a page of calculations for bolted and snap-ring closures, which we use to determine the appropriate sizing for combustion chambers and propellant tanks.

Below are screenshots of the user-facing pages of HalfCatSim which show the simulation of Half Cat in a typical test scenario. As can be seen by comparing to the actual test results in Appendix 2, HalfCatSim provides a high degree of confidence in design choices.



Summary		
Chamber Pressure	476	psi
O/F Ratio	3.50	
Pressure Drop	83%	
L*	1.42	m
Thrust	557	N
	125	lbf
Burn Time	5.17	s
94% K-Class K477		

INDEX	
HalfCatSim	Home page with all the important values at a glance
Engine Design	Combustion simulation
Casing Design	Hardware calculations
Propellant	Reference data for fuels and oxidizer
References	Miscellaneous reference data
Math	Back-end calculations for Engine Design
License	Copyright information

Copyright 2021 Half Cat Rocketry
This program comes with ABSOLUTELY NO WARRANTY.
HalfCatSim is free software. You can redistribute it according to the GNU GPL version 3.
See the License tab for details.

NOTIFICATIONS https://www.halfcatrocketry.com/halfcatsim

HalfCatSim is a tool for the design and simulation of nitrous oxide (N_2O) blowdown liquid bipropellant engines.
It is primarily made for "Half Cat style" self-pressurization of oxidizer and fuel (using a piston).
This program is not a guarantee of safety, or that your engine will work.
Simulation results are to be treated as approximate, even with experimental data.
Rockets are dangerous; build and test at your own risk.
ALWAYS FOLLOW THE TRIPOLI RESEARCH SAFETY CODE, especially with regard to safe distances. (Click here)
By using this program, you hereby release Half Cat Rocketry from any and all liability arising from your usage.

Thrust Curve		
Engine Diameter	3	in
Total Length	44	in
Hardware Mass	11	lb

Enter values in the blue spaces.
Select the **T** column and copy.
Paste into a text file.
(extra semicolons do not matter)

IMPORTANT!!!
This program is designed to work for reasonable values within the typical bounds of amateur liquid motors.
Reality may differ from unrealistic values. **Some understanding of reasonable inputs and outputs is required.**

```
; HCR K47
K477 76.2
0 170.9
0.05 335.2
0.1 556.7
0.15 505.2
0.2 535.5
0.25 530.6
0.3 516.7
0.35 523.9
0.4 522.2
0.45 517.5
0.5 519
0.55 518.1
0.6 516
0.65 515.6
0.7 514.9
0.75 513.7
0.8 512.7
0.85 512
0.9 511.1
0.95 510.1
1 509.3
1.05 508.4
1.1 507.5
1.15 506.6
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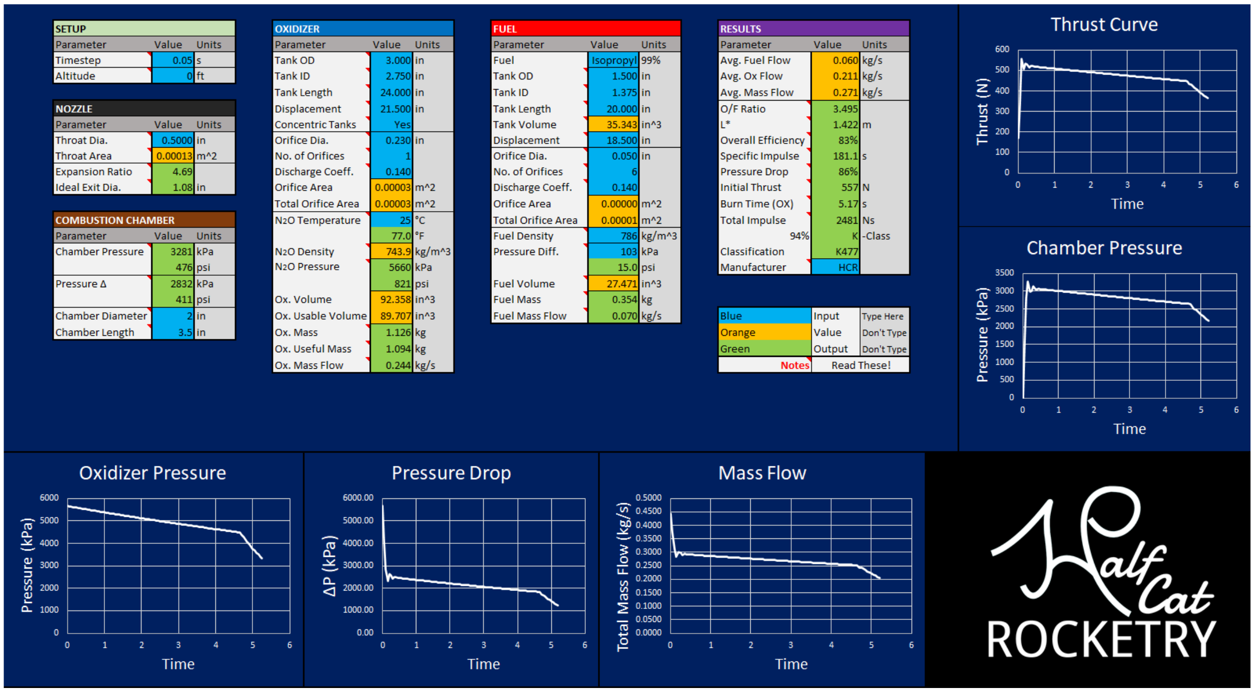


SETUP		
Parameter	Value	Units
Timestep	0.05	s
Altitude	0	ft

NOZZLE		
Parameter	Value	Units
Throat Dia.	0.5000	in
Throat Area	0.00013	m^2
Expansion Ratio	4.69	
Ideal Exit Dia.	1.08	in

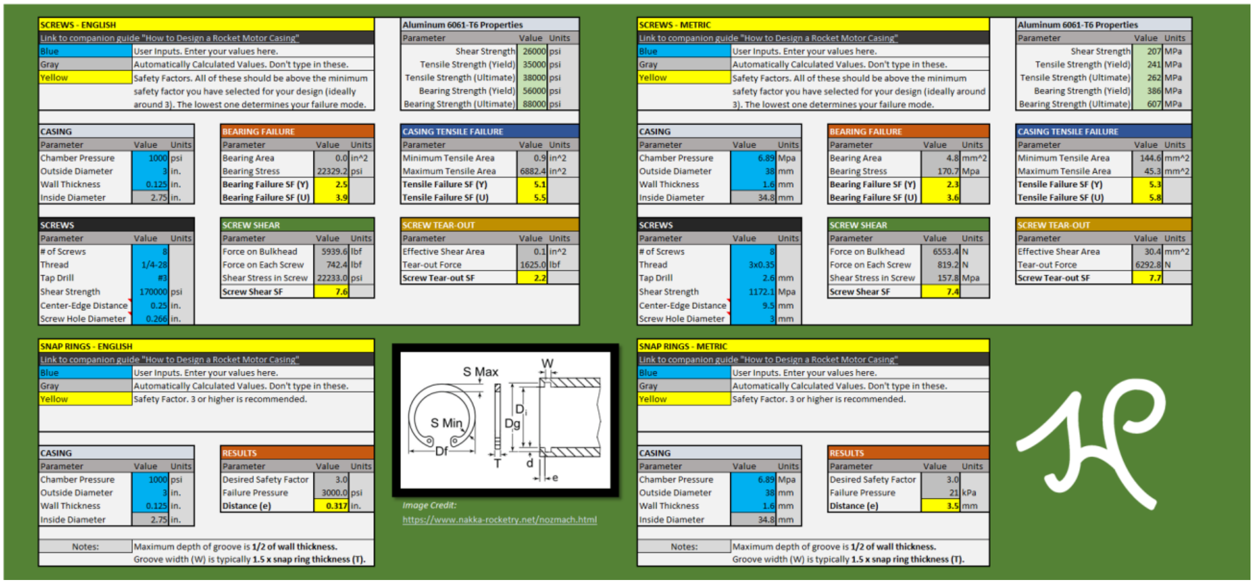
COMBUSTION CHAMBER		
Parameter	Value	Units
Chamber Pressure	3281	kPa
	476	psi
Pressure Δ	2832	kPa
	411	psi
Chamber Diameter	2	in
Chamber Length	3.5	in

OXIDIZER		
Parameter	Value	Units
Tank OD	3.000	in
Tank ID	2.750	in
Tank Length	24.000	in
Displacement	21.500	in
Concentric Tanks	Yes	
Orifice Dia.	0.230	in
No. of Orifices	1	
Discharge Coeff.	0.140	
Orifice Area	0.00003	m^2
Total Orifice Area	0.00003	m^2
N_2O Temperature	25	°C
	77.0	°F
N_2O Density	743.9	kg/m^3
N_2O Pressure	5660	kPa
	821	psi
Ox. Volume	92.358	in^3
Ox. Usable Volume	89.707	in^3
Ox. Mass	1.126	kg
Ox. Useful Mass	1.094	kg
Ox. Mass Flow	0.244	kg/s

FUEL		
Parameter	Value	Units
Fuel	Isopropyl	99%
Tank OD	1.500	in
Tank ID	1.375	in
Tank Length	20.000	in
Tank Volume	35.343	in^3
Displacement	18.500	in
Orifice Dia.	0.050	in
No. of Orifices	6	
Discharge Coeff.	0.140	
Orifice Area	0.00000	m^2
Total Orifice Area	0.00001	m^2
Fuel Density	786	kg/m^3
Pressure Diff.	103	kPa
	15.0	psi
Fuel Volume	27.471	in^3
Fuel Mass	0.354	kg
Fuel Mass Flow	0.070	kg/s

RESULTS		
Parameter	Value	Units
Avg. Fuel Flow	0.060	kg/s
Avg. Ox Flow	0.211	kg/s
Avg. Mass Flow	0.271	kg/s
O/F Ratio	3.495	
L*	1.422	m
Overall Efficiency	83%	
Specific Impulse	181.1	s
Pressure Drop	86%	
Initial Thrust	557	N
Burn Time (OX)	5.17	s
Total Impulse	2481	Ns
94%	K	-Class
Classification	K477	
Manufacturer	HCR	

Blue	Input	Type Here
Orange	Value	Don't Type
Green	Output	Don't Type
Notes	Read These!	



SCREWS - ENGLISH	
Link to companion guide "How to Design a Rocket Motor Casing"	
Blue	User Inputs. Enter your values here.
Gray	Automatically Calculated Values. Don't type in these.
Yellow	Safety Factors. All of these should be above the minimum safety factor you have selected for your design (ideally around 3). The lowest one determines your failure mode.

Aluminum 6061-T6 Properties		
Parameter	Value	Units
Shear Strength	26000	psi
Tensile Strength (Yield)	35000	psi
Tensile Strength (Ultimate)	38000	psi
Bearing Strength (Yield)	56000	psi
Bearing Strength (Ultimate)	88000	psi

CASING		
Parameter	Value	Units
Chamber Pressure	1000	psi
Outside Diameter	3	in.
Wall Thickness	0.125	in.
Inside Diameter	2.75	in.

BEARING FAILURE		
Parameter	Value	Units
Bearing Area	0.0	in^2
Bearing Stress	22329.2	psi
Bearing Failure SF (Y)	2.5	
Bearing Failure SF (U)	3.9	

CASING TENSILE FAILURE		
Parameter	Value	Units
Minimum Tensile Area	0.9	in^2
Maximum Tensile Area	6882.4	in^2
Tensile Failure SF (Y)	5.1	
Tensile Failure SF (U)	5.5	

SCREWS		
Parameter	Value	Units
# of Screws	8	
Thread	1/4-28	
Tap Drill	#3	
Shear Strength	170000	psi
Center-Edge Distance	0.25	in.
Screw Hole Diameter	0.266	in.

SCREW SHEAR		
Parameter	Value	Units
Force on Bulkhead	5939.6	lbf
Force on Each Screw	742.4	lbf
Shear Stress in Screw	22233.0	psi
Screw Shear SF	7.6	

SCREW TEAR-OUT		
Parameter	Value	Units
Effective Shear Area	0.1	in^2
Tear-out Force	1625.0	lbf
Screw Tear-out SF	2.2	

SCREWS - METRIC	
Link to companion guide "How to Design a Rocket Motor Casing"	
Blue	User Inputs. Enter your values here.
Gray	Automatically Calculated Values. Don't type in these.
Yellow	Safety Factors. All of these should be above the minimum safety factor you have selected for your design (ideally around 3). The lowest one determines your failure mode.

Aluminum 6061-T6 Properties		
Parameter	Value	Units
Shear Strength	207	MPa
Tensile Strength (Yield)	241	MPa
Tensile Strength (Ultimate)	262	MPa
Bearing Strength (Yield)	386	MPa
Bearing Strength (Ultimate)	607	MPa

CASING		
Parameter	Value	Units
Chamber Pressure	6.89	Mpa
Outside Diameter	38	mm
Wall Thickness	1.6	mm
Inside Diameter	34.8	mm

BEARING FAILURE		
Parameter	Value	Units
Bearing Area	4.8	mm^2
Bearing Stress	170.7	Mpa
Bearing Failure SF (Y)	2.3	
Bearing Failure SF (U)	3.6	

CASING TENSILE FAILURE		
Parameter	Value	Units
Minimum Tensile Area	144.6	mm^2
Maximum Tensile Area	45.3	mm^2
Tensile Failure SF (Y)	5.3	
Tensile Failure SF (U)	5.8	

SCREWS		
Parameter	Value	Units
# of Screws	8	
Thread	3x0.35	
Tap Drill	2.6	mm
Shear Strength	1172.1	Mpa
Center-Edge Distance	9.5	mm
Screw Hole Diameter	3	mm

SCREW SHEAR		
Parameter	Value	Units
Force on Bulkhead	6553.4	N
Force on Each Screw	819.2	N
Shear Stress in Screw	157.8	Mpa
Screw Shear SF	7.4	

SCREW TEAR-OUT		
Parameter	Value	Units
Effective Shear Area	30.4	mm^2
Tear-out Force	6292.8	N
Screw Tear-out SF	7.7	

SNAP RINGS - ENGLISH	
Link to companion guide "How to Design a Rocket Motor Casing"	
Blue	User Inputs. Enter your values here.
Gray	Automatically Calculated Values. Don't type in these.
Yellow	Safety Factor. 3 or higher is recommended.

CASING		
Parameter	Value	Units
Chamber Pressure	1000	psi
Outside Diameter	3	in.
Wall Thickness	0.125	in.
Inside Diameter	2.75	in.

RESULTS		
Parameter	Value	Units
Desired Safety Factor	3.0	
Failure Pressure	3000.0	psi
Distance (e)	0.317	in.

Notes:	Maximum depth of groove is **1/2 of wall thickness.** Groove width (W) is typically **1.5 x snap ring thickness (T).**

Image Credit:
https://www.nakka-rocketry.net/nozmach.html

SNAP RINGS - METRIC	
Link to companion guide "How to Design a Rocket Motor Casing"	
Blue	User Inputs. Enter your values here.
Gray	Automatically Calculated Values. Don't type in these.
Yellow	Safety Factor. 3 or higher is recommended.

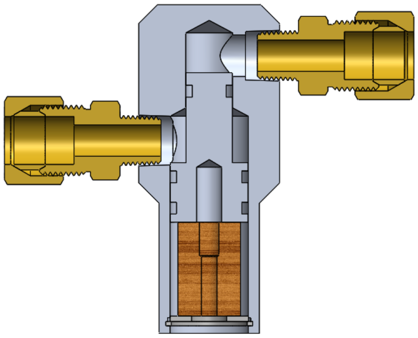
CASING		
Parameter	Value	Units
Chamber Pressure	6.89	Mpa
Outside Diameter	38	mm
Wall Thickness	1.6	mm
Inside Diameter	34.8	mm

RESULTS		
Parameter	Value	Units
Desired Safety Factor	3.0	
Failure Pressure	21	kPa
Distance (e)	3.5	mm

Notes:	Maximum depth of groove is **1/2 of wall thickness.** Groove width (W) is typically **1.5 x snap ring thickness (T).**

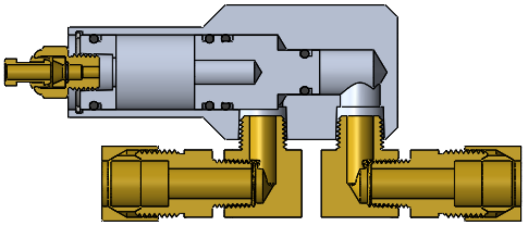
Pyrotechnic and Hydraulic Valves

One of the innovations that made Half Cat revolutionary was its pyrotechnic valves. Shown in cross-section below, they differ from valves like Tom Mueller's in one key aspect: The actuation force is provided by the working fluid itself. The pellet of solid rocket propellant is used *as a structural member* to keep the valve closed. The fact that is burns quickly and completely is a convenient property exploited to rapidly remove the structural member and allow the sealing piston to be forced open by the pressurized fuel and oxidizer.



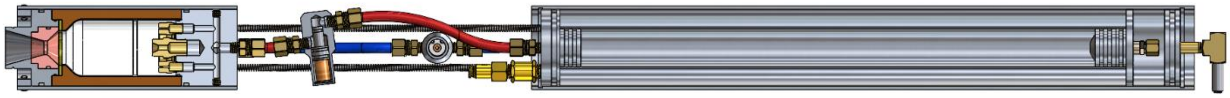
Fluid enters the top-right fitting and exits through the bottom-left fitting once the piston has been pushed out of the way. This design is based on Waterloo Rocketry's Vidar III hybrid rocket injector scheme, but isolated into a separate component. To activate, one only needs to fire an E-Match (embedded inside the piston and pellet as part of loading the valve), the same process as initiating any other solid motor. Fire and sparks exit the valve briefly as part of its normal operation, so care must be taken that there is nothing important downstream of the pyrotechnic outlet.

Another form of this same device is the hydraulic valve, which we intend to use on future engines. It functions the same way, but instead of a pellet of solid propellent it contains an incompressible fluid (i.e., water) which is kept sealed inside the valve and a small nylon line that comes out of the bottom. When the line is severed – either by a piece of solid propellant or a "cable cutter" mechanism – the hydraulic fluid, under pressure from the propellant, is forced out of the line as the piston moves. Besides the safety aspect of reducing and isolating pyrotechnics, it allows multiple valves to be manifolded together and trigger at exactly the same time with more consistency than separate pieces of solid propellant.



Motor Architecture

There are several variations of our designs, but the core principles are the same: Nitrous oxide autogenous pressurization of fuel and oxidizer, and fluid-actuated, pyrotechnically initiated valves. The Half Cat engine can be taken as a typical example:



Regardless of how the propellant tanks are arranged, whether the valves are pyrotechnic or hydraulic, and what the ignition scheme is, the functionality is the same: N_2O presses down on itself and the fuel (via a piston) to force the propellants into the combustion chamber, where they are combusted and expelled through the nozzle.

All designs include a static pressure vent at the head end of the N_2O tank to allow complete filling of the tank with liquid, as well as ensure that pressure can never be trapped in the system by a failed or stuck valve. This makes a dump valve unnecessary, although it is still a good idea to have one. Half Cat takes 40+ minutes to bleed out a full tank, which is a long time to make other flyers at a public research event wait before opening the pads in the case of an abort, so future motors will include a dump system.

Unlike hybrid and solid motors, which have solid grains to block most combustion flame and thin thermal liners to take the rest, the combustion chamber of a purely bipropellant engine is completely exposed to the hot gases, which often have a higher flame temperature than other propellant combinations. The most effective way to protect the chamber is with an ablative liner which slowly burns away under heat and pressure. Half Cat uses an original formulation called CHAMBERSAFE, but many different materials will work with an appropriate thickness. It is important that the thermal liner not easily sustain fire by itself in atmosphere, as this may cause a nitrous decomposition event in the residual gas even after all pressure has been expelled. Such an eventuality was discovered shortly after the first static test of Half Cat, and it spurred the development of CHAMBERSAFE and was the reason for adding a CO_2 purge to the system. This particular event will be discussed in more detail in the coming sections.

It should be noted that these engines cannot be considered “tripropellant” by any definition. Although an ablative thermal liner contributes small amounts of particles to the overall mass flow, this proposal is considering truly bipropellant engines. Attempting to pass them off as tripropellant motors is disingenuous, and we would like to make it very clear that we are not attempting to mislead the Board by making comparisons to the likes of RATTworks and Contrail.

Ground Support Equipment and Control Systems

The GSE for liquid motors of this style is very simple – in fact, it is no different than a Contrail-brand hybrid, as was the intention. It consists of a N_2O supply tank (usually an automotive nitrous bottle), a servo-actuated ball valve, connecting lines rated to appropriate pressures, and a remote-controlled fill system. Accessories to the fill system include a CO_2 purge and oxidizer dump, using identical servo-actuated ball valves. Up to this point, we have used an off-the-shelf R/C aircraft transmitter and receiver to control the engine at a distance. Currently, we are building a wired ethernet cable-based control box that similarly allows us to fill, fire, purge, and dump at a distance.

The R/C transmitter was modified with switch covers to prevent accidental movement of the switches that initiate filling and firing. The receiver was also set up with the failsafe positions set so that if it loses connection, it will close the fill valve and cut power to the firing switches. This means that in an emergency scenario (and in normal operation following an attempted firing), the operator may simply turn off the transmitter and the system will automatically revert to a safe mode.

Similarities and Differences to Solid and Hybrid Motors

Liquid bipropellants at the amateur scale are almost identical to hybrids and share the same similarities with solids. According to the architecture outlined previously, nitrous oxide is remotely loaded onboard, then using pyrotechnics allowed to flow into the combustion chamber and burn until depletion of the propellants. This sequence is exactly the same for certified Contrail hybrid motors.

The similarity with solid motors is the pressure vessel design: Snap ring retained, bolted, and threaded closures all work the same in liquid designs. However, the combustion mechanism and flame temperatures are quite different, as is the existence of a feed system, so the difference between solids and liquids are quite apparent. The same is true of failure modes, but this is actually a point in favor of liquid propellants; when destroyed, solid motors throw burning chunks of propellant dozens or hundreds of feet in all directions. In a liquid state, it is difficult for burning fuel (especially alcohol) to be projected more than a few feet from the explosion, and the motor will in a worst-case scenario produce a rocket-enveloping fireball.

The main difference from hybrid motors is that the fuel is stored as a liquid rather than a solid. Although the phrase “hybrids can’t explode” is often touted, it has been evident from both hobbyists and corporations over the course of decades that explosions do still happen, especially when using nitrous oxide. The explosion magnitude is potentially greater in the case of concentric propellant tanks (like those found in Half Cat and the RATTworks tribrid), but it is no more dangerous to spectators than burning chunks of solid propellant, and likely not much worse than a nitrous oxide detonation in a hybrid motor.

As with any other amateur rocket, the potential exists for projection of metal shards, which is why all motors regardless of propellant type must adhere to the Tripoli Research Safety Code. Through multiple failures of Half Cat, we have gathered data on the debris ejection and potential hazards both on the ground and in-flight.

Compliance with the Tripoli Research Safety Code

The Tripoli Research Safety Code (TRSC) governs all experimental motors at officially sanctioned research launches. The most important aspects are its limitations on construction materials (frangible metals are prohibited) and the safe standoff distance table.

Aside from exclusion 5.2.1, our motors comply with all other aspects of the TRSC. The only minor exception is that the pyrotechnic valve pellets and combustion chamber igniter of Half Cat were made from KNSU (sucrose-based sugar propellant), which is not technically an allowed formulation. The reason for the specific exclusion of KNSU from the TRSC (despite it being included in the original proposal to the TRA Board) has been debated on both the Rocketry Forum and the official Tripoli forums, and the conclusion appears to be that it would introduce a possible association to the unsafe “rocket candy” motors advertised to the clueless public by the likes of Grant Thompson’s “King of Random” YouTube channel, among others. Regardless, if we decide to continue using sugar propellant in engines, and the small amount of KNSU is specifically a problem, we will either mix in a majority dextrose/sorbitol/erythritol or replace the sucrose entirely to be in full compliance with the TRSC.

The motors are constructed primarily from 6061-T6 aluminum, and the nozzle is typically made of copper. Both of these are very ductile materials and allowed under the TRSC, as is the brass that the fluid fittings are made from. There are some steel components (bolts, washers, snap rings, etc.) but these are exempt under 7.2.2.2. We have used graphite nozzles on two occasions, and the damage to them was consistent with what is seen in solid and hybrid motors during anomalies. The CHAMBERSAFE material, being epoxy-based, is akin to a hard plastic. In the only explosive failure it has been subjected to, it cracked into several chunks that were found no more than a few feet from the combustion chamber. Although brittle, its debris is low-energy like graphite.

During every static firing to date, and for every future firing and launch, we adhere to the safe standoff distance table. In fact, we have always exceeded the required distance out of an abundance of caution.

Storage and Handling Considerations

No hazard exists from the storage of N_2O/alcohol prior to connecting the igniter. The N_2O is stored and transported in an automotive bottle and kept away from heat sources; it is also good practice to keep nitrous oxide bottles out of the sun until necessary to prevent the pressure from rising higher than desired. Any solid propellant or blackpowder charges present must be kept away from ignition sources and protected from accidental ignition, which includes shunting any E-Matches or initiators that are installed during motor assembly.

It was the case with Half Cat, and likely will continue to be so for future engines, that the fuel was loaded during motor assembly one or more days before the planned firing. Since the room temperature vapor pressure of alcohol is less than 1 psi, there is no pressurization hazard as a result of this practice. The fuel is kept completely sealed and leak-tight until the moment of propellant valve opening; Half Cat has been pre-fueled and transported horizontally several dozen times without issue.

Half Cat Testing and Launch Results

Also known as RY-101, Half Cat is a 3in/75mm × 44in/1118mm liquid bipropellant rocket engine with the designation of K295. Although its exact total impulse and burn time depend on the ambient temperature (hotter nitrous will be less dense while the oxidizer tank is a fixed volume), it is usually on the very upper end of K-class and runs for 8 seconds (5 seconds of proper thrust and 3 seconds of low-pressure tail off). It has been fired a total of 10 times; an overview of the results is tabulated below:

Firing	Date	Result	Notes
Static Test 1	12/15/20	Partial Success	Propellant tank exploded
Static Test 2	1/25/21	Failure	Injector exploded
Static Test 3	2/25/21	Success	DAQ system failed
Static Test 4	3/9/21	Partial Success	Test stand fell over
Static Test 5	3/23/21	Success	Flight qualification
Launch 1	4/3/21	Partial Success	Explosion in flight
Static Test 6	7/16/21	Success	DAQ system failed
Static Test 7	7/27/21	Success	Flight qualification
Launch 2	8/21/21	Success	Nominal engine firing
Launch 3	8/21/21	Success	Nominal engine firing

Half Cat Test & Launch Results

The engine has existed in its current configuration since Static Test 3, although minor changes have been made since then and some repair/replacements have been made due to damage (mostly resulting from Launch 1). It is currently retired and development focus has been shifted to newer engines.

Successful results will not be discussed individually, but collective results and lessons learned are presented below. The failures and partial successes will receive more scrutiny in the next section as they provide a very good insight into the hazards resulting from an off-nominal firing.

During normal operation, the motor cannot be stopped or controlled in any way. This is a functionality shared with solid motors and simple hybrids – once the motor is initiated, it must be allowed to continue until propellant depletion. However, during static tests we have had the ability to extinguish the combustion chamber after motor burn by opening a CO_2 purge. This has proven itself a very effective method for rendering the motor safe to approach. After Static Test 3, the thermal liner remained on fire for a few minutes, fed by ambient pressure N_2O bleeding into the chamber, but it did not cause a catastrophic decomposition event as in Static Test 1, and went out on its own. While not strictly necessary, it is a very good idea for any liquid motor to include an inert gas purge for safing the test site. Regardless, personnel must wait before carefully approaching; in our case, this was 3 minutes after the last flame was observed.

The exhaust plume does not usually present any more of a hazard to surroundings than a standard solid motor; that said, up until Static Test 7 (when the feed lines were slightly modified), Half Cat was known for producing a large fireball for approximately one second during the burn. It is not fully understood why this happened, but it was quite consistent. Because of this potential (especially when operating at a low O/F ratio, where there is excess fuel), the LCO and RSO at a launch should immediately observe for fires if the surrounding area has grass or other readily flammable materials. Since it was stated above that personnel should wait before approaching the motor, keen judgment must be used by the responsible individuals in whether they approach to put out a serious field fire, and if so, how close they get to the engine. One suggestion in this scenario is to continuously run the inert gas purge while people are nearby so that the combustion chamber rapidly cools and all other gases inside the motor are displaced. In no situation should anyone *ever* approach while the motor itself is on fire. Due to the extreme risk of nitrous oxide decomposition, it must be left alone until it has extinguished itself or the propellant tanks have been completely destroyed by a detonation.

An operational parameter that has been observed to be somewhat inconsistent is the oxidizer fill level. Since the tank is statically vented, the operator relies on visually observing liquid N_2O spilling out the top of the motor to know that it is filled; this manifests as a sudden surge in the white cloud of vapor from the vent. In Static Test 7 and Launches 2 & 3, we filled the oxidizer tank based on the amount of time it usually took to fill previously. In none of those firings was the liquid vent observed; this was either due to a slight short-fill of the tank, or, in the case of the launches in the Mojave Desert, potentially a lack of water vapor in the air to condense and be seen. A short-fill scenario is not a hazard on its own, but it can reduce the total impulse of the motor.

During the first second of Static Test 7, the chamber pressure was unusually high, and only about 100 psi less than the oxidizer tank pressure. This was determined to be from the igniter, which was still burning during that first second. To some degree this has always been present: Every static fire video shows a brief phase of higher pressure exhaust tinted purple from the potassium in the KNSU igniter.

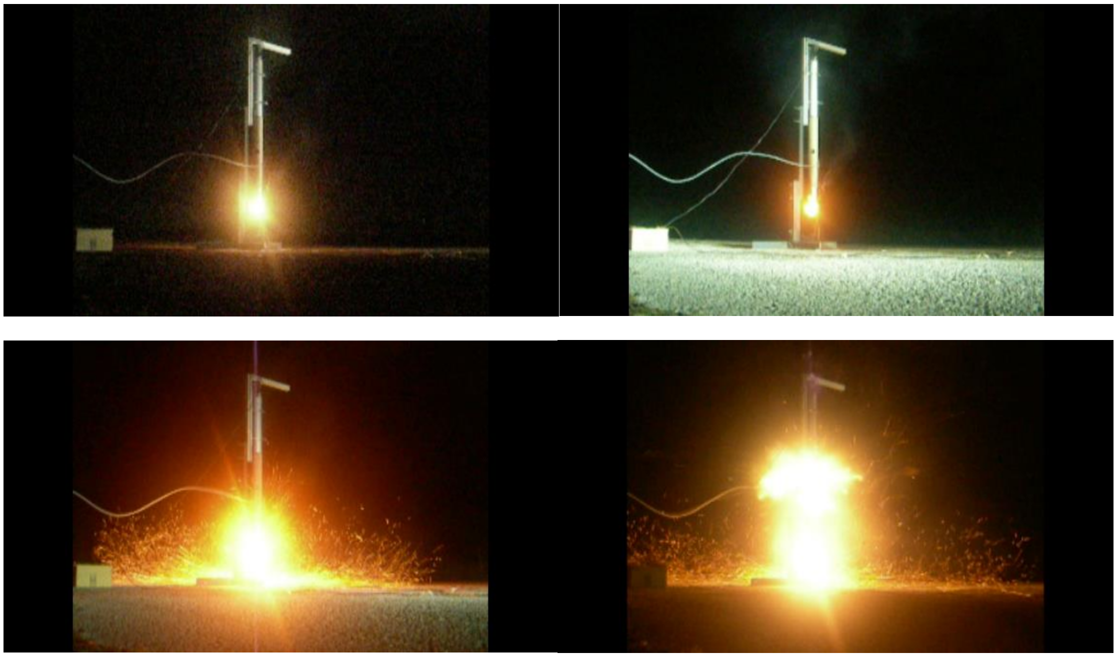
One other effect demonstrated by Half Cat, and rarely seen in other motors, is the instantaneous spike to full thrust. No meaningful ramp-up time has ever been observed; the time from zero to peak thrust is a few milliseconds. While not a problem on its own, it has implications for launches: At the beginning of Launches 2 & 3, the N_2O quick disconnect was supposed to easily release simply by the rocket moving upwards, and indeed this was shown to be very reliable in testing both on and off the rail. But when it actually launched, it developed full thrust so fast that the mechanism bound up and stayed attached, ripping out the fill line from the supply tank and taking the fill valve with it both times. As a result, the entire nitrous tank was left to dump its contents. There are definitely ways to fix the quick disconnect problem, but one must be aware of the jerking behavior bipropellant motors may exhibit.

Failure Data and Analysis

Static Test 1

The engine fired nominally, but after shutdown the thermal liner remained on fire. Shown below, it is a combination of PVC pipe shoved into an RCS paper phenolic liner with brown craft paper to take up the gap. The thought behind PVC was the RATTworks tribrid: A solid fuel should help eliminate hard starts and be consumed during burn. It was only because of what happened that we determined that a self-extinguishing liner was necessary.

Approximately one minute after the end of the burn, the engine, against all expectations of a motor that has fully consumed its propellants, suddenly re-ignited for about a second before the propellant tanks violently exploded.



In chronological order:

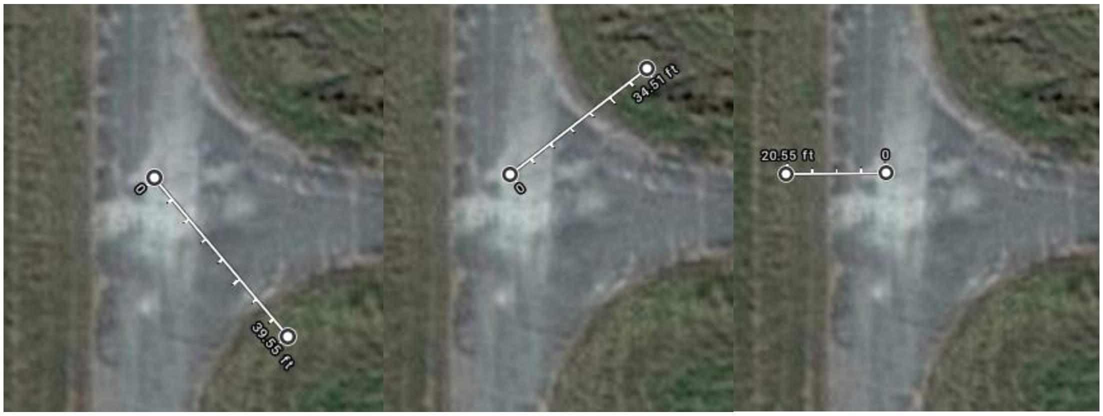
1. The thermal liner stays on fire due to residual N_2O bleed

2. Personnel have approached with fire extinguishers to about 100 feet away and stopped

3. The combustion chamber once again pours out flame and the characteristic sparks associated with a nitrous oxide decomposition event in progress

4. The propellant tanks explode

From this event, we implemented the safety procedure of staying outside the full safe standoff distance for three minutes after the last flame is seen (over twice the amount of time from the end of Static Test 1 to when the motor detonated). We did not get any closer than 100 feet because we knew that with an ongoing fire, there was still danger present.



Shown above are the locations of three pieces of debris recovered afterwards. The furthest distance any piece was known to have landed was about 40 feet. Some parts were never found: The fuel piston and bits of the lower tank bulkhead undoubtedly landed in the grass nearby and were lost due to their small size. Had the tanks been full, there would have been a larger explosion comparable to a nitrous hybrid. Fortunately, since we adhere to the TRSC, the fragmentation of the casing is limited by the ductility of the metal, and shards will generally be quite large. The smallest piece was about one inch long.

The thermal liner fire initiated the decomposition event, but the final detonation was suspected to be from a small fuel-air explosion inside the well below the fully depressed fuel piston. In the picture shown below, you can see the destroyed bulkhead next to its replacement; the original one had a much deeper well in the center that unused fuel sat in, unpressurized after the end of the burn. It is obvious that the detonation started here because the fuel tube mount has completely vanished, and a close examination shows that it failed in tension- pulled apart in all directions by a high-pressure wave.

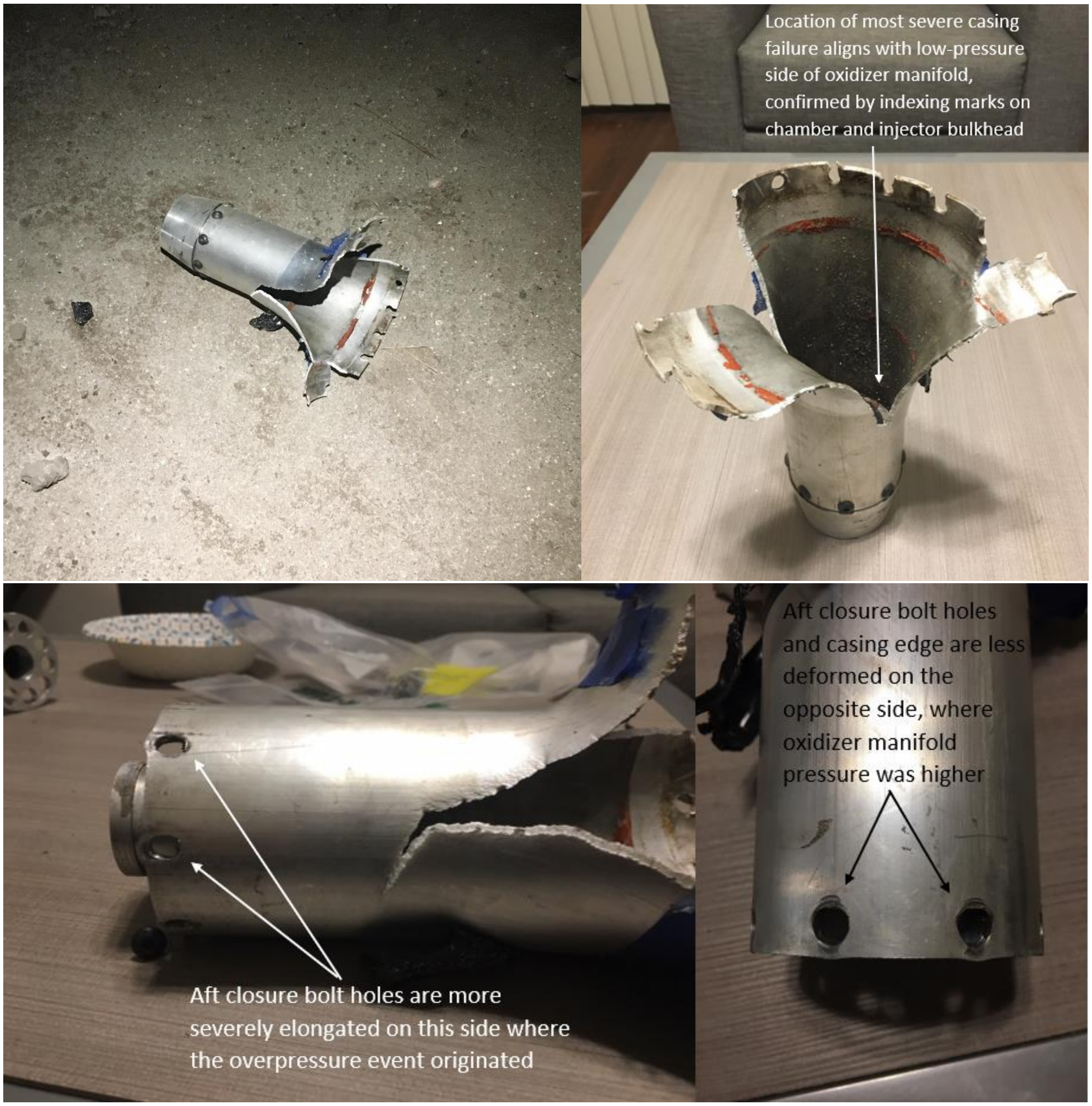
An examination of the curvature of several tank segments showed that the spherical wave was indeed centered just below the fuel piston.

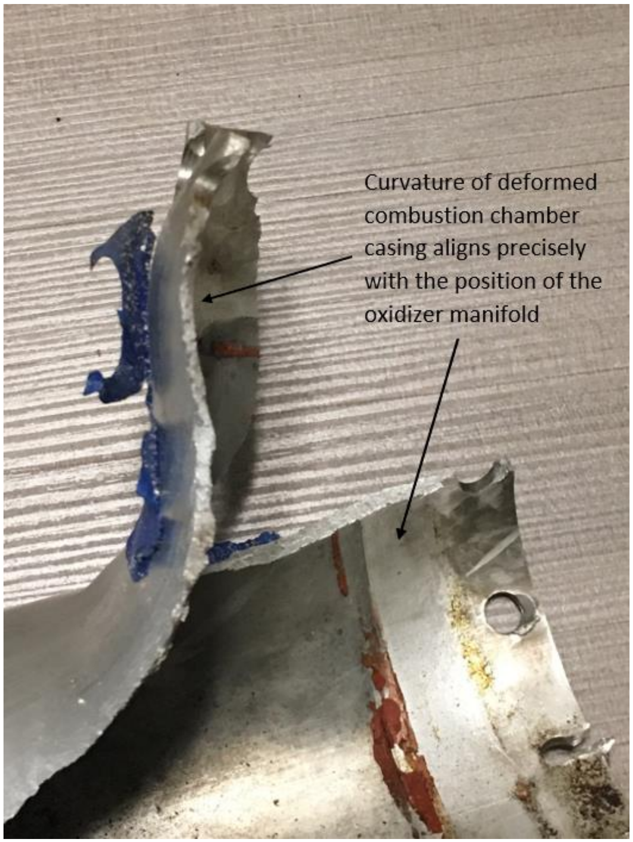
Overall, most of the motor survive just fine despite the explosion. The graphite nozzle was cracked from the combustion chamber being fired into the ground, but the rest of the engine itself was undamaged. The load-bearing threaded rods were bent and the nylon feed lines had burst; both needed to be replaced. Interestingly, it was discovered from this event and Static Test 2 that the nylon tubes act as a sort of burst disc: They fail from temperature and pressure before an explosion can spread to the other side of the system.

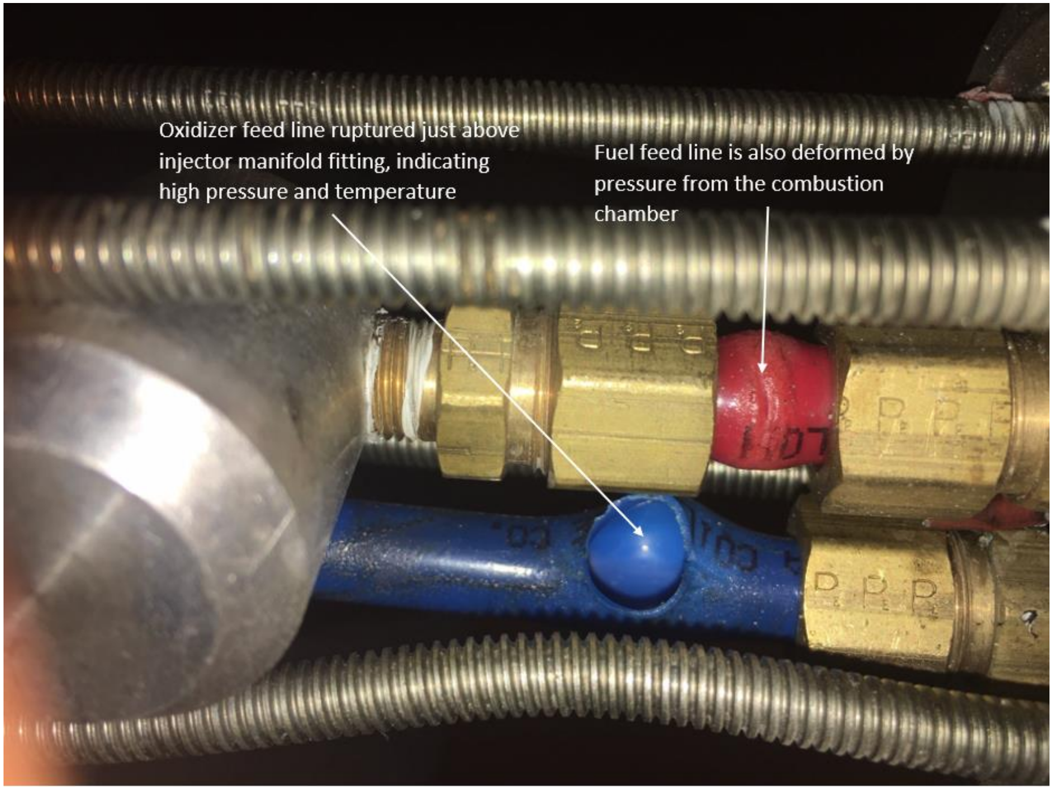
Another curious observation was that despite the catastrophic failure and presence of fire, both the oxidizer and fuel tanks were still very cold and iced over.

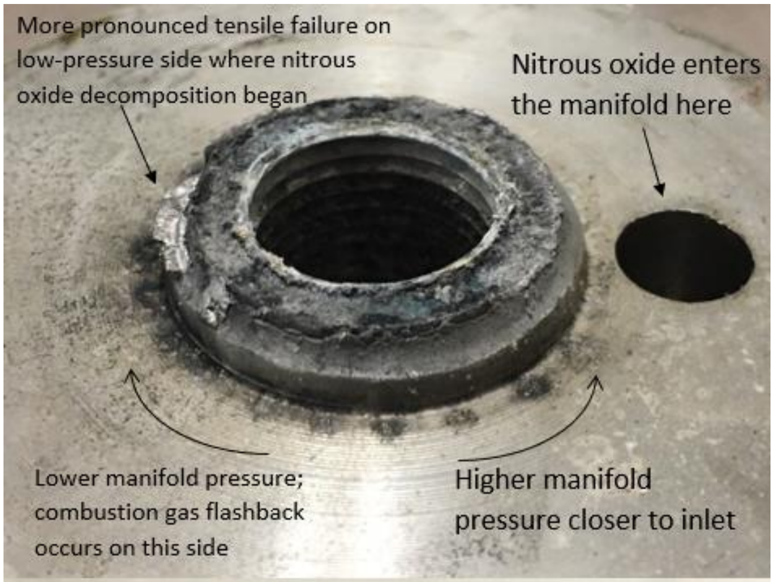
Static Test 2

In this attempt, there had already been one aborted fill cycle. As a result, the nitrous oxide supply tank was quite cold. Presented below is a detailed analysis we put together following the event. In summary, the low initial pressure from a colder supply, plus feed system losses, plus an uneven pressure distribution inside the oxidizer manifold, meant that after about a second of burning the flow reversed on one side of the injector and caused an N_2O decomposition that produced a detonation inside the oxidizer manifold.

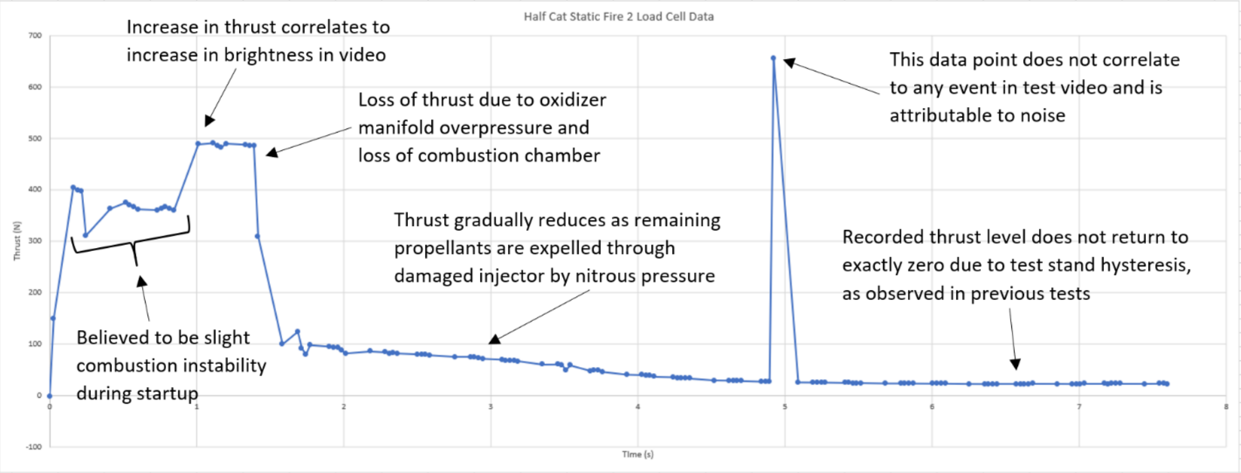


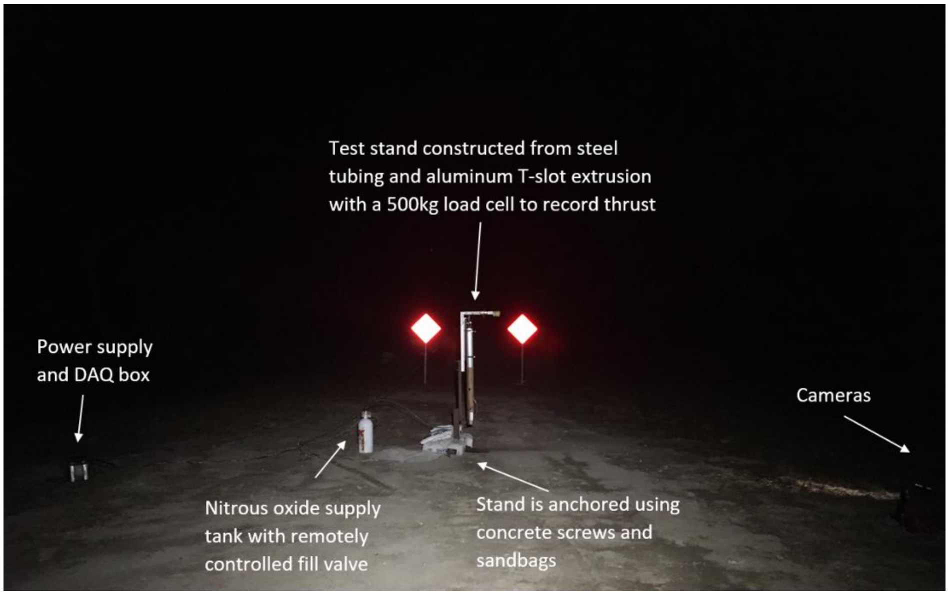

Curvature of deformed combustion chamber casing aligns precisely with the position of the oxidizer manifold


Oxidizer feed line ruptured just above injector manifold fitting, indicating high pressure and temperature
Fuel feed line is also deformed by pressure from the combustion chamber


More pronounced tensile failure on low-pressure side where nitrous oxide decomposition began
Nitrous oxide enters the manifold here
Lower manifold pressure; combustion gas flashback occurs on this side
Higher manifold pressure closer to inlet


Close-up of tensile elongation occurring only on the low-pressure side of the oxidizer manifold


Half Cat Static Fire 2 Load Cell Data
Thrust (N)
Time (s)
700
600
500
400
300
200
100
0
-100
0
1
2
3
4
5
6
7
8
Increase in thrust correlates to increase in brightness in video
Loss of thrust due to oxidizer manifold overpressure and loss of combustion chamber
This data point does not correlate to any event in test video and is attributable to noise
Thrust gradually reduces as remaining propellants are expelled through damaged injector by nitrous pressure
Recorded thrust level does not return to exactly zero due to test stand hysteresis, as observed in previous tests
Believed to be slight combustion instability during startup



Following Static Test 2, the whole combustion chamber aside from the nozzle carrier had to be re-made. The injector was changed to a design that put fuel on the outside and oxidizer in the center and did not have any manifold that would cause an uneven pressure drop.

Once the chamber had been lost, combustion ceased, and propellants were expelled unburnt until depletion. No fires were started in the surrounding area as a result of the explosion. There was also no scattered debris from this event; seen in the first picture, the chamber tore open as if it had a seam, thanks to the ductility of aluminum. The face of the injector was ripped away from the rest and found by the test stand.

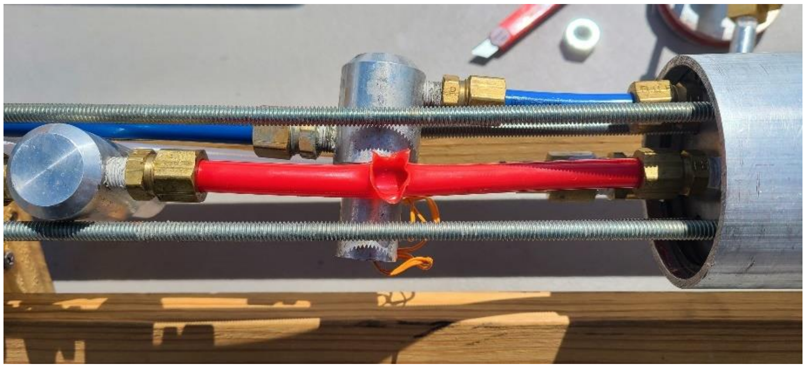
Static Test 4

All was nominal in this attempt, except for the test stand coming uprooted and falling over. Up to this point it was screwed into the ground (which was made of compacted sand) and weighed down with bags of cement. The jolt from startup tore through the cement bags and allowed the motor to tip over and land horizontally on the ground, where it burned for longer than usual due to the off-nominal liquid level inside the oxidizer tank. Thus, the depleted while nitrous oxide was still flowing, which raised the chamber temperature at the end and partially melted three out of six brass fuel injector fittings. Aside from this, there was no damage to the engine. In the data, a small spike in oxidizer pressure can be noted as the liquid wave splashes back against the pressure transducer at the head end of the tank. The data also shows a drop-off in thrust and chamber pressure correlating to the time when the engine fell below the level where liquid N_2O could still enter the tank outlet.

The solution to this issue was the addition of a heavy concrete slab over the base of the test stand, which also acted as a much better blast deflector. No other rapid test stand configuration changes have occurred since this incident.

Launch 1

The imminent in-flight failure of Launch 1 was known before the rocket left the launchpad. Prior to Static Test 5, it was discovered that the fuel line had burst during an aborted fill cycle.



At the time, this was attributed to fatigue resulting from ~10 pressure cycles on that particular tube, which pressed up against the oxidizer valve and likely had a minor stress concentration when pressurized.

Out in the hot sun of the Mojave Desert, the nitrous oxide tank was at a higher temperature and pressure than in previous testing at night in Florida. This pushed the fuel to just the wrong side of the nylon tube's ultimate strength and it burst about halfway into filling the oxidizer tank. The rocket was taken off the rail, the engine disassembled, the tube changed, the stack reassembled, and put back on the rail within a couple hours of the first attempt. Knowing that the same result was likely, the decision was made to fire the engine anyway.

In chronological order:

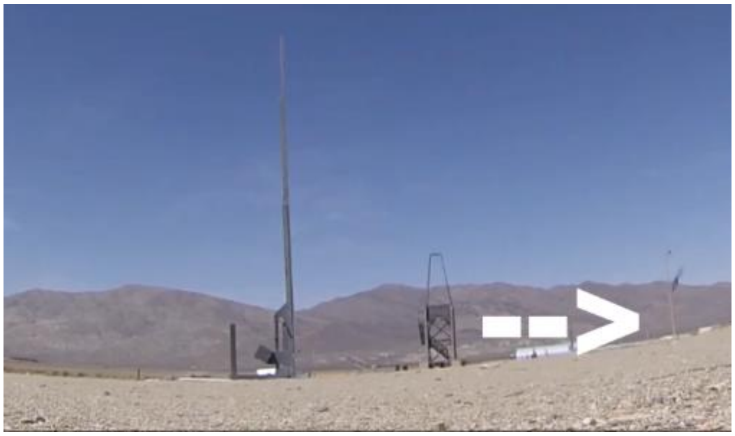
1. Ignition after the fuel line burst and sprayed out all alcohol

2. Liftoff, where smoke and combustion exhaust is pouring out around the valves

3. Residual fuel and leaking decomposed N_2O from the combustion chamber creates a fuel-air explosive mixture and detonates inside the plumbing section of the aiframe

4. The combustion chamber is ejected out the back of the rocket and the rest of the airframe tumbles

Despite the off-nominal ascent, the recovery system fired and the parachutes deployed, although they did not have enough time to fully inflate. The combustion chamber landed next to the launchpad.



Following this launch, the existing nylon tubes were changed out for higher pressure versions. The reason the high-pressure tube was not used in the first place was that the oxidizer flow area was uncomfortably low, and the tube itself was much more rigid and inflexible than the thinner, softer tube. Static Fire 7 was performed with both fuel and oxidizer lines changed out for high pressure, and no further issues arose relating to the nylon line.

Besides the tests shown here, there were many more attempted firings that did not occur for a number of reasons. Early on, we had many issues with the electrical system and components failing for various reasons. The first attempt of Static Test 2 ended prematurely when the valve pellets suddenly ignited while we were connecting the E-Matches. Although we were not in danger, we instinctively jumped back due to the flame coming out the side of the motor. This was determined to be from the brushed ESC we were using as an ignition switch: When the transmitter was not powered on, it would send a pulse every few seconds to what it thought was an aircraft motor to twitch the propeller. This was enough current to set off the E-Matches.

Going forward, we made a step in our procedure to turn the transmitter on before anything else was powered up or connected. We also replaced the brushed ESC with R/C switches that have proven to be much more reliable. Additionally, from then on we also connected spare E-Matches to the ignition leads and let them sit for 30 seconds before continuing to be sure that no undesired current was being allowed through the circuit. These spare E-Matches would then be used in a mock fill and fire cycle to check that everything was working correctly; afterwards, more E-Matches were connected to again check that no current was flowing before connecting the leads to the real igniters.

There were also a few scrubbed attempts related to failed ignitions. The first time was a result of the chamber igniter not having a well-developed flame and the solid propellant grain being snuffed out by the cold nitrous oxide flow. After that, we put the chamber igniter on a separate channel from the valves and initiated it 1-2 second before the valve pellets. Another failed ignition was a result of the E-Matches not lighting the igniter grain and being blown out when valves were opened. This was fixed by cutting slots on the outside the grain for the E-Match wires to be captured between the igniter and the thermal liner.

Two other scrubbed attempts were caused by a blockage in the static vent. Normally, about one second after opening the fill valve there is a characteristic high-pitch chirp as the tanks pressurize. This chirp did not occur in attempts leading up to Static Test 5. After struggling to diagnose possible issues, a small piece of foreign object debris (FOD) was found to be partially blocking the static vent, which was only 0.8mm in diameter. After removing the FOD, the chirp returned and Static Test 5 proceeded nominally.

By the time of its final two launches on August 21, 2021, Half Cat was a touchy but reliable engine that successfully proved out many concepts and paved the way for other mechanically simple bipropellant motors. Its failures have taught many lessons and shaped safety procedures for both itself and future engines.

Tripoli Insurance and Legal Considerations

At this time, we do not have insight into how TRA's insurance will treat bipropellant motors; however, given the certification of the RATTworks tribrid, the close similarities to existing hybrid motors, and the allowance limited to only two experienced Tripoli members, this architecture should not present new legal issues to TRA.

Conclusion

By the submission of this proposal, the authors hope to be granted Board of Director approval for the testing and launch of bipropellant rocket motors at sanctioned Tripoli research events. Throughout this proposal, we have demonstrated a thorough competence in experimental amateur rocketry, a complete understanding of the letter and intent of the Tripoli Research Safety Code, and a robust adherence to strict safety practices. The contents of this report prove that our engines are safe for public events regulated by the Tripoli Rocketry Association, and that we have characterized the potential hazards both on the ground and in the air.

References

Tripoli Research Safety Code

Isopropanol Safety Data Sheet

Nitrous Oxide Safety Data Sheet

Thermophysical Properties of Nitrous Oxide

The physics of Nitrous Oxide (Aspire Space / Rick Newlands)

LIQUID ROCKET COMPONENTS: PYROTECHNIC VALVES (Tom Mueller)

Tribrid Motors (RATTworks)

Vidar III Hybrid Rocket

CHAMBERSAFE

Pyrotechnic Valves

Propellant Piston Pressurization

Low-Cost, Remote-Controlled Servo-Actuated Ball Valve

Appendix 1: Half Cat Testing and Launch Videos

Static Test 1

Static Test 2

Static Test 3

Static Test 4

Static Test 5

Launch 1

Static Test 6

Static Test 7

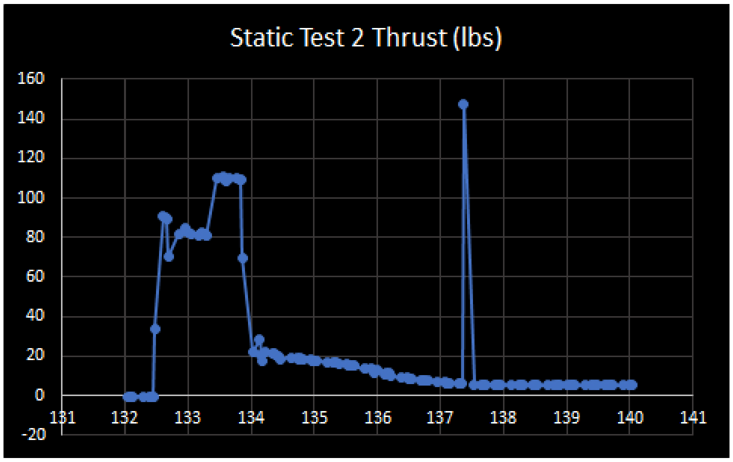
Launch 2

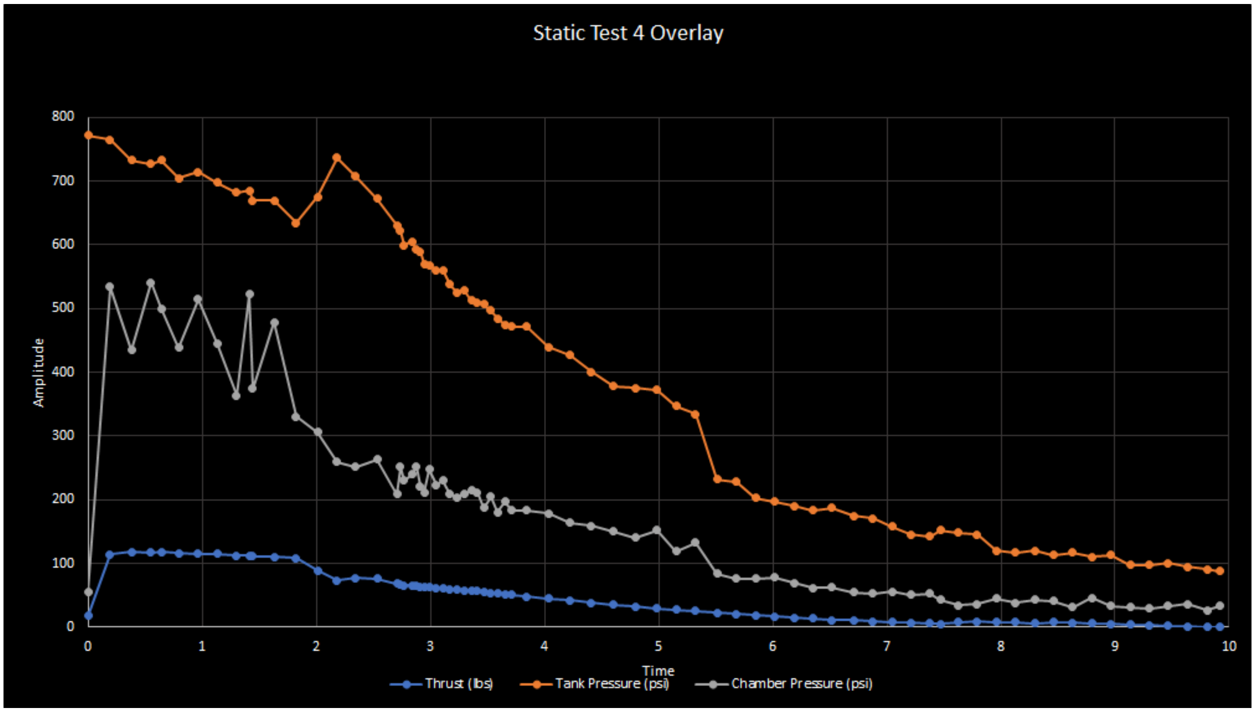
Launch 3

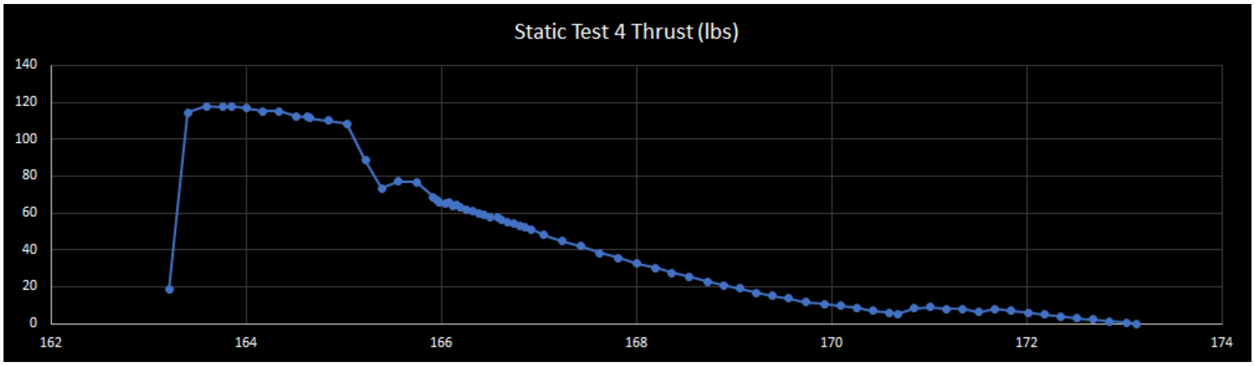
Launch 2 Onboard Video

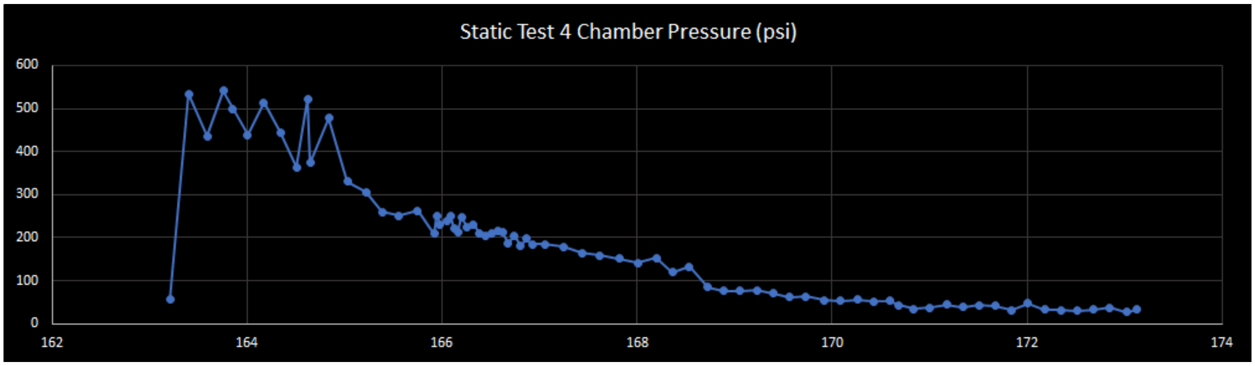
Failed Ignition Attempt

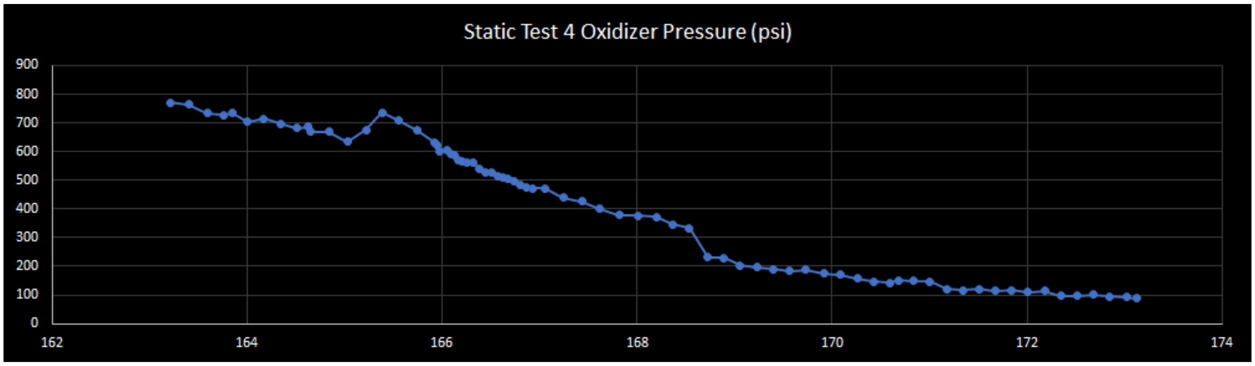
Appendix 2: Half Cat Test Data

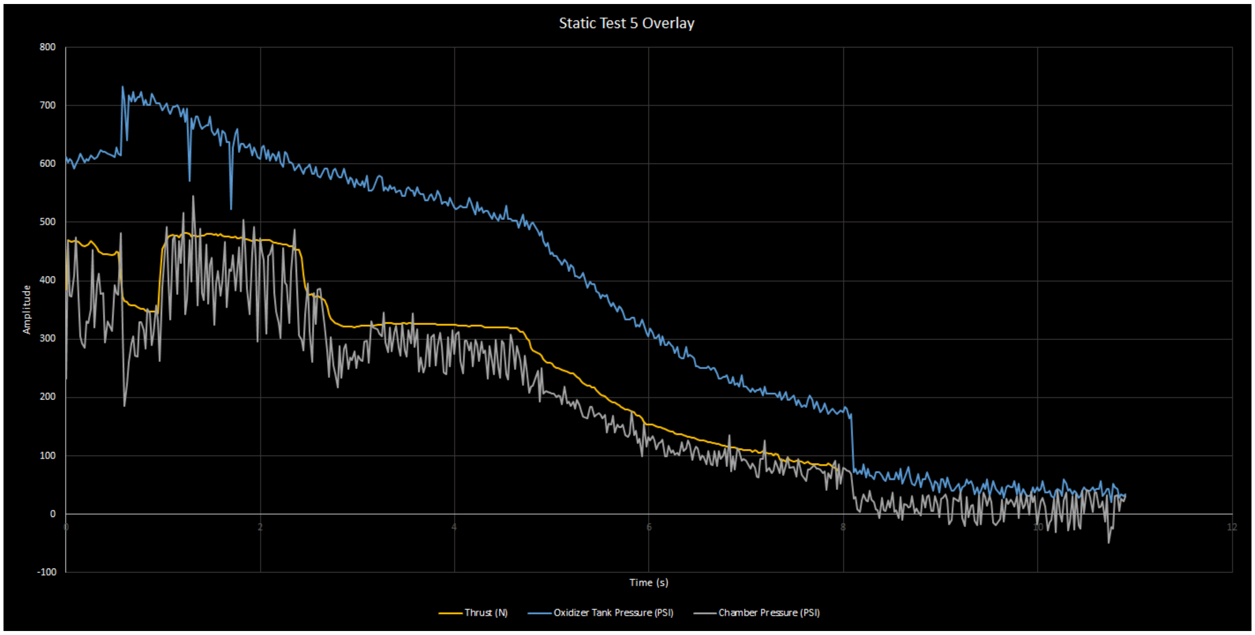


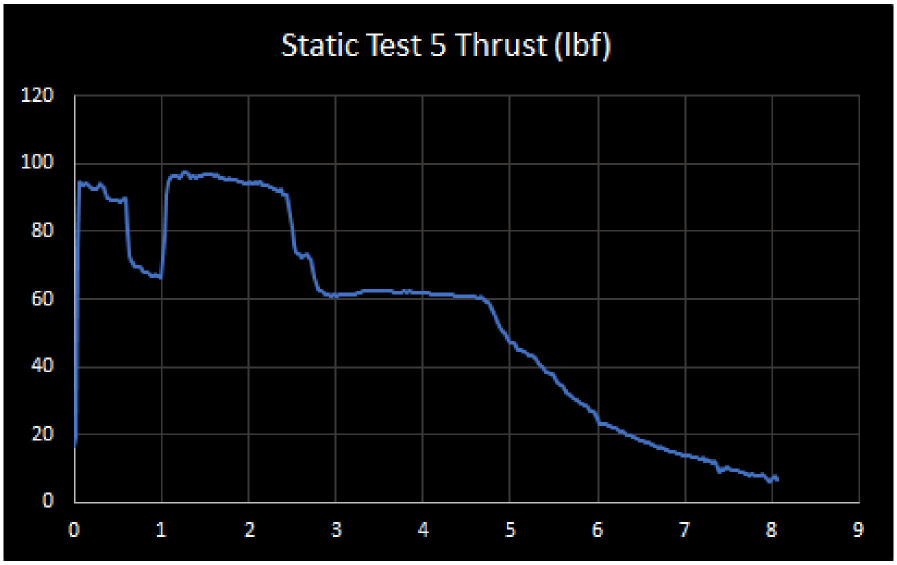


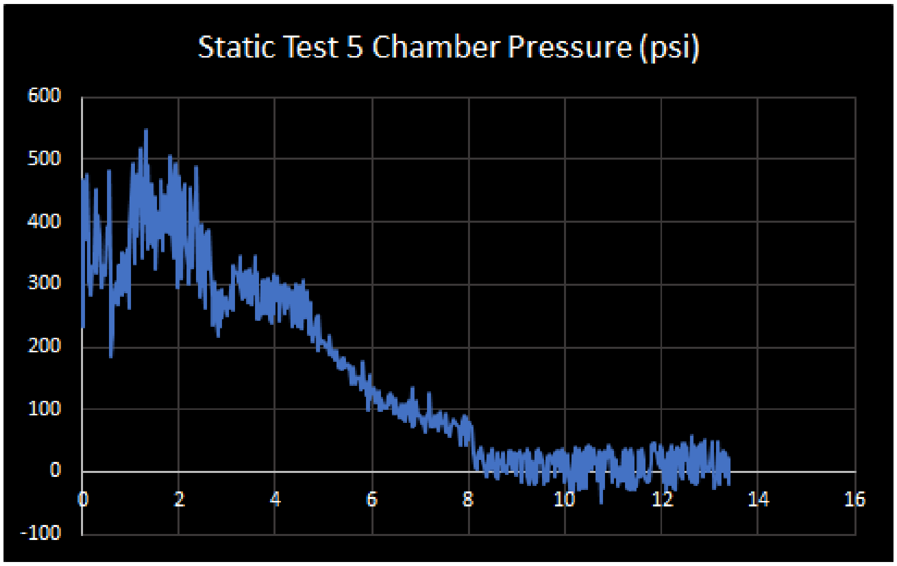


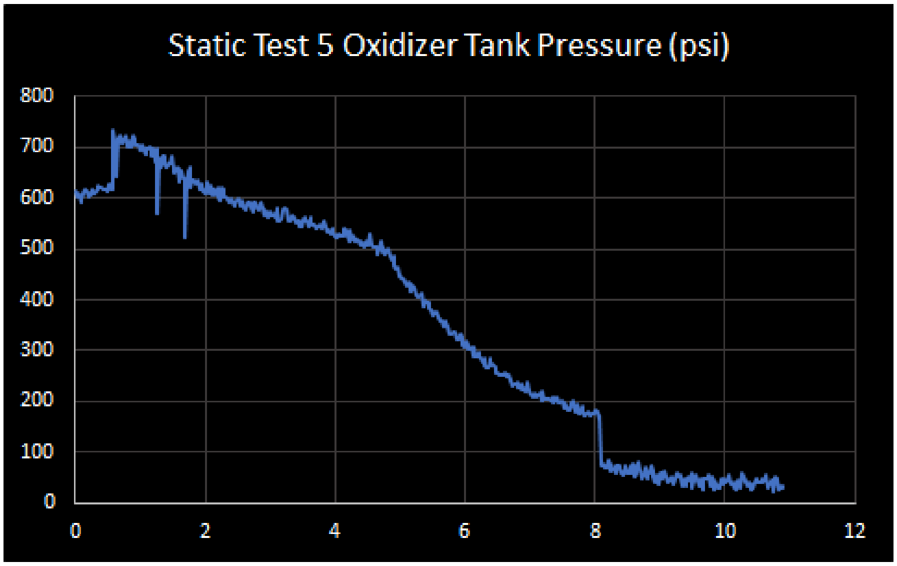

Static Test 4 Chamber Pressure (psi)
600
500
400
300
200
100
0
162
164
166
168
170
172
174

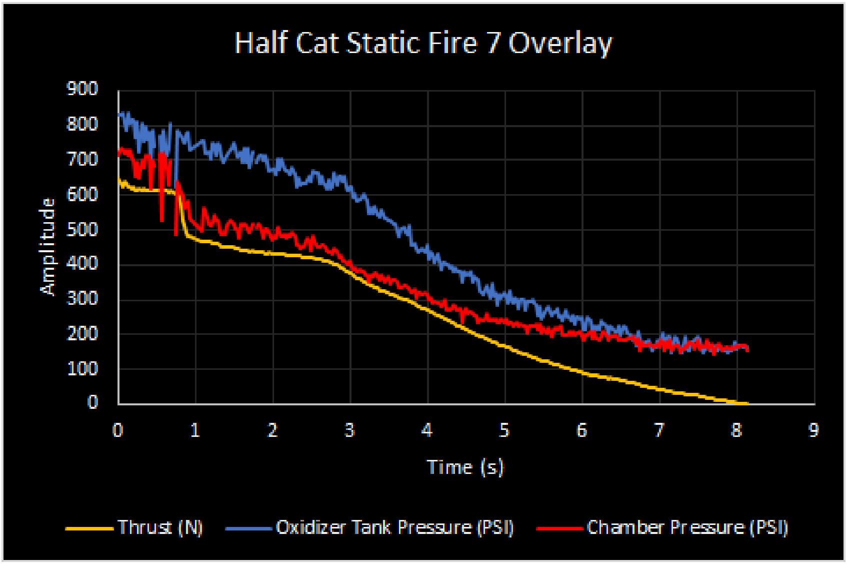

Static Test 4 Oxidizer Pressure (psi)
900
800
700
600
500
400
300
200
100
0
162
164
166
168
170
172
174

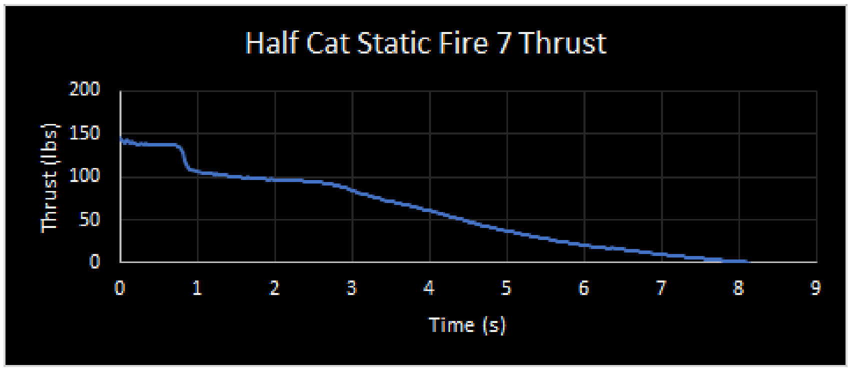

Static Test 5 Overlay
Amplitude
800
700
600
500
400
300
200
100
0
-100
0
2
4
6
8
10
12
Time (s)
Thrust (N)
Oxidizer Tank Pressure (PSI)
Chamber Pressure (PSI)

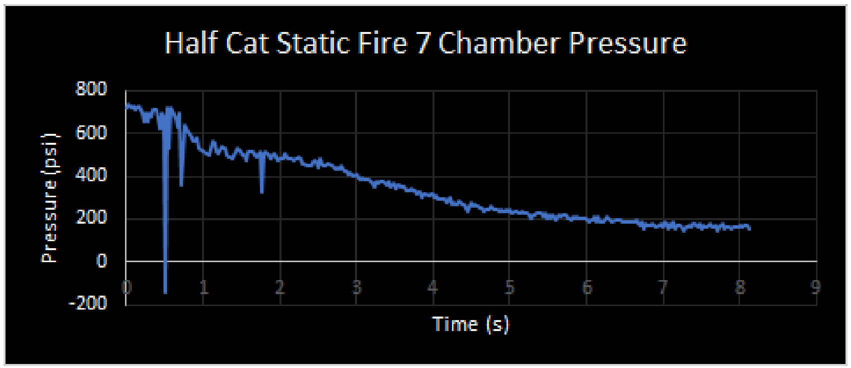

Static Test 5 Thrust (lbf)
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9

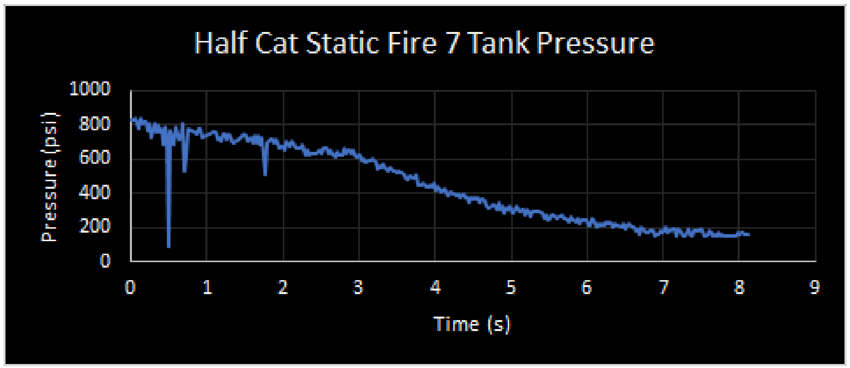

Static Test 5 Chamber Pressure (psi)
600
500
400
300
200
100
0
-100
0
2
4
6
8
10
12
14
16


Static Test 5 Oxidizer Tank Pressure (psi)
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12


Half Cat Static Fire 7 Overlay
Amplitude
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
Time (s)
Thrust (N)
Oxidizer Tank Pressure (PSI)
Chamber Pressure (PSI)


Half Cat Static Fire 7 Thrust
Thrust (lbs)
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
Time (s)


Half Cat Static Fire 7 Chamber Pressure
Pressure (psi)
800
600
400
200
0
-200
0
1
2
3
4
5
6
7
8
9
Time (s)


Half Cat Static Fire 7 Tank Pressure
Pressure (psi)
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
Time (s)