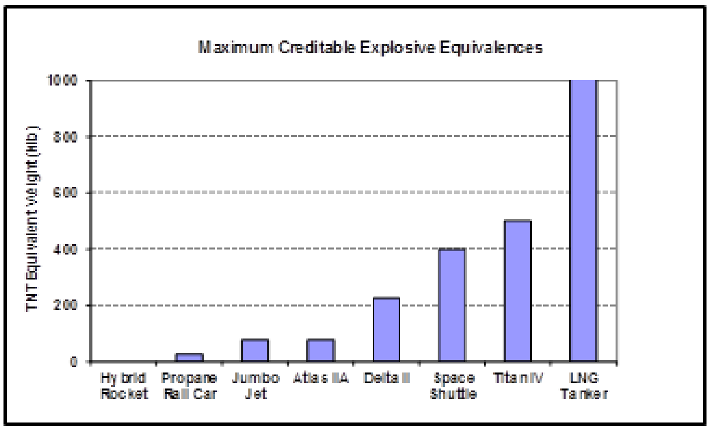
Rocket Propulsion and Launch Safety

During the last half century, over half of all launch failures have been attributed to rocket propulsion anomalies - most causing the vehicle to explode resulting in a catastrophic loss. Therefore, any discussion about launch safety has to start with an objective conversation about the rocket propulsion systems that power these vehicles and a willingness to honestly address the question of why government and industry leaders have come to accept a failure rate that would be unacceptable in any other form of transportation.

While there are many forms of rocket engines capable of propelling a spacecraft into orbit, only chemical rockets, using highly-energetic propellants, are capable of creating the thrust needed to accelerate a payload from or near the Earth's surface to orbital altitude and velocity. A chemical rocket by definition is a reaction machine that operates in accordance with Newton's Third Law of Motion, i.e., *for every action, there is an equal and opposite reaction*. In all chemical rockets, the fuel and oxidizer are mixed and ignited to create hot gases which are expelled through the rocket's nozzle to generate thrust.

To appreciate the amount of onboard stored energy needed to launch a payload into low earth orbit, consider that the rocket engines must accelerate the vehicle, overcoming gravitational and atmospheric drag losses, to approximately 25,000 feet per second. This is over nine times faster than a 30-06 rifle bullet. Highly energetic chemicals like those used in rockets can be very volatile and explosive. To dramatize this point, the graph (left) compares the explosive potential (TNT equivalence) of several orbital launchers with other transportation vehicles carrying highly energetic fuels. Note also the "0" TNT equivalency for Hybrid Rockets (to the left on the graph) which will be discussed later.



As part of the arms race between the U.S. and the former Soviet Union following the end of the Second World War, chemical rockets were aggressively researched and developed by both superpowers. Orbital launchers developed over the last half century by civil space agencies like NASA as well as commercial spaceflight firms can trace their technical heritage to the intercontinental ballistic missiles developed and produced during this period. These highly complex systems were designed with performance and speed of development in mind – not safety or economy.

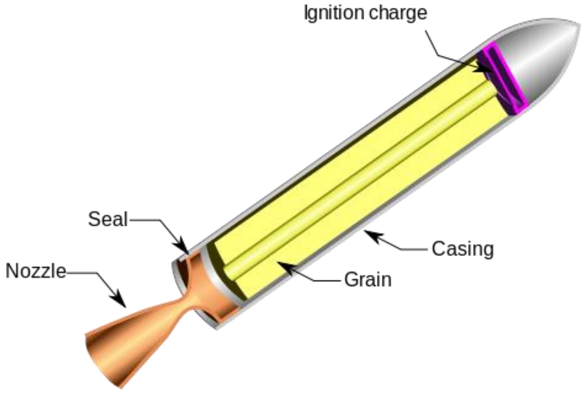
Despite almost a half century of efforts by governments and private industry alike to improve the safety and reliability of chemical rockets, launch failure rates remain stubbornly persistent. According to the FAA, 6.1% of all U.S. orbital launches since 1980 ended in failure. Officials with NASA and the U.S. Department of Defense, as well as many space industry leaders and scientists have come to accept this poor safety record as an intractable fact of life. NASA's William Gerstenmaier exemplified this view when commenting on the string of U.S. launch failures in 2015. Following the Falcon-9 explosion he said, "We expected through the commercial cargo program we would lose some vehicles. I didn't think we would lose them all in a one-year time frame. But we have."

Rocket Crafters, Inc. (RCI) is challenging this paradigm. We believe our radically different approach and disruptive patented hybrid rocket propulsion technology will enable us to build the world's first safe, reliable and affordable orbital launcher – Intrepid-1.

There are three basic forms of chemical rockets in use today, differentiated by propellant states of matter and their combustion methods: Solid, Liquid, and Hybrid.

Solid Rockets

The first solid rockets were built centuries ago using gun powder as propellant. They were the forerunners of today's solid rocket motors used in many military weapon systems and as boosters for launch vehicles. In a solid rocket motor, the fuel and oxidizer (both in solid state) are blended intimately together to form a grain. As can be seen in the system diagram (below right), an ignition charge located forward of the grain starts the combustion reaction. The rocket's propellant combusts until it is exhausted. Solid rockets cannot be shut down, restarted, or throttled. By design they are dangerous. They have been known to ignite unexpectedly. They are sensitive to shock, high temperature exposure, and static electrical charges. Any crack or fault in the grain can generate an event causing a catastrophic loss. Shipping, handling, and operating procedures are necessarily strict, cumbersome, and expensive.



Solid Rocket Motor System Diagram

Liquid Rockets

A second type of rocket uses a liquid engine. Within this category, there are several types. However, only the bi-propellant form is used as primary propulsion for space launch. In this type of rocket, the oxidizer and fuel are both stored in a liquid state. Liquid oxygen, which must be maintained at or below -183^{o} C, is a favored oxidizer in combination with either cryogenic liquid hydrogen (-253^{o} C) or an ambient temperature fuel such as kerosene, methane, alcohol, or more recently natural gas.

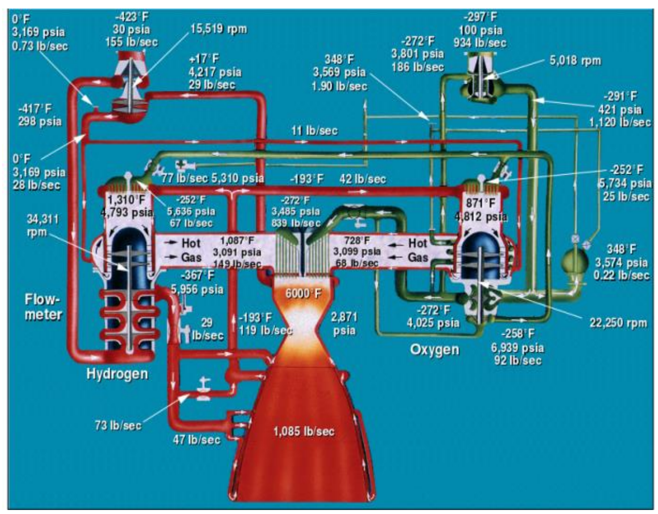
The oxidizer and fuel are brought together in the combustion chamber under high pressure and temperature to generate the hot gases needed to produce thrust. Traditionally, liquid bi-propellant engines employ ultra-high-speed turbo pumps to accomplish this task. These pumps, driven by exhaust gases from a pre-burner that use a small portion of the on-board oxidizer and fuel, operate at speeds of up to 44,000 rpm. These are precision, complex pieces of equipment that are typically hand-crafted to extreme tolerances. Made from expensive lightweight metals, some require over 10,000 man hours to build and inspect. When they (or their associated plumbing) fail, they usually do so catastrophically.

Liquid Bi-Propellant Rocket Systems Diagram

Alternatives to turbopumps such as pressure fed systems, requiring heavier tanks, have also been tried. However, this approach results in significant performance penalties. Other alternative approaches such as piston pumps, operating at much lower speeds and pressures have also been tried. In all cases, liquid bi-propellant engines are very complex with hundreds of moving parts and sensors, extensive plumbing systems - all creating complex failure modes. (This is where the expression, '*This is not rocket science'* comes from.)

Due to the volatile nature of the propellants used, fueling is limited to weather conditions free of area storm clouds. Since liquid oxygen as well as liquid hydrogen both boil off and evaporate at ambient temperature, fueling must be completed just before the planned launch. Liquid oxygen will react aggressively with any fuel source. All it needs is a spark or a high temperature source to ignite.

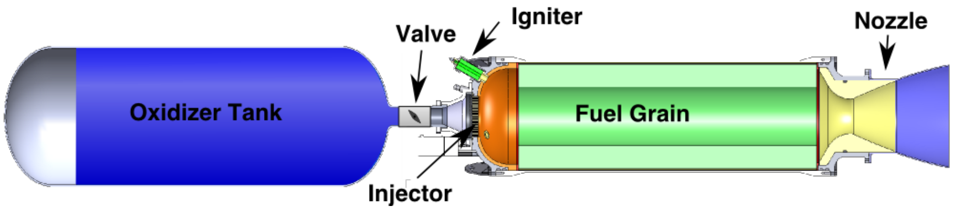
Although the engine may look simple in the systems diagram (previous page), an actual photo of a liquid bi-propellant engine (below left) gives a better idea of the complexity as does the plumbing schematic illustration (below right).



Hybrid Rockets

There is a third type of chemical rocket that is often overlooked – hybrid rockets. In the rocket propulsion community, owing to its inherent safety and mechanical simplicity compared to solid or liquid rockets, there is a consensus that if a hybrid rocket engine can be developed that runs consistently with reasonable performance, and without combustion instability, it would be ideal to power launch vehicles and spacecraft. This is especially true for commercial launches and crewed flights where safety and economy are a high priority. Hybrid rockets are inherently safer to build, store, transport, and operate than either solid or liquid rockets. In a traditionally configured hybrid rocket, the fuel is in solid state and the oxidizer is in liquid state. By storing the propellants onboard in two different states of matter, coming together only as designed within the combustion chamber, it is almost impossible for the propellants to accidentally mix and detonate. By comparison with solid and liquid rockets, hybrid rockets, if they fail, do so more benignly.

Given their inherent simplicity, safer storage of fuel and oxidizer, benign failure mode and lower cost, a legitimate question is why are hybrid rockets not the first choice for military, space exploration, and launch vehicle applications? The answer relates to the relatively small amount of Government funding that has been invested in hybrid rocket research over the last half century compared to solid and liquid rockets. As previously discussed, during the Cold War years rocket research focused on performance and speed of development – not safety or economy. Consequently, hybrid rockets, which were historically lower performing, simply did not get any real attention by the U.S. Military or NASA. This lack of research funding resulted in a built-in bias in favor of solid and liquid rockets by university researchers, government officials, and private industry executives and scientists. However, the landscape is changing. Government budgets are being reduced, launch failures are less acceptable, especially if it results in loss of life, and the fast-growing commercial space industry has different priorities - with safety and economy ranked higher.



Hybrid System Diagram

D-DART™ Hybrid Rockets

Rocket Crafters is pioneering a new hybrid rocket technology – one that is significantly more reliable, consistent, and higher performing. Our proprietary D-DART™ (Direct-Digital Advanced Rocket Technology) hybrid rockets use a propellant combination of nitrous oxide (N_20) and a blend of acrylonitrile butadiene styrene (ABS) thermoplastic and high-energetic aluminum. ABS is the same material that LEGO bricks are made from and nitrous oxide, a self-pressurizing liquefying gas is used in drag strips as a fuel additive as well as an anesthetic in medical and dental offices throughout the world. Nitrous oxide, unlike cryogenic liquid oxygen is stored at ambient temperature. It does not possess the aggressive reaction characteristics of liquid oxygen. Since it is self-pressurizing, no pumps or heavy tankage is required.

However, what sets RCI's D-DART hybrid rockets apart from other hybrid rockets is the production method used to form the solid fuel into a carefully engineered grain. D-DART fuel grains are 3D printed – not cast or molded the way fuel grains have been made in the past. RCI uses state-of-the-art giant-scale additive manufacturing machine technology like the Cincinnati BAAM (pictured top next page) to precisely and repeatedly print near-perfect grains. This eliminates the grain flaws and resulting inconsistencies common to other hybrid rocket designs. Printed ABS grains are significantly stronger and able to resist the compressive pressures exerted upon the fuel grain during operation. Consequently, pressure fluctuations and related performance consistencies inherent in other hybrid rockets are eliminated.

D-DART Fuel Grains Being 3D Printed on the Big Area Additive Manufacturing (BAAM) Machine – Courtesy Cincinnati, Inc.

Moreover, the additive manufacturing and related factory robotics used extensively in our operations will support rapid rocket engine development, testing, and improvement. This attribute helps RCI address another significant and seemly insurmountable safety challenge – the ‘experimental conundrum’. The experimental nature of launch vehicles and their rocket engines is often cited as the real reason why space transportation cannot achieve the same level of operational safety that other forms of transportation enjoy. This premise is based on the question: how does a launch vehicle that has only launched a dozen or so times develop and mature the same way as an aircraft or automobile that has undergone continuous improvements involving dozens of models produced in the hundreds or thousands?

Our rocket engines are being developed to power Intrepid-1, the first in a family of launchers designed specifically to launch small payloads. Small satellites are increasingly being built and launched to conduct serious commercial business in space. However, existing launchers are unable to meet these customers’ requirements for short lead times, low cost, and precise orbital delivery. RCI’s Intrepid-1 is being developed specifically to meet the needs of the fast-growing small satellite community. It is only through rapid development and high launch frequencies that space launch firms can hope to evolve and mature their launchers and launch systems to a much higher level of safety and reliability. Add to this RCI’s much safer, lower cost rocket engines, and you have a winning formula.

Intrepid-1 Launch artist illustration

The unique characteristics of RCI’s D-DART hybrid rockets stem not just from the patented technology, but from the conscious decision to prioritize safety, reliability and affordability ahead of performance in the design of our Intrepid-1 launch vehicle and Company operations. At RCI, safety is not an afterthought. Rather it is inherent in the selection of our rocket engines and the design of our launch vehicles.