Replacing hydrazine fuel with a greener alternative

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After half a century of using a highly-toxic chemical propellant called hydrazine for space propulsion, governments and experts are demanding change. With rapid expansion of an increasingly privatised space industry, a new green alternative and a new way of thinking is needed to address the international demand to protect our planet and its atmosphere. Joshua Rea asks how hydrazine came to dominate the industry, why finding a replacement has proven so difficult and whether a viable solution exists.

Almost 100 years ago, back in 1922, Dr Robert H Goddard began experimenting with rocket engines while lecturing at Clark University, Massachusetts, and he achieved the first ever flight of a liquid propelled rocket just four years later. A decade later saw Luigi Crocco testing the first monopropellant, comprising both fuel and oxidiser.

By the end of World War II, the United States knew that guided and ballistic missiles would be the weapons of the future and propellants were needed. Pumping cryogenic propellants like liquid oxygen just before firing was fine for long-range ballistic missiles, but not when it came to short-range tactical missiles. They needed a finger on the pulse at all times, which required a storable propellant.

The US Navy engaged all companies with a vested interest in weapons, and a few in aviation, to conduct surveys that analysed every prospective fuel they could think of, rigorously looking into the performance of each. All performed similarly, with the exception of one: hydrazine.

Near-perfect propellant?

Hydrazine also turned out to have a number of properties that made it an (almost) near-perfect fuel for space. It has a density of 1.004 - equivalent to water – making it compatible with satellite

NASA/Isaac Watson

▲ Fuelling a satellite with hydrazine requires technicians to wear Self-Contained Atmospheric Protective Ensemble (SCAPE) suits which are supplied with air either through a hardline or through a self-contained environmental control unit.

tanks and, just like short-range tactical missiles, it could be stored long term and used at any time. It has a very high specific impulse (a measure of efficiency), which means that relatively small amounts have a large effect. It is also easy to ignite with a catalyst as a monopropellant, making ignition reliable and repeatable, and is hypergolic as a bipropellant, meaning that, with the right oxidiser, there is no need for an ignition system.

When the need for satellites to have their own onboard propulsion systems arose, hydrazine was the obvious choice. It has remained so for the past 50+ years.

But hydrazine comes with some serious pitfalls. When released into the atmosphere, hydrazine emits dense yellow clouds of highly-poisonous vapour. If it touches human skin, painful burns ensue. There have also been numerous cases of exposure leading to premature disease and mysterious ailments; it is highly carcinogenic and widely considered to be fatally toxic. The hazard is significantly increased in bipropellant systems that commonly use nitrogen tetroxide as an oxidizer.

Anyone watching hydrazine being put into a satellite would think they were watching a scene from Steven Spielberg's ET - The Extraterrestrial. Significant effort and safety precautions are required during ground operations and full-body Self-Contained Atmospheric Protective Ensemble suits, also known as SCAPE suits, need to be worn at all times. Refuelling needs to be done on-site, meaning launch sites must be evacuated by all other personnel and can be shut down for up to three days.

Risk is reduced when the correct infrastructure to manage this fuel is available, but proper infrastructure can't be counted on. Some Chinese civilians, for example, have suffered when Long March boosters impacted their villages, emitting thick clouds of yellow smoke, while Russian civilians have watched the yellow clouds from exploding rockets and been close enough to take videos with their phones (see YouTube: Proton M rocket explosion).

The fuel and refuelling systems for hydrazine are also extremely expensive - typically US$500,000 per satellite - but with large satellites traditionally costing upwards of $300 million, $500,000 is a drop in the bucket.

Better options

Today, companies worldwide are working to build amazing new capabilities using enhanced satellite technology, claiming that what they are doing will improve life on Earth and often boasting their environmental responsibility credentials. But

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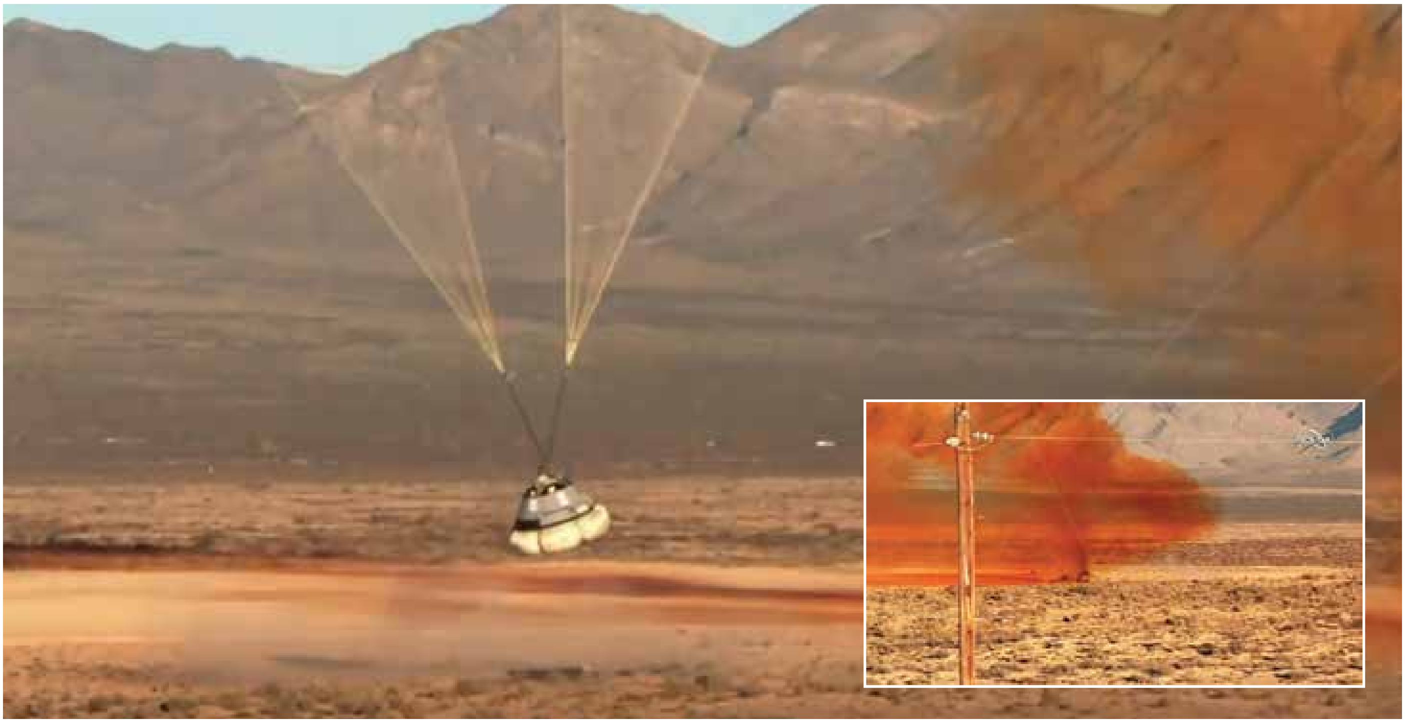

▲ A cloud of tetrazine billows to the right of Boeing's CST-100 Starliner at the end of a pad abort test on 4 November 2019. Boeing said that the hydrazine cloud was expected due to "dribble volume" from the Starliner service module.

this technology comes with the risk of damaging potentially thousands of lives when hydrazine is used, as Intelsat experienced directly when it bought a ride on the Long March 3B. So, naturally, the space industry needs a better option.

Satellites must have some sort of propulsion to enable them to de-orbit, thus fighting the increase in space debris and avoiding the Kessler Syndrome (collisional cascading). So just removing propulsion is not an option. For the past decade, huge investments in time, money and resources have been made by some of the world's largest institutions to try to find a replacement.

The European Union is leading the charge with plans to ban hydrazine by 2021 and its Horizon 2020 fund has pumped millions into supporting R&D for hydrazine replacement. As a result, novel non-toxic fuels are making their way to market and competing to become the next big player.

One that has gained the most popularity is a fuel based on ammonium dinitramide (ADN), invented by the USSR in 1971, called LMP-103S. There are others too, such as hydroxylammonium nitrate (HAN), also called AF-M315E, and proprietary bipropellant combinations of hydrogen peroxide combined with the hydrocarbon NHMF (non-toxic hypergolic miscible fuel). These new non-toxic alternatives embody many of the characteristics that make hydrazine so great for use in space, but for most manufacturers they are not hitting the mark and they have not been widely adopted over the decades they have been available. Some space companies have been obliged to use these alternatives due to environmental pressures, but they are forced to accept engineering design trade-offs and very high fuel costs as a result.

For one, they are not hypergolic; catalysts need to be preheated, meaning that it can take upwards of an hour before the system can be used, so they are no good for tiny manoeuvres. And finding a catalyst that actually works has been a huge problem. It also puts additional thermal stress on the system, reducing lifespan. Performance is typically lower than hydrazine alternatives and, although they are stated to be higher-performing than monopropellant hydrazine systems, they fall short against bipropellant systems. Fuel prices are also significantly higher than hydrazine.

Moreover, availability is scarce as there are only two suppliers that make ADN in Europe, that keep a close hold on supply, and only one supplier globally of the proprietary hydrogen peroxide-NHMF mix. This brings huge limitations to anyone wanting to conduct thorough on-ground testing of new systems or integrate their satellite in parts of the world that cannot get supplies.

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Although classied as green, there are often logistic restrictions when shipping these chemicals. This further reduces the pool of launch providers, often meaning they cannot take the cheapest or most convenient ride.

Arguably worse than this, the salt formed by these propellants is a friction-sensitive explosive, which requires significant handling effort on the ground and increases risk in orbit. If there is a leak and propellant evaporates, salt is left behind and can build up in systems over time, leading to potential detonations when lines are opened, causing the satellite to explode. This makes the decision to go green far worse than using hydrazine, as it potentially adds to the space debris issue. Finally, most of these systems use a 'blow down' pressure system, meaning that tank pressure decreases as the tanks empty, thus reducing propulsion efficiency. This is inconvenient for many reasons, especially when ensuring reliability for end-of-life deorbiting, unless expensive, complicated workarounds are implemented.

All this means that space companies are losing capabilities by using these new fuels, instead of gaining them. Propulsion systems are leading the drive of satellite design, but it's the payload that pays. As the industry of building space products and services moves away from government and military ownership towards privatisation, this disconnect between the technology and the customer will not result in a sustainable and scalable practice.

Never before has there been such a level of access to space. Since Sputnik, roughly 8,500 satellites have been put into orbit. Now, a multitude of customers want to put this number up themselves – in a single constellation – and others hope to exceed this amount over the next few years.

Market analysis

At Dawn Aerospace we wondered: what is it people actually want to do with their satellites? What is the objective of their payload? And what do they really need in a propulsion system? We talked to as many people as possible to find out.

Transportation and logistics are the foundation for accomplishing anything in space and propulsion is at the heart of both. You can't get to space, stay in space, move around in space, or come back from space without propulsion.

But if we were to offer a replacement technology, we needed to make sure we would not just replace hydrazine, but also bring to market a vastly better solution. We needed to understand what the customers and their payloads were actually trying to accomplish, then design products to suit.

We discovered that it comes down to versatility, simplicity and transparency.

Jim Waymer/Florida Today/SpaceX

▲ Swimmers enjoy themselves at Cocoa Beach, Florida, in April 2019, while a highly toxic orange plume rises from nearby Cape Canaveral after a failed test fire of SpaceX's Crew Dragon capsule. If the cloud had reached people, it would have potentially caused severe burns on contact.

Versatility

Constellations need high-performance propulsion. Constellations that get online faster make money faster. They need fast manoeuvres, rapid responsiveness, to maintain very low Earth orbits, and precise de-orbiting. This rules out entire classes of propulsion, such as electric or water plasma. These types are perfect for long missions, where the payload is dormant, like a mission to an asteroid, but cannot compare to chemical in terms of responsiveness. Operators want stable mass flow-rates and a constant specific impulse. This is so that one system can be used for both in-orbit operations and for de-orbiting, having the same reliability at the end of life as it did at the start. It must be highly versatile and, ideally, the same technology and philosophy will work on a 1U or 10,000U satellite.

Simplicity

Manufacturers want a lightweight and simple feed system, like those used for monopropellants, to reduce operational risk and launch costs. Ideally, this could be designed to be even simpler than a

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monoprop system, without the need of propellant pressurisation systems. Operators need the ability to perform major manoeuvres, like rapid de-orbiting in hours and days, not months or years. They also need the ability to do very small impulses to allow for the tiniest of manoeuvres anytime they want, without pre-heating.

Power must be dedicated to the payload, so power consumption of the propulsion system must be kept to a minimum. Anything the propulsion systems uses is power not available for the business of collecting data and sending it to the ground. Operators want to refuel anywhere, anytime, without special environments, equipment or multi-million dollar investments in ground support. Doing so would save days in launch preparation, significantly opening up launch provider options and reducing costs. People also want to be able to test themselves and test often throughout integration. This means being able to run a system in their own lab environment, and being able to get their hands on more fuel when they run out, cheaply and quickly. Fuel needs to be made highly available - able to be sourced from nearly any country, at the quality needed, quickly and at a reasonable cost. There should be hundreds if not thousands of suppliers, ensuring prices are low and supply is high.

Transparency

New commercial space ventures coming to market are having an extremely tough time with the quagmire of half information, secrecy and lack of transparency across suppliers. This is coupled with an increasing trend of suppliers boasting capabilities they just don't have. There's a special term for this in industry - it's called BS. In bids to win contracts, suppliers are saying they can provide capabilities and deliver on timelines that are just not realistic. These leads to unneeded months spent on complex missions analysis and design, with goal posts that keep moving and further taking away from payloads paying. People want transparency, a vendor that will work with everyone, and an affordable price tag that all can see. Full specifications upfront, realistic timelines, advice on the implications on their bus when they make certain feature designs, and suppliers that do what they say they will do. And if something is going to take longer than expected? Just tell them.

Solutions

This is a hefty list of requirements. We knew that chemical propulsion was the only way

Dawn Aerospace

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forward, but what propellant can accomplish all of this?

The advances in 3D printing now allow for significant increases in design complexities, previously unattainable through traditional engineering. These complexities also open an entirely new pool of potential propellants that were previously unviable for application in space. So, with this in mind, we went back to the drawing board and re-evaluated all possible fuels with the following conditions: they must be powerful, they must be self-pressurising and they must be so common that you can buy them at The Home Depot. Instead of developing a new fuel, we needed to ‘build the smarts required’ to make common propellants applicable in space.

Enter nitrous oxide and propene (also known as propylene or methyl ethylene). Nitrous oxide and propene maintain the high-thrust capability and specific impulse figures of classical bipropellant chemical propulsion. Used correctly, their total impulse density greatly outperforms cold-gas systems. Self-pressurising, when fuelled into a system to manage this, they deliver stable pressures and mass flow-rates. Feed systems are therefore simpler than monoprop alternatives, as no helium pressurisation is needed, and hardware such as high-pressure regulators are completely redundant. The propellants can also be stored under their own vapour pressure for years on end.

They also work in highly scalable architecture, allowing for use across a large number of in-space applications. Thrust levels of 0.5N has been encapsulated within a standalone 0.7U unit, ready to bolt on to the smallest CubeSat. The thrusters are also sized for 1U to 12U+ satellites, allowing use for any CubeSat. For much larger satellites and CubeSat deployers, 22N thrusters have been developed, delivering capabilities and accessibility unavailable anywhere else in the market. We even scaled this up to 200N for an autonomous rocket-powered unmanned air vehicle (UAV).

Combustion chambers are designed with regenerative cooling, allowing for sustained burn times. Ignition-based, with no catalysts, these systems also offer near-instant ignition from sleep with minimum impulses of less than 4Ns, and require very little power to fire. In combination with such high thrust, virtually instantaneous changes to orbital parameters can be made.

The combination of all this means payloads can get online faster and stay online longer. Payloads can do what they are designed to do: pay. As well as being very cheap, these propellants are also safe. In fact, they are so safe, one of them is classified as food grade and used within whipped cream canisters; the other is used in a BBQ.

This technology is not just a viable alternative, but one that significantly upgrades spacecraft capability. It is a technology designed from the ground up to be usable and scalable for a modern space age, one with an architecture that can be scaled for an entire ecosystem, not just a subset of it. It is a technology that companies and their customers can be proud to fly with for generations to come. ■

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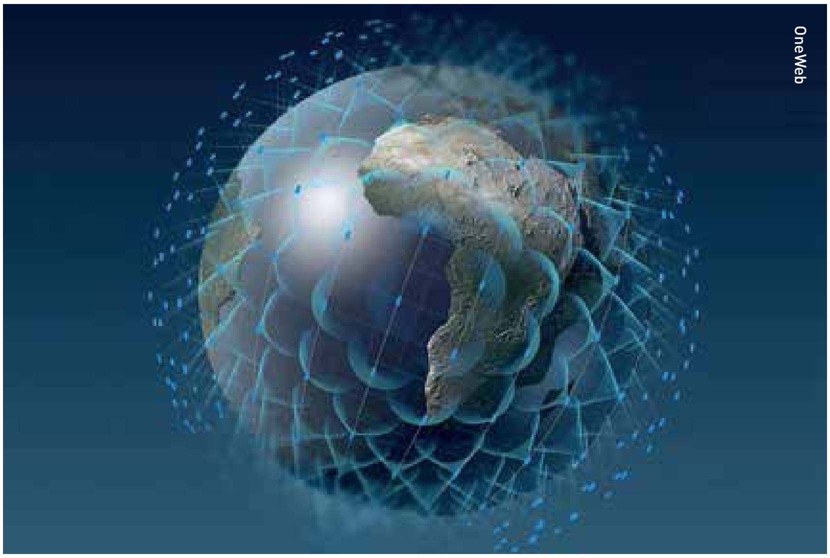
About the authors

Joshua Rea is responsible for business development at Dawn Aerospace and was the first non-engineer hired by the company. After spending almost a decade expanding a hundred million dollar ad-tech company into new global markets, Josh knows how to listen and how to provide solutions that solve problems. Once told to surround himself with smart people, Josh took this to the extreme, surrounding himself only with rocket scientists. Recognising that space technology was stuck in an upward spiral of cost, waste and toxicity; that was unscalable and unsustainable, Josh is helping bring Dawn’s highly reusable suborbital spaceplane and high-power, sustainable propulsion products to market in a bid to change this. Josh spends his spare time as a deep-sea exploration diver, living life on Earth as closely as one can to an astronaut’s.

Stefan Powell has been building rockets since his early student years and spent his entire career in both rocket and satellite start-ups that push the envelope. CTO of Dawn Aerospace, Stefan now heads various technical teams building reusable launch vehicles and new space transportation technologies. A Kiwi at heart with a dash of Dutch eccentricity, Stefan is currently spending his spare time exploring all ways his green thrusters can be used to cook the company’s weekly BBQ or dance the dance to classic music.

▼ Artist’s rendition of the OneWeb constellation, which will ultimately total more than 900 satellites. Other companies have similar, if not greater ambitions. To succeed in a highly competitive market, constellations will need high-performance propulsion to get online faster and to make money faster.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