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Spacecraft Propulsion

By
Michael McCollum

One of the most endearing qualities of human beings is that we are never truly satisfied. Time was when life was considered good if you had food in your belly and the saber tooth tigers weren't prowling the entrance to your cave. Later, people were happy if they managed to accumulate 40 acres and a mule. My father's generation lived through the Great Depression, World War II, and the Cold War. They were happy if they could buy a small house and a new car every few years. My generation is different. We baby boomers are acquisitive by nature. We aren't content no matter how many houses, automobiles, television sets, computers, cell phones, and VCRs we acquire. We still want more.

While unattractive, this trait has positive effects on society. There would be no progress if everyone were satisfied with his or her lot in life. I just finished reading *A World Lit Only By Fire* by William Manchester, and he points out that one of the defining characteristics of the medieval mind was a total lack of ambition. You were born, lived your life in the same hovel as your parents, and you died. The vast majority of people lived on the land, worked their squalid farms, and never dreamed of anything better. As a result, progress in Europe came to a halt for a thousand years following the collapse of the Roman Empire. Only with the rise of the merchant class did things start moving again. (And yes, I am aware that I am perilously close to giving a "Greed is Good" speech like the one the Michael Douglas character gave in *Bonfire of the Vanities*.)

Luckily for those of us with an acquisitive nature, we live in a universe that is custom designed to feed our addiction. Ever since the end of the Apollo program in the early 1970s, the news media (primarily in the United States, but also around the world) has preached the doctrine of limits. "We have only one planet," "less is better," "limit growth," are recurring themes among those who would form public opinion. But as we discovered in the last article, it just ain't so! The human race is rich beyond the dreams of King Midas. We own one small star, nine planets in assorted sizes, 61 moons, tens of thousands of asteroids, and hundreds of billions of unborn comets. Granted, we have some work to do before we can reach our possessions, let alone exploit the riches they represent. But that is a mere technical detail and one thing we humans have proven we are good at is dealing with mere technical details.

Just as it was inevitable that Europeans would bump into the Americas as they tried to find a cheaper route to the riches of the Orient, so it is inevitable that our children and grandchildren will build an interplanetary civilization. The going will be slow and painful at first, with many setbacks and much heartbreak. But then no one ever said that progress was pretty. Nor will it be the antiseptic utopia so beloved by early science fiction writers. The future will be messy, just as the past was messy. It will hold as many fools, charlatans, and crooks as have past eras; and also as many heroes, saints, and doers of great deeds. Of that we can be sure.

In the previous chapter we surveyed our future domain and found it in need of work (only one planet out of nine can currently be classified as prime real estate). If we are to write stories set in the great interplanetary civilization that will one day dominate local space, we will eventually have to write about spaceships. Since most SF writers are not scientists or engineers, they have only the vaguest notion of how spaceships operate. Nor is it necessary that they be experts on the subject. As I am fond of reminding new writers, "We don't have to build the damned things, we merely have to describe them!" Still, some knowledge of the subject is necessary in the practice of our craft if we are to write convincingly. Do you think that Tom Clancy could have written *The Hunt for Red October* if he hadn't been a submarine enthusiast in the first place?

The subject of this article, then, will be the technology required to get a spaceship from one planet to another. For the foreseeable future that means rocket propulsion and so we will be reviewing the basic principles that allow a rocket to operate in space.

Caution: We will be getting a little technical because even a rudimentary understanding of how rockets work requires a bit of mathematics. Even if you normally shy away from anything with an equation in it, try to follow along. Anyone who has successfully navigated high school algebra should have no trouble understanding the principles involved. What follows are the rudiments of how reaction propulsion systems work. Trust me, it's easy. After all, this ain't exactly rocket science we're dealing with here!

Spacecraft Propulsion and Science Fiction Writing

For more than ten years I have been a professional after dinner speaker. My most popular talk is titled "Spacecraft Propulsion and Science Fiction Writing: The Art of Matching Propulsion to Plot." In it, I review the various types of science fiction stories and then explain the importance of having spaceships that match the requirements of the story line. If all of this sounds very dry, that is my secret weapon. I give my talk mostly to engineering groups, and afterwards a spouse or two will inevitably come up and say, "That wasn't nearly as boring as I thought it would be, and I even liked the jokes!"

So what has spacecraft propulsion to do with plotting a science fiction story? If you are writing an interplanetary romance, it has everything to do with it. If the ships are too good, there will be no tension developed in the story. The heroes will merely hop in their spacecraft and an instant later, be at their destination. Where is the fun in that? If the ships are too poor, then the story will lack verisimilitude. If your spacecraft remains something from out of the 1960s, people are going to find it difficult to believe that your characters actually live in a spacefaring civilization.

Stretching the reader's credibility leads to a violation of the contract between the writer and reader, and your book will probably go unfinished. Worse, your next book will not be bought, costing you a portion of your potential income. In other words, this is serious stuff we're discussing here!

The rule in science fiction is that you don't explain how your ship works, you describe what it looks like. The reason for this is simple. Most readers' eyes glaze over when they reach the part of the story where the author explains in loving detail how the engines operate. "The rocket rose high on a plume of fire as twin 5000 hp turbopumps forced liquid hydrogen and oxygen into the combustion chamber at 3000 psi pressure, where the mixture ignited to burn at a white hot 10,000 degrees, before being forced out of the bell shaped, convection cooled nozzle to expand into a white contrail as the hot water vapor cooled in the upper stratosphere to form ice crystals."

Is everyone still awake out there?

It is better to say, "The rocket rose high on a plume of silent fire, trailing a long snake of white condensate behind. The condensed ice crystals of the ship's exhaust were torn by the variable winds aloft, turning the contrail into a twisty snake." Even that might be excessively technical for some readers. Note: Tom Clancy gets accused of this sin a lot. It hasn't exactly hurt his book sales.

But even though you don't give the readers the technical details of your ship's propulsion system, it is important that you, the writer, be at least aware of them. By understanding how spaceships operate, they become more real to you, and that reality will be reflected in your writing. More importantly, understanding what you are writing about is a good way to avoid making really stupid mistakes!

Remember, civilizations that span the Solar System require spaceships to get from place to place, and spaceships need propulsion systems. Our current favorite propulsion device for space travel is the oxy-hydrogen chemical rocket, which has the best performance of anything we have yet produced. Unfortunately, our best efforts have not yet proven good enough. As we will see later, a chemical rocket is not an appropriate choice on which to build an interplanetary civilization. We need something better, and luckily, we have just such a candidate.

The Rocket Propulsion Principle

In this universe, there are precisely two methods for propelling vehicles: reaction drives and traction drives. Your car is a traction drive machine. The engine sends energy to the wheels, which turn, and due to the friction between your tires and the ground, your vehicle moves forward. Since they require something to push against, traction drives are obviously not suited for operating in the limitless vacuum of space. In the 1930s, the *New York Times* published a famous editorial in which they opined that space travel would never be feasible because there was nothing in space for the rocket to push against. Frankly, most news media have no better understanding of technical subjects today.

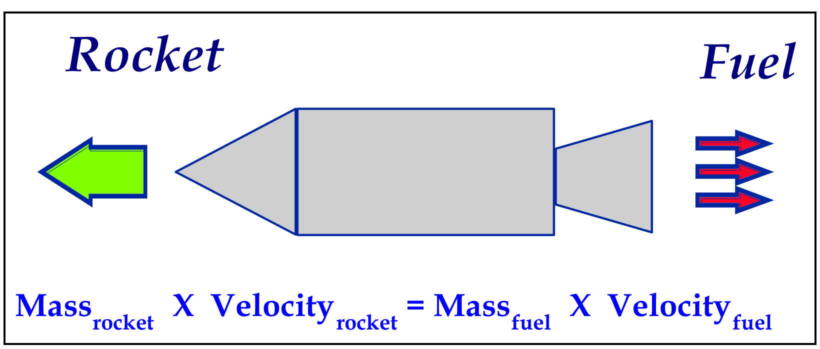

Figure 1: The Rocket Propulsion Principle

For space travel you require a reaction drive (also for propelling a ship through water or an airplane through the air). The reaction drive works on Newton's Third Law, which states "For every action, there is an equal and opposite reaction." In other words, in order to go one direction in space, it is necessary to throw mass in the opposite direction, and the final velocity attained is a function of how much mass you threw and how hard you threw it.

As is shown graphically in Figure 1. To make the ship's mass (M_{rocket}) accelerate to a velocity (V_{rocket}), it is necessary to throw mass (M_{fuel}) out the back at high velocity (V_{fuel}). Is it not intuitively obvious that for a spaceship of a given size with a fixed capacity of fuel (fixed mass $M_{rocket} + M_{fuel}$), you want to maximize fuel velocity, V_{fuel}, in order to make ship velocity, V_{rocket}, as fast as possible?

For those of you who skipped the preceding paragraph because it looks too much like a textbook, go back and read it. The concept is vital for a science fiction writer.

At this point in my lecture I put up the equations, and elicit a groan from the spouses in the audience. "Oh no, he's got equations and they've got Greek letters in them!" Don't be afraid, we aren't going to delve too deeply into the rocket performance equations. However, there are certain things you need to understand if you are going to understand how spaceships work.

There are three things one needs to know about rockets in order to evaluate their suitability for space travel. These are:

* Exhaust Velocity
* Specific Impulse
* Delta V Capability

Exhaust Velocity

$$V_e = \gamma C_v \sqrt{2g\,(1545)\,(\lambda/(\lambda-1))\,(T_c/m)}$$

Where T_c = chamber temperature
m= molecular weight of reaction mass

Specific Impulse

$$I_{sp} = V_e/g$$

Delta V Capability Of A Rocket

$$\text{Delta V} = g\ \text{Isp}\ \ln(\text{M.R.}),$$

where $\text{M.R.} = \dfrac{\text{Fueled mass}}{\text{Empty mass}}$

Figure 2: The Rocket Equations

As we noted, the way to make your ship go very fast is to throw your fuel (reaction mass) out the back end of the ship as quickly as you can. This means that exhaust velocity is critical in determining the performance of a rocket. Now look at the exhaust velocity equation in Figure 2. Note the term (T_c/m). This means that the combustion chamber temperature (T_c) is in the numerator of the equation, while the molecular weight of the reaction mass is in the denominator. To maximize exhaust velocity, and therefore, performance, you want to maximize combustion chamber temperature and minimize molecular weight. Increasing the temperature increases the speed with which the molecules bounce off the walls of the combustion chamber, and the more energetic they are, the greater velocity they impart to the ship before being lost forever out the exhaust nozzle. The effect of temperature on performance is therefore intuitive.

Not so the molecular weight term. Just what is molecular weight anyway? For that we all have to remember our high school chemistry. The Space Shuttle is an oxy-hydrogen rocket. It burns hydrogen in oxygen to form di-hydrogen-monoxide as a combustion product. The common name for di-hydrogen-monoxide is water, chemical equation H_2O. Now a water molecule consists of two hydrogen atoms, molecular weight 1, and one oxygen atom, molecular weight 16, for a total molecular weight of 18. So, no matter how hot we make our rocket combustion chamber to get the exhaust velocity up, we have to divide the resulting number by the square root of 18, or 4.24, to determine our exhaust velocity. This, as we shall see a little further on, is inefficient.

The reason molecular weight degrades performance is simple. The bigger the molecule, the slower it travels as it exits the exhaust nozzle for a given energy. Not that a heavy molecular weight is necessarily bad. You want something heavy when thrust is of primary importance. But for maximum efficiency, there's nothing better than a reaction mass with a molecular weight of 1. Luckily, there is a reaction mass with m=1 and it is both plentiful and relatively cheap.

Specific Impulse

An extremely important measurement of rocket performance is specific impulse, I_{sp}, the equation for which is shown in Figure 2. Basically, you compute specific impulse using the exhaust velocity, V_e.

Unfortunately, that doesn't really tell you what it is. Most people have heard of Newton's Second Law, F=*MA*, force equals mass times acceleration. There are two corollaries to Newton's Second Law, basically principles that say the same thing, but in a different way. One of these is the *impulse-momentum* principle. This states that impulse equals momentum, or Ft=*mv*. Impulse then is defined as a force that acts for a length of time on the object. Because engineers have a tendency to take simple things and make them obscure, let's give a real world example.

As a child I'm sure you pushed a friend on a swing. Each time the swing's arc returned to where you were standing, you would give your friend another push. If you were a teenager, then you tried to push your friend so hard that he or she would fly over the bar (an event much talked about, but seldom seen). What you are doing with each push is applying an impulse. The more impulse you impart to the swing, the higher the arc.

Specific impulse is the term for rockets that equates to the miles-per-gallon rating for automobiles. In effect, it measures rocket efficiency. About the only thing a science fiction writer must remember is that the higher the specific impulse number, the more your spaceship can maneuver before being refueled.

Specific impulse is the period in seconds for which a 1-pound (0.45-kilogram) mass of propellant (total of fuel and oxidizer) will produce a thrust of 1 pound (0.45-kilogram) of force. In other words, specific impulse measures the amount of *impulse* each unit mass of fuel delivers to your rocket when you throw it overboard. Don't worry if this is all Greek to you. All you really need to know is that a good spaceship has a high specific impulse rating.

The highest specific impulse yet obtained from a rocket is 455 seconds for the Rocketdyne engines on the Space Shuttle, and we have only achieved that level by having to overhaul the engines after practically every flight. As we shall see, while good, this isn't nearly good enough performance on which to build an interplanetary civilization.

Okay, people are probably getting tired of all this technical stuff by now, so we have only one to go. That is *Delta V*. The Greek letter delta (Δ) is used in science to denote *change*. Thus ΔV, or delta V, means the amount a rocket is able to change its velocity without refueling. This is extremely important for a spaceship because spaceships maneuver by changing their velocity. If, for instance, you want to travel from the surface of Earth to that of Mars, you need to *increase* your velocity to reach Earth orbit, *increase* your velocity to enter a transfer orbit for Mars, *increase* your velocity when you reach Mars to go into orbit about the planet, *decrease* your velocity to fall out of Mars orbit, and *decrease* your velocity on landing to keep from crashing. Unlike an automobile which stops by essentially dragging its feet, the only way to change velocity in a rocket is to throw mass overboard (for purposes of illustration, I am excluding aerobraking in the atmosphere). If you want to know whether or not you can get to Mars, you just perform the following math calculation:

Earth Surface to Earth Orbit	ΔV =	8 kps
Earth Orbit to Transfer Orbit	ΔV =	4 kps
Transfer Orbit to Mars Orbit	ΔV =	2 kps
Mars Orbit to Mars Surface	ΔV =	3 kps
Total:	ΔV =	17 kps

If you determine that your spaceship is capable of more than 17 km/sec of delta V, then you can safely land on Mars. If not, then you will run out of fuel before you get there and either die of starvation, oxygen deprivation, or crash on landing. Better not to go.

The formula for delta V is shown in Figure 2. Note that it uses the specific impulse term and a new term called *Mass Ratio*. Mass ratio is a measure of how much of the total mass of a rocket is fuel and how much is structure and payload. While high mass ratios are technically feasible (and the reason why all rockets to date are designed to break pieces off while climbing into orbit), as we will see, having a high mass ratio isn't very economical. And, in fact, you can't build an interplanetary civilization using high mass ratio rockets. People just wouldn't be able to afford shipping things like that two-pound fruitcake you and your family have been circulating among yourselves for the past five Christmases if delivering it requires the expenditure of a full ton of reaction mass. This may seem a trivial point, but it is such trivial points on which an interplanetary civilization will be built.

Chemical Rocket Performance

As a reward for all of you who managed to slog through the technical detail in the previous section, let's put our newly gained knowledge to work. Figure 3 shows a plot of specific impulse versus combustion chamber temperature for an oxy-hydrogen rocket like the Space Shuttle. Note how specific impulse, or efficiency, rises with increasing temperature. At 10,000°F, the specific impulse of our rocket is 520 seconds. Better than the Space Shuttle, but not spectacularly so.

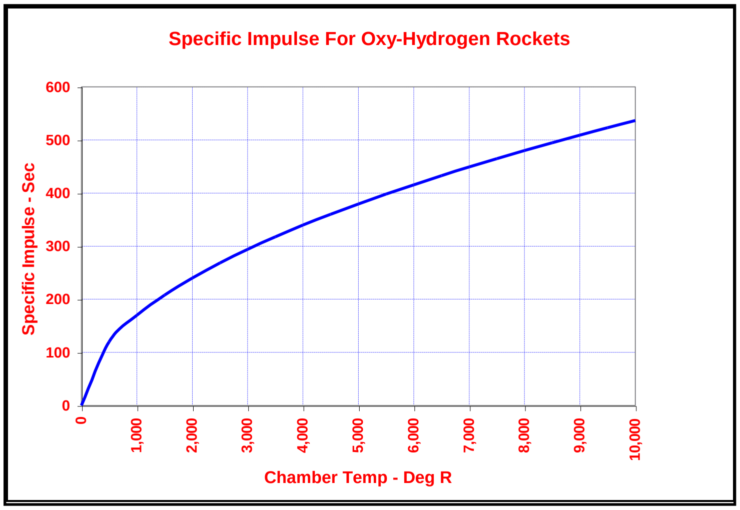

Figure 3: Specific Impulse

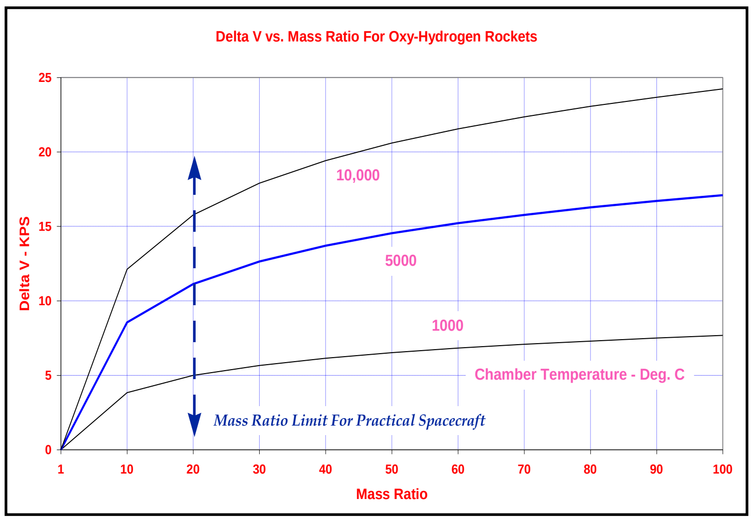

Figure 4: Delta V for Oxy-Hydrogen Rockets

Note: Figure 3 is conservative in that it doesn't take into account the disassociation of the water molecules at high temperature. Remember that you're just a science fiction writer. What is important for you to understand is the way the I_{sp} rises with temperature.

Taking a chamber temperature of 5000°F as a baseline, Figure 4 computes the delta V capability of a rocket operating at that temperature as a function of increasing mass ratio (*M.R.)*. And here we need to make an assumption. While it is theoretically possible to have mass ratios of 1000 and even 10,000, a viable civilization can't afford to throw away a thousand kilograms of reaction mass for every kilogram of cargo being delivered. So, to make the calculation manageable, I hereby decree that the maximum M.R. for a practical spaceship is 20. In other words, for every kilo delivered, the ship exhausts 20 kilos of fuel. How can I make such a claim? Simple. I'm the writer, the Supreme Being in my fictional universe. I can decree anything I damned well please.

So, operating at 5000°F chamber temperature with a mass ratio of 20, our spaceship can change its velocity by 12 km/sec (7.2 miles/sec). That isn't very much. In fact, it's only 1.5 times as fast as is required to reach Earth orbit. Not very impressive for a spaceship with which we will travel the Solar System. Essentially, our spaceship will just manage to break free of Earth's gravity when it runs its tanks dry, leaving nothing with which to stop at Mars.

Obviously, we need a better spaceship.

Hydrogen Rocket Performance

If you return to the equations of Figure 2, you will remember that the exhaust velocity on which specific impulse and delta V are based has something to do with the molecular weight of the reaction mass. Specifically, water vapor (the combustion product of hydrogen and oxygen) has a molecular weight of 18, and the square root of 18 is 4.24. Wouldn't it be wonderful if we could find a reaction mass with a molecular weight of 1? We could achieve a 424% increase in rocket exhaust velocity instantly.

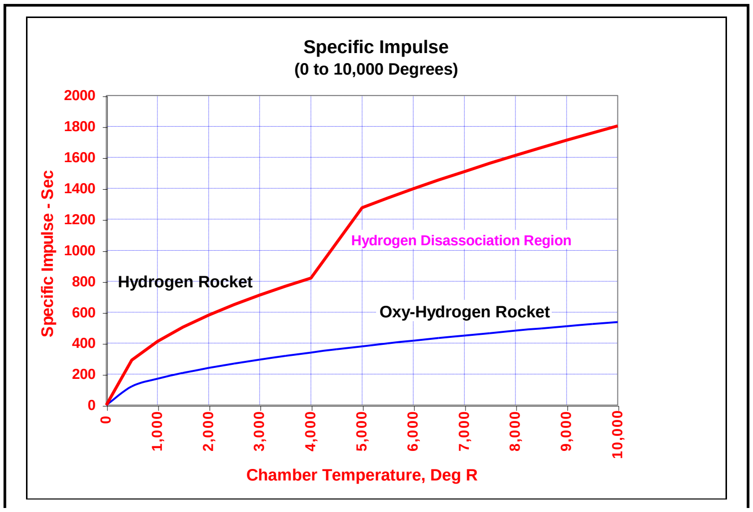

Figure 5: Specific Impulse for Hydrogen Rockets

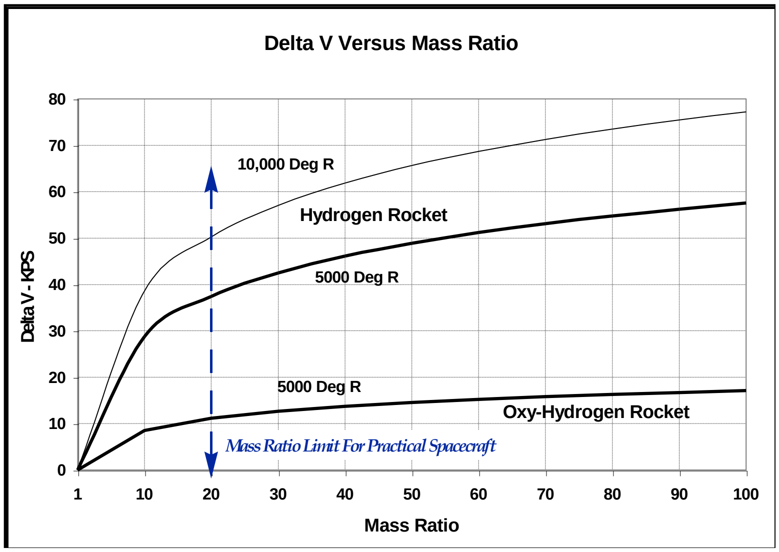

Figure 6: Delta V for Hydrogen Rockets

Luckily there is just such a fuel. It's called monatomic hydrogen, the favorite fuel of the science fiction writer. Like oxygen and nitrogen, hydrogen is a diatomic gas at room temperature. In other words, each hydrogen molecule consists of two hydrogen atoms. However, when the hydrogen gets hot enough, the high temperature splits the bond between hydrogen atoms and turns them into plasma. This results in the molecular weight dropping from 2 to 1 as the atoms break away from one another. This means each "molecule" is lighter and we can "throw" it away more quickly. And since the speed of our ship is dependent on the speed of our throw, we get a 41% increase in efficiency if we operate our engine in the range where hydrogen consists of single atoms.

Figure 5 shows the same graph as Figure 3, but with the specific impulse of a hydrogen rocket superimposed on that of the oxy-hydrogen rocket. Note the step in specific impulse (efficiency) between 4000°F and 5000°F. This is the range at which hydrogen disassociates. You can see how the specific impulse rises as this disassociation takes place. Now for a quick quiz to see if you are paying attention: You are writing your book and have an opportunity to mention how hot the engines operate. Do you say 4000°F or 5000°F? The answer is left to the common sense of the student.

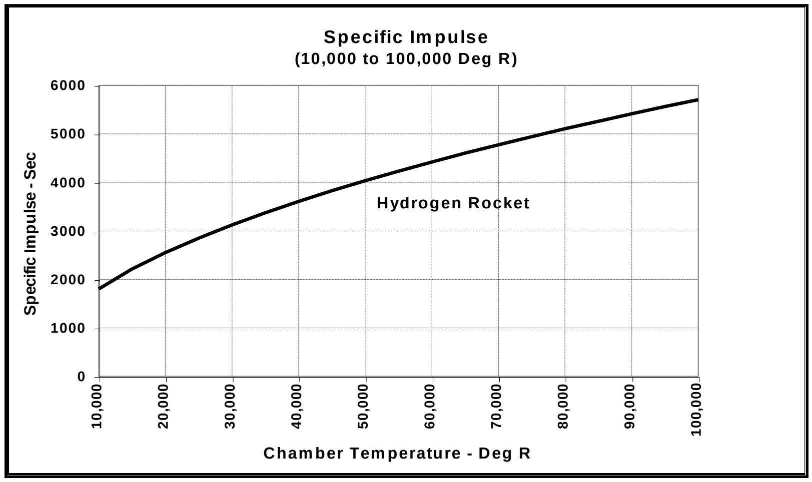

Figure 7: Specific Impulse (10,000-100,000 Degrees)

Figure 6 shows the delta V curve for hydrogen and oxy-hydrogen rockets. Note that where before we could barely make 12 km/sec with oxy-hydrogen, our spaceship now has the ability to change its velocity by 36 km/sec. That means that we can indeed do our landing on Mars.

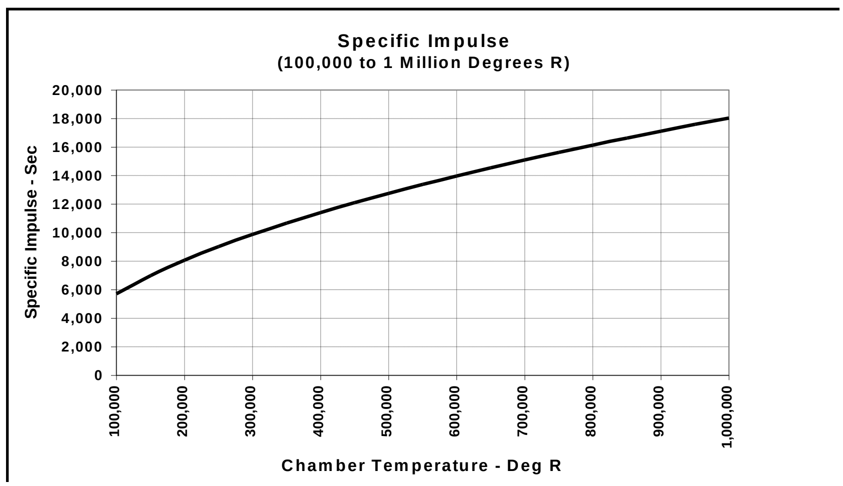

Figure 8: Specific Impulse (100,000 to 1 million degrees)

The above example was run using a chamber temperature of 5000°F. What if we increase the temperature? Figure 7 shows how specific impulse increases from 10,000°F to 100,000°F. Figure 8 shows the delta V performance between 100,000°F and one million °F. At one million degrees chamber temperature, we obtain a specific impulse of 18,000 seconds, which equates to a delta V capability of 1246 km/sec. Now *that* is a spaceship!

So how does one build a spaceship with a million-degree chamber temperature? What materials can you use that won't melt? Frankly, I have no idea. But as I indicated earlier, I just have to describe the thing. So, insert a comment about the ship's "electromagnetic nozzle" and proceed with the plot.

But, wait! Haven't we overlooked something important? Just exactly how does one heat up the hydrogen in the first place? In the oxy-hydrogen rocket, we burn the hydrogen fuel in oxygen. The resulting fire heats the reaction mass and sends it speeding out the nozzle. And, of course, it also adds a heavy atom (oxygen) to the mix and ruins our performance. How does one heat hydrogen without combusting it?

Two words: fission and fusion.

Nuclear Rockets

Back in the 1960s there was a nuclear rocket program called the NERVA. The principle behind the NERVA was fairly simple. The NERVA reactor core was approximately the size of a standard office desk, but it generated the power of Hoover Dam. To cool it, the physicists ran liquid hydrogen through the reactor. In the process, the hydrogen became very hot and was then exhausted through a nozzle to provide thrust. Voila!!! A hydrogen rocket.

Another way to heat hydrogen is by using a nuclear fusion reaction. In a nuclear fusion rocket, a little of the hydrogen is fused into helium. The reaction, which is the same one that powers the hydrogen bomb, releases heat to the rest of the hydrogen. This extra hydrogen is heated to the point where the molecules disassociate and the rocket spews monatomic hydrogen out the nozzle. No fuss, no muss, no fission products for the environmentalists to complain about! There's only one problem. We've been working on controllable fusion for the past fifty years and have yet to sustain the reaction for more than a few fractions of a second.

Conclusion

Barring some amazing new development such as antigravity, we are stuck with using reaction drives to travel the Solar System. This is a major inconvenience because such spaceships must maneuver by spewing large quantities of mass out into space. So long as this is true, your interplanetary civilization is going to have to invest in a lot of refueling stations and refineries.

However, all is not lost. As we noted in our analysis of hydrogen rockets, the opportunity for improvement is vast. We can move from our current measly record of 455 seconds of specific impulse to 18,000 seconds and beyond. Our practical spaceship can increase its ability to change velocity more than 100 times over what is now possible. All it will take is time, brainpower, and money.

Nor is a nuclear powered hydrogen rocket the only possibility. However, by this time your brain is probably starting to hurt (I know mine is), so we will save that for the next article. Also, now that we know something about our spaceship, we need to ask ourselves a question: Just exactly where do we want to go and how long will it take to get there?

The End

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NOVELS

1. Life Probe - US$5.00

The Makers searched for the secret to faster-than-light travel for 100,000 years. Their chosen instruments were the Life Probes, which they launched in every direction to seek out advanced civilizations among the stars. One such machine searching for intelligent life encounters 21st century Earth. It isn't sure that it has found any...

2. Procyon's Promise - US$5.00

Three hundred years after humanity made its deal with the Life Probe to search out the secret of faster-than-light travel, the descendants of the original expedition return to Earth in a starship. They find a world that has forgotten the ancient contract. No matter. The colonists have overcome far greater obstacles in their single-minded drive to redeem a promise made before any of them were born...

3. Antares Dawn - US$5.00

When the super giant star Antares exploded in 2512, the human colony on Alta found their pathway to the stars gone, isolating them from the rest of human space for more than a century. Then one day, a powerful warship materialized in the system without warning. Alarmed by the sudden appearance of such a behemoth, the commanders of the Altan Space Navy dispatched one of their most powerful ships to investigate. What ASNS Discovery finds when they finally catch the intruder is a battered hulk manned by a dead crew.

That is disturbing news for the Altans. For the dead battleship could easily have defeated the whole of the Altan navy. If it could find Alta, then so could whomever it was that beat it. Something must be done…

4. Antares Passage - US$5.00

After more than a century of isolation, the paths between stars are again open and the people of Alta in contact with their sister colony on Sandar. The opening of the foldlines has not been the unmixed blessing the Altans had supposed, however.

For the reestablishment of interstellar travel has brought with it news of the Ryall, an alien race whose goal is the extermination of humanity. If they are to avoid defeat at the hands of the aliens, Alta must seek out the military might of Earth. However, to reach Earth requires them to dive into the heart of a supernova.

5. Antares Victory – First Time in Print – US$7.00

After a century of warfare, humanity finally discovered the Achilles heel of the Ryall, their xenophobic reptilian foe. Spica – Alpha Virginis – is the key star system in enemy space. It is the hub through which all Ryall starships must pass, and if humanity can only capture and hold it, they will strangle the Ryall war machine and end their threat to humankind forever.

It all seemed so simple in the computer simulations: Advance by stealth, attack without warning, strike swiftly with overwhelming power. Unfortunately, conquering the Ryall proves the easy part. With the key to victory in hand, Richard and Bethany Drake discover that they must also conquer human nature if they are to bring down the alien foe …

6. Thunderstrike! - US$6.00

The new comet found near Jupiter was an incredible treasure trove of water ice and rock. Immediately, the water-starved Luna Republic and the Sierra Corporation, a leader in asteroid mining, were squabbling over rights to the new resource. However, all thoughts of profit and fame were abandoned when a scientific expedition discovered that the comet's trajectory placed it on a collision course with Earth!

As scientists struggled to find a way to alter the comet's course, world leaders tried desperately to restrain mass panic, and two lovers quarreled over the direction the comet was to take, all Earth waited to see if humanity had any future at all…

7. The Clouds of Saturn - US$5.00

When the sun flared out of control and boiled Earth's oceans, humanity took refuge in a place that few would have predicted. In the greatest migration in history, the entire human race took up residence among the towering clouds and deep clear-air canyons of Saturn's upper atmosphere. Having survived the traitor star, they returned to the all-too-human tradition of internecine strife. The new city-states of Saturn began to resemble those of ancient Greece, with one group of cities taking on the role of militaristic Sparta...

8. The Sails of Tau Ceti – US$5.00

Starhopper was humanity's first interstellar probe. It was designed to search for intelligent life beyond the solar system. Before it could be launched, however, intelligent life found Earth. The discovery of an alien light sail inbound at the edge of the solar system generated considerable excitement in scientific circles. With the interstellar probe nearing completion, it gave scientists the opportunity to launch an expedition to meet the aliens while they were still in space. The second surprise came when *Starhopper's* crew boarded the alien craft. They found beings that, despite their alien physiques, were surprisingly compatible with humans. That two species so similar could have evolved a mere twelve light years from one another seemed too coincidental to be true.

One human being soon discovered that coincidence had nothing to do with it...

9. Gibraltar Earth – First Time in Print — $6.00

It is the 24th Century and humanity is just gaining a toehold out among the stars. Stellar Survey Starship *Magellan* is exploring the New Eden system when they encounter two alien spacecraft. When the encounter is over, the score is one human scout ship and one alien aggressor destroyed. In exploring the wreck of the second alien ship, spacers discover a survivor with a fantastic story.

The alien comes from a million-star Galactic Empire ruled over by a mysterious race known as the Broa. These overlords are the masters of this region of the galaxy and they allow no competitors. This news presents Earth's rulers with a problem. As yet, the Broa are ignorant of humanity's existence. Does the human race retreat to its one small world, quaking in fear that the Broa will eventually discover Earth? Or do they take a more aggressive approach?

Whatever they do, they must do it quickly! Time is running out for the human race…

10. Gibraltar Sun – First Time in Print — $7.00

The expedition to the Crab Nebula has returned to Earth and the news is not good. Out among the stars, a million systems have fallen under Broan domination, the fate awaiting Earth should the Broa ever learn of its existence. The problem would seem to allow but three responses: submit meekly to slavery, fight and risk extermination, or hide and pray the Broa remain ignorant of humankind for at least a few more generations. Are the hairless apes of Sol III finally faced with a problem for which there is no acceptable solution?

While politicians argue, Mark Rykand and Lisa Arden risk everything to spy on the all-powerful enemy that is beginning to wonder at the appearance of mysterious bipeds in their midst…

11. Gridlock and Other Stories - US$5.00

Where would you visit if you invented a time machine, but could not steer it? What if you went out for a six-pack of beer and never came back? If you think nuclear power is dangerous, you should try black holes as an energy source — or even scarier, solar energy! Visit the many worlds of Michael McCollum. I guarantee that you will be surprised!

Non-Fiction Books

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This collection covers the Art of Writing articles published during 1998. The book is 62,000 words in length and builds on the foundation of knowledge provided by Volume I of this popular series.

14. The Art of Science Fiction, Volume I - US$10.00

Have you missed any of the articles in the Art of Science Fiction Series? No problem. The first sixteen articles (October, 1996-December, 1997) have been collected into a book-length work of more than 70,000 words. Learn about science fiction techniques and technologies, including starships, time machines, and rocket propulsion. Tour the Solar System and learn astronomy from the science fiction writer's viewpoint. We don't care where the stars appear in the terrestrial sky. We want to know their true positions in space. If you are planning to write an interstellar romance, brushing up on your astronomy may be just what you need.

15. The Art of Science Fiction, Volume II - US$10.00

This collection covers the *Art of Science Fiction* articles published during 1998. The book is 67,000 words in length and builds on the foundation of knowledge provided by Volume I of this popular series.

16. The Astrogator's Handbook – Expanded Edition and Deluxe Editions

The Astrogator's Handbook has been very popular on Sci Fi – Arizona. The handbook has star maps that show science fiction writers where the stars are located in space rather than where they are located in Earth's sky. Because of the popularity, we are expanding the handbook to show nine times as much space and more than ten times as many stars. The expanded handbook includes the positions of 3500 stars as viewed from Polaris on 63 maps. This handbook is a useful resource for every science fiction writer and will appeal to anyone with an interest in astronomy.