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The Tyranny of the Rocket Equation

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By Expedition 30/31 Flight Engineer Don Pettit

Tyranny is a human trait that we sometimes project onto Nature. This projection is a form of rationalization, perhaps a means to cope with matters that we cannot control. Such is the case when we invent machines to free us from the bounds of Earth, affecting our escape into space. If we want to expand into the solar system, this tyranny must somehow be deposed.

Rockets are momentum machines. They spew gas out of a nozzle at high velocity causing the nozzle and the rocket attached to it to move in the opposite direction. Isaac Newton correctly defined the mathematics for this exchange of momentum in 1687. Conservation of momentum applied to a rocket was first done by Russian visionary and scientist Konstantin Tsiolkovsky in 1903. All our rockets are governed by Tsiolkovsky's rocket equation.

The rocket equation contains three variables. Given any two of these, the third becomes cast in stone. Hope, wishing, or tantrums cannot alter this result. Although a momentum balance, these variables can be cast as energies. They are the energy expenditure against gravity (often called delta V or the change in rocket velocity), the energy available in your rocket propellant (often called exhaust velocity or specific impulse), and the propellant mass fraction (how much propellant you need compared to the total rocket mass).

The energy expenditure against gravity is specified by where you want to go. For human exploration, there are only a handful places we can realistically consider at this time. The most likely candidates are: from the surface of Earth to Earth orbit, Earth orbit to surface of the Moon, Earth orbit to surface of Mars, Earth orbit to cis-lunar space (the region between the Earth and the Moon, including a variety of locations such as Lagrange points, geostationary orbit, and more). Of course there are permutations to these routes but they are the most likely ones considering our current state of technology.

In planning an expedition into space, we first must select where we want to go. The energy expenditure against gravity is then specified by the starting and ending points of our journey. As humans, we are powerless to change this number. We simply have to accept its consequences. I like to think of this as the travel cost.

Next we need to choose the type of rocket propellant, thus specifying the available energy. Currently, all our human rated rocket engines use chemical reactions (combustion of a fuel and oxidizer) to produce the energy. There are limits to the quantity of energy that can be extracted from chemistry and thus bounds placed outside of human control on the energy we can pack into a rocket. Some of the most energetic chemical reactions known are chosen for rocket propulsion (e.g. like hydrogen-oxygen combustion) and thus, the second variable is now specified. Again, we simply have to accept the limit to what chemistry can offer (unless we choose other energy sources, such as nuclear). I like to think of this selection as what you have to pay for the travel cost.

With these two variables set, the rocket mass fraction is now dictated by the rocket equation. We must build our rocket within this mass fraction or it will not reach its destination. This also applies to existing rockets when new uses are contemplated. There is very little we can do to alter this result. With some clever engineering we might be able to shave a few percentage points off the fraction, but the basic result is set by the gravitational environment of our solar system (choice of where we want to go) and the chemistry of the energetic bonds of our selected chemical components (choice of propellant).

It is constructive to put a few numbers together to illustrate the grip that simple momentum balance places upon our rockets. Here the approximate cost in energy has been given in terms of velocity (kilometers per second, km/s), a common ploy engineers use to simplify the discussion. These numbers assume ideal conditions such as no losses for atmospheric drag or combustion but are close enough for the sake of this illustration.

Destination	Energy Cost (km/s)
Surface of Earth to Earth orbit:	8
Earth orbit to cis-lunar locations: • Lagrange points: • Low Lunar orbit:	 3.5 4.1
Earth orbit to near-Earth asteroids:	> 4
Earth orbit to surface Moon:	6
Earth orbit to surface Mars:	8

Space shuttle Endeavour launches in November 2008 carrying seven STS-126 crew members including Mission Specialist Don Pettit. Credit: NASA

From this simple table, a few conclusions can be drawn. Travelling from the surface of Earth to Earth orbit is one of the most energy intensive steps of going anywhere else. This first step, about 400 kilometers away from Earth, requires half of the total energy needed to go to the surface of Mars. Destinations between the Earth and the Moon are only a fraction of that required to simply get into Earth orbit. The cost of this first step is due to the magnitude of Earth's gravity. And physics dictates that paying a penny less than the full cost will result in Earth repossessing your spacecraft in a not so gentle way. The giant leap for mankind is not the first step on the Moon, but in attaining Earth orbit.

Listed next are the major categories for our chemical rocket propellants and their energy content used for payment of the gravitational cost of travel. These are selected from propellants with an operational history in manned spacecraft. "Hypergols" are contact-ignited propellants, used in the Lunar Module ascent stage to simplify the engine design and methane-oxygen has not been used in space to date, but is under consideration for future human missions to the Moon and Mars. The first law of thermodynamics was used to convert the energy of combustion into an equivalent exhaust velocity so that these units of payment are consistent with the costs shown above.

Propellant	Payment Energy (km/s)
Solid Rocket	3.0
Kerosene-Oxygen	3.1
Hypergols	3.2
Earth orbit to near-Earth asteroids:	3.4
Methane-Oxygen	4.5

The Soyuz TMA-03M spacecraft launches in December 2011 carrying three Expedition 30 crew members including Flight Engineer Don Pettit. Credit: NASA

Hydrogen-oxygen is the most energetic chemical reaction known for use in a human rated rocket. Chemistry is unable to give us any more. In the 1970's, an experimental nuclear thermal rocket engine gave an energy equivalent of 8.3 km/s. This engine used a nuclear reactor as the source of energy and hydrogen as the propellant.

Since the giant leap for mankind is the first step off of Earth, our illustration of the rocket equation uses earth orbit as the destination with the cost of 8 kilometers per second. To pay for this cost, each of the chemical propellants above are used with the rocket equation which results in the following mass fractions (given as percent of the total rocket mass):

Propellant	Rocket Percent Propellant for Earth Orbit
Solid Rocket	96
Kerosene-Oxygen	94
Hypergols	93
Methane-Oxygen	90

NASA astronaut Don Pettit enjoys a snack in the Unity node. Credit:

Hydrogen-Oxygen	83	NASA

These are ideal numbers free from losses due to atmospheric drag, incomplete combustion, and other factors that reduce the efficiencies of a rocket. Such losses make these numbers even worse (moving the mass fraction closer to a rocket being 100% propellant). However, clever engineering constructs such as rocket staging, multiple kinds of propellants (1st stage solids or kerosene, upper stages hydrogen), and gravitational lean (converts radial velocity into tangential) can help compensate. When making a rocket that is near 90% propellant (which means it is only 10% rocket), small gains through engineering are literally worth more than their equivalent weight in gold.

Real mass fractions from real rockets include the effect of many engineering details. However, these machines at root are the result of the simple application of Tsiolkovsky's rocket equation. The ideal results presented here are not far removed from actual rockets. The Saturn V rocket on the launch pad was 85% propellant by mass. It had three stages; the first using kerosene-oxygen and the second and third stages using hydrogen-oxygen. The Space Shuttle was also 85% propellant by mass, using a blend of solids and hydrogen-oxygen for the first stage and hydrogen-oxygen for second. The Soyuz rocket is 91% propellant by mass and uses kerosene-oxygen in all of its three stages. There is an advantage to using hydrogen-oxygen as a high performance propellant; however, it is technically more complex. Kerosene offers less performance but gives a simpler, robust, and easier to fabricate rocket. These numbers represent the best that our engineering can do when working against Earth's gravity and the energy from chemical bonds.

What are the engineering implications of fabricating a rocket that is 85% propellant and 15% rocket? The rocket must have engines, tanks, and plumbing. It needs a structure, a backbone to support all this and it must survive the highly dynamic environment of launch (there is fire, shake, and force at work.) The rocket must be able to fly in the atmosphere as well as the vacuum of space. Wings are of no use in space; small rocket thrusters are used to control attitude. Then there are people with their pinky flesh and their required life support machinery. Life support equipment is complex, problematic, and heavy. You can't roll down the windows if the cabin gets a bit stale. If you want to return to Earth (and most crews do), there has to be structure to protect the crew through a fiery entry and then provide a soft landing. Wings are heavy but allow soft landings at well equipped airfields. Parachutes are light, giving a big splash finale. The Soyuz goes thump, roll, roll, roll; aptly described by one of my colleagues as a series of explosions followed by a car wreck. And finally, you want to bring some payload – equipment with which to do something other than just be in space. “Because it is there” (or possibly because it is not there, depending on your definition of a vacuum) is fitting for the first time but subsequent missions need a stronger justification. Missions into space to do meaningful exploration require bringing significant payload.

Real payload fractions from real rockets are rather disappointing. The Saturn V payload to Earth orbit was about 4% of its total mass at liftoff. The Space Shuttle was only about 1%. Both the Saturn V and Space Shuttle placed about 120 metric tons into Earth orbit. However, the reusable part of the Space Shuttle was 100 metric tons, so its deliverable payload was reduced to about 20 tons.

It is instructive to compare rocket mass fractions to those of other everyday Earth vehicles. Here, the approximate numbers for propellant (or fuel when air is used as the oxidizer) are given to illustrate the general categories of mass fractions:

Vehicle	**Percent Propellant (fuel)**
Large Ship	3
Pickup Truck	3
Car	4
Locomotive	7
Fighter Jet	30
Cargo Jet	40
Rocket	85

NASA astronaut Don Pettit works with two still cameras mounted together in the Destiny laboratory. Credit: NASA

The percent propellant has huge implications on the ease of fabrication and robustness in achieving the engineering design (and cost). If a vehicle is less than 10% propellant, it is typically made from billets of steel. Changes to its structure are readily done without engineering analysis; you simple weld on another hunk of steel to reinforce the frame according to what your intuition might say. I can easily overload my ¾ ton pickup by a factor of two. It might be moving slowly but it is hauling the load.

Once the vehicles become airborne, the engineering becomes more serious. Light weight structures made of aluminum, magnesium, titanium, epoxy-graphite composites are the norm. To alter the structure takes significant engineering; one does not simply weld on another chunk to your airframe if you want to live (or drill a hole through some convenient section). These vehicles cannot operate far from their designed limits; overloading an airplane by a factor of two results in disaster. Even though these vehicles are 30 to 40% propellant (60 to 70% structure and payload), there is room for engineering to comfortably operate thus there is a robust, safe, and cost effective aviation industry.

Rockets at 85% propellant and 15% structure and payload are on the extreme edge of our engineering ability to even fabricate (and to pay for!). They require constant engineering to keep flying. The seemingly smallest modifications require monumental analysis and testing of prototypes in vacuum chambers, shaker tables, and sometimes test launches in desert regions. Typical margins in structural design are 40%. Often, testing and analysis are only taken to 10% above the designed limit. For a Space Shuttle launch, 3 g's are the designed limit of acceleration. The stack has been certified (meaning tested to the point that we know it will keep working) to 3.3 g's. This operation has a 10% envelope for error. Imagine driving your car at 60 mph and then drifting to 66 mph, only to have your car self-destruct. This is life riding rockets, compliments of the rocket equation.

Here are a few other interesting examples from container engineering to further illustrate the extreme nature of rocket design:

Other Containers	Percent Useful Contents
Soda Can	94
Shuttle External Tank	96
Molotov Cocktail	52

A zucchini plant grows inside the International Space Station. Credit: NASA

› Read Don Pettit's Letters to Earth and the Diary of a Space Zucchini

The common soda can, a marvel of mass production, is 94% soda and 6% can by mass. Compare that to the external tank for the Space Shuttle at 96% propellant and thus, 4% structure. The external tank, big enough inside to hold a barn dance, contains cryogenic fluids at 20 degrees above absolute zero (0 Kelvin), pressurized to 60 pounds per square inch, (for a tank this size, such pressure represents a huge amount of stored energy) and can withstand 3gs while pumping out propellant at 1.5 metric tons per second. The level of engineering knowledge behind such a device in our time is every bit as amazing and cutting-edge as the construction of the pyramids was for their time.

A veteran astronaut who has been to the Moon once told me, “Sitting on top of a rocket is like sitting on top of a Molotov cocktail”. I took his comment to heart by first weighing a bottle of wine, emptying the bottle, and weighing it again. Simple engineering analysis allowed me to estimate and compensate for the density difference between wine and gasoline (which, for this particular vintage, I am sure was not much different). A Molotov cocktail was measured to be 52% propellant. So sitting on top of a rocket is more dangerous than sitting on a bottle of gasoline!

Another less recognized side effect of the rocket equation is the sensitivity of completing the rocket burn to obtaining your goal. To illustrate this, I will use some numbers from my Shuttle flight, STS 126 in November 2008. Our target velocity at main engine cut off was 7824 m/s (25819 ft/s). If our engines shut down at 7806 m/s (25760 ft/s), only 18 m/s (59 ft/s) shy of the target value, we would make an orbit but not our designated target orbit. We would not be able to rendezvous with space station and would lose our mission objective. Like being two pennies short of a ten dollar purchase, this is only 0.2% less than the price of admission into space. In this case, we do have some options. We could burn our orbital maneuvering propellant and make up this difference. If we were 3% shy of our target, 7596 (25067 ft/s) we would not have sufficient orbital maneuvering propellant and we would not make any orbit. We would be forced into a trans-Atlantic abort, falling back to Earth and landing in Spain. This final 3% of our required velocity comes during the last 8 seconds of our burn. For astronauts and bull riders, 8 seconds is a long time.

If the radius of our planet were larger, there could be a point at which an Earth escaping rocket could not be built. Let us assume that building a rocket at 96% propellant (4% rocket), currently the limit for just the Shuttle External Tank, is the practical limit for launch vehicle engineering. Let us also choose hydrogen-oxygen, the most energetic chemical propellant known and currently capable of use in a human rated rocket engine. By plugging these numbers into the rocket equation, we can transform the calculated escape velocity into its equivalent planetary radius. That radius would be about 9680 kilometers (Earth is 6670 km). If our planet was 50% larger in diameter, we would not be able to venture into space, at least using rockets for transport.

Revolting against tyranny is a recurring human trait and perhaps we will figure some way to depose the rocket equation and venture away from our planet in a significant way. I am referring to exploration with continuous human presence with the first step like Antarctic-type bases (which support several thousand people) and eventually leading to colonization, a template comparable to the expansion of western civilization across the globe during the 17th and 18th centuries. To call yourself a sea-faring nation in that time meant that you could set sail on a variety of missions in a number of different types of vessels to a myriad of destinations whenever you wanted. We have a long way to go before anyone can claim to be a space-faring nation.

The giant leap for mankind is not the first step on the Moon but attaining Earth orbit. If we want to break the tyranny of the rocket equation, new paradigms of operating and new technology will be needed. If we keep to our rockets, they must become as routine, safe, and affordable as airplanes. One of the most rudimentary and basic skills to master is to learn how to use raw materials from sources outside the Earth. Our nearest planetary neighbor, the Moon is close, useful, and interesting. Extracting and producing useful products from the raw materials of the Moon would relieve us from the need to drag everything required in space from the bottom of Earth’s deep gravity well, significantly altering the consequences of the rocket equation more in our favor. The discovery of some new physical principle could break the tyranny and allow Earth escape outside the governance of the rocket paradigm.

The need for new places to live and resources to use will eventually beckon humanity off this planet. Having access to space removes the lid from the Petri dish of Earth. And we all know what eventually happens if the lid is not removed.

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