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HALF WAY TO ANYWHERE: ON-ORBIT ELECTROLYSIS TO CUT THE COST OF TRAVELING TO LOW EARTH ORBIT AND BEYOND

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ABSTRACT

Robert Heinlein was quoted as saying "Once you're in low Earth orbit (LEO), you're halfway to anywhere." This is due to the mechanics of space launch, where accelerating into LEO is a large portion of your journey. As a corollary, storing mass in LEO is a way to make trips beyond LEO easier. This paper discusses a project that, for on the order of $1B, creates a flexible cache of rocket propellants (hydrogen and oxygen) and human consumption supplies (oxygen and water) in low Earth orbit. Part of the project involves increasing launch vehicle flight rates through open competition, which will lower the per-kilogram cost of launching payloads into LEO. Exploiting this cache will cut the launch weights of interplanetary spacecraft by up to 2/3. This material, stored on orbit for years, would serve any space mission. The plan is modeled after historical cases that jump-started the airline industry, and calls for the best of governmental and/or commercial efforts to get us half way to anywhere.

HISTORICAL CONTEXT

Before a proper discussion about a solution can take place, it pays to review the historical events that led to its need. While many of the discussions here are tired, there are some essential points to take from them. The majority of this discussion relates to the United States' experience in space exploration, although many of the same lessons apply internationally.

Space Launch

Space launch got its start as an outgrowth of ballistic missiles, both intermediate-range ballistic missiles (IRBMs) and intercontinental ballistic missiles (ICBMs). Ballistic missiles were built on the premise that after much preparation, they could be stored for long periods of time and then be ready to go on short notice to destroy enemy targets. Because of the preparation time followed by storage time, rapid change-out of missiles (or payloads, in this case, the warheads) was not a priority. Long maintenance cycles with individual missiles out of service were the norm, and large fleets of missiles kept an acceptable launch readiness rate.

At about the same time, the United States developed a keen interest in what was going on inside The Soviet Union. The secretive adversary was growing more technologically adept, which made it difficult to rely on traditional spyplanes to carry out reconnaissance.

At about the same time, the United States developed a keen interest in what was going on inside The Soviet Union. The secretive adversary was growing more technologically adept, which made it difficult to rely on traditional spyplanes to carry out reconnaissance. The US government decided to move into the realm of satellite reconnaissance, and was willing to pay a lot of money for the information the satellites would gather. Since IRBMs and ICBMs already traveled to the edge of space in their travels, adapting them to launch these satellites was the simplest, fastest way to achieve the desired result.

As satellites grew in mass and complexity, and the new National Aeronautics and Space Administration (NASA) started to gain interest in crewed flights to orbit, missiles (mostly re-named rockets or boosters by this time) grew in size, largely through upgrades to their missile cousins. As new boosters were developed, many of the same people who worked on missiles worked on rockets, so many of the same design strengths (reliability grew as time went on) and weaknesses (the price for launching a kilogram into orbit continued, as a rule, to go up, and timelines between launches were not significantly shortened). Something that hadn't been tried yet was reusability.

After its stunning victory in the cold war of landing a man on the Moon, NASA looked for another mission. Since a crewed journey to Mars was too expensive for the seemingly war-ravaged country at that time, the space agency built a space truck, known as the space shuttle. The shuttle was conceived to make space travel routine, and in 1971 launch costs were estimated to be on the order of $10.5M[i] per flight, or a cost of $330/kg. As design and budget realities hit the program, however, NASA found itself building a vehicle that wasn't designed to operate on short timelines. Meticulous construction led to difficult maintenance and preparation for launch. Architectural compromise led to several design flaws, one of which cost a crew their lives. The space shuttle was not the answer for routine space flight.

Commercial interests, at times, seemed like the answer to driving the cost of space launch down. In the late nineties, the number of satellites scheduled for launch outstripped the supply of launch vehicles by an order of magnitude, and the number of commercial launches consistently exceeded the number of government launches. New commercial ventures sprung up to meet this demand, including many of the old, familiar names in rocketry (now Lockheed-Martin and Boeing) as well as some unlikely partnerships (Russian and US companies) and some new startups, taking their own approach to cut the cost of launch to orbit (Kistler Aerospace and Pioneer Rocketplane). The recession of 2000, as well as the very public failures of some of the satellite industries driving this new revolution (Iridium, Globalstar), caused the market that the new space launch industries were to support to collapse.

The Existing Impasse

Today, there are several launch services providers chasing after a small (and steady or declining) market. In most industries, this type of situation leads to a decrease in costs, but the US government still has a need for reliable rides into orbit, and they've grown used to paying a lot of money for the service. While two hybrid governmental/commercial rockets are nearly ready for launch as of this writing (the Evolved Expendable Launch Vehicle, or EELV, for Boeing and Lockheed Martin), many of the market assumptions that were made to make the systems cheaper are no longer valid. To maintain the programs (and a viable method of achieving orbit) the US government has increased its sponsorship of the programs, perpetuating the high-cost launch business.

It is an industrial fact that production volume (or flight rate, in the case of a resource used repeatedly), leads to efficiency and cost savings in an un-tampered-with market. While predictions of the late 1990's showed that launch rates would reach a sufficient number to provide production volume for space launch, the foundations of the predictions were shaky at best. Even with fully functional Iridium (72 satellites) and Teledesic (numbers varied, but some early market research showed a requirement for 288 large satellites) constellations, once the original satellites were launched, the number of missions required to replace aging satellites would not be enough to sustain a viable launch industry. Communications satellites are not the only possibility, however.

Some advocates, including Buzz Aldrin, maintain that space tourism is the only market driver that will create enough demand for launches to make launch cost-effective. While this is possible, space tourism faces a lot of challenges as a start-up business. For example, one factor playing a major role in how much (and how often) people are willing to pay to ride on a vehicle is its safety record. The safety record for commercial airliners is on the order of 99.99%, and some people will still not fly. (The safety record for automobile travel is significantly worse, and many of the people who won't fly don't mind riding in a car, but that's a discussion for another day.) Safety records are very difficult to prove without a large sample size, in this case the number of flights. In the case of a new launch vehicle, 14 launches must be successful in order to claim a 95% success rate, which translates directly into a safety factor if your cargo is paying customers. The investment required to build a new launch vehicle and demonstrate its safety through that number of launches (likely without any paying customers until an FAA certification takes place, which doesn't exist for orbital vehicles, by the way) is prohibitive.

So, following capitalistic principles, the launch rate must go up in order to decrease costs, but the most talked about market driver is unrealistic because of startup costs for a new system. The uncertainty is multiplied in the risky business of rocketry, where a 95-97% success rate is excellent. What does that leave us?

A Success Story

The airline industry was cited above as a safe way to travel. The industry was not always as safe as it is today, nor was it a viable industry for many years. Early airlines got their start from airmail routes created by the post office. The Postal Service guaranteed an amount of cargo (or, lacking the cargo amount, would pay for a flight anyway) and made regularly-scheduled routes worthwhile for businesses to maintain. These routes, augmented by larger and more capable aircraft, became the first air travel routes in the nation. While the weaning process is by no means complete, (note the fragility of the airlines' financial situation in light of the change in world politics in September, 2001) the airlines are a much more viable industry than most space operations today. This comparison is not completely fair, due to the different timelines: air travel is approaching its 100th anniversary, while space travel is a bit over 40 years old. Plus there's been very little effort expended by agencies charged with space exploration to make it pay for itself.

PROJECT OVERVIEW

The HAWATA project is designed as a hybrid government/commercial project, although it has potential as a purely commercial venture. Either way, at project end there will be two solid results:

1. A multi-ton cache of rocket propellants and other supplies in Low Earth Orbit (LEO).
2. A launch system capable of rapid flight rates and a much-lower cost per kilogram to LEO compared to today's launchers.

For this discussion, a hybrid government/commercial project is assumed, meaning that government contracts build some portions of the system, while the government pays for launches on delivery, with minimal, or preferably no, interference with a capitalistic process. It could just as easily work with a corporation sponsoring the project, although until a marketable product or service (beyond what currently exists) is obvious in space, this possibility is slim. Throughout the rest of this paper, whatever entity runs the project will be referred to as The Agency.

The project begins with a decision as to a cost/kilogram that will allow a thriving space industry. Several studies have taken place to find this "magic" dollar-per-kilogram-into-orbit number, and the values vary from each. The purpose of this paper is not to come up with this number, so for discussion's sake, a value of $1000/kg will be chosen.

Once this dollar figure is determined, another factor must be set, that being the minimum useful cargo weight. Here again, a lot of theories abound, and these theories are not the topic for this paper. For this analysis, a value of 7500kg will be chosen. This puts the required lift vehicle between a light and medium EELV, and should still allow some company to build a craft to carry passengers or some other useful commodity into LEO. Note: This throw mass is not enough to launch a modern-day communications satellite into geosynchronous transfer orbit, a common make-or-break throw mass for rockets today. Market research will have to determine if such a goal is required. A larger payload capability may be good, as a vehicle that could later carry more passengers could cut its cost per passenger, much like the 747 does by carrying so many people today.

With these values determined, the government builds and launches (or contracts through normal procurement channels) an electrolysis station and a number (on the order of 100) of cargo vehicles. The electrolysis station will serve as a target for the cargo vehicles, which will carry water up to it. Once they dock, the station will use solar power arrays to electrolyze the water into its constituent hydrogen and oxygen elements. Because it is much more difficult to store liquid hydrogen and liquid oxygen compared to water, the option exists to leave the cargo vehicles' payload intact, simply keeping it from freezing, until its constituents are required. Any hydrogen and oxygen produced will be refrigerated and stored in orbit, awaiting its use by another vehicle.

Any mission desiring to use the cache of fuel and supplies provided by HaWaTa will have to design a docking port in accordance with design specs. After launch into LEO, and docking with the station, the user can take on a mix of liquid hydrogen, liquid oxygen, and/or water in whatever proportions they prefer. An interplanetary craft using HaWaTa's supplies will be able to get a much larger payload to its destination, either through launch of an unfueled upper stage or the re-use of a common upper stage used today (examples include Centaur and the unnamed liquid hydrogen/ liquid oxygen Delta IV upper stage)

COMPONENTS

The components of the HaWaTa system are relatively simple, being designed for long life and multiple users.

Electrolysis Station

The electrolysis station is envisioned as what is now considered a normal government procurement. The Agency requests bids from contractors and monitors the construction. When construction is complete, the station is lifted into orbit using one of the well-known launchers of the time. While the space shuttle (and its requisite human involvement) may be required if the station contains several complicated deployments, the job should be feasible as a payload on board the heavy version of an evolved expendable launch vehicle. The station is designed to be automated, with the possibility of an occasional crew visit to inspect the system and/or fix any problems.

The station is made up of many systems common to other uncrewed satellites (attitude control, power, thermal control, etc) but has some important differences:

1. Storage: The electrolysis station will have to store large quantities of liquid hydrogen and liquid oxygen. Liquid hydrogen is particularly difficult to store because of its low density (requiring large storage tanks) and tendency to leak (requiring meticulously constructed tanks, piping and valves) Cryogenic liquids are difficult to store because of their temperature extremes, and this storage will require some form of active refrigeration. Storage methods require study, using either multiple tanks (preventing a single meteor strike from puncturing the only oxygen tank, but making storage of large quantities difficult) or single tanks (requiring multiple layers of protective material to prevent punctures, but allowing much greater volume storage.)

2. Two Types of Docking Adapters: Because the station will have to receive cargo (the water) and pass on products (the hydrogen, oxygen, and water,) it will require two types of docking systems. Both require a mechanical locking mechanism to hold the docked spacecraft to the station. The adapters need to be located to provide a consistent flow (from the delivery tanks, into the processor/storage tanks, into the receiver craft)

Figure 1 shows a diagram of the station. Descriptions of components proceed from the ‘top’ of the spacecraft (the side with the solar arrays) to the ‘bottom.’

Multiple Water Intake Docking Ports – These ports would receive the water cargo ships for long-term storage. They also include electrical connections that allow the station to control temperature on board the cargo craft. Multiple ports prevent a failure in one from causing a mission loss. Each port requires a valve which, when opened, allows water to flow into the electrolysis reactor.

Solar Arrays – The solar arrays need to be large to meet the huge power requirements for electrolysis, but for this mission have no particular requirements other than separate steering (each array being able to move independently) that is common on communications satellites today. This capability allows the arrays to be used to steer the station along some axes using solar pressure. The size and number of arrays depends on the production rate of hydrogen and oxygen desired, and the power requirements for cryogenic storage. Further analysis is necessary in this area. One possible source of solar arrays for the satellite would be the International Space Station – some backup arrays or components should exist, although their functionality, depending on their design for the station, may be limiting.

Electrolysis Reactor – Most water delivered on orbit feeds from the cargo craft into the reactor for separation, although some water is split into a separate channel to flow the length of the station. The electrolysis reactor’s primary driver is reliability, as it will likely need to function for several years. Since the satellite itself will be rather light (it is launched almost devoid of fuel), it will likely pay to build a heavier electrolysis reactor if the added weight will add reliability.

Refrigeration Units – Redundant refrigeration units liquefy the by-products of the electrolysis reaction (hydrogen and oxygen) and maintain the liquids in the cryogenic storage tanks. They should be reliable and able to stand long periods of time without running.

Attitude/Orbit Control Thrusters – The station will likely rely on gravity gradient stabilization (a natural condition experienced by any spacecraft which doesn’t have its mass distributed uniformly throughout), but may require some form of attitude control thrusters. Orbit control thrusters will be necessary to maintain the station’s orbit. Any thrusters should run on gaseous hydrogen and oxygen, two materials readily available on board the craft. Gaseous hydrogen and oxygen are stored in pressure bottles located around the electrolysis reactor.

Liquid Hydrogen/Liquid Oxygen/Water Output Docking Port – This is where a visiting spacecraft will dock to ‘fuel up’. The pipe feeding each liquid to the docking port can be opened or closed, allowing the user to take any mixture of liquids on board. One design issue with this port is the fact that flowing water near the cryogenic liquids (hydrogen and oxygen) will freeze. A way around this is to avoid flowing all the fluids at the same time.

Longitudinal Thrusters – One great concern in orbital propellant transfer is how to get a liquid to flow into the new vessel when desired. While liquid oxygen is paramagnetic (meaning that a nearby magnet will induce a magnetism within the oxygen, and get it to flow)[ii], hydrogen does not have such a useful property. In order to keep things moving, longitudinal thrusters invoke a small acceleration when needed. Pressure within the tanks will force the fluids out once the fluid is located at the drain, although some thrusting may be required to keep the flow uniform. When water is required in the electrolysis chamber, valves open between the cargo ships and the station, and thrusters fire – the water then flows into the station. Water flow within the station is likely to be handled with a bladder and external pressure system, while the dynamics of refrigeration and storage of the cryogens requires more work. Smitherman, et al, describe gravity gradients (used to keep the spacecraft stable) as keeping the hydrogen and oxygen together in their tanks.[iii] When a visiting craft docks with the station and requires supplies, the necessary valves are opened and the longitudinal thrusters fire. Originally, it was thought that the longitudinal thruster firing would suffice for orbit maintenance, but aligning the longitudinal axis with the orbital velocity vector would be difficult for a (hopefully) simplistic attitude control system. More study will show if the trade-offs between attitude control and orbit maintenance are worthwhile.

Cargo Vehicles

The cargo vehicles may rank as the simplest, most mass-produceable spacecraft in history. A schematic of one appears in figure 2. Their design requires them to carry water and remain active for a couple days at most in order to dock with the electrolysis station. Depending on the amortization required to make the delivery-on-orbit contract feasible (see the next section), and whether the idea of on-orbit refueling catches on, the number of cargo vehicles ordered could range into the hundreds, making it a unique group of spacecraft. There are two components: the water tank and the orbit assist ring.

Water Tank – As its name implies, this portion of the cargo vehicle holds water. Design simplicity is important, although required units include a fore and aft docking port (so that it can attach to the electrolysis station or the tank ahead of it in line, and another can attach to it) and heating elements throughout to prevent the water from freezing. The heating elements must be able to be powered by the orbit assist ring or the electrolysis station. The tank may be made of composite materials, since it will be not have to face temperature extremes brought on by exposure to cryogenic propellants, and it should be outfitted to last in orbit for some time without leaking its contents. This requirement will likely drive the need for some form of meteorite shield.

Orbit Assist Ring (OAR) – The OAR's purpose is to deliver the tank to the electrolysis station. Once the cargo vehicle is delivered into orbit (within the parameters specified in the delivery contract) the OAR takes over, making final orbital adjustments and the precision maneuvers required to dock. This type of procedure has been automated in the past, such as with the Progress cargo vehicles' deliveries to the International Space Station, so the technology is not new. Once the tank is docked to the station, the OAR's job is complete. A small pyrotechnic charge will separate the OAR from its tank, and the OAR will maneuver itself to a safe burn-up in Earth's atmosphere. The internal components of the OAR include a guidance computer, telemetry equipment, batteries, and an orbit/attitude control system. The solar cells on the outside of the OAR are not fully researched. It is possible that given the craft's short lifespan in orbit, batteries alone may do the job, but solar cells would provide a longer life in case it was necessary.

Delivery-on-Orbit Contract

The primary difference between this program and others is the delivery-on-orbit contract. This option for space services, while it's been used in some cases such as the Navy's Ultra-High Frequency Follow-on (UFO) program and the Geostationary Operational Environmental Satellite (GOES), has never been used to pay for mass delivered to orbit. Of course, mass on-orbit has never been a stated goal of a space system before. After the mass and volume requirements for the cargo vehicles are established, the price desired, and the orbit where the electrolysis station will be is determined, an announcement in the Commerce Business Daily states the following (or something similar):

Z Agency will pay Y dollars to place X kilograms of water into orbit at W degrees inclination +/- W' degrees. The orbital altitude must be V kilometers +/- V'. Payment will take place when the orbit is verified by independent sources. The Agency will provide the cargo craft to carry the water, and will provide interface control information to anyone who contacts The Agency. Current launch services providers are eligible to make this effort, but upon a successful delivery, their launch costs to The Agency (and any of its parent organizations) for X kilograms will be Y from now on, in any contract. Any entity working to meet this contract should keep The Agency informed on its flight schedule. Bonuses will be paid to companies that demonstrate a high success rate (>U%), and high sortie (flight) rate (>1 flight every T days). Any launchers will adhere to the flight rules established at their chosen launch site. Entities seeking this delivery contract should consider other uses for their vehicle to make their launcher viable after this contract runs its course.

The contract is designed to be simple. Anyone who delivers the water into an orbit with the required parameters (only inclination and altitude are specified because others, such as phasing can be adjusted over time using the OAR. If solar cells aren't used in the OAR, then the phasing will be important to minimize flight time to the station) receives payment.

Since this has the potential of being a government contract, and the government has been accused of stifling free competition by cutting development costs for some companies by feeding development work, two clauses are designed to either keep existing players out, or changing their ways of doing business. By requiring any existing launch service provider to make the cost of launching water cargo vehicles their new standard launch cost, current launch providers will likely stay out of the business all together. Bonuses for high sortie rate will also likely keep the big players out, because the current demonstrated launch rate for a United States company off one launch pad is 28 days (Boeing, launching its Delta II vehicle during the Iridium launch campaign)

It must be noted that international launches are not prohibited. If an entity can establish a launch presence on some island, the cargo vehicles will be shipped to that island and payment will be honored upon successful delivery.

The method of lifting to orbit is left out on purpose as well, along with a required technical review of any proposed methods. The idea of the first concept is to allow any idea to be tried, so long as the entity in question can raise the cash to do so. At this writing, it's believed that the lift method would have to be reusable by a large percentage in order to be viable at the proposed launch costs per kilogram. The second concept may be a little outrageous, as current space activities require oversight beyond most other industry's imagination. It's been introduced however, to try and cut down on The Agency stating that design A is viable and design B is not, in which case the entity producing design A is now at a tremendous advantage over entity B.

The contract will not specify a number of flights, other than stating it will be more than 50. A recent article in Space News[iv] cites two reports describing 50 flights/year as the critical flight rate to make a reusable vehicle cost-effective. The idea here is to prove that there's enough business for more than one entity to make the effort. Amortization of a launch vehicle from development through profitability has never been accomplished with any degree of accuracy (the space shuttle serves as one example, and Ariane's repeated requests to its parent agency for more money is another), but the more guaranteed flights there are for a launch vehicle, the easier such an amortization is. It is hoped that the launch capacity and flight rate created by this project would open up new space industries, space tourism being one of them.

CACHE EFFECTS ON SPACE FLIGHT

Immediate Applications

Once The Agency starts paying a contractor for regular deliveries of water to orbit, any other user desiring the new low-cost launch service would be free to negotiate their own flight. It's possible that the launching contractor will negotiate a higher cost to low-use customers, (such as a single flight on board their launcher) but this type of price work is best left to the newly created market, and by definition, would be much more interesting and worthwhile if there are two launch service contractors available.

Assuming a launch cost of $1000/kg and a payload mass of 7500kg, a small company or university could contract to launch a large satellite into low Earth orbit for $7.5M. Depending on the dynamics chosen for delivery to LEO, (disposable vs. reused second stage, etc) that same university or small company could have the option to send a smaller payload (on the order of 2000kg) to the Moon or Mars. Unfortunately, since launch costs are largely the same no matter what the rocket is carrying, a small company or university who wanted to launch a 2000kg satellite into LEO would have to pay $7.5M, unless they combined their payload with another and launched more satellites at once.

When compared to today's rates for launching small payloads, these numbers are extremely favorable. The Ariane 5 launch vehicle has the option of launching small payloads along with its primary, but the costs per kilogram are actually greater than the primary. A 120kg microsatellite will run a customer $3M to launch, costing a whopping $25,000/kg. Ariane also offers flights for 300kg payloads at a cost of $6M, translating to a cost per kilogram of $20,000. These numbers are negotiable through Arianespace. A niche market may always exist for small payloads such as these, but these launches will not open space to large-scale use by the industrial or public sectors.

Short-term Future Applications

The Atlas IIAS rocket is a two-stage launcher in use today. Its payloads consist of military, civil and commercial spacecraft, most of which are destined for geosynchronous orbit. The rocket uses a first stage powered by kerosene and liquid oxygen (boosted by two or four solid rockets strapped to its side) and a second stage, called a Cenaur, powered by liquid hydrogen and liquid oxygen. Atlas is listed as having a LEO launch capability of 8610 kg[v]. The same source lists the Atlas' Earth escape throw mass as 2680kg Though it is not specified, for this analysis, this value is assumed to the mass that the booster can push to a hyperbolic excess speed of zero launched from Cape Canaveral Air Force Station. To achieve this mass to Earth escape, the first stage burns to depletion, followed by the second stage burning to depletion. Having an orbiting fuel depot in orbit allows a different flight plan and much greater capability.

By definition, a vehicle that can push 8610 kg to Earth escape can push that same amount of mass to geosynchronous transfer, with a little some propellant left over to raise the orbit a little closer to today's goal of geosynchronous orbit. This fact will almost double the size of current communications satellites, or allow a current design to achieve geosynchronous orbit with much more fuel, translating to a much longer life.

In order to exploit this capability, the Centaur upper stage would have to be modified from its current configuration. For this discussion, it is assumed that the modifications increase the weight of a Centaur by 500kg. Additional equipment required includes:

1. Docking Adapter – Designed to mate with the orbiting electrolysis station, this adapter will likely be mounted between the hydrogen and oxygen tank. The feeds to both tanks will need to be valved.
2. Additional Life – The current mission timeline of the Centaur is extremely short. Most missions last 6 hours or less. In order to take on an orbital refueling mission, the stage will need to be active for a much longer period of time, and may need to have re-chargeable batteries or solar panels.
3. Precision maneuvering/guidance – The Centaur has never been required to maneuver in any close quarters with another spacecraft other than an avoidance maneuver from the satellite it just dropped off in orbit.

In a possible scenario during the HaWaTa project, an Atlas IIAS with a modified Centaur lifts a payload of 8610 kg into LEO, and burns the Centaur to depletion, then docks with the electrolysis station. The longitudinal rockets on the station fire, pushing fuel from the station into the Centaur. When the Centaur takes on a full load of propellants, it will be able to push itself and the original 8610 kilograms launched to Earth escape, with an additional delta-v available of 1.2 km/sec. This method multiplies the Atlas IIAS throw mass to Earth escape by 3.2X, with propellant to spare. It should be noted that the Cassini spacecraft launch to Saturn in 1997 had a mass of 5712kg[vi].

A Centaur-derived upper stage is used as the second stage of the Atlas V version of the EELV, and the logic spelled out above applies. Boeing also uses a hydrogen-oxygen booster for the second stage of their EELV, and could use the same approach.

Long-term Future Applications

As humankind moves beyond low Earth orbit, fuel and/or oxidizer will be necessary to make such trips possible. No matter what form of propulsion is chosen, (such as chemical, which uses hydrogen and oxygen, or nuclear, which would likely use hydrogen) a cache of propellants in low orbit will decrease the amount of mass a particular mission will need to lift off the surface and accelerate to orbital velocity. The question comes in as how much mass is saved in such a launch?

Zubrin argues that a mission to Mars can be accomplished using a Saturn V (the rocket used to take humans to the moon) class booster[vii]. Such a booster does not exist operationally today, but could lift 140 tonnes into low Earth orbit. For a trip to Mars, of the 140 tonnes in LEO, fully 100 tonnes is fuel. Since Zubrin is a proponent of getting to Mars first and letting the newly-created need for nuclear propulsion drive the development of the technology, chemical propulsion (hydrogen/oxygen) is assumed. By this argument, in order to reach Mars a new heavy launch vehicle, capable of launching 140 tonnes at once or 2 launches of 80 tonnes (the proposed lift weight for a booster called Magnum, proposed by NASA), is required for a crewed Mars mission.

A refueling station in low Earth orbit changes the situation significantly. Assuming that a HaWaTa station could hold 100t of propellant, (additional would be required for chill-down fueling losses) it would be possible to launch a crewed Mars mission with a launch mass from Earth surface of 40t. Two launches of an EELV-H would achieve this mass to LEO. This doesn't make such a launch easy, since the current diameter limitation for an EELV-H is 4.8M (estimated, based on a 5 meter outer diameter payload shroud)[viii] . Launching a hydrogen tank that could hold 86t of extremely low-density fuel would make a 4.8 meter tank very long or require a much larger diameter tank.

If such difficulties were overcome, the HaWaTa project could support routine missions to Mars. If and when nuclear propulsion becomes an option, HaWaTa can still provide a useful service. A nuclear rocket destined for Mars launched with empty tanks will weigh between 40-50% less than a nuclear rocket launched with full tanks. Once again, the weight savings can be used to decrease the size of the booster required to start the mission.

DOLLAR VALUE

During or after the HaWaTA project, The Agency that operates the station will have a large supply (on the order of hundreds of tones) of material in low Earth orbit. The material is usable by a myriad of other agencies, but how much will they be willing to pay for it? Or, more importantly, how much money could The Agency expect to make in profit from the sale of its commodity?

The simplest (and most flawed) way to look at the project is to assume an initial cost, (we'll say $1B for the station, cargo vehicles, and delivery-on-orbit contract) an amount delivered to orbit, (for discussion, 50 flights of 7500kg of water each) and a current cost to low Earth orbit (dollar figures go as high as $10,000 a pound, or $22000 a kilogram, but we'll cut that by 25% to be conservative, and give everyone a discount). With 375000kg of supplies on orbit, multiplied by the 'going' rate off $16,500/kg, The Agency has $6,187,500,000 of commodity available for sale.

For the first launches, before the concept proves out that launching fuel and oxidizer in to orbit separately from the payload is a good idea, this sale price will be reasonable. Before the cargo launch vehicle proves itself to be reliable, mainstream missions such as those launched by NASA or The US Air Force will likely rely on existing launch vehicles. The spacecraft launched by these vehicles will then dock with the electrolysis station for a fill-up before traveling on to their final destination.

It is possible that this project will become a victim of its own success. Assuming that the cargo launch vehicle becomes a successful method of achieving low Earth orbit, the cost for one of its launches will be much lower than the going rate for other launches. Odds are, there will still be a core of government customers who'll desire the 'old' way of launching, where ultra-high maintenance satellites are babied in their cradle right up until the rocket is lit sending them on their way. Many users, including commercial interests that exist today and others that have not even been imagined yet will use the cheaper service with reliable schedules. Depending on the payload support team for this commercial business (the cargo vehicle for HaWaTa is designed to be extremely low maintenance, requiring very few crew personnel for preparation, so additional personnel will be required to support any other payload) the cost will go up slightly, but on a per-kilogram basis, the price for this new launch vehicle or method cannot be beat.

EXPANSION POSSIBILITIES

With a docking adapter designed to allow all products (hydrogen, oxygen, and water) flow through, the electrolysis station can be expanded quite easily if the demand for on-orbit fueling becomes more than one unit can handle. A second, near duplicate station could connect to the first via the docking port normally used to fuel customer vehicles. If the original station is fully functional, but simply needs a greater storage area, the additional station will be able to hold the extra hydrogen and oxygen, and use its own solar arrays to cool the fluids. If the original station is having difficulty, or operating at a reduced efficiency (without the need to be completely replaced) the auxiliary station can accept water flowing through the first station and process the feedstock into hydrogen and oxygen on its own. This same approach could be used with two stations operating at or near peak efficiency – together, they would produce hydrogen and oxygen at double the rate of the first station.

If the idea of on-orbit fueling catches on, it may be necessary to place electrolysis stations in orbit around Earth in different orbits. This would allow different launch sites to use the service without paying the penalties associated with a drastic change in orbital inclination.

REMAINING ISSUES

The following list is not exhaustive, but discusses some of the issues this project could face as it moved from concept to reality.

Power

Electrolysis is an extremely power-intensive process. Research found one commercially[ix] available electrolysis unit that produces 8.2 kg of hydrogen and oxygen per hour with a power feed of 100kW. At this production rate, it would take 38 days to process one 7500kg tank of water into its hydrogen and oxygen components. Plus, to maintain a power supply of 100 kW on orbit, much more power must be available to charge batteries that will supply energy during eclipse time, when the Earth shades the orbiting vehicle from the sun. Another power draw will be refrigeration of the hydrogen and oxygen. While storing water on orbit is not difficult, and could still support a 1/week flight rate, that storage will take power.

For comparison, one set of solar arrays for the International Space Station provides 60 kW, clearly not enough to provide an acceptable production rate. This vehicle will require multiple solar arrays of space-station design, or larger arrays.

Volume

The design shown here for the electrolysis station shows multiple tanks holding hydrogen and oxygen. This design provides redundancy for a single-tank failure, but may hamstring the project because of the need for large tanks to store hydrogen. Large-diameter tanks provide the most volume per unit length, but a single tank subjects the system to a single-point failure.

Reliance on One Type of Propulsion

In the current research-dollar-driven world of space programs, an idea such as this can generate as much negative interest based on its perceived threat to other programs as much, if not more than based on any technical flaws. For instance, one argument against this system is that it would provide an excuse to keep using liquid hydrogen and liquid oxygen to travel beyond low Earth orbit, instead of focusing research dollars on the more efficient, though more controversial, nuclear-powered propulsion. This argument has some validity, but much of it is diffused through the ability of HaWaTA to support nuclear engines. Even if nuclear propulsion makes a debut in the next 10 years, it will not become the mainstream method of propulsion for many years after that, so there will be plenty of hydrogen/oxygen burning rockets available to use the HaWaTA propellants.

In the case where a nuclear spacecraft fuels purely with hydrogen, leaving a store of oxygen on board the station, someone in low Earth orbit will find a use for it. Any developing space interest in orbit would not turn down such a supply, especially considering that The Agency would likely be willing to sell it at a discount. The alternative would be venting the precious fluid/gas into space.

It should also be noted that electrolyzing water provides oxygen and hydrogen at a mass ratio of approximately 8 to 1, that is 8 kilograms of oxygen for 1 kilogram of hydrogen. The best ratio of these propellants' rocket engines are operating on right now is 6 to 1, because of the troubles maintaining a stoichiometric (fully-balanced) reaction in a combustion chamber. Because of this imbalance, any station used to simply provide liquid hydrogen and liquid oxygen propellants for chemical engines will have a supply of leftover hydrogen.

Orbital Location

The best initial orbital location for the first electrolysis station will likely be hotly debated, assuming it moves beyond the concept phase. A primary use for the fueling service is expected to be interplanetary missions, and the optimal orbit to leave Earth from varies from one launch opportunity to the next. A station in the 28-degree inclined orbit would serve NASA and US Air Force launches from Cape Kennedy and Cape Canaveral, but would be unreachable (well, reachable, but at such a fuel cost the advantage gained by refueling is likely to be greatly diminished) from Russian launch sites. Depending on market growth, any second station should likely be placed in a 57-degree inclined orbit, to allow service for users from Russia. Users closer to the equator than 28 degrees would be able to reach the station rather easily, but will have to trade their natural 'boost' received by launching close to the equator as some of that advantage is lost by launching into a higher inclination.

Attitude Control

The electrolysis satellite is unlike any other previous spacecraft in its constantly changing center of mass. When first launched, the satellite will be largely devoid of fluids, and will have attitude characteristics based on its layout. When the first cargo craft is launched to it, the 7500kg of water carried on board will be a significant increase to the original craft's mass, and will shift the center of mass towards the cargo vehicles' docking ports. Further cargo deliveries will compound the problem. Once the electrolysis process begins, the center of mass of the vehicle will shift again, only the total mass will remain steady.

These changing conditions make selection of an attitude control system problematic. A common attitude control method, reaction or momentum wheels, work well when a spacecraft is nearly balanced, that is, distributed evenly around its center of mass (a materially-uniform sphere meets such balance perfectly). This spacecraft, however, will likely not be evenly distributed about its center of mass. Even if such a design were possible at the start, the above-mentioned shifts in center of mass would force changes in attitude control. Thrusters are another option, and though the station will have plenty of fuel on board, relying on thrusters for full-time attitude control is not an elegant solution.

One of the simplest ways to control the attitude of a spacecraft is to not do anything. When left alone, the natural 'lop-sidedness' of the satellite will cause it to orient its long axis pointing towards Earth (the physics are a little more involved than that, but the description will suffice for now) as evidenced by images of the Long Duration Exposure Facility. The LDEF was deployed to test materials for their response to long periods in space. When STS-32 approached the facility in 1990, it was very stable, and allowed easy grappling and retrieval[x].

The same principal can be applied to the electrolysis satellite. When the satellite is first launched, it will orient in one direction, depending on its mass properties. If such a direction requires some active control, the solar arrays can be used to rotate the spacecraft along its primary axis. As cargo vehicles dock with the station and the center of mass changes, the craft will rotate 180 degrees in a slow yaw (or roll, or pitch as the case may be). This motion, while not common in spacecraft, is manageable, and is worthwhile considering the added complexity other attitude control strategies would bring. If such a rotation is undesirable, water could be processed into hydrogen and oxygen, shifting the center of mass and managing any undesired changes. More analysis is required in this area, as the size of the cryogenic storage tanks, and possible shifting of hydrogen and oxygen within them, will make it difficult to predict exactly where the center of mass will move to.

Valving/Leakage

As mentioned before, the handling, transfer, and storage of cryogenic propellants are not simple on the ground. Doing so on orbit is only going to be more difficult. As this paper is written, the space shuttle is grounded due to flaws in cryogenic propellant lines, with a launch date listed as 'indefinite.'

Hydrogen is a particularly difficult commodity. The frigid temperatures (only liquid helium stores at a lower temperature) and tiny molecular size provide challenges to ground operations involving the liquid. Some technology development is required in the automated transfer, valving, and leakage detection/control of hydrogen before this project is feasible.

SIMILAR RESEARCH

Smitherman, et al[xi] described a system similar to this in a paper presented at the Space Resources Utilization Roundtable III at the Colorado School of Mines. Their research showed an increasing need for hydrogen and oxygen in LEO, both to resupply craft in LEO and to fuel missions beyond. In their paper, they discuss how this type of electrolysis system must wait for some exotic future transportation to LEO, not how this system could bring about such a new form of transportation.

CONCLUSION

The implementation of an orbiting electrolysis facility was discussed. While challenges remain in the production and control of on-board cryogens, the payoff in both common access to low Earth orbit and leverages for exploration beyond are immense. Using the low-tech mass of water as a guaranteed payload also has the capability of jump-starting a low-cost transportation option to low Earth orbit, and could be run by any government or large corporate entity. Immediate payoffs include increasing the interplanetary throw mass of a currently medium-sized booster Atlas IIAS booster to greater than that of the accepted heavy-weight Titan IV. Immediate payoff in communications satellite size and lifetime are worthwhile, and future applications include allowing a Mars-Direct style mission to Mars using this plan and existing EELV launch technology. A business model showing the value of hydrogen and oxygen stored on orbit is unclear, as the lowered cost of lifting the material may decrease the material's value, but the end payoff in decreased cost to orbit is likely worthwhile.

FIGURES

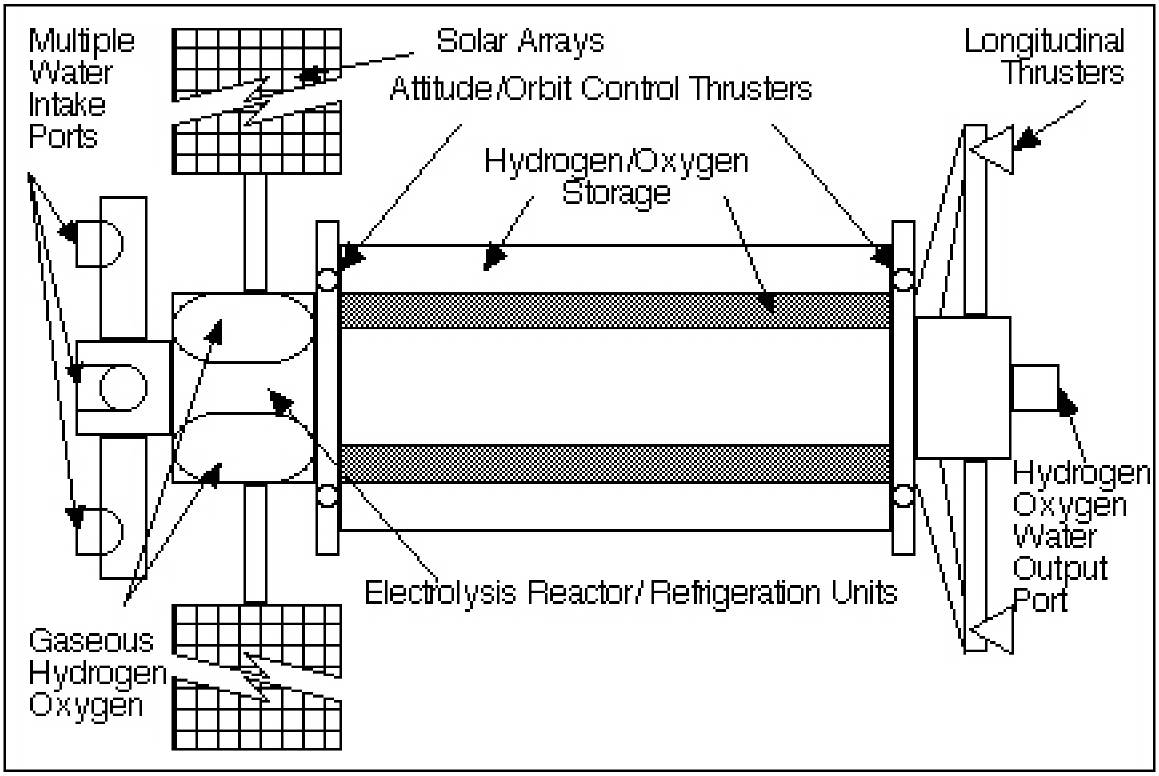

Figure 1 – The electrolysis station

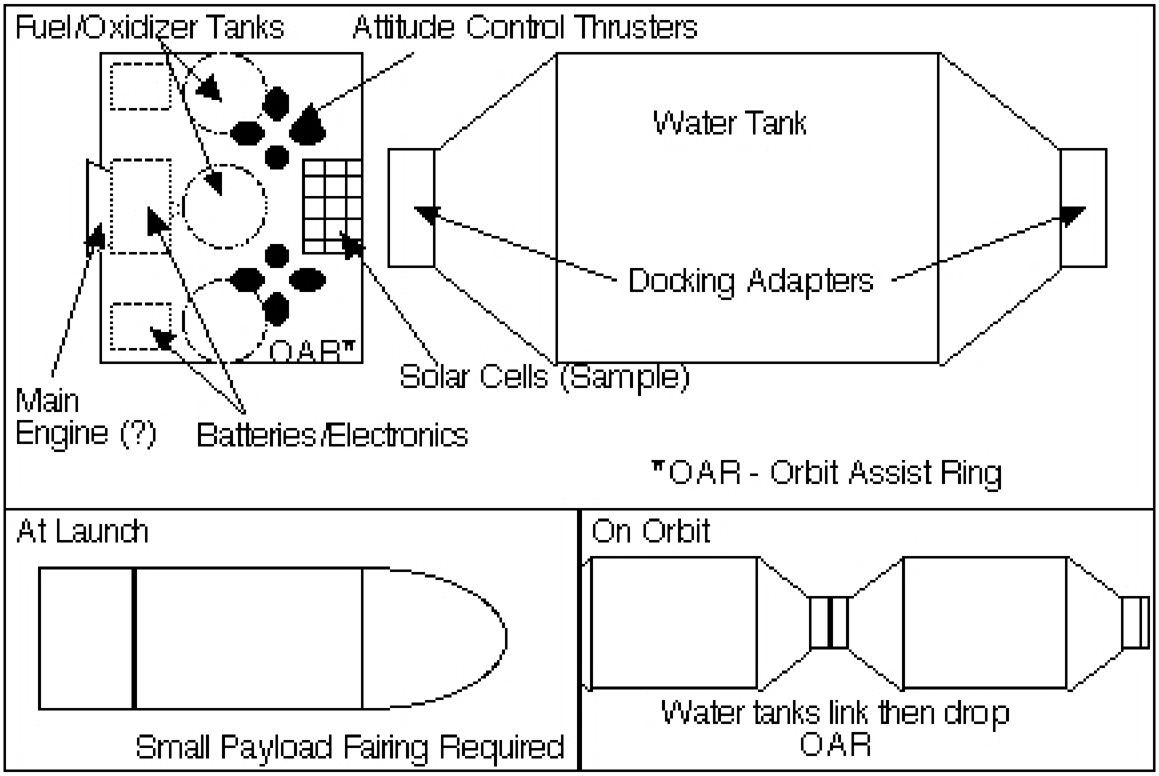

Figure 2 – Cargo Vehicles

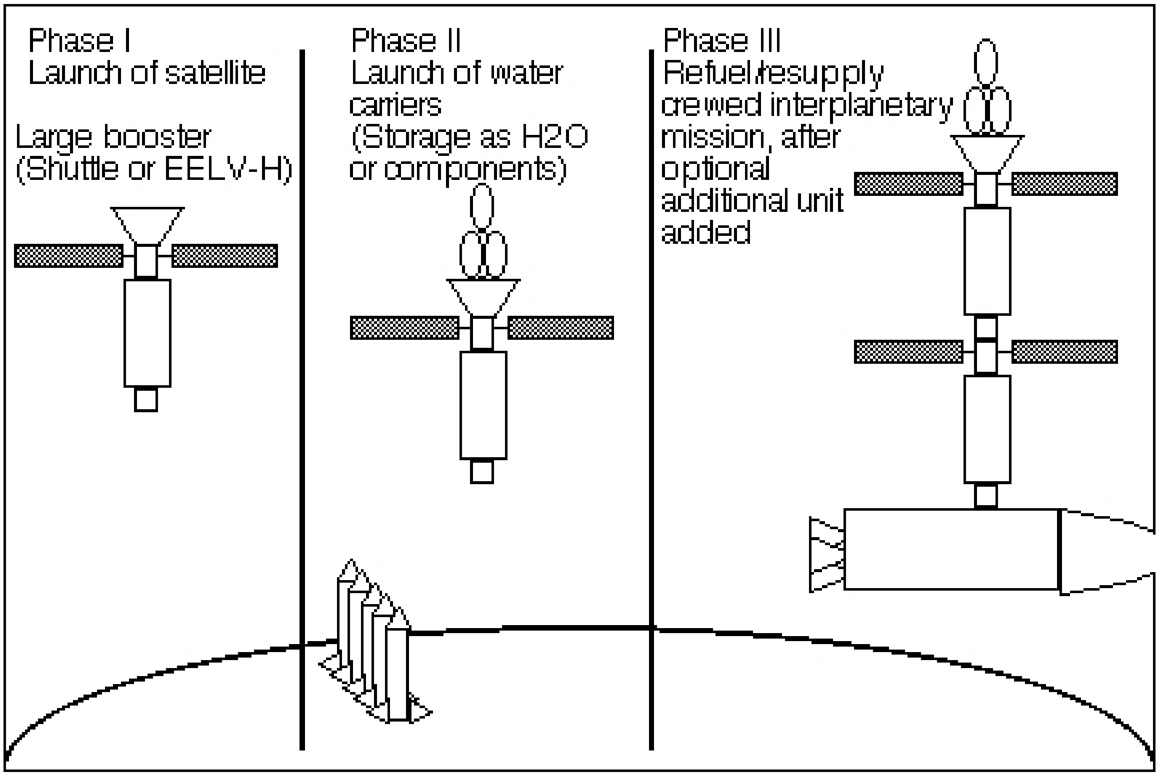

Figure 3 – An overview of the HaWaTa program

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