A Review of Current Developments in SSTO Technology and their Viability

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What if traveling to space could be almost as simple and affordable as getting on a commercial flight? Single-Stage-to-Orbit (SSTO) launch vehicles could revolutionize the space industry by doing just that, through massive reduction of launch costs and waste. Their reusability would allow for minimal hardware replacement as well as fast turnaround times between launches. Reducing launch vehicles to a single stage would remove inherent complications involved in multi-stage rockets. However, while the reusability of SSTO vehicles is highly desirable, many challenges to its practical implementation have yet to be overcome. Challenges such as having to carry empty fuel tanks, requiring a light thermal protection system, and storing enough fuel to carry payload to orbit all display the overarching problem of weight. As of today, such challenges have made SSTO vehicles technically nonviable, but with new developments and breakthroughs in the field that lower vehicle mass and improve engine efficiency, there may be a possibility for SSTO vehicles in the near future. Developments in fuel tank technology like the BHL composite fuel tank allow for a decrease in vehicle weight, which increases payload capacity. In addition, new engines like the SABRE engine are more efficient and capable. SSTO concepts like the Skylon vehicle have built on these advancements and presented seemingly plausible SSTO designs. This paper will explore the many challenges of designing an SSTO vehicle and the current attempts to solve those challenges. Based on these developments, this paper will describe the viability of SSTO vehicles in the near future (next 15 years).

Introduction

Space travel has long captured the global imagination, yet it has been inaccessible to the average person. Only highly vetted and trained astronauts—and now billionaires as well—have had the opportunity to travel to space. This is of course because every rocket launch ends with the entire rocket (or a large part of the rocket) being destroyed creating enormous costs and waste. Reusable SSTO vehicles have the potential to completely change all of this. The rapid reusability of SSTO vehicles could allow it to be launched perhaps hundreds of times for the same cost as one launch of a vehicle like NASA's Space Launch System, which is estimated to cost in the billions per launch. Furthermore, time in between launches would be massively shortened because there would be no new rocket to build and, given SSTO vehicles' single stage, no complicated rocket stages to integrate, further resulting in much cheaper costs. The single stage of SSTO vehicles has the added benefit of requiring much simpler launch complexes, reducing the infrastructure costs of the launch[1]. If successfully implemented, SSTO vehicles would function much like an airliner; they would be able to get their payload to orbit, return to earth to refuel, and then be ready again for another launch[2]. Reaching space would no longer be just a dream to the average person, and we would see a new era of commercial space travel emerge.

The SSTO concept, while intriguing, has never flown and has rarely gotten past the design phase because of the many difficulties surrounding it. To understand the difficulties of SSTO vehicles, it is important to understand why multi-staged vehicles are used instead. When a rocket launches, it starts to burn fuel, and eventually its lower stage fuel run out of fuel. Rather than wasting fuel by carrying these empty fuel, multi-staged vehicles get rid of the lower stage, allowing the upper stage engines to have less mass to propel, therefore allowing it to reach orbit. In addition, staging allows for the different stages to have engines optimized for varying altitudes, further improving their efficiency[3]. Because SSTO vehicles do not eject their empty fuel tanks, weight is a significant issue, an even larger one than it already is with multi-staged launch vehicles. Because of this issue, SSTO vehicles generally have a worse payload mass fraction (payload mass / vehicle mass + payload) than their multi-staged counterparts. The less the vehicle's structure weighs, the better the payload mass fraction gets, so every pound matters with SSTO vehicles.

SSTO vehicles are incredibly difficult to launch on Earth, but on other surfaces like the moon or Mars, launching SSTO vehicles would likely be fairly easy because of their significantly lower gravity and thinner atmosphere (or no atmosphere in the case of the moon). The Apollo Lunar Module was capable of achieving orbit from the moon without much difficulty at all. On Earth, however, the planet's much larger gravity and thicker atmosphere makes SSTO that much harder. Creating a rocket that can fight through Earth's gravity and atmosphere while still having a usable payload mass fraction is an enormous challenge. The crux of the issue is that a vehicle must carry enough fuel to be able to reach orbital velocity, and the less efficient a vehicle is, the more fuel it will need to carry. Current vehicles are not efficient enough for the vehicle to reach orbital velocity with the amount of fuel it is capable of carrying. Moreover, Earth's atmosphere creates one additional significant weight-related problem: the need for a thermal protection system. Due to the high velocities during re-entry, re-entering Earth's atmosphere creates incredibly high temperatures, requiring a thermal protection system. However, thermal protection systems are heavy, which creates the need for an effective, but light thermal protection system[2]. Creating a reusable SSTO vehicle is difficult, but creating a non-reusable SSTO vehicle could likely be done now. If a vehicle were to have no thermal protection system and a payload mass fraction of zero, it could possibly reach orbit in a single stage. In fact, Elon Musk has claimed that Starship would be able to reach orbit in one stage if it was stripped down[4]. However, creating an SSTO vehicle that is reusable and has a usable payload mass fraction is the real challenge. There have been many attempts to solve this problem, and attempts continue to be made to date. Yet the challenges facing SSTO vehicles have persisted.

This paper aims to identify the biggest developments in SSTO technology and analyze their effectiveness. The possible solutions to this problem will be separated into the categories of general design and engine, fuel tanks, thermal protection system, and propellants—the main areas in which innovations could lead to successful SSTO vehicles in the near future. Finally, this paper will lay out next steps for future research on the topic.

Methodology

For this paper, I started off with initial research to determine the problems of SSTO vehicles and ascertain the developments that have aimed to solve these problems. This research led me to organize these developments into the following categories: general design, engines, fuel tanks, TPS, and propellants, which informed the organization of this paper. Furthermore, understanding the challenges of SSTO vehicles through my research enabled me to create a set of requirements for a successful reusable SSTO vehicle. General design and engines were highly interrelated, so I combined them into one category. I then conducted additional research within these categories and, based on that research, further subdivided them into subcategories. From there, I investigated the subject of each subcategory and evaluated its suitability for a successful SSTO vehicle against the requirements I had enumerated.

In order to find sources, I searched databases for peer-reviewed articles that discussed the different subcategories I had created. If possible, I tried to find articles specifically concerning developments related to SSTO vehicles, but if not possible I analyzed the development and extrapolated its applicability to SSTO vehicles myself. In order to mitigate bias, I read many different articles from different researchers in order to get a holistic and accurate view of the subject and to gain an understanding of the general consensus of experts in this field. If an article was peer-reviewed and about the desired topic, I believed the article to be a suitable source for this paper. Interviews were not used, as a result of access and a limited time frame. Experiments were also not included, as a result of the resources available to me (any experiment useful for this paper would require resources far beyond the average individual). Keywords that I used were "SSTO" and words suggested by the category and subcategory I was researching. I aimed to find articles with such key words, but if not possible, I searched the category. The databases I used the most were AIAA and MDPI, but if I could not find anything in those databases, I would run a Google search. These combined strategies enabled me to find the research necessary to complete this paper.

A limitation of the methodology carried out for this paper is that all of the data used in the paper was presented to me through the lens of another individual in the form of peer-reviewed journal articles. As stated previously in this section, I tried to mitigate the effects of any potential bias or inaccuracy by reading many articles from a variety of different sources.

Requirements for SSTO Vehicles

In order to accurately analyze the viability of developments in SSTO vehicles, it is important to create a few basic requirements for SSTO vehicles. These requirements will be revisited throughout the paper:

1. **Rapidly Reusable:** The vehicle must be completely reusable so that the cost of producing a new vehicle for each launch can be significantly reduced. It must also be able to have minimal refurbishment time in between flights (less than one week). This requirement was established so that the vehicle can be refurbished with minimal difficulty and cost and therefore function like an airliner.
2. **Simplicity:** While an SSTO system will of course be extremely complicated, it should not be complicated to the point of creating extraneous time waste or costs. For example, launch assists (equipment that supports a rocket

launch) that require an extraordinary amount of effort or infrastructure that would take decades to build will not be taken into account. Simplicity is necessary for an SSTO vehicle in order to make it financially realistic and worthwhile.

3. **Present Viability:** Every SSTO concept must be achievable within the somewhat near future (15 years). Predicting technological developments further away than this time frame becomes to a certain extent, guesswork, so 15 years has been set as an outside timeline. 15 years is also sufficient time for the breakthroughs considered in this paper to come to fruition. If a concept requires substantial scientific breakthroughs, it will not be considered. For instance, nuclear propulsion or laser propulsion are both so far away from what is possible today that it is not practical to consider them.

4. **Usable Payload Fraction (payload mass / vehicle mass):** The vehicle must have a payload fraction of at least 1% in order to allow for enough payload to be put into orbit. Any less than 1% would be an amount of payload too small to justify a vehicle since there would be such a negligible amount of payload relative to the mass of the vehicle. Even among rockets where payload fractions are very low, 1% is borderline, but sacrifices must be made for complete and rapid reusability.

5. **High Specific Impulse:** Specific impulse is the change in momentum per unit of propellant. The vehicle's specific impulse must be high enough that the vehicle can have a somewhat low mass ratio (wet mass / dry mass). A higher specific impulse allows for a lower mass ratio because it means the engines are more efficient, therefore requiring less fuel.

6. **Purposeful:** Any SSTO vehicle must have substantial advantages over a multi-stage-to-orbit vehicle.

General Design and Engines

This section will focus on the best combinations of general designs and engines. There are three main combinations that make sense. Conventional rocket + conventional rocket engine, conventional rocket + aerospike, and hybrid rocket-plane + hybrid air breathing-rocket engine. While there have been SSTO concepts falling outside of these categories in the past, none have had enough success to be worth discussing here.

Conventional Rocket + Conventional Rocket Engine

This is the combination seen in almost every rocket flying today, consisting of a rocket using a traditional bell nozzle engine. In a bell nozzle engine, a chemical reaction occurs creating hot gas, which shoots out of a bell nozzle, thereby creating thrust. Out of all the combinations, this is by far the easiest one to analyze. Plugging values into the rocket equation shows that by using conventional rocket engines, it is not possible to achieve a mass ratio of much less than 101. However, this mass ratio is too high for there to be very much payload or for the vehicle to have enough structural mass[2]. There are three ways to solve this problem: increasing the vehicle's specific impulse, improving the vehicle's structural efficiency, or some combination of the two. To achieve an SSTO vehicle through the first option, a vehicle would need a specific impulse of around 500s to create a mass ratio of 5, which would be much more viable for current technology[5]. Of course, this is a very simplistic use of the rocket equation, but it does indicate why SSTO vehicles are near impossible to achieve using conventional bell nozzle rocket engines because of their very low specific impulse. As stated earlier, according to Elon Musk, Starship could theoretically reach orbit in a single stage, but it "wouldn't have enough mass margin for a heat shield, landing propellant or legs"[4]. Even though Starship could technically be an SSTO vehicle, it would not be able to have any payload and without a heat shield, it would not be reusable, defeating the whole purpose of making it an SSTO vehicle. Therefore, while SSTO vehicles using conventional engines could theoretically reach orbit, without extra mass for payload or for systems to make them reusable (like TPS systems), they do not fulfill the previously mentioned requirements of having a usable payload fraction and being rapidly reusable.

Rocket Equation:

$$\Delta v = I_{sp} \cdot g_0 \ln \frac{m_0}{m_f} \tag{1}$$

Where:

Δv : Change in velocity
I_{sp} : Specific Impulse
g_0 : Acceleration due to gravity
$\frac{m_0}{m_f}$: Mass ratio
m_0 : Wet mass (mass of rocket with fuel and payload)
m_f : Dry mass (mass of rocket with payload but no fuel)

For the RS-25 Engine (366s at sea level), the equation becomes:

$$7800\,\text{m/s} = (366\,\text{s}) \cdot (9.81\,\text{m/s}^2) \cdot \ln \frac{m_0}{m_f} \tag{2}$$

This gives a mass ratio of $m_0/m_f = 8.78$.

For an engine with a 500s specific impulse, the equation becomes:

$$7800\,\text{m/s} = (500\,\text{s}) \cdot (9.81\,\text{m/s}^2) \cdot \ln \frac{m_0}{m_f} \tag{3}$$

This gives a mass ratio of $m_0/m_f = 4.91$.

The Rocket Equation above can be used to determine a vehicle's change in velocity from specific impulse, gravitational acceleration, and mass ratio. Here, change in velocity is set to 7800 m/s because a launch vehicle should accelerate from rest at 0 m/s to orbital velocity at 7800 m/s. The RS-25 engine is used as an example of a conventional engine that a conventional rocket would use (the RS-25 engine has one of the highest specific impulses out of any conventional bell nozzle rocket engine). 500s is used as the specific impulse for the second calculation because it is a value that produces a very low mass ratio while still being theoretically viable for the hybrid airbreathing engines that will be discussed later on in the paper.

Conventional Rocket + Aerospike

Conventional bell nozzle rocket engines experience diminished efficiency when not at their optimal altitude mainly as a result of the phenomenon called geometric loss[6]. Geometric loss occurs as a result of the rocket plume expanding to meet the atmospheric pressure. Bell nozzle engines reach their maximum efficiency when the engine plume is parallel to the direction of the engine. When it is not, the engine plume produces less thrust in the direction parallel to the engine. This happens because engines generate thrust by having gas shoot out opposite the direction of motion. If the gas is expanding outward and not moving opposite the direction of motion, less thrust in the desired direction is produced, therefore lowering specific impulse. This phenomenon is displayed in Figure 1 below. When the ambient pressure P_∞ is greater than the exhaust pressure (Pe), the exhaust plume contracts to match the higher ambient pressure. However when the ambient pressure is less than the exhaust pressure, the exhaust plume expands to reach equilibrium with the atmosphere. As shown in the diagram, when this happens, thrust is not maximized because parts of the plume go in directions not parallel to the nozzle. This problem limits the specific impulse that a conventional bell nozzle rocket engine can achieve.

Aerospike engines have a distinct advantage over engines utilizing bell nozzles because aerospike engines are able to for the most part be equally efficient at all altitudes. They achieve this efficiency because the outside air functions like a nozzle does and compresses the exhaust plume inward[6]. Aerospike nozzles could possibly have "90% overall better performance than the conventional bell shaped nozzle" for this reason[6]. This improvement to performance is not large enough to make SSTO vehicles viable using current technology. As shown by simplistic rocket equation analysis, a specific impulse near 500s would be required to achieve a mass ratio below 5 (a ratio viable using current technology). However, aerospikes have a great number of difficulties associated with them. Aerospikes weigh more than conventional bell nozzle engines, which is a big issue for any rocket, but an even bigger issue for SSTO vehicles. Despite these issues with aerospikes, it is important to consider that aerospikes share many structural elements with the vehicle structure, which can even lead to a lower weight[8]. Cooling the aerospike presents another challenging design problem[6]. These challenges, while difficult, seem to be much easier than many other engine design difficulties (like SABRE).

The combination of a conventional rocket with aerospike engines is the SSTO concept, which came closest to flying. The X-33 (shown in Figure 2) was a subscale demonstrator of the VentureStar, a reusable SSTO vehicle utilizing linear aerospike engines[10]. Even after over a billion dollars (worth 1.72 billion dollars in 2023) were spent on the program, it was canceled in 2001 as a result of a fuel tank failure. 95% of the vehicle's components were built and tested, and 75% of the vehicle was constructed[10]. While the X-33 was not a success, there is still a possibility that other SSTO vehicles making use of aerospikes can be viable.

While the X-33 program made many inherent challenges of building an SSTO very clear, many of those issues have since been significantly improved upon. As previously mentioned, the X-33 program failed because of a liquid hydrogen fuel tank failure. In order to save valuable weight, the X-33's tanks were made out of composite materials, but failed as a result of microcracks in their walls[10]. However, in 2004, three years after the X-33 program's end, Northrop Grumman designed a successful composite liquid hydrogen tank. A 2014 study showed that there are even better possible composite fuel tanks that could weigh as much as 75% less than the current best fuel tanks[11]. Such fuel tanks will be explored further later in the paper. In addition, new advancements in aerospike engines have allowed for even more increases in their specific impulse, thereby bringing the possibility of an aerospike-powered SSTO even closer. One such development is the utilization of an expander-bleed cycle in aerospike engines. In the expander-bleed cycle, a driving gas powers a turbopump, and that driving gas is eventually "bled" out of the engine. In a normal engine, this "bled" gas results in a decrease in specific impulse, but in an aerospike it can be used as a secondary injection into the engine. In addition, the expander-bleed cycle allows for a higher chamber pressure, but also requires a large heat absorption area, which aerospikes are able to provide. Aerospikes and the expander-bleed cycle turn each other's weaknesses into strengths and therefore allow for a higher specific impulse. A simulation study displayed that an aerospike making use of an expander-bleed cycle could result in a specific impulse high enough to make a viable SSTO with sufficient advances in material science[12]. Specific impulses of 387s at sea level and 460s in a vacuum were reached. This presents a specific impulse in between the RS-25 and 500s,

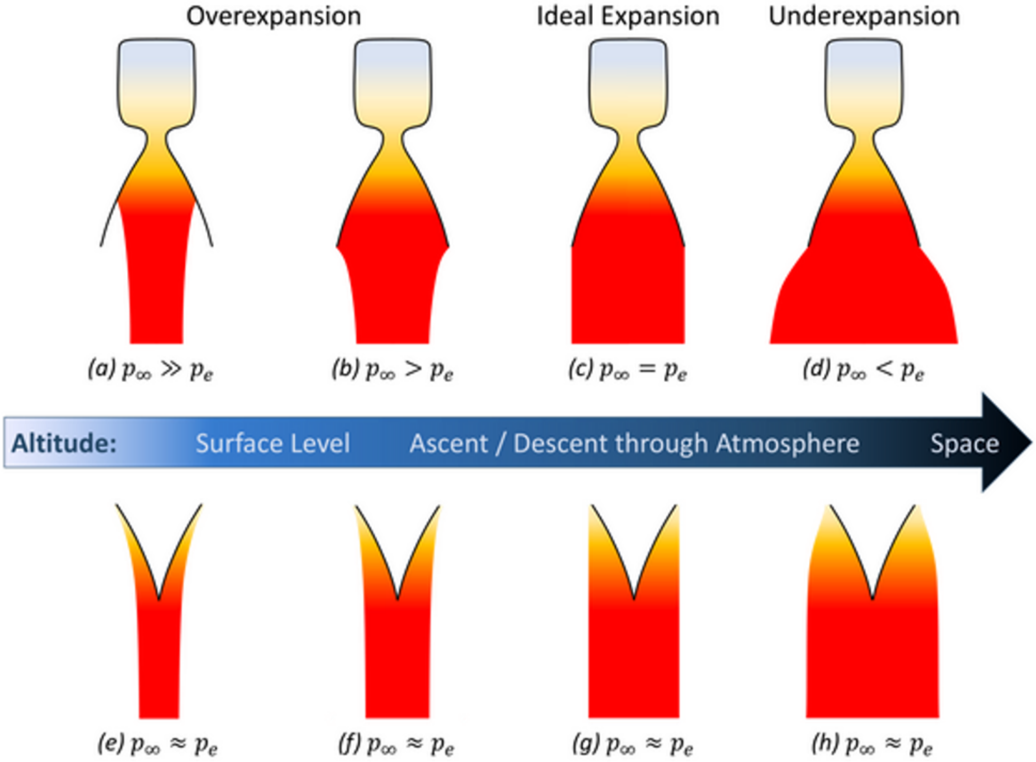

Fig. 1 Exhaust plume for bell nozzle (top) and aerospike (bottom). P_∞ is ambient pressure, and Pe is exhaust pressure[7].

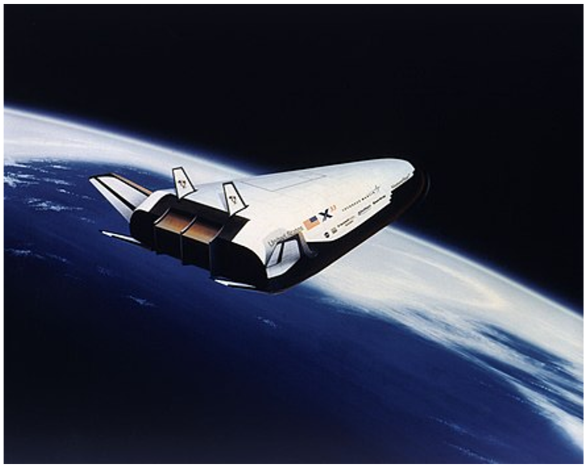

Fig. 2 A depiction on the X-33 in orbit[9]

requiring some new technological advancements (albeit less advancements than the RS-25 would require).

These new advancements in composite materials and aerospikes make it clear that the X-33 program's failure does not mean that SSTOs making use of aerospikes is an impossibility. The biggest challenge is creating a vehicle structure light enough to have a viable propellant mass fraction. However, this challenge seems to have become a smaller challenge with improving technology. It does seem to be very much within the realm of possibility for there to be an SSTO making use of aerospikes in the near future.

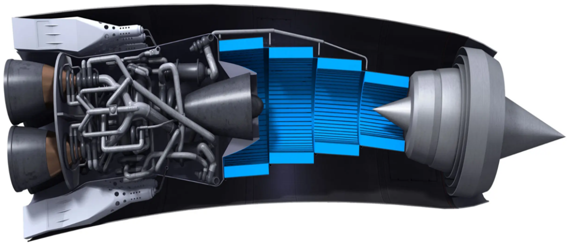

Fig. 3 A depiction of the SABRE engine[13]

Hybrid Rocket Plane + Hybrid Air Breathing Rocket Engine

This is the SSTO category that has received the most traction in recent years. Conventional rocket engines can only have a limited amount of specific impulse. Even aerospikes, while having much better efficiency, can only reach a certain specific impulse. Plane engines, on the other hand, can reach specific impulses over 10,000s because they use the oxygen in the atmosphere as an oxidizer, and therefore have an unlimited source of oxidizer that they do not have to carry. The aim of a hybrid air-breathing rocket engine is to make use of this high air-breathing specific impulse while in the atmosphere and then switch over to rocket power once out of the atmosphere[14]. By far the most prominent hybrid air-breathing rocket engine is the SABRE engine (shown in Figure 3), which is expected to be able to have a specific impulse of 3500s within the atmosphere and 450s in a vacuum[15]. When combining the air-breathing specific impulse with the rocket-powered specific impulse, a number near 500s (which yielded a mass ratio of 4.91 when plugged into the rocket equation) should be reached. As a result of this high specific impulse, Skylon is theoretically achievable using current technology.

Fig. 4 A depiction of Skylon in Orbit[16]

While hybrid air-breathing rocket engines drastically improve specific impulse and the mass ratio, these benefits are counterbalanced by the extra weight of a hybrid-air breathing engine and hybrid space-plane vehicle body[2]. Furthermore, hybrid rocket planes function with a very low payload mass fraction, and therefore can be made obsolete with an incorrect simulation. Doing a correct simulation of re-entry is exceptionally difficult due to a wide variety of legitimate methods that yield different results. Atmospheric flow over a vehicle can be modeled by viewing the atmosphere as a continuum rather than a composition of particles. The Knudsen number is the molecular mean free path divided by a representative physical length scale, and it can show the extent to which atmospheric flow can be modeled as a continuum. As the Knudson number increases, it becomes important to look at a system as not a continuum as well. The two methods can yield very different predictions (as shown in Figure 5), and it is very difficult oftentimes to tell which method yields better predictions leading to uncertainties of 10%[2]. The thermal protection system also presents a large amount of inert weight, which further lowers the weight available for payload. These challenges, while hard, are not impossible to solve. Hybrid rocket plane SSTO designs have been put forth and, for the most part, seem to be viable. The most prominent of these designs is the Skylon vehicle (shown in Figure 4), a hybrid rocket-plane SSTO vehicle that uses the SABRE engine. Research into the Skylon vehicle has had promise, and the European Space Agency claimed, concerning Skylon, that ”no impediments or critical items have been identified”[17]. However, Skylon is far behind schedule and likely will not be flying for at least another decade. Despite this delay, Skylon seems to be a promising vehicle, which—given time—will likely eventually fly.

Fuel Tanks

A significant problem of SSTO vehicles is having enough weight left over for payload. There are such thin margins for weight, and fuel tanks, being very heavy, are a major contributor to this problem. However, as stated earlier, new developments in composite fuel tanks have the potential to lower fuel tank weight by up to 75%. This weight reduction is made possible by Gloyer-Taylor Laboratories BHL composite propellant tank technology (shown in Figure 6). A large problem with reusable SSTO vehicles is that they must be large in order to support the added mass of systems for reusability like the thermal protection system[11]. The large vehicles create a degree of impracticality, and no doubt this has played a role in Skylon's less-than-ideal development. Skylon is 83 meters long, over twice the length of the Space Shuttle Orbiter's length (37.24m). This is an issue that BHL technology can help address.

Composite materials have been used successfully in many rocket fuel tanks, but have suffered when having to carry cryogenic fuels[11]. This is an issue because most SSTO concepts make use of liquid hydrogen and liquid oxygen to achieve high specific impulse. It becomes hard for composite materials to hold their structure at low temperatures, which is exactly the reason for the X-33 composite fuel tank's failure. Many composite tanks, in order to reduce weight, make use of leak-tight laminates, but these laminates are often prone to cracking at cryogenic temperatures. BHL has an “innovative manufacturing process,” which allows it to have thin leak-tight laminates while still maintaining structural integrity. BHL tanks are capable of undergoing many cryothermal-pressure cycles.

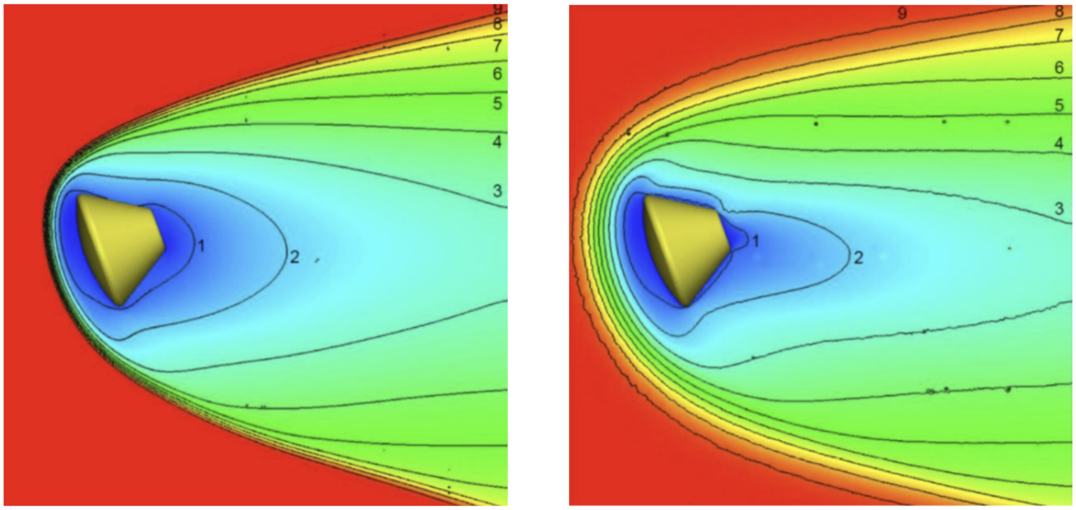

Fig. 5 A depiction of airflow using a continuum method (Left) and a particulate method (Right)[18]

Fig. 6 A GTL 16”x25” cryotank[19]

These results have been backed by numerous tests on subscale tanks[11].

BHL subscale tanks have reached densities of 1.4 lb/ft3, and as the tank is scaled up, the density decreases with the lowest-possible density expected to be 0.1 lb/ft3, which is four times better than current best tanks like Al-Li Isogrid tanks (as shown in Figure 7). Air has a density of 0.08 lb/ft3, just under BHL tank density. BHL tanks reach a point of having a near-negligible volume relative to the vehicle’s total volume, thereby allowing for a significantly higher payload mass fraction. As a result of BHL technology, payload mass fraction could increase by 2.5%[11]. While that seems like a small number, it is important to remember that typical rockets have a payload mass fraction around 2.5%, meaning that the integration of BHL technology could double the payload mass fraction of many vehicles. In SSTO vehicles, where the payload mass fraction is even less than in multistage vehicles, the effects of BHL technology are even more significant in lowering vehicle weight and allowing for more payload

Thermal Protection System

The thermal protection system (TPS) presents a large challenge in reusable SSTO vehicles. Typical TPS materials have been very heavy, which makes it difficult to integrate into SSTO vehicles. Furthermore, TPS materials oftentimes can be very brittle and require extensive refurbishment. This is what happened in the case of the Space Shuttle, which had massive refurbishment times due to its poor TPS[2]. As stated previously in the requirements section, turnaround times must be kept low, meaning that there must be a big focus on finding a lightweight but durable TPS material. The TPS System for an SSTO vehicle must be light, but durable allowing for minimal refurbishment in between flights and hundreds of reentry cycles.The three main TPS methods are passive, semi-passive, and active, but since passive and semi-passive methods are the most cost and weight-efficient, only those will be considered[21].

Current Solutions

Ablative TPS solutions are a type of semi-passive surface, which involve having a surface material absorb heat through a phase change to liquid or gas. Ablative materials have the advantages of “high heat shock resistance, low density, good mechanical strength, and good thermal insulation capabilities”[21].

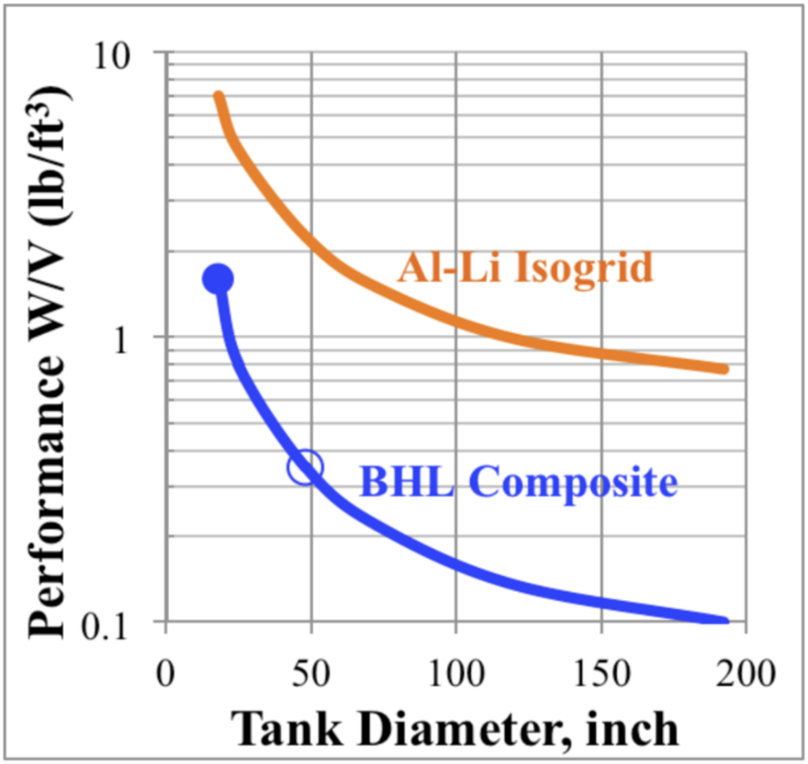

Fig. 7 BHL Tank Performance. Closed circle: 18" tank; Open circle: 48" tank under development[20]

However, given that ablative materials partially melt or evaporate, they are not reusable. While there have been proposed methods of quickly swapping out the thermal protection system between launches, it is not practical for a vehicle built on rapid reusability to have to swap out a thermal protection system[22]. Heat sinks are a passive solution that involve using metals with high heat storage capabilities. However, heat sinks have proven to be unsuccessful in the past. They were used on the Mark 1 and Mark 2 reentry vehicles, but had failures of loss of strength, which led to the destruction of the vehicles[21]. Therefore, it is unlikely they would be adaptable for SSTO vehicles due to their lack of durability.

Hot structures and insulated structures are the two types of TPS methods that show the most promise. Hot structures are able to re-radiate because of their high emissivity. Insulated structures contain a reflective outer layer and a lower layer that insulates against the heat. Both hot structures and insulated structures are for the most part light and able to withstand high temperatures. TPS structures have commonly been composed of C/C composites, C/C-SiC composites, and titanium aluminide. In addition, TPS structures have also been composed of Ceramic Matrix Composites (CMC's) like zirconium carbide, hafnium diboride, and silicon carbide. Skylon makes use of a silicon carbide ceramic for its TPS due to its effective use in Skylon's low-heat, high altitude reentry[23]. Skylon, like most conceived SSTO vehicles, has a high lift-to-drag ratio. This high lift-to-drag ratio is what causes Skylon to have its peak heating at a high atmosphere. As a result, Skylon has a lower peak heat, but experiences a longer re-entry time. By controlling its angle of attack, Skylon maintains a temperature under 3000 degrees Fahrenheit[2]. While hot structures and insulated structures can successfully deal with this re-entry, they take up a lot of weight in order to have sufficient structural integrity making their integration into SSTO vehicles difficult because of their weight[21]. However, many new projects are under development to help reduce this weight problem.

New/Future Solutions

Integrated Thermal Protection Systems (ITPS) solutions are a light, reusable TPS solution. ITPS solutions involve having a Thermal Protection System, which also serves as a load-bearing structure. This is different to typical TPS solutions that are put on top of the load-bearing structures.Typically these systems would be composed of corrugated core ceramic matrix composite (CMC) sandwich structures (shown in Figure 8). This would theoretically allow a TPS to have the light weight of ablative solutions while still maintaining reusability[22]. Studies indicate that ITPS solutions could result in 50% weight reductions. If oxide-fiber-reinforced oxide-matrix composites were to be used, weight reductions could reach 75%[21]. Many different implementations of ITPS have been proposed. Among the first proposals was a corrugated core with fibrous insulation, but different cores have since been investigated. It is indicated that the best core is dependent on the specific thermal and mechanical loads[22].

Rather than corrugated CMC structures, phase change materials (PCM) can be used in ITPS lattice structures. Materials have diminishing strength and stiffness at higher temperatures. PCMs have a high thermal energy storage, meaning that heat can be stored in the PCMs resulting in lower temperatures on the surface and thereby greater strength and stiffness. PCMs store heat so efficiently because of the inherent energy required to achieve a phase change while maintaining a constant temperature. PCM lattice structures are far more theoretical than CMC corrugated core structures. However, if they were to become a reality, they would allow for very efficient thermal protection systems. The main challenges facing PCM use in TPS are containing them, and having a high thermal conductivity. However, using lattice structures helps to solve this problem through their high thermal conductivity and ability to contain PCMs[22]. ITPS lattice PCM structures could result in much more efficient TPS systems, but they remain mainly theoretical at this point. CMC corrugated core ITPS structures, while less efficient, could be ready in a much shorter time frame and still achieve massive weight reductions for an SSTO's TPS. These weight reductions are extremely important because the TPS is one of the two major sources of inert weight in an SSTO. Because of their low weight and high durability, these structures, if successfully developed, could be integrated into SSTO vehicles.

Propellants

By far the most common proposed fuel combination for SSTO vehicles is liquid hydrogen and liquid oxygen (both the X-33 and Skylon use this fuel combination). This is because these two fuels produce a specific impulse higher than any other fuels, and are accordingly more efficient, producing more thrust for the same amount of propellant. However, hydrogen fuel comes with many disadvantages, which must be taken into consideration. Liquid hydrogen has a very low density, meaning that it requires very large fuel tanks and hence uses up a large amount of weight capacity. In addition, hydrogen has an extremely low boiling point at -254 Celsius and is very explosive, making containing it very difficult[25]. This has been proven the case with the X-33 program being canceled as a result of failures of a liquid hydrogen tank, but with new technologies like BHL, it is not unfathomable to envision that liquid hydrogen could be stored efficiently enough to allow for a successful SSTO. There are arguments to be made in favor of denser fuels like RP-1, which would have a lower specific impulse but require a much smaller fuel tank. However, while denser fuels may be a valid option for multi-stage launch vehicles, which have much larger margins, SSTO vehicles cannot realistically afford a lower specific impulse. To summarize, while dense fuels like RP-1 have the distinct advantage of being lighter (meaning that less weight can be spent on fuel tanks), their lower specific impulse makes them not viable for SSTO vehicles. The combination of liquid hydrogen and liquid oxygen, while being much less energy dense, provides a higher specific impulse that is so desperately needed in SSTO vehicles. This fuel combination's low energy density (and therefore larger fuel tanks required), is a problem, but it is likely easier to overcome this challenge (as has been done with developments like BHL) than the challenge of RP-1's low specific impulse.

While liquid oxygen and liquid hydrogen are currently the most widely accepted best fuel combination for SSTO vehicles, this wasn't always the case. In the 1990s, NASA's "Access to Space Study" recommended that an SSTO vehicle make use of tripropellant propulsion[26]. Tripropellant propulsion achieves higher specific impulses by making use of three propellants as opposed to two. Tripropellant SSTO vehicles were based on the RD-704 engine, which was a tripropellant engine that used oxygen, hydrocarbon, and hydrogen propellants[26]. However, the RD-704 program was shut down, and there have been no major attempts to create tripropellant engines since. Reinvestigating tripropellant engines could possibly lead to major advantages in specific impulse gains, which could potentially overcome the weight-efficiency challenges facing SSTO vehicles described above. However, the main disadvantage with this concept is that since it has been so long since tripropellant engines have been seriously investigated, there have been significant developments in making bipropellant engines work such as BHL fuel tanks and hybrid air-breathing engines. There would be significant costs associated with tripropellant development as well as significant time spent, thereby making tripropellant engines a far less viable option at present[2].

Conclusions

This paper discussed how SSTO vehicles raise the possibility of unprecedented reusability and low launch costs. However, there are numerous difficulties associated with weight such as the TPS and fuel tanks. Four categories of the development of SSTO vehicles were discussed: general design and engines, fuel tanks, thermal protection system, and propellants.

It is quite clear that a conventional rocket making use of conventional bell nozzle engines is not viable. It simply cannot achieve a specific impulse high enough to have a suffi-

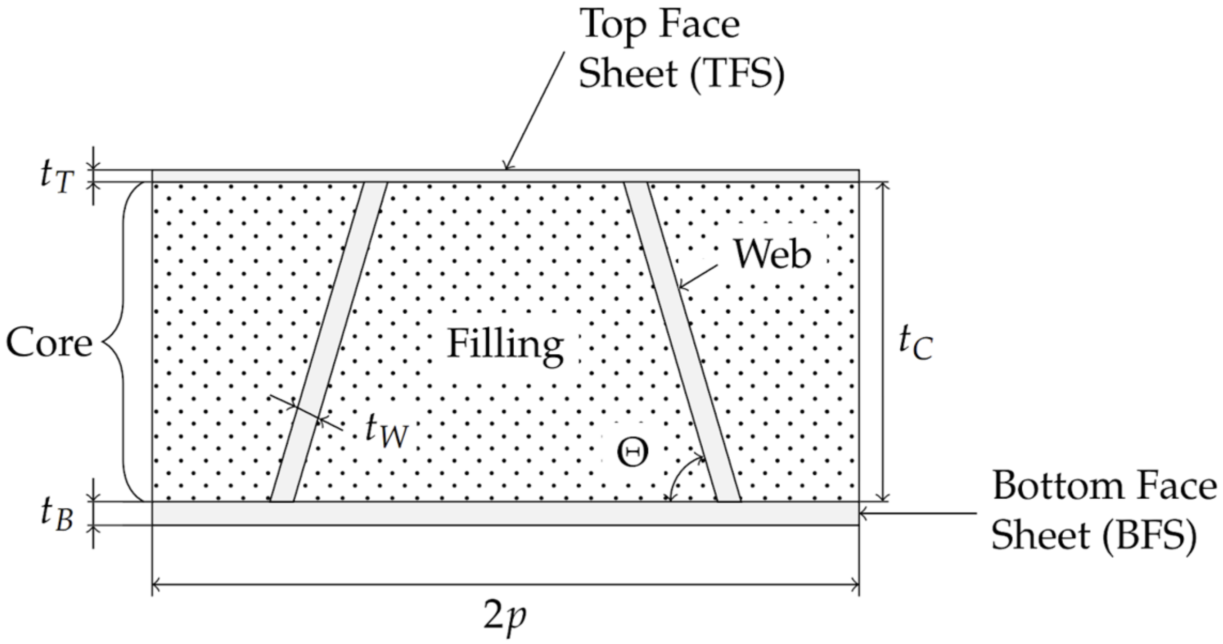

Fig. 8 A diagram of corrugated core CMC ITPS; t_T: TFS thickness; t_B: BFS Thickness; t_C: core thickness; t_w: web thickness; Θ: angle of corrugation; $2p$: the unit over which this structure is replicated.[24]

ciently low mass ratio. Aerospikes and hybrid rocket air-breathing engines could possibly have a high enough specific impulse, but each have their own specific challenges. Aerospikes have a lower specific impulse than hybrid rocket air-breathing engines, meaning that they require more weight-saving innovations in fuel tanks and TPS. However, aerospikes have been tested during the X-33 program, whereas hybrid rocket air-breathing engines are still in the early stages of development. Furthermore, because of the new weight-saving developments in SSTO technology (such as BHL tanks and alternate TPS designs), the advantages aerospikes have over conventional engines may be significant enough. However, hybrid rocket air-breathing engines have a higher specific impulse, which has resulted in plausible SSTO designs using air-breathing engines. These engines are of course still in a developmental stage, and SSTO designs making use of them hinge on the viability of these engines. Furthermore, developing a vehicle that can function as both a plane and rocket is a significant challenge. However, if these engines are developed successfully, they have the potential to make SSTO vehicles a reality.

Fuel tanks are a large source of inert weight in all launch vehicles, but especially in SSTOs. Weight margins are razor thin in SSTO vehicles, and because most SSTOs use liquid hydrogen propellant, they require heavier tanks with the capability to store liquid hydrogen. While this weight is theoretically fine for hybrid rocket air-breathing vehicles like Skylon, for vehicles making use of aerospikes, there is not enough weight available for a heavy fuel tank. Advancements in fuel tank technology, specifically the BHL composite propellant tank technology, have the capability to lower cryogenic tank weight to a mere quarter of typical cryogenic tanks. For aerospike-powered vehicles, this could be a determining factor in the viability of SSTOs. While Skylon and other hybrid rocket air-breathing vehicles theoretically do not need this improved fuel tank, implementing it would make their weight margins significantly less razor thin.

As with an SSTO's fuel tanks, the TPS presents another large source of inert weight. Decent solutions using CMC materials can be implemented currently, but improved solutions making use of integrated TPS can provide weight reductions of up to 75%. CMC materials or PCM materials can be used to provide even greater weight reductions. Additionally, ITPS and PCM solutions have been researched, and while these are far away developments, they provide significantly more heat protection for less weight. Structures making use of corrugated core sandwich structure or lattice structure could possibly even result in weight reductions over 50%. There are still challenges in these areas to overcome, but they would provide significant benefits if overcome.

While it is worth noting the existence of tripropellant combinations of fuel, they have not been seriously explored for some time, and it seems unlikely that an SSTO would make use of this combination. If the prospect were to be reopened, development costs would likely be significant, and it would take perhaps decades of development, during which time other advancements could lead more quickly to a successful SSTO vehicle. Liquid oxygen and liquid hydrogen are seen in virtually every SSTO design, and it seems that this is for good reason. Although other fuels could potentially allow for lighter fuel tanks, they do not provide the same high specific impulse that liquid oxygen and liquid hydrogen do. The high specific impulse of this combination is essentially a necessity. Furthermore, with advancements in composite fuel tank technology, the negative effects of liquid hydrogen could soon be diminished.

Skylon is a vehicle that is theoretically viable. To date there has been nothing that has disproved its viability. Unfortunately, there is also nothing that has concretely proven its viability either. Theory is a little different from reality in all cases, and a little difference goes a long way with SSTO vehicles, which are built on razor-thin margins. Skylon is far behind schedule and is still in engine testing phases despite its planned first flight in 2021. While this delay has disheartened many from the SSTO concept, such delays should be expected. With a vehicle like Skylon where a small variance in atmospheric drag from predictions can result in destruction, it is understandable why Skylon is so far behind schedule.

There are, of course, no guarantees that a viable SSTO vehicle can be achieved. Investing in SSTO vehicles could thus become an enormous monetary cost without achieving the desired result. However, even if a successful SSTO vehicle does not come to fruition, there have been numerous technological developments in the pursuit of a viable SSTO vehicle, as described in this paper, that can still have massive impacts on space travel and in general, even if those impacts do not include the successful creation of an SSTO vehicle.

Moreover, although the vehicles and developments discussed in this paper require new technological improvements, and the viability of SSTO vehicles hinges on such developments, the developments discussed in this paper are by no means inconceivable and are instead within the realm of possibility. If even one of the developments listed in this paper were to come to fruition, a SSTO vehicle would be significantly more viable. Skylon is already borderline viable, and the performance improvements discussed in this paper could bring Skylon over the finish line.

In the future, research should be directed more heavily into weight loss developments such as BHL tanks and new TPS designs. These are the developments that have the most significant potential to bring successful SSTO vehicles within reach. Skylon of course, is the furthest along in development, but little is known about its current progress, and it is therefore difficult to make an assessment on its true viability at present. Furthermore, only improvements that were somewhat far along in development were considered for this paper. However other developments such as nuclear power and using machine learning to discover new fuel combinations and materials, while far off, could have significant impacts on SSTO vehicles. While many are pessimistic about SSTOs, there is much to be hopeful for in their continued study and development, and much to be gained from them for the future of space flight.

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