Single Stage to Orbit Vehicle: Future of Space Industry

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Abstract. A general review of present advancements in the field of **Single-Stage to-Orbit** Vehicles. This article provides an overview of possible propulsion systems that we can use for **SSTO** vehicles. It also includes a quick overview of various ongoing initiatives based on **SSTO** vehicles.

1 Introduction

A **single-stage-to-orbit**(or SSTO) vehicles are vehicles capable of reaching the earth's orbit without dropping any hardware. They could function like conventional winged aircraft and eliminate the replenishment of rockets' hardware after each launch becoming an entirely reusable space vehicle. This reduces the cost of space transportation and offers increased reliability compared to existing vehicles. However, the dream of a working single-stage-to-orbit has not yet been fulfilled. These vehicles require extraordinary, propulsive performance, which limits the payload of such vehicles.

There are several advancements in the space industry, among which is the development of the first reusable rocket: *Falcon 9*. But this is again a 2-stage rocket, and only the first stage has been made reusable. So indeed, the development of the first utterly reusable rocket system will revolutionize the space industry, making the dream of navigation into space like on earth or in the air come true.

2 Propulsion Systems

In every industry, it is the payload trade-off that determines the value of any transportation system. In **SSTO** vehicles, the demand for fuel increases resulting in the reduced payload. Here is some proposed Propulsion System that can be used for SSTO Reusable launchers:

2.1 Hydrogen/Oxygen Rocket Engines

Hydrogen/Oxygen fuels have a high Thrust/Weight ratio(60-80) but relatively low specific impulse (470-475 secs in a vacuum)..[5] To maximize Specific Impulse, high area ratio nozzles are required, leading to a high chamber pressure cycle to reduce back pressure losses at low altitudes, which results in the selection of altitude compensating nozzle since conventional bell nozzle have high divergence and over-expansion losses.

The high thrust/weight ratio and low specific impulse favour vertical take-off. Therefore, the ascent trajectory is extremely benign, and hence the material selection is dependent on reentry. Rocket engines broadly represent the present space technology and are best suited to the technology we have available till now.

The relatively straightforward reentry mechanism would be basely re-entering first with active cooling of engine nozzles and the vehicle base. After reaching a low altitude, some of the main engines should be restarted to regulate the subsonic descent before landing on legs tail first. However, some designs attempt nose-first reentry of the blunt cone-shaped vehicle or a blended body configuration. This approach potentially increases the lift/drag ratio by reducing the fuselage wave drag and increasing the aerodynamic lift. However, this approach is aerodynamically unstable since the centre of gravity is pulled behind the centre of pressure, which requires the addition of nose ballast or large control surfaces reducing the small payload capability of this engine.

2.2 Ramjet and Scramjet Engines

A ramjet engine is a simple device with an intake, combustion, and nozzle system where the cycle pressure rises due to the ram compressor. Conventional hydrogen-fuelled Ramjet can operate up to around Mach 5-6 because the limiting effect of dissociation reduces the practical heat addition of the airflow.[5] Scramjet engine avoids the dissociation limit by partially slowing the air stream through the intake system. Scramjet has a high specific impulse up to a very high Mach number.

The conception of Scramjet thermodynamically seems very simple, but it is technically the most complex propulsion system among all. The system is susceptible to intake, combustion, and nozzle systems.
Scramjet doesn't work for low super-sonic speeds. Hence the internal geometry is designed so that Conventional Ramjet is used up to Mach 5 followed by a transition to Scramjet Mode. Further trade-off of net vehicle specific impulse shows that it is effective to shut down Scramjet at Mach 12-15 and continue with the pure rocket. Hence the entire system consists of four modes(with increasing Mach number) as follows:
Low Speed Accelerator Mode $\rightarrow$ *Ramjet Mode* $\rightarrow$ *Scramjet Mode* $\rightarrow$ *Rocket Mode*

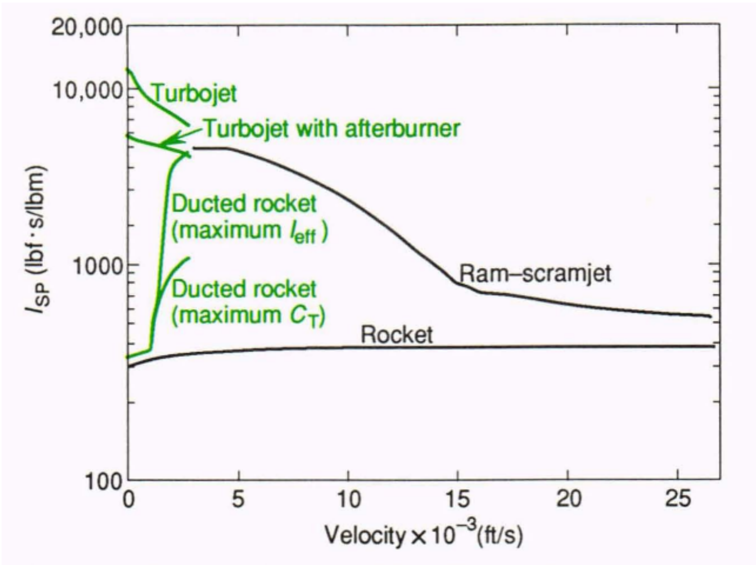

Figure 1: Computed Values of Specific Impulse[1]

2.3 Turbojets and Turborockets

These are the airbreathing engines that use turbocompressors to compress the airflow without any help from pre-coolers. This makes them capable of operation from sea level static conditions.

Turbojets show a rapid thrust decay above about Mach 3 because of the reduction in both flow and pressure ratio, which is caused due to rising compressor inlet temperature. The consequent reduction in pressure ratio and mass flow results in a rapid loss in net thrust. The uninstalled turbojet has a thrust/weight ratio of around 10.[5] This falls even less to 5 when the nozzle and intake system is added.

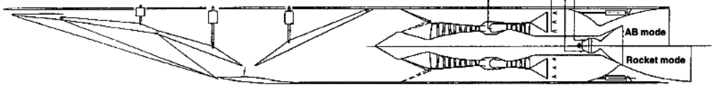

Figure 2: Turbo-ramjet Engine[5]

The pure turborocket consists of a low-pressure ratio fan driven by a separate turbine. Due to separate turbine working fluid, the matching problems of the turbojet is reduced because now the compressor can be operated anywhere. Compared to a turbojet, the turborocket is much lighter. Due to the low cycle pressure ratio, the particular thrust is reduced at low Mach numbers. Also, the pre-burner liquid flow results in a poor specific impulse as compared to turbojets.

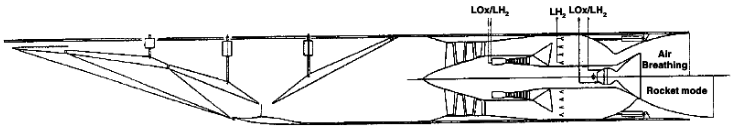

Figure 3: Turborocket[5]

2.4 Liquid Air Cycle Engines (LACE) and Air Collection Engines (ACE)

Marquardt proposed Liquid Air Cycle Engines in the 1960s. A simple LACE engine uses liquid hydrogen, exploiting its low temperature and high specific heat to liquefy the captured airstream in a condenser. This approach makes it possible to combine the airbreathing and rocket propulsion systems with only a single nozzle resulting in mass saving. However, the LACE engine has high fuel consumption.

In Air Collection Engine(ACE), a liquid oxygen separator is incorporated after the air liquefier. The aim is to take off with the primary liquid tanks empty and fill them during airbreathing ascent, thereby reducing the undercarriage mass. However, the basic thermodynamic principle of ACE is wholly unsuited to an SSTO launcher. Due to the high percentage of oxygen in airflow, an equivalent mass of hydrogen is required for liquefication. Therefore, there is no saving in take-off fuel, and indeed there is a severe structure mass penalty due to increased fuselage volume.

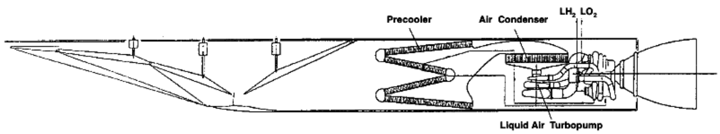

Figure 4: Liquid Air Cycle Engine(LACE)[5]

2.5 Precooled Hybrid Airbreathing Rocket Engines

The first engine of this type was *RB545* powerplant. Furthermore, the thermodynamic of the engine was refined to result in *SABRE*[3]. The LACE and RB545 resemble each other, except that LACE has high fuel consumption. In fact, the RB545 used high-pressure hydrogen from the hydrogen turbopump to directly cool the airstream before splitting the hydrogen stream. This reduced the fuel/air ratio to approximately 0.1.

The SABRE engine is a complex variant of the original cycle in which lower fuel flow is achieved at the expense of a minor mass penalty. An *Brayton cycle* helium loop has been placed between the 'hot' airstream and the 'cool' hydrogen stream in this engine. The power to run the air compressor comes from the helium loop's work output. The improved thermodynamics of the SABRE engine results in an air/fuel ratio of about 0.08.[5]

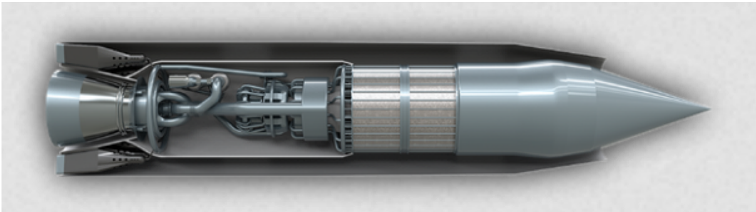

Figure 5: Synergetic Air Breathing Rocket Engine(SABRE)[3]

2.6 Other Alternatives

2.6.1 Nuclear Propulsion

This type of propulsion system relies on some form of nuclear reaction as a source of energy. The nuclear energy generated is used to heat Liquid Hydrogen propellants.

There are some project based on it like *TEM*[7],*EPPP*[2].

These propulsion systems are highly efficient due to the low amount of fuel requirements but are riskier. There is a possibility of a rocket explosion in the atmosphere, contaminating the entire air with radiation.

2.6.2 Metallic Hydrogen

The production of metallic hydrogen in the laboratory is one of the most significant challenges of high-pressure physics. If metallic hydrogen becomes a metastable substance that can be created cheaply in a laboratory, it will be the most powerful chemical rocket fuel ever..[6] The immense energy of recombination and the very light mass of hydrogen makes it the most powerful rocket fuel.

3 SSTO Projects

Based on the propulsion systems discussed above, companies are working to develop a working prototype of SSTO. Some of them are discussed below:

3.1 Skylon

Skylon[4] is a single-stage-to-orbit space-plane designed by *REL*[1] using *SABRE*, a combined cycle, air-breathing rocket propulsion system. The vehicle design is for a hydrogen-fuelled aircraft that would take off from a runway and accelerate up to Mach 5.4 using the atmosphere's oxygen and then switch to the engines using internal liquid oxygen.

3.2 Avatar

Avatar is a concept study of a single-stage reusable spaceplane capable of horizontal take-off and landing by India's DRDO. Avatar would take off horizontally from an airstrip using turbo-ramjet engines that burn hydrogen and atmospheric oxygen. During its flight in the atmosphere, it collects air from the atmosphere and separate oxygen from it and store it as liquid oxygen for use in the final phase.

4 Conclusion

A Single-Stage-to-Orbit Vehicle plays a vital role in future deep exploration of space. It not only provides reusability but also reduces the cost of replenishment of hardware as in current technology.

There are many propulsion systems available for such vehicles, but again all come with their limitations. So, marking a trade-off among them and developing new technologies, some companies are working to develop a working prototype of SSTO such as Skylon, Avatar.

"We are approaching the day when we will be able to fly in space as easily as we can on Earth or in the air.".

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