Combined Cycles for Reusable and Cost-Efficient Space Flight

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This paper will review the implementation of combined cycles and air-breathing engines in a reusable multi-stage spaceflight to LEO. Rocket engines have low specific impulses and require more fuel than air-breathing engines. Some modern-day systems also are not reusable. These factors lead to high launch costs. Air-breathing engines and combined cycles could take much of the load off of rocket engines. Air-breathing engines have high specific impulses and are easy to reuse. These two factors alone can significantly reduce the high expenses seen in spaceflight. Throughout this paper, I will discuss different propulsion systems, their strengths, weaknesses, and applications. I will also briefly mention thermal protection issues and explain how combined cycles could be implemented in a multi-stage vehicle to get to LEO.

I. Nomenclature

TBCC	=	*Turbine Based Combined Cycle*
RBCC	=	*Rocket Based Combined Cycle*
TCC	=	*Triple Combined Cycle*
LEO	=	*Low Earth Orbit*
SSTO	=	*Single-Stage to-Orbit*
TSTO	=	*Two-Stage to-Orbit*

II. Introduction

Over NASA's brief history, they have achieved momentous accomplishments. Events like getting to orbit, putting humans on the Moon, and partaking in the construction of the International Space Station are feats to behold. Each achievement increases with our ambition and our available technology. However, the cost of space travel has largely remained the same. The stagnation in these costs can lead back to two key factors. One is the lack of reusability with previous programs. The another is the low specific impulse of rocket engines. These high expenses limit our use of space travel, and more cost-efficient options will be available with air-breathing engines and combined cycles. This paper will discuss how combined cycles/scramjets/ramjets work, their problems, their uses in flight to Low Earth Orbit (LEO), and how a mission may look.

III. Present Spaceflight Issues

Adjusted for inflation, Saturn V cost around 1.5 billion dollars per launch [1], the Space Shuttle was approximately 1.6 billion dollars per launch [2], and the Artemis launches are expected to be around 4 billion per launch [1]. These costs come from the single-use aspect of most of these spacecraft, other than the partially reusable Space Shuttle. Even though the Space Shuttle had a reusable body, its use of ceramic tiles as thermal protection prohibited its use in consecutive launches, due to the high maintenance costs and time needed for the ceramic tiles.

Currently, the Artemis program lacks reusability. Unlike the Space Shuttle program, they are not reusing their solid rocket boosters. With that said, these boosters are better and cheaper than the ones used for the Space Shuttle Program. Still, they may cost around 290 million dollars per booster [3]. These high-cost limit space flight dramatically and make failure a significant loss of time and money. SpaceX has substantially reduced these costs with fully reusable spacecrafts in the Falcon 9 and Heavy Falcon, but improvement is still available. As systems become more reusable, expenses will continue to decrease. It is easier to justify a 10 billion dollar spacecraft if it can be launched 20 times

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with minimal downtime and maintenance between flights (averaging around 500 million per flight) than in it to justify a two billion dollar spacecraft that can only be launched once. The example above is an oversimplification of maintenance and research and development costs. However, it shows the general idea of cost efficiency with reusable spacecraft.

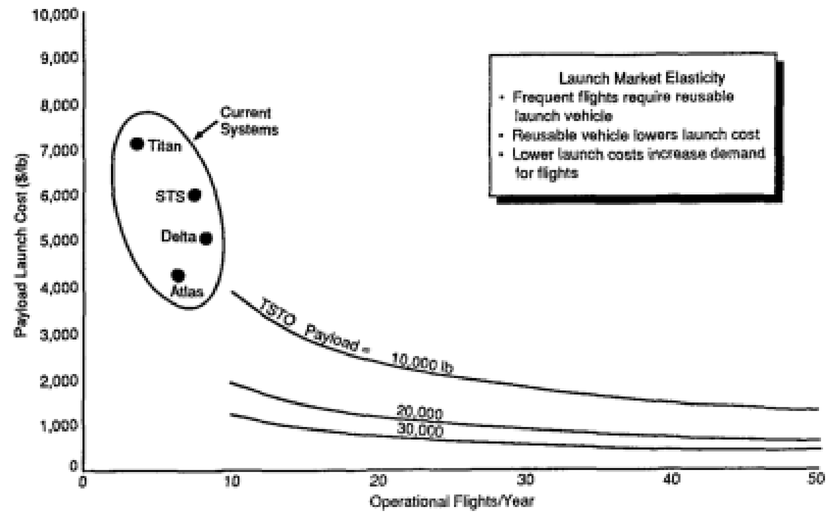

Figure 1 Increased reusability can lead to decreased cost [4].

Other issues come from the rocket engines themselves. When compared to air-breathing engines, rockets have lower specific impulses and are less fuel efficient. Rocket engines need to carry both their fuel and oxidizer, unlike an air-breathing engine that does not need to carry an oxidizer. With the increase of mass at launch from the oxidizer, additional fuel is necessary, which also requires more fuel. With an air-breathing engine, space flight to LEO can be made more affordable in the future, thus making it easier to justify more missions. It currently costs thousands of dollars to put one kilogram into space; but a study by the Highly Reusable Space Transportation (HRST) program estimated that with TBCC and RBCC engines, the cost could be less than 400 dollars per kilogram of payload [5].

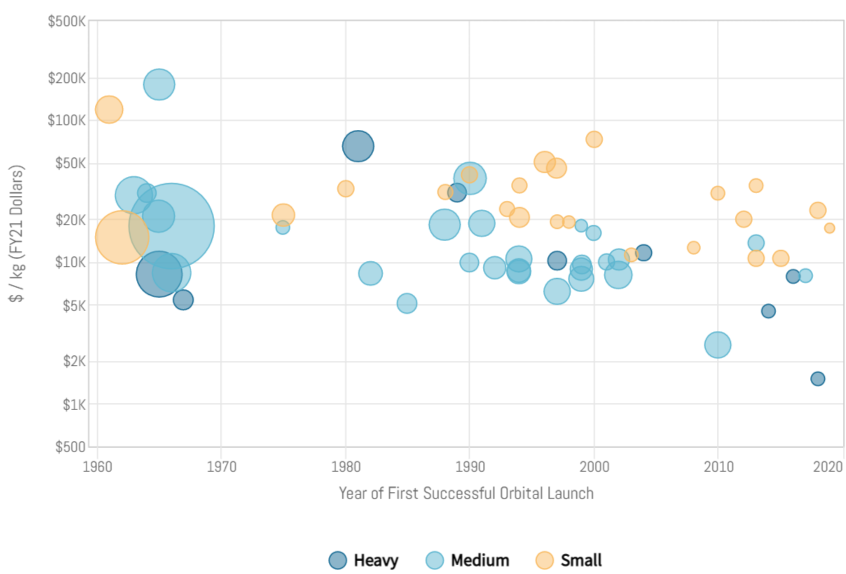

Figure 2 Visualization for the cost per launch of spacecrafts [6].

IV. Ramjets and Scramjets

Ramjets and scramjets are air-breathing engines capable of high speeds. They achieve these speeds by "raming" the air into the engine, compressing it, and slowing it to combustible speeds. The ramjet slows this air to subsonic speeds, while the scramjet slows the air to more manageable supersonic speeds. One example of a scramjet is the hydrogen-powered X-43. The X-43 was part of NASA's Hyper-X program and was the first free-flying scramjet-powered vehicle. It had three test flights; the first ended in failure as the rocket booster lost control. The second flight broke the record for the fastest jet-powered aircraft, nearly reaching Mach 6.8 at 95,000 ft. The third test broke this record again, reaching speeds around Mach 9.6 at 110,000 ft. The X-43 was a big step for scramjets, however, the scramjet-powered flight was operational for around 10 seconds [7]. The X-51A broke this flight time record, as it was in powered flight for 200 seconds. Though the X-51A did not reach the same speeds as the X-43, the hydrocarbon-powered scramjet showed that flight sustained at Mach 5 was possible with a scramjet [8].

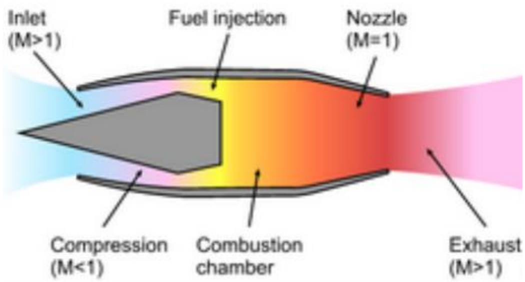

Figure 3 Ramjet engine diagram [9].

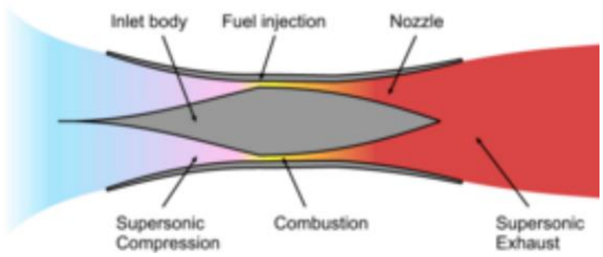

Figure 4 Scramjet engine diagram [9].

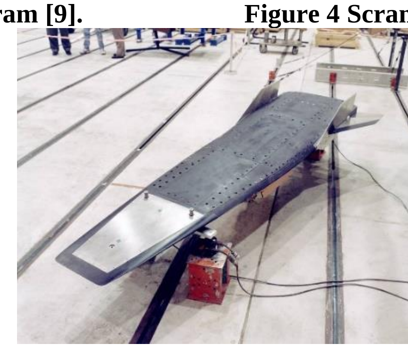

Figure 5 X-43 [10].

While ramjets and scramjets offer more possibilities for high-speed flight, the engines have significant limitations. Ramjets can operate effectively between around Mach 3 to around Mach 5, and scramjets face similar constraints. Scramjets must be flying at a minimum of Mach 6 to operate efficiently. Because of these limitations in the range of efficient operation, other forms of propulsion are necessary to employ ramjets and scramjets. Typically, airplanes tow them, and rockets boost the aircraft to these high speeds. The X-43 was carried by a B-52B and then boosted by a Pegasus rocket [7].

Figure 5 The X-43 being released from a B-52 before the Pegasus begins its burn [10].

More restrictions are put on these engines because they are air-breathing. Meaning they must operate within the lower levels of the atmosphere where they can get the necessary oxygen needed for combustion. As stated previously, one of the pros of air-breathing engines is that they do not need to carry an oxidizer. However, this also means that they are constrained to regions of that hold enough oxygen to use as an oxidizer. The atmosphere's rarefication is not a problem if you intend to stay within it, but it limits the operations of air-breathing engine-based aircraft to a maximum altitude of 30 km.

To summarize, ramjets and scramjets have two distinct obstacles. First, neither can reach their own necessary speeds of operation by themselves. Second, ramjets and scramjets are air-breathing engines and have ceilings well below the altitude needed to obtain LEO (160 km). Because of these limitations, combined cycle engines are the best option for operations of ramjets and scramjets to reach LEO.

V. Combined Cycle Engines

Combined cycles integrate multiple propulsion systems into a single engine that can operate at different modes. In NASA’s Marquardt study, 36 different engines were analyzed to determine their application in the first stage of a reusable launch vehicle. Their results concluded that combined-cycle engines were more efficient than rockets at reaching high speeds [5]. With these engines, a larger variety of speeds can be reached in a single system. Many combined cycles bridge the gaps of operation for ramjets and scramjets, making these systems more applicable. The primary benefit of combined cycle engines is their ability to allow aircraft to operate efficiently under different flight conditions.

A. Turbine Based Combined Cycles (TBCC)

Turbine-based combined cycle engines allow for low and high-speed flight by transitioning from a low-speed turbojet to a high-speed ramjet or scramjet. This engine allows for operational speeds from Mach 0 to possibly Mach 6. The most well-known example of a TBCC is the SR-71 Blackbird. This aircraft held the speed record for an air-breathing engine of Mach 3.3, until the X-43 flights shattered the record [11]. Presently, there are multiple TBCC engines in development. These modern systems expect to reach speeds around Mach 4 and 5 and possibly higher. As stated earlier, scramjets and ramjets must fly at significant velocities to operate efficiently, often resulting in them receiving rocket boosts and unable to achieve vertical takeoff. A TBCC allows a high-speed, ramjet/scramjet-based, aircraft to take off from a runway. The lack of operation at low speeds was a massive hurdle for the ramjet and scramjet, but TBCCs allow for easy reusability and application of these high-speed air-breathing systems in aircraft.

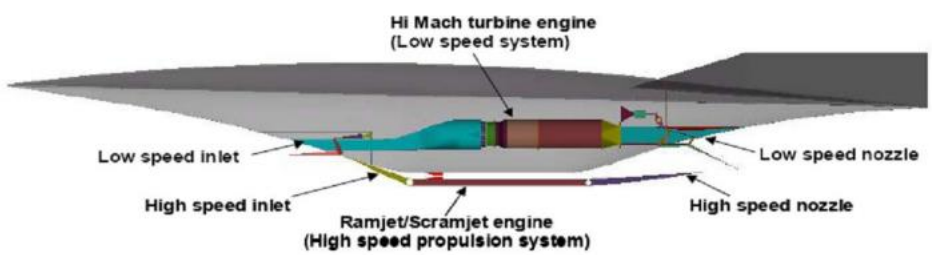

Figure 6 Turbine Based Combined Cycle Engine diagram [12].

The company, Hermeus, is currently developing two TBCC engines. Their first engine, Chimera, is a hybrid turbojet/ramjet engine. Rather than create a whole new engine Hermeus is repurposing a GE J85-21 turbojet engine. By repurposing this powerful engine, Hermeus is able to spend significantly less on the research and development of a new system. They are replacing the afterburner and adding their version of an afterburner in the form of a ramjet. This engine is designed for their unmanned aircraft Quaterhorse and is expected to hit speeds of Mach 4 at an altitude of 80,000 ft. Hermeus’ next engine, Chimera II, is not as far in development as the Chimera but is more powerful. Hermeus is repurposing a Pratt and Whitney F100 turbofan engine, the same engine as the F-15 and F-16. Chimera II is under development for their unmanned defense and intelligence aircraft, Darkhorse, which is expected to reach speeds of Mach 5 [13].

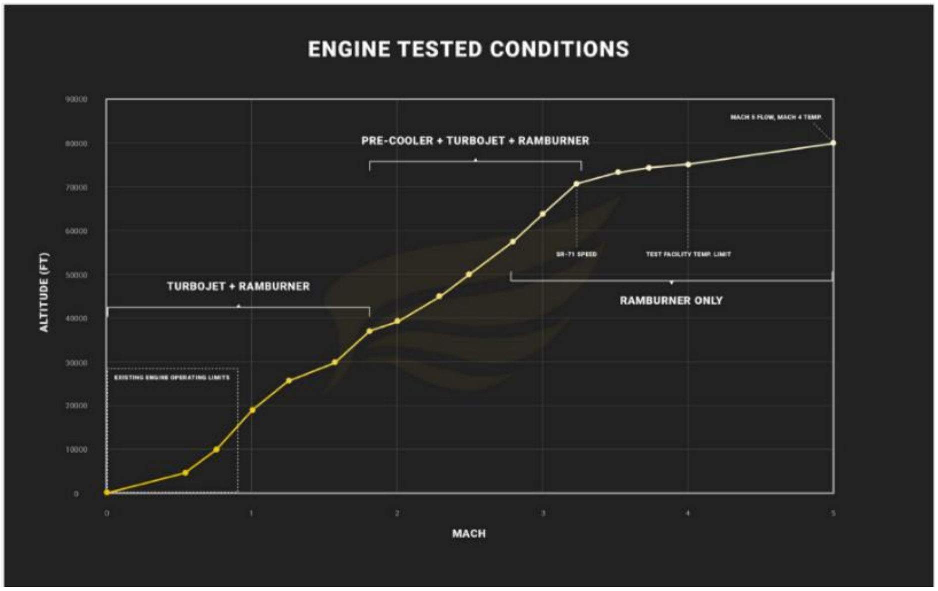

Figure 7 Altitude and Mach of Hermeus' engine [14].

B. Triple Combined Cycle (TCC)

Triple combined cycle engines are another solution to bridge the operational range of air-breathing engines. This system operates similarly to the TBCC but integrates more propulsion systems. Though, these engines have not received the same development as the TBCCs. They offer a more expansive range of speeds than the TBCC, as they integrate a turbofan, ramjet, and dual-mode scramjet engine. It uses two channels for airflow. One channel is for low speeds with a TBCC engine, and the other channel is for high speeds with the dual-mode scramjet. In their paper, Yuan Gao , Yuchun Chen , Linyuan Jia , Ruiyuan Kang, analyze the use of this engine and explains how the engine designs can be slightly altered to better fit different missions [15]. The triple combined cycle engine is believed to reach speeds of around Mach 7 and an altitude of nearly 30 km.

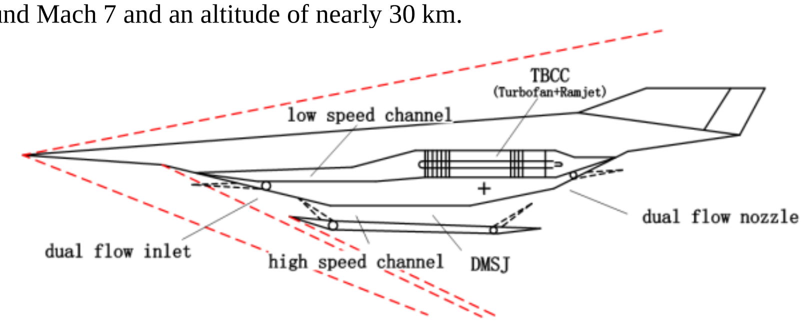

Figure 8 Structure of Triple Combined Cycle Engine [15].

C. Rocket Based Combined Cycles (RBCC)

A rocket-based combined cycle is capable of operating as both a rocket and a ramjet or scramjet jet. These engines could propel a spacecraft to orbit or get an aircraft off the ground to the operational speeds for a ramjet/scramjet. RBCCs integrate the flow path of a ramjet/scramjet and a rocket. When working as a ramjet/scramjet the inlet allows air to enter the engine. When operating as a rocket, the inlet is closed, ending the flow of oxygen to the air-breathing engine, thus functioning fully as a rocket. RBCCs allow for some of the benefits in the efficiency of an air-breathing engine, but also have the operational range of a rocket engine. They offer a wide range of speeds and can reach orbit, unlike a TBCC engine. This system has been proposed for single-stage to-orbit (SSTO) and two-stage to-orbit TSTO launch vehicles, but is yet to see significant testing. A few examples of these RBCC programs are the X-30 National AeroSpace Plane, NASA's Advanced Reusable Technologies Program, GTX, and many more.

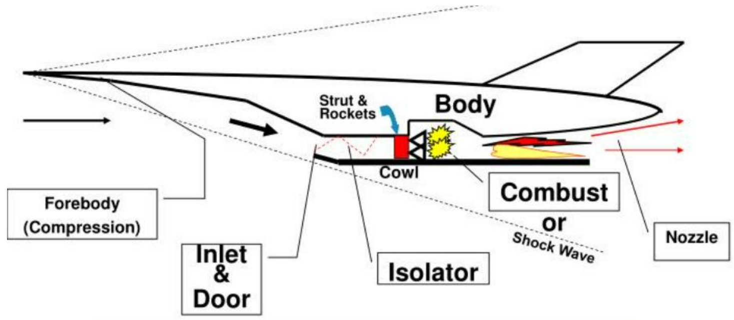

Figure 9 Diagram of a basic RBCC [16].

VI. Thermal Protection

This paper primarily covers combined cycle engines and their application; however, thermal protection deserves recognition. No matter how good a propulsion system is, it means nothing if the aircraft is inoperable due to thermal loads. If a combined cycle engine were utilized to get to LEO, it would experience high temperatures for an extended period due to the time needed to build speed and climb to its maximum altitude. Rockets are only in the atmosphere for a few short minutes and require less thermal protection. Thus, when using an air-breathing engine in space applications, thermal protection is an even bigger issue.

There are two forms of thermal protection, these being active and passive protection systems. These systems help to mitigate and control the extreme temperatures experienced on high-speed aircraft. Active thermal protection systems are powered systems and are generally more effective at controlling temperatures. Passive thermal protection systems can be less effective but require no input power, and they are also typically cheaper and less voluminous [17].

Active thermal protection systems are great at cooling, yet they see limited use due to cost, power, volume, and weight. In spacecraft, these factors are limited. With combined cycle engines, often flow paths are cut off to a specific propulsion system mid-flight. This “cocooning” typically leads to swelling of heat within the engine. The heat can lead to damage to the internal structure of the engine and eventually failure [12]. Here, active thermal protection systems, like fluid loops, can be utilized effectively. Fluid loops pump fluids through the engine to dissipate the heat and cool the engine. Though an active system is more expensive, it is necessary for areas vulnerable to overheating and damage from thermal loads.

Passive thermal protection systems are less effective but cheaper and easier to use than active systems. Passive systems are easy to see in space programs. Artemis uses ablative material in the Orion capsule to dissipate the thermal energy of re-entry. The Space Shuttle used ceramic tiles to deal with thermal loads. For a fully reusable system, these methods may not be the best choice of passive protection systems. The ceramic tiles used on the Space Shuttle require a considerable portion of time and money between launches to apply. These systems are an easy solution to extreme heat but are not cost-effective. Heat pipes are a better passive system that can be employed in future flight applications. Heat pipes transfer the heat from high-temperature areas, like the nose or leading edge of a wing, to other low-temperature regions of the aircraft that encounter less thermal loads.

Materials are also a critical factor when facing high temperatures. Most materials would deteriorate under the extreme temperatures of hypersonic flight, making options limited. However, not all materials that can withstand heat are good choices. For example, Tungsten can take these high temperatures but are extremely heavy. A better selection would be carbon-carbon. Carbon-carbon materials can take the high temperatures and are also lightweight. Though carbon-carbon is flawed as its manufacturing is difficult and expensive [18].

VII. Theoretical Missions

In order to take a reusable air-breathing engine to LEO, a multi-stage system must be implemented. It is possible to create a SSTO vehicle, but it would not be efficient with current technologies. An SSTO would have to be a rocket engine or an RBCC. Both options would work but may not function as well as current launch systems. As rockets climb, the atmospheric pressure decreases, and the rocket nozzle becomes less efficient. With an SSTO vehicle, the only mass you lose is the fuel you burn, unlike current systems that drop their massive fuel tanks and boosters. Because of this, a lot of extra weight is taken to orbit with an SSTO vehicle, requiring more fuel at launch. It is more efficient to use a reusable multiple-stage rocket with present technologies.

With a multi-stage combined cycle vehicle takeoff could be performed with a TBCC, RBCC, or TCC. Thinking about a cost-efficient vehicle, the RBCC is the least attractive option due to the rocket engine's low specific impulse compared to a turbojet/turbofan at low speeds [19]. With an air-breathing engine, you have the opportunity to take off from a runway. The issue with a horizontal takeoff is that it must produce the lift needed for takeoff. Lift can lead to induced drag on the aircraft at low speeds. This drag is mostly irrelevant because the vehicle will not be at these low speeds for long, but it can lower the efficiency in early flight. Options are more limited for a second-stage vehicle. Again, an RBCC is an option, or a scramjet. TBCCs and TCCs could both, potentially use scramjets in the first stage. However, their maximum speeds are around Mach 5 for the TBCC or Mach 7 for the TCC. At these high speeds, the use of a scramjet comes into question due to their fuel. If the scramjet uses hydrocarbon fuel its specific impulse and max operational speed is significantly lowered. Using hydrogen fuel results in a much higher specific impulse, speed, and engine coolant power. The choice seems simple, but liquid hydrogen is more difficult to work with compared to hydrocarbon. Liquid hydrogen must remain in cryogenic conditions and is less dense, requiring more space. This fuel comparison can be viewed in figure 10. In order to fully utilize a scramjet, liquid hydrogen should be used. Hydrocarbon is still a viable option, though the final-stage rocket would have to activate sooner. Using an RBCC for the second stage is also a feasible option. A second-stage RBCC would allow air-breathing engines to efficiently gain speed and altitude before transitioning to a rocket. The downside to the RBCC in the second stage is that it would bring extra weight to orbit. The added weight of a heavy scramjet engine would require more money to be spent on fuel to accelerate the rocket to orbit. Finally, if the vehicle employed air-breathing engines thus far, the final stage would consist of a rocket engine. A final-stage rocket allows for a rocket engine, the most inefficient propulsion system, to be activated only when required. When the rocket engine launches from an altitude of around 30 km at a speed of around Mach 10 or greater, depending on the fuel, a significant portion of the work is already done.

The use of multi-stage vehicles makes for the most efficient spacecraft as the propulsion systems can work closer to their most efficient conditions. The early stage air-breathing engines could land on a runway after towing the rocket engine and be reused. Some complications with this vehicle are faced when transitioning between, and containing, the different propulsion systems. The easiest way to put a vehicle in LEO is with a rocket, so the RBCC could be the easiest option for using a combined cycle engine in space travel. However, the easiest method does not make it the most effective one, especially when planning a cost-efficient spacecraft.

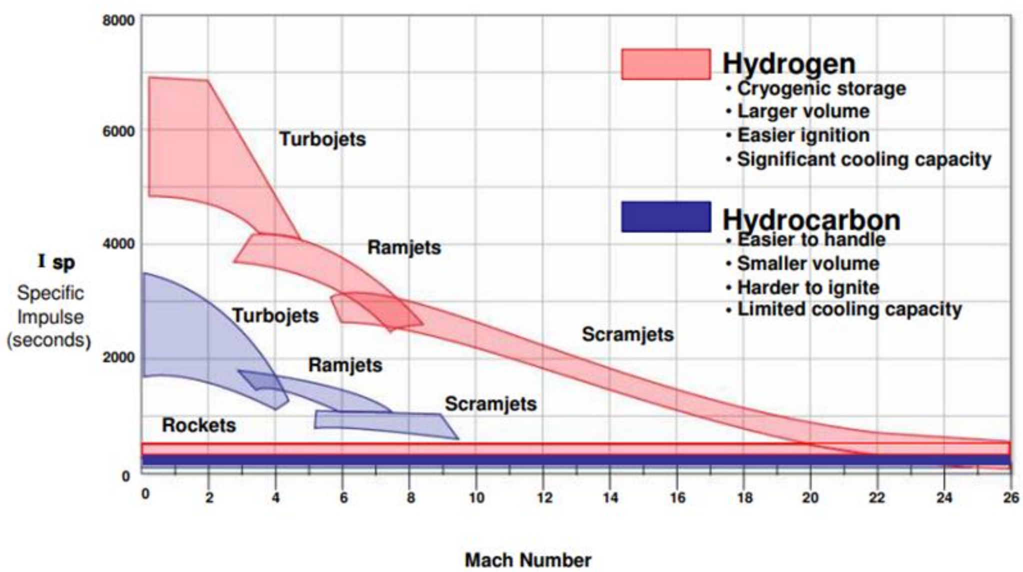

Figure 10 Illustrates the operational ranges of different propulsion systems with different fuels [20].

VIII. Conclusion

In this paper, reusable propulsion systems were reviewed for space applications. Air-breathing, high-speed engines offer higher specific impulses than rocket engines, making them more favorable for continued use. However, high-speed air-breathing engines, like the ramjet or scramjet, have operational limits in flight. Combined cycle engines can be employed to overcome their restrictions. These integrated engines allow for a more efficient flight at a variety of flight conditions. Combined cycle engines in a spacecraft can operate up to around 30 km. The early utilization of air-breathing engines can decrease the ineffective use of a rocket engine and increase efficient flight time. Multi-stage air-breathing vehicles have issues, as they must make complicated in-flight transitions. Rocket engines still need to be implemented in the final stages of a multi-stage vehicle, because they are the only engines capable of space flight. Currently, multi-stage rocket systems are the easiest to operate. However, more cost-efficient methods need to be utilized in the future to increase access to space.

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