OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Hybrid Air-Breathing Engines for Orbital Launch Vehicles: Performance and Challenges

Anirudh S
ani.robot2020@gmail.com

ABSTRACT

Access to space still depends on traditional rocket propulsion that involves carrying the propellant consisting of fuel and oxidizer. This leads to relatively heavy launch mass and inefficiency. The use of air-breathing engines during the initial ascent phase and then switching into the rocket propulsion at higher altitudes is an alternative to this problem. This work describes a literature comparison of hybrid air-breathing rocket propulsion systems and their performance relative to traditional rocket engines and air-breathing engines.

The literature comparison covers various ideas on propulsion technologies like SABRE, HOTOL, LAPCAT Scimitar, and NASA GTX using journal articles, technical reports, and other official sources for each program. Comparison of performance parameters includes specific impulse, thrust, thrust-to-weight ratio, propulsive efficiency, Mach number, fuel consumption, integration into launch vehicle, reliability, and reusability.

Hybrid air-breathing engines have been found to have higher atmospheric specific impulses and lower on-board oxidizer requirements and therefore qualify to be considered for the design of reusable rockets and future single-stage-to-orbit designs. The complexity of the systems, difficulty in thermal management, and the absence of in-flight demonstration of the systems pose major challenges.

INTRODUCTION

The challenge of accessing Earth's orbit remains one of the greatest engineering challenges faced by the aerospace industry. Reusable rockets (Mane, 2024) and launch systems have seen a great deal of development in the past 10 years (Jones, 2018), but it is still expensive to get into space. As commercial space continues to expand with increasing desire for sustainable, low-cost access to orbit, many engineers and researchers are looking at several alternative propulsion concepts that could help avoid the limitations of chemical rockets.

Aug 2026
Vol 10. No 4.

Traditionally, rocket engines are limited by requiring both fuel and oxidizer to be carried on board the vehicle. The mass of the oxidizer increases the mass of the rocket which decreases the payload capacity. Researchers have been interested in hybrid air-breathing systems (Varvill et al., 2019): engines that intake atmospheric oxygen during initial launch, resulting in decreased oxidizer mass, and then transitioning to a standard rocket engine when the launch has achieved higher altitude. Developing a hybrid system with elements of a jet engine and a rocket engine maximizes potential performance improvements, reusability, and the ability to enable future vehicles that achieve single-stage-to-orbit. One of the most advanced examples of this concept is the Synergetic Air-Breathing Rocket Engine (SABRE), whose integrated airflow, precooling, and rocket propulsion systems are illustrated in Figure 1.

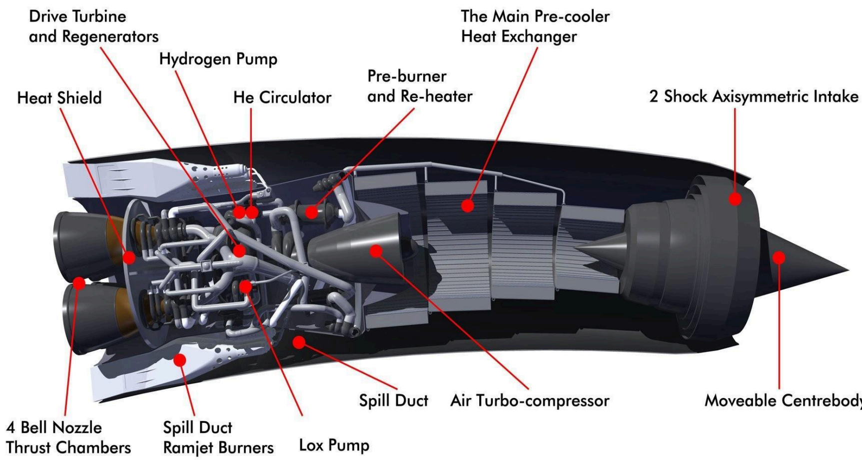

Figure 1: Detailed schematic of the SABRE engine.

This paper explores hybrid air-breathing engines as a pathway to more efficient and reusable orbital launch vehicles. It covers the fundamentals of rocket, air-breathing, and combined-cycle propulsion, examines their performance across flight regimes, reviews recent projects and test results, and looks at applications from commercial launch to single-stage-to-orbit systems.

METHODS

Literature Search and Source Selection

The study was carried out as a comparative literature analysis of hybrid air breathing propulsion systems for orbital launch vehicles. Relevant literature was gathered using searches of Google Scholar, NASA Technical Reports, and technical reports by relevant organizations like NASA, UK Space Agency, Reaction Engines Ltd., and SpaceX. Search phrases included "hybrid air breathing engine", "SABRE engine", "RB545", "HOTOL", "LAPCAT Scimitar", "NASA GTX", "rocket-based combined cycle", "engine metrics", "reusable launch vehicle", and "single-stage-to-orbit propulsion". Additional sources were found through bibliographies of cited reviews and technical reports.

Sources were chosen depending on their relevance, credibility, and presence of technical performance data. The preference was given to peer-reviewed journal papers, conference proceedings, official government reports, and technical reports issued by respected aerospace agencies. Conventional propulsion systems, such as RS-25 (Ha et al., 2023) , Merlin 1D, F135 turbofan, J85 turbojet, X-43A scramjet, and RJ43 ramjet were chosen as benchmark engines since they represent well-operational or thoroughly tested propulsion systems which could be used to compare with hybrid concepts. Hybrid propulsion systems like SABRE, HOTOL RB545, LAPCAT Scimitar, and NASA GTX were chosen due to extensive documentation and substantial performance data.

Data Collection and Comparative Analysis

The performance figures for the engines were obtained from the literature and compared by employing various engine metrics, including specific impulse, thrust, thrust-to-weight ratio, propulsive efficiency, Mach number, fuel requirement, ease of integration into the launch vehicle, reliability, safety, and reusability. For engines with conflicting performance figures, priority was given to more recent articles in scientific journals and technical reports. Earlier references were included where they contained basic technical information still relevant to hybrid propulsion technology today. Since many of the hybrid air-breathing engines are still at the conceptual or prototype stage, a number of the figures for these engines are only estimates based on design calculations, simulations, or laboratory tests. These figures were understood in light of their technological readiness level, and wherever possible, consistent figures from authoritative sources were used.

RESULTS

Hybrid air-breathing engines combine the high-speed, high-altitude capability of rockets with the fuel efficiency of air-breathing propulsion, creating a single propulsion system capable of operating from take-off to orbit. By using atmospheric oxygen during much of the ascent, they achieve much higher specific impulse than conventional rockets. This adaptability makes them suitable for a wide range of missions, from single-stage-to-orbit vehicles and hypersonic passenger transport to rapid-response military platforms. Their reusability potential, aided by reduced thermal loads and robust cooling systems, offers low operating costs and high launch cadence. However, these benefits come with significant engineering challenges. Mode transition between propulsion types must be precise and stable. Safety concerns include cryogenic fuel handling and maintaining inlet stability at high Mach numbers. The balance between these advantages and challenges will determine how quickly hybrid air-breathing propulsion can move from experimental testing to operational deployment.

Efficiency and Performance at Different Flight Regimes

Hybrid air-breathing engines are designed to maintain high performance from take-off through hypersonic speeds and into near-space, where they transition to rocket mode for orbital insertion. Their efficiency and performance vary with altitude and Mach number, and are typically evaluated using standard aerospace performance metrics.

Thrust: Thrust, the fundamental performance metric in propulsion, represents the net force an engine produces to accelerate a vehicle.

$$F = \dot{m}_e V_e - \dot{m}_0 V_0 + \left(p_e - p_0\right) A_e$$

$\dot{m}_e$ = exit mass flow rate

$\dot{m}_0$ = free-stream mass flow rate

V_e = exit velocity

V_0= incoming velocity

p_e = exit static pressure

p_0 = ambient static pressure

A_e = nozzle exit area

Note: The term $\dot{m}_0 V_0$ is zero for a rocket engine.

Among hybrid air-breathing propulsion concepts, thrust capability varies significantly with engine design and operating mode. The SABRE engine is projected to deliver around 1350 kN of thrust in air-breathing mode and shifting to about 1800 kN in rocket mode (Hempsell & Longstaff, 2010) . The earlier RB545 engine, though never demonstrated, was reported to achieve about 340 kN in air-breathing mode and about 735 kN in rocket mode. The LAPCAT Scimitar (Steelant, 2008) engine produced around 168 kN of thrust at Mach 5 cruise. NASA's GTX (Krivanek et al., 2003) programme tested its engine at subscale, generating 25-30 kN under Mach 5 conditions, with full-scale projections suggesting thrust in the range of 1,500-2,000 kN in rocket modes, competitive with mid-class rocket engines. These figures show that hybrid systems bridge the gap between conventional rockets, which achieve thrust on the order of thousands of kilonewtons, and air-breathing engines, which typically operate in the low hundreds of kilonewtons, offering a balance of atmospheric efficiency and rocket-like performance at higher altitudes.

Specific Impulse (Isp): Specific impulse measures the thrust produced per unit weight flow of propellant.

$$I_{sp} = \frac{F}{\dot{m}_p g_0}$$

F = Thrust of engine

$\dot{m}_p$ = Mass flow rate

g_0= Gravitational Acceleration

In air-breathing mode, SABRE has an Isp of 3500s, because the oxidizer is drawn from the atmosphere instead of being carried onboard. In rocket mode, SABRE has an Isp of 450s (Aggarwal et al., 2015). The Specific Impulse of Scimitar is similar to that of SABRE. NASA's GTX cycle analysis indicates Isp can remain above 2000 s through most of the ramjet/scramjet phases before switching to rocket mode. Specific impulse values for air-breathing engines are conventionally calculated using fuel mass flow only, whereas rocket engine specific impulse includes both fuel and oxidizer mass flow. Consequently, Isp values should not be interpreted as directly equivalent across propulsion types.

Thrust-to-Weight Ratio (T/W): Thrust-to-weight ratio is a measure of engine acceleration capability, defined as:

$$\frac{T}{W} = \frac{F_{max}}{W_{engine}}$$

F_{max} = Thrust of engine

W_{engine} = Mass of e

For hybrid engines, T/W in air-breathing mode is generally lower than in pure rocket engines due to the added mass of precoolers, inlets, and multi-mode hardware. SABRE's design targets a T/W of around 14 in rocket mode and >8 in air-breathing mode, which is high for an air-breathing engine but slightly below top-end chemical rockets (~50-70 for expendable stages). NASA's GTX designs typically fall in the T/W=6-10 range depending on inlet size and transition hardware.

Propulsive Efficiency (p): Propulsive efficiency reflects how well the engine converts the energy in the working fluid into useful thrust and is given by:

$$\eta_p = \frac{2V_0}{V_e + V_0}$$

V_0 = exhaust velocity

V_e = flight velocity

Air-breathing modes allow the exhaust velocity to be better matched to flight speed, yielding higher p at subsonic and supersonic speeds compared to rockets. For example, Scimitar's Mach 5 cruise efficiency is above 0.8, while a rocket at the same speed would have an efficiency closer to 0.3-0.4 due to higher exhaust velocity mismatch.

Versatility and Reusability

Hybrid air-breathing engines offer an unusual level of operational flexibility because they can function efficiently from take-off to orbital speeds in a single propulsion system. By combining air-breathing and rocket operation, they can adapt to changing atmospheric conditions without separate engines or staging events. At low speeds, they operate in turbo-compressor mode to generate the high thrust needed for take-off and climb. In the supersonic and hypersonic regime, they switch to ramjet or precooled air-breathing operation, which provides higher specific impulse and better fuel efficiency. Once above the atmosphere, they transition fully to rocket mode to deliver the final velocity required for orbital insertion. This seamless mode-switching allows the same engine to serve in multiple mission profiles, from suborbital point-to-point transport to orbital payload delivery.

Reusability is one of the added benefits of such an engine. Precooled air-breathing operation reduces inlet air temperatures and limits thermal stress on turbines and combustors, extending component life. The reliance on atmospheric oxygen during much of the ascent reduces onboard oxidizer mass, lowering launch weight and structural loads. Liquid hydrogen cooling loops, used in engines like SABRE (Aggarwal et al., 2015) and Scimitar (Jivraj et al., 2007), also protect hot-section components, reducing wear and turnaround maintenance. Vehicle concepts such as Skylon were designed for horizontal take-off and landing, enabling rapid turnaround similar to aircraft and supporting high flight rates. This combination of operational range and reusable design offers the potential for significant cost reductions and broader applicability, from SSTO launch vehicles and hypersonic passenger aircraft to high-speed military platforms.

Safety and Environmental Factors

Hybrid air-breathing engines introduce safety considerations that differ from those of conventional rockets and aircraft. Most designs use liquid hydrogen as the primary fuel, which offers excellent specific impulse but requires cryogenic storage at -253 °C and careful handling to avoid leaks or boil-off. Hydrogen's low ignition energy means that even small leaks can present a fire or explosion hazard, especially during ground operations or mode transitions where hot components are nearby. The integration of high-pressure oxidizer systems for rocket mode adds another layer of risk, demanding robust seals, fault-tolerant valves, and rapid shutoff systems. Precooled engine cycles, like SABRE's, also involve complex networks of fine tubing for heat exchangers, which must remain leak-free under extreme temperature gradients and vibration. From a flight safety perspective, maintaining stable inlet flow across a wide Mach range is critical.

Environmental impacts are a mix of advantages and concerns. Air-breathing ascent reduces onboard oxidizer consumption, potentially lowering the total emissions per mission compared to an equivalent pure rocket launch. Liquid hydrogen produces only water vapor when burned, but at high altitudes this can contribute to contrail formation and may have localized climate effects in the stratosphere. Noise from high-Mach operation is significant, with both take-off and supersonic cruise generating acoustic footprints that would require management for commercial applications. The use of cryogenic fuels also raises lifecycle considerations-current hydrogen production is energy-intensive unless sourced from renewable electrolysis. Balancing the safety and environmental factors will be essential for public acceptance, regulatory approval, and sustainable operation of hybrid air-breathing launch systems.

Developments

Hybrid air-breathing propulsion has moved from early theoretical studies to focused development programs that have validated critical technologies such as high-performance precoolers, wide-Mach-range inlets, and multi-mode combustors. International efforts -from the UK's SABRE and the EU's LAPCAT, to NASA's GTX and historical concepts like HOTOL (Conchie, 1986). - have demonstrated that the core principles are technically achievable. However, these advances have come mainly at the component level, and no complete hybrid engine has yet been flown through its full operational profile. The following sections review key projects, their demonstrated technologies, and the remaining challenges that must be addressed before such systems can become operational.

Hybrid air-breathing propulsion has progressed through several major research and development programs worldwide. While each follows a different engine cycle and mission profile, they share the same core goal: combining the efficiency of atmospheric oxygen intake with the orbital reach of rocket propulsion.

SABRE and Skylon: The Synergetic Air-Breathing Rocket Engine (SABRE) (Hempsell & Longstaff, 2010), developed by Reaction Engines Ltd., was designed to operate as an air-breather up to about Mach 5.5 and 28 km altitude before switching to pure rocket mode for orbital insertion.

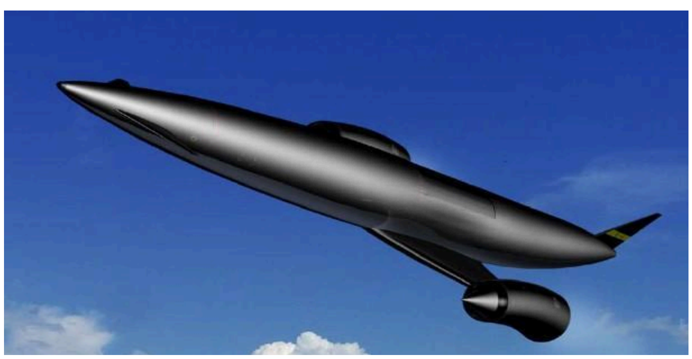

Figure 2: Skylon C2 in Flight

The precooler rapidly lowers incoming airflow temperatures by hundreds of degrees, keeping turbine hardware within safe limits and allowing sustained operation at hypersonic speeds. SABRE was intended to power Skylon, a single-stage-to-orbit (SSTO) spaceplane capable of runway take-off, orbital insertion, and horizontal landing. While the engine passed significant component tests-including a precooler heat-exchange demonstration at simulated Mach 5-both SABRE and Skylon development stopped in 2024 due to lack of funding.

LAPCAT and Scimitar: The Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) program (Steelant, 2008), funded by the European Commission, investigated high-speed civil transport concepts, notably the A2 passenger vehicle. Its Scimitar (Jivraj et al., 2007) engine is a hydrogen-fuelled, precooled air-breathing design derived from SABRE but optimized for sustained cruise at around Mach 5 rather than orbital ascent. The precooler and helium heat-transfer loop were adapted to support long duration operation and high efficiency over intercontinental ranges. LAPCAT validated large-scale precooler modules, intake designs, and nozzle integration for efficient high-Mach cruise, laying the groundwork for reusable hypersonic passenger transport.

Figure 3: LAPCAT A2 in Flight

NASA GTX: NASA's GTX explored a Rocket-Based Combined-Cycle (RBCC) engine for SSTO applications (Krivanek et al., 2003). The GTX concept integrates a rocket within a duct, operating initially as an ejector, then transitioning to ramjet mode in the supersonic regime, to scramjet mode at higher Mach numbers, and finally returning to pure rocket propulsion at orbital velocity. GTX aimed to achieve air-breathing flight to Mach 10, reducing oxidizer mass and increasing payload fraction compared to pure rockets. NASA conducted extensive wind-tunnel tests on RBCC inlets, combustors, and mode transitions, as well as CFD simulations to define the timing and control strategies for smooth switching between modes.

Figure 4: NASA GTX Vehicle Concept

HOTOL: The Horizontal Take-Off and Landing (HOTOL) (Conchie, 1986) project, developed in the 1980s by British Aerospace and Rolls Royce, was an early attempt at a single-stage-to-orbit spaceplane using a precooled air-breathing rocket engine. The design used liquid hydrogen fuel and a precooled turbojet/rocket hybrid known as RB545, which would breathe atmospheric oxygen at lower altitudes and switch to onboard oxidizer in near-space conditions. The HOTOL programme was ultimately discontinued, largely because engineering difficulties and payload limitations reduced its feasibility. But, HOTOL pioneered many of the concepts-such as high-effectiveness precooling, integrated airframe-engine design, and runway operations-that later shaped the SABRE and Skylon programs.

Test Results and Demonstrated Components

The hybrid air-breathing propulsion programs described above have not yet flown a complete operational engine, but they have produced a substantial amount of experimental and analytical results. Much of the progress has come from testing critical subsystems-such as precoolers, inlets, combustors, and nozzles-under simulated flight conditions. These tests have validated core design assumptions, uncovered operational challenges, and guided refinements for future prototypes.

Precooler Technology: The most significant advances have been in heat exchangers. Reaction Engines' SABRE precooler (Scheidlinger et al., 2022), built using fine-walled micro-tubing, successfully demonstrated the ability to cool incoming air from over 1000°C to near ambient temperature

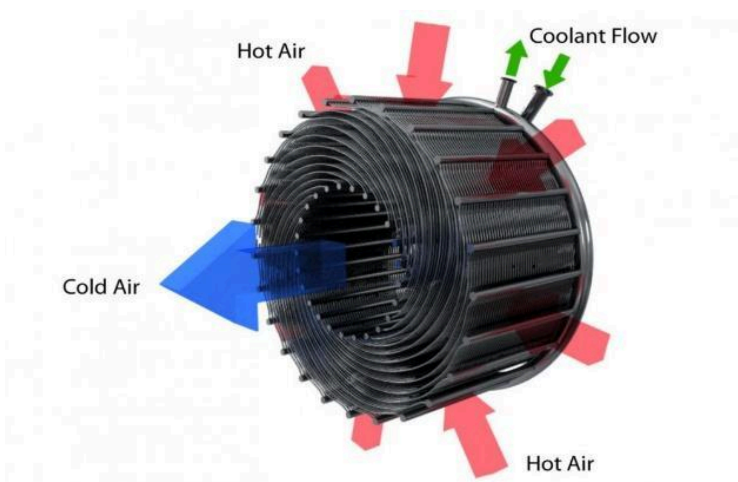

Figure 5: SABRE Precooler Design

In less than 0.05 seconds at mass flows representative of Mach 5+ flight. Tests carried out at facilities in the United States confirmed its thermal performance and addressed issues such as frost prevention and pressure loss. The LAPCAT Scimitar program built and tested large-scale precooler modules for sustained high-Mach cruise, validating manufacturing methods and airflow distribution strategies.

Inlet and Ducting Development: Inlet design is critical for hybrid engines, as it must provide stable, high-pressure air across a wide range of speeds. NASA's GTX program performed extensive wind-tunnel campaigns with sub-scale inlets, measuring pressure recovery, shock control, and bleed requirements during mode transitions. This data supported refined inlet geometries that reduce drag and improve stability during transitions. LAPCAT also tested its A2 intakes and nozzle/afterbody integration in CFD (computational fluid dynamics) and wind-tunnel experiments.

Combustor and Mode Transition Studies: NASA's GTX research included combustor tests for each operating mode (rocket and air-breathing). These tests identified challenges such as thermal choking, flame stability, and mixing efficiency.

HOTOL: Although HOTOL never reached the hardware testing stage for its full RB545 engine, its early design and simulation work produced valuable data on engine-airframe integration, center-of-gravity management, and the mass penalties of precooled combined-cycle systems. These findings directly influenced later SABRE and Skylon design choices, particularly in balancing structural mass against the thermal and aerodynamic requirements of high-speed ascent.
Across these programs, component-level testing has shown that hybrid air-breathing propulsion is technically feasible, with major breakthroughs in precooling, inlet stability, and mode-transition control. However, the results also highlight the complexity of integrating these subsystems into a single, reusable engine that can operate reliably across the full flight envelope from take-off to orbital insertion.

DISCUSSION

Performance Trade-offs

The comparison of propulsion systems reveals that hybrid air-breathing engines provide a compromise between the high efficiency of conventional air-breathing engines and the high thrust required for orbital launch. During atmospheric flight, these engines use oxygen from the surrounding air rather than carrying an onboard oxidizer, reducing propellant mass and improving overall efficiency. Switching to the rocket mode once at higher altitudes where atmospheric oxygen becomes insufficient allows continuing acceleration towards the orbital velocity. In this way, hybrid engines address one of the major limitations of the traditional rockets, while still being able to operate in vacuum.

As is clear from the results of the analysis, the increase in the efficiency of the hybrid systems is attained through the greater engineering complexity of the system. Precoolers, variable geometry inlets, more complicated heat exchangers, and dual-mode combustion chambers add up to the engineering complexity of the system compared with conventional rocket engines. Consequently, reliable operation during the transition between the air-breathing and the rocket modes constitutes one of the most difficult tasks to solve.

A further important finding of this review is that no propulsion system performs best across every performance metric. Traditional rockets have the greatest amount of thrust needed for takeoff and years of experience in operation, making them very reliable for existing launches. Air-breathing engines are very efficient in terms of fuel consumption in the atmosphere, but they cannot operate in space orbit. Hybrid air-breathing engines share many positive features of these two technologies by flying in the atmosphere for extended periods while being able to access space. The majority of the performance data provided for these engines is obtained from computer simulations, research, and tests of individual components and not from actual flight operations.

Table 1: Engine Comparison in Air breathing Mode.

Engine Metric	SABRE (Air breathing)	Scimitar (Air breathing)	NASA GTX (Air breathing)	Turbofans (F135)	Ramjets (XRJ43)
Thrust (kN)	1350	168 (Mach 5)	25-30	191	53
Specific Impulse (s)	3500	3800	2000	8000	1800
T/W ratio	8	10-12	6-10	11	6
Mach number	5.5	5	5	2	5
Propulsive Efficiency	0.6-0.7 (Mach 5)	0.7 (Mach 5)	0.5-0.6 (Mach 5)	0.8-0.9 (subsonic)	0.5-0.6 (Mach 2)
Cycle Complexity	Very High	Very High	High	Moderate	Moderate

Table 2: Engine Comparison in Rocket mode.

Engine Metric	SABRE (Rocket mode)	Scimitar (Rocket mode)	NASA GTX (Rocket mode)	Merlin Vacuum	RS-25
Thrust (kN)	1800	2000	1500-2000	981	2279
Specific Impulse (s)	450	~450	~450	348	452
T/W ratio	14	10-12	6-10	150	73
Propulsive Efficiency	0.3-0.4	0.3-0.4	0.3-0.4	0.3	0.3-0.35
Cycle Complexity	Very High	High	High	Low	Moderate

Note. Values for hybrid air-breathing engines are primarily projected or theoretical estimates reported in the literature, as no complete operational engine has undergone full-scale flight testing. Specific impulse values for air-breathing engines are conventionally calculated using fuel mass flow only, whereas rocket engine specific impulse includes both fuel and oxidizer mass flow. Consequently, Isp values should not be interpreted as directly equivalent across propulsion types.

Fuel Versatility and Cost

Fuel choice directly affects performance, storage complexity, cost, and operational flexibility. Hybrid air-breathing combined-cycle (HBCC) engines typically use liquid hydrogen (LH2) as the primary fuel. LH2's high specific energy and low molecular mass maximises exhaust velocity, enabling high I_{sp}. in both air-breathing and rocket modes. For example, SABRE and Scimitar both rely on LH2 to allow effective pre-cooling without condensation blockages and to maintain Mach 5+. The drawback is its very low density (~70 kg/m³), requiring large insulated tanks that increase vehicle size. Hydrogen production and liquefaction are also energy-intensive, pushing operational costs higher than kerosene-based systems.

In comparison, rocket engines span multiple propellant combinations:

- Hydrolox (LH2/LOX) - RS-25, with high I_{sp} but the same LH2 density issue.
- Kerolox (RP-1/LOX) - Merlin, RD-180; denser fuel, smaller tanks, lower cost, but lower I_{sp}.
- Methalox (LCH4/LOX) - emerging choice (e.g., Raptor), offering a middle ground in density and performance.

Conventional air-breathing engines generally burn kerosene-type fuels (Jet-A, JP-7). These are dense, easily stored, and relatively cheap per unit energy. For instance, the F135 turbofan and J85 turbojet use JP fuels with good global availability and infrastructure. JP-7 was formulated for extreme temperature stability in the SR-71's high-Mach environment, yet its expense and specialized handling requirements restricted broader adoption. Ramjets and scramjets (RJ43, X-43A) also run on kerosene or hydrogen depending on mission profile; hydrogen gives better high-Mach efficiency but complicates storage.

From a cost standpoint, hybrids suffer both the infrastructure needs of LH2 (cryogenic handling, boil-off management) and the additional hardware costs of a dual-mode system. However, their ability to reduce onboard oxidizer mass lowers total propellant cost for orbital ascent, particularly for reusable vehicles where fuel is a smaller fraction of launch cost. In contrast, kerosene-fuelled rockets have low fuel unit costs but must carry all oxidizer, raising mass and launch stage costs. Overall, fuel selection represents a trade-off between performance, storage requirements, operational cost, and mission flexibility, with no single propellant providing an optimal solution for every application.

Launch Vehicle Integration

Integrating a hybrid air-breathing engine into a launch vehicle imposes different problems compared to pure rockets or conventional air-breathing systems. Hybrids such as SABRE, HOTOL's RB545, and NASA's GTX reduce oxidizer tank volume by drawing oxygen from the atmosphere during the initial climb, lowering take-off mass. This advantage is counterbalanced by the need for large cryogenic hydrogen tanks, which have low fuel density and require heavy insulation, increasing fuselage diameter and affecting structural weight distribution. In contrast, chemical rockets like the RS-25 or Merlin carry all their oxidizer, resulting in larger total propellant mass but more compact, higher-density tank arrangements that simplify internal layout. Conventional air-breathing engines such as the F135 turbofan or J85 turbojet avoid oxidizer tanks entirely, but require large volumes of fuel for sustained cruise and cannot operate beyond the atmosphere.

Airframe integration varies with different systems. Hybrid designs must incorporate large, variable-geometry inlets and precoolers into the vehicle, as seen in Skylon's (Hempsell & Longstaff, 2010) side-mounted pods or the GTX's ventral inlet system. These features improve air capture and thermal management but increase frontal area and drag in rocket mode. Rockets avoid this entirely, enabling slender cylindrical shapes optimised for minimal aerodynamic resistance during ascent. Conventional air-breathers, while also having inlets, size them for a narrow Mach range and do not require the multi-mode ducting or high-Mach shock control systems of hybrids. Control and operations follow the same pattern. Hybrids must manage precise transitions between air-breathing and rocket modes, coordinating fuel flows, inlet geometry, and nozzle expansion ratios. This complexity enables continuous acceleration from take-off to orbital insertion without staging, something rockets cannot achieve, but it adds more potential points of failure. Pure rockets operate in a single propulsion mode from ignition to cutoff, reducing operational variables. Conventional air-breathers are similarly simple in propulsion control but are tied to their operational altitude and Mach limits, making them unsuitable for orbital launch.

Overall, while hybrids share some integration challenges with air-breathers and some mission capabilities with rockets, their unique requirements-large cryogenic fuel tanks, complex inlet systems, and multi-mode controls-place them in a design space that demands more careful trade-offs between aerodynamic efficiency, structural mass, and operational flexibility.

Reliability and Safety

The reliability and safety profile of a propulsion system depends on both its inherent complexity and the operational environment in which it runs. Hybrid air-breathing engines, such as SABRE, HOTOL's RB545, and NASA's GTX, are mechanically more complex than pure chemical rockets or conventional air-breathing systems because they combine multiple propulsion modes in one engine. They require variable-geometry inlets, high-capacity precoolers, multimode combustors, and control systems capable of mode transitions. Each of these subsystems introduces additional components that can fail, from heat exchanger tube leaks to inlet malfunctions. Pure rockets, like the RS-25 or Merlin, operate in a single mode with fewer moving parts and no external airflow management, reducing mechanical failure points but still facing extreme thermal and pressure stresses in combustion chambers and turbopumps.

Operational environments also differ. Hybrid engines in air-breathing mode must cope with issues faced by high-speed ramjets and scramjets such as the RJ43 or X-43A. Rockets avoid these aerodynamic inlet instabilities entirely, as their combustion is decoupled from atmospheric airflow, but they remain vulnerable to combustion instability, pump cavitation, or cryogenic tank ruptures. Conventional air-breathing engines like the F135 or J85 face fewer thermal extremes than hybrids at high Mach but are still susceptible to compressor stall or turbine blade failure over repeated cycles. Mode transition is a particular safety concern unique to hybrids. Switching from air-breathing to rocket propulsion involves rapidly changing fuel flows, oxidizer sources, and nozzle configurations. An unsuccessful transition could result in loss of thrust or unstable engine operation during a critical phase of ascent. Rockets avoid this entirely, while conventional air-breathers never operate in vacuum conditions, eliminating the need for such transitions.

However, hybrids can offer safety benefits in certain abort scenarios, since an air-breathing mode can allow controlled, fuel-efficient return to base before committing to orbital ascent-something rockets typically cannot achieve once launched.

Remaining Gaps

Full-System Integration: Most achievements so far have been at the component level-precoolers, inlets, or combustors tested individually. No program has yet demonstrated a fully integrated hybrid air-breathing engine operating through all modes in a single test campaign. This integration requires solving compounded issues of mass, thermal management, and control across the entire flight profile.

Mode Transition Control: Switching between propulsion modes-such as from air-breathing to rocket-without loss of stability or thrust is a central challenge. Further challenges arise due to the repetitive nature of such transitions in an actual mission. Repeated transitions between propulsion modes introduce additional thermal and mechanical stresses that must be addressed to ensure reliable long-term operation.

Thermal Management Under Operational Loads

Precoolers have shown impressive cooling performance in tests, but their durability in full-scale, high-humidity, and long-duration operations is not yet demonstrated. Testing in the thermal management system under operational loads is necessary to confirm the feasibility of the system. Failure of such a crucial system would lead to a total engine failure which would be catastrophic.

Mass and Structural Efficiency: Hybrid engines often require multiple flow paths, complex ducting, and heavy heat exchangers. Balancing structural strength with weight savings is a persistent issue. Lessons from HOTOL and LAPCAT show that even small increases in structural mass can significantly reduce payload capacity in SSTO applications.

Materials and Reusability: Components must endure extreme temperature cycles, exposure, and high dynamic pressures over many flights. Developing seals, turbine blades, and heat exchanger materials with long service lives under these conditions is still an open area of research.

Flight Demonstrations: Ground and wind-tunnel tests are essential, but they cannot fully replicate the coupled thermal, aerodynamic, and structural loads of real flight. No hybrid air-breathing propulsion system has yet been flown through its complete operational envelope, leaving a critical gap between laboratory validation and operational readiness.

Program Stability and Funding: The 2024 halt of SABRE and Skylon development shows the vulnerability of long-term propulsion programs to funding shortfalls. Sustained investment is required to carry these technologies through their long development cycles, especially in the absence of immediate commercial returns. Addressing these gaps will require coordinated work in high-temperature materials, adaptive control systems, lightweight structures, and large-scale demonstrators. Without this integration and sustained support, hybrid air-breathing propulsion will remain proven in parts but unproven as a whole.

Future Applications

The characteristics identified in this review suggest that hybrid air-breathing propulsion could support several future aerospace applications if the remaining technical challenges are successfully addressed. Its ability to operate effectively from take-off and into orbit makes it well suited for multiple uses, from commercial satellite launches to military rapid-response missions. The same technology can enable reusable vehicles with shorter turnaround times and support advanced concepts such as single-stage-to-orbit spacecraft and point-to-point hypersonic travel. As these systems become better, they have the potential to lower launch costs, increase flexibility, and expand the ways we operate in both the atmosphere and space.

Commercial Launch Systems: The hybrid air-breathing propulsion presents a large opportunity in the commercial launch market as it can reduce propellant mass to increase payload capacity which reduces the launch cost. As air-breathing ascent vehicles carry less liquid oxygen, this frees up mass that can now be used for satellites or cargo. For customers this means the same launch vehicle can send bigger payloads to orbit. It can even send the spacecraft to higher orbit for the same cost. Programs, such as the Skylon program (Longstaff & Bond, 2011), will operate like an airline with rapid turnaround for flight, similar to the take-off and landing of a runway launch. In the small-satellite market, hybrid engines could enable responsive launch services, where payloads are sent to orbit on short notice without complex ground campaigns. The scalable nature of this concept will allow for heavy-lift missions.

However, both SABRE and its spaceplane, Skylon, have had their development stopped following the collapse of Reaction Engines in late 2024 due to funding shortfalls.

Military and Strategic Uses: Military planners value propulsion systems that can operate efficiently across wide Mach and altitude ranges. Hybrid engines offer high-speed global reach, which can reduce the time from launch to target from hours to minutes. For hypersonic strike platforms, air-breathing ascent to Mach 5-7 in the atmosphere before switching to rocket mode allows long-range cruise followed by space-based deployment of reconnaissance or weapons payloads. This technology, with its ability to function as both atmospheric propulsion and orbital injection, could support dual-role vehicles: one configuration for ISR (Intelligence, Surveillance, Reconnaissance) missions and another for rapid satellite deployment (Hillion & Mangeot, 2023). From a strategic standpoint, hybrid engines could provide on-demand space access for replacing or servicing military satellites, and also function as a ballistic missile with a larger warhead due to the increase in payload capacity.

SSTOs and Future Launch Vehicles: A Single Stage to Orbit (SSTO) (Hunt, 1995) rocket is a launch vehicle that reaches orbit using only one stage, without dropping empty fuel tanks or swapping engines during ascent. All the propellant, oxidizer, and systems remain part of the vehicle from take-off to orbital insertion, after which it can return to Earth and be used again. Historically, SSTO has been challenging because the vehicle must carry all the fuel needed for both atmospheric climb and orbital insertion, while also keeping structural mass extremely low. The emergence of hybrid air-breathing engines has renewed interest in SSTO. By using atmospheric oxygen for part of the ascent, these engines significantly improve the efficiency and reduce the onboard oxidizer mass. This improves payload fraction and brings SSTO concepts closer to practical reality.

One of the most notable SSTO designs was Skylon, developed by the company Reaction Engines. Skylon was to be powered by the SABRE. The vehicle would take off from a runway, reach low Earth orbit in a single stage, and then glide back for a horizontal landing.

Other SSTO concepts have appeared over the years:

- Venture Star (Lockheed Martin, 1990s): A lifting-body SSTO using a linear aerospike engine, cancelled due to cost and material challenges (Baumgartner, 1997).
- DC-X / Delta Clipper (McDonnell Douglas, 1990s): A vertical take-off, vertical landing SSTO demonstrator that validated rapid turnaround but never reached orbit (Gaubatz, 1995).

Future SSTO designs may combine hybrid air-breathing propulsion with advanced lightweight materials, high-density fuels, and optimized aerodynamic structures. If successfully implemented, SSTOs could drastically reduce launch costs, increase operational flexibility, and enable true aircraft-like space access.

Reusable Launch Systems: Reusability is one of the strongest cases for hybrid air-breathing propulsion. Air-breathing ascent keeps thermal and mechanical loads lower in the early stages compared to pure rockets, potentially extending component life. SABRE/Skylon envisions a full reuse cycle with no major engine overhaul for many flights, similar to aircraft maintenance intervals. Concepts such as NASA's GTX studies show that a well-integrated air-breathing stage could return for reuse, either as a booster for a two-stage-to-orbit system or as part of a fully recoverable SSTO. For commercial and government operators, this reduces lifecycle cost and increases launch cadence.

LIMITATIONS

This study is based on a review of existing literature, technical reports, and publicly available program data. No complete hybrid air-breathing propulsion system has undergone full-scale flight testing, so the performance metrics presented remain largely theoretical or extrapolated from component-level demonstrations. As such, the findings should be interpreted as indicative rather than definitive.

CONCLUSION

Hybrid air-breathing rocket engines represent a significant step forward in propulsion technology by combining the efficiency of atmospheric oxygen utilisation with the capability of rocket propulsion in vacuum. The two-mode operation has the potential to reduce launch mass, increase operating Mach ranges, and make concepts such as SSTO vehicles feasible. In this paper, hybrid propulsion systems have been compared with traditional rockets and air-breathers in terms of performance, integration, safety, and operational viability, with case examples such as SABRE, HOTOL, LAPCAT Scimitar, and NASA's GTX programme. The results indicate that hybrid engines are capable of attaining much higher specific impulse during atmospheric flight-up to 2000-3500 seconds-compared to 350-450 seconds for rockets, while retaining competitive rocket-mode performance. Their high Mach capability and reduced oxidizer demand bring clear efficiency benefits, but at the cost of increased complexity, heavier cryogenic tankage, and lower thrust-to-weight ratios than dedicated rockets. Reliability remains a pressing issue, as hybrids face the same challenges as both groups: inlet control, thermal cycling, and critical mode transition. However, their efficiency in atmospheric climb and promise of reusability make them prime contenders for next-generation launch systems. The primary limitation is the absence of full-scale demonstrations and the technical development of key components such as lightweight precoolers and transition control systems. These challenges can be addressed through a combination of integrated flight testing, advances in materials, and exploration of alternative fuels to enhance storage and structural efficiency. Whether hybrid propulsion becomes viable for orbital launch will ultimately depend on demonstrating that its efficiencies and flexibility outweigh the risks of increased complexity. If realised, these engines could redefine access to space by enabling more efficient, reusable, and affordable launch vehicles.

ACKNOWLEDGEMENTS

I sincerely thank my mentor, German Saltar Rivera (University of Illinois Urbana-Champaign), for his invaluable guidance, encouragement, and constructive feedback throughout this research. His mentorship greatly improved the quality of this paper and contributed significantly to its successful completion. I thank all the staff of Lumiere Education for their cooperation and kind support throughout my research period. Their extraordinary contributions have greatly improved the quality of this paper.

REFERENCES

Aggarwal, R., Lakhara, K., Sharma, P. D. P., Darang, T., Jain, N., & Gangly, S. (2015). SABRE engine: Single stage to orbit rocket engine. *International Journal of Innovative Research in Science, Engineering and Technology*, 4. https://www.ijirset.com/upload/2015/october/107_SABRE.pdf

Baumgartner, R. I. (1997). Venturestar single stage to orbit reusable launch vehicle program overview. *AIP Conference Proceedings*, 387(1), 1033-1040. https://doi.org/10.1063/1.51920

Conchie, P. (1986, March). The HOTOL space transportation system. *11th Communications Satellite Systems Conference*. https://doi.org/10.2514/6.1986-786

De Vault, R. T. (1957). The ramjet-turbojet propulsion system for supersonic flight. *Marquardt Aircraft Co. Technical Report*. https://doi.org/10.4271/570206

Ferri, A. (1968). Review of scramjet propulsion technology. *Journal of Aircraft*, 5(1), 3-10. https://doi.org/10.2514/3.43899

Gaubatz, W. (1995). DC-X and beyond. *International Aerospace Planes and Hypersonics Technologies.* https://doi.org/10.2514/6.1995-6117

Grindle, L. (2011). X-43A final flight observations. *NASA Dryden Flight Research Center Technical Report.* https://ntrs.nasa.gov/citations/20110014424

Hempsell, M., & Longstaff, R. (2010). SKYLON users' manual (Rev. 1.1). *Reaction Engines Ltd.* https://aerofabrika.wordpress.com/wp-content/uploads/2011/05/skylon_user_-manual_rev131.pdf

Hill, P. G., & Peterson, C. R. (1992). Mechanics and thermodynamics of propulsion (2nd rev. & enl. ed.). *Addison-Wesley Publishing*. https://ui.adsabs.harvard.edu/abs/1992aw...book.....H

Hillion, P. J.-D., L., & Mangeot. (2023). A preliminary sizing and study of a hybrid rocket-based combined cycle. *Frontiers in Space Technology*. https://doi.org/10.3389/frspt.2023.1103981

Hunt, J. (1995). Airbreathing/rocket single-stage-to-orbit design matrix. *International Aerospace Planes and Hypersonics Technologies*. https://doi.org/10.2514/6.1995-6011

Jivraj, A. B. F., Varvill, R., & Paniagua, G. (2007, July). The SCIMITAR precooled Mach 5 engine. *2nd European Conference for Aerospace Sciences.* https://www.researchgate.net/publication/263849692_The_Scimitar_Precooled_Mach_5_Engine

Jones, H. W. (2018, July). The recent large reduction in space launch cost. *International Conference on Environmental Systems*. http://hdl.handle.net/2346/74082

Krivanek, T. M., Riehl, J. P., & Thomas, J. M. R. (2003). Affordable flight demonstration of the GTX air-breathing SSTO vehicle concept. *NASA Glenn Research Center*. https://ntrs.nasa.gov/citations/20030055618

Ha, D., Roh, TS., Huh, H. et al. Development Trend of Liquid Hydrogen-Fueled Rocket Engines (Part 1: Performance and Operation). Int. J. Aeronaut. Space Sci. 24, 131-145 (2023). https://doi.org/10.1007/s42405-022-00519-7

Longstaff, R., & Bond, A. (2011). The SKYLON project. *17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference.* https://arc.aiaa.org/doi/10.2514/6.2011-2244

Mahmoudi, R. M. A. A., & Rabiee, A. H. (2022). Predicting the energy and exergy performance of F135 PW100 turbofan engine via deep learning approach. *Energy Conversion and Management*. https://doi.org/10.1016/j.enconman.2022.115775

Mane, S. (2024). Overview on reusable space launch system. *International Journal of All Research Education and Scientific Methods*, 12, 1346-1353. https://www.researchgate.net/publication/383181934_Overview_on_Reusable_Space_Launch_System

Saunders, J. D., Stueber, T. J., Thomas, S. R., Suder, K. L., Weir, L. J., & Sanders, B. W. (2012). Testing of the NASA Hypersonics Project's combined cycle engine large scale inlet mode transition experiment (CCE-LIMX). *NASA Glenn Research Center Technical Report*. https://ntrs.nasa.gov/citations/20120002930

Space Exploration Technologies Corp. (2025, March). Falcon payload user's guide (Updated release ed.). *SpaceX.* https://www.spacex.com/assets/media/falcon-users-guide-2025-05-09.pdf

Steelant, J. (2008). LAPCAT: High-Speed Propulsion Technology. *Advances on Propulsion Technology for High-Speed.* https://www.academia.edu/89447294/LAPCAT_High_Speed_Propulsion_Technology

Sutton, G. P., & Biblarz, O. (2016). *Rocket propulsion elements* (9th ed.). Wiley. https://books.google.co.in/books?id=pFktw0GYSX8C

Thompson, J. R. (1980). Space shuttle main engine. *NASA Report.* https://commons.erau.edu/space-congress-proceedings/proceedings-1980-17th/session-1/5/

Scheidlinger, V. L., Atkins, K., Radcliffe, T., Mayberry, J. P., McCall, S. P., & Meholic, G. (2022). *Synergetic air-breathing rocket engine (SABRE) programme evaluation report 2022.* UK Space Agency. https://assets.publishing.service.gov.uk/media/63b556fce90e073a3b7b9299/Synergetic_Air-Breathing_Rocket_Engine__SABRE__Programme_Evaluation_Report_2022.pdf

Varvill, R., Duran, I., & Others. (2019, July). SABRE technology development: Status and update. *European Conference for Aeronautics and Space Sciences*. https://www.eucass.eu/doi/EUCASS2019-0307.pdf