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Hybrid Air-Breathing Rockets & their Potential

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Abstract

Research and analysis of proposed hybrid air-breathing rocket engines will take place to make determinations about their suitability for future use as a reusable space-grade engine for human transport. This paper will go in-depth and discuss its theory of operation and mechanism of action specific to the Synergetic Air-Breathing Rocket Engine or SABRE as it is more commonly referred to. To this end, published information that is readily available on concept engines of this type and their related systems will be reviewed. By examining the general configurations of systems in these designs there is hope to definitively conclude whether they are the next evolution in space capable propulsions. Consultations of experts in the field as well as in academia will also be made when and where possible. After these studies, an attempt to verify optimum compromises that were made will be tested by calculating a theoretical design point.

Keywords: Propulsion, Aerospace, Hybrid Engines, Hypersonic

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Introduction

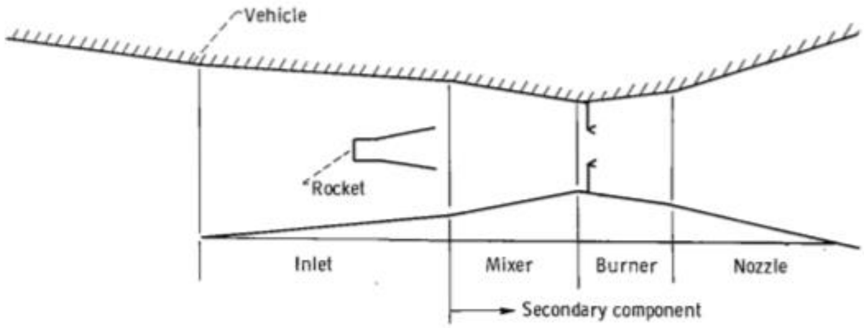
The concept of hybrid air-breathing rocket engines is not a brand-new ideology being presented. Publications on the idea go back as far as the 1960s from NASA. The reason for the optimism surrounding the idea is the potential weight savings and additional fuel efficiency projections of using atmospheric oxygen as the oxidizing agent during part of the ascent journey. However, despite huge government programs with significant expenditures nothing has been successfully tested as of yet. That could potentially change with the testing of Reaction Engines Synergetic Air-Breathing Rocket Engine (SABRE) in late 2020. SABRE is the culminating project born out of the stagnation of government research and development into hybrid air-breathing rockets. This research is uniquely interesting and of relevance given recent public funding and interest in a revival of space exploration and commercialization of the industry. The SABRE engine is of specific importance as it is at the cutting edge of development in the field to which it belongs and could provide the gateway for modern expansion in space. If successful the engine would allow a more conventional take-off and transition from low speed, to hypersonic, to out of atmospheric flight, unassisted. This is achieved by having a large precooler that feeds into a small core engine for subsonic flight. Once the craft reaches a speed of Mach 5, the engine switches from a conventional ramjet system to rocket propulsion to escape the earth's atmosphere. The advantages are apparent, among them are reduced infrastructure dependence and onboarding of fuel. With that said, academics must be critical of the proposed concept engine to ensure that it is a sound scientific undertaking and not a potentially wasteful dead-end bound program.

Background

In selecting materials to include within the scope of literature sourced for this paper, we discriminated against out of industry reviews and writings by individuals and organizations with nontechnical focuses. In place of these lesser reliable pieces, we instead sought out publications from academic and industry sources from third parties without a vested interest in the success of the SABRE. Obtaining sources discussing the SABRE engine in depth is difficult due to the tightly held proprietary specifics of the engine. However, the concept of hybrid air-breathing rockets is readily discussed in technical papers regarding the technologies required, some of which have not been possible because of technological limitations. The first study discusses the concept of hybrid air-breathing rockets as a booster stage for launching to space.

The NASA technical report, "Conceptual Study of Rocket-Scramjet Hybrid Engines in a Lifting Reusable Second Stage", by Andrzej Dobrowolski and John L. Allen proposed a highly simplified approach to an orbital booster that could range from a pure rocket to a pure ramjet depending on the altitude [1]. The basis for this idea is the fact that much of the required energy needed for orbit is supplied by a second stage booster and reducing the energy carried can increase the payload capacity greatly. In addition, the proposed design would allow for a substantially increased usability instead of waste after launch. This very simplified design discussed in the report was to place a rocket in the geometry of the ramjet which is built using the vehicle as part of the engine. This design came to be known as the air-augmented rocket. An example of the proposed design is shown in Figure 1.

Figure 1. *Schematic of Rocket-scramjet Hybrid Engine*

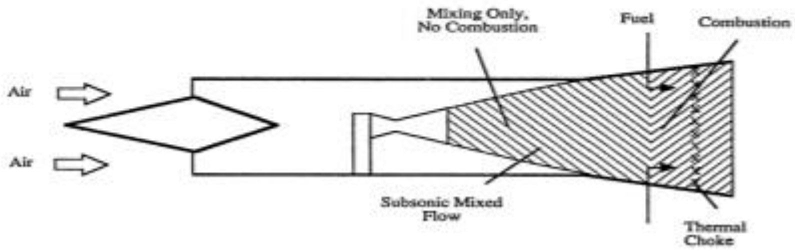


Source: Conceptual Study of Rocket-Scramjet Hybrid Engines in a Lifting Reusable Second Stage 1969.

The design above features a fixed geometry design for the rocket an inlet and has been assumed to have a chamber pressure of 1000 psi [1]. The air-breathing component of the engine also identified as the secondary component is sized by matching the inlet, mixer, and burner according to given interface requirements which are determined later in the report. Downstream of the rocket inlet location is a section to allow complete mixing of the supersonic air with the primary jet [1]. Additional fuel is added in the burner to complete the stoichiometric combustion in the chamber. The combustion occurs at supersonic speeds then exits a fixed geometry nozzle attached to the rear of the vehicle. The vehicle in this study was configured as a wingless lifting body for simplicity of design and the aerodynamic characteristics have been proven to be some of the most ideal for this type of flight. The final concluding remarks of this report determined that on the same trajectory path a conventional scramjet had a higher Lift/Drag ratio but had a 14 percent less payload capacity compared to the air-augmented case. This technical report proves there are tremendous benefits associated with the air-augmented rocket hybrid engine of payload capacity compared to a scramjet along with the same capacity. There is also the ability to lower fuel consumption greatly because a lifting body is being used instead of using pure thrust to escape the atmosphere. The theory for this engine was developed in the late 1960s when the technology available was not sophisticated compared to modern times. Andrzej and John injected this concept into NASA and the minds of many young scientists knowing that the future would hold the key to unlocking the potential of a hybrid rocket/scramjet engine design. Since this initial design, many companies and motivated researchers have proposed new ideas for a type of propulsion to achieve the single stage to orbit goal.

There have been many proposals as to new types of propulsion systems that can provide SSTO goals. Improving the design of an air- breathing rocket has been discussed by Amar.S, Gowtham Manikanta in, "Air-Breathing Rocket Engines and Sustainable Launch Systems." An air-breathing rocket engine ingests air during the flight to greatly remove the amount of oxidizer needing to be carried on board [2]. The design presented differs from the NASA design by implementing a Rocket Engine Nozzle Ejector (RENE) design. This design works by shrouding the rocket by which the shrouded area allows for extra combustion during flight greatly increasing thrust [2]. The design also helps improve thrust augmentation by keeping the mixing chamber conical instead of cylindrical, air to rocket propellant ratio is kept low around 2, and a supersonic exhaust is used on the exit [2]. It is also proposed to use a thermal choke ramjet engine which is similar to the air-breathing rocket but has a pointed intake. Figure 2 shows the concept of the air augmented ramjet with a thermal choke.

Figure 2. *Air Augmented Ramjet with Thermal Choke*

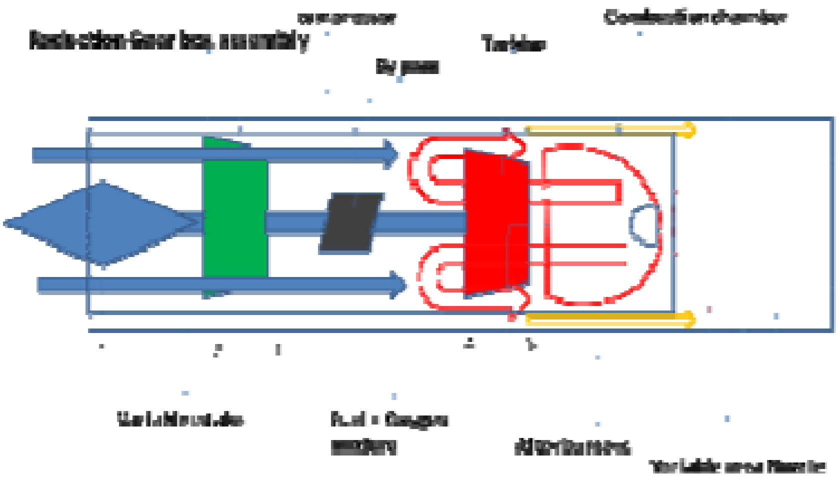


Source: Air Breathing Rocket Engines and Sustainable Launch systems 2012.

The advantage of this design is that it projects a virtual throat into the flow's divergent path allowing for a convergent-divergent section without the need for any physical hardware. This would greatly reduce the complexity of the engine design. This design is a good concept but the ability to take off from ground level would not be possible. This brings the concept of a magnetic launch system that could propel a craft to 600 MPH in 10 seconds [2]. This concept is feasible but the increased cost of creating a rail system and supplying power would cost an astronomical amount. This leaves the concept of the SABRE engine which uses turbomachinery to compress air into the rocket combustion chamber. This allows this type of engine to take off from the ground and achieve high speeds and altitudes. This concept is known as an Air Turbo Rocket, a combination of a turbojet and rocket proves to have the most promise if Single Stage to Orbit (SSTO) is to be achieved.

Ankit Dimri and Racheet Matai authored, "Improved Air Turbo Rocket for Space Applications Application to Orbital Vehicles and Reentry" which proposed an engine much similar to the SABRE with a few additional features that would be of use for space flight and re-entry paths. Besides, it is indicated that the use of an air turbo rocket could span to ballistics, a satellite launch, and hypersonic commercial travel uses. Dimri and Matai propose an improved air turbo rocket that can work in a vacuum environment [3]. The proposed design is as follows and operates in three modes (Figures 3-5).

Figure 3. *Improved Air Turbo Rocket-Air Breathing Mode*

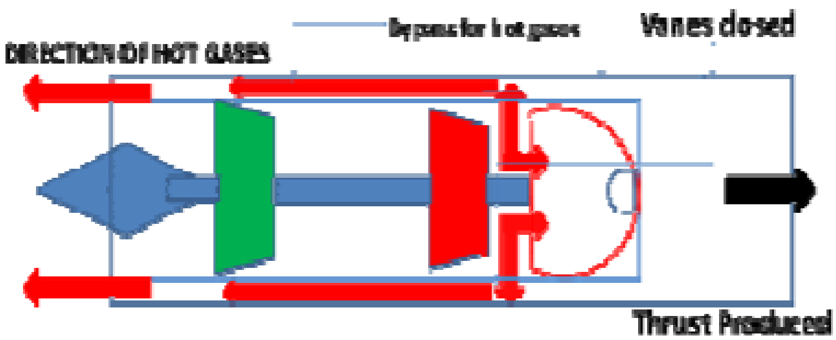


Source: Improved Air Turbo Rocket for Space Applications Application to Orbital Vehicles and Reentry 2012.

Figure 4. Improved *Air Turbo Rocket-Rocket Mode*

Source: Improved Air Turbo Rocket for Space Applications Application to Orbital Vehicles and Reentry 2012.

Figure 5. Improve *Air Turbo Rocket- Reentry Mode*

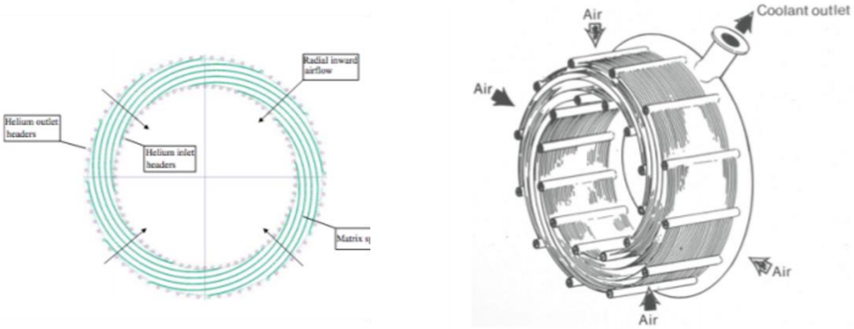


Source: Improved Air Turbo Rocket for Space Applications Application to Orbital Vehicles and Reentry 2012.

The ability to implement a reverse thrust upon entry to the atmosphere is very important to the safety of space missions. The benefits from this are huge such as allowing to slow the vehicle upon reentry, reducing the heat shielding required, as well as give it more directional capability upon re-entry. The ability to maneuver on re-entry is convenient for missiles to become lighter and navigate to their target more quickly. Simulations were performed to determine the flow characteristics in this engine but were only performed in a 2D simulation thus not providing much insight into actual values. Overall, the ideas proposed show forward-thinking into air turbo rockets but the SABRE engine and Skylon spaceplane prove to be the most conceptual sound idea presented today.

The report titled, "The Skylon Spaceplane" by Borg, K., and Matula, E. provides an in-depth review of the Skylon spaceplane platform which implements the SABRE engines. Borg and Matula give many capabilities of the proposed Skylon spaceplane but also indicate that if feasible the project will have to overcome numerous manufacturing hurdles. The Skylon spaceplane is an interesting aircraft that was born out of the ashes of the Horizontal Takeoff and Landing Aircraft (HOTOL) project which met its demise in 1988 due to lack of funding and interest in the project [4]. In 1994, three members of the recent shutdown HOTOL project erected Reaction Engines to take over the concept and to this day have been designing the Skylon spaceplane. The most important part of this project is the SABRE engine which is a proprietary idea of Reaction Engines Limited (REL). The Skylon's mission criteria are to land and take off from a runway carrying a payload of 15 mT (Tonne) [4]. Borg and Matula also explain in detail the problems with attempting to use an air-breathing engine to go into orbit and the specifics on how the SABRE engine is designed. Typically for space-bound programs air-breathing is not a viable option compared to rocket propulsion due to the great L/D ratio discrepancy between the two at 10:1 as opposed to 35:1 [4]. However, air-breathing engines use atmospheric air to cool the components, compress, and burn greatly reducing the need to carry onboard fuel. The issue with using turbomachinery at high Mach speeds is heating, which is where the SABRE has its most useful component, the pre-cooler. The pre-cooler can cool the extremely high-temperature air so the turbomachinery can operate effectively and reduce the strain on the compressor. The pre-cooler and heat exchanger work in a helium loop where the helium extracts heat from the heat exchanger and is used to power turbopumps within the system. Figure 6 shows diagrams on the design of the heat exchanger provided by Borg and Matula.

Figure 6. SABRE *Precooler Flow Model*

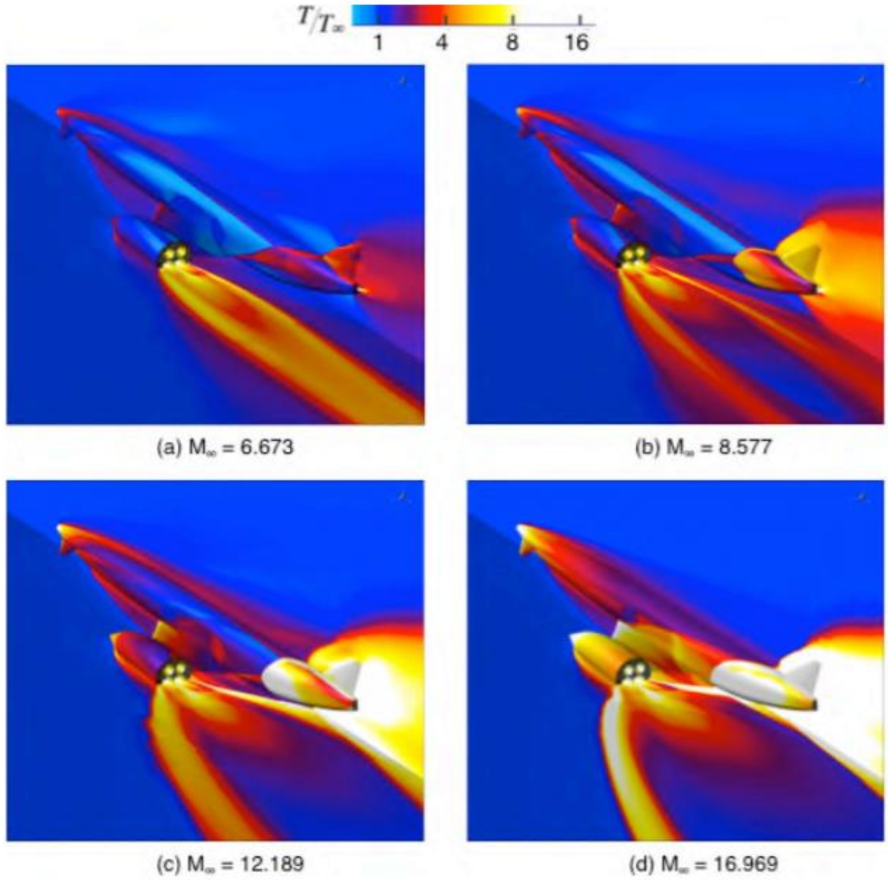


Source: The Skylon Spaceplane 2015.

This report concludes with a statement on how many obstacles the Skylon and SABRE have to overcome. The European Space Agency (ESA) performed an analysis of the project and determined that to complete all the prototyping and have a working model would cost around 12.3 billion dollars. This explains how difficult it is to develop an SSTO spacecraft since the expense of designing them outweighs the cost of launching a more commonly used platform. Borg and Matula performed a detailed discussion of the components making up the Skylon and SABRE but it is important to discuss the aerodynamics of the SABRE engine in hypersonic flight.

Analyzing the aerodynamics and plums of the Skylon and SABRE can provide an insight into the effects the passing air will have along with how the exhaust can interact with the body. This is exactly what was done by Unmeel Mehta, Michael Aftosmis, Jeffrey Bowles, and Shishir Pandya in their report, "Skylon Aerodynamics and SABRE Plumes." This report went into detail on the aerodynamics of the Skylon and the effect of SABRE plumes on the Skylon using mathematical and computational models in the form of computational fluid dynamics. The authors claim that REL's values for coefficients above Mach 8.5 have increased accuracy [5]. At this speed, the aft area of the fuselage environmental effects is inherently unknown and is a huge risk that must be substantiated before the aircraft takes flight [5]. Using a program called CART3D, the authors created a computer model with detailed mesh and simulated at multiple Mach numbers to gain a better understanding of aerodynamic effects of the environment on the Skylon aircraft. It was observed at a speed higher than Mach 8.5 detrimental effects of the flow began to increase greatly [5]. The CFD models showing the detrimental effects at high speeds are shown in Figure 7 to give representation to the flow dynamics of temperature.

Figure 7. *Skylon Temperature Distribution at Varying Mach Numbers*



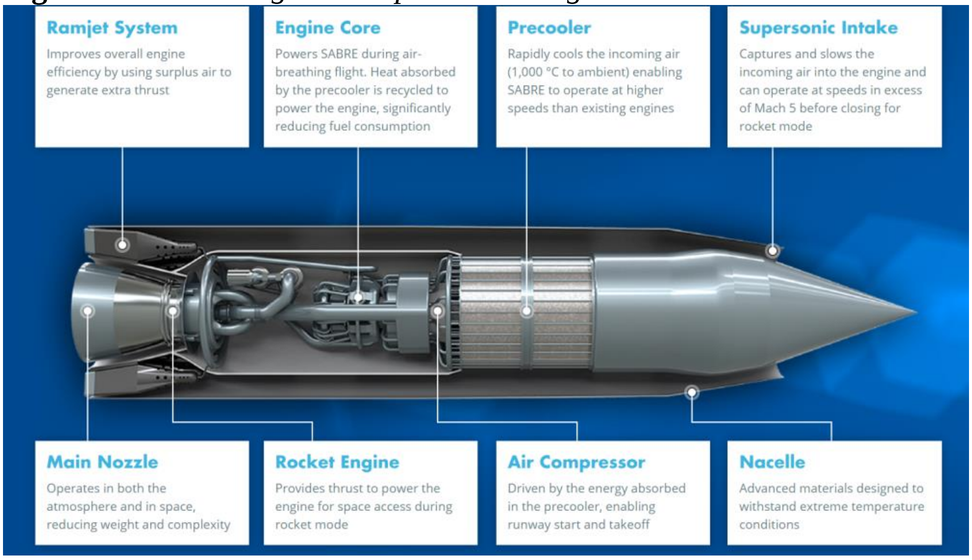
Source: Skylon Aerodynamics and SABRE Plumes 2015.

The image shown above helps indicate how much heating is associated with flying at high speed and the exhaust from the SABRE engines. This poses an inherent problem as the constant heating and vibration to the aft fuselage can be catastrophic. Authors Mehta, Aftosmis, Bowles, and Pandya proved how much heating and turbulence that the Skylon aircraft will experience and expressed their concerns about the damage and complications this could cause. However, it is stated that even with these concerns the pre-cooler developed by REL is the defining point of their whole project. It is a design that when proved for flight conditions will change the capability of hypersonic air-breathing engines. At a Mach number greater than 12.19 it was found that the static temperature on the fuselage was found to be 8-16 times greater than the freestream temperature. The heating seen by the fuselage is still an estimate and, in this case, is considered an inviscid flow due to the limitations of software available to use [5]. The simulations were performed at gamma=1.4 therefore the skin temperatures calculated are not accurate because the simulation is missing air/oxygen chemistry, radiant heating from the plumes, and proper heat transfer conditions at the surface of the Skylon [5]. With that said, most of the values missing from the simulation would likely drive the temperatures higher than what was calculated. Overall the SABRE engine and Skylon aircraft have the potential to change the space industry as an SSTO launcher, however, it is suggested that this system would be more beneficial as a Two Stage to Orbit (TSTO) launcher to carry the spacecraft to near orbit then launch and return to the ground.

Approach

The approach used to explain the potential of Hybrid Air-Breathing Rockets is performed by investigating Reaction Engines, SABRE engine, which is one of the most developed concepts currently being pursued for a single stage to orbit engine. The engine components will be discussed upon and how the engine operates. Using collective educational and industry experience, the statements and claims put forward by Reaction Engines were investigated. In addition, industry experts regarding the SABRE's state of development were used to further discuss Reaction Engines statements. This investigation will consist of a top-down system-level approach without going into the specific details of how the combustion chemistry works. The arrangement of the engine is detailed in Figure 8).

Figure 8. *SABRE Engine Component Arrangement*

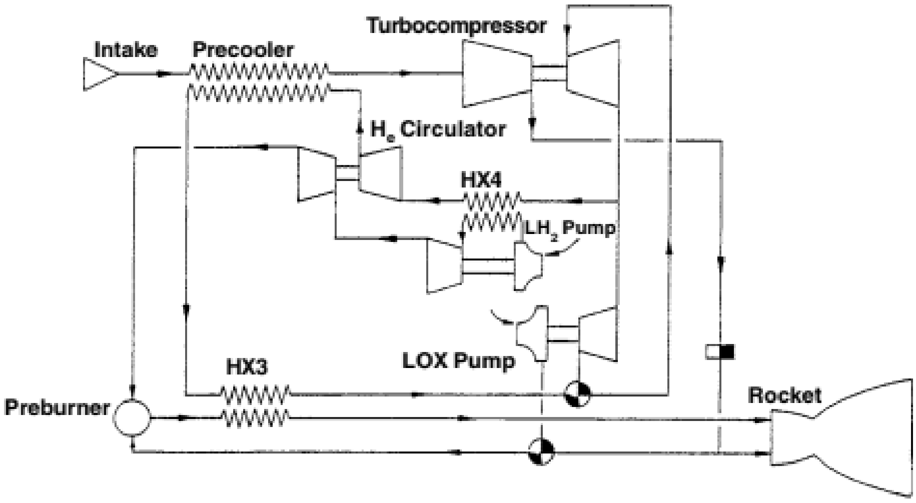


Source: https://www.reactionengines.co.uk/beyond-possible/sabre.

SABRE is the product of a development cycle that far exceeds its program existence with REL. Before Reaction Engines Limited's inception, the government of the United Kingdom was funding a program interested in synergetic air cycle rocket engines for a horizontal takeoff space platform known as HOTOL. The program's name itself is derived from the acronym for Horizontal Take-Off and Landing was commenced in roughly 1982 and shuttered by 1989. However, the key figure for the program, Alan Bond, became one of three founders of REL carrying the torch for the engine onward by way of research and development on SABRE and Skylon. It was Bond's initial research into pre-cooled jet engines which brought about the conceived systems layout for the predecessor RB545 and the culminating work of the SABRE engine.

The SABRE consists of a Supersonic Intake that will capture and slow all incoming air to the engine up to speeds over Mach 5 at which point it would then switch to a fully closed rocket mode. The Nacelle is designed to help guide the air along the length of the engine while being able to withstand extreme temperatures at high speeds. Figure 8 shows the components of the engine well but does not provide a great scale on how large the engine is which is projected to be 30 to 40 feet [6] and Figure 9, the diagram of engine cycle for the SABRE.

Figure 9. *Diagram of Engine Cycle for the SABRE*



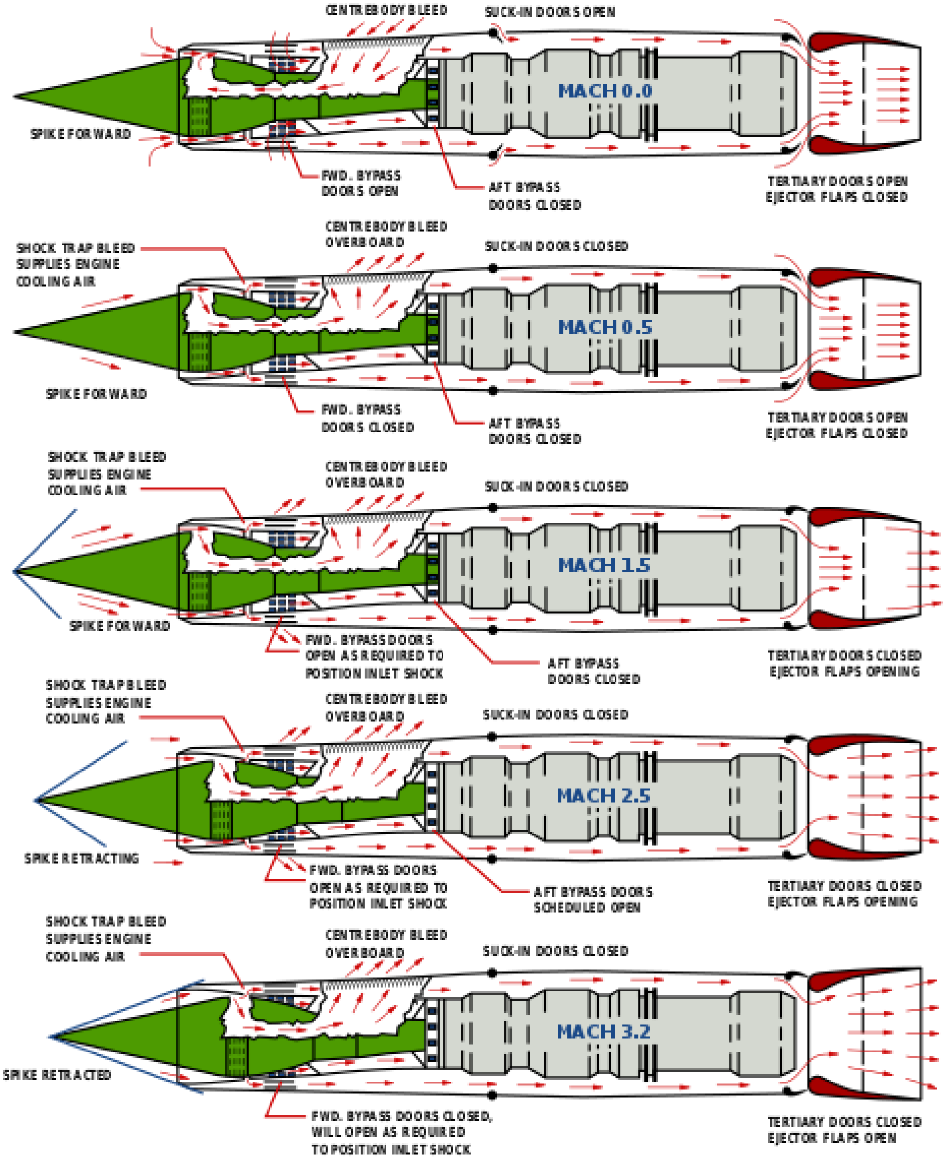
Source: A Comparison of Propulsion Concepts for SSTO Reusable Launchers 2003.

Intake

The intake is a fairly simple piece of hardware as far as the SABRE is concerned given that much of the concepts at work are tried and proven. There will of course be a non-blunted movable conal type intake flanked by inward flared nacelle working surfaces. The design shares significant aesthetic and functional similarity to the moving cone intake of the Pratt Whitney J58 found on the SR-71 Blackbird. To help understand how this cone intake operates Figure 10 provides a representation.

The function at the intake during SABRE’s take off in non-sonic flows is simply to allow free stream to move through the engine in a traditional turbine engine sense with minimal obstruction. Once vehicle velocity is in the sonic range the intake cone will facilitate an oblique shock formation exchanging freestream kinetics for thermal energy which will need to be addressed by the precooler. In the hypersonic mode of flight, the intake serves to seal off the turbomachinery entirely and force the engine to function as a pure rocket. At this point, a critical role of the equipment within the intake cone will be thermal management due to the extreme heating likely to take place on the engine’s surfaces.

Figure 10. *Diagrams of the Intake on the SR-71 Blackbird Engine*

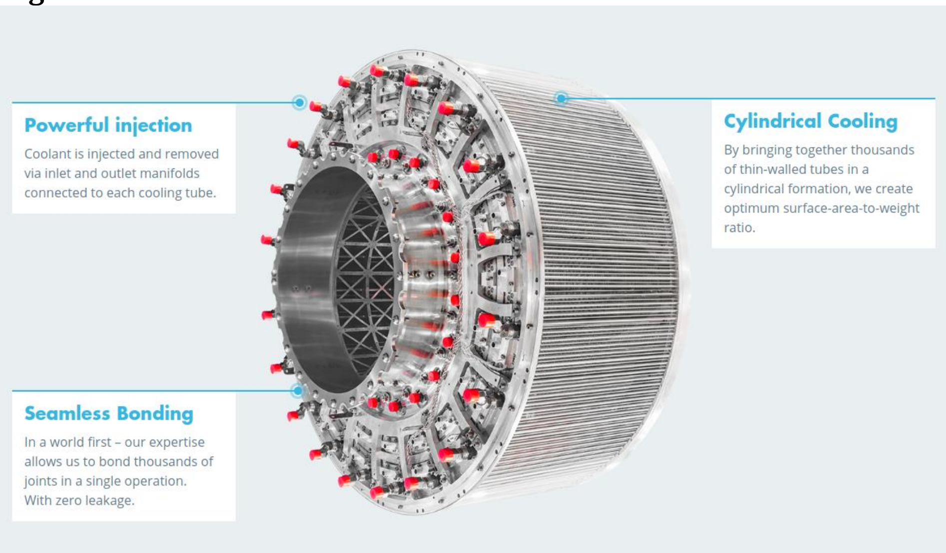


Source: https://www.sr-71.org/blackbird/manual/1/1-33.php.

Pre-Cooler

The pre-cooler is by all accounts an entire system unto itself, the necessity of which cannot be overstated for the success of the SABRE (Figure 11). During sonic flight conditions the SABRE needs to continue to make use of atmospheric oxygen, but there is a critical problem. The now shocked inbound flows are too hot for the compressor's turbomachinery to effectively compress and force it into the combustion chamber. This is the problem for which the pre-cooler is the solution. Reaction Engines has a proprietary design weighing in at a roughly disclosed 2,500 pounds that makes use of a helium based closed-loop heat exchanger. According to their public statements, the exchanger works by cooling the inbound air with liquid helium which is then used to drive a series of heat pumps. After some work is extracted from the fluid, it is then passed through another exchanger which both cools the helium before recirculation as well as preheats the liquid hydrogen for the preburner combustion chamber. The reason for not exchanging heat directly with the liquid hydrogen is apparent as this would require approximately four times as much hydrogen as is needed to balance the burn stoichiometry to achieve the necessary heat dissipation. Therefore, extracting work from the pre-cooler loop itself is such a clever solution to the energy gap in the cycle of the engine [6].

Figure 11. *SABRE Pre-cooler*



Source: https://www.reactionengines.co.uk/beyond-possible/heat-exchanger.

The heat exchanger itself is reportedly a rather complex arrangement of tubes with special coatings. It reportedly also had a problem rather early on in its development due to icing saturation. Although the development team has been completely closed lip about how they resolved this problem there are a few speculations in the wild. One of which is that they induce a vibration through the matrix of tubes to ensure that significant icing clusters fail to form in the first place.

Air Compressor

The compressors function within the engine is straightforward and limited in scope. It will be powered by a turbine in the helium pre-cooler loop. This turbine will extract energy from the helium working fluid from the pre-cooler. The compressor itself will take the now cool dense airflow from the pre-cooler and further compress it from approximately one atmosphere to approximately one-hundred forty to one-hundred-fifty atmospheres. From here the compressed flow moves into the engine core for combustion through the synergetic rocket cycle phase of the engine’s thrust creation.

Engine Core

The engine core will then extract further work from the helium pre-cooler circuit and combust the hydrogen and extremely dense compressed flow from the compressor and force it from the engine core combustor and out the main nozzle. The engine core in concept is fleshed out, but little detail of its actual physical structure can be found. Likely, the engine core will also house the preburner assembly. The preburner assembly is responsible for further raising the thermal energy in the helium before it is introduced to the compressor and liquid oxygen turbines.

Rocket Engine

The rocket functions are achieved through two modes; a pure rocket mode that is active when the inlet is closed-off post Mach 5 flight which is entirely conventional, and a synergetic mode that uses the air from the compressor and burns it in the engine core up until that point. The extent to which these two systems operate simultaneously or the level of overlap that occurs as inlet closure approaches is not known but is likely to ensure seamless engine operation.

Ramjet

The ramjet components of the engine will serve to improve overall engine efficiency during flight regiments between sonic and hypersonic conditions. The ramjet system will operate conventionally by taking spillover air from the intake that circumnavigates the pre-cooler and makes additional thrust with it. The system currently proposed would not be operational after the main nozzle closure, but this is an area for possible improvement. Through variable internal geometry or maybe a split type system it might be possible for REL to use the system in a scramjet configuration as well. Although something like this hasn't been effectively implemented yet, it might be an innovation worth pursuing without too much additional complexity or weight. This would allow an improved net specific impulse over pure rocket mode of operation in the Mach five to perhaps as high as Mach ten region. However, this could be quickly offset if such alterations to the system came at additional structural or support equipment weight.

Main Nozzle

The main nozzle as a subcomponent of the rocket engine as described just prior also serves to produce thrust through the two different modes of operation. It will be used for expanding both the conventional rocket engine as well as the engine core combustion products for thrust. The current depicted designs make use of a traditional bell-type nozzle which is not atmospheric pressure compensating and thus must have a predetermined optimization point. SABRE would likely greatly benefit from an alternative nozzle type that would pressure compensate for the expansion. Aerospike nozzles are one such type that would help SABRE expand its combustion products more efficiently across the entirety of the flight regime.

Discussion

Although there is tremendous interest in the potential advantages of the system's configuration of the SABRE as proposed, there is yet to be any real substantive data from testing to warrant undue hope for hybrid air-breathing engines now. The idea itself has had some sixty years to come to fruition but has failed to do so thus far. The engine consists of an intake, pre-cooler, air compressor, engine core, rocket engine, ramjet system, and a main nozzle. To date the only component successfully tested is the pre-cooler, leaving a lot to speculation at this moment in time. There is reason to be hopeful for the concept, but perhaps not in the packaging proposed at this time. Modern engineers recognize that there is a fine line to be walked between the number of moving parts or intertwined systems and the need to find a balance between different battling principles of the natural world be they thermodynamics or reaction mechanics. Most recognize that the current iteration of the rocket engine isn't going to necessarily be our vehicle to manned travel of the stars, but exactly what will take its place is still a hotly contested grey area. The solutions to the fuel and vehicle mass problems for a single stage to orbit that SABRE presents are enticing, but one cannot lose sight of the fact that the system depends on two of the most emissive gases on our periodic table; one of which is noble and the other the complete opposite both trying to escape their captivity to the detriment of the engine's function. Some clever solutions have certainly been presented especially when it comes to the pre-cooler's heat absorption and helium loops subsequent dissipation via useful means, but skepticism is not totally unwarranted.

It is important to discuss what the future could hold if the SABRE is successful. How versatile would this engine be as a commonplace powerplant for hypersonic vehicles? If commercial operators were to use this type of engine the risk of aircraft loss is unknown but could be greater due to the fact that a profit is trying to be made occasionally causing deadlines or safety items to be pushed. Currently costs for engine overhaul are greater than 2 million the price of SABRE even though fewer moving parts most likely would have a much greater cost. Over time the pre-cooler would likely be replaced completely because there would not be a way to inspect and repair for damage on such small internal components. The idea to consider is that the cost of repair for the engine may be great but there is still the ability to save the vehicle that the engine is implemented on. Hypersonic travel also has an incredible risk that even the smallest issue can cause a catastrophic failure so the margin for error must be extremely small.

Even if SABRE failed to come to fruition, the pre-cooler itself might live on as an extremely innovative piece of technology in its own right with industrial and commercial aviation applications of its own. The solution to the icing problem is perhaps the most curious piece of the puzzle that remains unknown to the public. However, after some consideration, we propose that instead, it could be that they are simply removing the water which is necessary for the formation of ice itself. A water gas shift reaction at the inlet might be induced by introducing carbon monoxide into the flow prior to or in the pre-cooler. A WGSR at the pre-cooler would serve to combine atmospheric water and form residual hydrogen and carbon dioxide due to the temperatures and conditions experienced there. The reaction itself favors the rapid cooling that can be found on the pre-cooler itself. All that is necessary would be for the constituent reactants to be present at the surface of the pre-cooler whose coating could be doped with catalyzing agents. This would also produce trace additional hydrogen for burning downstream.

Conclusions

There has been nothing that conclusively disproves the workability of the proposed designs, however, there remain significant technical challenges that need to be surmounted. Among these is the need for high efficiency, expedient heat exchangers for cooling of the inbound flows while also addressing shock interactions that occur there. The hypersonic nature of the end product will entail serious material costs that will withstand the heat, vibration, and ablation experienced due to the flows encountered. Upon successful testing of the given configuration, reusability will become the next deciding factor. The complexity of the system will necessarily need to be countered by proven reliability and serviceability or it will ultimately fail to be viable due to the disposable costs of the platform.

References

[1] Dobrowolski, Andrzej and Allen, John. L. May 1969, CONCEPTUAL STUDY OF ROCKET-SCRAMJET HYBRID ENGINES IN A LIFTING REUSABLE SECOND STAGE, Lewis Research Center - Cleveland, Ohio. NASA TN D-5218.

[2] Amar.S, Gowtham and Manikanta Reddy. T, 2012, Air Breathing Rocket Engines and Sustainable Launch systems, SRM University, Chennai, India. Applied Mechanics and Materials Vol. 232 (2012) pp 310-315.

[3] Dimri, Ankit and Matai, Racheet. Improved Air Turbo Rocket for Space Applications Application to Orbital Vehicles and Reentry. University of Petroleum & Energy Studies, Dehradun, India. Applied Mechanics and Materials Vols. 110-116 (2012) pp 2554-2561.

[4] Borg, K. and Matula, E. The SKYLON Spaceplane, 2015. University of Colorado, Boulder, CO, 80309, USA. ASEN 5053 - Rocket Propulsion.

[5] Unmeel Mehta, Michael Aftosmis, Jeffrey Bowles, and Shishir Pandya. Skylon Aerodynamics and SABRE Plumes. NASA Ames Research Center, Moffett Field, California 94035, USA.

[6] Bond, Alan and Varvill, Richard. 2003, A Comparison of Propulsion Concepts for SSTO Reusable Launchers. Reaction Engines Ltd, D5 Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK. JBIS, Vol. 56, pp.108-117.