The SKYLON Spaceplane

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This report outlines the major technical aspects of the SKYLON spaceplane as a final project for the ASEN 5053 class. The SKYLON spaceplane is designed as a single stage to orbit vehicle capable of lifting 15 mT to LEO from a 5.5 km runway and returning to land at the same location. It is powered by a unique engine design that combines an air-breathing and rocket mode into a single engine. This is achieved through the use of a novel lightweight heat exchanger that has been demonstrated on a reduced scale. The program has received funding from the UK government and ESA to build a full scale prototype of the engine as it's next step. The project is technically feasible but will need to overcome some manufacturing issues and high start-up costs. This report is not intended for publication or commercial use.

Nomenclature

SSTO	Single Stage To Orbit
REL	Reaction Engines Ltd
UK	United Kingdom
LEO	Low Earth Orbit
SABRE	Synergetic Air-Breathing Rocket Engine
SOMA	SKYLON Orbital Maneuvering Assembly
HOTOL	Horizontal Take-Off and Landing
NASP	National Aerospace Program
GTOW	Gross Take-Off Weight
MECO	Main Engine Cut-Off
LACE	Liquid Air Cooled Engine
RCS	Reaction Control System
MLI	Multi-Layer Insulation
mT	Tonne

I. Introduction

The SKYLON spaceplane is a single stage to orbit concept vehicle being developed by Reaction Engines Ltd in the United Kingdom. It is designed to take off and land on a runway delivering 15 mT of payload into LEO, in the current D-1 configuration. It will be be unmanned and uses innovative dual-mode SABRE engines. These engines have an air-breathing and rocket modes and have evolved from the liquid air-cooled engine designs of the 1980s and the HOTOL project.

The European Space Agency has reviewed the concept and found no technical or economic impediments[1] and the UK government has pledged 60 million euros for its development.[2] REL has successfully demonstrated a lightweight heat exchanger[9] that is critical to enable full engine functionality and is currently working towards a full engine prototype to test across the range of air-breathing and rocket mode conditions by 2019.[2] This report will cover a brief background of SSTO history, then describe key features of SKYLON and SABRE. This will be followed by a discussion of the details and some final conclusions.

Figure 2 shows the nominal profile that takes off from a runway and uses air-breathing ascent to reach 28.5

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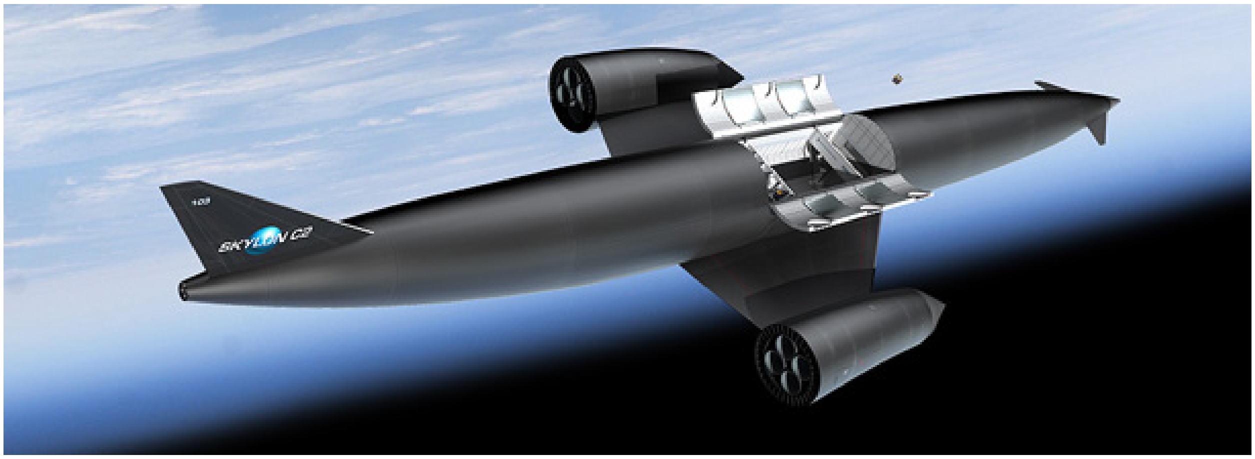

Figure 1. Artist visualization of C-2 version of SKYLON deploying a payload.[3]

km and Mach 5. At this point the engine switches to rocket mode to travel the rest of the way to MECO (~80 km) which will place it on a transfer orbit to reach a desired circularized orbit at apogee. The SOMA thrusters will then be used to circularize the vehicle into the appropriate orbit. The estimated re-entry interface is 120 km and the spacecraft will maneuver to reduce heat loads and meet the necessary glide range for descent and landing on a runway at the spaceport.

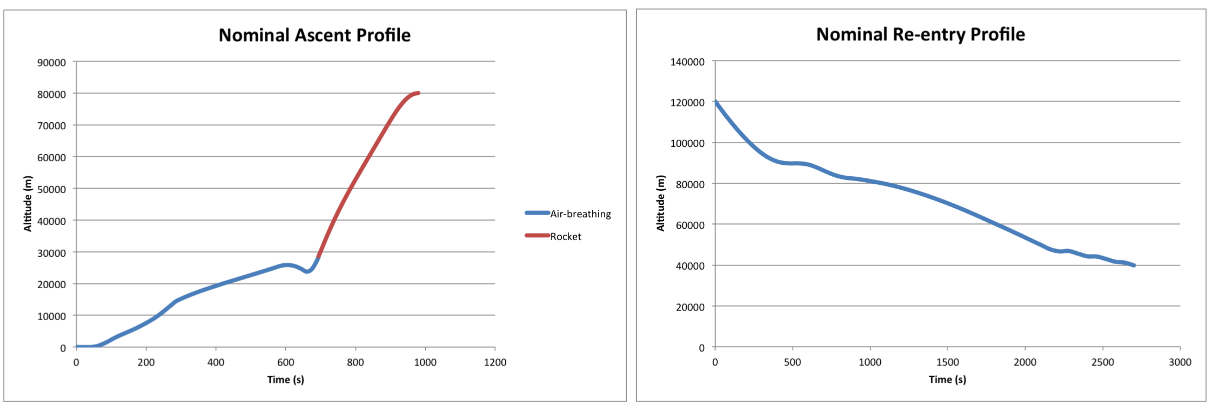

Figure 2. Ascent and Re-entry profile for equatorial launch.[3]

A. Background

The single stage to orbit concept has been pursued in various guises since humans began to investigate spaceflight. In the early 1960s SSTO concepts began to be investigated and by 1965 Robert Salked had designed a space shuttle precursor that would be launched from a C-5 to take a small crew into orbit.[4] More direct precursors to the SKYLON design first started to appear in the mid 1980s. The national aerospace program (NASP) was initiated by the United States to develop two X-30 SSTO planes.[5] These were to consist of dual ram/scramjet engines to take the plane to the edge of space where a rocket engine would finish orbital insertion. The program stayed funded up to 1994 when it was finally decided the concept was too expensive to actually construct the planes. In a similar vein the United Kingdom started the Horizontal Take-Off and Launch project.[6] This program built on earlier work by Alan Bond on pre-cooled jet engines, in an effort to develop an unmanned reusable launch vehicle for satellite payloads. The program used the Rolls Royce RB545 engine designed by Bond.[7] The program lost funding in 1988 when the UK government and Rolls Royce withdrew. Alan Bond and other veterans of the HOTOL program kept the work alive though.

They created a new company in 1994, Reaction Engines Ltd, and renamed the spaceplane SKYLON. The program has gone through several design revisions until reaching the current D-1 version.

II. SKYLON

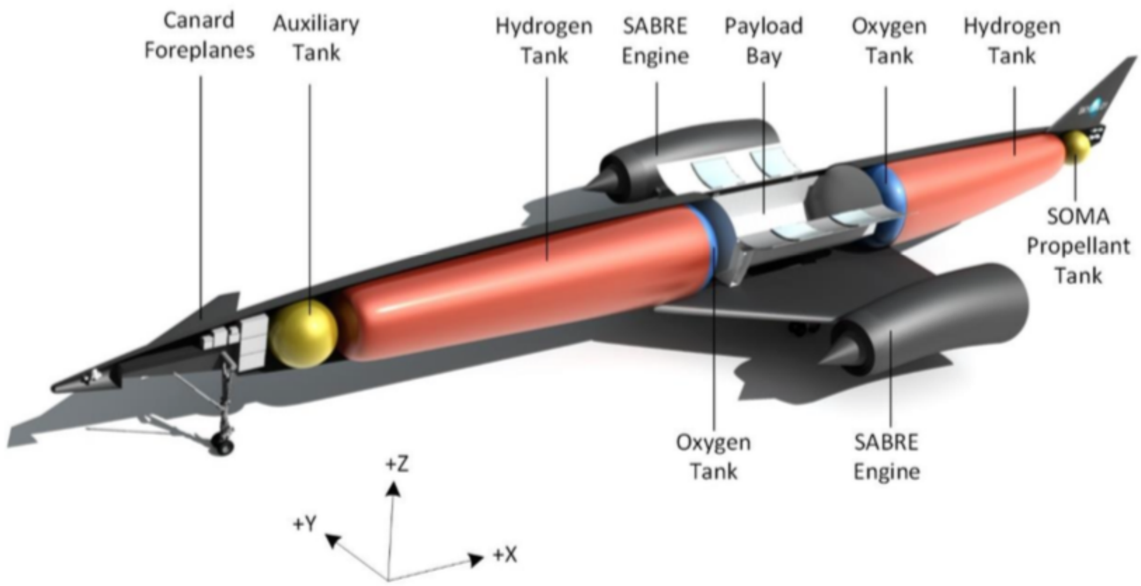

Figure 3. SKYLON internal layout.[8]

The SKYLON spaceplane draws design characteristics from the space shuttle and the HOTOL project. It consists of a long narrow frame with delta wings located roughly at the midpoint of the fuselage. The payload bay is directly between the wings and the engines are placed in nacelles on the wingtips. There is an orbital positioning assembly located in the most aft part of the frame with associated cryogenic propellant tanks.

A. Structural

The main frame holding the fuel tanks and supporting the aeroshell will be constructed of titanium reinforced with silicon carbide fibre. This material was chosen for a relatively easy and robust joining operation as well as high strength and operating temperature range.[9] The primary propellant tanks are designed as non-structural aluminum at 2 bar absolute on the ground. They are designed to maintain 1 bar delta P throughout the mission profile. These tanks will be suspended within the frame by Kevlar ties and the entire frame will be covered in a ceramic aeroshell with layered MLI beneath.

B. Aeroshell

The SKYLON aeroshell is designed to be 0.5mm thick and is based off of a silicon carbide reinforced glass ceramic called System2. This material was developed by the the Atomic Energy Authority at Harwell but production was halted in 1990 for profitability reasons. Reaction Engines is currently working with a firm called Lateral Logic to rebuild a supply chain for this material. This material was chosen due to the high altitude, low-heating, re-entry profile projected for SKYLON.
Re-entry analysis was performed using the 3-D Euler/ Navier-Stokes flow solver from DLR Braunschweig.[10] The study examined four points on the expected re-entry profile and found that at ~82 km peak heat loads of up to 3000K were found corresponding to the areas depicted in figure 6 below. The other parts of the profile had no points on the fuselage exhibiting temperatures above 1300K. No shock-shock interactions were found

corresponding to the sharp edges in the design. There is forward work in reducing the heating in these area with adjusting canard angles and introducing selected filleting. As of the current iteration of the design the areas of high heat are designed to have active cooling provided in the form of pumped water. Further work has been recommended in characterizing the heating in the critical junction of the wing and engine nacelle to add further evidence that shock-shock interactions are not present.

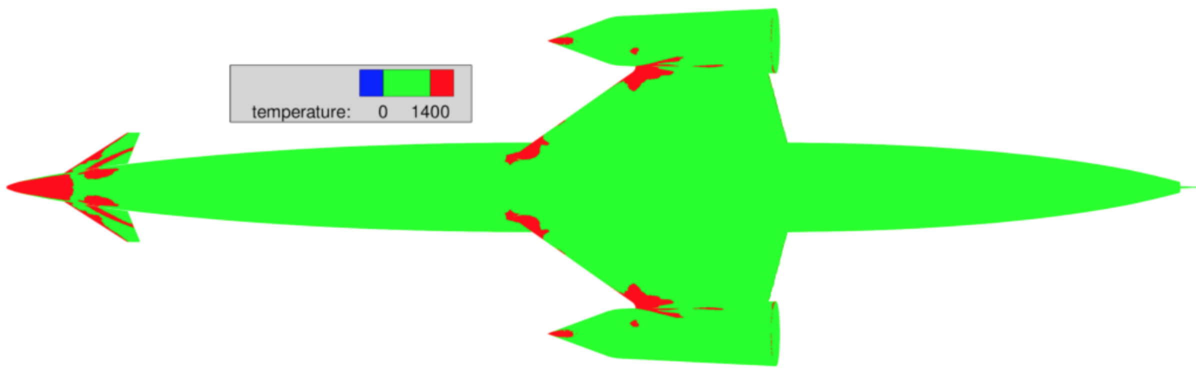

Figure 4. Re-entry heating profile on the underside of SKYLON[10]

C. Attitude Control

The primary control surfaces in atmosphere are canards for pitch, ailerons for roll and a rudder for yaw. During the rocket powered transition from lifting flight to orbit yaw authority is taken over by differential engine throttling and pitch by engine gimbaling until reaction control thrusters take over at MECO. The re-entry will be guided with a combination of RCS and control surfaces as atmospheric conditions and heating profiles allow.

Table 1. SOMA Parameters[8]

Thrust	40 kN
Chamber Pressure	90 bar
Mass	102.5 kg
Throat Diameter	0.0391 m
Specific Impulse	4562 Ns/kg
Mixture Ratio	5.2:1
Expansion Ration	285:1
Total Length	1.328 m

Similar to the abilities of other launch vehicles, it isn't efficient for the SKYLON vehicle to use its larger SABRE system to position itself or correct orbits. Typically cold gas thrusters (in the case of satellites) or smaller, mono-propellant engines (for spacecraft) are used to enable acute position modifications. The SOMA is activated after MECO. At this point the vehicle is at a high enough altitude and fast enough speed that it has started its orbit around Earth, and requires only slight impulses for orbit modification. Due to the size of SKYLON, a larger engine is necessary to overcome the momentum required to move the vehicle. SOMA uses an expander cycle engine with a turbine to supply the liquid oxygen and liquid nitrogen designed by Airbus Defense and Space. Table 1 above details the capabilities of the SOMA engine. The configuration is designed as a cluster of 2 twin-chambered engines. The larger SOMA system is in the back of the plane near the elevator. For very small maneuvers, reaction control thrusters in the front of the spaceplane are used. Liquid oxygen and liquid hydrogen tanks that are separate from the SABRE containers feed both maneuvering systems. The reaction systems fully control the spacecraft during descent, down to Mach 9, at which at that point the foreplanes, ailerons and tail fin gain control again.[8,11]

D. Undercarriage

In order to make the SKYLON spaceplane reusable, it needs to be returned back to the surface of the Earth in an operational (or possibly repairable) state. The Reaction Engines Ltd group has modeled its landing system after the Space Shuttle. Using a set of oleos and bogies sized for rotation at Mach 0.45, the SKYLON is able to use a specially designed 5.5 km runway for takeoff and landing. The designed tire pressure of 385 psi is similar to that found on fighter jets, and allows the tires to be slim enough to be stowed during flight. It has been discussed that a more robust runway, than what is found in the typical commercial airport, is required due to the increased GTOW of the spaceplane. When the spaceplane lands, the propellant mass is negligible due to consumption during the mission. A 5:1 ratio of takeoff to landing mass allows for a safe landing using the oleos. There are two take-off abort scenarios, abort after rotation and abort prior to rotation. If the spaceplane had fully lifted off the runway, it would have to dump all of its fuel to emulate an end-of-mission landing, shutoff its engines, and land on the runway using gliding flight. Since there is no way to dump fuel if SKYLON needed to abort before rotation, an alternative method for stopping is used. Brakes on the spaceplane have been sized so that it can stop a fully loaded SKYLON, but only with the help of a water-cooling system. The kinetic energy required to stop the plane, $3.24x10^9$ J, would require a massive conventional disk braking system, calculated as 4000 kg. Rather than the conventional approach, the brakes have been undersized and use cooling water to remove the heat energy. The braking system carries 1200 kg of water to be blown through the brakes in the event of a runway abort and vented off as steam. After a successful takeoff, this mass is dumped overboard to reduce the launch mass. This leaves the effective cooling and braking mass to be ˜515kg.[12]

Figure 5. Visualization of SKYLON undercarriage deployed for landing.[1]

E. SABRE

The SABRE engine system is the most innovative and important part of SKYLON. It is this propulsion system which enables the spacecraft to be single stage to orbit. The system is based around a rocket engine that uses liquid hydrogen for fuel and ignites with either liquid oxygen or condensed air. The choice between the two oxidizers is determined by the altitude of the spacecraft's flight. When SKYLON is below a predetermined threshold, or 28.5 km in altitude and Mach 5 speed, the air-breathing capabilities are used to avoid using on-board liquid oxygen. An innovative helium loop system chills and compresses the ingested air to an almost liquid state to be used by the rocket engine. After SKYLON reaches an altitude of 28.5 km and speed of Mach 5, the compressor is unable to supply the rocket engine, and the liquid oxygen is supplied from the launched reserves to complete the ascent.[3] Combining both of these capabilities into one system reduces the mass of launching a separate air-breathing system and a rocket in the same flight, therefore eliminating the need to have multiple staging.

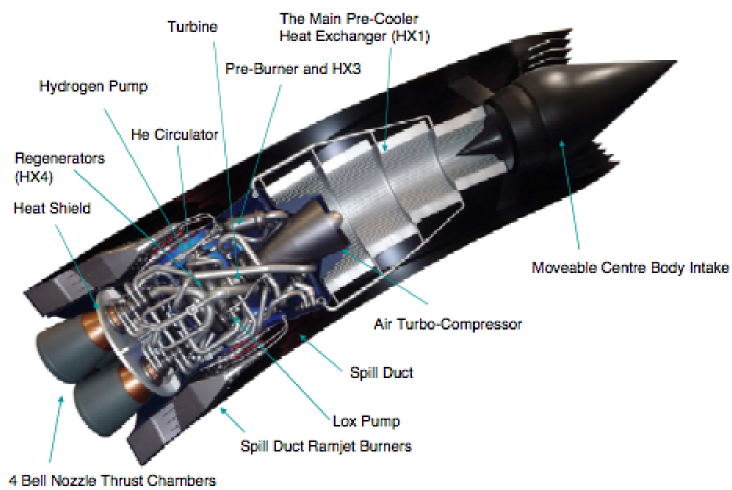

Figure 6. SABRE cutaway[11]

III. SABRE

As stated before, the SABRE system is the defining factor of the SKYLON vehicle. The patented helium cooling loop design is what supports this vehicle's single stage to orbit design, and allows for one engine to provide both air breathing and rocket propulsion capabilities. The following section will describe in greater depth the engine operations, components, and the cooling loop design. While in operation, the SABRE engine progresses through two distinct configurations, to ensure the most efficient flight possible. This allows for the included rocket engine to be used both in the higher density atmosphere and space. The availability of the engine in both settings means there is reduction in duplicate mass by not having two separate systems for the flight.

A. Air-Breathing

Typically for space-bound vehicles, air-breathing engines are not viable. When compared to rockets, their thrust to weight ratio is lower, ˜10:1 as opposed to ˜35:1.[13] A maximum T/W value is critical when trying to escape Earth's gravity well. However, the turbofan engine does use atmospheric air for cooling, combustion, and powering turbines, which reduces required flight mass. It was this idea of using in situ resources that inspired the research into condensing atmospheric air to feed rocket engines. The current SABRE design uses its air-breathing capabilities from sea level to an altitude of 28.5 km due to the intake of a higher density airstream. Unfortunately, the forces produced by the high-density gas impinging the intake at Mach speeds, yields increased frictional heating, and temperatures above the melting points of most metals. To expand the list of useable materials for chamber design, a helium-cooling loop reduces the temperature and pressure. This also allows for the bi-propellant rocket engine to be used both on the ground and in vacuum. Due to the higher density of the air at a lower altitude providing greater oxidizer capabilities, not as much is required. The fixed intake of the nacelle ingests too much air in the lower altitudes, and requires diversion. The excess air is guided through an internal bypass system. The air mixed with hydrogen in a bypass burner, increasing the overall thrust. The bypass system is throttle-able to allow for the most efficient burn. As SKYLON reaches altitude, the internal center body moves forward and three conical frustums are stacked in front of the intake. This closes off the intake nacelle and creates a very aerodynamic surface.[12]

Table 2. SABRE 4 Modes[8]

Mode	Altitude Range (km)	Mach No. Range	Approx. Gross Thrust (MN, per nacelle)	Approximate Specific Impulse (Ns/kg)
Air-breathing	0-28	0-5.5	0.8-2	40,000-90,000
Rocket	28-90	5.2-27.8	2	4500

B. Rocket Propulsion

When the SKYLON vehicle reaches Mach 5 and an altitude of 28.5 km, it has reached a point where the condensed atmosphere doesnt meet the needs of the core rocket engine. As previously stated, the intake of the nacelle closes up and the liquid oxygen tanks supply the engine. This mode is used through the rest of the mission until orbit and descent. During orbit the SOMA and reaction engines are used for correctional maneuvers, and in descent, the vehicle is converted to a glide-to-land configuration.[8] The tables below detail the capabilities of the SABRE engine, and make a comparison of the SABRE engine to other LEO-bound vehicles.

Table 3. Single engine comparison

	SABRE[11]	Orion 50S (XL)[17]	SSME[18]	RS-68[20]
Thrust (MN)	2	0.7	1.8	3.4
Isp (vac)	450s	295s	453s	409s
Fuel	LH2	Solid	LH2	LH2
Oxidizer	LOX	Solid	LOX	LOX
Modes	Air Breathing/ Rocket	Rocket	Rocket	Rocket
Mass (mT)	15	–	3.2	6.7

C. Components

1. Intake

The stagnant intake has been sized to consume enough air in the end of its air breathing capabilities (Mach 5 and 28.5 km altitude). However, this means that during lower velocity and altitude flight, the intake allows for too much air to come through. Bypass chambers direct extra flow around the core inside the nacelle to a special burner chamber. These chambers are able to expand to capture more overflow or close towards the end of air breathing flight. The intake also contains cowls to reduce the speed of the incoming air so that it can be more efficiently cooled.[11]

2. Precooler

Since the stagnation temperature of the Mach 5 intake air can be in excess of $950°C$, a pre-cooler is required to reduce the overall power necessary to run the compressor. Cooling the incoming air decreases the energy state of the gas, and allows it to be compressed more easily. The pre-cooler uses a helium loop to remove the heat from the air, and then transfers that heat to the hydrogen fuel loop.[11]

3. Turbo Compressor

This high pressure-ratio compressor (150:1) is what feeds the rocket combustion chamber. It allows for in situ resources use of air in the rocket instead of carrying more liquid oxygen up during launch. The compressor increases the pressure of the gas to just below liquid level. Doing this does not compromise the burn characteristics of the rocket, and reduces the amount of energy needed to be put into the compressor system. It also helps to protect the material from degrading faster due to the higher pressures. The heated hydrogen from the pre-cooler is fed into a turbo pump to drive the air turbo compressor, resulting in a higher efficiency system.[1,11]

4. Pre-Burner

The pre-burner in the SABRE system has a slightly different function than that in a typical liquid propellant engine. Instead of the output powering the turbo pumps or compressors in the upstream, it instead gives additional heat to the helium loop feeding the turbo machinery. After some of the heat is removed from the pre-burner output, it is fed into the combustion chamber for further burning since the mixture is always fuel-rich.[1]

5. Helium Circulator

The innovative cooling for the incoming air is provided by a helium loop, instead of the commonly used hydrogen. Helium acts as an intermediate thermal buffer between the extremely hot air and the cryogenic liquid nitrogen, reducing material embrittlement failure. After the helium cools the intake air to $-250°$C, it travels past the output of the pre-burner to absorb more heat, and then drives the liquid oxygen turbo pump and drives the turbo compressor for the intake air. Any of the remaining energy left in the helium as energy is removed by running the helium past a cooler loop of hydrogen. After the nacelles are closed and SABRE is converted to a conventional rocket engine, the leg powering the turbo compressor is turned off and only the liquid oxygen turbo pump is powered.[1,12]

6. Bell Nozzle & Thrust Chambers

SABRE currently employs conventional bell nozzles in their design, but has left the possibility open for an extendable nozzle for greater efficiency in higher altitude flight. The chamber also encounters a unique problem with cooling, since the hydrogen loop is already used for cooling the helium loop. Instead, film cooling with compressed air is used during the air-breathing portion of flight. When in rocket mode, this is switched to a liquid oxygen loop fed through a coil around the nozzle.[1,8]

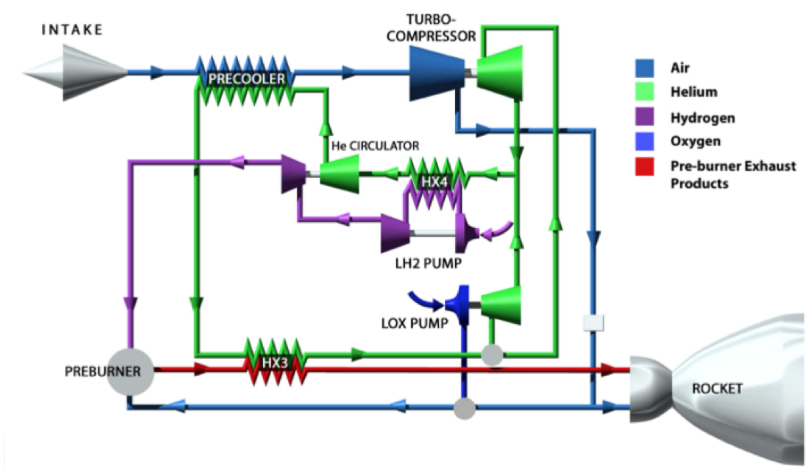

Figure 7. SABRE system schematic[11]

D. Heat Exchanger

In order for the liquid rocket engine to use atmospheric air as a source of oxygen, it has to be compressed to just above the vapor pressure of air. Trying to compress a hot gas into a liquid is inherently more difficult than compressing a cool gas due to the amount of heat energy that needs to be overcome. If the gas is cooled first, the compressor doesn't have to work as hard. It also allows for the SKYLON vehicle to accelerate from rest without a separate launching system. This is the logic behind including a pre-cooler loop in the SABRE design. In the following section the requirements and design constraints, technology overview, and a brief heat transfer example will be presented.

1. *Requirements and Design Constraints*

Engine components were sized so that the SABRE system would be most efficient at 28.5 km in altitude and Mach 5 flight. This meant that braking the incoming air speed from 1.7 km/s to 0 km/s would greatly increase the temperature of the system to ˜$950°C$. During the compression cycle this temperature would further increase, possibly causing structural damage to the compressor (for example, the melting point of Inconel 718 is ˜$1350°C$). The cooling system allows for the gas to be safely compressed to just before liquid form. Direct exposure of the hot air to a loop cooled by liquid hydrogen was considered for mass savings as hydrogen is already an on-board propellant. This idea was dismissed for two reasons, it is not safe to flow the oxidizer over tubes of fuel and the temperature gradient between the two chemicals ($950°C$ to $-250°C$) would cause thermal stress to the tubing matrix and cause possible material failure. Placing a helium buffer loop between the two chemicals allows for a thermal step. The exact temperature of the helium has not been reported, but the pressure of the flowed chemical is 200 bar. Helium was selected because of its inert properties, and its ability to reach both the hot air and liquid hydrogen temperature regimes without changing phase.[15]

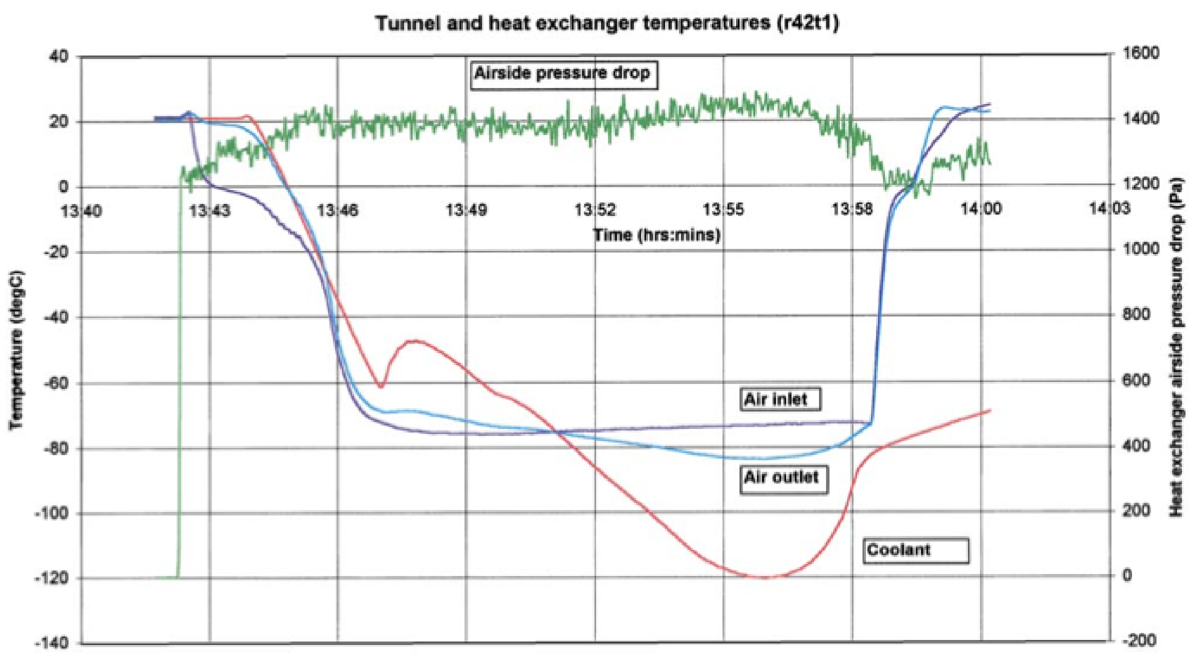

Figure 8. Heat exchanger temperatures[16]

Some of the issues concerning previous designs were rooted in the very low gas temperatures the compressor requires. The previously discussed material embrittlement has been reconciled by using a helium buffer loop to reduce the temperature gradually, reducing thermal stress on material. The other issue stems from cooling the constituents of the intake air. Since atmospheric air is being used, it inevitably contains some moisture. Cooling the moisture will nucleate it into ice particles, which will adhere to the cooling loop matrix and reduce the airflow capabilities. Figure 8 shows that the current pre-cooler configuration is able to operate in 100% humidity, varying inlet air and coolant temperature to reflect inflight parameters for approximately 13 minutes without a pressure flux. This is 3 times the required time of 4 minutes without a pressure drop.[16]

2. Technology Overview

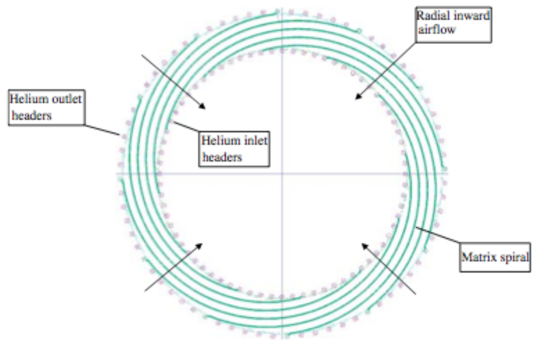

Figure 9. Pre-cooler flow diagram.[16]

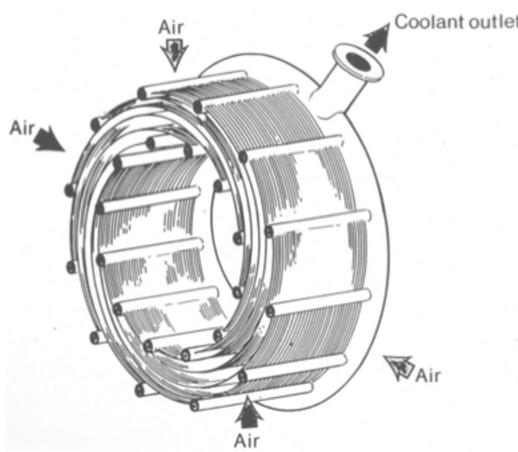

Figure 10. Pre-cooler Prototype.[15]

In the designed cooling helium loop, both the pre-cooler and the HX3 system have the same goal, dump as much heat into the passing helium as possible. HX3 is the post pre-burner heat exchanger that adds more heat to the helium loop to keep the temperature constant. Both systems are cross flow heat exchangers, a very space-efficient way to heat or cool liquid. Figure 9 shows the flow diagram for the pre-cooler and figure 10 shows a picture of the pre-cooler prototype. The cooled helium swirls around the matrix helix in 1 mm inner diameter Inconel 718 tubes. The tube wall thickness is only 25 μm, allowing for near negligible conduction across the wall. In order to reduce pressure loss through the tubes, they are only ˜2.2 m in length. These thin long tubes are then laid in panels and overlapped to give the air flowing through more surface contact with the cooling helium. The HX3 system ensures that the helium exiting the pre-burner loop is at a constant temperature to power the main turbines. The constant temperature is necessary to ensure stable operating conditions. Since the output of the pre-burner is an oxygen-rich mixture (condensed air during air-breathing), non-reactive and temperature-resistant materials needed to be used. Silicon carbide was selected as the best material due to its high thermal conductivity. A reaction bonding process has also been developed since the complex internal geometry has a major pressure gradient across the cooler (200

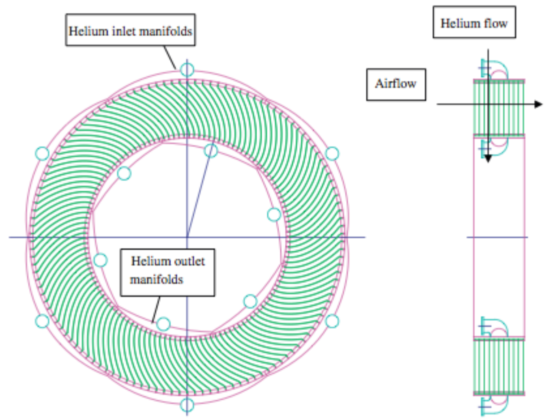

Figure 11. Helium flow in pre-cooler.[16]

bar to 0.5 bar) and required a very resilient material. This is also why the flow of helium is radially inward, to use the compressive strength of the material to its advantage, see figure 11.

3. Heat Transfer Example

Using the given parameters from design documents, the amount of heat energy removed from the air gas stream, at Mach 5, before it is compressed is calculated below.

$$T_{aI} = 1223K$$
$$T_{aO} = 123K$$
$$\dot{m}_{air} = 382\ kg/s$$
$$c_{pa} = 1.1\ kJ/kgK$$

Where T_{aI} is the temperature of the stagnate intake air, T_{aO} is the temperature of the intake air after passing through the helium cooler, $\dot{m}_{air}$ is the mass flow rate of air through the system, and c_{pa} is the specific hear for the intake air. c_{pa} was averaged between the c_p of air at $1200K$ and the c_p of air at $120K$. Using:

$$\dot{Q} = \dot{m}_{air} c_{pa} (T_{aI} - T_{aO}) \tag{1}$$

We find that the cooling loop removes

$$\dot{Q} = 462,220kW \tag{2}$$

This shows that ˜460 MW of energy is removed from the air before being compressed. If this energy is not removed by the helium loop, the compressor will have to overcome this energy by pumping harder to get it into the semi-liquid state. Instead of this massive amount of energy going to waste, it will power turbo pumps and compressors in the vehicle.[14]

IV. Discussion

A. Structures

SKYLON has several difficulties to overcome if it is to be successful. The titanium reinforced with silicon carbide fibre frame poses some difficulties for manufacturing. It was noted that due to the high stress and thinness of the material the manufacturing process is prone to defects.[9] The effects of these defects has been determined to be tolerable but is still subject to ongoing investigation. This material has a high manufacturing cost and REL is currently investigating methods to drive down cost.[9] Another manufacturing issue that will need to be addressed is the System2 aeroshell material. As mentioned earlier this material was taken out of production and the means to faithfully, and reliably, recreate the material must be developed. A suitable supply chain must be established as well to ensure enough of the material may be produced in a timely manner to meet initial and future operational needs.

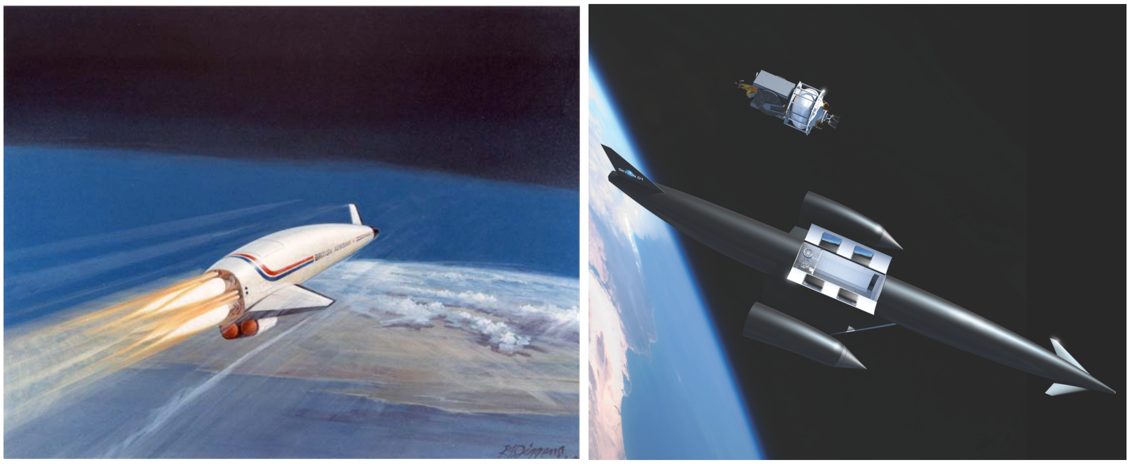

Figure 12. Artist rendering of HOTOL RD1 concept and SKYLON version D-1[1,8]

B. Trim and Payload

The HOTOL project revealed large issues with center of pressure shifting ahead of the center of gravity for this class of vehicles as speed increases, putting the vehicle into an out of trim condition.[8] SKYLON aims to relieve this issue through control of aerodynamic shape and mass distribution. SKYLON has mounted the wings to the middle of the frame as compared to the original HOTOL design with delta wings that extended to the aftmost section of the spaceplane as seen in figure 12. The original HOTOL designs also placed the engines at the aft end of the craft while SKYLON designs have placed them midway on the wing-tips. The current design to account for the mass distribution problem is for differential hydrogen burn-off between the fore and aft tanks as well as coordinated payload placement. The payload bay is centered directly between the wings and top loading. It has forward and aft mounting points 3 m from the ends of the bay. In light of the center of gravity versus center of pressure constraints mentioned above the forward mounting point is used preferentially. This configuration will lend to payloads being loaded facing the back of the vehicle and experiencing negative longitudinal accelerations. This will be an important design factor to consider for those who wish to use this platform for orbital delivery.

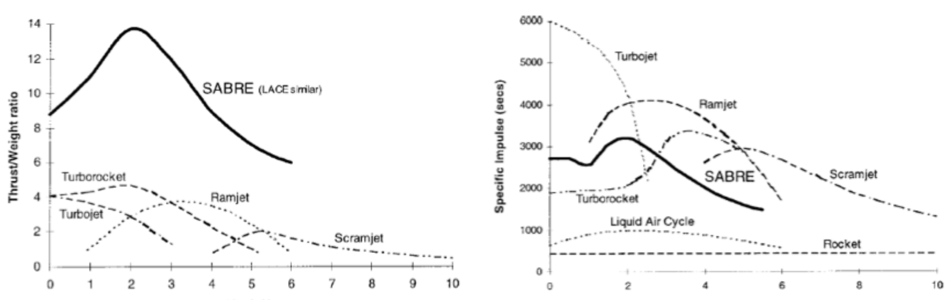

Figure 13. SABRE comparisons to other classes of engines.[11]

C. SABRE

As seen in figure 13, when compared to other supersonic propulsion choices, SABRE consistently has the highest thrust to weight ratio per Mach number while in air-breathing mode. It has a higher specific impulse than most rocket engines and the previously evaluated LACE. These two positive specifications indicate that the SABRE system is appropriate for SSTO operation.

D. Preliminary Heat Exchanger Testing

In the mid 2000's REL was able to test an integrated, full-size pre-cooler including frost control (Figure 14). A Rolls Royce Viper served as the propulsion system being cooled. While the cooling loop ran on liquid nitrogen instead of liquid hydrogen, it was stated that this was an appropriate surrogate heat sink. This was due to the large amounts of liquid nitrogen on site.The pre-cooler was able to work below 100°C for over 5 minutes. The test included over 200 test runs, and the pre-cooler operated with great thermo-mechanical integrity throughout all test. While the test was deemed complete, the facilities and pre-cooler modules are still available for more testing.[9,12]

Figure 14. Full sized pre-cooler on the test stand.[9]

E. Launch Vehicle Comparison

Table 4 provides comparisons of the SKYLON concept to the Pegasus XL, Space Shuttle and Delta IV M+(4,2). The Pegasus XL is an multi-stage expendable launch vehicle, operated by Orbital Sciences Corporation, that is launched from a L-1011 Stargazer Aircraft. The Space Transportation System, colloquially known as the Space Shuttle, was used by the United States as a partially reusable primary space access vehicle from 1981-2011. It consists of an orbiter, external fuel tank, and two solid rocket boosters. The Delta IV is a work horse expendable multi-stage launch vehicle operated by the United Launch Alliance. It has many different configurations, we choose to highlight the medium+ (4,2) as this has a published mass to LEO comparable to that promoted by SKYLON.

SKYLON launchpad mass is estimated as close to that of the Delta IV M+ (4,2). Both of these are an order of magnitude less than the Space Shuttle mass and an order of magnitude larger than the Pegasus. The Space Shuttle was capable of taking the greatest payload mass to LEO, of the launch systems compared here. The Pegasus XL can take the least mass to LEO. Of the four types of launch vehicles the SKYLON is estimated to have the largest payload mass fraction. The Delta IV M+ is the second largest and then Pegasus

Table 4. **Performance comparison to other launch vehicles**

	SKYLON D-1[8]	Pegasus XL[17]	Space Shuttle[18,19]	Delta IV M+ (4,2)[20]
Launchpad Mass (mT)	270	23	2040	290
Mass to LEO (mT)	15	0.4	25	12.5
Payload Mass fraction to LEO	0.056	0.017	0.012	0.043
Staging	N/A	3 serial	2 parallel SRBs	2 serial 2 parallel SRBs
Launch Cost (Million $)	9.5 - 132	11	450-1500	80

and Shuttle are much less. SKYLON operational costs are estimated at $9.5 million for 70 flights a year.[1] We extrapolated this to $132 million for 5 flights a year to compare with more standard launch schedules. This is much higher than the Delta IV M+ (4,2) but still less than the final Space Shuttle costs. Direct comparison with the Space Shuttle is difficult as the Shuttle was human rated and designed for a different mission set. The quoted values for SKYLON are estimates from cost models that have been independently checked,[1] but still must be taken with caution. At high operational tempo, 70 missions per year, the SKYLON costs are estimated to be as low as that of the Pegasus XL. The lifetime of a SKYLON vehicle is designed for 200 missions with a nominal mission duration of 2 days. The nominal ground operations call for three vehicles located at the spaceport to facilitate high turnover rate between missions.

V. Conclusions

The SKYLON spaceplane is one of the latest in a line of SSTO concept vehicles that have been designed in parallel with expendable vehicles since the 1980s. This progression has slowly refined the designs and homed in on more feasible designs. The SKYLON design has been deemed technologically and economically feasible by ESA.[1] Feasibility does not tell the full story. There will be many challenges ahead for REL. First in successfully testing a full scale version of the SABRE engine. This in and of itself will be a large achievement and will add to the overall advancement of SSTO vehicles by demonstrating the ability to combine different operating modes into a single engine for considerable mass savings. The SKYLON spaceplane will have key challenges in materials manufacturing, specifically in the construction of the primary structural frame and the aeroshell. Establishing these manufacturing abilities and supply lines will require special attention and set backs could drive up cost quickly. Building ground operations from scratch will also require significant start up costs. As of the ESA review the entire program is estimated to cost $12.3 billion. This demonstrates one of the difficulties that SSTO vehicles have experienced compared to expendable vehicles throughout the history of spaceflight. Namely, the development cost is typically higher than that of expendable vehicles and the reusability cost savings are considered too unreliable or far-off to be competitive. The extensive replacement and recertification above what was originally anticipated for the Space Shuttle has only added to this. That being said, the SKYLON spaceplane, and the SABRE engine in particular, is still an important avenue to pursue to further develop alternative technological avenues to transport equipment to space. Reusability is currently being sought after by the major launch companies of SpaceX and ULA in the form of stage recovery. An alternate paradigm of entire vehicle reusability will help drive innovation and enable a future where achieving orbit will be a much more routine occurrence.

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