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PROGRESS ON SKYLON AND SABRE

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The Synergetic Air-Breathing Rocket Engine (SABRE) engine is comprised of state-of-the-art jet engine and rocket technology combined in a novel cycle with light-weight heat exchanger technology. Reaction Engines Ltd is gaining momentum programmatically and technically towards the first ground based demonstration of the SABRE air-breathing cycle. The SABRE engine development programme has transitioned from key technology demonstration into the design and development phase of the SABRE engine. The focus of the activities are now towards the ground-based air-breathing cycle demonstration and the engine test programme. The accomplishments over the last two years include completion of the Preliminary Requirements Review (PRR) and successful test firing of the novel rocket combustion chamber and nozzle for use in both the engine's air breathing and rocket modes. The SABRE Engine is designed to enable the realisation of the SKYLON spaceplane. SKYLON is a reusable singe stage to orbit spaceplane that can take off from a runway to reach a 300 km altitude low earth orbit with a payload of 15 tonnes and then return to Earth for a runway landing. This paper summarises the recent technical and programmatic accomplishments, as well as the programme's future activities to progress the design and development of both SKYLON and the SABRE engine

Keywords: SKYLON, SABRE, Heat Exchangers

1. INTRODUCTION

For 30 years there has been activity in the United Kingdom to realise the vision of a single stage to orbit launch system using combined cycle engines that work in both air-breathing and pure rocket modes. This activity started in the 1980's with the British Aerospace / Rolls-Royce HOTOL project using the Rolls-Royce RB545 engine that had been invented by Alan Bond. Whilst the project was not pursued at this time, for various reasons, the HOTOL study had established that the use of combined cycle engines with an aircraft like airframe is a technically realistic proposition.

Despite the decision to discontinue with the development of a single stage to orbit launch system in the 1980's, the concept was progressed by Alan Bond, and two engineers, Richard Varvill and John Scott-Scott, who founded Reaction Engines Ltd. The concept was evolved further by the team to overcome the technical problems incorporated in the HOTOL project, from which the SABRE (Synergetic Air Breathing Rocket Engine) propulsion system was created. The company has continued airframe work with the SKYLON spaceplane to ensure the joint advancement of the propulsion system and vehicle, however the company's main focus is on the development of SABRE.

In 2013 the SABRE engine key technology validation programme successfully demonstrated the heat exchanger technology at the heart of the SABRE engine cycle; the pre-cooler. This technology will enable the air-breathing operation at vehicle speeds of Mach 5. From that point onwards, the company has been advancing the design of the engine and continuing with the development of other key technology areas in the engine.

2. SABRE

The SABRE engine (Figure 1) enables a reusable transportation vehicle, SKYLON, to achieve low Earth orbit. It is this engine that enables SKYLON to fly at over Mach 5 and an altitude of 25 km while air-breathing which greatly reduces the burden on the subsequent less fuel efficient rocket phase of the ascent trajectory to low Earth orbit. It means the mass

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fraction required to reach orbit is 22% compared with 13% for an equivalent pure rocket system.

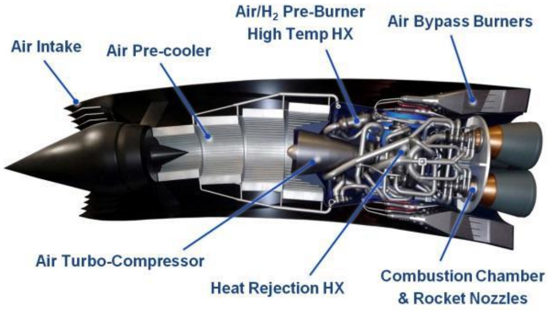

Figure 1: The SABRE 3 Engine

The SABRE 3 engine cycle shown in Figure 2 uses sub-cooled liquid hydrogen as its fuel and sub-cooled liquid oxygen as the oxidiser in rocket mode. In rocket mode the engine operates as a closed cycle high performance rocket engine. In air-breathing mode the liquid oxygen flow is replaced by atmospheric air. The airflow is drawn into the engine via an axisymmetric intake and is cooled to cryogenic temperatures by a pre-cooler heat exchanger. The Pre-cooler heat exchanger is part of a closed cycle helium loop using the hydrogen fuel as the heat sink before it enters the combustion chamber. After cooling the air is compressed and fed to the combustion chamber.

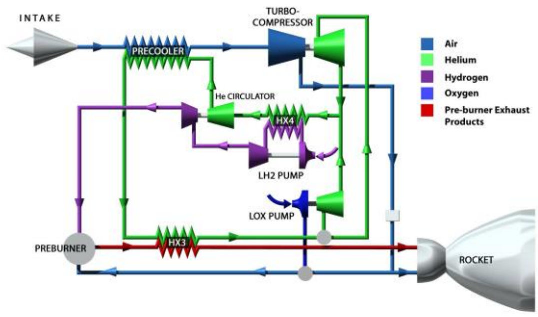

Figure 2: The SABRE 3 Engine Cycle

During the Technology Development Programme the knowledge gained from nearly 20 years of work on the engine led to the evolution of an improved cycle; SABRE 4. This configuration improves the efficiency of the air breathing phase, and will be discussed in Section 4.

3. SABRE DEVELOPMENT PROGRAMME

The SABRE technology development activity falls into three phases. Up until 2009 technology development was undertaken through separate projects each addressing a specific issue, and each independently funded. Information on the status of the programme in 2008 can be found in Reference 1. In 2009 a programme called “Experimental Investigation of Key Technologies for a Turbine Based Combined Airbreather Rocket Engine” was started. This programme was mainly funded by private investment but also supported by the UK Subscription to the European Space Agency. The purpose of this phase of the programme was to advance all the engine technologies to the point where they could be used with confidence in an engine design and development programme and this goal has been successfully been achieved with regards to the SABRE 3 engine.

In 2013, the final stage of the concept validation phase was completed with the successful testing of a full scale section of the pre-cooler heat exchanger.

The current phase of the programme has the primary objective of advancing the system engineering and design of the SABRE engine together with the associated requirements definition. This phase includes engine system design, manufacturing process improvements for the heat exchangers, the design of a long life rocket chamber demonstrator, the design and test of an altitude compensating integrated nozzle concept, intake development and associated testing and supporting studies for the SKYLON vehicle. As part of this phase, the team have successfully completed the Preliminary Requirements Review (PRR) with the European Space Agency (ESA) and are currently progressing towards the System Requirements Review (SRR).

The next phase will continue the engine design with many of the preliminary sub-system designs being significantly advanced. Further technology development will be undertaken, this time with an increased emphasis on unit testing in order to advance the technology readiness of the various engine sub-systems.

Subsequent phases of the programme will take the SABRE development engine to Critical Design Review (CDR). This will include the manufacture and assembly of a ground based air-breathing cycle demonstration engine.

4. SABRE 3 vs. SABRE 4

During a period of evaluation of the payload requirements of SKYLON, it was determined that the Low Earth Orbit (LEO) payload requirement should be 15 tonnes rather than the previous 12 tonnes.

The SABRE 3 engine maximised common hardware, in particular, the rocket and air-breathing modes of the engine had a common combustion chamber and nozzle throat. This results in a very high air-breathing combustion pressure (103bar) and high equivalence ratio (2.8) with a low exit temperature from the pre-cooler necessitating frost control. This results in a low mass engine but relatively high fuel consumption.

The SABRE 4 (Figure 3) engine however employs a dual throat nozzle which decouples the air-breathing and rocket combustion chambers resulting in a reduced fuel consumption. The penalty incurred is the provision of two, almost separate, engines sharing a common nozzle with the consequence of increased mass, parts count and cost. However, the programme challenges are reduced as the air-breathing and rocket engines are now separate and can be developed independently. Also, due to the higher pre-cooler exit temperature compared to SABRE 3, the frost control system is no longer required. The frost control system employed on the SABRE 3 engine enables the cooling of the incoming air to minus 150°C without the build-up of ice on the pre-cooler. The frost control concept was presented at the 2015 AIAA conference (Reference 2).

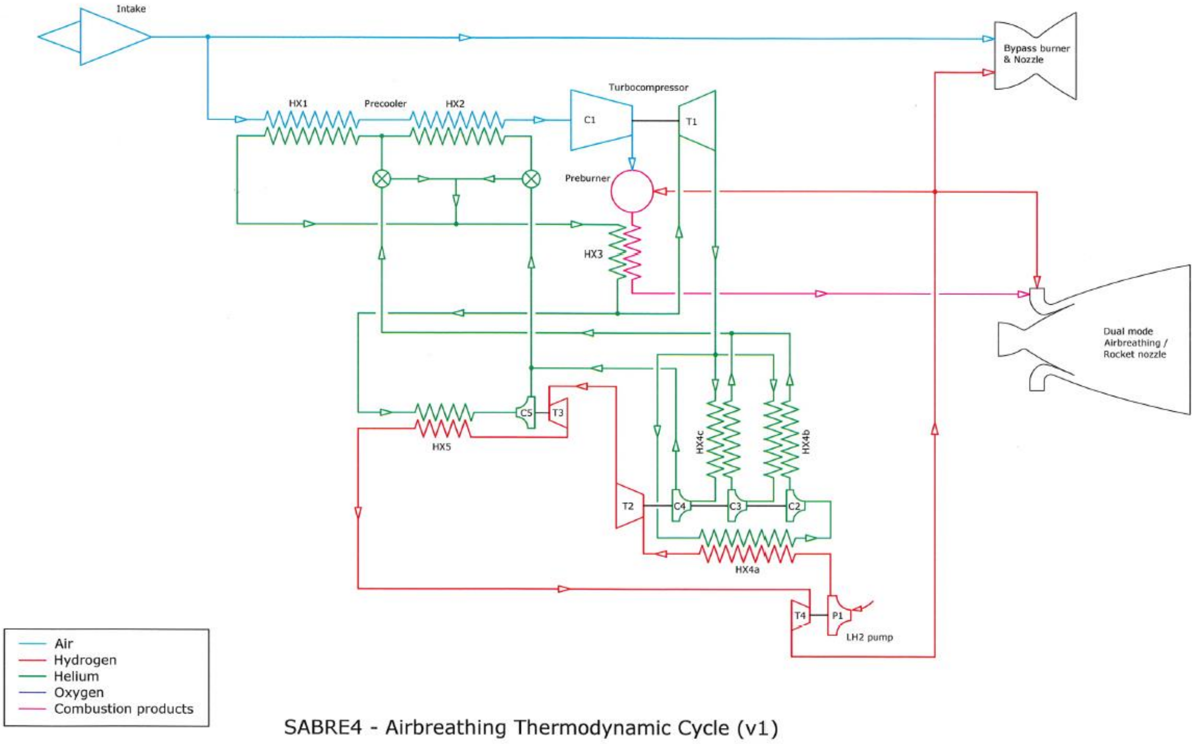

Figure 3: SABRE 4 Engine Cycle

5. SABRE TECHNOLOGY DEVELOPMENT

The current phase of the project has a strong focus on technology development alongside the system and sub-system designs of the SABRE engine.

5.1 Intake Development

Design of the intake has progressed and will be supported by testing later this year. Two separate test programmes are planned; a supersonic windtunnel test programme and a subsonic part-scale test programme.

The supersonic intake test programme will be conducted in partnership with Bayern-Chemie GmbH and Gas Dynamics Ltd., using the DLR's TMK trisonic wind-tunnel at Cologne and GDL's impulse flow facility. Five intake concepts will be compared across a range of Mach numbers at on- and off-design incidence angles in the first round of tests at the TMK facility, and then down-selected over two subsequent sets of tests to the two most promising concepts. GDL's facility will provide subsequent tests at Mach 3 and Mach 5 for select intake concepts, providing datasets that will enable both cross-facility performance validation, and data on the importance of accurately simulating the split in air flow streams between the core engine and the nacelle bypass. These tests will ultimately result in a full intake performance dataset across the entire air-breathing flight speed range, enabling the down-selection to a single baseline concept, as well as in-house design code validation.

The subsonic testing will be looking at the flow distribution and pressure loss of the intake internal flow passages and the effects of downstream flow conditioning devices. Reaction Engines have modified their existing pre-cooler test facility, which uses a Viper jet engine to draw air through the new test article.

5.2 Pre-cooler Manufacturing Development

Reaction Engines completed a successful test programme of a Pre-cooler module in 2013. The demonstration Pre-cooler used flight representative heat-exchanger modules (Figure 4) that were produced in a prototype manufacturing facility. This proved the manufacturing feasibility of the heat exchangers.

Figure 4: The integrated test Pre-cooler

The Pre-cooler was tested in a special facility (Figure 5) that employed a Rolls-Royce Viper jet engine to draw air through the heat exchanger at the correct flow rates.

Figure 5: The Pre-Cooler on the test stand

Following on from the successful test programme, the next phase of the Pre-cooler development is improving the manufacturing processes to meet the cost and weight requirements for the SABRE engine. As part of this activity, Reaction Engines are currently commissioning a new state-of-the-art vacuum furnace.

Figure 6: The Consarc High temperature vacuum furnace installed at the Reaction Engines facility in Oxford, UK.

The furnace has an internal diameter of nearly 3m, and a total internal volume of 25m^3, enabling it to manufacture the full-scale SABRE Pre-cooler modules which will be validated over the course of the SABRE Engine Demonstrator Programme.

5.3 Nozzle Test Programme

The SABRE 4 engine requires a novel design of the rocket engine's thrust chamber and nozzle to allow operation in both air-breathing and rocket modes, as well as having a smooth transition between the two. The Advanced Nozzle project has been demonstrating the feasibility of this concept and represents a significant technology development effort towards the development of the SABRE engine.

The test engine incorporates several new technologies, including a 3D printed, actively cooled propellant injector, see Figure 7.

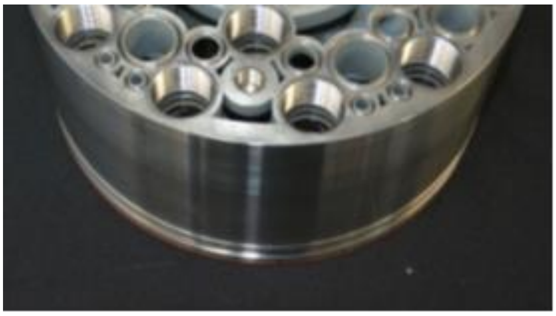

Figure 7: 3D printed injector system for the Advanced Nozzle Project

The test engine has been successfully fired over 30 times since commissioning in spring 2015, Figure 8. The aerodynamic data collected from the firings is being used to validate in-house computational modelling and verifying the flow stability and expansion efficiency.

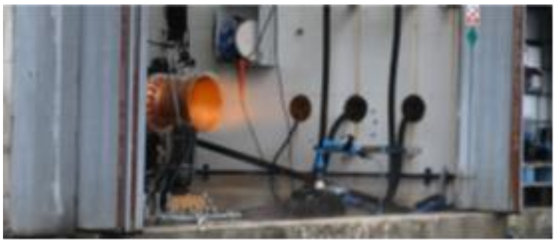

Figure 8: Image during testing of the SABRE Advanced Nozzle at Airbourne Engineering Ltd., Westcott, UK

Operations are planned to continue throughout 2015, including long duration burns and tests investigating the transition between air-breathing and rocket operation planned for later in the year.

6. SKYLON

6.1 History

The status of SKYLON and SABRE in 2013 was reported at the 64th IAC in Beijing (Reference 3). This paper presented a full summary of the design evolution and all the supporting technical work going back to the origins of the programme. At that time the key work was to finalise the definition of a new SKYLON configuration called D1 which used the SABRE 4 engine, whereas the earlier C1 configuration had used the SABRE 3 (Figure 9).

The Configuration D1 was used as the basis for a study conducted for the European Space Agency (ESA) Launcher Directorate into the use of SKYLON to meet the requirements of the next European launch system. The study was conducted in 2013 and 2014 and was called “a SKYLON based European Launch Service Operator (S-ELSO)”. The study results were reported in two papers at the 65th IAC in Toronto 2014 (References 4 and 5). The S-ELSO study confirmed that SKYLON combined with a reusable Upper Stage (SUS) was an effective means to launch the payloads anticipated by the ESA future payload model. Most importantly, it was shown that a system operational by the early 2020s could launch satellites in the 6.5 tonne class into geostationary transfer orbits.

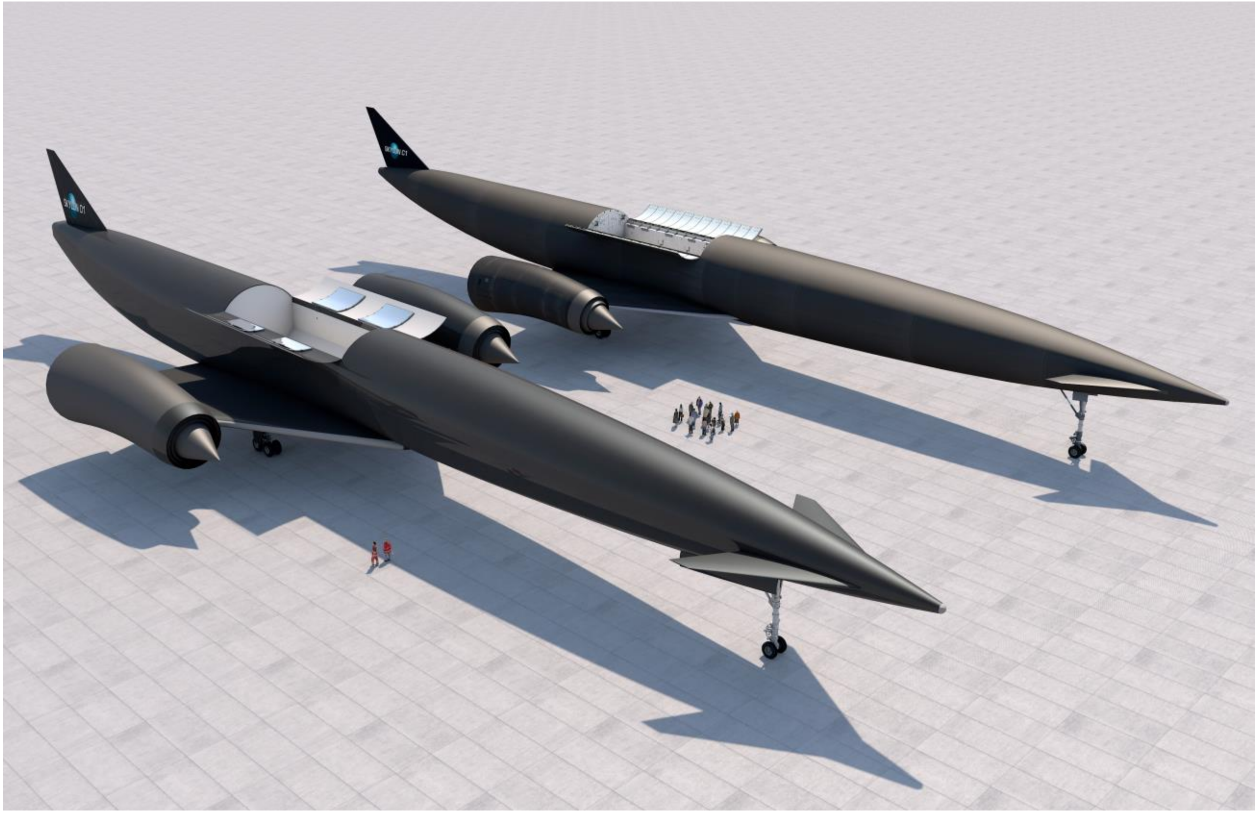

Figure 9: SKYLON D1 (left) and SKYLON C1 (right) Configurations Compared

6.2 Current Status

In the autumn of 2014 the SKYLON system was placed under formal change control process; a change control board has been established and all of the requirements have been moved from paper specifications to a computer based requirements tracking programme. The formal tracking of requirements was a necessity for the SABRE design and development programme so the inclusion of SKYLON was to provide a customer context for the SABRE engine development. From this the specifications and interfaces for SABRE could be generated with confidence since they were related to a realisable and commercial viable end product that could meet the market for space launch systems.

The formal change control process was also required to enable compliance with the emerging certification requirements.

The board consists of members of the Reaction Engines System engineering team and ESA personnel representing the customers' interests.

6.3 The Skylon Upper Stage

The SKYLON Upper Stage (SUS) is intended to extend SKYLON's LEO capability by placing payloads into higher orbits than 600km. After SKYLON reaches LEO the SUS will be removed from the payload bay and manoeuvred to a safe distance before igniting its main engines. After deploying its payload the SUS will in most cases return to rendezvous with SKYLON for retrieval and reuse. However for exceptionally large payloads or at its end of life the SUS could be used expendably. In 2014 a new design for the SUS (Configuration C1) was developed by Reaction Engines (Figure 10). This design is shorter and lighter than previous versions increasing the allowable payload length from 4.4m to 8.6m and the reusable mode GTO payload from 6387kg to 7259kg. In addition a lightweight interchangeable payload mounting and docking system has been proposed to attach the payloads to the SUS, and the SUS to SKYLON. This permits multi-stage missions and payload recovery (an operational capability unique to reusable transport systems).

In parallel with the Reaction Engines design an alternative SUS configuration is being explored by Hempsell Astronautics Ltd utilizing a different approach to the payload and Skylon mounting interface.

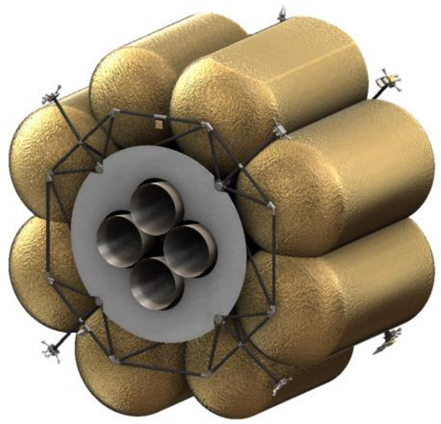

Figure 10: Illustration of the SKYLON Upper Stage (SUS)

6.4 Mission Analysis

The system performance of the SKYLON D1 with its SABRE 4 engine has been extensively modelled with in house mission analysis software to track the impact of any changes as the SABRE 4 engine design evolves. It also provides a comparison for the performance of SKYLON with a SABRE 3 engine.

Although the required performance for SKYLON is specified as a 15 tonnes payload to a 300km circular orbit from an equatorial launch site the modelling uses a “standard mission” from a launch site at a latitude of 5.2 degrees corresponding to the CSG spaceport at Kourou, French Guiana. The altitude versus time graph for the powered ascent trajectory until Main Engine Cut off is shown in Figure 11. This trajectory leaves SKYLON in a 90 km by 300 km elliptical orbit, which is circularised at apogee using the orbital manoeuvring engines.

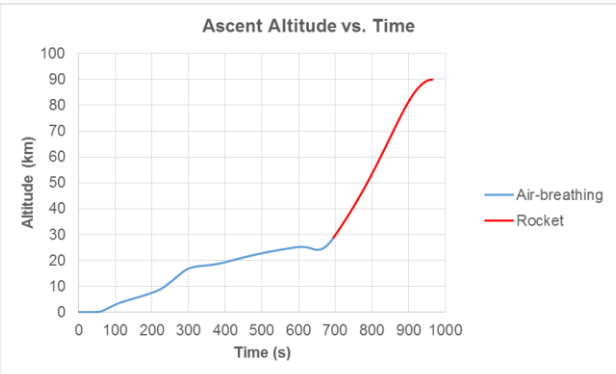

Figure 11 SKYLON Standard Mission Ascent Altitude Vs. Time

These mission analysis studies confirmed that SABRE 4’s air-breathing performance improvements more than compensate for its increased mass, resulting in an overall payload improvement. The sensitivity of take-off thrust to weight ratio was also explored and it was found that the performance was surprisingly insensitive to moderate changes. This gives some scope to alter the vehicle take off mass after the engine thrust has been fixed.

The performance to very low orbits has also received more attention than in past SKYLON performance studies. This was a consequence of the results of the S-ELSO study which showed the potential increase in performance in Geostationary Transfer Orbit (GTO) missions that a very low deployment could give. It confirmed that SKYLON D1 could place 17 tonnes into a 185 km circular orbit which was required to meet the GTO payload requirements established by the European Next Generation launcher initiative.

The mission analysis activity has been extended to consider various possible missions of the SUS. First as a verification of delivered payload to GTO and secondly to prove it can be synchronised with SKYLON to enable its return. In these cases the result of the Reaction Engines in house codes have been checked using NASA’s G-MAT mission analysis software.

Extensive re-entry trajectory analysis has also been conducted to verify the changes in SKYLON D1 compared with C1. The key change from this point of view is that the ballistic coefficient is increased by 15.6% due to heavier engines and smaller hydrogen tanks. Further more detailed consideration of payload centre of mass requirements introduced more constraints on the angle of attack that can be allowed. Both these factors were expected to increase the predicted skin temperatures. However the new modelling also incorporated the results computational fluid dynamics analysis of SKYLON and in practice the resulting temperatures similar to earlier C1 re-entry models.

The return trajectories confirmed SKYLON’s flexibility of touchdown point with a wide range of downrange and cross range available. The vehicle can recover to any airfield with compatible latitude at least 6 times per day from any orbit, and can recover to an Equatorial airfield from a low inclination orbit (less than 40 degrees) on any pass. It was also found that the vehicle is capable of operating from any airfield, overflying any location on Earth, and recovering to the same airfield within a single orbit.

6.5 Technical Support Studies

The programme continues to maintain a series of technology and assessment studies related to the SKYLON airframe. The key areas of recent investigation are of the primary structure and aeroshell material and the electrical harness.

The primary structure consists of a truss framework composing over 50,000 struts made in titanium that is reinforced with silicon carbide fibres. Previous development work established the technical viability but the struts produced were considerably more expensive than the carbon fibre reinforced struts they replaced. The programme is now looking at reducing the manufacturing costs of these struts.

Reaction Engines has produced a finite element structural model of the whole fuselage to refine the analysis of the loads on the struts, to further the optimisation of the primary structure.

The multi-foil blanket that lies between the aeroshell and truss structure has been looked at and a new method of construction devised which makes its integration into the vehicle easier and more reliable. Previously it was assumed that each foil layer would be laid one at a time. The new approach creates the monolithic block of foils and spacers all of which are integrated in one piece.

Development work to refine the ceramic glass / silicon carbide composite material continues.

An examination of the SKYLON power and data harness was started in April 2015. This project was tasked to establish a realistic harness mass for the SKYLON airframe. This follows a late realisation that the mass of the electrical and optical harness is likely to exceed the total mass of the units that it serves, and therefore it is an important component of system viability.

7. CERTIFICATION STUDIES

There is no international agreed process on the safety certification of space systems, each nation doing what it regards as sufficient to meet its obligations under the Outer Space Treaty. However, under the terms of the Chicago Convention on International Civil Aviation, any launch system that at some point relies on wings for lift will require certification from the civil aviation authority of the country from which they operate or over-fly. SKYLON is a spaceplane that flies through the atmosphere and then continues its trajectory under rocket power to reach orbit. Throughout the ascent the vehicle has abort capability, including returning to the launch site or aborting to a single orbit in order to return to the launch site. During the atmospheric (air-breathing) phase which includes aborting back to the launch site, SKYLON acts as an airplane i.e. it uses the wings for lift and therefore meets the ICAO definition of an aircraft/aeroplane (Reference 6),

> *"An aircraft is any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the Earth's surface"*

Hence SKYLON (including SABRE) will adopt a certification approach by a competent Authority. The certification basis (airworthiness requirements) will require all phases of flight to be covered and therefore this includes the space segment with associated space system requirements. This then requires a unique approach integrating air and space requirements with appropriate means of compliance and guidance material.

Reaction Engines are currently working with the UK CAA as well as ESA to derive such requirements that can be verified and validated throughout the development (EASA are currently not resourced for commercial spaceflight activities). The primary focus is certification of SABRE which will be carried out through an incremental approach with sub-system tests, through to ground engine tests and finally to flight test engines.

8. COMPANY EXPANSION

In order to meet the needs for the advancing project Reaction Engines Ltd has grown significantly over the last two years, transitioning from a small to medium sized company. As a result, the team have now moved to larger premises to cater for the current and future staffing demand of the project. Reaction Engines have also developed industrial collaborations in order to draw on the existing industry expertise for various sub-systems of SABRE and SKYLON.

The two manufacturing companies owned by Reaction Engines have also expanded into new premises which will enable the company to manufacture components for rapid technology and sub-system testing over the coming years to support the SABRE engine development programme.

9. CONCLUSIONS

The work being undertaken by Reaction Engines is making significant progress to the advancement of SKYLON and SABRE.

There have been several areas of technology demonstration activities which are due to conclude over the coming year however, it is clear that the project is moving from technology demonstration to engine design and development. This has enabled the project to successfully complete the Preliminary Requirements Review (PRR) and currently work toward the System Requirements Review (SRR).The project is now making significant progress towards a ground-based air breathing engine test programme.

10. ACKNOWLEDGMENTS

The work described in this paper was carried out by the entire Reaction Engines Ltd. team and its consultants.

11. ABBREVIATIONS

ACR – Alternative Concepts Review
ESA – European Space Agency
EASA – European Aviation Safety Agency
GSTP - General Support Technology Programme
LEO – Low Earth Orbit
PRR – Preliminary Requirements Review
S-ELSO – Skylon Based European Launch Service Operator
SRR – System Requirements Review
SUS – Skylon Upper Stage
UK CAA – United Kingdom Civil Aviation Authority

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6. Annex 8 to the Chicago Convention