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PROGRESS ON SKYLON AND SABRE

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SKYLON is a reusable single stage to orbit spaceplane that can take off from a runway reach a 300 km altitude low earth orbit with a payload of 15 tonnes and then return to Earth for a runway landing. The unique feature of SKYLON that enables it to achieve this objective is the Synergistic Air-Breathing Rocket Engine (SABRE) which has both air breathing and pure rocket modes. The SKYLON development programme has concentrated on the SABRE engines and the component level technology development programme was completed in 2013 with the successful demonstration of a complete pre-cooler system using flight representative modules. The technology readiness has reached the point when the next phase of the development programme has begun. This £250 million programme will demonstrate the technologies in a system complex and take the design of the flight SABRE to CDR. The SKYLON airframe has also been subject of a slower paced programme including a series of technology development projects, mostly centred on the structure and thermal protection system, and a revision of the system design to incorporate the results of both the airframe and engine programmes.

Keywords: SKYLON SABRE Pre-coolers

1 INTRODUCTION

For 30 years there has been activity in the United Kingdom to realise the vision of single stage to orbit launch system using combined cycle engines that work both in airbreathing and pure rocket modes.

This activity started in the 1980's with the British Aerospace / Rolls Royce HOTOL project [1] using the Rolls Royce RB545 engine that had been invented by Alan Bond [2]. The programme was cancelled after the UK Government and Rolls Royce withdrew their support. However before the work was completed the HOTOL study had established that the use of combined cycle engines with an aircraft like airframe is a technically realistic proposition. It also established that many of the design assumptions in the feasibility concept were not the optimum approaches.

To ensure the continuation of this concept Alan Bond and two Rolls Royce engineers, Richard Varvill, and John Scott Scott, founded Reaction Engines Limited. Although the company has continued airframe work with the SKYLON vehicle it has mainly concentrated on the propulsion system, called SABRE (Synergistic Air-Breathing Rocket Engine). The HOTOL studies had shown that the technologies in the combined cycle engine were the biggest risk to the successful vehicle development and concentrating on that area was judged the best strategy to realising the project.

In 2013 the final stage of the technology validation programme was complete for the original SABRE engine concept. This paper outlines the history leading to this point and planning for the next phase leading to the Critical Design Review.

2 THE SABRE ENGINE

The SABRE engine (Fig. 1) [3] has only one purpose, which is to power the SKYLON spaceplane. It is this engine that enables SKYLON to fly to 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 fraction required to reach orbit is 22% compared with 13% for an equivalent pure rocket system.

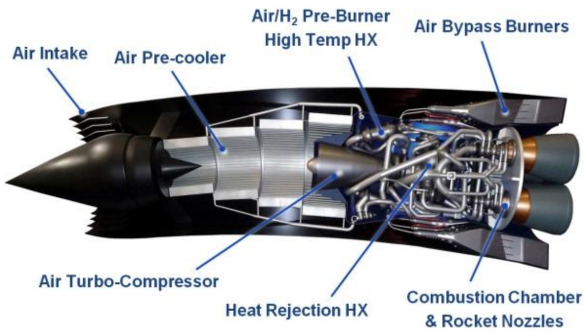

Fig. 1: The SABRE Engine

The SABRE 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.

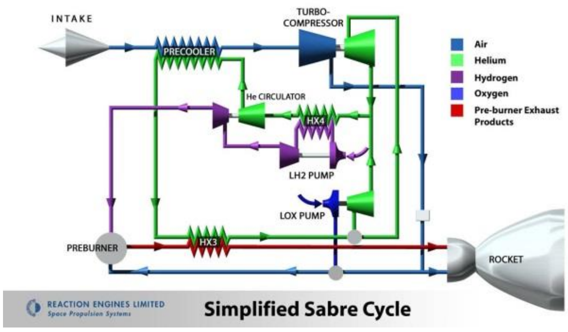

Fig 2: SABRE Cycle

The technology development activity falls into three phases. Up until 2009 technology development was undertaken through separate projects each addressing a specific issue, and each separately funded. The status of the programme in 2008 is summarised in Reference 4. In 2009 a programme called "Experimental Investigation of Key Technologies for a Turbine Based Combined Airbreather Rocket Engine" was started. This programme was jointly funded programme by Reaction Engines and from the UK Subscription to the European Space Agency and was conducted in two phases (Phase 1 and Phase 2). The purpose of this programme was to bring all the engine technologies up to the point where they could be used with confidence in an engine design and development programme. Both Phase 1 and Phase 2 have successfully achieved this goal with regard to the SABRE 3 engine.

During the Technology Development Programme the knowledge gained from the nearly 20 years of work on the engine led to the development of an improved configuration; SABRE 4 [5]. This configuration improves the efficiency of the air breathing phase. The details of the SABRE 4 remain commercially confidential to Reaction Engines and so a description of the new cycle is not possible here. However it does require some new technologies that were not covered by the Technology Development Programme, so some additional development work is currently on going to bring those technologies up to the same development level as the rest of the engine. That additional work is expected to be completed in mid 2014 when the final decision between SABRE 3 and SABRE 4 will be made, however the current expectation is that it will be SABRE 4 that will be the variant taken forward in the remainder of Phase 3.

3 PRE-COOLER DEVELOPMENT

3.1 Background

The bulk of the technology development activity has focused on the pre-coolers which are required to extract around 400 MWatts of heat from the incoming air to enable it to be compressed to pressures that are suitable for a high performance rocket engine. The extracted heat then provides the energy required to power the engine's compressors and pumps. To make the engine viable, these pre-coolers need to have a mass around 1/50th of the current state of the art in terrestrial applications.

Prior to the Technology Demonstration Programme, all the component level development work had taken been funded by Reactions Engines' private resources and some small UK Government industry grants.

3.2 Precursor Pre-cooler Projects

The following experimental programmes were conducted before the Technology Demonstration Programme and enabled the successful development of the pre-cooler technology required for the SABRE engine. The Pre-cooler research has always been by far the largest activity within REL.

3.2.1 Laboratory Scale Heat Exchanger

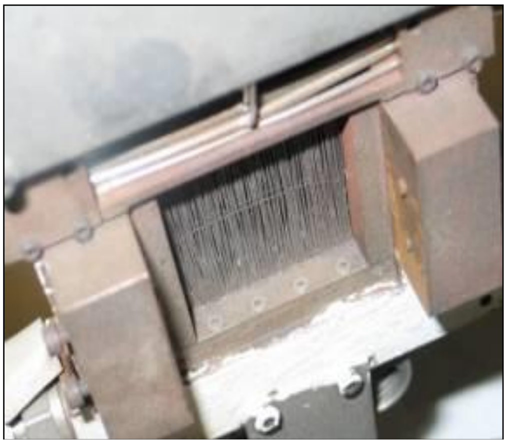

Fig. 3: Laboratory Scale Heat Exchanger

The first successful heat exchanger exploring the concept used by the SABRE engine (Fig. 3) was achieved during a PhD research project at the University of Bristol in the 1990s. It successfully cooled air from over 900ºC and achieved nearly 1 GW/m^3 power exchange [6]. This work was the basis of the subsequent heat exchanger development at REL in the early 2000's.

3.2.2 Wind Tunnel Heat Exchanger Module

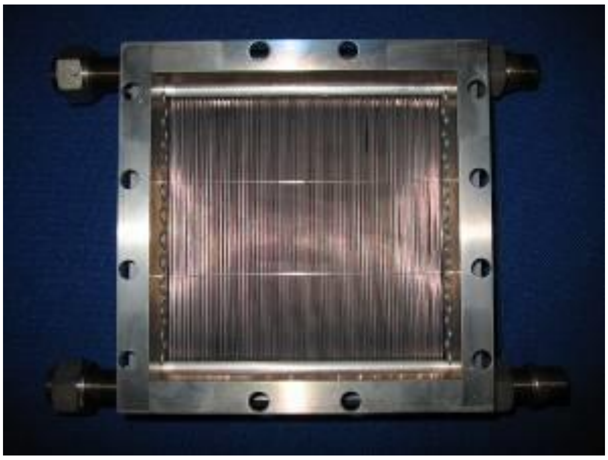

Fig. 4: Inconel 718 Heat Exchanger

The first heat exchanger module using Inconel 718 tubes of the correct diameter and wall thickness was manufactured for the frost control wind tunnel in 2001 (Fig. 4). This work was supported by a DTI SMART award (DTI is the UK Department for Trade and Industry).

3.2.3 Pre-cooler Module Demonstration

Fig 5. First Pre-Cooler Module

The first full size SABRE Pre-Cooler Module was manufactured in 2004 with the assistance of a DTI "Grant for R&D" award. The construction of this module further developed the pre-cooler processing and brazing techniques of the earlier programmes.

3.2.4 Pre-cooler Frost Control

Fig. 6: Frost Control Test Facility

A vital pre-cooler technology relates to preventing the matrix clogging with frost due to condensation of water vapour in the engine airflow. REL have developed an efficient solution which was developed in a purpose-built frost control wind tunnel in the early 2000s [4].

3.2.5 Pre-cooler Heat Transfer Augmentation

Fig 7: Low Speed Wind Tunnel

On-going research is being carried out in a special low speed wind tunnel (Fig. 7) which was designed and constructed in the course of a PhD thesis at the University of Bristol. This work is exploring the flow through tube arrays and investigating novel surface geometries to augment the airside heat transfer coefficient [7].

3.3 Pre-Cooler Demonstration

The main focus of the Technology Demonstration Programme was to combine the development work undertaken in the precursor projects and combine them to produce a complete operation pre-cooler which could successfully demonstrating continuous operation with air cooled to cryogenic temperatures.

The demonstration of the feasibility of deep pre-cooling was achieved by the manufacture, assembly and test of a complete prototype pre-cooler including frost control (Fig. 8). The Pre-cooler is a high performance state-of-the-art heat exchanger employing superalloys and requiring the development of advanced manufacturing processes. The pre-cooler used flight representative heat exchanger modules (Fig. 9) that were produced in a prototype manufacturing facility. This proved the "productionisation" of the heat exchangers demonstrating that they can be produced in the quantities required for the SKYLON production programme.

Fig. 8: The Integrated Pre-cooler

Fig. 9: Pre-cooler Modules before Integration

The Pre-cooler was tested in a special facility (Fig. 10) that employed a Rolls Royce Viper jet engine to draw air through the heat exchanger at the correct flow rates. To prevent freezing of the fuel at the low compressor outlet temperature, the Viper was modified to run on butane. The heat exchanger was supplied with 200 bar helium loop at cryogenic temperatures using liquid nitrogen as the heat sink.

Fig. 10: The Pre-Cooler on the Test Stand

The test programme achieved its objectives demonstrating sustained operation substantially below -100 °C for over 5 minutes. During the test programme the heat exchanger went though over separate 200 test runs, indeed it was subjected to more cycles than expected from an operational SABRE pre-cooler. The Pre-cooler showed complete thermo-mechanical and aerodynamic integrity throughout the test programme and the result provided considerable information and learning to guide the detailed design of the flight Pre-cooler. This test programme is now considered complete although the test facility and Pre-cooler are being maintained in an operation conditional for a few months as final evaluation of the test results is undertaken, so that, should any unexplained results emerge, further tests can be conducted to resolve the issue.

4 OTHER SABRE TECHNOLOGIES

4.1 Background

As already discussed, the Pre-Cooler heat exchanger has always been seen as the major new technology that would be required to realise deep precooled combined cycle rocket engines from the HOTOL studies on, however other features of the engine have also been the subject of technology development projects. Although the remainder of the required engine technologies are variants of existing rocket and jet engine technology, these additional studies confirm their readiness for the SABRE application.

4.2 Engine Technology Projects

4.2.1 Contra-rotating Turbine

Fig. 11: The Contra-rotating Turbine

Under the LAPCAT programme, partially funded by the European Union, REL designed and built a contra-rotating turbine (Fig. 11), which is required for both the LAPCAT A2 hypersonic airliner with its Scimitar engine and the SKYLON SABRE engine. The blading for this demonstration was designed by the Von Karman Institute in Belgium using their in-house codes and optimised by Ceraero. The programme proved that the aerodynamics of such turbines can be designed with current know-how and achieve associated mass benefits.

4.2.1. Advanced Nozzles Background Studies

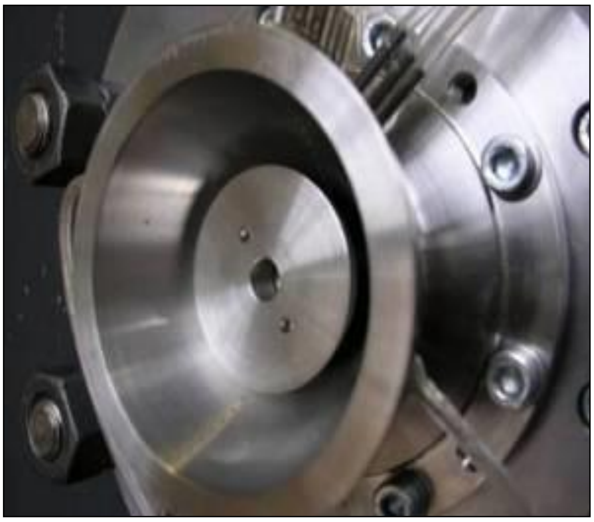

Fig. 12: Cold flow Expansion/Deflection Nozzles

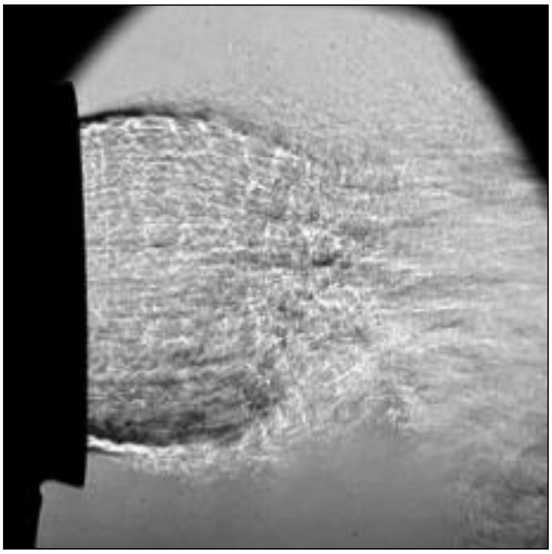

Fig. 13: Cold Flow Nozzle Visualisation

A number of studies have investigated the possibilities of several altitude compensating nozzle concepts which have the potential for efficiency gain over the large altitude range of a single-stage launcher. These include a studies of Expansion/Deflection (E/D) nozzles (Fig. 12) [8,9,10], dual bells, and over expanded classic bell (Fig. 13). These studies were performed at the University of Bristol, on the Medium Enthalpy Gas Generation (MEGG) facility some of this work was prior to the Technology Demonstration Programme and some a part of it.

4.2.2 STERN E/D Nozzle Experimental Engine

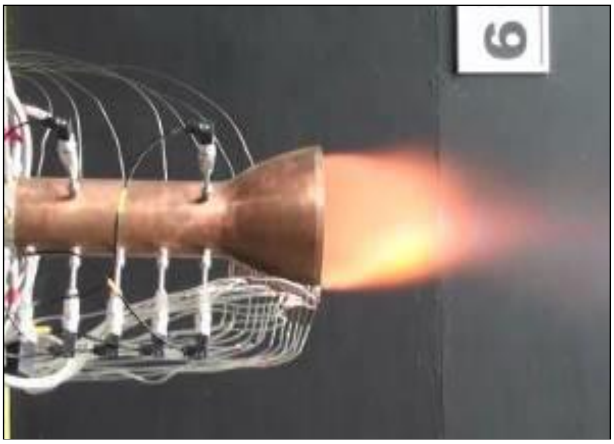

Fig. 13 STERN E/D Nozzle

The STERN E/D Nozzle experimental engine (Fig. 13) was a privately funded project to explore the altitude compensation capability of E/D nozzles. It was managed by the University of Bristol and successfully completed 22 hot test firings with test support by Airborne Engineering Ltd [11].

4.2.3 STRICT Nozzle Experiment

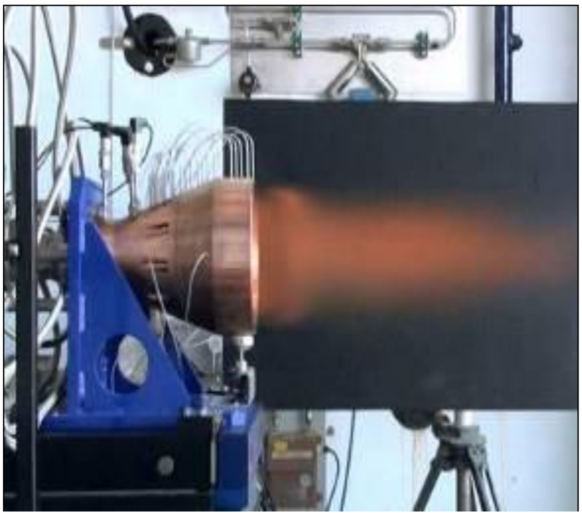

Fig. 14. STRICT E/D Nozzle

The STRICT E/D Nozzle experiment (Fig. 14) was a follow on project to STERN project and was part of the Phase 2 Engine Technology Demonstration programme. The objective was to further explore stable nozzle operation of a pressure-compensating nozzle. The project culminated in a series of experimental hot firings testing two nozzle configurations which were conducted at the Westcott rocket test site by Airborne Engineering Ltd.

4.2.4 STRIDENT Flow Test

Fig.15 STRIDENT Cold Flow Test Engines

The STRIDENT cold flow test nozzle (Fig. 15) was a programme internal funded by Reaction Engines to explore advance nozzle configurations further in light of the result from the STRICT project and a CFD modelling. In 2012 a test programme was successfully conducted which confirmed the ability to predict the complex nozzle behaviour at least at static sea level conditions. The STRIDENT engine is the basis for a hot fire advanced nozzle test engine called STOIC which is currently in development.

4.2.5 Air/Hydrogen Cooling test

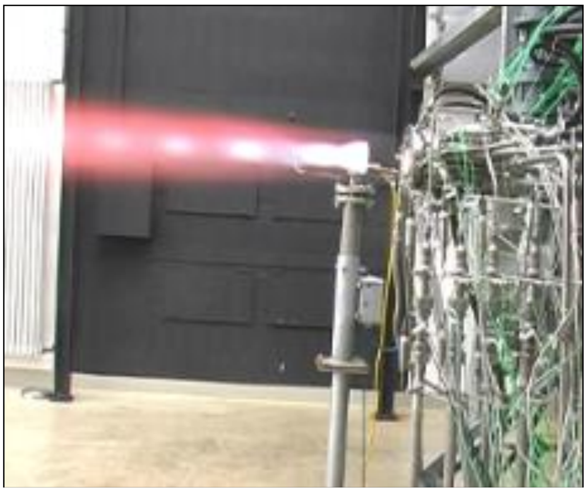

Fig. 16: Air/Hydrogen Cooled Nozzle

The feasibility of cooling the rocket combustion chamber with a combination of air in the cooling jacket and heavy hydrogen film cooling as required during the SABRE's air-breathing mode was experimentally tested. A special test combustion chamber was constructed by Astrium and tested at the DLR Lampoldshausen test site (Fig. 16). This work was conducted as part of the Phase 2 Engine Technology Demonstration Programme.

4.2.6 LOX Cooling Test

Fig. 17: LOX Cooled Chamber

The feasibility of using LOX in the cooling jacket as required during the SABRE's rocket mode was experimentally verified. An existing test chamber was modified for this project by Astrium at the DLR

Lampoldshausen test site (Fig. 17). This work was conducted as part of the Phase 2 Engine Technology demonstration programme.

4.2.7 STILETTO Combustor Experiment

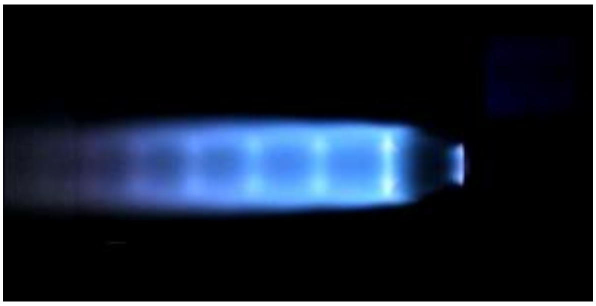

Fig. 18: STILETTO Combustor Experiment

A low nitrous oxide (NOX) combustor, called STILETTO (Fig. 18), for the SCIMITAR Mach 5 cruise engine has been conceived, designed and successfully tested at Airborne Engineering's Westcott test site. This work was conducted as part of the LAPCAT high speed air transport technology project. Measurements during the test programme have shown that the NOX emission is less than 100ppm. The engine employs a staged combustion system that has relevance to the SABRE combustion chamber.

4.2.8 Intake Design

Fig. 19: SABRE Nacelle Wind Tunnel Test Model

Gas Dynamics Ltd carried out a nozzle validation study that included both analysis using in-house codes and experimental testing of the SABRE nacelle intake in their hypersonic gun tunnel operating in Ludweig tube mode (Fig. 19). This work was conducted as part of the Phase 2 Engine Technology Demonstration Programme.

4.2.8 Micro-channel High Pressure Heat Exchangers

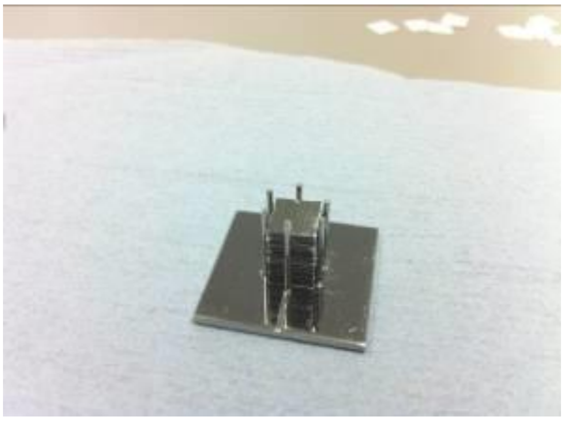

Fig. 20: Micro-channel Manufacture Test

For applications in SABRE where both fluid streams are at high pressure a different surface morphology to the pre-cooler has potential benefits. Reaction Engines has an internally funded on-going project looking at micro-channel heat exchangers for these cases examining heat transfer and manufacturing issues (Fig. 20). The immediate application of this technology will be in HX4 where the waste heat from the SABRE helium loop is rejected to the hydrogen stream.

4.2.9 Silicon Carbide High Temperature Heat Exchangers

Fig. 21: Silicon Carbide Tube Demonstration

For high temperature applications the possibility of silicon carbide matrix manufacture was explored leading to the manufacturing of test articles (Fig. 21). This work started in the LAPCAT1 study for the SCIMITAR engine but has application for the high temperature HX3 heat exchanger in the SABRE engine.

5 SABRE PHASE 3

With the completion of the Phase 2 Engine Technology Demonstration Programme, nearly all the technology readiness issues have been resolved and SABRE development has now moved to Phase 3, which has the objective of taking the SABRE Block 1 engine to its Critical Design Review. The Block 1 is the engine on which the development testing would be based, both ground based static testing and flight testing in a SKYLON pre-production System Flight Demonstrator vehicle.

Preliminary Phase 3 activities started in spring 2013 solely funded by Reaction Engines. In the autumn of 2013 an 8 million Euro Phase 3a programme will be kicked off. This programme of work is designed to last 18 Months and will be 50:50 funded from Reaction Engines' private resources and the UK subscription to the European Space Agency. The agency side of the funding is subject to a successful proposal and contract negotiation.

Phase 3a activities include:

- SABRE 4 Design to take it to its System Requirements Review
- The preliminary design of a ground demonstration engine (Sceptre)
- Pre-cooler tube cost reduction
- Further work on Microchannel manufacture (HX4)
- Further work on High temperature (HX3) technologies
- Further work on chamber technology
- Further work on altitude compensation nozzles
- Investigation of the intake in subsonic conditions
- Further work on the intake in supersonic conditions
- A series of SKYLON studies (discussed in Section 9)

The SABRE 4 System Requirements Review will be the final decision point between the SABRE 3 and the SABRE 4. Outside of the formal Phase 3a activity of the joint Reaction Engines/ESA programme the final technology readiness work to support that decision will be completed.

Phase 3a will lead into (and overlap) the main Phase 3 which is a programme with around £240 million budget. By far the majority of this budget is the process of detailed design of the SABRE Block 1 engine and the engineering testing to support that design. However the programme includes the construction of the ground system level demonstration engine called Sceptre which has all the various technologies interacting in a SABRE like engine. Sceptre will not be a fully integrated engine in a "packaged" configuration, but rather an open test rig. Other ground test engines will further explore altitude compensating nozzles and demonstrate the chamber lifetime required by SABRE and the SKYLON Orbit Manoeuvring Assembly (SOMA) engines

The Phase 3 programme also includes a test rocket called Valkyrie (Fig. 22) which matches the Mach number/altitude profile of SKYLON and will test the operation of altitude compensating nozzles with the correct, dynamically altering, back pressure and supersonic external flows. The propellants used in the Valkyrie's SPEAR engine are nitrous oxide, ammonia and liquid nitrogen which were selected to match the exhaust products of the altitude compensating ground test engines (e.g. STERN and STRICT) and the SABRE Engine in Air breathing mode. Valkyrie flies to Mach 5 at 25 km under power in around 50 seconds, In unpowered flight it then reaches an altitude of 140 km before a destructive return to earth.

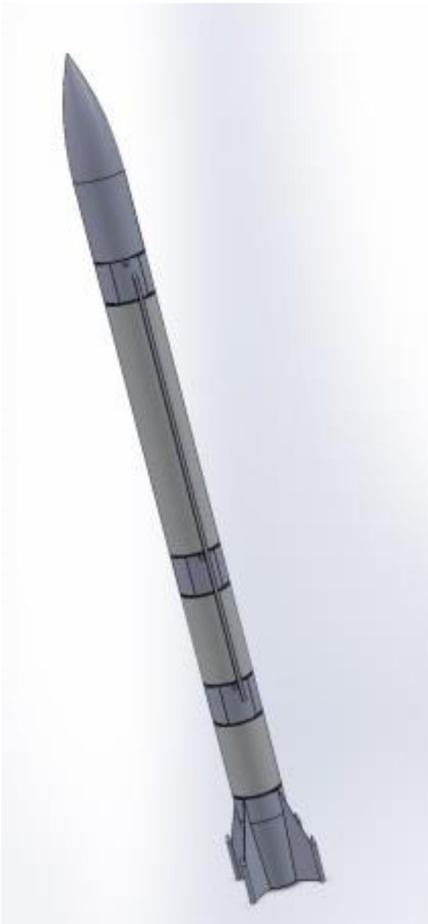

Fig. 22: The Valkyrie Test Rocket

Valkyrie is still in its preliminary design phase. It is around 4.3 m long with a body diameter of 250mm. The Valkyrie will be rail launched and has a take-off mass of around 190 kg including two solid propellant booster packs. In addition to the preliminary design work there are also technology development projects on the manufacture of tanks, the avionics, the combustion of ammonia with nitrous oxide and the production of the SPEAR flight chamber. It is currently planned to launch Valkyrie in 2014.

The Nacelle Test Vehicle (NTV), a rocket powered Mach 4.5 unmanned experimental aircraft that was outlined as part of the development programme in past papers [5], is currently under review. Phase 3 will contain work that proves the SABRE Nacelle as a complete system, which was the objective of the NTV, but alternatives such a wind tunnel modelling and simplified flight testing are being explored that may provide the same level of verification at less cost and risk.

As with all past phases of the SKYLON Development, it is planned that the funding for Phase 3 will be a mix of public and private funding, with the private funding forming the substantial majority of the investment. In July 2013 the UK Chancellor of the Exchequer, George Osborne, announced that the UK Government through the UK Space Agency was set to invest £60 million as the public side of that investment with the intention that it would “prime the pump for the remainder of the investment capital” [12]. The UK Government money is planned for £35 million in 2014/2015 and £25 million in 2015/2016.

6 SKYLON

The SKYLON launch vehicle is a winged single-stage-to-orbit space plane [13, 14]. The vehicle takes off from a special extended runway with the SABRE engines in air-breathing mode. It accelerates to Mach 5.14 and 26 km altitude before the SABRE engines switch over to the pure rocket mode and power the vehicle to a Low Earth Orbit. Once the payload is deployed and operations in orbit are completed, the vehicle is placed on a return to earth trajectory, re-enters the atmosphere and glides back to a runway landing.

The payload requirements for were the subject of a review in 2008 [15]. As a result of this review SKYLON has been designed to carry 15 tonnes into low Earth orbit in a 4.8 m diameter 13 meter long payload bay. Payloads are attached by a three trunnion mount designed to structurally decouple the payload from the SKYLON structure.

SKYLON (Fig. 23) consists of a slender fuselage which contains propellant tankage and a payload bay. Its delta wings attached midway along the fuselage carry the SABRE engines in axisymmetric nacelles on the wingtips.

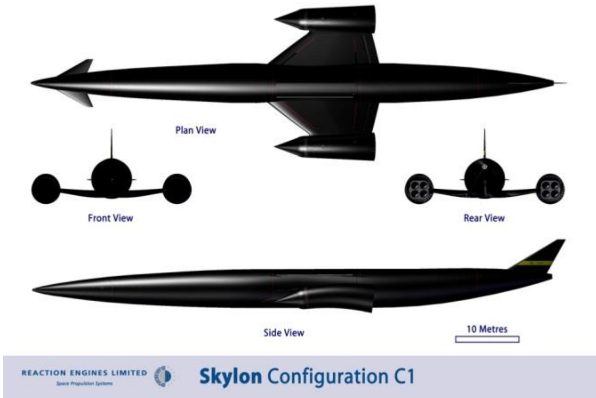

Fig. 23 SKYLON

The internal layout (Fig 24) is dominated by two liquid hydrogen tanks that have propellant differentially drawn from them to help maintain trim. The main contributors to the overall mass (the oxygen tanks, payload and engine) are placed in line with the wings, an arrangement that again helps trim the vehicle but also leads to the lightest structure by keeping load paths as short as possible.

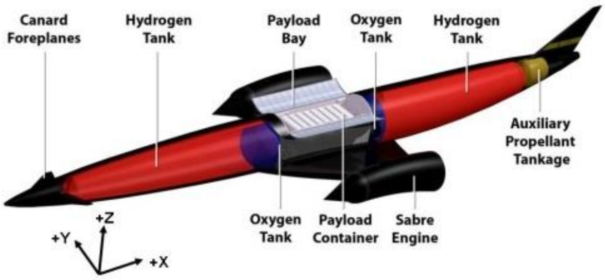

Fig.24: SKYLON Internal Layout

There are three configurations of SKYLON that have been explored in these studies.

Configuration C1 – is a 275 tonne take off mass system that was the end result of studies ending in 1993. Although it had a target of 12 tonnes in practice the mass analysis showed a payload of 10.3 tonnes. This uses a SABRE 3 and was been the focus of the SABRE and SKYLON development work, and was used as the technical basis for the SKYLON System Requirement Review in 2010.

Configuration C2 – is a 345 tonne take off mass system scaling of C1 that was produced in 2010 to meets the revised system requirements and in particular a 15 tonne payload that had been defined by the requirements review process

Configuration D1 – this is a version of SKYLON that employs the SABRE 4. It currently has a take off mass of 325 tonnes, and like C2, it is sized to meet the revised system requirements [16]. The D1 also incorporates the results of the other technology development. On the assumption the SABRE 4 will be the engine that is finally developed then the D1 configuration will be the basis for the final flight vehicle.

7 SKYLON STUDIES

The SKYLON airframe work is a combination of a continuous system design but has also included a series of discrete separately funded system analysis studies and technology development programmes the latter mostly centred on the structure and thermal protection system. Most of these studies represent on-going work that has not yet reached its final conclusions.

7.1 System Analysis Studies

7.1.1 Subsonic Wind Tunnel Investigation

Fig. 25: Low Speed Wind Tunnel Test

Low speed wind tunnel tests (Fig. 25) have been carried out by Kingston University to investigate low speed handling characteristics and crosswind landings. This confirmed the fin control surface sizing and subsonic lift to drag estimates.

7.1.2 Mach 9 Hypersonic Wind Tunnel Investigation

Mach 9 tests were carried out in the DERA low density wind tunnel in Farnborough to investigate the overall flowfield and shock structure (Fig. 26).

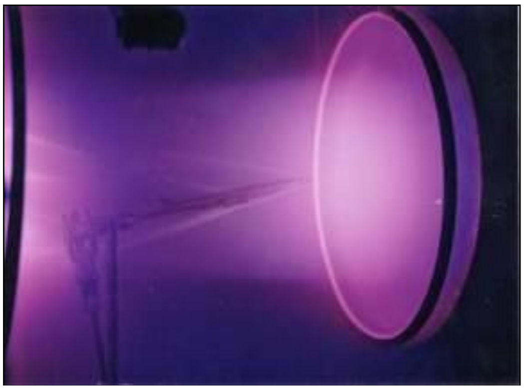

Fig. 26: Mach 9 Wind Tunnel Test

7.1.3 Mach 12 Hypersonic Shock Tunnel Investigation

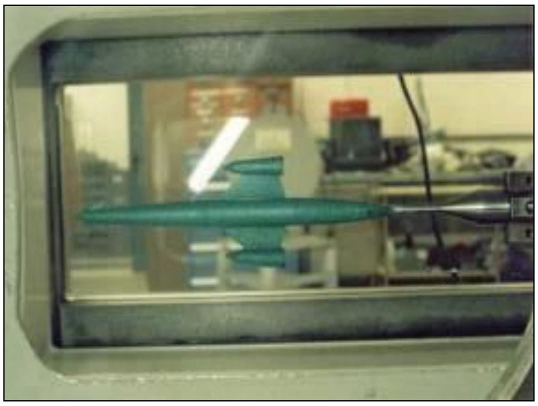

Fig. 27: Mach 12 Gun Tunnel

Mach 12 tests were carried out in the DERA gun tunnel (Fig. 27) to investigate re-entry heating and shock interaction locations.

7.1.4 Re-entry Aerodynamics

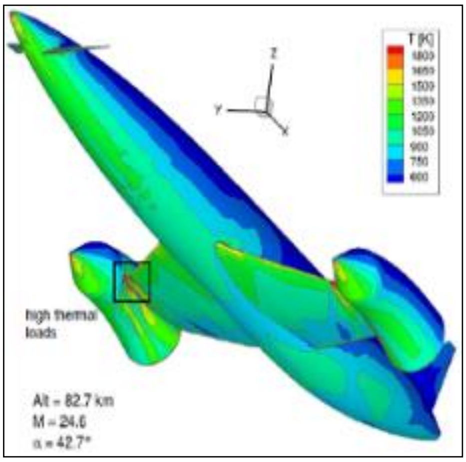

Fig. 28: CFD Model of Re-entry

The German Space Agency (DLR), funded by Reaction Engines, carried out CFD calculations of SKYLON re-entry using TAU, in particular focusing on the unique aspects of its aircraft-like configuration. The results (Fig. 28) confirmed REL's estimates for the overall heating levels but importantly predicted that the local heat fluxes at shock impingement locations and the foreplanes were less than previously anticipated.

7.1.5 Ascent Trajectory Modelling

In-house codes have been developed within REL over the last 20 years for ascent performance modelling, aerodynamics, vehicle layout and pitch trim, and re-entry. ASTOS Solutions have also carried out performance analysis on the SKYLON C1 design, which both validated REL's codes and optimised the trajectory to maximise the delivered payload.

7.1.6 Payload Mounting Interface

There has been a revision of the payload interfaces in light of more detailed analysis and feedback on the Version 1 of the SKYLON User's Manual. A major activity on establishing the certification requirements for the vehicle has been started. Also more detailed studies of the ancillary support systems such as payload carriers and upper stages have been started.

7.2 Structure and TPS Studies

The following technology development activities are focused on the primary structure and thermal protection system.

7.2.1 CFRP Truss Structure

Fig. 29: CFRP Test Struts

Various research programmes have addressed the unique fuselage truss structure. The original concept was to use struts engineered in Carbon Fibre-Reinforced Plastic with bonded titanium end fittings (Fig. 29). This concept was explored in a £2.5 million programme led by the University of Bristol and funded by the UK Engineering and Physical Science Research Council. This work was reported in References 17 to 21.

7.2.2 TiSic Truss Structure

Fig. 30: TiSiC Test Struts.

Current work is on-going with TISICS Ltd on the development of a silicon carbide fibre reinforced titanium variant of the truss structure (Fig. 30) to overcome the technical disadvantages of the above CFRP baseline. Two successful research programmes on this material have now been completed. A third programme is on-going as part of a collaborative TSB (UK Technology Strategy Board) grants to address the economic and production issues entailed in full scale production.

7.2.3 Aeroshell

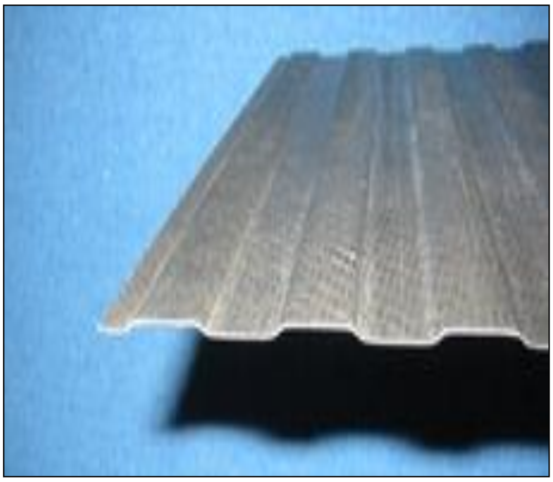

Fig. 31: Pyromeral Demonstration TPS Panel

Preliminary investigations have examined the manufacturing feasibility and technology of silicon carbide fibre reinforced glass ceramic as a better alternative to the conventional vapour deposited materials. A past involvement with the French Company Pyromeral resulted in the manufacture of a number of corrugated aeroshell panels (Fig. 31) which have been used for structural and oxidation experiments. There is current work within Reaction Engines supported by several Universities to improve on this work by reinventing the SYTEM 2 material developed by the UK Atomic Energy Authority in the 1990s.

8 CURRENT SKYLON ACTIVITY

The main current airframe system level activity is a €1 Million feasibility study of a SKYLON based European Launch Service Operator (S-ELSO) for the European Space Agency Launcher Directorate. This is examining how a launch infrastructure based on the SKYLON D1 combined with other systems, such as upper stages and spaceports, can meet Europe's space access demands in terms of performance, cost, flexibility and responsiveness, from the early 2020's [22].

Fig. 32: SKYLON Upper Stage

The key European requirement is to launch satellites into Geostationary Transfer Orbit (GTO) with masses up to 6.5 tonnes. As SKYLON is a low earth orbit launch system an upper stage is required to address this market. A concept for a SKYLON Upper Stage (SUS) has been produced (Fig. 32) and is reported in Reference 23. Since this published work, Reaction Engines has studied both very low orbital deployment and the use of the SUS combined with orbit raising using electric propulsion on-board the satellite. The provisional conclusion based on this work is that the 6.5 tonne to GTO is achievable with an upper stage that can be recovered by the SKYLON that launched it and returned for earth for reuse [24].

During the S-ELSO Study Thales Alenia Space in Italy will be examining the SUS systems in more detail considering its requirements, revising its design and establishing its feasibility.

The S-ELSO study is also examining the airborne support equipment needed to carry low Earth orbit satellites that cannot use the main trunnion mounting system, work that will be carried out by Qinetiq Space in Belgium, and the necessary spaceport facilities at Kourou for SKYLON, work that will be carried out by Grafton Technology and Jacobs in the UK.

The S-ELSO study is not confined to technical feasibility, the study will also produce business plans for the SKYLON producer and the European operator to explore the commercial viability of both enterprises. This work is supported by London Economics who are preparing the business model to independently assess the economic case for investment.

The SKYLON team are also currently supporting the on-going UK Civil Aviation Authority (CAA) study into the regulation of Spaceplanes which is due to report to the UK Government in 2014 with options for the regulatory regimes that should apply to SKYLON (and other spaceplanes, both orbital and suborbital).

9 FUTURE SKYLON STUDIES

Although the Reaction Engines focus is on the SABRE engine, because of the intimate connection between SKYLON and SABRE it is necessary that the definition of SKYLON remains at a level that ensures the SABRE engine specification remains valid and can meet the demands of a viable space launch system. It is the purpose of the SKYLON Vehicle Configuration Studies to maintain sufficient level of definition of the customer system that ensures the SABRE engine is correctly specified.

These studies have three objectives

i. To ensure commercial viability of the combined SKYLON/SABRE system by meeting market needs and is therefore a sellable product for an economic price;

ii. To establish the technical viability by demonstrating that a combined

SKYLON/SABRE system can meet customer demand, can be built and built for a cost that is consistent with the economic price.

iii. To ensure the SKYLON airframe definition is in a condition that the IPR can be transferred to an airframe prime contractor capable of constructing the vehicle.

Thus a small part of the Phase 3 budget has been allocated to SKYLON studies to meet these objectives. This activity comprises 8 sub-studies that are listed in Table 1.

Table 1: List of Skylon Phase 3 Studies

Title	Description
D1 System Studies	Overall vehicle definition, performance analysis and examination of the associated infrastructure.
Certification Activities	Both the supporting of the establishment of an appropriate legislative environment and ensuring meets the resulting certification requirements
Structural and TPS Technology	Looking at the airframe technologies and their integration into a working structural and thermal system
Other Technology Studies	Looking into various subsystem technologies
Payload Carriers Studies	Continuing the work started in the S-ELSO on payload carriers for small and medium LEO payloads
Upper Stage Studies	Continuing the work started in the S-ELSO on the Skylon Upper Stage
Re-entry Test Vehicle Study	Starts the feasibility and concept design work for the re-entry test vehicle that validates the re-entry modeling
Pre-prod. Prototype Study	Starts the feasibility and concept design work for the Pre-production system demonstration vehicle

10 CONCLUSIONS

The engine technology development activities led by Reaction Engines that were successfully concluded in 2013 have enabled the SABRE engine development to begin with the Phase 3 Programme. This £250 million programme will demonstrate the technologies in a system context and take the design of the flight SABRE Block 1 engine to its Critical Design Review.

The SKYLON vehicle studies keep the configuration maintained in sufficient detail to validate the SABRE Engine requirements. However the SKYLON definition is also at a level that an airframe prime contractor can begin a development programme from the System Requirement Review milestone point.

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