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THE SKYLON SPACEPLANE: PROGRESS TO REALISATION

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The Skylon spaceplane will enable single stage to orbit delivery of payloads with aircraft like operations. The key to realising this goal is a combined cycle engine that can operate both in airbreathing and pure rocket modes. To achieve this new low mass structure concepts and several new engine technologies need to be proven. An extensive program of technology development has addressed these issues with very positive results. This now allows the project to proceed to the final concept proving stage before full development commences.

Keywords: Skylon, heat exchangers, expansion deflection nozzles, composite truss structures

1. INTRODUCTION

Skylon is a single stage to orbit launch system that can takeoff from a runway and, after delivering its payload, return to a runway landing in the same manner as a conventional aircraft. As such it represents a unique technical challenge, with the aim of achieving a system that is commercially developed and operated. Therefore it must incorporate:

- Reusability
- Single-stage
- Un-piloted operations
- Abort capability
- User friendly operations
- Re-entry cross-range
- Low Environmental impact

while keeping the overall mass low enough and the engine performance high enough to reach orbit with a viable payload.

The problem is illustrated in Fig. 1 where mass ratio (fuelled mass/empty mass) is plotted against the velocity ratio (mission velocity/exhaust velocity). This shows that (with achievable structure mass fraction and rocket engine specific impulse) current technology cannot reach the point at which viable single stage to orbit is possible. This result is very sensitive to the achievable mass fraction, which explains why there have been several unseccessful past attempts at pure rocket systems, such as Delta Clipper and VentureStar. However none of these programs have managed to demonstrate either the engine or structure performance required to achieve the single stage to orbit goal.

The Skylon reduces the required mass ratio by improving the engine specific impulse by operating in an airbreathing mode in the early stages of the flight – up to around Mach 5.5 and an altitude of 25 kilometres before the engine switches to a pure rocket mode to complete the ascent to orbit. This makes a very significant difference; a pure rocket needs to achieve an equivalent velocity of around 9200 m/sec (7700 m/sec orbital speed and 1500 m/sec in various trajectory losses) whereas the airbreathing absorbs about 1500 m/sec of the orbital speed and 1200 m/sec of the trajectory losses so the pure rocket phases needs to provide only 6500 m/sec and this increases the minimum mass ratio from 0.13 to 0.21. Even with the extra engine mass required for the airbreathing operation this is a far more achievable target.

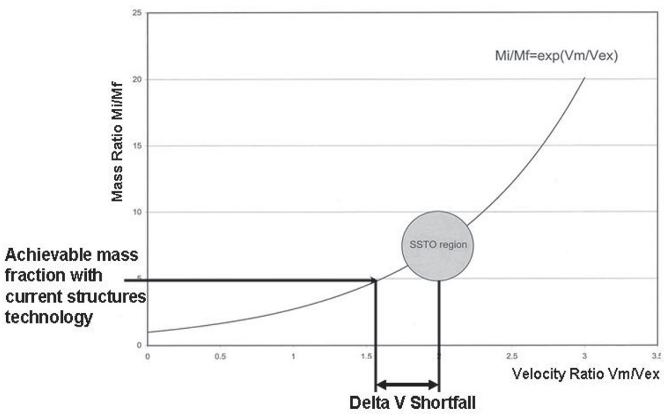

Fig. 1 Mass ratio versus mission velocity ratio.

However the technology for the airbreathing engine and for the achievable but still challenging structure mass, both need to be proven and this paper is an overview of some of the technology development work. It outlines the progress of the various supporting technology projects and shows how they are proving that the required performance can be achieved. They have also lead to technical options that are now being explored to further enhance the performance and these are also briefly outlined.

2. THE SKYLON VEHICLE

The Skylon spaceplane was derived from the British Aerospace HOTOL project [1] (Fig. 2) with its Rolls Royce RB545 engines. Together the two projects have been under active study for 25 years and a considerable amount of supporting work has been undertaken.

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Fig. 2 BAe HOTOL final configuration.

Although based on HOTOL, Skylon has substantial changes to the overall configuration, the airframe and the engines in light of lessons learnt on the earlier project. The overall configuration moved the engines to the wingtips to resolve HOTOL's trim problems. The airframe was altered from a semi-monocoque with structural hydrogen tank to a composite truss with suspended non-structural tank and aeroshell. The engine was revised to the Sabre concept which while more complex than the RB545 offers greater airbreathing performance (with an added Helium loop separating the hydrogen and air flows).

The current working configuration, designated C1 (Figs. 3 and 4), was finalised in 2003 and is described in References 2 and 3. The vehicle is 83 m long with a wingspan of 25 m and is designed to carry a payload 4.6 diameter and 12 m long. A summary of the mass breakdown is given in Table 1

The Skylon development is estimated to take 9.5 years and cost 9518 M (2004 prices). The development program will produce a vehicle with a life of 200 flights, a launch abort probability of 1% and a vehicle loss probability of 0.005%. Assuming a production run of 30 vehicles each vehicle would cost about €565 M. In operation it should be capable of achieving a recurring launch cost of €6.9 M per flight or less.

3. AIRFRAME RESEARCH

A key innovation in the Skylon vehicle is the use of a non-monocoque approach; in many respects similar to Zeppelin airships. The main load carrying structure is a truss framework made from a carbon fibre reinforced plastic composite. Aluminium propellant tanks are suspended within this structure by Kevlar ties and an outer aeroshell of a high temperature SiC fibre reinforced glass ceramic material. This concept (Fig. 5) is more fully described in Reference 4.

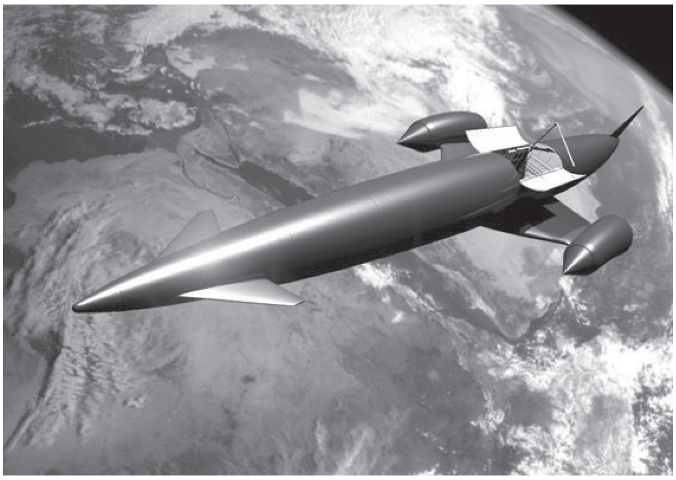

Fig. 3 Skylon configuration C1 external view.

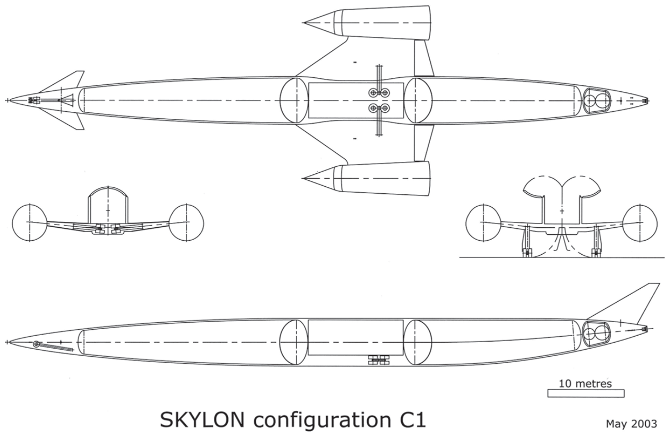

Fig. 4 Skylon configuration C1 general layout.

The active research program examined two aspects of this concept: the truss structure and the aeroshell skin material.

The Skylon truss structure requirements were included in a wide ranging 3 year study into composite structures for aerospace applications lead by the University of Bristol. This work confirmed the viability of the basic concept and resolved some of the key technical issues [5-8]

The aeroshell skin was originally designed in a proprietary material from the UK Atomic Energy Authority at Harwell - System2 (SiC fibre reinforced glass ceramic). This material maintains its structural properties up to 1470 K well above the 1100 K experienced during re-entry. Unfortunately this mate-

TABLE 1: *Skylon Summary Mass Breakdown.*

Vehicle	
Basic mass (incl. fluids)	41 tonnes
OMS+RCS propellants	2.3 to 4.1 tonnes (mission dependent)
Ascent propellants	217 tonnes
Residuals	1.3 tonnes
Brake coolant	1.2 tonnes (rejected after take-off)
Max. take-off weight	275 tonnes
Payload	
Equatorial 300km	12 tonnes
ISS (408km x 51.6°)	9 tonnes
Polar (250km x 98°)	4.8 tonnes

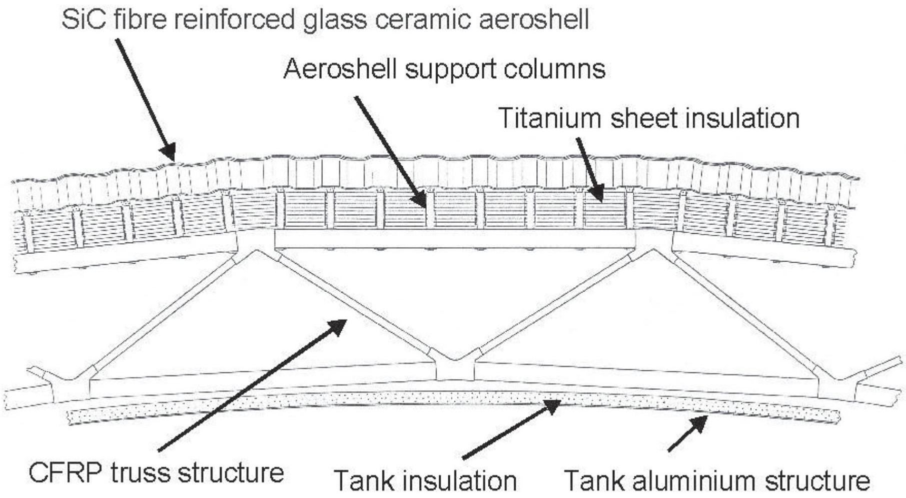

Fig. 5 Skylon fuselage structural concept.

rial has since been discontinued however an alternative called Pyrosic from Pyromeral Systems in France has come to light. Reaction Engines has undertaken some testing to determine whether it can meet the aeroshell requirements in particular re-entry.

To establish whether this new material can meet the Skylon requirements, full size panels with the linear corrugations (Fig. 6) have been manufactured and the material has been tested in a specially constructed chamber that simulates the conditions of atmospheric re-entry to establish the material survivability (Fig. 7). This included exploring erosion and resistance to oxidation at the elevated temperatures.

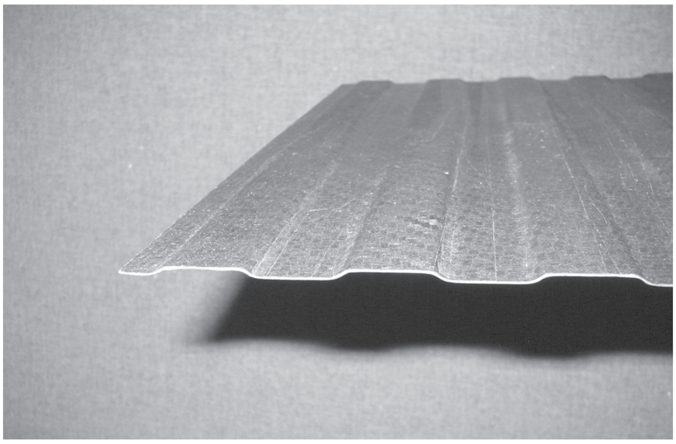

Fig. 6 Pyrosic test panel.

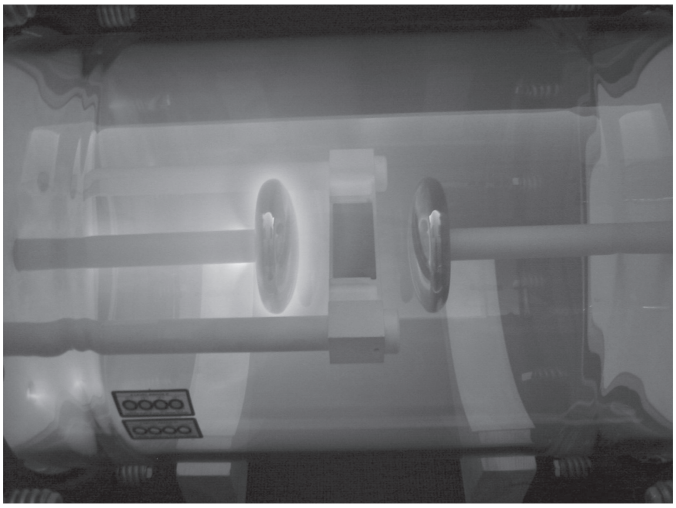

Fig. 7 Pyrosic under re-entry simulation test.

4. ENGINE RESEARCH

4.1 Sabre Engine Concept

The combined cycle pre-cooled class of engines (such as the RB545 and Sabre) have been shown to be superior to other candidate airbreathing engines [9] for propelling single stage to orbit vehicles.

The Sabre engine (Fig. 8) has a dual mode capability. In rocket mode the engine operates as a closed cycle LOX/LH_2 high specific impulse rocket engine. In airbreathing mode (from takeoff to above Mach 5) the liquid oxygen flow is replaced by atmospheric air, increasing the installed specific impulse 3-6 fold. The airflow is drawn into the engine and is cooled to cryogenic temperatures prior to compression. The hydrogen fuel acts as a heatsink for the closed cycle helium loop before entering the combustion chamber.

The Sabre engine is essentially a closed cycle rocket engine with an additional precooled turbo-compressor to provide a high pressure air supply to the combustion chamber. This allows operation from zero forward speed on the runway up to Mach 5.5 in air breathing mode during the ascent. As the air density falls with altitude the engine eventually switches to a pure rocket propelling Skylon to orbital velocity.

4.2 Heat Exchanger Development

4.2.1 Precooler Heat Exchanger

The key component of the Sabre engine is the pre-cooler heat exchanger that cools the air captured by the intake. This heat exchanger consists of a series of “modules” that wrap around in a spiral fashion (Fig. 9). Air passing through the heat exchanger is cooled by helium flowing though the tubes. There are two technical concerns with this heat exchanger, the first is simply how to manufacture it and the second is how to control the frost build up.

When this class of pre-cooled engine was first proposed in the 1980s the key technical question was whether it would be possible to construct heat exchangers with the necessary mass and compactness. The basis of the Reaction Engines manufacturing expertise was a research project conducted by the Uni-

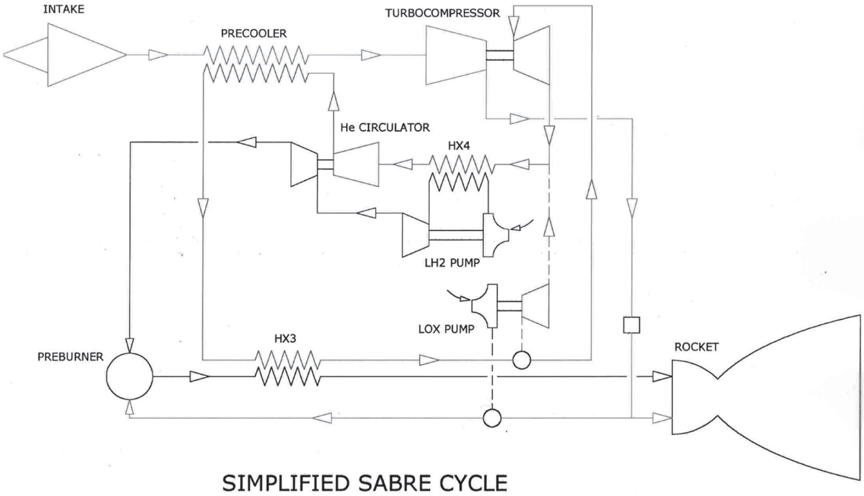

Fig. 8 Sabre engine simplified thermodynamic cycle.

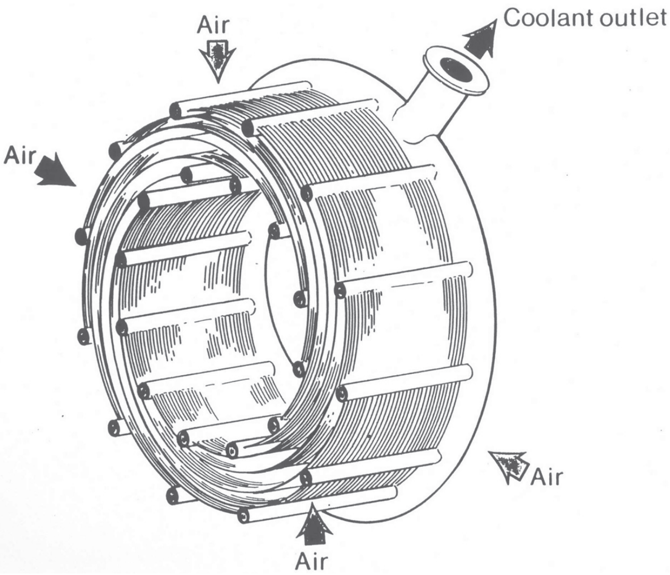

Fig. 9 SABRE precooler heat exchanger.

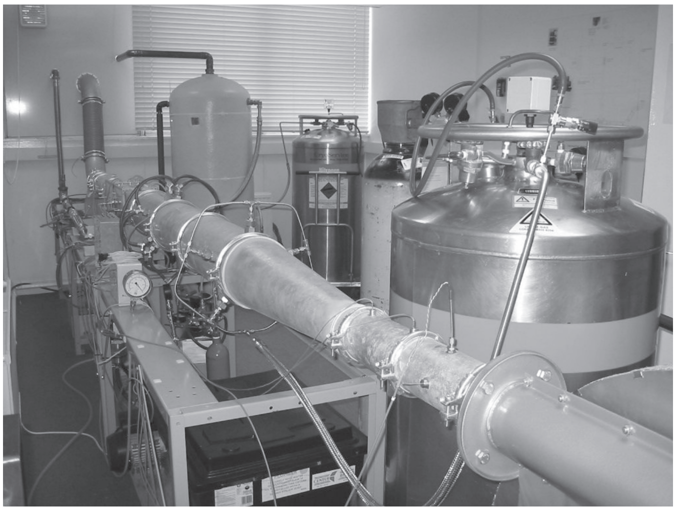

Fig. 10 Frost control experimental wind tunnel.

versity of Bristol (completed in 2000) leading to successful testing of a heat exchanger with a heat transfer of nearly 1 gigawatt per m^3, well within the required performance of the Sabre precooler [10].

This work has been extended with the successful manufacture of tubes in Inconel 718 which have 0.88 mm bore and 40˜m wall thickness which ensures good heat exchange properties without compromising physical strength. The tubes have been successfully creep tested at 200 bar and 720 °C and also for oxidation for 1800 hours. The other key technology is the method of brazing the fine tubes into the feeder headers which has also been successfully demonstrated.

The Precooler is designed to cool the engine airflow (about 400kg/s) from intake recovered conditions (up to 1000°C at Mach 5) down to about -140°C prior to compression. At sub-zero temperatures frost control becomes a critical problem as atmospheric water vapour freezes and blocks the air flow within seconds. The frost control system has been the researched since 2001 with the result that steady state operation can now be achieved without blockage.

The experiments were performed in a specially constructed cryogenic wind tunnel (Fig. 10) that has a 150mm square test section into which heat exchanger modules can be inserted. The wind tunnel draws in 0.3 kg/s of air whose temperature and humidity is controlled to simulate actual conditions in flight. The heat exchanger matrix is cooled by cold gaseous nitrogen whose thermal capacity matches the helium flow employed in the real engine. Although the test matrix is much smaller than the real pre-cooler, it is built with the correct tube diameter, wall thickness and material. Therefore no 'scaling' problems can arise since it is tested at identical flow mass fluxes and Reynolds numbers to the real engine.

A typical result from these experiments is shown in Fig. 11. During a test run lasting over 10 minutes at –80°C the pressure drop across the heat exchanger remains constant.

These successful technology programs have enabled the construction of a flight standard heat exchanger module (Fig. 12). The next stage is to construct a full precooler consisting of 48 modules which will be tested on a specially constructed static test stand.

The B9 test facility is shown in Fig. 13 with a "dumb" precooler used for the commissioning testing. The facility is built around a Rolls Royce Viper jet turbine which has been modified to run on liquid butane so it can operate at cryogenic temperatures. The engine is located, inside a protective concrete structure, together with a specially made silencer to muffle and cool the exhaust. The facility supplies liquid nitrogen, fed from a large storage tank to be used as a heat sink. The

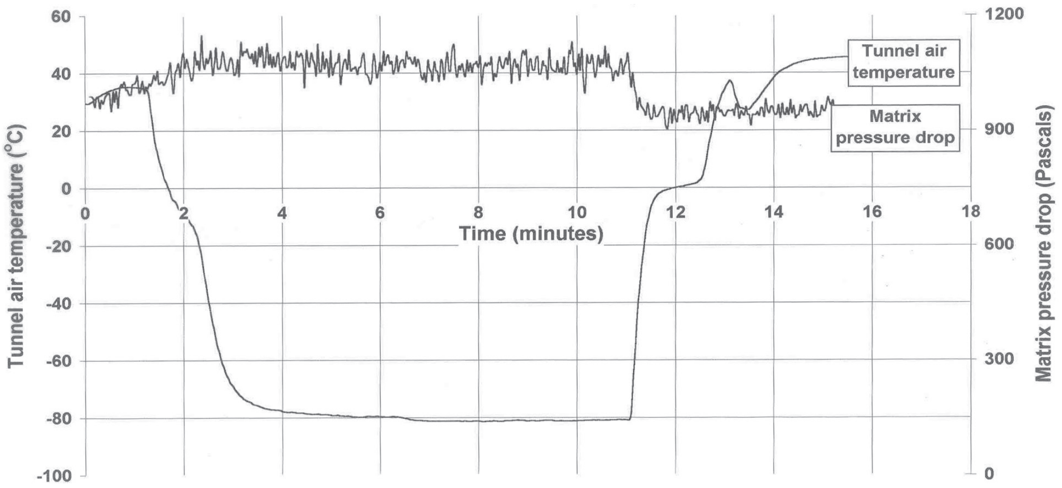

Fig. 11 Typical test result from frost control experiment.

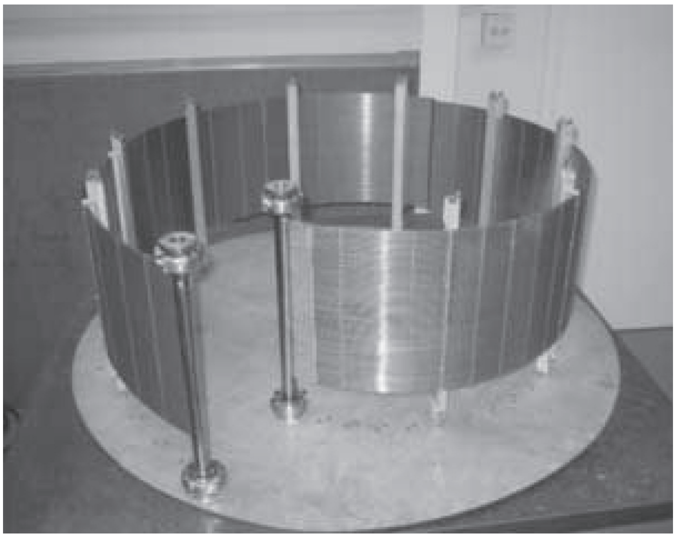

Fig. 12 Flight standard precooler module.

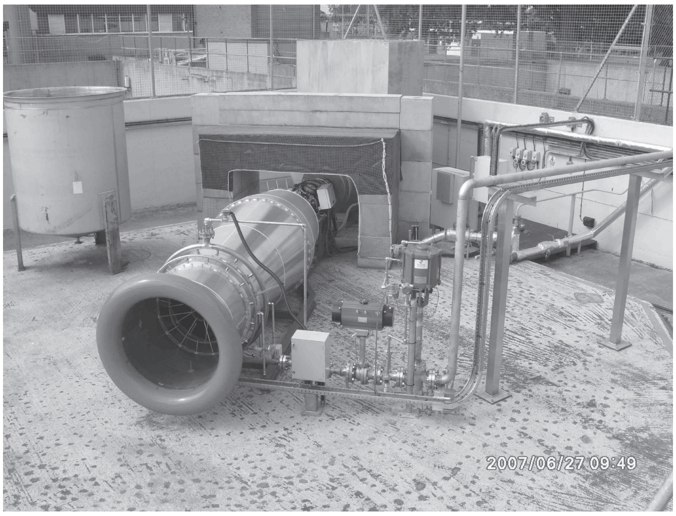

Fig. 13 B9 Test facility with commissioning 'dumb' precooler.

liquid nitrogen can either be injected into the incoming air stream to cool down the airflow directly, or employed as a heat sink for a closed helium loop in conjunction with a pre-cooler. Heat exchanger modules are then mounted in front of the engine intake for testing and characterisation at low temperatures.

Figure 14 shows a system diagram of the B9 facility. The test will not only prove the construction and heat transfer performance but also has water injectors to demonstrate the frost control in all atmosphere conditions including rain. The test article will be a full segment of the Sabre engine with 9% flow and area of the complete engine.

While this technology program has led to the manufacture of flight standard heat exchangers that exceeds the original project expectations, it does not represent the end of heat exchanger development. Increasing the heat transfer efficiency has a large impact on the overall engine performance [11]. A research program exploring methods to augment the heat transfer process has been initiated and may produce results that will be incorporated into the final design.

4.2.2 High Temperature Heat Exchangers

The majority of the development effort has been devoted to the main intake air heat exchanger as it dominates the overall engine performance. However there are other heat exchangers in the engine cycle and some of these are required to work with surface temperatures around 1100 K. This necessitates the tubes to be made from Silicon Carbide, which requires special manufacturing techniques. A manufacturing research project has been undertaken exploring a range of possible techniques:

Pressureless sintering,

Chemical vapour deposition,

Liquid silicon conversion of graphite,

Reaction bonding

Tubing suitable for the high temperature heat exchangers has been produced (Fig. 15) but the final conclusions as to the best manufacturing route, or the brazing techniques to attach the tubes to feed headers have yet to be determined.

4.3 Expansion Deflection Nozzles

The Sabre engine in the C1 configuration has four conventional bell nozzles which represent a compromise between over-expansion at sea level and under-expansion in vacuum. Conventional nozzle design avoids over-expansion in the nozzle due to the large sideloads that can result from unstable flow separa-

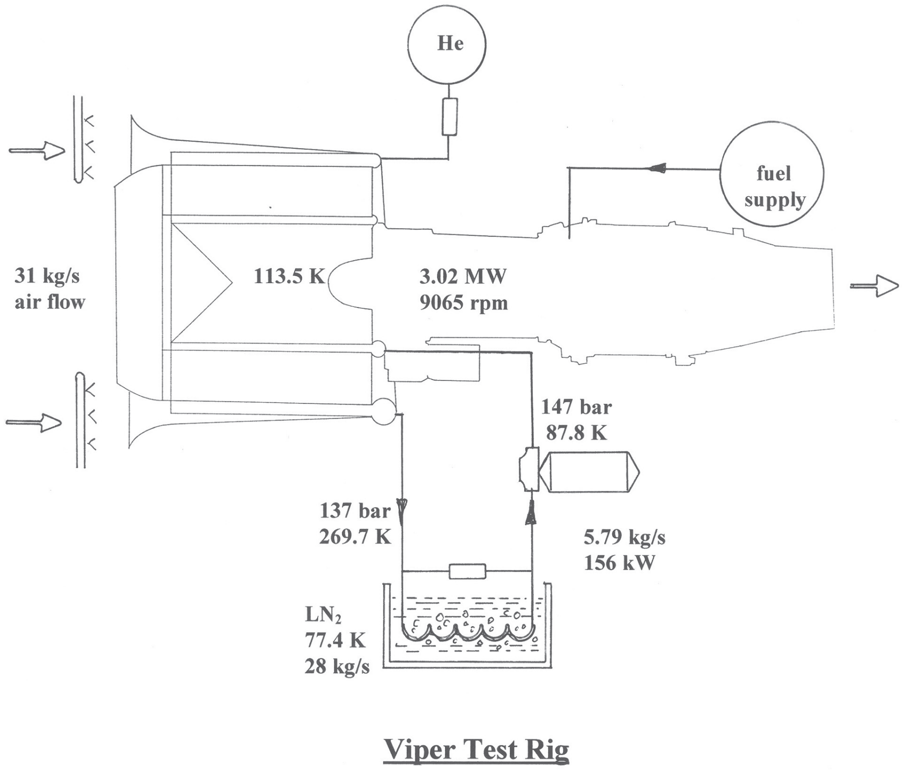

Fig. 14 System diagram for B9 precooler test.

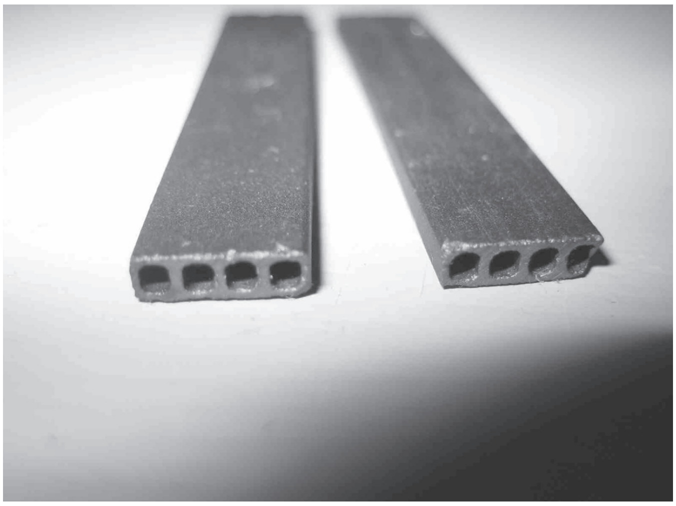

Fig. 15 Extruded silicon carbide heat exchanger section.

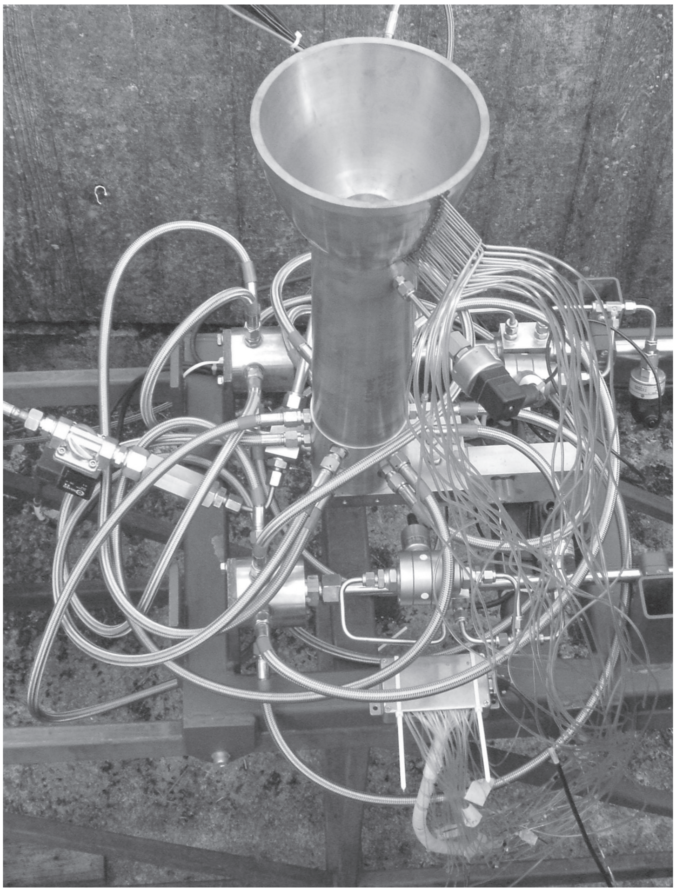

Fig. 16 The STERN test chamber on its test stand.

tion. However there are techniques that can avoid this problem and the Sabre engine benefits from an over-expanding nozzle to gain vacuum performance. Nevertheless the over-expansion remains undesirable at sea level since the loss of thrust results in a 500 metre longer take off run. Whereas the loss of specific impulse in vacuum under-expansion results in a payload loss of around half a tonne.

This situation led to an interest in nozzles that have the potential for pressure compensation, of which the expansion deflection type seemed to offer the most promise. A research programme was established at the University of Bristol, which developed the analytical tools to design these nozzles [12, 13] and experimentally determine their behaviour in open wake mode [14].

To build upon this work the STERN (Static Test Expansion deflection Rocket Nozzle) project was initiated by a consortium of Reaction Engines Limited, University of Bristol and Airborne Engineering Limited. A 5 kN thrust chamber with a 100:1 area ratio expansion deflection nozzle has been constructed fuelled by gaseous air and hydrogen (Fig. 16). This propellant combination enables the Sabre engine's injectors and ignition system to be tested as an additional program objective.

The engine is heat sink cooled and consequently can only be fired for a little under a second, however the flow is stable over this period. In the 8 firings achieved so far (at the time of writing) good results have been obtained from the heavily instrumented chamber. While it is too early to draw final conclusions it is clear that the desired altitude compensation in very high expansion ratio nozzles can be achieved. It is probable that this nozzle type will be incorporated into the final Sabre design.

5. CONCLUSIONS

The technology programs carried out over the last two decades have shown that the technology assumptions in the HOTOL/ Skylon projects are achievable. In many cases experimental investigation has led to further development in new areas so that greater performance may be available when the final design for Skylon is undertaken.

This extra performance can be used to both increase the system margins reducing the technical risk and increase the performance, with consequent reduction in the specific launch costs.

The next stage is a final set of research projects with substantially increased funding and a wider range of industrial partners. This will give high confidence in the technology assumptions used in the final design. Skylon configuration C1 is a relatively old design and work is underway to incorporate various improvements into a new baseline; configuration D.

ACRONYMS

HOTOL	HOrizontal Take Off and Landing
Hx	Heat Exchanger
ISS	International Space Station
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
OMS	Orbital Manoeuvring System
RCS	Reaction Control System
SiC	Silicon Carbide
STERN	Static Test Expansion deflection Rocket Nozzle

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