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DOCUMENT

Skylon Assessment Report

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1 INTRODUCTION

This document summarises the assessments performed by the Propulsion Engineering and Structures Sections of ESA- ESTEC into the design and development of the SKYLON Spaceplane, currently under development by Reaction Engines Ltd (REL).

This assessment was requested by the UK Space Agency (UKSA) to ESA to provide an independent assessment of the feasibility of the proposed design as well as to assess any areas of concern and provide recommendations for the future.

The SKYLON spaceplane and its associated SABRE engine is a completely different concept with regards to current expendable launch vehicles. If successfully developed, its proposed flexibility and high reusability has the potential to support the current launch market as well as leading to the development of new markets.

As well as the internal assessment performed by ESA, this report also includes the results and conclusions of the SKYLON Requirements Review, a technical and financial peer review, held on the 20th and 21st of September 2010.

This document will present the current results of the activities described above and will present recommendations/conclusions for future work.

The document concludes that, no impediments or critical items have been identified for either the SKYLON vehicle or the SABRE engine that are a block to further developments. It is clear that the SABRE engine is crucial for the successful development of the SKYLON vehicle.

The consensus for the way forward is to proceed with the innovative development of the engine which in turn will enable the overall development.

The SABRE engine offers to deliver both high thrust to weight ratio and high performance over the Mach 0 to 6 range based on a single cycle. This is a major advantage in comparison to alternate air-breathing engine designs.

In particular, based on REL's flight like heat exchanger technology and their successful demonstration of the frost control mechanism at laboratory scale (a major milestone that has so far eluded other international developments), ESA are confident that a ground test of a sub-scale engine can be successfully performed to demonstrate the flight regime and cycle and will be both a critical milestone in the development of this program and a major breakthrough in propulsion worldwide.

For the future SKYLON vehicle, the concept and structural design work undertaken by Reaction Engines Ltd does not demonstrate any areas of implausibility, due to the relatively benign environment of the flight trajectory.



2 SCOPE

This document is split into various sections, section 4 summarises the SKYLON and SABRE engine as designed by Reaction Engines Ltd and reproduces parts of reference RD1 as an introduction to the vehicle and engine designs. It also details the current GSTP/TRP funded technology developments.

Section 5 of the report details the UKSA SKYLON Requirements Review, and review conclusions reached by ESA.

This document does not cover vehicle performance and trajectory analysis as this was successfully performed and presented in RD1, but instead details the work performed subsequent to this which focuses on the technical review of the vehicle and engine programs, refer to sections 6 and 7.

The overall conclusions and proposed next development steps are outlined in section 8 of the report.

3 REFERENCE DOCUMENTS

- RD1 Hybrid Air-breathing and Rocket Propulsion for Launch Vehicles, ESA study contract report, ESA Contract no. 19713/06/NL/PA
- RD2 SKYLON System requirement Review: SKYLON Commercial Operation, Alan Bond, Reaction Engines Ltd
- RD3 Preliminary Independent stress test for SKYLON development and production costs, Presentation, London Economics
- RD4 Independent economic assessment of the future benefits to the UK of investment in the SKYLON reusable launcher, Presentation, London Economics
- RD5 Independent economic assessment of the future benefits to the UK of investment in the SKYLON reusable launcher, Report October 2010, London Economics
- RD6 SKYLON System requirement Review: The SKYLON vehicle, Richard Varvill, Reaction Engines Ltd
- RD7 SKYLON System requirement Review: The SABRE Engine, Alan Bond, Reaction Engines Ltd
- RD8 SKYLON System Requirement Review Economic Questions, SKY-REL-RP-0013, Rev 1, 28th OCT 2010
- RD9 SKYLON System Requirement Review Technical Questions, SKY-REL-RP-0014, Rev 1, 28th OCT 2010



- RD10 SKYLON Spaceplane JBIS Vol 57 pp 22-32, 2004
- RD11 Application of Carbon Fibre Truss Technology to the Fuselage Structure of the SKYLON Spaceplane, JBIS, Vol 57 pp xxx-xxx, 2004
- RD12 SKYLON Users Manual, Rev 1.1, SKY-REL-MA-0001
- RD13 ESA Co-Sponsored PhD on High-Speed propulsion cycles: Analysis and Optimization, TN3000: Optimization of a TBCC, V. Fernandez Villace, July 20 2010, Von Karman Institute for Fluid Dynamics.
- RD14 A comparison of Propulsion Concepts for SSTO Reusable Launchers, FBIS, Vol 56,PP108-117, 2003

4 SKYLON/SABRE OVERVIEW

4.1 Introduction

Sections 4.2 to 4.4 are an introduction to the SKYLON and SABRE engine. They are reproduced in part from RD1 – a study document produced for ESA by REL and provides an introduction and overview of the vehicle and engine from the REL perspective. The ESA assessment of these programs is detailed in sections 6 and 7.

4.2 Hybrid Air-Breathing-and-Rocket Propulsion for Spaceplanes

(Text extracted in parts from RD1)

Integrated rocket and air-breathing engines have been under continuous study at Reaction Engines Ltd (REL) and by the Company's founders for over 24 years, since before the inception of the BAe HOTOL project in which the use of this type of engine was first explored, (figure 4-1).

The motivation for this continued research is the promise of a propulsion system which can realise a single stage fully reusable launch vehicle having high re-entry cross range with short turnaround time and flexible mission operations (orbital parameters and duration, payload size, lead time, etc). This could be achieved in a vehicle having a significant payload fraction (4.3% to due east orbit, 1.7% to polar orbit) with a launch mass of 275 tonnes and runway operation (horizontal take-off and landing). Reaction Engines Ltd are proposing the SKYLON vehicle to achieve these goals.

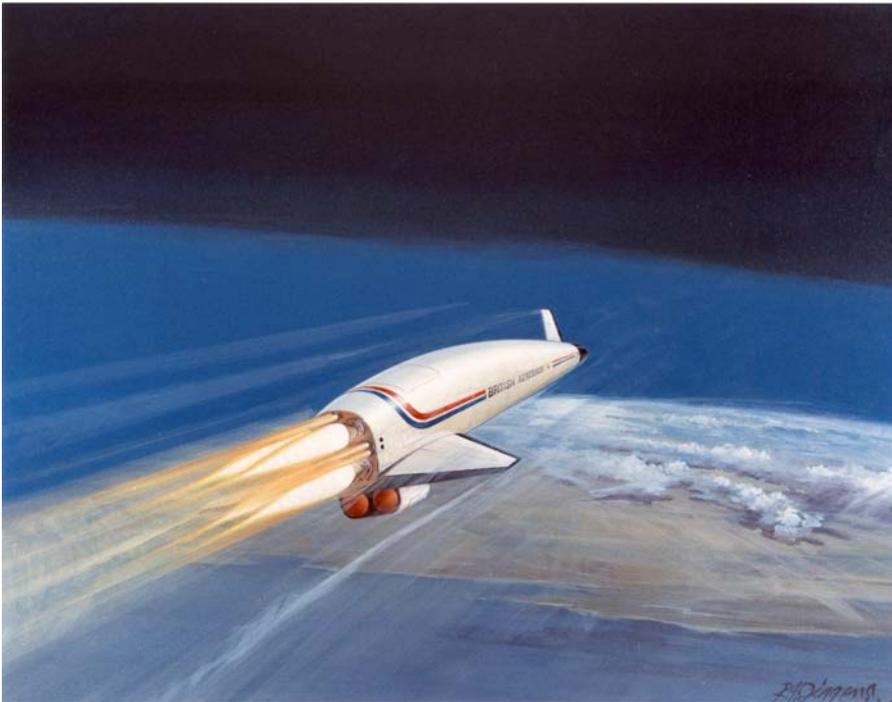


Figure 4-1 The HOTOL spaceplane concept (RD1)

If a future launch vehicle is to achieve a low specific launch cost (low cost per kilogram placed into orbit) and be genuinely easy to operate, then it must meet some general criteria:

- The vehicle should consist of only a single stage in order to reduce the development and operational cost compared to multi-stage vehicles.
- The vehicle should be as reusable as possible.
- The vehicle should be computer controlled, as qualifying a vehicle for piloted flight increases the development costs.
- The vehicle must use a launch trajectory which is benign to the airframe in terms of aerodynamic heating and loading.
- The vehicle should have simple launch and recovery procedures to minimize the turnaround time and cost.
- The vehicle must be capable of an aborted landing at any time during the ascent in the event of a propulsion system problem, preferably returning back to its launch site.
- The engine must be capable of open test bed operation to minimize development costs.
- The engine should employ well explored aerothermodynamics and existing materials technology.
- The vehicle systems must be designed for minimal maintenance between flights.

- The vehicle needs to interface with other elements if, as a new transport element, it is to become part of an efficient transport system.
- The vehicle should use environmentally friendly propellants in order to avoid atmospheric pollution.

4.3 The Reaction Engines Ltd SKYLON Design

(Text extracted in parts from RD1)

SKYLON is a reusable single stage to orbit (SSTO) winged spaceplane designed to give routine low cost access to space. The current design has a gross take off weight of 275 tonnes, of which 220 tonnes are propellant, the vehicle is capable of placing 12 tonnes into an equatorial low Earth orbit.

SKYLON (Figure 4.2) consists of a slender fuselage containing the propellant and payload bay, with a delta wing located roughly midway along the fuselage. The engines are mounted in cambered axisymmetric nacelles in the wingtips. Control of the vehicle while in the atmosphere is achieved by foreplanes in pitch, ailerons in roll, and an aft mounted all moving fin in yaw. The rocket engine exhaust nozzles are gimballed individually but move together within each nacelle and are designed for ± 3 deg movement in pitch and yaw. The nozzles are 'frozen' during the air breathing ascent but become 'live' during the rocket ascent. During the rocket ascent main engine gimbaling takes over progressively from the aero controls as the dynamic pressure reduces, until finally reaction control thrusters take over at main engine cut-off. The vehicle is capable of takeoff and landing on conventional runways on its own undercarriage.

The SKYLON configuration evolved from a design review of the HOTOL airframe, and represents an efficient resolution of various problems encountered by the latter project.

The HOTOL airframe was derived from conventional vertical takeoff rockets, with the engines mounted at the rear of a blunt based fuselage. Since the dry centre of gravity was determined by the engine location the wings and fuelled centre of gravity (the liquid oxygen tank) had also to be at the rear. Consequently, the payload bay and hydrogen tanks were fitted into a projecting forebody. This configuration suffered from a serious centre of pressure/centre of gravity mismatch during the air-breathing ascent.

In order to trim the vehicle, various alterations were made to the design, all of which eroded the payload margin. In order to improve the payload fraction a conventional undercarriage was discarded and replaced by a specially designed takeoff trolley. Taken together, the above problems resulted in a vehicle with serious operational disadvantages and a small payload, with recourse often made to untried and speculative materials to counter the deficiencies of a poor design.

In contrast the SKYLON airframe is a new configuration that solves the trim and structural problems in a more efficient manner using broadly the same components. Some advantages of the SKYLON configuration over that of HOTOL are:



Figure 4-2 The SKYLON spaceplane during take-off and re-entry (Adrian Mann images – RD1)

- Independent design control over the empty centre of gravity is achieved by installing the propulsion system in nacelles on the wing tips; to avoid disrupting the trim during re-entry, the payload bay is coincident with the centre of gravity, over the wing; the liquid oxygen tank is split and placed either side of the payload bay; the hydrogen tank is also split in two and placed at the ends of the fuselage; in combination these measures almost eliminate any mismatch between centre of pressure and centre of gravity during ascent and re-entry.
- The wing area can be optimized for maximum ascent performance, because the trim problem is solved, which results in a lighter wing structure and greatly reduced flap power demands
- As a result of design the takeoff trolley has been eliminated and replaced by an integral undercarriage capable of a rolling takeoff.
- Existing or near term materials can be used in the engines and vehicle, thus minimising development risk, placing emphasis instead on advanced manufacturing techniques and novel structural concepts to achieve lightweight designs.

SKYLON differs from other spaceplane configurations in several key respects. Apart from the unique propulsion system, the main difference is an aerodynamic configuration that comprises a definite wing plus body. This was selected because it proved to be more optimum in terms of weight, lift and volume than the more fashionable blended bodies frequently portrayed for spaceplanes.

An additional advantage of this is it allows the separation of vehicle and engine for testing.

An unusual feature resulting from this is that the wing does not fit within the body bow shock wave during re-entry, giving rise to a localized heating problem that is addressed by actively cooling part of the wing.

The aeroshell forms the outer surface of the vehicle and therefore must withstand the local aerodynamic pressure loads and kinetic heating. The aeroshell is passively radiation cooled and during the ascent reaches a maximum temperature of 855 K. Re-entry occurs at a relatively high altitude on SKYLON (typically 10 km higher than the Space Shuttle) as a result of the lower ballistic coefficient (mass per unit plan area). During re-entry the temperature is kept down to 1100 K by dynamically controlling the trajectory via active feedback of measured skin temperatures. This is possible by virtue of the low ballistic coefficient and the controllability of a lifting vehicle with active foreplanes.

4.4 The SABRE Engine

The Synergistic Air-Breathing Rocket Engine (SABRE), refer to Figure 4.3, is designed to deliver a high air breathing thrust-to-weight ratio with moderate specific fuel consumption whilst reverting to a high specific impulse rocket engine at transition. Since the air-breathing mode operates on a turbomachinery based cycle (Figure 3.3) the engine is capable of generating static thrust (unlike ramjet cycles) and engine development can therefore take place on open test bed facilities.



According to RD10, optimum transition from air breathing to rocket mode with this type of power plant occurs at around Mach 5 and at 26 km, after which the vehicle climbs steeply out of the atmosphere to minimize drag losses. The resulting ascent trajectory is relatively benign to both engine and airframe, leaving a wide choice of airframe materials capable of withstanding the ascent and re-entry temperatures without active cooling.

The engine under consideration by REL (the SABRE engine) is an airbreathing engine that reverts to pure rocket mode once the vehicle has reached sufficient altitude and speed. This concept, like all types of airbreathing engine (Turbojets, ramjets, scramjets), offers a significant performance increase over rockets. This is of course because only the stored fuel mass is significant for performance for the airbreathing part of the engine operation.

The traditional downside with these types of engines are twofold, firstly that traditional air breathers only operate across a limited Mach number range. For example scramjets need to be accelerated up to speeds of at least mach 4 before they can operate. This leads to expensive ground test facilities or in-flight testing only.

The second issue with traditional airbreathing concepts is that they have very low thrust to weight ratios. Thus for any launcher employing these engines the inert mass of the launcher (non-payload mass carried into orbit) must also increase.

The SABRE engine whilst having a performance (ISP or specific fuel consumption) comparable to current scramjet concepts has two distinct advantages, firstly that it can operate across the entire Mach range from 0 to Mach 6, this enables testing on the ground using established principles without recourse to expensive large scale wind tunnel or flight test facilities. Secondly it has a high thrust to weight ratio in comparison to other concepts.

RD14 states that it is these two factors – Competitive ISP for high Mach number operation performance, coupled with high thrust and low installed weight which makes the engine competitive for SSTO applications. The key enabling technology for the engine has been identified as being a large, lightweight, highly efficient pre-cooler with associated heat exchanger. Prototype modules have been successfully operated at fully cryogenic temperatures and a version is presently entering a new experimental phase where it is due to be tested on a Viper jet engine.

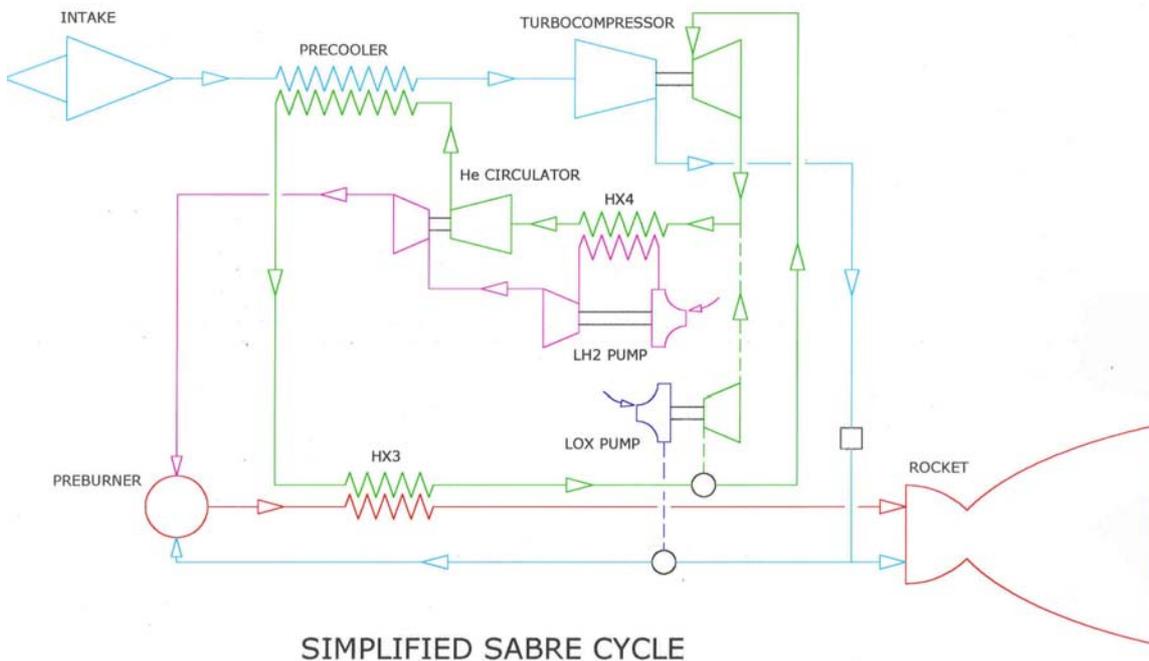


Figure 4-3 SABRE engine turbomachinery based cycle (RD1)

4.5 Current ESA involvement on the SABRE engine development

Since 2009 ESA propulsion has been involved to help develop the engine technology through the technical management of a combined GSTP/TRP program to test key components of the SABRE engine. This program consisted of several elements and these are described as follows:

- Demonstration of pre-cooled engine with frost control (REL) air intake

The largest component of the program is the precooler development. This will involve manufacture of a precooler module. A representative pre-cooler will be installed upstream of a jet-engine to simulate realistic operational conditions including the effectiveness of the frost control. (Frost control is required on the pre-cooled engine as humidity in the air will otherwise condense and freeze in the sudden temperature drop and the resulting ice formation can block the intake flow path rapidly).

- Thrust chamber and nozzle concept in conjunction with EADS-Astrium and Bristol University.



The thrust chamber must be cooled by the oxidiser, high pressure air during airbreathing and liquid oxygen during rocket modes.

The thrust chamber activities are targeted at demonstrating liquid oxygen and air cooling of a copper liner and the operation of a suitable atmospheric compensating nozzle.

A hybrid airbreathing and rocket engine must operate over the whole range of back pressure, from the Earth's surface to space. The engine performance is therefore very dependent on the expansion ratio of the nozzle. There is strong motivation to find an adaptive nozzle design which can compensate for atmospheric back pressure.

Phase 2 follows on from these activities and will conclude in 2012 and includes the following elements,

- Demonstration of the pre-cooled engine with frost control air intake.

The demonstration of the operational feasibility of the pre-cooler shall consist of the assembly of the pre-cooler and then integration on the test engine facility completed during Phase 1 (cooling loop and jet engine system). Following this a series of tests shall be performed in which the pre-cooler operation will be demonstrated. These tests shall be performed with ambient air at different relative humidities in order to demonstrate the control of frost build-up by the pre-cooler.

- Air intake

The investigation of intake operation shall consist of the analysis of the baseline intake design followed by the design of a representative model with correctly scaled parameters. The model will then be procured and tested across a range of representative supersonic Mach numbers in order to demonstrate its operation.

- Implementation and operational issues of the SABRE

This task will re-assess the vehicle performance using the updated engine performance results obtained in the activities described above.

The pre-cooler test on an actual jet engine is a critical milestone for the development of the engine. This will be the first time that a sub-scale heat exchanger module would be tested outside of the laboratory. The objectives of the test will be to demonstrate active cooling and control of frosting over the Mach 0-6 regime.



5 UKSA SPONSORED SKYLON SYSTEM REQUIREMENTS REVIEW.

5.1 Scope

On September 20-21st 2010, the UK Space Agency hosted a meeting at the International Space Innovation Centre at Harwell, United Kingdom to look at the feasibility of the design of the SKYLON vehicle and the SABRE engine. The meeting brought together nearly a hundred invited experts from Europe, Russia, the US, South Korea and Japan to examine the technical and economic prospects for the technology.

The purpose of the review was for an independent assessment of both the SKYLON and SABRE proposals and was intended to be an important milestone in the UK government's evaluation of the proposal.

The review agenda consisted of a two day programme where the overview of the vehicle and engine was presented, with the first day dedicated to the economic analysis of the vehicle and its operations and the second day focused on the technical assessment of the vehicle and engine.

5.2 Economic models presented

The following sections give an overview of the economic analysis presented by REL and London Economics (LE). It summarises the presentations and any concerns/comments that ESA have on this subject.

5.2.1 REL Economic Analysis

The economic case was presented by REL in RD2 and is reproduced and summarised as follows (with ESA comments):

- REL stated that the SKYLON vehicle program is fundamentally commercial being able to operate:
 - Without subsidies
 - Repaying development and production costs
 - Operate at profit
 - Have a lower specific price to orbit than Expendable Launch Vehicle (ELV) competition



- REL stated that the existing imperfect launcher market is not an insurmountable obstacle to introduction of a new vehicle
 - Through examination of externalities
 - Through Government best practice Cost Benefit Analysis.

Furthermore REL presented a number of requirements for such a system that are:

- 200 Operational flights per vehicle
- 2 day mission (+2 day contingency)
- 2 day turn round (mature operation)
- 2300 Km cross-range

The opinion of ESA is that of the above requirements the two most challenging are the number of flights and the two day turn around. The vehicle/engine reusability aspects are treated in sections 6 and 7 of this document. The aspect of turnaround has important impacts on the design of the both the vehicle and the engine and will be one of the factors that will heavily influence the economic model, as long periods of maintenance (and hence vehicle non-availability) will lead to increased maintenance costs and loss of potential revenue.

The economic model was explained to include several factors that are important for the success of the program, this included the explanation that that the vehicles will be sold and operated by independent operators (i.e. aircraft business model), who will lease/pay for facilities, maintenance, fuelling etc.

One point to be made is that ESA considers that the SKYLON Upper Stage (SUS) which is potentially required for GTO missions may need to be included in the overall development costs. This is because if telecoms spacecraft customers have to pay to develop a GTO stage on top of the launch price then this may push the cost to orbit to a point where the SKYLON becomes less competitive. ESA recommends that the development cost model of the vehicle be re-assessed to account for the additional cost of developing the SUS.

Another point made by REL was that insurance will be required for the launcher and this will be a significant percentage of the overall cost passed on to a potential customer. The argument was made that the insurance price will not go down with increasing payload demand and as the overall launch cost is reduced for SKYLON anyhow, therefore the actual percentage of the price dedicated to insurance will increase.

ESA does not fully believe this to be the case as launch site geography (and hence related hazard to over flight locations) will vary. (If the vehicle overflow a densely populated part of the globe, the impacts of a failure are much more important and hence the associated insurance/liability costs would increase).

In this respect REL have assumed a pessimistic approach to their economic model.



One important aspect of this economic model is the cost predictions made by REL. They have applied parametric cost models to assess the development/production costs of the vehicle and engine.

In order to assess the accuracy of their models they have cross checked their models against the actual costs of past aerospace projects. The results were presented and REL state that the model accurately predicts a standard deviation of 15% for the correlations. In particular they present a comparison to Concorde that appears to be extremely accurate. The following table is produced from the figures that REL presented during the review.

| Program Name | Program completed | Actual Cost | Model Predicted |
|-------------------------|-------------------|-------------|-----------------|
| SSME | 1983 | \$1427M | \$1520M |
| Vulcain | 1995 | \$1080M | \$1016M |
| Concorde | 1974 | | |
| - Engine development | | 446M pounds | 434M pounds |
| Airframe development | | 688M pounds | 689M pounds |
| 84 production engines | | 172M pounds | 169M pounds |
| 14 production airframes | | 482M pounds | 497M pounds |
| Airbus A380 | 2006 | 14000M Euro | 16700M Euro |

Table 5-1 REL Cost comparison (REL state that Concorde figures are obtained from Concorde: New shape in the Sky, by K. Owen ISBN 07106 0422X [1982])

Thus based on their model they have predicted costs for the total development of the vehicle to be \$12,300M (including airframe and engine development).

REL consider this to be a pessimistic estimate as the last entry in table 5-1 shows an overestimating of the cost model as compared to Airbus A380. REL state that this disparity is due to the fact that the model does not take into account modern manufacturing methods which will lower the predicted price. Thus this logic can be applied to the SKYLON development and hence the \$12.3Billion cost can be seen as an overestimation.

Finally REL presented an analysis of operator economics, again with a pessimistic view of trying to capture the existing market without looking at the new and expanded markets that this vehicle could establish. They showed that the estimated operating costs for 70 flights per year could be as low as \$9.47M per flight (Jan 2009 prices).

It is clear that REL have devoted a large amount of time to establishing their cost models, and ESA's perspective is that they have performed as much economic analysis as is possible for a new vehicle which has the potential to completely change the approach to commercial spaceflight.

5.2.2 London Economics (LE) analysis

London Economics (LE) was employed by REL to perform an independent assessment of SKYLON economics. LE is a specialist economic consulting company. One of the activities LE undertakes is providing micro economic analysis across a broad range of policy for presentation to the UK government for potential funding.

They were asked by REL to perform two tasks:

- One was to assess the sensitivity of the business model (“stress test”) to see if the development program costs can be recovered over the production lifetime of the vehicle.
- The second task was to use the UK treasury rules to assess the impact of the SKYLON program on the UK economy.

5.2.2.1 London Economics “stress test” analysis.

The following description of the tasks performed by LE is a summary of their work presented in RD3 and which was also presented at the review. *It should be noted that this was however preliminary results and an updated report produced by LE was not available for review in time for inclusion.*

The “stress test” performed by LE stressed the production and development costs of the entire SKYLON program. The objective of these tests is to illustrate what the production vehicle price would be required to cover the development and the production cost. The price assessed here is not the market price but the cost recovery price – i.e. the minimum return required to cover the production and development costs

Thus LE considered two cost scenarios for the production and development of the SKYLON vehicle.

- An expected cost scenario which is based on the REL parametric method. (Discount rate of 12%).
- A scenario where the costs have been increased by 39% and also applying a discount rate of 12%.

For both scenarios the development period was fixed at 10 years. These two scenarios were then taken by LE to be mid-points around which a distribution is applied (normal distribution with a standard deviation of 15%). Also a conservative approach was taken; cost savings of greater than 10% was removed from the simulation.

In all LE performed 2000 simulations (random selections of price points in the distributions) of project development and production costs for the two scenarios. The



parameters that were varied for the two scenarios were the number of vehicles produced and the discount rate. It should be noted that the actual UK government discount rate (official figure) is 3.5 %.

The results of the analysis showed that except for high discount rates and low final numbers of production vehicles (<10) then the cost recovery figures are less than \$2bn per vehicle which is the target price used in the analysis. In fact if 30 vehicles are produced and using the official UK government discount figure of 3.5% the cost recovery per vehicle is \$0.81bn. (It should be kept in mind that this is the total per vehicle and each vehicle has a design lifetime of 200 flights hence this recovery cost is actually \$4.05M per flight not including inflation).

The main conclusion from this analysis was that the cost results are robust to the “stress testing” and the main factor driving the cost recovery is the number of vehicles produced and sold.

5.2.2.1.1 *ESA comments on the Stress Test analysis*

This analysis performed by LE seems sensible to ESA however it would be recommended to re-visit the model and vary the time for development to see the sensitivity of the cost recovery to schedule delays. Whilst it can be argued that this is covered by the worst case (ie 39%), there are potentially different effects that appear due to schedule slippage (eg potential additional interest on the initial borrowed capital).

5.2.2.2 London Economics green book assessment

(The following description of the tasks performed by LE is a summary of the work presented in RD4 and RD5).

The objective is to undertake a preliminary independent assessment on the future benefits to investing economies of the SKYLON vehicle.

This assessment uses government best-practice project appraisal methodology to evaluate future benefits. (The same rules are applied to all proposed public sector projects and programmes despite their nature and where it is deemed sensible to complete a cost benefit analysis).

LE have used the UK Economic and Finance Ministry methodology (Green Book), this is the same method detailed in the EC Impact Assessment guidelines 2006. (In addition to many other nations using the same process).

LE state that it should also be noted that this appraisal is different to an appraisal performed by private investors. This is purely a government appraisal and the purpose is to see if government intervention is justified, as for government intervention there needs to be market failure.



In the preliminary presentation LE state that market failure means that there are benefits from a project that are not just for direct investors but benefits that flow to the society as a whole. This means that the market is imperfect in some sense, it cannot operate on its own to ensure these additional benefits to the investing economies are captured. That is then why there is a justified role for government. (Government wants to maximise the benefits to its economy).

Market failure means that there are these additional benefits that may accrue to the investing economies which are not fully captured by direct investors. These are public goods and externalities. Market failure can also arise when there are imperfections in the market which mean incumbent firms have an advantage relative to new entrants and this is called market power.

- Public goods
- Externalities
- Market power

Thus LE applied market failure analysis to the SKYLON project. It was found that there are indeed public goods and externalities that are associated with the SKYLON vehicle.

Thus LE qualitatively assessed what they maybe and then proceeded to quantitatively model some of the public goods and externalities.

They also state that there are two points to note first that forecasting these, based on a future technology, is a very difficult task and secondly assessing the financial benefits is even more difficult.

Thus because SKYLON is a future technology with the difficulties described above in forecasting, a cautious approach to manage this uncertainty was taken and as such SKYLON was placed at a disadvantage.

This was done by LE in two ways:

- One way is to assume that there is no increase in growth or demand for launch services. This reduces the future benefits from SKYLON.
- The other way was to assume that current launch technology has a price of zero. Namely, it costs economies nothing to use incumbent launch technology. This again reduces the benefits of SKYLON.

The results of the assessment are that LE has found that there are public goods and externalities applicable to SKYLON, and possible market power held by incumbent launch technology.



They state that therefore on first principles, SKYLON is a programme in which government intervention is justified because there are benefits to investing economies in addition to the private return to private sector investors.

LE continued with the assessment and identified a number of public goods and externalities that apply to the SKYLON project.

The identified public goods were:

- Advanced heat exchanger technology
- Advanced materials
- Hydrogen aviation
- Formulation of new markets
 - Maintenance and replacement parts industry
 - Space finance and professional services
 - Spaceports
- Downstream services
 - E-commerce
 - Global weather and navigation
 - Catastrophe management
 - Space manufacturing and research
 - Solar power
 - Space tourism

The externalities identified the “green credentials “of the SKYLON i.e. use of hydrogen and oxygen (only water as an exhaust by-product), reusability, zero space debris. One negative externality was that possibility of increased noise on re-entry (potential creation of sonic booms over land).

Other positive externalities identified was increased STEM (Science Technology Engineering Mathematics) in the UK economy. There is also possible market power as the current launcher market is subsidised.

The quantitative assessment involved a cost benefit analysis to calculate the net present value. This is the value in today’s dollars of the future stream of benefits minus the future stream of costs.

LE took a subset of the public goods and externalities detailed above and modelled the expected benefits over a 30 year time period with a 3.5% discount rate. They assumed that the project would start in Q1 2010 and assuming a 10 year development (commercialisation) program the cost benefit analysis was run to 2039.

The results of the final analysis differ from the preliminary results presented at the SKYLON Requirements Review, the finalised figures (refer to RD 5) are;



- Net present value if no growth in satellite demand is assumed: Minimum is -\$3,5B and Maximum is \$10.5B
- The main NPV ratio benefits/cost = if no growth in satellite demand is assumed = Minimum 0.8 and maximum 1.5
- Net present value if growth in satellite demand is assumed: -1.9 to 15.2 billion
NPV ratio if growth in satellite demand is assumed: 0.9 – 1.7
- In all but the pessimistic scenario the NPV ratio is greater than 1

Therefore the conclusion of LE is that in the first instance there is justification for government support and this support is expected to generate returns to investing economies in addition to the returns to private direct investors and in excess of costs.

5.2.2.2.1 ESA comments on the LE Green Book Assessment

ESA notes that the assessment performed by LE has yielded mainly positive figures despite a difficult analysis. A number of issues need to be appreciated when assessing the results, one issue is the difficulty in assessing the impact of future technology on the market as well as the creation of new markets and services. In addition LE put SKYLON at a disadvantage to try and generate more realistic cost estimation figures.

The comment from the previous section is also relevant here, it would have been useful to analyse the impact of development schedule slippage on the final cost benefit figures. It is recommended that both assessments of LE are repeated by varying this parameter to assess the impact of a development schedule delay.

5.3 REL Technical Presentations

The technical presentations are presented in RD6 and RD7, ESA has performed a more in-depth technical assessment of the vehicle and the engine in sections 6 and 7, and as such this assessment encompasses any ESA comments to the technical presentations in the review.

There is however one point to note concerning the technical presentations made at the review, and this is that the vehicle presentation focussed on the current C1 (baseline) design with some information on the new high performance configuration, the D1.

The D1 configuration is still a work in progress and REL presented the C1 configuration at the review as the design maturity and performance are well understood. D1 was presented as a work in progress. There are clear indications that D1 performance with an improved SABRE engine will give significantly greater margins w.r.t delivered payload for a given Gross Lift-Off Weight (GLOW).



5.4 Question and Answer sessions

In addition to the presentations at the review the participants were invited to submit written questions prior to the meeting both for the economic and technical parts. These were answered by the relevant members and consultants of Reaction Engines and LE during the two days. Economic and Technical Q&A sessions were also held at the review where questions were posed and answered in real time.

For the economic questions this covered a diverse range of subjects including, technical and commercial risk, cost per launch, markets, maintenance costs and development programme, reliability, availability, sortie rate, production demand, investment models, insurance costs, and the use of SKYLON for GTO missions.

Refer to RD8 for a full description of the economic answers and questions.

The technical questions covered a range of SKYLON and SABRE issues and included the following diverse range of topics; aerodynamic performance, SABRE engine development, performance and test programme, engine life cycle and reusability, payload mass sensitivity, reliability, aeroshell materials, structural loads, emissions, human flight certification, reusability, engine maintenance, turbo compressor pressure ratio, heat exchanger manufacture, safety aspects, performance simulations, air breathing aspects, thermal protection systems, structure and thrust augmented nozzle design.

Refer to RD9 for a full description of the technical answers and questions.

ESA is unaware of any questions that were not answered to the satisfaction of the questioner (except where IPR forbid a full answer being given).

The review ended with a consensus that no technical or economic impediments to the development of SKYLON or SABRE had been found.

Annex 1 contains a list of the topics submitted and answered at the review. Some of the questions were submitted up to and including the 17th of September and were answered during the review.

In total some 65 technical questions and 21 economic questions were raised and answered during the review process.

5.5 Review Conclusions

The feedback that ESA has had from the review can be summarised as follows:



No technical or economic impediments have been identified to ESA either during or post-review. A number of points were made to ESA during and after the review and these are detailed as follows:

- Positive feedback was forthcoming on the heat exchanger design and this was considered an achievement in its own right.
- The feedback to ESA has indicated that the SABRE engine is not only a key piece of enabling technology for SKYLON, but in itself an important development with potential worldwide impact.
- The main comment expressed to ESA is that the demonstration of the SABRE cycle is the next logical step.

On the basis of what was presented ESA notes the following points:

- The issue of maintainability/reliability of the vehicle and engine and hence impact on the turnaround time will certainly influence the business model. However achieving tens of flights rather than hundreds with no major maintenance effort would also be a major breakthrough in this area.
- The cost of development of the SUS should be re-assessed with the option to include it in the overall development costs of the vehicle.
- ESA suggests that both the vehicle production price “stress test” and Green Book assessment performed by LE should also consider variations in the development schedule. This will enable the evaluation of the sensitivity of the cost model to schedule delay (and hence potential rising development costs and effect on the cost/benefit analysis).

The review was considered to be a success with no impediments identified either in the economic or technical presentations.



6 ESA TECHNICAL ASSESSMENT – SKYLON VEHICLE

6.1 Scope

The following sections identify the findings of the visits to REL by ESA experts in 2010 on the SKYLON vehicle concept. The assessment details the key areas discussed between ESA and REL.

6.2 Structure Concept Review

ESA experts visited REL during 2010 to assess the maturity of the current vehicle design and to identify potential risk areas.

The objectives defined for the period of the visits were as follows:

1. Technical Assessment of C1 structure design
2. Identify potential risk areas, with primary focus on structural design

Objective 1 was to assess the technical design and details of the C1 configuration with respect to structural aspects, which as of then had not been investigated by ESA. Furthermore there exists a D1 evolution which will become the new baseline; however this structural assessment is based on the C1. The D1 configuration is still a work in progress and REL presented the C1 configuration at the requirements review as the design maturity and performance are well understood. There are clear indications that D1 performance with the new SABRE 4 configuration will give significantly greater margins w.r.t delivered payload for a given Gross Lift Off Weight (GLOW). Also any structural concerns from the C1 design and resulting from the review will be implemented on the D1 configuration. The underlying technology of the C1 design remains the same for D1, primarily these are the CFRP strut structure concept and the ceramic composite skin structure.

Objective 2 was to assess the C1 structural design and identify any major risk areas.

The following sections detail the review of the C1 structure design,

6.2.1 Structure

The structure is described in detail in RD11 and is essentially a fuselage truss structure. The main structure of the spaceplane is more akin to that of an Airship than a conventional launcher or aircraft. An internal lattice like structure (constructed of CFRP struts fitting

into Titanium Alloy end fittings, known as nodes) provides the main structural component with the Aeroshell mounted on the exterior and propellant tanks internally supported.

6.2.1 Aeroshell

SKYLON is not a typical Aircraft and, as such, the external surface is not a conventional load bearing skin as seen on an aeroplane or indeed launch vehicle. All flight loads are taken up by the lattice structure internal to the SKYLON Spaceplane. The Aeroshell is expected to be made up of 300mm x 300mm CSiC panels, having a low thermal conductivity, attached to flexible mounting structure to allow for thermal expansion during re-entry.

6.2.1.1 Struts/Ring Frames

The ring frames are manufactured as a lattice structure from carbon composite struts with Titanium end fittings (nodes). The ring frames are then spaced 300mm apart by shear diagonals and connected to the Longerons. The Longerons, providing longitudinal stability, are spaced at approximately every 45° to the normal

6.2.1.2 SABRE Engine structure connectivity

Structural assessment was focused more around the nacelle material and the connectivity to the wing. Engine Nacelle material has not yet been identified, it is thought it could be of sandwich panel construction and the external surface would need to be same as rest of Aeroshell. Connectivity to the main wing is via two points in the engine and similar to an aircraft engine. Loads are then transmitted directly through spars in the wing section, since this is based on standard aircraft technology there are no concerns.

The full design of this has not been consolidated, however it is intended to be covered on the D1 Evolution.

6.2.1.3 Wings

The structural design of the wings is based on that used for an aircraft. Spars (likely to be composite) are used as the main load carrying structure through the wings. It is intended that each spar will run the length of the whole wingspan. Spar spacing is sufficient to allow the main undercarriage to be retracted without impacting structural integrity. The aeroshell for the wings is intended to be the same as for the main fuselage, and the leading edge of the wings is intended to be a carbon-carbon matrix. Rivets are used to fix the skin to the wing structure. The approach is understood to be similar to that described for the aeroshell. Thermal expansion is dealt with, longitudinally, by the hair pin joints and, transversely, by the ribbing of the material.



The thrust structure and lifting structure are considered separately from an analysis perspective which should prove conservative as, under this assumption, one element does not provide a contribution to the function of the other.

6.3 Secondary Structure

The whole RCS system operates as a “gas ring main” and is supplied from the aft propellant tanks. 32 RCS thrusters + extra orbital manoeuvres are covered by 2x 40kN Engines at the rear of the Spaceplane. This is further assessed in section 7.6.

For the harness design, the current estimate is based on detailed figures put together for the HOTOL design.

6.4 Thermal

6.4.1 Fuselage MLI insulation

The temperature drop across the thermal blanket inside the structure and just beneath the ceramic heat shield is from 1070K to 288K, across 10 spaced layers of titanium foil. The last foil in the lay-up protects the hydrogen tank and is hence maintained at 288K by the hydrogen boil off in the tank. The foil layer above this sees a temperature of approximately 670K.

6.4.2 Wing internal MLI insulation

The wing internal structure requires some thermal protection around the spars ribs and thrust structure due to the hot skin. Furthermore there are several cryogenic lines in the wing cavity.

6.4.3 Re-entry cooling screens

There is not enough internal structure away from the regions containing tanks (nose, payload bay and tail) to absorb the heat generated during re-entry. In order to remove heat from these regions there is a 0.1 mm thick Aluminium sheet with cooling pipes at a 15 cm pitch. The hydrogen (H₂) for tank pressurisation taken from the APS tankage is routed through the tubes. The aim is to limit delta T to 45 degrees during re-entry.

6.4.4 Leading edge cooling

The impingement of fore-body shocks on the wing leading edge leads to potential Type 4 shock interaction. A separate leading edge active cooling system/insert is foreseen.

6.5 Control Surfaces

6.5.1 Aileron

The aileron is significant in size relative to the overall wing and is effectively an integral part of that element of the vehicle. The structure is taken as a cantilevered hot structure. A possible fan type rib/spar structure will be lighter than the current approach and realisable.

6.5.2 Fin

The fin is correctly sized for the vehicle trim in all cases including engine out. The structure and design of the fin is not thought to represent a critical issue “show stopper” as it is in the vehicle wake during re-entry

6.5.3 Foreplanes

The concern for the foreplanes relates mainly to the heating during re-entry. In this event the fins exceed their design limit temperature and as a result a water dump cooling system was included. In principle this can be shown to work but there is some residual concern in the complex flow region at the fuselage junction.

6.6 Propellant Tanks

The liquid hydrogen (LH₂) and liquid oxygen (LOX) tanks are effectively one joined tank, separated by insulation. The LH₂/LOX tanks are an unsupported structure, relying on an internal pressure of approximately 2 bar (absolute) on ground to maintain structural integrity during handling. The mission pressure schedule is designed to maintain a 1 bar delta P (2 bar absolute at ground roll and 1 bar absolute on orbit). Boost pumps are used to empty tanks prior to re-entry. The tank pressures are managed for this phase by control of venting via a relief valve system.

6.7 Hydraulics & Actuators

Actuators for the fore-planes, ailerons and tail are included along with the relevant supplies. The HOTOL estimates were scaled and there is no engineering factor or contingency applied. It should be verified that this estimate includes HOTOL contingencies and is not a raw estimate. This said, no further early actions relating to this topic are foreseen.



6.8 Avionics, electrics and thermal management

For the avionics, electrics and thermal management, the approach was again to apply a scaling of the HOTOL figures. This is likely to be conservative for the actual boxes due to advances in the avionics field. However; harnessing is difficult to address at this stage.

6.9 Undercarriage

A water-cooled under carriage is assumed as, without it, the brakes were originally sized by the abort case fully laden. Nitrogen (N₂) is used for inflation. High pressures are required for takeoff however; for landing, the vehicle only needs around 5 bar, 66kg of N₂ is required for take off and it is foreseen to vent to the lower pressure level for the trip to orbit (The effect of a failure to depressurise is not assessed but the mass penalty will be small). With water cooling, the brakes are now sized by the landing to 25.8 kg per wheel.

6.10 Conclusion

In summary, the overall concept and structural design work undertaken by REL does not demonstrate any areas of implausibility, given the relatively benign environment of the flight trajectory. It is believed that concept maturity in this area can be achieved rapidly through sophisticated CAD and FEM analysis, CFD modelling and subscale tunnel tests.



7 ESA TECHNICAL ASSESSMENT – SABRE ENGINE

7.1 Scope

The following section identifies the findings of the visits to REL by ESA experts in 2010 on the SABRE concept. The assessment details the key areas discussed between ESA and REL.

7.2 Overview

In principle all types of Air-breathing engine (Turbojets, ramjets, scramjets) offer a significant performance increase over rockets. This is of course because only the stored fuel mass is significant for performance for the Airbreathing part of the engine operation.

The traditional downside with these types of engines are twofold, firstly that traditional air breathers only operate across a limited Mach number range. For example scramjets need to be accelerated up to speeds of at least mach 4 before they can operate. This leads to expensive ground test facilities or in-flight testing only.

The second issue with traditional airbreathing concepts is that they have very low thrust to weight ratios. Thus for any launcher employing these engines the inert mass of the launcher (non-payload mass carried into orbit) must also increase.

The SABRE engine whilst having a performance (ISP or specific fuel consumption) comparable to current scramjet concepts, has two distinct advantages, firstly that it can operate across the entire Mach range from 0 to Mach 6. This enables testing on the ground using established principles without recourse to expensive large scale wind tunnel or flight test facilities. Secondly it has a high thrust to weight ratio in comparison to other air breathing concepts.

RD14 states that it is these two factors – Competitive ISP for high Mach number operation performance, coupled with high thrust to weight ratio which makes the engine competitive for SSTO applications (refer to figures 7-1 and 7-2).

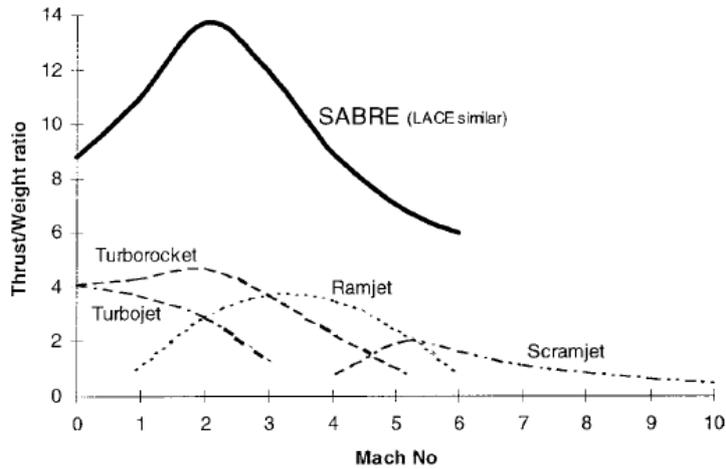


Figure 7-1 SABRE Thrust to weight ratio vs Mach no. (RD14)

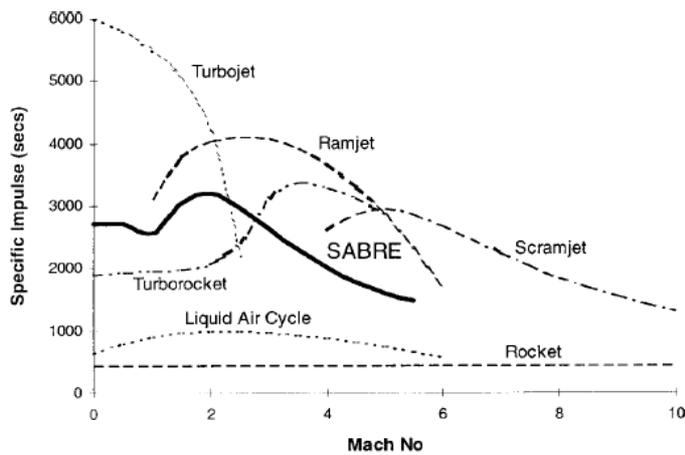


Figure 7-2 SABRE ISP vs Mach number (RD14)

7.3 SABRE Cycle Analysis (Von Karman Institute)

As part of the investigation into high speed propulsion ESA has sponsored a PhD with the Von Karman Institute (RD13). The following text is reproduced from a summary of the PhD work performed and provided separately to ESA.



VKI state that study considered three different cycles, the SABRE Engine, the Air Turbo Rocket and the Turbo Accelerator engine and that the Air Turbo Rocket is the cycle that the JAXA ATREX engine is based on and the Turbo Accelerator is the cycle employed in the engine for the Lockheed SR-71 “Blackbird” aircraft.

Their investigation into the SABRE engine focused on the maximizing the specific impulse of the cycle. The model derived is using the ESPSS libraries in the EcoSim software with updated turbine and compressor models. The derived model can predict the performance along the complete air-breathing trajectory of SKYLON and the results of this was presented in the LAPCAT II progress meeting in March 2010.

VKI also state that one of the limitations of this SABRE modelling is that the majority of the engine data is obtained from the final report of the SABRE engine for FESTIP, delivered to VKI by Reaction Engines in 1997. It is ESA understanding that the engine information in this report is for an earlier engine design and hence does not correspond to current version of the engine. However, the major cycle layout is still representative for the latest cycle version and hence raises some critical issues.

The VKI analysis identifies a number of issues for the SABRE engine and these are detailed as follows:

- **HEAT EXCHANGERS:** Their weight is a critical point. The number and geometry of the pre-cooler modules is going to influence the weight but also the efficiency of the engine. An optimized design based on their integral performance along the vehicle trajectory should be done. A single point optimization can be meaningless in an engine that does not cruise at any time. Having a numerical model of the engine is crucial for that purpose.
- **OVERALL PERFORMANCE:** The VKI numerical simulation shows an excursion of the working point outside the region of optimal efficiency of the turbomachinery map. This is especially important for the air turbo-compressor, where the power on the shaft is higher. The corrected mass flow through the air compressor experiences a maximum variation of 20% of the take-off value despite that the helium turbine inlet temperature is kept at 1080 K. If the compressor working point is desired to be still, then the by-pass valve of the hydrogen turbine that drives the helium circulator should be properly operated. In this way the helium mass flow through the helium turbine can be regulated. The design of the engine control mechanisms (turbine by-passes, diverting valves, intake variable geometry or even turbo machinery variable geometry) and the sizing of the turbo components will respond to a trade-off decision between the gain in overall engine performance and the weight increase that they may introduce.
- **ENGINE STARTUP AND SHUTDOWN AND TRANSITIONAL MODES:** Because of the presence of a high amount of interconnected components (turbo machines, heat exchangers, combustion chambers) the transitional regimen at engine start up and shut down is a delicate operation. During this period the operational temperature

and pressure of the different components cannot be exceeded. A proper turbo machinery operation needs to be verified as well to avoid dangerous regimes (stall, surge). The start-up/shutdown sequence must be analyzed and designed. Similarly to the engine start-up/shutdown unsteady regimes, the dual mode character of SABRE which switches from an air-breathing to a rocket cycle passing through a series of transitional states adds complexity to the control system. From the stand point of the turbomachinery and heat exchangers this transient operation needs to be analyzed to avoid hazardous situations (temperature peaks in the heat exchangers during turbomachine shutdown, or malfunction of the turbo machines itself).

ESA notes that the REL heat exchanger dimensions have already been optimised for SABRE 3 as part of the overall engine design process and in conjunction with trajectory modelling. Further, for SABRE 2 and 3, the results of REL's detailed in-house computer model differ from the VKI engine model. A possible reason for this is the control scheme employed.

ESA recommends performing an update of the VKI numerical model to the latest designs (SABRE 3, SABRE 4 and possibly the proposed Sub-scale test engine - see section 8). This modelling would have the following objectives:

- Re-assess the issues raised by VKI (see above) and cross validate the two codes.
- Validate the model using data from the proposed sub-scale engine testing
- Perform actual flight predictions using the validated model.

7.4 Demonstration of Frost Control Mechanism

REL state in RD 1 that while the majority of the SABRE engine components (combustion chamber, nozzle, pumps, turbocompressor) are relatively conventional, lightweight high power heat exchangers are a new feature unique to this type of engine and pose a challenging manufacturing problem. To address concerns over the novel nature of the technology, REL has performed a laboratory scale experimental programme directed at resolving those areas of difficulty relating to light weight compact heat exchangers operating in a frosting environment.

REL state in RD 1 that the water vapour in the atmosphere up to an altitude of around 12 km is a problem for pre-cooled engines, causing them to block with frost in a matter of seconds. A great deal of this water is precipitated in the liquid phase during the cooling of the air and has to be rejected from the engine before it can freeze. Provision then has to be made to stop the build up of ice within the matrix as it precipitates directly from the vapour.

Thus by reference to RD 1 REL confirm that a major part of the experimental programme has been to demonstrate that this can be achieved.



Therefore as part of the ESA technical evaluation of the SABRE engine, the design and operating principles of the frost control mechanism were explained to ESA.

In addition a number of tests were performed at laboratory scale on request of ESA to demonstrate the repeatability of the frost control.

ESA can confirm that the frost control mechanism of the SABRE engine, (at laboratory scale), works and is repeatable. In addition ESA expects these positive results to be repeated on the planned tests of the heat exchanger when it is tested on a VIPER jet engine.

7.5 ESA Evaluation of the Components within the SABRE Engine

The success of the SKYLON vehicle will depend wholly on the successful development of the SABRE engine.

The current SABRE engine design uses pre-cooling and high compression in the air breathing phase which allows the use of a common high pressure rocket combustion chamber in both air breathing and rocket mode. Further, this approach results in a low exit area for the engine (smaller than nacelle capture area). This consequently allows a vehicle design where no pre-compression is required and the nacelle can be positioned outboard at the wing tip.

The heat sink capabilities of the liquid hydrogen are used, indirectly, via a helium power loop to cool the incoming air at high Mach numbers. The pre-cooling further serves to permit the use of very high compression ratios on the incoming air charge due to the low (deep pre-cooled) temperatures achieved. In addition, due to the inclusion of this helium loop, the significant heat recovered from the air compression can be efficiently used to do additional useful work in the cycle.

7.5.1 Nacelle centre body and cowl

The engine cycle operates at high pressure ratios and incorporates pre-cooling. In this regard high efficiency of the inlet is no longer of paramount importance as, by adjusting the Mach number and altitude profiles flown, and by control of the bypass burner flow rate, the pressure conditions ahead of the core engine are maintained at a nearly constant value. The high compressor inlet temperatures associated with such intakes, which are normally an issue, are of no consequence due to the pre-cooling system.

In supersonic flight (with supercritical inlet operation) a three shock system is used to decelerate the incoming airflow to subsonic conditions. The three shock system comprises an oblique shock (generated by the nacelle centre body), a normal shock at the cowl position (upstream of the internal flow path and intake throat) and, as the flow re-accelerates after the intake throat, a second internal normal shock.



Adjustment to maintain shock on lip conditions for the oblique shock, throughout the flight, is provided by a translating 20° conical centre-body within an axis symmetric inlet.

Prior to orbital insertion the nacelle forebody closes to reduce drag and remains closed for the rest of the mission. The forebody proposed is composed of a series of conical sections picked up by the configuration.

The second normal shock which brings the intake air back down to subsonic Mach numbers is internal and is located in a flow passage of expanding cross-section downstream of the intake throat. Control of the position of this shock and the associated pressure rise is achieved by varying the area and throughput of the bypass burner.

For the air-breathing flight the high fuel load induces a requirement to fly the vehicle nose up for lift but intake operation at incidence is not desirable. The engine thrust vector, however, must point through the mean CoG for the rocket ascent. Nacelle curvature is therefore included to meet both requirements.

The design of an inlet with the required performance is well within current experience being similar to ramjet performance needs. The configuration of the nacelle presents some interesting challenges. Critical areas will be the translating centre-body and the conical sections “picked up” to close the inlet. These conical elements sit in the subsonic flow ahead of the second intake shock. The flow between them is assumed undisturbed but in reality some thickness will be required and their effect on the flow will need to be evaluated. REL propose a mechanical actuator for deployment of the intake. This is not seen as an issue. Naturally, a more detailed design for the deployable elements and the associated mechanism needs to be examined.

REL have further proposed the Nacelle Test Vehicle (NTV) as a risk reduction exercise allowing a functioning demonstration of the intake operation and more importantly a demonstration of the control of the intake performance, and therefore the core SABRE engine, by way of the bypass burner arrangement. The NTV vehicle constitutes a core element of the overall SABRE engine development. However, the engine can be demonstrated in isolation on ground.

7.5.2 Engine bypass burners

The core SABRE engine is installed in a nacelle. The design of this nacelle is such that at the end of the air-breathing phase (Mach 5 and 26 km altitude) the air swallowed by the nacelle inlet is equal to the required air consumption of the core SABRE engine. The hydrogen flow rate at this point leads to a very fuel rich engine mixture ratio as a significant fuel flow is required in order to maintain the inlet pre-cooler heat exchanger performance.

At lower altitudes it follows that, due to increased atmospheric density, the captured airflow exceeds the demand of the core engine. The nacelle is therefore designed to bypass

the excess air around the core engine. If this is done with no further action, a significant drag penalty is incurred as the excess air swallowed has lost a significant amount of relative momentum. As a result, the engine utilises a system of bypass burners arranged circumferentially around the core engine to add additional energy to the bypass airflow and recover the lost momentum. As the core engine runs fuel rich in order to maintain its cooling performance there is, conveniently, an excess of hydrogen fuel available with which to achieve this.

The bypass burners themselves are segmented which would be a standard approach based on jet engine heritage. However; the operation is quite lean and the range of lean operation is significant. This is addressed by a two zone combustion approach where the fuel is injected rich in the primary zone at relatively constant conditions and diluted further in the secondary zone depending on the overall airflow. The detail at this level needs to be filled in as there is some novelty and significant design work foreseen.

7.5.3 SABRE Core engine

7.5.3.1 Heat Exchangers

The heat exchangers used within the SABRE cycle are fundamental to its success. While a great deal of attention has been focused on the pre-cooler, for obvious reasons, it is understood by ESA that the other heat exchangers HX3, 4 and 5 are also fundamental to the cycle and also require technology development. This said, very similar design, construction and manufacturing technologies are baselined in the C1 configuration mass estimations for the HX4 and HX5 units. HX3 should however be considered separately as there are some detail differences.

7.5.3.1.1 Heat Exchangers HX 1 and HX 2

The basic tube arrays, must be incorporated in large numbers and, though individual tubes prove to be very light, the total mass of the (approx. 300,000) tubes is significant. Achieving the required process control for manufacturing, both at individual tube level (drawing, subsequent cleaning and machining for reduction of the wall thickness) and during the integrations (bending soldering tooling and jigs), is a significant challenge but is addressed within the phase 1 and 2 activities.

7.5.3.1.2 Heat Exchangers HX 4 and HX 5

The baseline heat exchanger designs for HX 4 and 5 are, from a construction standpoint, similar to HX 1 and 2. Materials variations are employed but essentially metallic tube based heat exchangers are baselined and the manufacturing issues are the same as for HX1 and 2.



Optional etched foil heat exchanger technology is also under examination at REL as a substitute for the current HX 4 design.

7.5.3.1.3 Heat Exchanger HX3

HX3 is an axial counter-flow heat exchanger sitting between the pre-burner and the chamber. Its purpose is to top off and control the energy input into the helium power loop which is then used to run much of the turbo machinery (Turbocompressor or LOX pump). It is relatively compact based on the fact that both the helium and flow from the pre-burner arrive at high pressures with correspondingly good heat transfer coefficients. The efficiency of the design is not, in this case, paramount as there is considerable reserve energy left to be able to raise the helium temperature to the desired level and, when pre-cooling is fully operational at high Mach numbers, the heat transfer requirement is reduced.

Control of the He temperature rise across the pre-burner heat exchanger is indirect via the control of the pre-burner temperature. This is one key difference to the power-cycle of a conventional staged combustion approach in that the pre-burner has no direct link to the turbo-machinery.

7.5.3.2 Turbo-compressor

The turbo-compressor design utilises three spools. On the compressor side the unit employs relatively conventional axial flow compressor stages, however, the pressure ratio targeted for the compressor (140:1) is significantly larger than in conventional axial applications even when looking at advanced core engines for current turbofan applications. In principle, however, the supercritical outlet conditions are achievable as an extension of current technology. The construction approach for the turbo-compressor employs several current but cutting edge technologies.

The compressor stages in the SABRE engine are powered, due to the original thermodynamic cycle employed, by helium driven turbines. The use of helium, and the temperature difference between the operating media of the low temperature compressor stage and the hot helium turbine unit driving it, have led REL to employ a counter-rotating turbine unit to drive both the low pressure (low temperature) compressor stage and the intermediate stage. This technological approach is the baseline for the engine and a reversion to conventional practice would both complicate the design and bring an additional mass penalty. Recognising this, a separate demonstration of the counter rotating turbine technology was undertaken by REL to give an accurate picture of the turbine performance. Though the required performance from the counter rotating turbine is achievable the construction approach needs to be verified.

7.5.3.3 Turbo-pumps

SABRE engine operating pressures are high both in air-breathing mode and in rocket mode, the latter being the most severe condition. Necessarily, multiple stage turbo-pumps are required to raise the pressure of both fuel and, for the rocket ascent, the oxidiser to the required levels

The turbo-pump technology required for the SABRE engine sits outside current experience within Europe but never the less relies on what can be described as relatively conventional approaches. Indeed, considering the worldwide technology landscape, pumps with the required performance are in existence; although some performance requirements are pushing the envelope of available technology.

In air-breathing mode each nacelle constitutes a single engine. However; in rocket mode, the nacelles effectively house two separate rocket engines. As a result two turbo-pumps are provided for hydrogen. In addition, with the turbo-compressor no longer operating, a further two oxygen turbo-pumps per nacelle are required to give two completely independent rocket motors.

7.5.3.3.1 Hydrogen turbo-pumps

The inlet pressure for the H₂ pump is a nominal 1 Bar, however; some variation of this will be seen due to hydrostatic pressure in accelerated flight phases. This will give the inlet operating pressure range.

The main issues here is the high pump speed and, to a lesser extent, avoidance of cavitation which is a major contributor to wear and which must be avoided if long life for the turbo-pumps is to be ensured. This should be possible via careful design, however the required performance can also be achieved in a less compact design, again, with associated mass penalty.

7.5.3.3.2 Oxygen Turbo-pumps

The inlet pressure for the oxygen turbo pump is a nominal 4 Bar supplied from the boost pumps located at the main tanks. The outlet pressure is 400 Bar during rocket ascent for comparison; the SSME has a design inlet pressure of 29 bar and a design discharge pressure of 500bar

7.5.3.4 Materials

From a materials standpoint, conventional approaches for the turbo-pump impellers will be sufficient. REL propose hydrostatic bearing technology for which there is a larger ground heritage now as compared to the project inception (even though this technology is yet to be flown). The design will most likely incorporate non-contacting aerodynamic face seals. Again, developments in these areas are applicable across the entire field of turbo-machinery.

7.5.3.5 Helium Loop

7.5.3.5.1 Helium Circulator

This unit is comprised by a single stage centrifugal compressor driven by a two stage hydrogen turbine. The unit operates at approximately 64000 rpm and maintains almost constant speed in both propulsion modes. Each nacelle contains two units for reliability during rocket operation.

In order to match the helium loop power demand in the two operating modes the circulator turbine has a bypass which operates in fixed configuration during rocket mode, when it passes approximately 15% of the hydrogen flow around the turbine. In rocket mode inlet temperature conditions increase but remain within limits as does the flow coefficient to the diffuser.

7.5.3.5.2 Helium Re-circulator

The helium re-circulator drives the cooling loop flow. The unit is a single stage axial flow fan coupled to a single stage hydrogen impulse turbine. The unit operates at a maximum speed of 57330 rpm. Again, the speeds employed are relatively high but no criticality is identified. The unit is relatively small allowing conventional technologies to be employed and the need for advanced sealing and bearing technology is already addressed under other developments needed within the program. Further, the cooling loop is only in operation in air-breathing mode from Mach 4 up to transition, giving a short 15 hour operational life.

The unit operates over a narrow range of non-dimensional conditions far from the limits of its performance. The technology required is similar to the turbo-compressor and does not require a dedicated program of technology development.

7.5.3.6 Pre-burner

The pre-burner is required to handle a large range of flow rates and mixture ratio variations in the course of the SKYLON mission.

This said; its function differs from that of a classical pre-burner in that, whereas a classical staged combustion approach uses the output of the pre-burner to directly power the turbo-machinery for the pumps, the SABRE engine uses it as a heat source to top off the heat input into the helium loop. The helium then goes on to power the turbo-machinery for the turbo-compressor and LOX pumps.

With no turbo-machinery down stream, requirements for injection and combustion uniformity as well as those related maintaining a tight range of the outlet non-dimensional flow are less important.



In both operating modes the entire supply of hydrogen passes through the pre-burner and through HX3. The pre-burner is always fuel rich. The remaining oxidiser is supplied direct to the main combustion chambers.

Each nacelle contains two pre-burners for reliability in rocket mode operation. However; both pre-burners need to operate in air-breathing mode to power the single turbo-compressor.

7.5.3.7 Combustion Chamber

The proposed common combustion chamber for the SABRE engine is relatively conventional in its design and construction using a liner into which the cooling channels are machined and a metallic shell close out completing the outer channel wall and carrying the mechanical loads generated by the high internal pressures.

Given the air breathing and rocket modes that the chamber needs to operate in, two cooling approaches for the chamber are required.

Due to the use of hydrogen in airbreathing mode as a coolant for the He power loop, cryogenic hydrogen is unavailable for regenerative cooling. Instead a combination of H₂ film cooling in conjunction with compressed air passing through the chamber cooling jacket is used as the baseline in air breathing mode. The film cooling approach is well understood in Europe and throughout the world. The use of the compressed air, which is fed through the same circuit in the chamber as the oxygen used in the rocket mode, provides the remaining cooling. This also serves to provide alleviation of the otherwise significant mechanical loads that the liner wall would see without pressurisation of the cooling circuit.

In the regeneratively cooled rocket mode the cryogenic H₂ is again unavailable due to the use of the hydrogen as a coolant within the helium power loop. As a result the liquid oxygen is baselined as coolant instead.

7.5.3.8 Nozzle

A conventional nozzle is baselined for the SABRE engine as presented. One of the difficulties, common for a single stage to orbit vehicles, is to deal with the variation in atmospheric pressure during the vehicle ascent. In a conventional nozzle the high pressure gasses, which are a product of the combustion, are accelerated through the rocket nozzle and, in this process, the pressure is reduced. The higher the final velocity: the higher the engine performance, for a given chamber and propellant. Higher velocities are achieved by increasing the ratio of the nozzle exit area to throat area.

7.6 Orbital Propulsion System

The focus in the previous sections has been the evaluation of the SABRE engine which is natural as it is the innovative core of the whole SKYLON system. However; it is worth noting that these engines alone do not allow the vehicle to complete its mission and the vehicle in space mission is supported by the orbital propulsion system. This, although based around relatively conventional elements, involves some innovative technologies in its own right. Not least, it is a low maintenance, reusable hydrogen-oxygen propulsion system relying on a novel tanking concept with helium and O₂ tanks located inside the main H₂ propellant tanking. This feeds a 2+2 redundant set of orbital manoeuvring engines (SOMA engines) used for final precision insertion to orbit and re-entry. These are high-performance reusable liquid propellant rocket engines. Further, the RCS thruster feeding via a gaseous supply system and a series of plenums is again novel - though manageable at a technology level.

The following sections describe the major elements

7.6.1 Reaction Control System Thrusters

Low pressure LH₂/LO₂ gas-gas injection thrusters are baselined to provide 3 axis control nozzle and tail clusters are implemented along with wing situated thrusters to give adequate roll control.

Thruster sizing has been driven by shuttle requirements. This should lend itself to the SKYLON core mission, which is in essence, similar. The thrusters are supplied from a series of local plenums in what is termed the Gaseous Propellant Supply System, refer to 7.6.2.

The positioning of the wing (roll) thrusters will provide some issues w.r.t re-entry but should be manageable.

7.6.2 Gaseous Propellant Supply System (GPSS)

The gaseous propellant supply system takes cryogenic propellant from the auxiliary propellant system tanks. The propellant is gasified and pressurised and then distributed by an internal supply ring to local reservoirs. These serve to decouple the RCS demand from the production of gaseous propellant within the overall demand requirements for any manoeuvre. The system comprises of a turbopump and a pair of heat exchangers for each propellant.

7.6.3 Skylon Orbital Manoeuvring Assembly (SOMA) Engines

The basic sizing for the SOMA engines has been made and it should be noted that this is, in reality, a separate high performance rocket motor development and cannot be regarded as a trivial task.



7.6.4 Auxiliary Propulsion System (APS) Tanks

The tank sizing is based on the propellant requirements from the SOMA engines, RCS, start turbines, H₂ tank re-pressurisation, fuel cell supplies and APU As such this covers all sources of consumption during the mission.

7.6.5 Propellant feed systems

The propellant feed systems are comprehensively described for the SABRE engines and the auxiliary propellant feed system. All valves and lines needed to operate the system are included in addition to the major components discussed. Again many of these elements may end up requiring a development in their own right as off the shelf items are unlikely to be available.

7.7 Conclusions

In summary, the ESA evaluation of the SABRE engine design has not identified any critical items that are a block to future developments. Both the SABRE cycle and the engine components have been assessed as well as the frost control mechanism.

For the SABRE engine cycle analysis the issues identified were the result of an investigation by an ESA sponsored PhD at the Von Karman Institute (RD13).

One of the limitations of this analysis by VKI is that the majority of the engine data is obtained from the final report of the SABRE engine for FESTIP, delivered to VKI by Reaction Engines in 1997.

It is ESA's understanding that the engine information in this report is for an earlier engine design and hence does not correspond fully to the current version of the engine. However, the major cycle layout is still representative for the latest cycle version and hence raises some critical issues.

Thus ESA also recommends performing an update of the VKI numerical model to the latest designs. The objective would be three-fold, firstly to reassess the issues raised by VKI and cross validate the two codes, secondly to validate the model against the data received from the proposed next phase of development, (the SABRE engine sub-scale ground test), and thirdly to perform actual flight predictions using the validated model.

In addition REL state in RD 1 that one of the major difficulties in developing any type of air-breathing engine such as SABRE is the operation of light weight compact heat exchangers in a frosting environment.

ESA notes that this is a major hindrance to worldwide efforts to develop these types of engines and can confirm that on the laboratory scale Reaction Engines have demonstrated a repeatable solution.



As part of the ESA technical evaluation of the SABRE engine, the design and operating principles of the frost control mechanism were explained to ESA.

ESA expects these positive results to be repeated on a version of the heat exchanger when it is tested on a VIPER jet engine.

ESA also concurs with the REL proposal that the Nacelle Test Vehicle (NTV) should be built as a risk reduction exercise, to demonstrate efficiently and with modest resources the engine intake operation and the control of the intake performance by way of the bypass burner arrangement.

8 CONCLUSIONS

8.1 Summary

Since 2009 ESA has been involved with the development of the SKYLON/SABRE program. The main activity has been on the SABRE engine development in particular focussing on key technical areas to improve the overall Technical Readiness Level (TRL) of the engine.

This has been performed by the TRP/GSTP programs investigating key areas of technology of the engine. The results of these developments so far are very promising with no technical problems so far being identified and ESA are confident of good results for the pre-cooler test on a jet engine. This will be a critical milestone for the development of the engine. It will be the first time that a SABRE sub-scale heat exchanger would be tested outside of the laboratory.

Other activities include the ESA technical assessment of the SKYLON vehicle and SABRE engine. This was performed in 2010 where ESA experts visited Reaction Engines to ascertain the design and development status of the SKYLON vehicle and SABRE engine. This included a full repeatable demonstration at laboratory scale of the critical technology for the frost control mechanism. This was in addition to a PhD sponsored by ESA at VKI investigating aspects of the SABRE cycle.

It is clear that this assessment has only been possible due to the extensive engineering work that REL has already performed on both the SKYLON and SABRE.

In the course of the assessment activities ESA has not identified any critical topics that would prevent a successful development of the engine.

Another activity was the ESA participation to the UK Space Agency hosted Skylon System Requirements Review at the International Space Innovation Centre at Harwell, United Kingdom on the 20-21ST September 2010. The purpose of the review was for an independent assessment of both the SKYLON and SABRE proposals and was intended to be an important milestone in the UK government's evaluation of the proposal.

The review was considered to be a success attracting wide interest by the international aerospace community. No impediments were identified either in the economic or technical presentations.

8.2 Next Development Steps.

The two day review at Harwell examined the feasibility of the next developments rather than presentation of exhaustive development plans.



In the review REL, stated that an evaluation is being undertaken of an engine demonstration programme to integrate all the engine technologies they presented into a sub-scale self sustaining engine.

They envision this to be a rapidly executed programme in parallel to the flight engine design. REL state that this approach is necessary as the engine is the critical path item for the entire vehicle development.

The need for a ground test demonstration of the SABRE engine is one of the conclusions reached by the ESA assessment exercise and the feedback ESA received from the SKYLON requirements review.

A successful test, in ESA's opinion would address many issues, not only the component issues raised in this document but also demonstrate much larger objectives.

The ESA proposed objectives for the ground test are detailed in Annex 2.

This testing is proposed to continue after the successful conclusion of the ESA managed phase 2 activities and thus is proposed as a possible "Phase 3 activity – Sub-scale SABRE Ground Test".

Also in the course of the ESA assessment, REL has proposed the Nacelle Test Vehicle (NTV). This would be developed and flown as a risk reduction exercise, to demonstrate the engine intake operation and the control of the intake performance by way of the bypass burner arrangement.

ESA also concur with REL on the need of the NTV as a flying test bed for critical aerothermodynamic and engine technologies.

8.3 Concluding Remarks

In conclusion the ESA assessment has identified a number of issues that must be addressed to increase the maturity of the vehicle and engine developments. However no impediments or critical items have been identified for either the SKYLON vehicle or the SABRE engine that are a block to further development.

It is clear that the SABRE engine is critical for the successful development of the SKYLON vehicle.

The consensus for the way forward is to proceed with the innovative development of the engine which in turn will enable the overall vehicle development.



The SABRE engine offers to deliver both high thrust to weight ratio and high performance over the Mach 0 to 6 range based on a single cycle. This is a major advantage in comparison to alternate air-breathing engine designs.

In particular, based on REL's flight like heat exchanger technology and their successful demonstration of the frost control mechanism at laboratory scale (a major milestone that has so far eluded other international developments), ESA are confident that a ground test of a sub-scale engine can be successfully performed to demonstrate the flight regime and cycle and will be both a critical milestone in the development of this program and a major breakthrough in propulsion worldwide.

For the future SKYLON vehicle, the concept and structural design work undertaken by Reaction Engines Ltd does not demonstrate any areas of implausibility due to the relatively benign environment of the flight trajectory.



9 ANNEX 1 – LIST OF TOPICS THAT WERE RAISED DURING THE REQUIREMENTS REVIEW.

Economic Questions

Pre-submitted Topics

Technical and Commercial Risk

Cost per launch
Polar LEO market
Loss of US or Asian Market
Launch Market
Maintenance Costs
Development Programme
Technology Identification and Maturation Plan
Existing Market Response to Disruptive Technology
Reliability
Availability
Sortie Rate and Production Demand
Mission Duration
Return Payload
NASA human spaceflight certification
Use of SKYLON for GTO missions:
Subscale Demonstrators

Questions asked during the economic Q & A session,

Investment Models

Insurance Costs

Technical Questions

Pre-submitted topics

Aerodynamic Performance of SKYLON
SABRE's air inlet thermal loads
Flow separation and related side loads in Nozzles
SABRE Engine Development and Test Programme
Engine Life Cycle and reusability
Payload mass sensitivity
Mass Margin
Establishing Reliability
Payload Coupled Loads



Landing Inertia Factors
Choice of Aeroshell Materials
Structure Loads Derivation
Engine Failure
NOx Emissions
Human flight Certification
Orbit Propulsion Subsystem
Thrust Chamber Reusability
Engine Maintenance
SABRE Operating Parameters
Certification Loads
Turbocompressor pressure ratio
Heat Exchanger Manufacture
Aeroshell mass
Air flow in ducts
SABRE Thrust to weight ratio
Air-breathing SI
Guidance laws
Helium Leak Rate
Aerodynamic stability in off-nominal conditions:
Safety aspects: Propellant draining in case of aborted flight:
Performance simulations
Air breathing Aspects
Basis of Mass Estimates
TPS Questions

Questions asked during the technical Q & A session,

Turbine failure
Lift to Drag Ratio
Fuselage Structure
Engine Position
Heat Exchanger Weight
Structure Inspection
LOX Tank Cooling During Decent
Injector Pressure Drop
Equivalence Ratio
Brake Water Management
Progress on Hx3, 4 and 5
140:1 Compression Ratio
Inlet Recovery Ratio
Results of Cycle Analysis
Scaling up to the D-1 version
Sealing the Inlet during Re-entry
Duct burner/ ramjet Optimization
Back up Design for the Pre-cooler



H2 Leaks Detection Use of Thrust Augmented Nozzle



10 ANNEX 2 – OBJECTIVES OF THE SABRE ENGINE GROUND TEST.

The objectives for the test can be split into three distinct categories, those that address particular component issues, objectives for demonstrating successful air-breathing demonstration and objectives for demonstrating successful rocket mode demonstration.

10.1 Component issues resolved by ground test

A number of the issues raised can be resolved by ground testing of a sub-scale SABRE engine, the particular issues this would address as a risk mitigation exercise are:

- Engine Cycle overall performance
- Engine Start-up, shutdown and transitional modes.
- Engine Bypass Burner Functionality
- Engine Bypass burner reliability and maintainability
- Hydrogen Turbopump performance requirements
- Demonstration of reusable combustion chamber technology

10.2 Test Objective for Airbreathing and Rocket Mode Testing.

Air-breathing Demonstration Objectives

Due to scaling issues, Neon is proposed to be used instead of helium for the cooling loop, however the cycle should be fully representative otherwise and meet the following objectives:

- Demonstration of the engine cycle for turbine inlet conditions corresponding to Mach 0.0-6.0, with full operation of the heat exchanger/frost control.
- Obtain measured values for the performance of key components (via a measurement plan) e.g. redundant inlet outlet temperatures and pressures for key equipment, mass flow rates at key locations.
- Assessment of engine maintainability and reliability

This will allow the validation of engine performance modelling tools (based on predicted engine data) for both steady state and transients (particularly air breathing shutdown and transition to rocket mode), demonstration of performance under varying engine flow demands and further validation of the engine simulation under different demand conditions.

Rocket mode demonstration objectives

The objective of this test would be the partial demonstration of critical rocket mode technologies:

As a minimum the following objectives are considered compulsory to be demonstrated:

- Transition for air breathing to rocket mode
- Mimic shut down of Sabre core engine air breathing mode
- Demonstrate venting of high pressure air during transition
- Assessment of engine maintainability and reliability

As a minimum for the test hardware requirements:

- all heat exchangers are to be (flight representative from a technology standpoint) elegant breadboards to allow:
 - Component performance assessment as close to SABRE as possible
 - Materials and processed representative of actual construction
 - Demonstrate that the realisation of the performance and mass metrics proposed are possible
- the test shall demonstrate variation of core engine demand to mimic flight schedule demand

In order to achieve the above a test bench/cell will need to be developed that shall have the following requirements:

- Allow interchange of heat exchangers and other components for breadboard testing where considered appropriate
- Provide representative or at least well controlled external/internal environments for key equipments (this includes not only the heated/vitiated air supply but also the HX3 environment and that for the “bench” heat exchanger items
- Allow in-situ test of key elements between firings

This proposed subscale SABRE test program will give confidence for the engine development proper; allow investment in the creation of a significant project management capability at REL ahead of the need from the full project initiation. It will also provide the option of a test bed for further evolutions of key components and will generate actual test data to take to prospective partners.