SABRE – ENABLING COMMERCIAL SINGLE STAGE TO ORBIT, SAFELY

Dr Andy Quinn MSc PhD MRAeS CEng (1), Richard Varvill, Founder/Technical Director (2)

(1) Saturn Safety Management Systems Ltd, Bath, BA2 9BR, UK

(2) Reaction Engines Ltd, Culham Science Centre, Abingdon, OX14 3DB, UK

ABSTRACT

Single Stage to Orbit (SSTO) has been the 'Holy Grail' since the beginning of astronautical thinking. However, the technical solution has been out of reach due to costs, technical feasibility of designs, and low Technology Readiness Levels. SSTO spaceplanes can take off from a spaceport's runway and reach Low Earth Orbit with their design payload for delivery, the spaceplane could then recover the same payload or a previously deployed payload and return safely to the same spaceport for a glide approach and landing. The vehicle will then be ready for its next mission after a few days of maintenance and payload integration. The main enabling feature of such a spaceplane is an engine that can provide the required performance in terms of thrust, weight and specific impulse with typically an air-breathing engine envisaged as a requirement to achieve this. The Synergetic Air-Breathing Rocket Engine (SABRE) is such an engine. In the SABRE engine, the Air-Breathing system is employed from take-off up to 25km altitude at Mach 5.5 before transitioning to the separate rocket system for the remainder of the ascent into orbit. SABRE engines are usable in systems for space access and hypersonics and in this paper we explore SABRE within a SSTO spaceplane concept. This concept has 2 engine nacelles on the wingtips and this allows for excellent abort capabilities, whether aborting on the runway before take-off, back to base or 'aborting to orbit/once around'. As the air-breathing and rocket engines are separate systems (except for the nozzles) separate development programmes can be accomplished with several thousand engine tests planned prior to achieving full certification. As part of the certification process a demonstrator flight test vehicle would prove the airworthiness/ spaceworthiness of the SABRE; even this aspect can be split into high altitude atmospheric flight tests (for the Air-Breathing engine) and later flight testing of the rocket engines to prove the transitioning aspects and rocket mode. This design approach provides not only redundancy, hence reduced vehicle loss rates, but more capabilities to abort the mission safely in the event of anomalies. This paper will provide an overview of the design features of SABRE as integrated into a spaceplane concept (such as Skylon) along with abort strategies, safe design philosophy and loss of vehicle/abort targets.

1. INTRODUCTION

For 30 years there has been activity in the United Kingdom to realise the vision of a single stage to orbit launch system using combined cycle engines that work in both air-breathing and pure rocket modes. This activity started in the 1980's with the British Aerospace/Rolls-Royce Horizontal Take-Off and Landing (HOTOL) project using the Rolls-Royce RB545 engine invented by Alan Bond. Whilst the project was not pursued for various reasons, the HOTOL study had established that the use of combined cycle engine with an aircraft like airframe would be a technically realistic proposition to insert a payload of up to 7 tonnes in orbit.

Figure 1: HOTOL Concept (BAE)

In 1989 Alan Bond formed Reaction Engines Limited (REL) together with Richard Varvill and John Scott-Scott. The HOTOL concept was progressed to overcome identified technical problems, from which the Synergetic Air Breathing Rocket Engine (SABRE) propulsion system was created. REL developed various SABRE configurations over the following 20 years culminating in the successful demonstration of the key heat-exchanger technology in 2013. This demonstrated that the intake air could be cooled to the required (minus) -150° Celsius within a fraction of a second.

In parallel with the SABRE design, REL developed a spaceplane concept called Skylon in order to explore the potential to apply SABRE in space access systems. This vehicle would be scalable during the early concept phase with the goal of inserting 15 tonnes to Low Earth Orbit (LEO) as its reference mission.

2. SABRE

SABRE is an enabler for orbital spaceplanes as well as other markets such as Hypersonic Transportation and Two-Stage To Orbit satellite launchers (see section 3.2).

The air-breathing part of the engine includes a helium closed loop system as part of a Brayton Cycle, which means the mass fraction required to reach orbit, for an SSTO, is 22% compared with 13% for an equivalent pure rocket system.

The SABRE 3 version is shown in Figure 2:

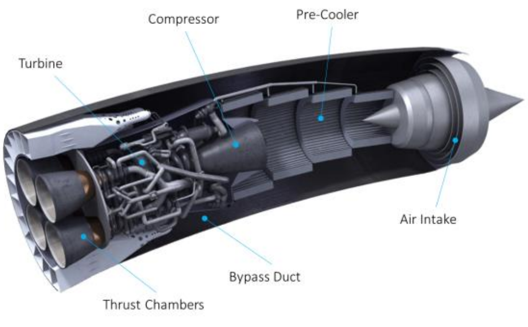

Figure 2: SABRE 3 (Reaction Engines)

2.1. Technology Development

2.1.1. Pre-Cooler

The pre-cooler demonstration included one heat-exchanger section mounted on the front of a Rolls-Royce Viper engine shown below in Figure 3:

Figure 3: Pre-cooler Tests (Reaction Engines)

The pre-cooler development has progressed since the 2013 demonstration and REL now has in-house manufacturing capability with the addition of a high temperature vacuum furnace for brazing. A typical pre-cooler heat exchanger subsystem for a large engine would have over 1 million leak-tight joints with over a 1000km of 1mm diameter tubing (20 microns thick) [1] and this would enable a total heat transfer of >400MW.

2.1.2. Nozzle

The current SABRE 4 engine requires a novel design of the rocket engine's thrust chamber and nozzle to allow operation in both air-breathing and rocket modes, as well as having a smooth transition between the two. The Advanced Nozzle experiment has been explaining the feasibility of this concept and represents a significant technology development effort towards the SABRE engine. The test engine incorporates several new technologies, including a 3D printed, actively cooled propellant injector (Figure 4).

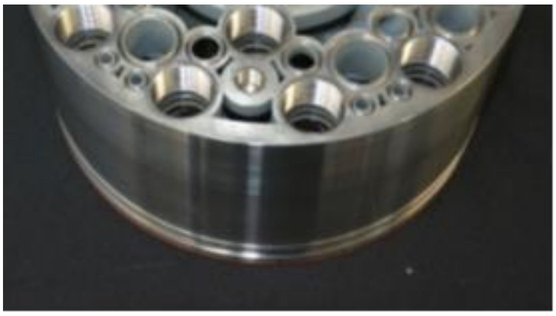

Figure 4: 3D printed injector system for the Advanced Nozzle Project

The test engine has been successfully fired over 30 times since commissioning in spring 2015, Figure 5. The aerodynamic data collected from the firings is being used to validate in-house computational modelling and verifying the flow stability and expansion efficiency.

Figure 5: Image during testing of the SABRE Advanced Nozzle at Airborne Engineering Ltd., Westcott, UK

2.2. Technology Timeline

The main focus for REL is on SABRE and particularly on the air-breathing novel technologies. The aim is to have an engine undertaking ground tests by 2020.

2.3. Space Access Applications

Once proven and incrementally developed, SABRE will be ready for use in space access vehicles (section 3 details the Skylon Spaceplane as an example); these will be developed by suitable vehicle manufacturers i.e. REL will not develop any space access vehicles.

The proven SABRE will also be available to integrate into non-orbital vehicles i.e. suborbital hypersonic vehicles, suborbital vehicles deploying (orbital) satellite systems etc.

Having a reliable and safe engine such as SABRE will provide good confidence for developing Commercial Human-Rated spaceplanes as well. This will open up the access to space for commercial ventures such as Bigelow Aerospace (space hotels) and other Space Stations.

2.4. Other Applications

SABRE technologies also have ground-based uses and the technology can be exploited appropriately. Examples of this include the heat exchanger manufacturing and frost control technology.

3. SKYLON SPACEPLANE CONCEPT

The Skylon concept is a SSTO winged spaceplane designed to give routine low cost access to space and is useful in exploring the impact of using SABRE engines in space access systems. At a gross take-off weight of 325 tonnes of which 270 tonnes is propellant the vehicle is capable of placing 15 tonnes into an equatorial Low Earth Orbit (LEO). The vehicle configuration consists of a slender fuselage containing the propellant tankage and payload bay with delta wings located midway along the fuselage carrying the SABRE engines in axisymmetric nacelles on the wingtips. The vehicle takes off and lands horizontally on its own undercarriage. The fuselage is constructed as a multilayer structure consisting of aero-shell, insulation, structure and tankage.

Figure 6: Skylon (Reaction Engines)

3.1. Skylon Mission

The system performance of the Skylon D1 with its SABRE 4 engine has been extensively modelled with in-house mission analysis software to track the impact of any changes as the SABRE engine design evolves. Although the required performance for Skylon is specified as a 15 tonnes payload to a 300km circular orbit from an equatorial launch site, the modelling uses a “standard mission” from a launch site at latitude 5.2 degrees; corresponding to the CSG spaceport at Kourou, French Guiana. The altitude versus time graph for the powered ascent trajectory until Main Engine Cut off is shown in Figure 7 below. This trajectory leaves Skylon in a 90 km by 300 km elliptical orbit, which is circularised at apogee using the orbital manoeuvring engines.

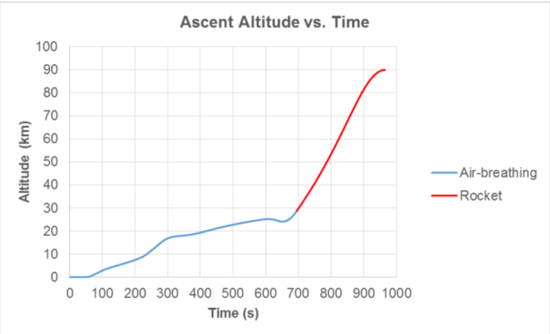

Figure 7: Skylon Standard Mission Ascent Altitude Vs. Time (Reaction Engines)

The mission analysis studies also confirmed the sensitivity of take-off thrust to weight ratio performance was insensitive to moderate changes (over the 0.35 to 0.5 range). This gives some scope to alter the vehicle take off mass after the engine thrust has been fixed during the detailed design phase. On orbit, Skylon is able to deploy a 15T payload to Low Earth Orbit. The payload includes a reusable Skylon Upper Stage (SUS) system. The SUS provides a means to insert payloads to higher orbits such as Geostationary Transfer Orbit (GTO). After delivering the payload to the GTO the SUS would then be able return back and rendezvous with Skylon; hence its reusability.

The return trajectories confirmed Skylon’s flexibility of touchdown point with a wide range of downrange and cross range availability. The vehicle can recover to any spaceport with compatible latitude at least 6 times per day from any orbit, and can recover to an Equatorial spaceport from a low inclination orbit (less than 40 degrees) on any pass.

4. SAFETY BY DESIGN

Space safety standards dictate a Design for Minimum Risk (DMR) philosophy. This includes deriving Fault Tolerance, Safe-Life and Fail Safe criteria. The DMR philosophy within Advisory Circular AC 437.55-1 [2] details the following Safety Precedence Sequence:

- Eliminate hazards (by design or operation)
- Incorporate safety devices
- Provide warning devices
- Develop and implement procedures and training

Notice that in space the key term is ‘hazard’. Hazards are analysed and then, as part of Probabilistic Risk Analysis (PRA), cumulative assessment is made in order to determine whether the Target Level of Safety has been met i.e. top-down analysis. In aviation, although the term hazard is recognised, the focus is on lower level failure conditions associated with failure modes i.e. in order to meet safety objectives such as $1x10^{-9}$ per flying hour for catastrophic events i.e. bottom-up analysis.

Hence REL is adopting a top-down safety target approach (this is also the approach taken by NASA). The REL Loss of Vehicle (LOV) target is 1 in 2000 per mission (all causes). This is much safer than the best of the current space launch systems (Soyuz family) with a 97% success rate i.e. 1 in 33. REL has noted lessons from previous space programmes such as Shuttle where initial predictions for LOV were in the order of 1 in 100,000 per mission (which were then realistically reduced to 1 in 100 by the in-service phase; actual achieved rate at retirement being nearer 1 in 70).
The risk budget will be apportioned between the Skylon systems and it is estimated that the apportioned level of safety for the SABRE engines is estimated in the order of 1 in 10,000

per mission (for a catastrophic event from an engine technical fault).
Additionally, as the vehicle is a spaceplane with 2 engine nacelles, there is much more scope to abort safely. During the Air-Breathing and transition to rocket phases of flight Skylon can abort by returning to the launch site. During the rocket phase of flight Skylon can abort to a Transoceanic Abort Landing (TAL), Abort Once Around (AOA) or Abort to Orbit (ATO).

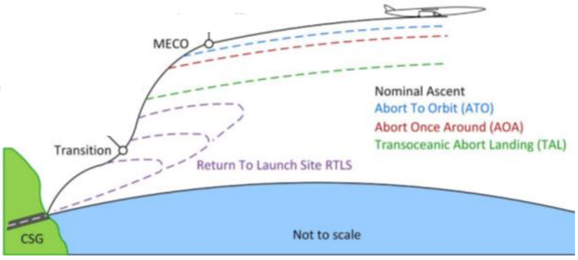

Figure 8: Spaceplane Abort Capability

REL system safety analysis will follow best practice from aviation and space by influencing the design from the beginning with key high level safety requirements (from standards and rationalised accordingly) and providing derived safety requirements from analyses.

4.1. Key Safety Requirements

For an SSTO and in particular spaceplanes, it is essential to understand both space and aviation requirements and thereby identifying relevant key safety & functional requirements that should be achieved in the design. For instance, a space requirement is that any Inadvertent Failure Modes that could result in a catastrophic outcome should have 3 Inhibits. This means 3 separate and independent inhibits which could be hardware (physical switches/guards etc.), software (latches) or combination thereof. The IAASS Space Safety Manual [3] is based on the NASA and European ECSS standards and rationalised/consolidated into one manual; in relation to 'Functions Resulting in Catastrophic Hazards' the following requirement is stated:

"A system function whose inadvertent operation could result in a catastrophic hazard shall be controlled by a minimum of three independent inhibits, whenever the hazard potential exists. One of these inhibits shall preclude operation by a radio frequency (RF) command or the RF link shall be encrypted. In addition, the ground return for the function circuit must be interrupted by one of the independent inhibits. At least two of the three required inhibits shall be monitored."

In relation to Skylon & SABRE this important safety requirement is already defined and as the programme develops, these inhibits will be detailed and then form part of the Validation & Verification Plan.

A key safety requirement is that catastrophic hazards should be controlled such that no combination of two failures or operator errors can result in a catastrophic event (for the unmanned system this would relate to ground control, and for a manned system the 'pilot in command' has limited control functions as unmanned spaceplanes, such as Skylon, cannot be 'flown'). In relation to SABRE this would concern the Engine Control System failure modes for example and ensuring adequate Design Assurance Levels along with appropriate fail-safe and redundancy (as detailed by derived safety requirements). In terms of functional requirements, a system whose loss of function could result in a catastrophic outcome should be two fault-tolerant.

Another requirement is that a spaceplane shall be able to abort its nominal powered ascent at any point and return safety to a landing site following a single engine failure (as well as other hazardous/ critical system failures) i.e. return to base directly or per *Figure 8* via TAL/AOA/ATO as required.

5. SABRE CERTIFICATION

There is no international agreed process on the safety certification of space systems, each nation doing what it regards as sufficient to meet its obligations under the Outer Space Treaty. Currently NASA has the 1100-Series certification requirements which appear to contain a well-structured set of high level requirements with applicable means of compliance from previous NASA Standards:

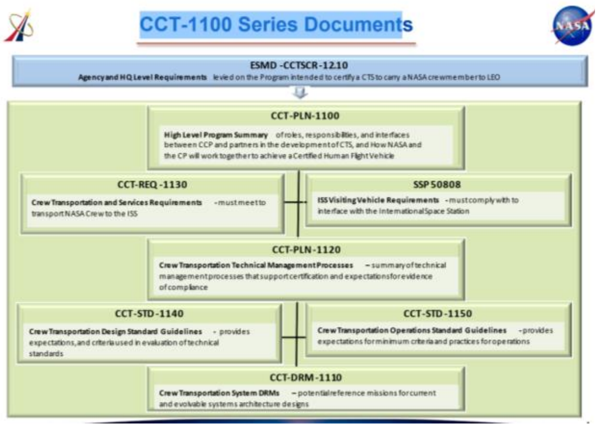

Figure 9: NASA High Level Requirements Set

In addition to obtaining the NASA certification approval, space launch systems (such as Space-X) must then meet the FAA-AST Launch Licensing requirements.

For aircraft-based systems, under the terms of the Chicago Convention on International Civil Aviation, any launch system that at some point relies on wings for lift will require certification from the civil aviation authority of the country from which they operate or over-fly. Spaceplanes would fly through the atmosphere (i.e. Skylon using an air-breathing engine) and then continue the trajectory under rocket power to reach orbit. Throughout the ascent the vehicle has a good abort capability (per *Figure 8*). During the atmospheric phase which includes aborting back to the launch site, spaceplanes such as Skylon act as an airplane i.e. they use the wings for lift and therefore meet the ICAO definition of an aircraft/aeroplane [4]:

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

Hence spaceplanes within Europe (and systems including SABRE) should adopt a certification approach by a competent Authority. The certification basis (airworthiness requirements) would require all phases of flight to be covered and therefore this would include the space segment with associated space system requirements; hence this would require the Authority to consult with ESA specialists. This then requires a unique approach integrating air and space requirements with appropriate means of compliance and guidance material.

In regards to SABRE, Reaction Engines are currently working with the UK CAA as well as ESA to derive such requirements that can be verified and validated throughout the engine development (EASA are currently not resourced for commercial space-related activities). The primary focus is (experimental) certification of SABRE which will be carried out through an incremental approach with sub-system tests (as part of qualification), through to ground engine tests and finally to flight test engines. However, to derive appropriate engine requirements one needs an understanding of higher level (space and aviation) requirements, including those that may be imposed by the Authorities.

REL envisage a rationalised high-level risk and performance based requirements approach from the Authorities; thus leaving the designer to arrive at the product (solution) based on agreed means of compliance in accordance with agreed standards. This would be similar to the NASA approach but perhaps leaner and taking cognisance of the changing European certification approach:

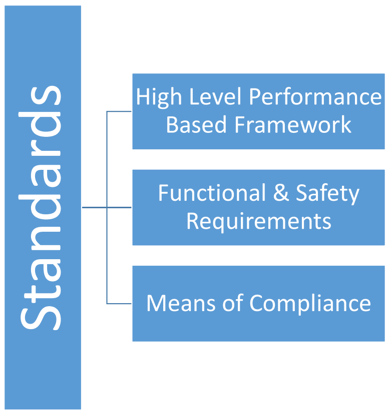

Figure 10: High Level Performance Based Requirements

The SABRE propulsion system has many functional requirements that are similar to aviation engines (in relation to the Air-Breathing phase) and hence CS-E is considered a good starting point. As indicated in *Figure 11* below, REL's initial findings are that roughly a third of CS-E airworthiness codes apply, a third do not apply (reverse

thrust, etc.) and a third of requirements require Special Conditions (meaning a re-write of the intent of the requirement for SABRE). These lower level airworthiness (and relevant spaceworthinesss) requirements will be linked with the higher level functional, performance and safety requirements. Additionally Space standards (ECSS) will provide additional requirements for SABRE, particularly in rocket mode and also for the remainder of the flight (orbit through to re-entry).
The V&V programme will provide appropriate test and analysis evidence to demonstrate the means of compliance in order to attain certification (in the first instance experimental approval for flight demonstration).

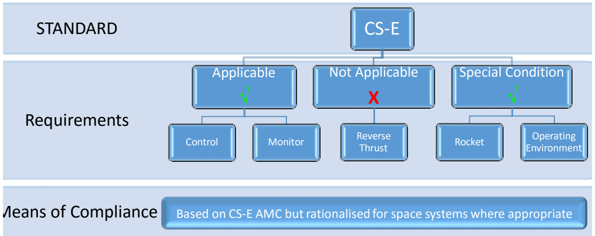

Figure 11: CS-E Requirements

6. SUMMARY

This paper has discussed an SSTO spaceplane concept which can take off from a spaceport's runway, deliver a 15 Tonne payload to Low Earth Orbit, then recover the same payload or a previously deployed payload and return safely to the same spaceport. The spaceplane could then be ready for its next mission after a few days of maintenance and payload integration. The main enabling feature is SABRE, encompassing an innovative air breathing engine to Mach 5.5 at 25km and a separate rocket engine to propel the vehicle to orbit. The aim is to have an air-breathing engine on test by 2020. The abort capability is an important part of the safety case.
Spaceplanes are predicted to be much safer than current vertical launch systems. The LOV target for spaceplanes (such as Skylon) is in the order of 1 in 2000 per mission for all causes.
A rationalised European-based certification programme should be derived with the Authorities; this is likely to be a high-level performance and risk-based regulatory framework focusing on functional and safety requirements, thereby allowing the designer to develop the product (vehicle/engine) whilst demonstrating means of compliance to appropriate standards.

7. REFERENCES

[1] R. Varvill "Technological Evolution of Propulsion Systems in the UK", Culpepper Lecture, presented at the 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, July 2015

[2] FAA-AST, Advisory Circular AC 437.55-1

[3] IAASS-ISSB-S-1700-Rev-B, Space Safety Standard, Commercial Human-Rated System, Requirement 201.2.2

[4] ICAO – Annex 1 to the Convention on Civil Aviation, Annex 6 Part I. Montreal, ICAO. Available to order from www. icao.int

8. ACRONYMS/ABBREVIATIONS

Acronym	Meaning
AOA	Abort Once Around
ATO	Abort to Orbit
CAA	Civil Aviation Authority
DMR	Design for Minimum Risk
EASA	European Aviation Safety Agency
ESA	European Space Agency
FAA-AST	Federal Aviation Administration – Office for Commercial Space Transportation
FMECA	Failure Modes Effects & Criticality Analysis
FTA	Fault Tree Analysis
GTO	Geostationary Transfer Orbit
HOTOL	Horizontal Take-Off and Landing
LEO	Low Earth Orbit
LOV	Loss of Vehicle
NASA	National Aeronautics & Space Administration
REL	Reaction Engines Limited
SMS	Safety Management System
SPP	Safety Program Plan
SQEP	Suitably Qualified Experienced Personnel
SSTO	Single Stage To Orbit
SUS	Skylon Upper Stage
TAL	Transoceanic Abort Landing
TSTO	Two Stage To Orbit
V&V	Validation & Verification