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Executive Summary Report

CAS/R2595 Issue A

SABRE Technology Development De-Risking - Flight Test Vehicle

ESA Contract No. 4000129097/19/NL/BJ/rk

Deliverable: ESR

August 2020

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on behalf of Cranfield Aerospace Solutions Limited

~~The technical content of this document is approved under the authority of~~
*~~DOA ref. EASA.21J.145 *~~*
*~~CAA approval number AD/2015/05 *~~*
*~~The technical content of this documentation is approved under the authority of: MAA DAOS ref. UK.MAA.DAOS.0034 *~~*

** delete as appropriate*

AMENDMENT RECORD

Issue	Date	Author	Detail of Changes
A	August 2020	M Loffell	First Issue.

DISTRIBUTION LIST

1. Archive
2. ESA
3. UKSA
4. BAE Systems
5. Reaction Engines Ltd
6. Cranfield University
7. Frost & Sullivan

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1. INTRODUCTION

The Reaction Engines Limited (REL) SABRE (Synergetic Air Breathing Rocket Engine) propulsion system aims to bring to space launch vehicles many of the benefits of commercial aviation. A SABRE propulsion unit consists of three major elements: Core Engine, Rocket System and Nacelle Systems. These are illustrated in Figure 1.

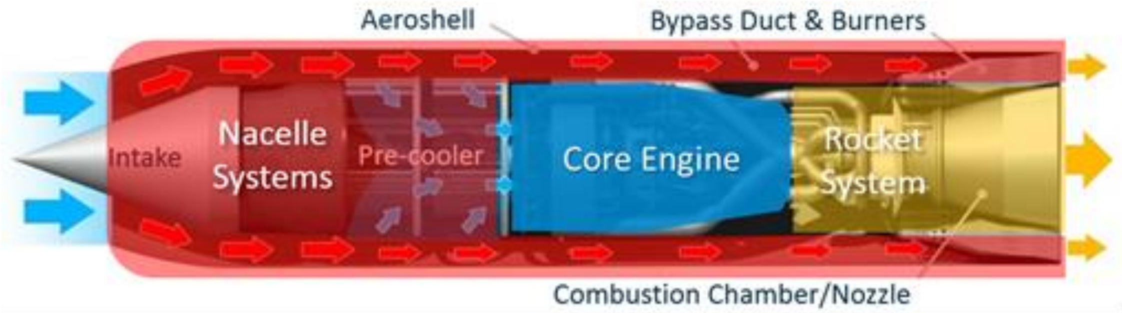

Figure 1: Major elements of the SABRE propulsion system

Ground testing to a suitable Technology Readiness Level (TRL) is possible for both the core engine and the rocket system. This leaves the nacelle systems (which include the air intake, pre-cooler, bypass burners and aeroshell) to be tested, in order to raise their TRL sufficiently to allow integration for an appropriately limited risk test of the entire propulsion system. The approach of producing a bespoke flight test air vehicle was selected as most suitable for this, leading to an investigation comprising Task 1: Define and evaluate flight test vehicle concepts, and Task 2: Estimation of a 2030+ space transportations segments and the potential for future SABRE-based systems. This Executive Summary Report of all work performed, is to satisfy the requirements for Doc ID ‘ESR’, Executive Summary Report, as defined in the table of deliverable documentation on pages 38 and 39 of Ref 1.

1.1. ABBREVIATIONS AND NOTATION

DDVP	Design Development and Verification Plan
ESR	Executive Summary Report
FTV	Flight Test Vehicle
GT	Gas Turbine
HSV	High-Speed Vehicle
LH2	Liquid Hydrogen
LSV	Low-Speed Vehicle
OML	Outer Mould Line
REL	Reaction Engines Limited
SABRE	Synergetic Air Breathing Rocket Engine
TRL	Technology Readiness Level
WPD	Work Package Description

1.2. REFERENCES

1 ESA Contract No. 4000129097/19/NL/BJ/rk with Cranfield Aerospace Solutions Ltd – Assessments to Prepare and De-Risk Technology Developments – SABRE Application – FTV, ESA, Signature completed by both parties 2 December 2019.

2. TASK 1

Workshops between representatives from the participants in Task 1 were held to assist in addressing required topics. The focus was to generate possible concepts and discuss the aspects pertaining to development, verification, safety, reliability and control of each one.

2.1. CONCEPTS CONSIDERED

Note that in illustrations for each concept option: bronze represents SABRE test propulsion components, silver a conventional Gas Turbine (GT) engine, and red a rocket engine.

2.1.1. Concept Option 1 (CO1)

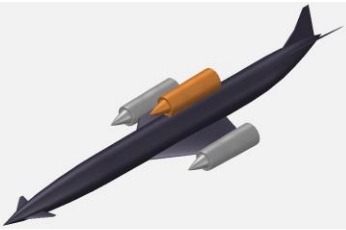

Figure 2: Concept Option 1 LSV

A nacelle intended for the test propulsion components is always present above the fuselage.

A Low-Speed Vehicle (LSV) with conventional GTs is used for low speed de-risking of air vehicle handling.

With reheat, an LSV could achieve transonic and low supersonic flight.

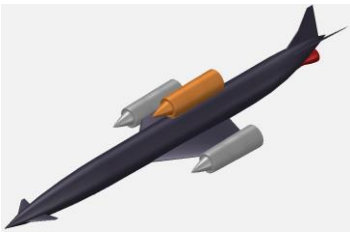

Figure 3: Concept Option 1 HSV

Further testing to higher speeds is done with a High-Speed Vehicle (HSV) that has a rocket mounted in the rear fuselage.

Test propulsion components are then added to the test nacelle with a conventional GT core.

The reduced-scale SABRE engine cores are added as a final step.

Figure 4: Concept Option 1 alternative configuration

A variation on this would either have test propulsion in the fuselage or put test propulsion in tip nacelles and conventional GTs in the fuselage.

This is a lower risk solution with more benefits for airframe development, but is heavier, more complicated, and costly.

2.1.2. Concept Option 2 (CO2)

Figure 5: Concept Option 2 HSV

An initial LSV would use only a podded conventional GT for propulsion above the fuselage.

Even with re-heat, this would not result in flight much above Mach 1.

A throttle-able liquid rocket in the rear fuselage enables incremental testing to Mach 5.

Figure 6: Concept Option 2 HSV with test propulsion components

The podded GT is then replaced by the experimental nacelle containing the same GT core.

The reduced-scale SABRE engine core replaces the conventional GT core as a final stage.

This concept is smaller, lighter and cheaper, but with less redundancy and fewer benefits for development of the intended final product.

2.1.3. Concept Option 3 (CO3)

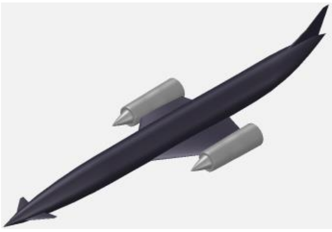

Figure 7: Concept Option 3 LSV

An initial LSV would only attempt flight up to Mach 0.7 using conventional GTs in wing-tip nacelles.

The second stage would add reheat to allow flight up to perhaps Mach 1.7.

The third stage would add the Liquid Hydrogen (LH2) bypass ramjets in test nacelles, allowing increase in maximum speed to perhaps Mach 2.2.

Figure 8: Concept Option 3 HSV with test propulsion components

A fourth stage introduces the reduced-scale SABRE cores to the test nacelles.

The final, fifth, stage would add the pre-cooler in front of the SABRE cores.

This option is very dependent on development of SABRE, but most like the intended product.

2.1.4. Concept Option 4 (CO4)

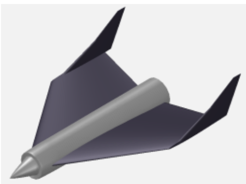

Figure 9: Concept Option 4 LSV

The first stage would use a Commercial Off-The-Shelf military engine in a nacelle sized to the SABRE test propulsion.

This nacelle would form the ‘fuselage’ with wings added to its sides.

Figure 10: Concept Option 4 HSV with test propulsion components

A second stage would add the test nacelle with bypass ramjets, supplied from LH2 storage tanks on the wing tips.

The third stage would add the pre-cooler in front of the core engine.

Finally, the GT is swapped for a reduced-scale SABRE core.

This is a much higher risk solution.

2.1.5. Concept Option 5 (CO5)

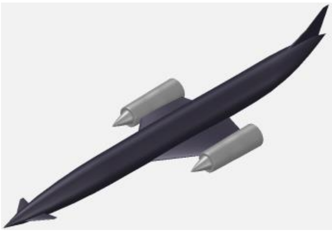

Figure 11: Concept Option 5 LSV

Initially the same as Concept option 3.

Use of conventional GTs in the tip nacelles for subsonic testing.

Reheat to provide capability to Mach 1.5-2.0.

Figure 12: Concept Option 5 HSV with test propulsion components

A liquid rocket engine at the rear of the fuselage is then added to produce an HSV.

The final stages include test propulsion components, with the GT cores eventually replaced by scaled SABRE cores.

This option is also very similar to an intended product, with more complication added compared to option 3.

2.1.6. Concept Option 6 (CO6)

Figure 13: Concept Option 6 small-scale HSV

This option was initially put forward as a variation of Concept Option 5, but is generalised here as a potential variation for all Concept Options.

Initial de-risking of the airframe is performed using test vehicles of a smaller scale, perhaps 2 m span.

Rather than adding reheat to the small GT, a solid rocket engine could be used to achieve Mach 2.0.

Figure 14: HSV of Concept Option 6 as a variation of Concept Option 5

Beyond this, the testing would use the same full-scale FTV and progression as the relevant Concept Option. Having already progressed to supersonic speed at sub-scale, higher speed testing with GTs fitted is not required.

The final stages, replacing the GTs with test propulsion including scaled SABRE cores, is as for the relevant Concept Option.

2.2. DESIGN DEVELOPMENT AND VERIFICATION PLANS (DDVPS)

The development roadmaps of all concepts are similar, with key features detailed below:

- Since the start and end points of all options are similar, they will likely be a similar scale. This scale will be driven by the minimum size of a functional, scaled, SABRE core.
- Where concepts maintain the Outer Mould Line (OML) for all FTVs, the preliminary design of all FTVs needs to be completed before proceeding with detailed design.

- Flight Test Vehicle (FTV) development runs in parallel to SABRE development.
- The first LSVs could potentially be flight test ready 3-4 years after project kick-off.
- Concept design and preliminary design is likely to take up to 2 years.
- Detailed design of later stage FTVs proceeds in parallel to manufacture of earlier FTVs.
- Options that are intended to be similar to an eventual product may require that the configuration of the intended product be defined to a certain level first.
- Ground testing of individual hardware systems will be necessary in parallel to FTV assembly. Ground functional testing and taxi trials of full FTVs will also be required.
- Initial limited low-speed testing with GTs may be possible within ranges in the UK, later testing requires very large range areas.
- Options that do not consider the use of rocket engines in their development rely on the test propulsion to reach the required high speeds and altitudes, taking advantage of the fact that the SABRE core can be developed and de-risked through ground testing alone,

The progression of intended testing is similar between each Concept Option. Table 1 summarises the possible stages in testing and indicates to which options they apply.

Table 1: Intended steps in testing

	CO1	CO2	CO3	CO4	CO5	CO6
1. Small-scale LSV						
Shakedown (including repeat of previous stage)	NA	NA	NA	NA	NA	✓
Incremental testing to indicated Mach	NA	NA	NA	NA	NA	< M1
2. Small-scale HSV						
Shakedown (including repeat of previous stage)	NA	NA	NA	NA	NA	✓
Check operation of rocket and support systems	NA	NA	NA	NA	NA	✓
Incremental testing to indicated Mach	NA	NA	NA	NA	NA	M2
3. LSV						
Shakedown (including repeat of previous stage)	✓	✓	✓	✓	✓	As for relevant Concept Option
Incremental testing to indicated Mach	M2	< M1	< M2	M2	M2	
4. HSV without test propulsion components						
Shakedown	✓	✓	NA	NA	✓	NA
Check GT shutdown, close, open and restart	✓	NA	NA	NA	✓	NA
Check operation of rocket and support systems	✓	✓	NA	NA	✓	NA
Incremental testing to indicated Mach	≤ M5	≤ M5	NA	NA	≤ M5	NA
5. HSV with test propulsion components, GT core						
Shakedown (including repeat of previous stage)	✓	✓	✓	✓	✓	As for relevant Concept Option
Check bypass burners with LH2 from rocket	✓	✓	NA	NA	✓	
Check bypass burners with separate LH2 supply	NA	NA	✓	✓	NA	
Check pre-cooler operation	✓	✓	NA	✓	✓	
Incremental testing to indicated Mach	M5	M5	> M2	M5	M5	
6. HSV with test propulsion components, SABRE demo core						
Shakedown (including repeat of previous stage)	✓	✓	✓	✓	✓	As for relevant Concept Option
Check pre-cooler operation	NA	NA	✓	NA	NA	
Incremental testing to indicated Mach	M5	M5	M5	M5	M5	

2.3. Safety, Reliability and Control Considerations

2.3.1. Common Safety, Reliability and Control Aspects

- The degree of damage that can be caused in the event of a failure goes up with increasing speed and altitude.
- The consequences of failure of the test propulsion need to be catered for, including the potential for large moments to appear very rapidly.
- For high speed testing, all Concept Options require LH2, some require liquid Oxygen.
- All FTVs have lift generation capability and use conventional take-off and landing, which provides more options to cater for failures.
- All options use a staged approach to validate aerodynamics, flight control and propulsion system elements to gradually extend operation to hypersonic flight.
- It will be necessary to assume that most, if not all, items will fail, putting the emphasis on redundancy, with safety reliability being evidenced through a safety case.
- All options assume no pilot onboard, with FTVs that are either controlled remotely, automatic, autonomous, or some combination.
- It is likely that there will be a requirement for a Pilot in Command at all times, with the ability to take over or terminate the flight if necessary.
- A flight termination system will require independent, proven communications links, or some degree of autonomy.
- The requirement for relatively large control surfaces (sized for low speed flight) to be accurately actuated to small deflections with high loading (in high speed flight) presents a significant challenge.

2.3.2. Aspects specific to Safety, Reliability and Control of Individual Concepts

- Loss of a single GT would not produce safety issues when there are two GTs onboard.
- Where test propulsion components are used in conjunction with the GT, the types of failure which could be suffered by the GT are increased.
- Addition of rocket propulsion brings in many safety considerations, including inadvertent operation.
- Concept Option 6 avoids the concerns related to liquid rockets initially, but inadvertent operation of solid rockets is still a concern, and they cannot be stopped once started.
- Rocket propulsion is required for take-off for Concept Option 2, increasing the safety and noise concerns. Other Concept Options with rockets can rely on GTs to position the aircraft before making use of the rockets.
- The SABRE development core will be required to return the air vehicle to landing in the final HSV stage for all but Concept Option 1.
- Test propulsion is relied on for operation towards Mach 5 in Concept Options 3 and 4. For Concept Option 4 any failures will result in total loss of thrust and likely the air vehicle. Even though there are two test propulsion units in concept Option 3, common failures will need to be considered.
- The development of the flight control system becomes more complicated when more different types of propulsion need to be used at any one time.
- The higher the size and mass of an FTV, the greater the consequences of failure in terms of surface impact effects.

3. TASK 2

To achieve the requirements of Task 2, Frost & Sullivan generated a flexible future market Excel spreadsheet-based tool. The potential market is split into: Orbital, sub-orbital, space tourism (further split into orbital and sub-orbital), and high-speed travel.

The variation of total market demand is reviewed by year, from 2020 to 2040, and region, for each market sector. This is then reduced to a total available market for each sector and region, to account for markets that may not be open to the particular system, for various reasons. Figure 15 shows the total and available market potential for all sectors by region. The effect of varying prediction certainty, pricing, and accessibility is indicated.

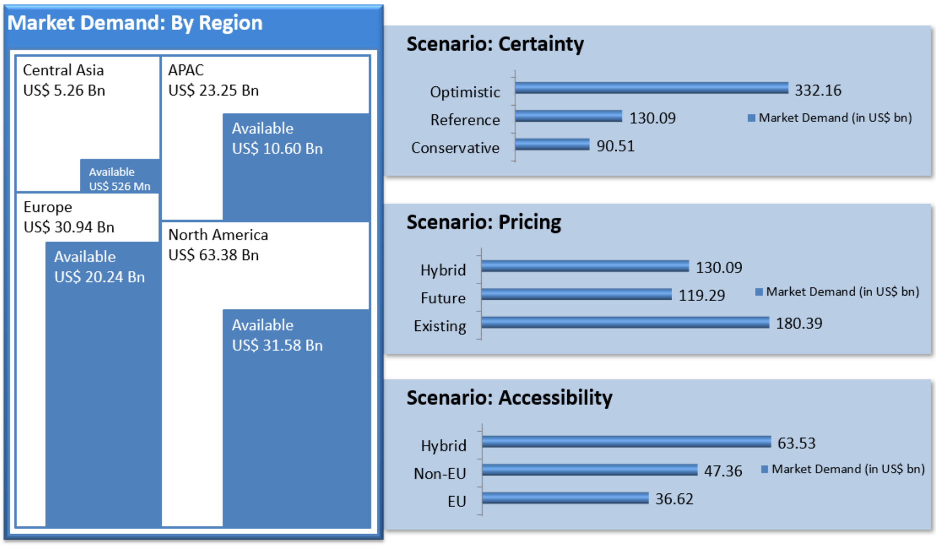

Figure 15: Market potential: Total vs available (2020-2040)

Factors relevant to general operational characteristics are matched with those of an expected SABRE-powered launch system for each market sector. Figure 16 illustrates the market size, market accessibility, and operational alignment of SABRE to each sector.

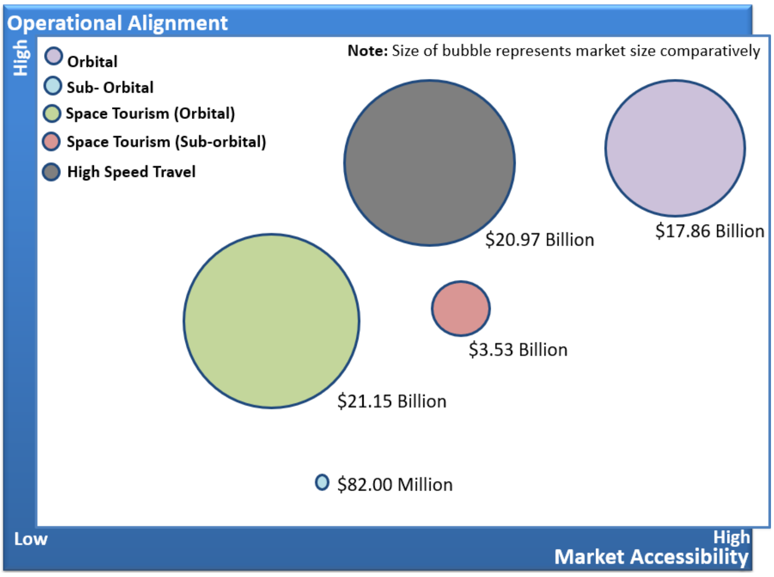

Figure 16: SABRE Positioning

4. CONCLUSIONS

4.1. Task 1 Conclusions

It has not been possible or sensible to select through this study a single most suitable Concept Option, resulting in the need for evaluation of six Concept Options in terms of their design, development and verification, safety, reliability and control. The major aspects are summarised below.

- Concept Option 1 offers the greatest degree of caution in its approach, with the increase in safety reliability being achieved at the expense of increased size, mass, cost and complexity.
- Concept Option 2 offers potentially smaller and lighter FTVs with the hope of reducing cost. This is at the expense of safety reliability, with very little redundancy available.
- Concept Option 3 offers the closest configuration to that of a product space launcher, at the expense of relying heavily on the development of the test propulsion and requiring greater thermal protection.
- Concept Option 4 is an attempt to concentrate on SABRE propulsion development only. There is no consistency in OMLs, no resemblance to the intended product, and no propulsion redundancy.
- Concept Option 5 intends to address the disadvantages of Concept Option 3 through the use of a liquid rocket. This comes at the expense of cost and complexity, and it introduces safety and reliability concerns.
- Concept Option 6 intends to improve on Concept Option 5 by using small-scale vehicles in the early stages of testing to reduce cost and improve safety early on. The difficulty will be ensuring that anything learned from the small-scale vehicle is applicable to a full-scale FTV.

4.2. Task 2 Conclusions

- The orbital segment, covering the dedicated launch services for small satellites, will remain the most significant market to target with a service utilising a SABRE-powered flight system. A SABRE-based platform suited to this segment would likely have a payload of 2000 kg (100-250 kg micro-satellites), and a range of 2000 km.
- A relevantly optimised SABRE-powered flight system, to match commercial aviation operations, will enable efficient and economically sustainable high-speed air travel services. A SABRE-based platform suited to this segment would likely have a payload of 6000 kg (30 passengers), and a range of 18000 km.
- After satellite launch and high-speed travel, sub-orbital space tourism is the next best market segment to target long term. A SABRE-based platform suited to this segment would likely have a payload of 2000 kg (6-8 passengers), and a range of 250 km.