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Synergetic Air-Breathing Rocket Engine (SABRE) Programme Evaluation Report 2022

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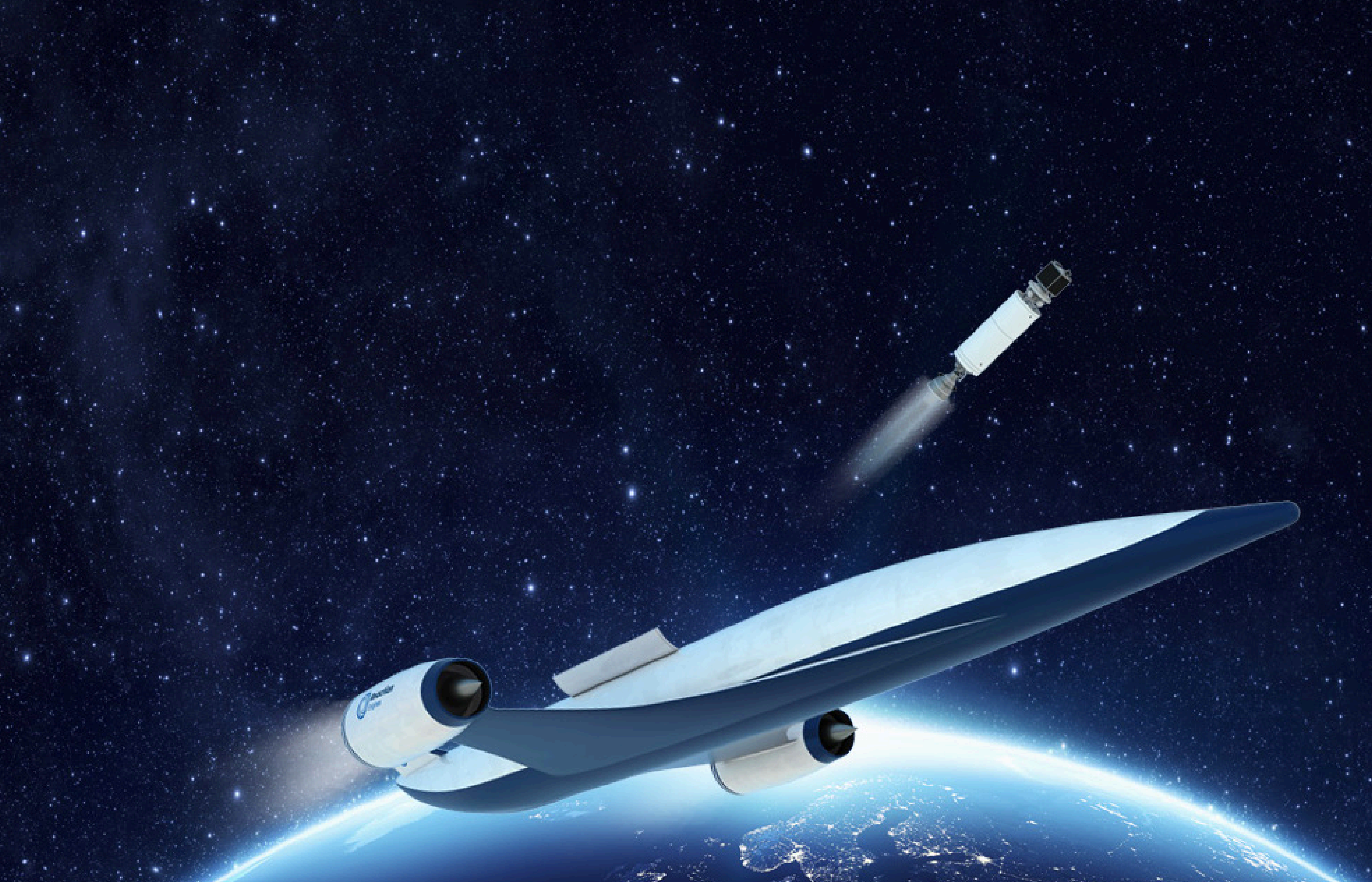

DECEMBER 2022

SYNERGETIC AIR BREATHING ROCKET ENGINE (SABRE) PROGRAMME EVALUATION REPORT 2022

THE AEROSPACE CORPORATION UK LTD

Reaction Engines

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Final Report

The Aerospace Corporation UK Ltd

December 2022

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1 Table of Contents

Table of Contents 4
Table of Figures 6
Table of Tables 6
1 Executive Summary 7
1.1 The Evaluation 7
1.2 The SABRE Programme 7
1.3 Impact Evaluation 8
1.4 Value for Money 10
1.5 Grant Administration 11
2 Introduction 11
2.1 The Evaluation 11
2.2 The Approach 11
2.3 The Report 12
2.4 Programme Logic Model 12
3 The SABRE Programme 13
3.1 Background and context 13
3.2 SABRE Programme Grant Timeline 17
4 Impact Evaluation 19
4.1 Technological Advancements 20
4.1.1 Technical Progress of SABRE 4.1 engine cycle components 20
4.1.2 Development of Key Technologies 22
4.1.3 Technical Deliveries 25
4.2 Positioning of RE as a “space” company 32
4.2.1 Self-assessment: “RE is a “space” company” 32
4.2.2 Involvement in the Larger Space Economy 33
4.2.3 Providing Goods and Services Associated with Space 33
4.3 Employment and People Development 34
4.4 Labour Productivity Gains 37
4.5 Intellectual Property and Partnerships 39
4.5.1 Patent Portfolio 39
4.5.2 Knowledge Exchange and Partnerships 40
4.5.3 Applied Technologies 42
4.5.4 Induced Supply Chain Spending 44
4.6 New and Strengthened Partnerships 46
4.6.1 ESA Programme Framework 46

4.6.2 European Industry/Agency Collaboration 47
4.6.3 Airframe Engagement 49
4.7 Technological and Scientific Inspiration and Prestige 49
5 Value for Money 53
5.1 Direct Impact 54
5.2 R&D Spill-over Impact 55
5.3 Contract Spill-over Impact 57
5.4 Estimated Total Economic Impact 58
6 Grant Administration 58
6.1 Pre-Award Phase 59
6.1.1 Proposal was not evaluated against relevant, standard criteria 59
6.1.2 Grant objectives were not clearly documented 60
6.2 Award Execution Phase 61
6.2.1 Administrative processes improved over time 61
6.2.2 Grant administration included innovation solutions, such as ESA support for technical assurance 63
6.2.3 Administrative overhead was appropriate given the size and scope of the grant 64
6.2.4 The grant structure allowed for sufficient flexibility for all parties to adapt to changing circumstances 65
6.2.5 SABRE Programme lacked a robust risk management process at the initiation of the grant 66
6.3 Post-Award 67
6.4 Lessons Learnt and Best Practices 67
7 Conclusions 68
7.1 On the impact of the programme 68
7.2 On the value of money 69
7.3 On the administration of the grant 70
Appendix A Methodological Annex 72
A.1 Study approach 72
A.2 Main Methods 72
A.3 Funding Milestone Details 72

2 Table of Figures

Figure 1: SABRE Programme Logic Model 13
Figure 2: SABRE 14
Figure 3: SABRE sub-systems 15
Figure 4: SKYLON spaceplane concept 16
Figure 5: Simplified SABRE cycle 21
Figure 6: SABRE Design Maturity “scorecard” 22
Figure 7: Precooler Mach 5 Test Process 23
Figure 8: Preburner Test 24
Figure 9: HX3 Nozzle 24
Figure 10: RE Permanent Employees 35
Figure 11: Infographic: Size & Health of the UK Space Industry 2021 38
Figure 12: Green Aviation using SABRE Technology 43
Figure 13: HTX Test Article 44
Figure 14: RE’s UK and Europe Spending Profile, 2020-2021 45
Figure 15: Space Value Chain 51
Figure 16: Key Finding 5 from 2015 GIAA Report 62
Figure 17: Key Finding 2 from 2015 GIAA report 66

3 Table of Tables

Table 1: Fundamental features of SABRE 14
Table 2: Major SABRE Programme Milestones (2015) 18
Table 3: Summary of RE Job Openings 36
Table 4: RE Patent Portfolio 2015-2021 39
Table 5: RE Technology Transfer and Knowledge Exchange Activities 40
Table 6: Potential Native UK Launch Service Providers 50
Table 7: Publications and Conference Presentation List, Post 2015 52
Table 8: Summary of Research Funding, Contracts, and Investment Since 2015 Grant 54
Table 9: R&D Spill-over Calculations 57
Table 10: Contract Spill-over Calculations 57
Table 11: Total Economic Impact of RE’s Activities in the UK, 2015-2021 58

1 EXECUTIVE SUMMARY

In 2015, the Secretary of State for Business, Innovation and Skills (BIS, now Business, Energy & Industrial Strategy (BEIS)), acting through the UK Space Agency (UKSA), awarded Reaction Engines (RE) a UKSA grant not exceeding £50,000,000 (fifty million pounds) for the development of a novel engine concept that combines air breathing and rocket technologies into a single engine system enabled byground-breaking heat exchanger technology. This engine system is known as the Synergetic Air-Breathing Rocket Engine (SABRE) Programme.

The purpose of this Grant Funding Agreement (GFA) was to advance the SABRE technology, stimulate growth in the UK space sector, increase the relevant skills and knowledge base in RE and the UK, and support the development of bilateral agreements between RE and UK and international partners.

The UKSA commissioned The Aerospace Corporation UK Ltd to evaluate the SABRE Programme grant, and this report presents the findings of that evaluation.

1.1 The Evaluation

The objectives of the evaluation were to assess the benefit and impact of the grant funding, its value for money, and the processes by which the grant has been administered.
The study was undertaken between January and March 2022. The approach involved a review of available documentation and data as well as a series of interviews with relevant personnel within UKSA and RE.

1.2 The SABRE Programme

RE is a privately held company based in Oxfordshire, UK, that employs over 200 staff across its sites in the UK and US. Founded in 1989, RE's primary objective was to develop technologies for their SABRE engine toward the goal of creating next-generation hypersonic flight and space access vehicles.

SABRE is a hybrid combined-cycle air-breathing/rocket engine that, if successful, may enable hypersonic travel within the atmosphere and could lead to reduced access-to-space costs. RE claims that the SABRE concept represents a major breakthrough in propulsion technology, which could enable the realization of a reusable, single-stage-to-orbit (SSTO) launch vehicle. The SABRE engine is designed to operate in air-breathing mode (using atmospheric air and on-board liquid hydrogen) up to velocities of Mach 5, then transition to a rocket mode (using onboard liquid oxygen and hydrogen) to enable exo-atmospheric flight and powered re-entry.

In order to further illustrate the performance capabilities of SABRE for space access, RE had also conceived a notional SSTO vehicle called SKYLON that used SABRE as its primary propulsion. Performance evaluations by RE of a SABRE-based SKYLON vehicle seemed to support the potential benefits of SABRE not only for SSTO systems, but for other launch vehicle architectures.

Funding for the SABRE and SSTO launch vehicle concept has largely been through private equity, supplemented by European Space Agency (ESA) contracts in recent years. However, SABRE gained ministerial attention, and the economic case for UKSA support for SABRE development began in 2012, with funding first ear-marked in 2013. The SABRE Programme was ultimately awarded a grant of £50M over 48 months in 2015 following a successful European Commission State Aid Decision.[1] This grant between RE and the UKSA was, at the time, the largest value grant to a single entity in the Agency's history.

Planned SABRE development is divided into four Phases. The focus of the grant awarded in 2015 was Phase 3 (Design and Demonstration), building on the successful development and demonstration of key technologies in the previous Phases 1 and 2 (Engine Technology Demonstration Programme). Phase 4 (Design and Development) is planned to evolve SABRE based on Phase 3 demonstration testing, complete the engine certification, and then lead to Phase 5 (Engine Production).

As proposed in 2015, Phase 3 was divided into four tasks, two of which were to be funded in-part by the £50M UKSA grant:

- Phase 3a – System Definition and Requirements (funded by ESA and RE, completed Q1 2017)
- Phase 3b – System Preliminary Definition (£10,317,760 from UKSA)
- Phase 3c – System Detailed Definition (£39,682,240 from UKSA GFA)
- Phase 3d – Demonstration Engine Manufacture

Following completion of SABRE Engine Level System Requirements Review (SRR) in December 2016 through Q1 of 2017, RE and their various stakeholders and funding sources opted to realign the programme with a focus on advancing the design of the air-breathing engine technology demonstrator through a dedicated ground test initiative called DEMO-A in preparation for testing of the integrated DEMO-A Engine by the end of 2019. This realignment resulted in a modified grant agreement aimed at reducing future design risks and which was approved in 2017.

Due to delays in SABRE technical development and issues with test facility readiness, the DEMO-A test was not achieved in the time period covered by the SABRE Programme grant. Although not all the original project objectives were achieved, considerable progress has been made in the design and manufacture of components and facilities needed.

1.3 Impact Evaluation

The overall purpose of this impact evaluation is to assess whether the grant met its objectives, and to determine what impact the grant funding had on RE, as well as on the wider UK space industry. The study team was able to identify several strong programme impacts, including:

- Technological advancements – SABRE technology was advanced as a result of grant funding; however, due to the inherent challenges of technology development and maturation, many of

[1] https://ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=3_SA_39457

the initial technical goals and milestones were not achieved. Notably, the heat exchanger technology development programme (HTX) achieved the goal of advancing through several critical design reviews as well as test. The successful test campaign, undertaken at the RE purpose built hypersonic ground test facility, enabled the precooler to be tested multiple times at Mach 5 conditions. This was a world first and represents a significant step forward in demonstrating and de-risking a critical element of the SABRE engine. The DEMO-A project achieved all of its key design maturity goals whilst also undertaking subscale testing of some subsystems, with focus given to the critical subsystems supplied by RE. While the realigned Phase 3 Programme goal of achieving test readiness for DEMO-A and the test facility was not achieved, the study team finds that accomplishments achieved to date do fall largely in line with the original 2015 GFA intent, which was to progress the demonstration engine through the Critical Design Key Point (CDKP) and Critical Design Review (CDR). It appears that there was some growth in ambition during the programme realignment that advanced the main objective from CDR to test readiness. Furthermore, the scaled subsystem testing undertaken within the programme together with the full-scale subsystem and coupled subsystem testing now underway, represents a significant step forward in validating the design. To successfully move into the next phase in SABRE development, further components and systems associated with DEMO-A need to be tested.

- Positioning of RE as a “space” company – A space company is a company involved in the larger space economy, providing goods and services associated with space or space access. These goods and services could include but are not limited to research and development activities, manufactured hardware, and space-enabled services (such as telecom) provided to end-users. While RE considers itself a space company, the grant has improved RE’s position as a space company within the larger space economy and positively impacted RE’s ability to provide goods and services associated with space or space access. As a result of the grant funding, RE has developed new and strengthened relationships with international and domestic space agencies and companies, and has made relevant technological and process advancements associated with space and space access.

- Employment and people development – RE has grown from 61 employees in 2014 to 204 permanent employees in 2020. The workforce is made up of highly skilled, diverse, and young employees from across the country, Europe, and throughout the world. RE recruits professional engineers across a broad range of engineering disciplines; most recruits have a university education, with many holding PhDs and being industry experts in their field. RE employees induce positive externalities through productivity and knowledge spill-overs, where knowledge generated within RE enhances the productivity of other organisations. RE also promotes continuous professional development and encourages its workforce to achieve professional accreditation through recognised bodies such as the Institute of Mechanical Engineering, Royal Aeronautical Society, and the Institute of Physics.

- Labour productivity gains – According to findings presented in the UK government’s recently published Size and Health of the UK Space Industry 2021 every direct RE employee, supported by the income they receive, should be viewed as a force multiplier, delivering 2.6-times greater return on investment to the UK economy over the average UK employee.

Additionally, space industry employment has indirect and induced UK industrial base impacts, such that direct employment by RE supports an additional 367 UK jobs through indirect and induced efforts.

• Knowledge exchange and partnerships – RE has successfully generated tradable Intellectual property (IP) as a result of the SABRE Programme grant funding. Since 2015, RE has had 12 granted patents, registered in several countries, for an average rate of just under 2 grants per year. However, often RE chooses instead to protect its IP by retaining it as a non-public trade secret, of which they currently have 35 internally documented. In addition to protecting its IP, RE has also leveraged their IP to facilitate knowledge transfers in industry and form partnerships with other organisations. The technologies developed on the path toward SABRE have broad benefits beyond space-access and the mainstay SABRE Programme. In line with the conditions of initial UK Government investment, RE has pursued early commercialisation of SABRE technology in adjacent and alternative applications and industries such as ammonia heat exchange, battery cooling, green and sustainable applications, and high-speed flight. RE has won contracts for spin-out technologies in these areas with future opportunities expected to generate additional revenue. These spinouts have also allowed RE to industrialise its technology and processes to accommodate efficient higher yield output, a key step in the commercialisation of new technology. These spinouts also have the potential to generate positive spill-over effects in the larger economy.

• New and strengthened partnerships – The grant has significantly strengthened RE's reputation and provided the opportunity to gain interest and, in many cases, work directly, with important government bodies and industry players. When the original 2015 grant was approved, RE had a relatively small number of industry relationships; RE now has 990 registered suppliers and 650 active suppliers. RE has also built new and strengthened partnerships with key government agencies such as ESA, the French National Centre for Space Studies (CNES), the Italian Space Agency (ASI), the German Aerospace Centre (DLR), and key UK Ministries and Departments.

• Technological and scientific inspiration and prestige – RE is a homegrown company that aims to rival incumbent launch providers, which could reduce the UK's reliance on foreign launch service providers for access to space and provide more resilient launch alternatives. RE actively promotes their profile and company through a variety of communication avenues and participates in events designed to stimulate interest and excitement around space topics. The company attracts attention with their numerous publications, presentations, and accolades, which could result in attracting additional talent from other parts of the world. This benefits the UK space industry as a whole by creating a hotspot for big-name business leaders and companies.

1.4 Value for Money

The study determined that the SABRE grant could have had a very large impact on the UK economy. The company has achieved £96 million of follow-on investment, funding, and revenues since the initial grant funding. Using relevant spill-over multipliers, the study team estimated that RE could have generated as much as £233.3 million in spill-over economic impacts, for a total of £379.3 million in gross economic impact to the UK economy over the seven-year grant period (~£54 million per year).

Comparing the £50 million of grant received by RE in 2015 to the £379.3 million gross economic impact from the grant funding and RE's research, contracts, and investment activities, it is suggested that for each £1 million in grants, RE's activities could have generated a gross economic impact of as much as £6.3 million across the UK from 2015 to 2021. This is an upper-bound value and represents a maximum, best-case value, based on academic productivity multipliers.

1.5 Grant Administration

The study determined that the SABRE Programme grant was well administered, especially related to the amount of administrative overhead, flexibility to adjust to changing circumstances, process improvements seen over time, and the use of innovative solutions for technical assurance.

However, several notable weaknesses were also identified. The initial proposal was not evaluated against standardised criteria, and the government's overall goals and objectives of the SABRE Programme grant were not clearly documented. Additionally, prior to awarding the grant, the UKSA did not have a risk management process in place to actively address the risks identified in the initial proposal.

The study also captured specific lessons learnt, best practices, and recommendations for improvement associated with the administration of this and future grants. Many of these lessons learnt were related to continuing to formalize and mature existing processes and increase interactions between the Agency and grant recipients.

2 INTRODUCTION

2.1 The Evaluation

This document presents the Final Report from the evaluation of the SABRE Programme grant received by RE. The Aerospace Corporation UK Ltd has undertaken the evaluation on behalf of the UKSA in 2022. Following the standard intervention evaluation process outlined by the Magenta Book, there were three main elements in this study:

- Impact evaluation – Did the grant achieve its objectives? What was the impact of the grant on RE's positioning as a "space" company? What were the other benefits and impacts of the grant funding?
- Value for money assessment – What were the direct and indirect economic impacts of the grant on the UK space industry? How do these impacts compare to the initial grant investment?
- Process evaluation – How effectively was the grant administered? What processes and practices worked well, and what areas could be improved upon?

Due to the challenging nature of technology development efforts, the as-executed SABRE Programme differed from the plan proposed in the original 2015 Grant Funding Agreement (GFA). All changes to the scope of the original grant were reviewed and approved by UKSA. In order to capture the true impact of the grant, the scope of this evaluation includes both the original objectives and goals, as well as the objectives and goals of the realigned Programme.

2.2 The Approach

This study employed a mixed-method approach to this evaluation, organized around three main packages of work:

- Scoping – A short preliminary step to review initial programme documentation and relevant UKSA guidance documents and develop an evaluation approach.
- Data Gathering – The main phase of the study, including requesting additional data from UKSA and RE, performing open-source research, and conducting interviews with relevant personnel from UKSA and RE.
- Analysis – The final phase of the study, analysing the data collected throughout the study, and addressing the key evaluation elements.
- Reporting – Weekly reporting occurred throughout this study to provide updates on progress. A draft of this report was provided to both RE and UKSA for review and comment. This Final Report represents the final deliverable.

Significant programme documentation and data were available to the study team, so the evaluation approach was primarily a table-top review by subject matter experts. The study also included a series of interviews with relevant personnel within UKSA and RE to gather additional primary data.

As stated previously, the SABRE Programme did experience challenges and setbacks during the execution of the grant resulting in non-trivial, agreed changes to the programme execution plan and milestone delivery schedule. The study team evaluated the impact of the grant against both the original objectives and goals, as well as the objectives and goals of the realigned Programme.

Further details on the study requirements, approach, and methods are provided in Appendix A

2.3 The Report

The remainder of this Final Report is structured as follows:

- Section 3 – Introduces RE and the SABRE Programme and presents a brief overview of the SABRE technology as well as a timeline of changes experienced over the course of the grant.
- Section 4 – Presents the results of the impact evaluation organized according to the objectives of the grant and the key areas of consideration.
- Section 5 – Presents the assessment of the grants' direct and indirect impact on the UK economy.
- Section 6 – Presents findings associated with the administration of the grant including lessons learnt and areas of improvement for future UKSA grants.
- Section 7 – Summarizes the main findings of the study.

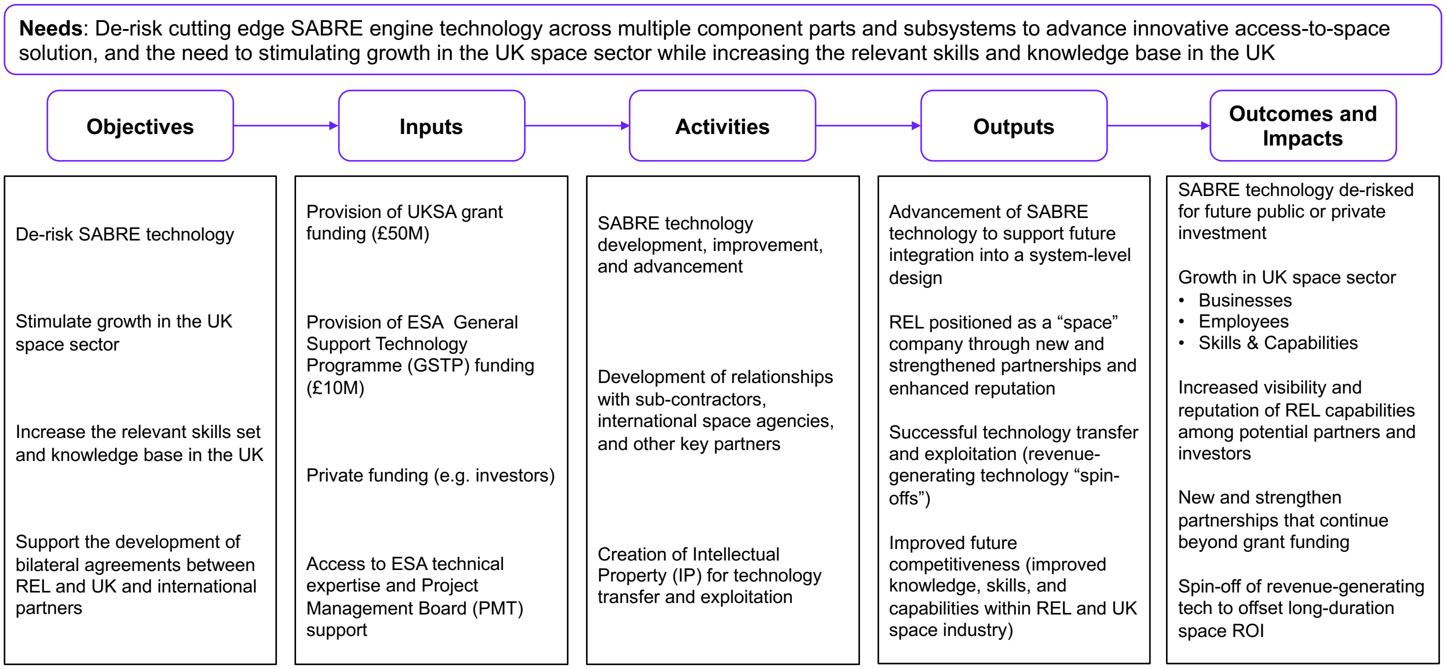

Figure 1: SABRE Programme Logic Model

2.4 Programme Logic Model

As part of the Scoping activities, the study team developed a logic model for the SABRE Programme, based on the evidence obtained through independent research and discussions with UKSA (Figure 1). This model describes the logical sequence and relationships between the Objectives of the grant, the available resources (Inputs), the Activities undertaken as a result of the grant, and the anticipated results (Outputs) and changes (Outcomes and Impacts) that should address the initial Objectives.

3 THE SABRE PROGRAMME

3.1 Background and context

RE is a privately held company based in Oxfordshire, UK, that employs over 200 staff across its sites in the UK and US. RE develops technologies for an advanced combined cycle air-breathing rocket engine called SABRE toward the goal of creating next generation hypersonic flight and space access vehicles.

RE was founded in 1989. RE has invested over 30 years in research into thermodynamics and heat exchanger technology and intends to develop the SABRE engine (see Table 1). SABRE is a hybrid combined-cycle air-breathing/rocket engine that, if successful, will enable hypersonic travel within the atmosphere and greatly reduce access-to-space costs. The SABRE concept represents a major breakthrough in propulsion technology, which could enable the realization of a reusable, SSTO launch vehicle (the SKYLON spaceplane). The SABRE is designed to operate in both air-breathing mode (using atmospheric air and on-board liquid hydrogen) and rocket mode (using onboard liquid oxygen and hydrogen).

Table 1: Fundamental features of SABRE[2]

• *The integration of an air-breathing engine with a rocket engine whilst minimising the duplication of equipment.* • *Deep pre-cooling of the air used in the engine to enable the operation of a compressor at high Mach numbers.* • *Use of the energy absorbed from the air to power internal turbomachinery.* • *Use of the hydrogen fuel as a heatsink for the residual energy prior to combustion*

Since its inception, the SABRE thermodynamic cycle has progressed through several iterations as RELs knowledge base and capabilities grew. The 2015 SABRE Programme grant proposal was for development of what was referred to as the "SABRE 4" engine concept. It improved on SABRE 3 with a better equivalence ratio (ratio of actual to stoichiometric fuel/air ratios) for potentially increased SKYLON performance. Unlike SABRE 3, the SABRE 4 separated the air-breathing and rocket combustion chambers, but they still share a common nozzle. This would also allow "clearly defined programmatic separation of the two technologies" (i.e., separate air-breather and rocket engine developments).

Two SABRE demonstration engines were planned and designated E1 and E2. They would likely consist mainly of the Air-Breathing Core; other sub-systems (e.g., Combustion System/air-breathing & rocket, Nacelle Structure, Intake System, etc.) would be introduced in later configurations.

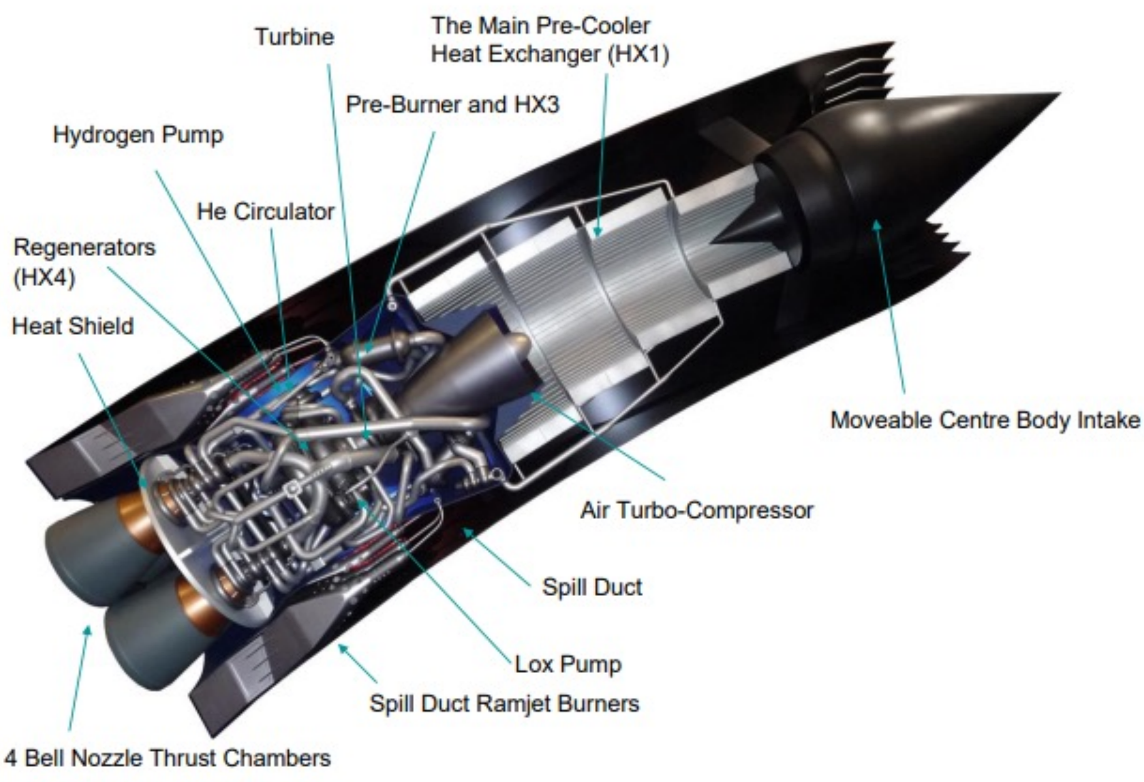

Figure 2: SABRE[3]

[2] Proposal, SABRE Development Programme, Ref SABRE-REL-OF-0022, Rev 03, 14 November 2017
[3] The SABRE Engine – Phase 3 Development Resource and Implementation Plan, Ref BSDEV-REL-OF-0018, Rev 08, 12 November 2015

The SABRE engine itself consists of five major sub-systems: the air-breathing core engine sub-system; the rocket engine sub-system; the nacelle; the data instrumentation and electrical supply sub-system; and the ancillary sub-systems (see Figure 2). The air-breathing core engine and rocket engine are considered separate sub-systems and are further broken down into sub-system elements (see Figure 3).

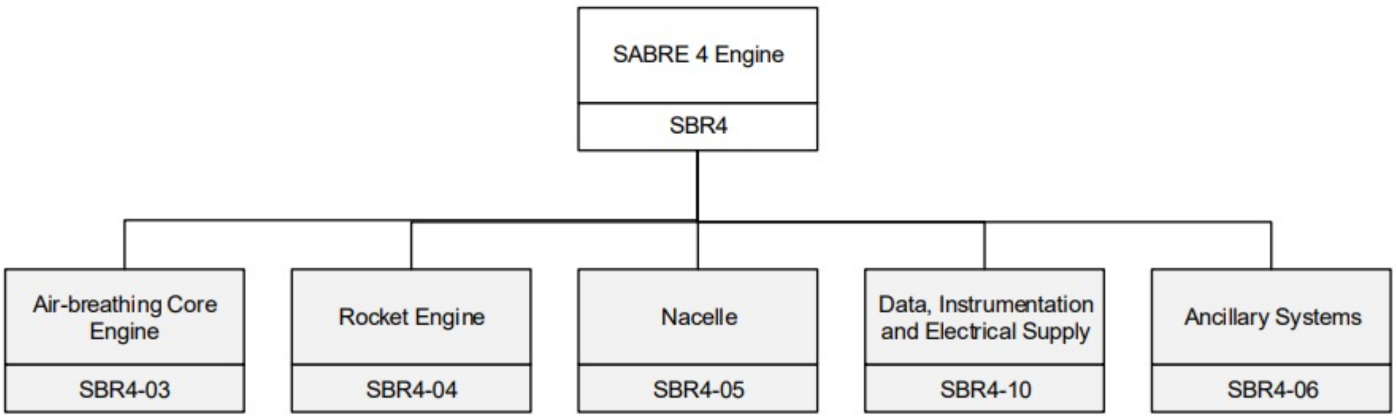

Figure 3: SABRE sub-systems[4]

RE's original SABRE concept envisioned the rocket engine development in parallel with the nacelle and air-breathing core. It would be highly integrated with the air-breathing core and sub-contracted to an experienced rocket engine manufacturer. However, RE's most recent design separates the rocket engine development from the integrated whole. The rocket engine would be purchased or developed separately and assembled with the air breathing core during final integration and test.

SKYLON is the original conceptual SSTO launch vehicle powered by SABRE to take advantage of SABRE's dual-mode air breathing and rocket modes. The SKYLON concept began in 1989 and has been advanced by internal RE study work since 2009. SKYLON would leave horizontally from a runway in air breathing mode, like a traditional aircraft, climb in altitude and speed until it reached Mach 5, then transition to rocket mode into Low Earth Orbit (LEO). After delivery of its payload, SKYLON would re-enter Earth's atmosphere and glide back to the runway for landing.

[4] The SABRE Engine – Phase 3 Development Resource and Implementation Plan, Ref BSDEV-REL-OF-0018, Rev 08, 12 November 2015

However, the SKYLON structure is quite complex and different from traditional aircraft or launch vehicles. It includes corrugated reinforced glass ceramic aeroshell, multilayer foil insulation, Titanium/Silicon Carbide (Ti/SiC) spaceframe primary structure with titanium nodes, and aluminium cryogenic tankage with foam insulation. These advanced manufacturing capabilities would need to be developed to make SKYLON a reality. (See Figure 4.) SKYLON development was not a major focus of the SABRE Programme grant.

Figure 4: SKYLON spaceplane concept[5]

Funding for the SABRE and associated SKYLON Spaceplane concept has largely been through private equity, supplemented by ESA contracts in recent years. However, the SABRE gained ministerial attention, and the economic case for UKSA support for SABRE development began in 2012, with funding first ear-marked in 2013. The SABRE Programme grant of £50M over 48 months was ultimately awarded in 2015 based on a successful European Commission State Aid Decision.[6] At the time of the award, this grant represented the largest grant to a single entity in the Agency's history.

If successful, the grant would de-risk cutting-edge SABRE technology across multiple component parts and subsystems, advancing an innovative access-to-space solution. The grant would also stimulate growth in the UK space sector while increasing the relevant skills and knowledge base in the UK.

[5] The SABRE Engine – Phase 3 Development Resource and Implementation Plan, Ref BSDEV-REL-OF-0018, Rev 08, 12 November 2015

[6] "Commission State Aid Decision" https://ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=3_SA_39457

3.2 SABRE Programme Grant Timeline

Planned SABRE development is divided into four Phases. The focus of the grant awarded in 2015 was Phase 3 (Design and Demonstration), building on the successful development and demonstration of key technologies in the previous Phases 1 and 2 (Engine Technology Demonstration Programme). Phase 4 (Design and Development) is planned to evolve SABRE based on Phase 3 demonstration testing, complete the engine certification, and then lead to Phase 5 (Engine Production).

As proposed in 2015, Phase 3 was divided into four tasks, two of which were to be funded in-part by the £50M UKSA grant, with the balance from RE match funding:

- Phase 3a – System Definition and Requirements (funded by ESA and RE, completed Q1 2017)
- Phase 3b – System Preliminary Definition (£10,317,760 from UKSA GFA)
- Phase 3c – System Detailed Definition (£39,682,240 from UKSA GFA)
- Phase 3d – Demonstration Engine Manufacture

The SABRE Programme grant largely funded activities associated with Phases 3b and 3c. Phase 3a had been funded by RE (via a private equity fund) and ESA (£4M each). Major activities planned for Phase 3b included the completion of a successful Preliminary Design Review (PDR), and further technology development with emphasis on engine sub-systems development unit testing. Major activities planned for Phase 3c included advancing the SABRE flight design for the Block 1 demonstration engine, and the completion of a successful Critical Design Point Review (CDPR).

The major SABRE Programme milestones as proposed in 2015 are summarized in Table 2 below.

Table 2: Major SABRE Programme Milestones (2015)

Programme/Task	Purpose	Proposed Outcome	Proposed Start (CY)	Proposed Complete (CY)
Phase 3	Demonstrate SABRE operation in a ground-based installation.	Demonstrate the technical viability of the SABRE design. Foundation for Phase 4.	Q1 2016	Q4 2021
Phase 3a System Definition and Requirements Phase	Advance SABRE system design together with the associated requirements definition. Culminate in a System Requirements Review (SRR) and provide input into Phase 3b.	Culminate in a System Requirements Review (SRR) and provide input into Phase 3b.	N/A (before grant)	Q2 2016
Phase 3b System Preliminary Design	Continue engine design to completion of the preliminary design phase.	Culminate in the system Preliminary Design Review (PDR).	Q1 2016 (overlapping some with Phase 3a)	Q1/2 2018
Phase 3c System Detailed Definition	Advance SABRE detailed design to a flight engine and complete the design of the associated Block 1 demonstration engine,	End with the Block 1 demonstration engine Critical Design Key Point review (CDKP).	Q2 2018	~Q3/4 2019 (roughly end of 48-month grant period)
Phase 3d Demonstration Engine Manufacture	Manufacture and assemble the Block 1 demonstration engine and undertake the initial engine testing.	Culminate in the Critical Design Review (CDR) for the Block 1 engine.	Q4 2019	~Q4 2021 for Phase 1 Block 1 engine demo (beyond 48-month grant period)

Following the SABRE Engine Level SRR (completed in December 2016 through Q1 of 2017), RE and their various stakeholders and funding sources decided to realign the programme with a focus on advancing the design of the air-breathing engine technology demonstrator (DEMO-A) in preparation for testing of the DEMO-A Engine by the end of 2019. Due to this realignment, a modified grant agreement focused on reducing future design risks was approved in 2017.

The programme as planned in 2017 was realigned into 19 projects within the following key elements:

- SABRE Integrated Design
- Vehicle Studies
- Technology Demonstrators (at subsystem level) including Test Facilities
- A series of Technology Development Projects (enabling Technologies)

Phase 3b was planned to be concluded at a SABRE Intermediate Key Point (IKP) review in mid-2018. Successful execution of the following activities was a stated pre-requisite for holding the IKP:

- DEMO-A PDR conclusion
- Results of the Test facility design review
- Results of heat exchanger technology development programme (HTX)
- Preliminary studies of the DEMO-N (design and develop a Nacelle demonstrator)
- Preliminary studies of the DEMO-R (design and develop a staged combustion rocket engine demonstrator)
- Continuation of the technology development programmes required for the SABRE engine

Schedule details for Phases 3c and 3d were not presented; Phase 3 was planned to culminate in the SABRE CDR in late 2026. Phase 4 was planned to consist of test integration, production readiness, and the beginning of engine production, completing in late 2033.

Due to delays in SABRE technical development and issues with test facility readiness, the DEMO-A test was not achieved in the time period covered by the SABRE Programme grant.

4 IMPACT EVALUATION

This section addresses the assessment of the impact of the SABRE Programme grant. The overall purpose of this impact evaluation is to assess whether the grant met its objectives and to determine what impact the grant funding had on RE as well as on the wider UK space industry.

The material is structured around the main outputs and impacts that were expected to result from the SABRE Programme grant (see Figure 1 above). Significant programme documentation and data was available to the study team, so the results are largely based on a table-top review, supplemented as needed by data gathered through a series of interviews with relevant personnel within UKSA and RE.[7]

[7] A significant portion of the information in this section was graciously provided by RE. The information was reviewed by the study team and is accepted as accurate and truthful.

4.1 Technological Advancements

One of the main objectives of the SABRE Programme grant was to advance the SABRE technology with a goal of maturing understanding of system performance through detailed design and demonstration. In order to determine whether the grant met its technical objectives, the study team:

- Reviewed technical progress of each component associated with SABRE 4.1 engine cycle
- Reviewed the summary of development of key technologies as provided by RE
- Reviewed the technical deliveries associated with the main activities in the realigned 2017 proposal, compared original cost vs actual as-invoiced cost, and the timeliness of the deliveries

It is important to note that the study team did not evaluate the “goodness” of the milestone accomplishments – only that the deliverables were submitted and accepted by the customers. The technical assurance of the milestones was completed by ESA as part of the GFA.

Significant technical progress was achieved during the period of the grant on all the elements that are both novel and critical to successful development of a SABRE engine. This progress (detailed in the next subsections) all feeds into the planned demonstration which will validate the SABRE concept. At the conclusion of the grant, RE had the capacity to produce all the needed elements for DEMO-A. Only after the DEMO-A goals have been achieved will there be enough confidence to pursue development of full engine.

4.1.1 Technical Progress of SABRE 4.1 engine cycle components

In the 2017 programme realignment proposal, the DEMO-A subsystems were intended to advance through the Critical Design Key Point (CDKP) gate review, then through CDR at the DEMO-A system level. Following the CDPK/CDR gates, the DEMO-A subsystems were intended to progress to the Manufacturing, Assembly, and Test phase, culminating in TRRs at the subsystem and DEMO-A system level. The rocket engine and nacelle elements of the SABRE system were to receive limited pre-PDR development during the Phase 3 realignment, but the content was eventually cancelled, and funds transferred to other milestones. The precooler (HX1) was not part of the DEMO-A project but developed separately as the HTX project. HTX was intended to progress through TRR and initial testing.

Shown below in Figure 5 is a schematic of the airbreathing elements of a simplified SABRE cycle with the hardware elements of the DEMO-A and HTX projects highlighted.

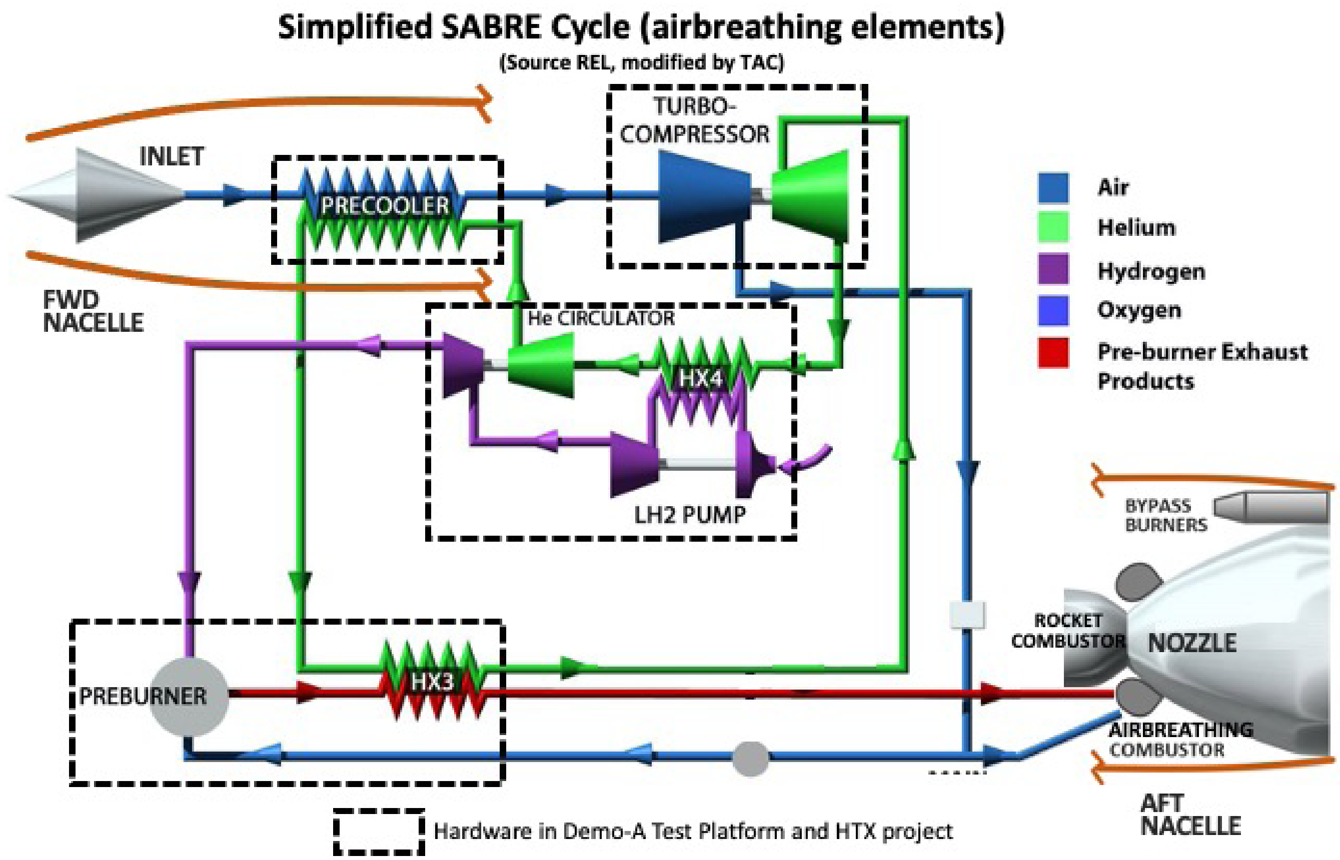

Figure 5: Simplified SABRE cycle.[6]

[6] Image provided by RE, and modified by TACUK

Figure 6 below shows a "scorecard" of the design maturity and hardware status achieved during the Phase 3 grant period. The HTX project achieved the goal of advancing through CDR, TRR and test. The DEMO-A project achieved the CDKP/CDR design maturity goals but did not achieve the TRR goals. It should be noted that there was substantial testing and manufacturing trials at various scales during the design phase.

NACELLE	Design	Hardware/Test
Air Inlet	~	~
Precooler (HX1)	CDR	Test
Nacelle Structure	~	~
Bypass Burners	~	~

AIR-BREATHING CORE	Design	Sub element	Integrated Test
Turbo-compressor (C1T1)	CDKP		~
Preburner (PB1)	CDKP		MRR
High Temp HX (HX3)	CDKP		~
LH2/He Regen (HX4)	CDKP		~
He Circulator (C2T2)	CDKP		MRR
LH2 Turbopump (P1T4)	CDKP	SOC	SOC
Airbreathing Combustor	~	~	~
Ancillary (valves, instr., elec., etc.)	CDKP		FPS
DEMO-A System	CDR	~	~

ROCKET	Design	Hardware/Test
Turbomachinery	~	~
Main Combustor	~	~
Nozzle	~	~

DEMO-A / HTX STATUS KEY

Design Status
- Pre-PDR
- PDR+
- CDR/CDKP
- ~ (unknown or not in DEMO-A)

Sub-element Test
- Manufacturing capable
- Manufacturing Demonstrated
- Partial Testing
- Full scale testing
- SOC (Supplier On-Contract)
- ~ (unknown or not in Phase 3)

Integrated Test Status
- MRR (Manufacturing Readiness Review)
- SOC (Supplier On-Contract)
- FPS (First Parts in Stores)
- TRR (Test Readiness Review)
- Test (Testing Achieved)
- ~ (unknown or not in Phase 3)

Figure 6: SABRE Design Maturity "scorecard"

4.1.2 Development of Key Technologies

Five major SABRE elements were advanced by RE using the UKSA Grant: HX1 (precooler), C1T1 (helium turbine air compressor), PB1 (hydrogen-fuelled combustor), HX3 (microtube heat exchanger), and HX4 (microchannel heat exchanger).

RE has made significant strides in developing knowledge and capabilities to model and manufacture each of the five major elements. Integrated analytical models of varying fidelity were developed and cross validated. The models have been tuned and validated with experimental test results. RE has improved understanding of material properties at the extreme operational environments the systems will operate under. Design and manufacturing techniques were validated though fabrication and assembly of key components. The work performed under the grant has allowed for extensive understanding of the design and operational challenges of the complex heat exchangers and hydrogen combustor that enable SABRE.

The grant funding enabled the full design, analysis, manufacture, and test of the precooler. This included taking the precooler successfully through a rigorous set of design, quality and safety review gates overseen by ESA and in some instances, supported by Reactions Engines' strategic partner, BAE Systems. The project required a unique test set-up including newly designed, manufactured, and integrated test equipment (GSE) and a new bespoke test facility. After successful integration of the test article, GSE and control system within the test facility, the precooler was successfully tested multiple times at Mach 5 conditions. The results were analysed, and the performance models verified. All equipment was then transported back to the UK for disassembly and condition inspection. The test process for the precooler Mach 5 test is seen in Figure 7 below.

Figure 7: Precooler Mach 5 Test Process[8]

The DEMO-A Programme is a unique and complex engineering programme aimed at the development of all major subsystems within the air breathing core, the system level design and integration (e.g., controls, instrumentation) and ultimately a series of test demonstrations. The programme has taken the SABRE air breathing core from thermodynamic cycle diagrams and basic concept design to a fully designed system ready to be tested. This has involved multiple design iterations in order to update and simplify the design in accordance with learning achieved through the design and analysis of individual components and the system design/models. Ten major subsystems have been designed and analysed and taken through design gate reviews from concept to critical design (i.e., to the point of drawings produced and configuration ready for part manufacture). Suppliers have also been sourced for all hardware. This process also involved taking the overall system design through an equivalent set of rigorous design gates, from initial concept design to a fully analysed, detailed design (Critical Design Review). This included the testing of key system elements to demonstrate viability ahead of part manufacture (e.g., testing of key control system elements in a specially designed lab). Successful completion of both the subsystem and system design gates was achieved through approval from the project's technical leadership team and ESA. Periodic review (approximately 6 monthly) of the programme's technical progress was also undertaken by an independent Technical Advisory Board comprised of experienced individuals from the aerospace and space industry. Images of testing from the DEMO-A are seen in Figure 8 and Figure 9 below.

[8] Image provided by RE

Figure 8: Preburner Test[9]

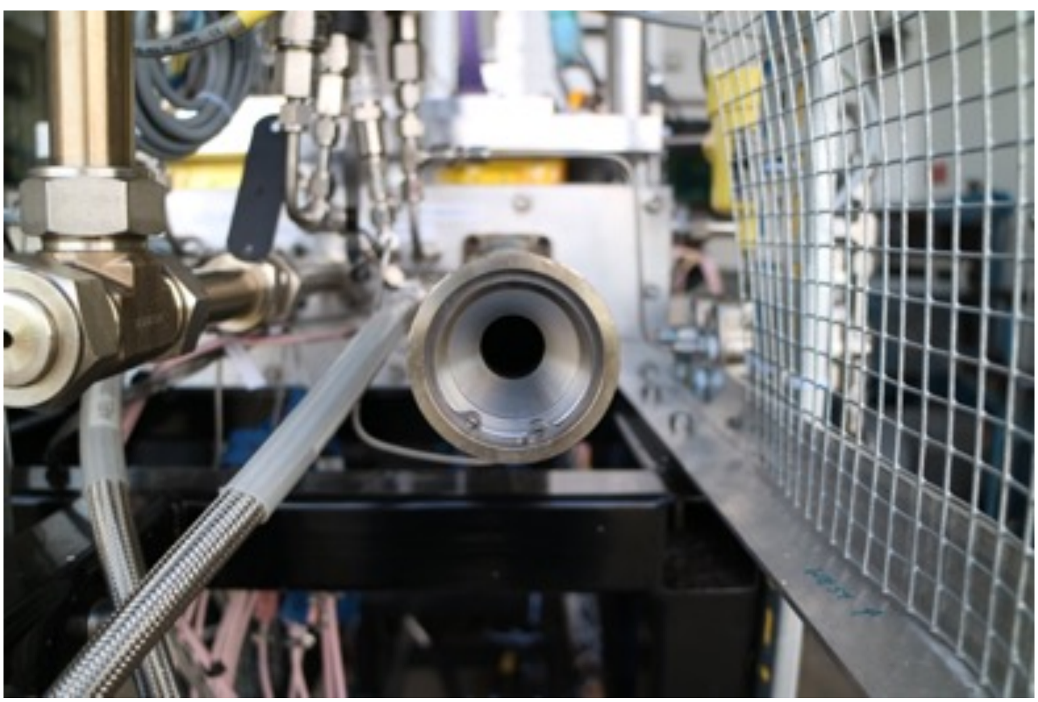

Figure 9: HX3 Nozzle[10]

[9] Image provided by RE
[10] Image provided by RE

In addition to the design of the hardware and software, significant effort was required to create the tools and models needed to understand and evaluate the design. This has included the in-house development of bespoke steady state and transient performance models, controls methodologies and design robustness tools (i.e., Monte Carlo models). These models and tools have been analysed by ESA ahead of being accepted as funded programme deliverables.

Since CDR, the programme has delivered several successful component and subsystem tests focused primarily on the combustor and heat exchangers. Planned future work includes more complex, multi-subsystem testing ahead of full system demonstration.

4.1.3 Technical Deliveries

As discussed in Section 3.2 above, the SABRE Programme was realigned following the SABRE Engine Level System Requirements Review in 2017. The realigned programme was focused on advancing the design of the air-breathing engine technology demonstrator in preparation for testing of the DEMO-A Engine by the end of 2019.

The projects proposed in the 2017 programme realignment were as follows:

- 001 SABRE System Integration – Not included in GFA grant
    - Complete Interim Key Point (IKP) for the SABRE Engine
- 002 Vehicle Studies – Not included in GFA grant
- 003 DEMO-A Subscale airbreathing ground demonstration engine
- 004 DEMO-R Rocket engine demonstrator
- 005 DEMO-N Nacelle subsystems demonstrator
- 006 Test Facility for airbreathing core development engines (e.g. DEMO-A)
- 007 HTX Design, build and test of a high temperature precooler demonstrator
- Technology Development Projects
    - 008 Pre-Burner Test Rig
    - 009 DEMO-A Microchannel HX Manufacture Development
    - 010 Tubular HX Research
    - 011 Advanced Nozzle Research
    - 012 Intake & Bypass Burner Research
    - 013 Nacelle Engineering
    - 014 High Temperature Turbine Research
    - 015 Hydrogen Embrittlement Research
    - 016 Centrifugal Compressor Test Rig
    - 017 SABRE Microchannel HX Manufacture Development
    - 018 Rocket Design Study
    - 019 Nacelle Base Drag Research
    - 020 SABRE Rep-planning

The study team reviewed the technical deliveries associated with these activities and summarized the originally planned and as-invoiced costs and the timeliness of the deliveries.[11]

003 DEMO-A

Project 003 DEMO-A Subscale airbreathing ground demonstration engine was the primary activity in the 2017 realigned grant, accounting for over 50% of the GFA funding value:

- Original Re-Alignment Amount: £25,615,863
- As-Invoiced Amount: £27,852,767

The major DEMO-A milestones in order of delivery were:

- Alternative Concept Key Point (ACKP) Reviews (July 2017)
  - o 10 review packages
  - o Total GFA value invoiced was £809,390
  - o All packages were delivered on schedule
- Baseline Design Review (BDR) Reviews (November 2017 to January 2018)
  - o 8 review packages
    - -1 package removed from programme
  - o Total GFA value invoiced was £1,282,101
  - o Packages were delivered on average 30 days late
- Preliminary Design Key Point (PDKP) Reviews (May 2018 to July 2020)
  - o 28 review packages
    - -1 package determined to be Out of Scope and moved to the 007 HTX project
    - -1 package removed from programme
  - o Total GFA value invoiced was £7,175,387
  - o Packages were delivered on average 201 days late
- Mid-Design Review (MDR) Reviews (November 2018 to April 2020)
  - o 20 review packages
    - -1 package determined to be Out of Scope and moved to the 007 HTX project
    - -1 package removed from programme
  - o Total GFA value invoiced was £4,320,104
  - o Packages were delivered on average 270 days late
- Critical Design Key Point (CDKP) Reviews (December 2018 to December 2020)
  - o 27 review packages
    - -1 package moved to Post-PDR Close-out
    - -1 package reduced to £0
    - -1 package determined to be Out of Scope and moved to the 007 HTX project
    - -1 package removed from programme
  - o Total GFA value invoiced was £5,491,223
  - o Packages were delivered on average 162 days late

[11] 18 review packages were invoiced under the 2015 milestone structure prior to the 2017 realignment. Those review packages are also referenced below.

- Preliminary Design Review (PDR) Reviews (March 2019 to May 2021)
    - o 11 review packages
    - o Total GFA value invoiced was £3,786,240
    - o Packages were delivered on average 29 days late
- Critical Design Review (CDR) Reviews (March 2019 to November 2020)
    - o 16 review packages
    - o Total GFA value invoiced was £3,027,924
    - o Packages were delivered on average 20 days late
- First Parts in Store (FPS) Reviews (August 2019 to November 2020)
    - o 5 review packages
    - o Total GFA value invoiced was £844,165
    - o Packages were delivered on average 16 days late
- Manufacturing Readiness Review (MRR) Reviews (May 2021)
    - o 2 review packages
    - o Total GFA value invoiced was £283,803
    - o Packages were delivered on average 285 days late
- An additional 7 review packages associated with 003 DEMO-A were invoiced under the 2015 milestone structure

Additional details on these deliveries are detailed in Appendix A.3 Funding Milestone Details.

004 DEMO-R

Project 004 DEMO-R Rocket engine demonstrator project had three milestones: A Scoping Study, a Trade Study, and Concept Design & Requirements Definition. In December 2019 it was determined that DEMO-R was under-resourced due to the focus on HTX and DEMO-A. DEMO-R was declared Out of Scope and the funding transferred elsewhere.
- Original Re-Alignment Amount: £898,722
- As-Invoiced Amount: £0

005 DEMO-N

Project 005 DEMO-N Nacelle subsystems demonstrator has a single milestone for Bypass Burner Development. However, funding was transferred to 003 DEMO-A in July 2020.
- Original Re-Alignment Amount: £1,520,825
- As-Invoiced Amount: £0

006 Test Facility

Project 006 Test Facility for airbreathing core development engines (DEMO-A) was originally planned and invoiced as follows:
- Original Re-Alignment Amount: £8,216,070
- As-Invoiced Amount: £4,924,876

A total of 27 Test Facility milestone packages were delivered. However, there were also 23 planned Test Facility milestone packages that were eliminated due to “Change of Scope-Not planned to be delivered.”

An additional 6 review packages associated with 006 test Facility were invoiced under the 2015 milestone structure.

Project 006 Test Facility should culminate in facility handover and test facility readiness review. Additional details on the delivered packages and eliminated packages are detailed in Appendix A.3 Funding Milestone Details.

007 HTX

Project 007 HTX Design, build and test of a high temperature precooler demonstrator, was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £6,154,957
• As-Invoiced Amount: £9,644,627

A total of 25 HTX milestone packages were delivered. An additional 5 review packages associated with 007 HTX were invoiced under the 2015 milestone structure. The HTX project culminates in a post-test TRB.

008 Pre-Burner Test Rig

Project 008 Pre-Burner Test Rig was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £906,878
• As-Invoiced Amount: £1,006,878

A total of 4 Pre-Burner Test Rig milestone packages were delivered.

009 DEMO-A Microchannel HX Manufacture Development

Project 009 DEMO-A Microchannel HX Manufacture Development was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £292,526
• As-Invoiced Amount: £654,993

A total of 7 milestones were delivered.

010 Tubular HX Research

Project 010 Tubular HX Research was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £202,197
• As-Invoiced Amount: £215,045

A total of 2 milestone packages were delivered; a third milestone delivery planned but funding was transferred to 003 Demo A.

011 Advanced Nozzle Research

Project 011 Advanced Nozzle Research was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £227,856
• As-Invoiced Amount: £63,928

A single milestone package was delivered on the Nozzle Architecture Study-Interim Report. Another milestone package on the Nozzle Architecture Study was originally planned but funding was transferred to 003 DEMO-A.

012 Intake & Bypass Burner Research

Project 012 Intake & Bypass Burner Research was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £129,426
• As-Invoiced Amount: £129,426

A single milestone package was delivered for Demo-N planning.

013 Nacelle Engineering

Project 013 Nacelle Engineering was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £60,016
• As-Invoiced Amount: £0

A single milestone package was originally planned for to achieve an Interim Key Point (IKP), but in December 2019 it was determined to be Out of Scope and the funding transferred elsewhere.

014 High Temperature Turbine Research

Project 014 High Temperature Turbine Research was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £28,675
• As-Invoiced Amount: £0

A single milestone package was originally planned for Design & Analysis to IKP. However, this milestone was never delivered or paid.

015 Hydrogen Embrittlement Research

Project 015 Hydrogen Embrittlement Research was originally planned and invoiced as follows:
• Original Re-Alignment Amount: £285,131
• As-Invoiced Amount: £326,911

Two milestone reports were delivered.

016 Centrifugal Compressor Test Rig

Project 016 Centrifugal Compressor Test Rig was originally planned and invoiced as follows:
- Original Re-Alignment Amount: £202,130
- As-Invoiced Amount: £0

Milestone associated with the Centrifugal Compressor Test Rig project were never delivered or paid.

017 SABRE Microchannel HX Manufacture Development

Project 017 SABRE Microchannel HX Manufacture Development was originally planned and invoiced as follows:
- Original Re-Alignment Amount: £110,006
- As-Invoiced Amount: £51,703

One delivery was made on the Regenerator Module Manufacturing Process Report.

018 Rocket Design Study

Project 018 Rocket Design Study was originally planned and invoiced as follows:
- Original Re-Alignment Amount: £56,261
- As-Invoiced Amount: £100,000

One delivery was made on the Rocket Engine Design Report.

019 Nacelle Base Drag Research

Project 019 Nacelle Base Drag Research was originally planned and invoiced as follows:
- Original Re-Alignment Amount: £51,147
- As-Invoiced Amount: £0

Nacelle Base Drag Research was originally funded for three activities, but delivery delays promoted a transfer of its funding to 003 DEMO-1 in July 2020. Therefore, the GFA value delivered was £0.

020 SABRE Re-planning

Project 020 SABRE Re-planning was originally planned and invoiced as follows:
- Original Re-Alignment Amount: £182,000
- As-Invoiced Amount: £182,000

A single delivery was made on the SABRE Proposal & Milestones Table.

This study determined that there were numerous revisions to the payment milestones and associated work content that were approved by the customer. These changes included:

- Splitting and/or adding milestones
- Transferring amounts between existing and/or added milestones
- Changing milestone names and/or deliverables
- Relegating milestones to lower phases, e.g. originally subsystem Test Readiness Review (TRR) revised or moved to subsystem ARR (Assembly Readiness Review)
- Removing milestone and moving content and/or funding

Delays in deliveries may have also been driven by limited RE staffing; UKSA personnel did note that the RE staffing ramp-up in the initial years of the grant was much slower than anticipated, which impacted the overall programme schedule.

A review of emails from ESA to RE regarding milestone deliveries found that ESA was very complementary of RE and noted “The team has achieved a high level of design definition, commensurate with the needs of a CDR, and all aspects of planning for manufacture, V+V planning and supply chain are in place.”

Near completion of the MDR, ESA stated “…a number of highly successful manufacturing trials have been evidenced to date. These provide confidence that the critical elements needed can be available in good time,” although they did note performance risks that would need to be retired by a module flow test ahead of CDR. ESA concluded the MDR “represents significant progress” and “largely confirms manufacturability and identifies critical areas.”

However, none of the original 24 DEMO-A subsystem and system-level TRR milestones were accomplished. Many were relegated to lower phase levels (TRR to ARR, MRR, FPS or even lower phases), sometimes over several revisions. Some were outright “removed from programme” and the funds distributed elsewhere. All CDR milestones were accomplished. Six subsystems have FPS, and two subsystems accomplished MRR milestones.

Facility readiness for the airbreathing core test facility was not achieved. Approximately 40% of the allocated GFA funding was moved to other projects. Much of the removed content was for contracted structures, components, subsystems, materials, and commodities.

The DEMO-R and DEMO-N content were eliminated, and the funding allocated to other projects’ milestones.

The HTX project invoiced 57% more than the originally allocated GFA amount. Test readiness was achieved (with additional scope and milestones added) and initial testing was conducted.
The as-invoiced distribution of the £50M GFA amount from the 2017 proposal is shown below:

- DEMO-A: £27,852,767 invoiced (vs £25,615,863 proposed)
- DEMO-R: No milestones accomplished (£898,722 moved to other milestones)

- DEMO-N: No milestones accomplished (£1,520,825 moved to other milestones)
- Test Facility: £4,924,876 invoiced (vs £8,216,070 proposed)
- HTX: £9,644,627 invoiced (vs £6,154,957 proposed)
- Technology Demonstration Projects: £2,734,884 invoiced (vs £2,746,716 proposed)
- Previously invoiced before programme realignment, £4,846,846

While the realigned Phase 3 Programme goal of achieving test readiness for DEMO-A and the test facility was not achieved, the study team finds that accomplishments achieved to date do fall largely in line with the original 2015 GFA intent, which was to progress the demonstration engine through the CDKP and CDR. It appears that there was some growth in ambition during the programme realignment that advanced the main objective from CDR to test readiness.

4.2 Positioning of RE as a “space” company

The study team was specifically tasked with evaluating the impact of the SABRE Programme grant on RE’s positioning as a “space” company. The study team considers a space company to be a company involved in the larger space economy, providing goods and services associated with space or access to space. These good and services could include but are not limited to research and development activities, manufactured “flight hardware,” and space-enabled services (such as telecom) provided to end-users. In order to evaluate the impact of the grant on RE’s positioning as a space company, the study team took several elements into consideration including interviews with RE personnel, technical advancements, new and strengthened relationships, publications, prizes received, creation of IP, and technology transfer. While RE considers itself a space company, the study team found that the grant has improved RE’s position as a space company within the larger space economy and positively impacted RE’s ability to provide goods and services associated with space and access to space. As a result of the grant funding, RE has developed new and strengthened relationships with international and domestic space agencies and companies, and has made relevant technological and process advancements.

4.2.1 Self-assessment: “RE is a “space” company”

RE’s self-assessment is that RE was a space company prior to receiving the SABRE Programme grant, but that the grant funding has allowed the company to progress and evolve in this role. According to information provided by RE, SABRE and SKYLON were in development for several years before the award of the SABRE Programme grant via private equity funding and ESA contracts. This demonstrates RE’s pre-existing focus on providing goods and services associated with access to space. While RE has always seen itself as a company with space ambition, RE personnel agreed that the grant has added a level of credibility to their position within the larger space economy, especially in dealings with the United States. RE personnel also agreed that the grant allowed the company to work with international space partners (state agencies and private industry) with a sense of confidence and credibility. Due in part to the SABRE Programme grant, RE now views itself as an integral part of the UK space economy.

4.2.2 Involvement in the Larger Space Economy

The study team concurs with RE's self-assessment that the SABRE Programme grant improved their position as a space company within the larger space economy by allowing RE to build new and strengthened partnerships, and to increase their public recognition across the space economy.
As summarized in Section 4.6 below, the SABRE Programme grant did have a significant impact on RE's relationships throughout the domestic and international space community. The grant has significantly strengthened RE's reputation and provided the opportunity to gain interest and, in many cases, work directly with important government bodies and industry players.

During interviews with the study team, RE personnel specifically highlighted the importance of having additional access to ESA through the SABRE Programme grant.
While RE did have commercial relationships with ESA prior to the grant, RE feels that these relationships have been strengthened through its participation throughout the programme duration including technical oversight on the critical review gates (PDR, CDR, TRR, etc). In addition to simply having a relationship with ESA through the grant, RE has also been able to leverage that relationship for additional opportunities that wouldn't have otherwise been available.

RE personnel also cited their role at the 2019 UK Space Conference and their membership in the International Astronautical Federation (IAF) as evidence of their maturing position as a space company. Additionally, as discussed in greater detail in Section 4.7 below, RE actively promotes their profile and company through a variety of communication avenues and participates in events designed to stimulate interest and excitement around space topics. The nature of the SABRE Programme has resulted in many publications and invitations to attend conference events within the space industry. Accolades can also be used as a means of determining the success of the SABRE Programme in provoking industry interest; RE has received several notable accolades from within the space industry in the past several years.

4.2.3 Providing Goods and Services Associated with Space

The study team determined that the SABRE Programme grant had a positive impact on RE's ability to provide goods and services associated with space and access to space. As discussed in greater detail in Section 4.1 above, technical advancements were made over the course of the SABRE Programme grant, and the objectives associated with progressing the demonstration engine through the CDKPs and CDRs were met as well as the full testing objectives for the precooler system. In addition to advances in hardware design, there have been upgrades to physics and engineering models and tools.

RE has also conducted several integrated vehicle studies analysing how the SABRE engine would perform in an orbital vehicle. This emphasis on total system performance as opposed to just the technical aspect of the SABRE development indicates that RE is maturing as a space company focused on space access.

Additionally, RE has significantly matured its business and manufacturing processes over the life of the grant. These changes were driven by the complexity of the programme as well as increasing coordination with other members of the space industry. Actions that may have been more ad hoc previously now have command media. These processes range from requirements management and verification to interface control and resource management. Such Systems Engineering and Programme Management capabilities are crucial for space companies developing highly complex and interconnected systems.

The grant resources were also used for several manufacturing demonstrations which allowed RE to industrialize their manufacturing processes and achieve ISO9001 accreditation.
As discussed in greater detail in Section 4.5 below, RE has also successfully generated tradeable IP as a result of the SABRE Programme. RE has leveraged their IP to facilitate knowledge transfers in various industries and form partnerships with other organisations.

The only direct space-related transfer that has resulted in a commercial contract to date is the rocket engine plume cooling for the test stand. However, there are multiple thermal management challenges within the space product market and RE is actively exploring further opportunities with industry players and agencies where it can play a future role.

RE personnel also emphasized that the purpose of their technology transfer and exploitation programme is to expand beyond space into a more diversified portfolio with short-term commercial gains. Space technology development projects require long-term investments with a great deal of capital required upfront. In order to fund SABRE, RE needs to realize earlier commercial gains through technology transfer to other industries with a shorter return on investment timeline, such as motorsport.

4.3 Employment and People Development

RE has grown to 204 permanent employees since 2015. The workforce is made up of highly skilled, diverse (currently at 19% women) and young (average employee age is 34) employees from across the country, Europe (28 European employees), and throughout the world (e.g., Australia, Canada). The company includes professionals in many sectors of the economy, from high-performance motorsport to the video gaming industry. Figure 10 below shows the actual recruitment profile of RE. Overall head count for 2021 is similar to 2020. The compound average growth rate of 24% per year has exceeded the planned profile from the 2014 Business Case. Note that this figure does not include subcontract personnel, of which there were approximately 30 during 2019.

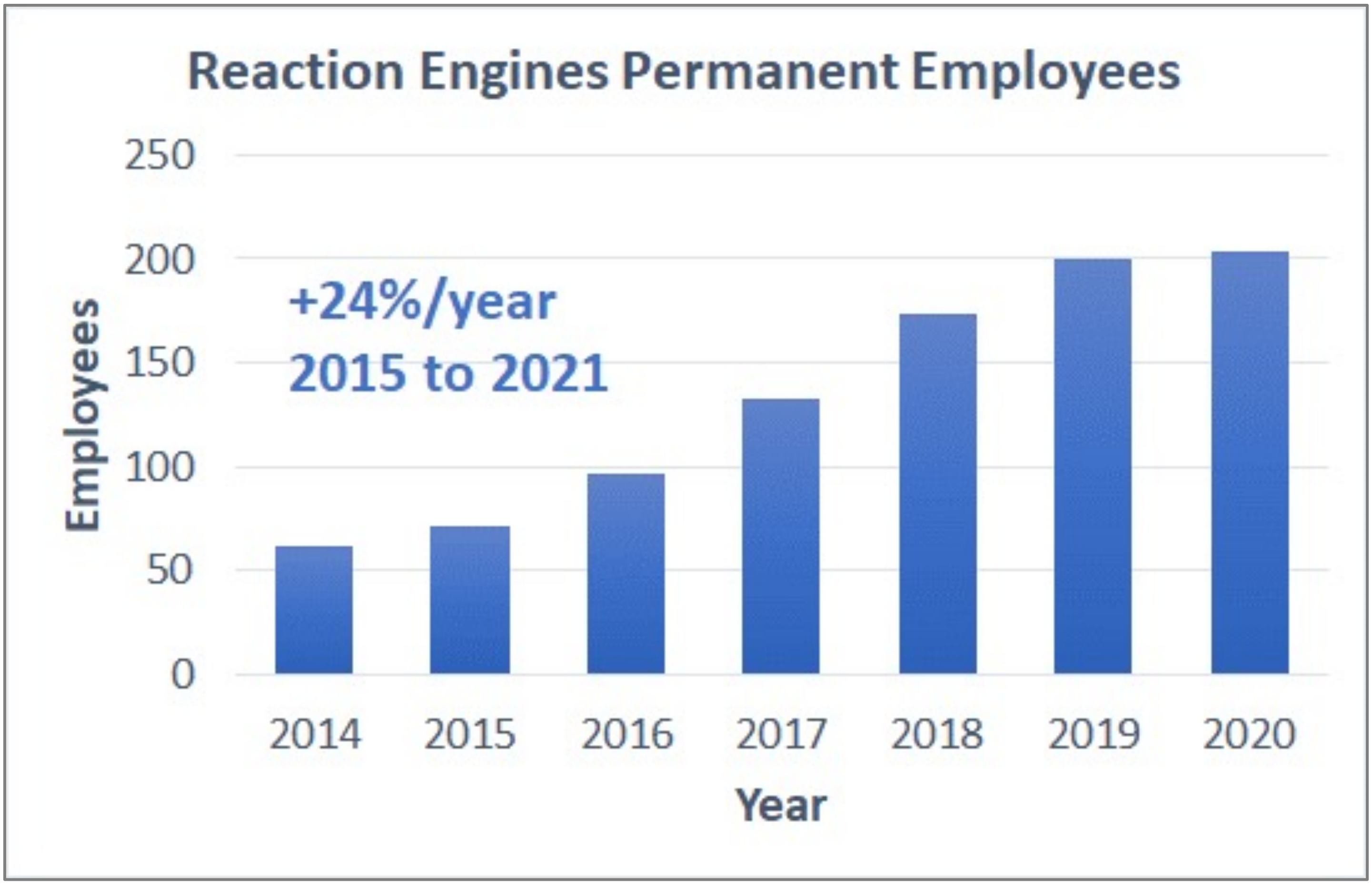

Figure 10: RE Permanent Employees[12]

In the 2015 grant, RE identified staff retention and recruitment as a top-level risk associated with the programme stating that a workforce of up to 204 would be needed to complete the programme. According to Figure 10 above, the company has grown from 61 employees in 2014, to 204 employees in 2020, effectively reaching their risk mitigation goal. However, UKSA personnel did note that the staffing ramp-up in the initial years of the grant was much slower than anticipated, which impacted the overall programme schedule.

RE recruits professional engineers across the design, manufacture, and testing phases and across a broad range of engineering disciplines such as those listed below.

[12] Employee headcount provided by RE

• Heat Exchanger Thermodynamics
• Mechanical Design
• Performance & Aerodynamics
• Systems Engineering
• Turbo-Machinery
• Rockets & Turbo-Pumps
• Technical Support
• Manufacturing
• Stress & Structural Analysis
• Control Systems
• Safety and Reliability

The company also recruits Operations, Programme Management, and Science and Technology professionals to support the main programme and a broad range of individuals into support functions that assist the main project activity. Most recruits will have a university education with many holding PhDs and being industry experts in their field (due to the specialist nature of the activity). As of early 2022, the company has 21 job openings on its website. A summary of the job types and locations is shown below in Table 3.

Table 3: Summary of RE Job Openings[13]

Job Groups	
Applied Technologies	5
Chief Operations Office	5
Engineering	6
Programmes	2
Supply Chain & Production	3
Total Job Postings	21

Job Groups	
Littleton, CO (United States of America)	1
Culham Science Centre (United Kingdom)	20

[13] https://reactionengines.co.uk/careers/vacancies/

In addition to the direct impact of the research these employees perform, they also induce positive externalities through productivity and knowledge spill-overs where knowledge generated within RE enhances the productivity of other organisations. Employees also contribute to induced effect wage spending impacts supported by the organisation's research, contract, and investment income. Employees spend their pay checks on goods and services in the economy. This, in turn, produces wage income for workers in the industries that produce these goods and services resulting in additional rounds of spending, i.e., a ripple effect throughout the UK economy.

RE promotes continuous professional development and encourages its workforce to achieve professional accreditation through recognised bodies (e.g., Institute of Mechanical Engineers, Institute of Physics, Royal Aeronautical Society, Association for Project Management). As part of its commitment to investing and developing people, the company supports both an engineering apprenticeship and engineering graduate programme, which has become an attractive opportunity for early career professionals. Thus far, 12 graduates and 8 apprentices have been through the programme. This attracts high-potential talent from top UK universities around the country. The representation of women has been high in these programmes and the retention of graduates and apprentices within the company after completing the programmes has been good.

There are numerous ways in which university research might have positive spill-over effects on the private sector. For example, spill-overs are enabled through direct Research & Development (R&D) collaborations between universities and firms, such as engineering apprenticeships and engineering graduate programmes, the publication and dissemination of research findings, or university graduates entering the labour market and passing on their knowledge to their employers.

RE is an employer of highly skilled and productive employees in the space industry with a high likelihood of being employed, as well as having enhanced earnings, and the company supports its core activities through significant expenditures throughout the UK economy. RE's physical footprint also supports jobs and promotes economic growth throughout the UK economy. Section 5 summarizes the gross economic benefits of the direct and induced impacts of research, contracts, and investment supported by the employee base.

4.4 Labour Productivity Gains

The UK government's recently published Size and Health of the UK Space Industry 2021 report cites employment of 46,995 in the UK space sector and estimates it is valued at £16.5 billion (both figures relate to 2019/20). Among the findings of the 2021 report was evidence of a productivity increase from employees of the UK space industry. While the total UK space industry income decreased from £16.8 billion in 2018/2019 to £16.5 billion in 2019/2020, income in the Space Manufacturing segment increased from £2.2 billion to £2.7 billion. The industry directly contributed £6.9 billion of Gross Value-Added (GVA) to UK economic output in 2019/20. That GVA divided across the 46,995 direct employee workforce results in a labour productivity ratio of £146,000 per employee, which is 2.6-times greater than the UK average labour productivity (£57,000 per employee). This high level of labour productivity reflects the UK space industry's highly skilled workforce. This data can be seen in Figure 11 below.

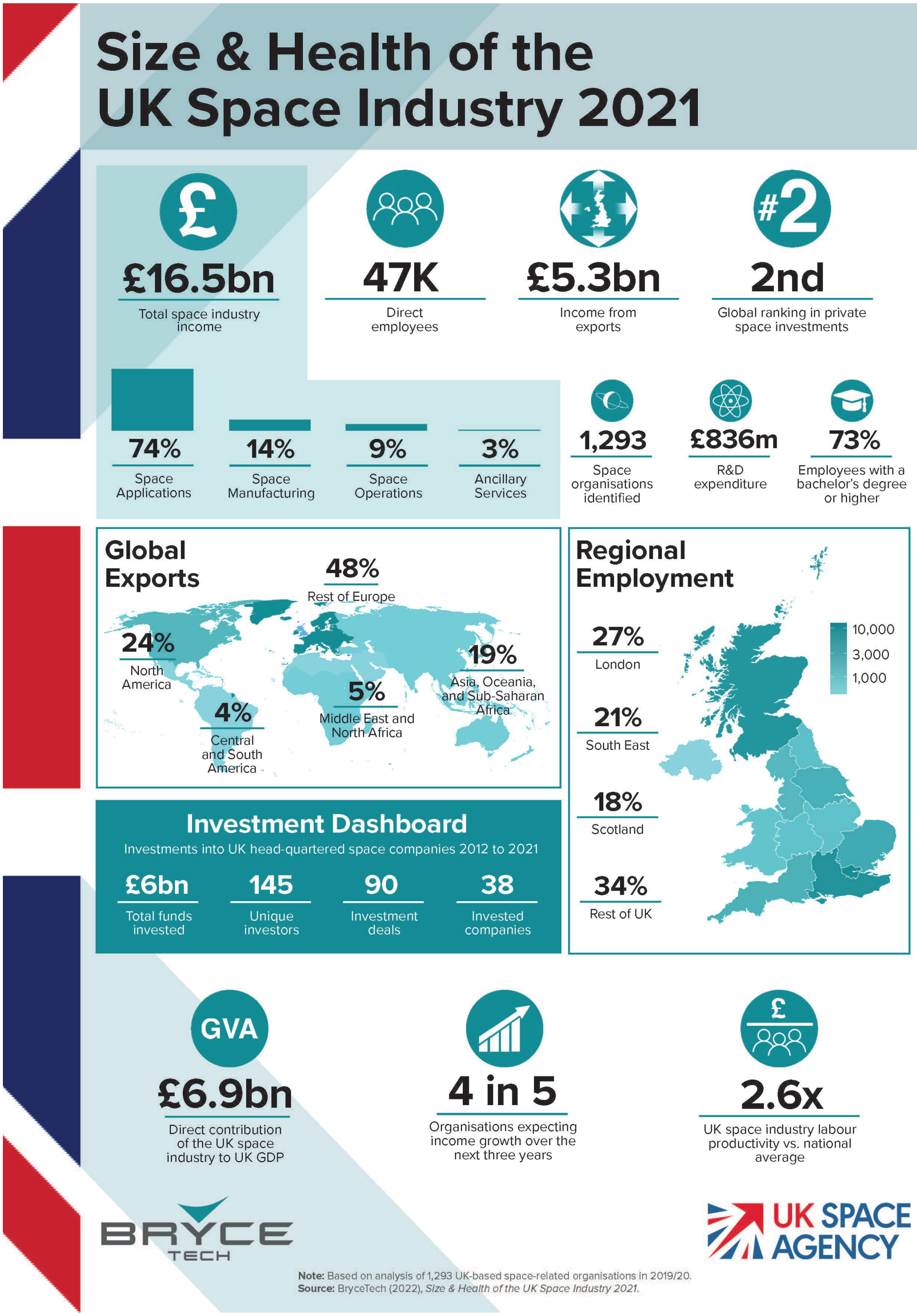

Figure 11: Infographic: Size & Health of the UK Space Industry 2021[14]

[14] Bryce Tech. "Infographic: Size & Health of the UK Space Industry 2021". UK Space Agency, April 2022. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1070143/Bryce_UK_S_H_Infographic_MASTER_v4.pdf

Space industry employment also has indirect and induced supply chain impacts. It is estimated that the activity of 100 employees in the space industry supports 300 additional employees among suppliers and in other economic sectors (such as retail and services).[15] Direct employment in RE (204 employees) could potentially support 612 additional UK jobs through indirect and induced effects. Therefore, the total UK-based employment supported by the activities of RE is estimated to be 816 employees. These quantified estimates appear reasonable when compared to the comprehensive supply chain RE has developed since 2015, which includes 990 registered suppliers and 650 active suppliers.

4.5 Intellectual Property and Partnerships

4.5.1 Patent Portfolio

Information from RE's patent portfolio provides additional valuable insights into the company's wider knowledge dissemination activities. A broad suite of technologies is in development for SABRE, at various levels of maturity, generating tradeable IP. Most mature, and pivotal, is the heat exchanger technology which has already demonstrated its spin-out potential and generated revenue in other applications. Most of the IP generated to date is around the heat exchangers, the whole system design and the turbomachinery required for the SABRE cycle. In some cases, RE has protected its IP with a series of patents. Since 2015, RE has had 12 granted patents, registered in several countries, for an average rate of just under 2 grants per year. However, often RE chooses instead to protect its IP by retaining it as a non-public trade secret, of which they currently have 35 internally documented. Table 4 shown below, provides a summarization of the technical areas where RE holds patents and the countries in which they have been granted patent protection.

Table 4: RE Patent Portfolio 2015-2021[16]

Inventions	Date Granted	UK	USA	AUS	CN	Japan	FR	Italy	DEN	Spain	UKR	RUS	KOR	CA	IL	Patent #
SABRE 3 Cycle	7-Sep-16	●	●	●	●	●					●	●	●	●		GB2519152B
SABRE 4 Cycle	12-Oct-16	●	●	●	●	●	●	●	●	●	●	●	●		●	GB2519155B
Helium - EP	13-Sep-17	●	●		●	●	●	●	●	●		●				EP3055511B1
Pre-Cooler Case 1: Thermal Expansion	15-Apr-15	●	●	●	●	●	●	●	●		●	●	●	●		GB2519147A
Pre-Cooler Case 2: Load Element	4-Oct-17	●	●				●	●	●	●						GB2519153B
Pre-Cooler Case 3: Intermediate Header	24-May-17	●														GB2521113B
Pre-Cooler Case 4: Frost Control	24-May-17	●														GB2521114B
Pre-Cooler Case 5: Guide Vanes	12-Aug-20	●														GB2519148B
Pre-Cooler Case 6: Drum Structure	12-Aug-20	●														GB2578262B
Gas Turbine Improvements	27-Oct-21	●														GB2584331B
Multiple Fluid Spiral Module HX	6-Oct-21	●														GB2581840B
Internal Heat Dissipation for Battery Cells	15-Dec-21	●														GB2589149B

[15] Bryce Tech. "Size and Health of the UK Space Industry 2021".
[16] Information provided by RE.

In addition to those listed in Table 4, there is one further patent pending grant status (published in 2020) and another 6 patent applications (all published since 2018). RE also has 30-40 ideas that are currently underway in their internal patent process which will hopefully become patent applications in the future.

4.5.2 Knowledge Exchange and Partnerships

In addition to protecting its IP, RE has also leveraged their IP to facilitate knowledge transfers in industry and form partnerships with other organisations. The eleven activities listed in Table 5 describe the impacts associated with Reaction Engines' licensing of its IP to other organisations; the operations of spinout companies whose activities are based on RE IP; and the activities of partnerships with other companies.

SABRE is a technology concept that potentially has broader benefits beyond space access and the mainstay SABRE Programme. In line with the conditions of initial UK Government investment, RE has pursued early commercialisation of SABRE Technology in adjacent and alternative applications and industries. RE has won contracts for spin-out technology with future opportunities expected to generate additional revenue. These spinouts have also allowed RE to industrialise its technology and processes to accommodate efficient higher yield output, a key step in the commercialisation of new technology.

Table 5: RE Technology Transfer and Knowledge Exchange Activities.[17]

Activity	Description
Ammonia Heat Exchanger Joint Venture	Joint venture is majority-owned by RE and permits the use of heat exchanger IP strictly for the purposes of developing Ammonia reactors to crack Ammonia as a drop in fuel for engines
Partnership with Rolls-Royce	Signed a strategic partnership and route to market agreement in 2020 with investor Rolls-Royce. Will work exclusively together for some relevant gas turbine product applications, but not bound by exclusivity
Subscription & Working Partnership Agreement with BAE Systems	Signed agreement in 2015 that investor BAE will be their preferred supplier for high value packages that fall within a certain product scope
Water Cooled Charge Air Cooler for Motorsports	RE scaled down the Pre-cooler on motorsport cars and as won a multi-year contract with a motorsport team. The market size in motorsport is limited, so focus is expanding to other motorsport series and the exotic / supercar market

Waste Heat Recovery Projects	Projects include a supercritical CO2 waste heat recovery heat exchanger for a UK demonstration plant (delivered Q1 2020) and a rocket test facility plume intercooler Operational since May 2021.
Fuel Cell Radiator for Zero Emission Aircraft	RE is developing a high-performance radiator to cool the fuel cells on the FRESSON project being run by Cranfield Aerospace. The first aircraft set of radiators is to be delivered over summer (2022) with first flight planned September 2022.
Waste Heat Recovery Primary Heat Exchanger	In November 2019 RE delivered the primary heat exchanger for the first supercritical C02 demonstration plant in Europe
Rocket Test Facility Plume Intercooler	RE won a contract from Nammo UK to supply a rocket plume heat exchanger for the UK's National Space Propulsion Test Facility at Westcott
MORE & Less Collaborative Study on Commercial Supersonic Aircraft	Started in 2021. Includes DLR, VKI, and TU Delft. RE is contributing expertise in hydrogen combustion for sustainable, high-performance flight. Also providing a Hypersonic Test Bed concept as a case study for the project.
MAPS (Military High-speed Advanced Propulsion System) Programme	In 2019, RE secured a contract working alongside Rolls-Royce, BAE Systems, and the UK MoD to undertake design studies relating to high-Mach advanced propulsion systems. Phase 1 of the MAPS programme was successfully completed in early 2020.
DARPA, AFRL, and DoD Foreign Comparative Testing (FCT) Contracts	The HTX programme validated that a SABRE-type engine pre-cooler could successfully operate in the extreme temperatures expected during atmospheric flight at speeds up to Mach 5. FCT testing will take place in 2022 at RE's high-temperature test site in Colorado.

[17] Information provided by RE

4.5.3 Applied Technologies

Applied Technologies is a division within RE that was created to commercialise spin-out technology from the SABRE Programme. Applied Technologies has identified and transferred technology from the previous UK Government grant. It has developed relationships with customer groups in such a way as to realise successful commercial return. Since 2015, Applied Technologies has undertaken an exploration and assessment activity for its heat exchanger technology to identify potential market opportunities that could provide viable, near-to-medium term revenue generation. This covered technical, commercial, and programmatic considerations to ensure the areas selected were the most promising. The heat exchanger market stretches across almost every industrial sector, and all these sectors have different types of customers with differing needs and varying route-to-market. Conventional heat exchanger technology has not seen significant development for decades. The drive to reduce environmental impact is creating a huge pull for high-efficiency heat exchangers across the board. Furthermore, as the SABRE technology is designed for space, it is high performing compared with many industry incumbents. In some markets, including zero emission aviation, the technology is an enabler. Nevertheless, the organisation has focused on applications that exploit the greatest advantage and provide tangible benefits for customers whilst making commercial sense. The economic impact of this R&D spill-over is discussed in Section 5.2 below.

Ammonia Heat Exchanger Joint Venture

In 2021 RE, IP Group, and the UK Government funded Science and Technology Facilities Council (STFC) formed a joint venture (JV) company. The JV combines RE's SABRE heat exchanger with STFC's ammonia catalyst and funding from IP Group. The lightweight and compact ammonia reactors enable the use of ammonia as a zero-carbon fuel for use in transport applications, such as aviation and marine shipping, in addition to other hard-to-decarbonise applications such as power generation. The reactor will catalytically crack the ammonia into an easily combustible fuel for gas turbines and internal combustion engines.

Battery Cooling

RE's HXLife Foils simplify battery pack cooling system design. The HXLife Foils were developed via Innovate UK and APC grant funded technology accelerator programmes and are now undergoing testing in various customer battery packs including automotive, motorsport, and aerospace.

Green and Sustainable Applications

Reaction Engines' SABRE Technology is fundamentally designed to manage energy in its various forms (thermal, chemical, kinetic) through a variety of complex systems to intelligently optimise the use of that energy and drive efficiency into the system. This fundamental thermodynamic characteristic is the keystone for efficient systems which can yield lower emissions and promote greener applications and sustainable industry. Figure 12 below is a simple diagram of how SABRE technology can be inserted into aerospace propulsion to generate reduced or zero-emissions.

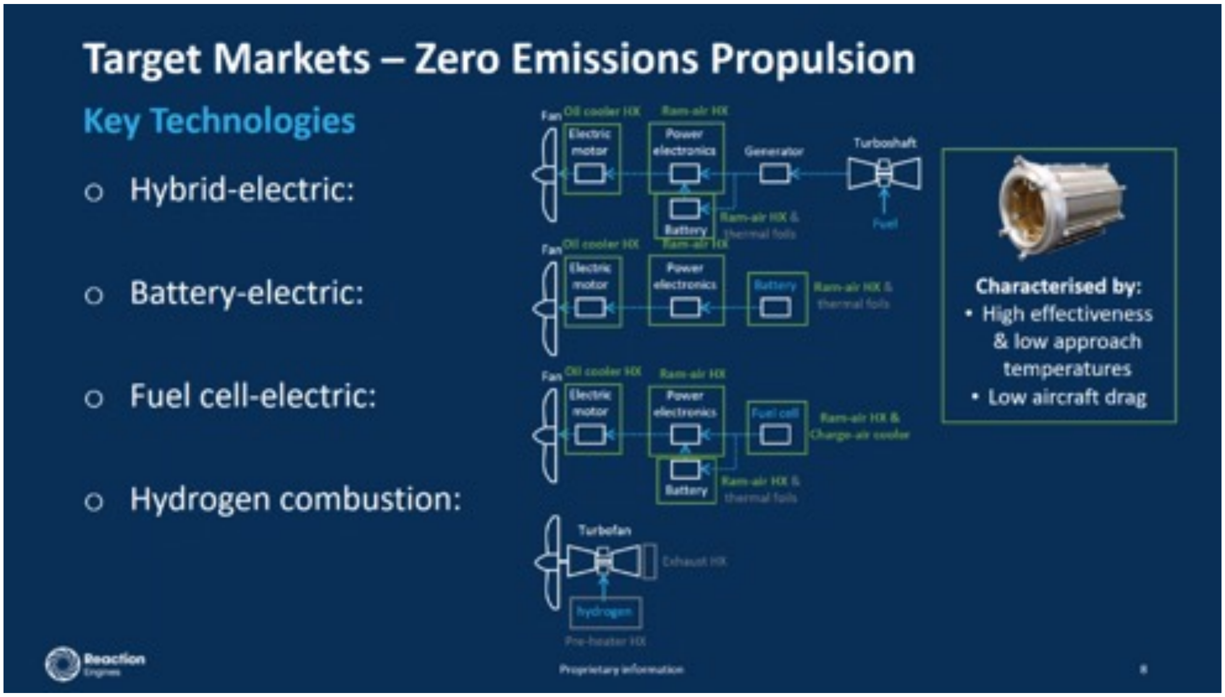

Figure 12: Green Aviation using SABRE Technology[18]

Cleaner flight is also possible by using the technology to improve existing aero-engines, while truly sustainable aviation can be achieved through the next generation of zero-emission hydrogen fuel-cell, hybrid/battery-electric or hydrogen/ammonia fuelled aircraft.

RE is currently in discussion with potential industry partners for multiple applications of its thermal management solutions aligned with the UK government's NetZero agenda.

High Speed Flight

During the last few years there has been a significant increase in activity related to high-speed (or high-Mach) and hypersonic technologies, including propulsion. Government expenditure of new technology is accelerating the realisation of hypersonic and high-speed programmes.
In addition to the public sector, there is growing interest in the civil domain. A renewed interest in the commercial benefit of high-speed flight has motivated both large aerospace players and start-ups to focus their attention on high-speed flight (HSF). This has been evident by announcements made during July and August 2020 involving Rolls-Royce, Virgin Galactic. and Boom Aerospace, all of which are pursuing high-speed flight.

High-speed flight applications, utilising SABRE-derived technologies, are of increasing interest to a broad range of aerospace primes for high-speed applications. RE SABRE technology, particularly its heat exchanger and thermal management technology, could prove useful in managing the extreme temperatures experienced during high-speed atmospheric flight. RE technology can augment the speed capability of an existing jet engine using SABRE-derived technology to cool the incoming air, mitigating issues associated with the high stagnation temperatures at high speed.

[18] Information provided by RE

This approach could improve the capability of existing jet engine technology allowing higher speeds. In 2019, RE tested its heat exchanger technology at conditions representative of Mach 5 flight at its Colorado test facility (see Figure 13 below). RE's Colorado test facility has the unique capability of replicating Mach 5 conditions on the ground. This has been a vital component in generating proven US interest throughout government and industry and is now being utilised for further projects to attract further government investment and commercial contracts.

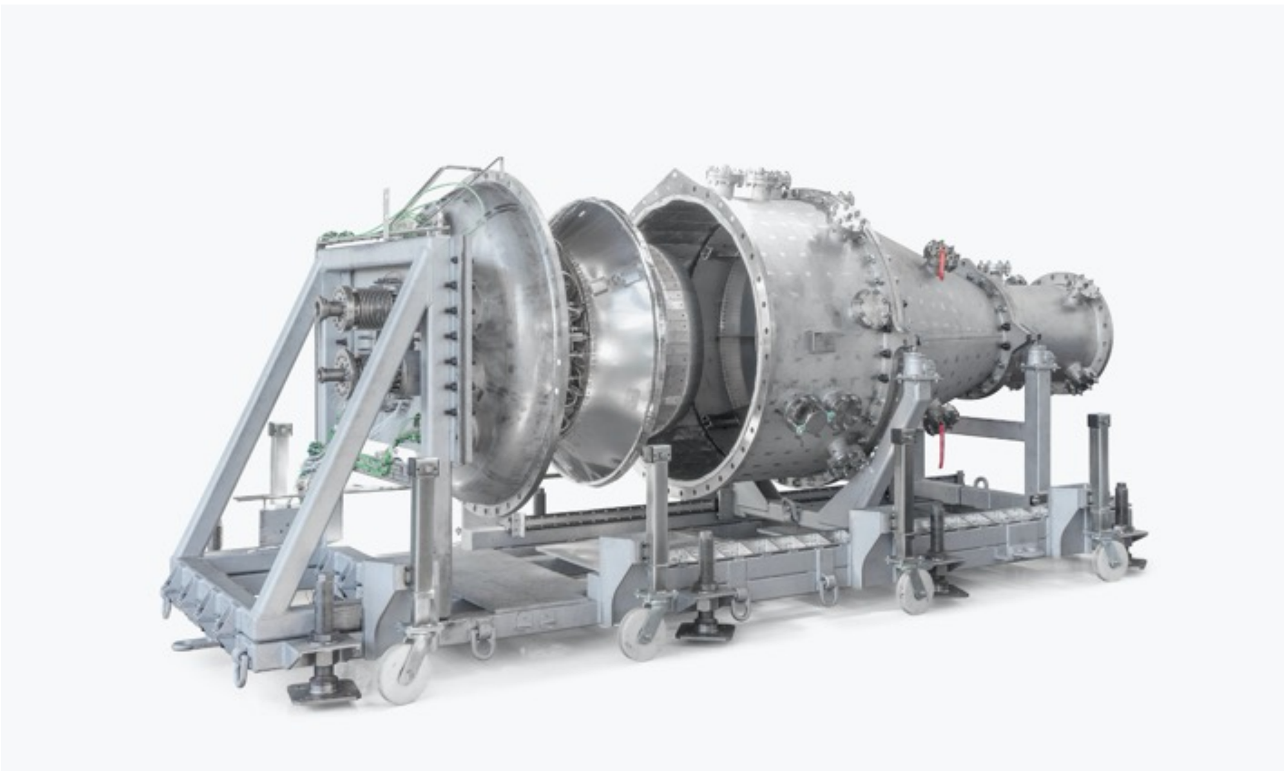

Figure 13: HTX Test Article[19]

4.5.4 Induced Supply Chain Spending

The execution of these research, contracts, and investment partnerships induces an impact on the supply chain that has positive impact on the UK economy. A wide range of partners will be required to deliver the SABRE programme. RE is already developing and nurturing a supply chain to contribute to its ongoing programmes and for the full SABRE engine. Since 2015, RE has developed a comprehensive supply chain strategy, individual commodity strategies, a strong supplier network, and supplier management system. RE has 990 registered suppliers and 650 active suppliers. As shown in Figure 11, the majority of Reaction Engines' supply chain from 2020 to 2021 was within the UK, however, there are also some important European relationships. A majority of spending occurred in the UK totalling £12.8 million with significant spending in France at £4.5 million. Section 5 summarizes the gross economic benefits of the direct and induced impacts of RE's supply chain spending resulting from research, contracts, and investment activities.

[19] Image provided by RE

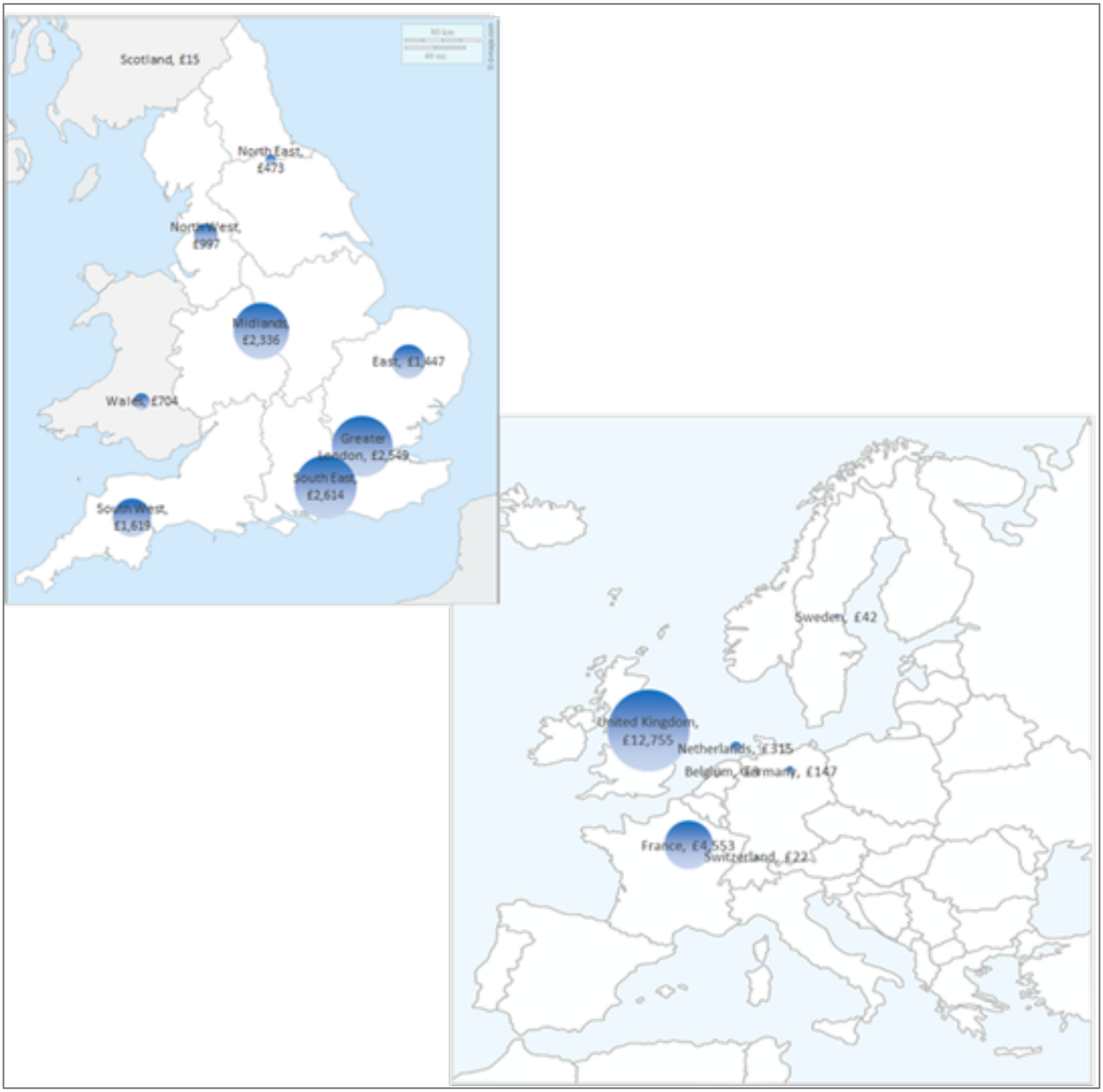

Figure 14: RE's UK and Europe Spending Profile, 2020-2021[20]

[20] Information provided by RE

4.6 New and Strengthened Partnerships

According to information provided by RE, the SABRE Programme grant did have a significant impact on RE's relationships throughout the domestic and international space community. The grant has significantly strengthened RE's reputation and provided the opportunity to gain interest and, in many cases, work directly with important government bodies and industry players.
When the original 2015 grant was approved, RE had a relatively small number of industry relationships:

1. IPT Engines UK Ltd
2. ITP (Spain)
3. Avio S.p.A
4. GKN Aerospace Engine Systems Sweden
5. Bayern-Chemie
6. Gas Dynamics Limited

As a wide range of partners will be required to deliver the SABRE programme, RE appears to be actively developing and nurturing a supply chain to contribute to its ongoing programmes and for the full SABRE engine. RE claims that they have developed and deployed a comprehensive supply chain strategy, individual commodity strategies, a strong supplier network, and supplier management system. RE has 990 registered suppliers and 650 active suppliers. The majority of RE's supply chain is within the UK, however, there are also some important European relationships as well. Under its sourcing strategy, RE will retain control of the critical areas of the SABRE system, retaining UK IP and adding value at the centre of technical development.

For the HTX Programme, RE reports having 300 suppliers and spending £7.5m externally; 90% of this spending was within the UK. For the other SABRE programmes, RE reports having 318 suppliers and has spent £20m externally; 65% of this spending was within the UK.

In conjunction with RE, several suppliers appear to have extended their technical capabilities, improved manufacturing processes and/or quality control in order to deliver the required components for RE's programmes.

The following subsections are descriptions of the key government agency and space industry relationships that both support the collaborative intent of the SABRE Programme and were a result of the UKSA grant. This summary is based on information provided by RE.

4.6.1 ESA Programme Framework

The credibility of the SABRE Programme has been established with the Technology Directorate of ESA. This directorate is responsible for developing technology building blocks for future European space technology. Through the grant, it was contracted to provide technical oversight of the ongoing SABRE programme on behalf the UKSA and validates the programmes milestone achievements.

The Space Transportation System (STS) Directorate of ESA is directly involved in new, developing, and current space-launch systems. RE's track record of successful testing achieved through the grant, along with the future potential of SABRE, has enabled the company to secure a contracted piece of work funded by ESA-STS, which ran through 2020. This piece of work is a significant step and is designed to investigate both the technical, programmatic, and commercial feasibility of a potential SABRE-Powered Launch System. The involvement of ArianeGroup within this activity is also an important addition in terms of marshalling European industry expertise.

ESA are generally supportive of SABRE and RE, with the recent and current Director-General regularly and publicly presenting SABRE as an innovative future launch option. As a result of successful grant activities, in 2020 the Director-General of ESA provided a letter-of-support detailing cross ESA support for the SABRE Programme.

4.6.2 European Industry/Agency Collaboration

As the SABRE Programme activity continued, it appears that interest in joining the SABRE Development Programme has grown from both European agencies and industry. The European nations most influential within the space-access domain (France, Italy, Germany) are most active in looking for ways to contribute and engage.

France

The French National Centre for Space Studies (CNES) is already primed to contribute skills, capability, and funding into SABRE. The UKSA and CNES already have a Memorandum of Understanding in place to provide a framework for cooperative activities relating to space.

In 2017, CNES formally expressed interest in SABRE propulsion. Shortly thereafter, RE entered into a tri-lateral relationship with the UKSA and CNES to investigate the technical feasibility of a SABRE-Powered Launch Vehicle. This activity concluded at the end of 2019 having defined a potentially viable launch concept. CNES were enthusiastic to carry this study into a second phase, which commenced in 2021. In addition, the current Director of Launchers within CNES has stated their interest to fund activity on SABRE through a two-step approach:

i. Funding of Applications studies through French industry prior to the ESA Ministerial 2022.
ii. Funding of significant SABRE Development Roadmap sections through a 2022 ESA Ministerial.

Furthermore, and following their stated interest in reusable launch systems, CNES have shown their readiness to stand alongside RE in investigating SABRE-Powered Launch Vehicles. This is evidenced by joint technical presentations at the 2019 EUCASS Conference on Reusable Launch and the 2020 International Astronautical Conference.

Beyond CNES, RE also has a growing relationship with a major European launch company, which has furthered its interest and engagement in both RE and SABRE. The companies signed an MoU in 2018 and have begun to collaborate on:

- Component Design/Manufacture for the SABRE Programme
- Reusable Rocket Engine Technology Development
- Application Studies involving SABRE-Powered Launch Concepts
- Hardware Test and Development
- Hydrogen Handling and Storage
- Business Development - including Industry Positioning and Funding
- Skills Development

All this engagement was a result of RE's continued development of the SABRE Programme facilitated through the UKSA GFA.

Italy

The Italian Space Agency (ASI) has also shown interest in initiating collaboration and funding focused on a SABRE-Powered Launch Vehicle.

The UKSA and ASI already have a Memorandum of Understanding in place to provide a framework for cooperative activities relating to space. At the 2019 UK Space Conference RE refreshed dialogue with the President of ASI to encourage their interest and contribution to the SABRE Development Roadmap. This sparked a series of meetings with both ASI and Italian industry during which ASI conveyed their interest in SABRE for a future European launch vehicle. ASI conveyed their desire to initiate a collaboration agreement in the near-term through a bilateral arrangement and in the longer-term via an ESA framework in order to contribute capability and funding towards SABRE.

Germany

The Germany Space Agency (DLR) is developed a renewed interest in SABRE and RE following a period of quiet around the 2019 ESA Ministerial.

RE is having advanced discussions with DLR Institutes of Space Propulsion, Space Systems and Aero & Flow around how they can contribute expertise into the SABRE Development Roadmap. RE has a strong relationship with Bayern-Chemie who have previously provided specialist expertise towards the SABRE Nacelle. RE is also in communication with smaller component suppliers for provision of equipment onto the current SABRE Demonstrator programme.

United Kingdom

The government's investment into SABRE technology has allowed RE to make a relevant contribution to the UK space industry, and to support UK Government's global and national priorities, such as net zero carbon emissions by 2050.

RE's small business and innovative technologies have been recognised across multiple Government Departments as high value capability disrupting various industries, enabling resilience, prosperity, and UK growth.

4.6.3 Airframe Engagement

As an organisation that has focused its technological development on propulsion, developing relationships within airframe organisations is critical to RE's route-to-market.
The work conducted under the 2015 grant has allowed RE to build industry interest and credibility and develop relationships with a wide range of airframe organisations with a wide variety of airframe ambitions, expertise, and experience. This is not limited to the space-access domain.
These airframers include Virgin Galactic, MBDA, CNES, ArianeGroup, JAXA, Dassault Aviation, BAE Systems, Boeing, and Airbus. All these organisations have a material relationship with RE related to either the organisations' space access, high-speed flight, or applied technology ambitions. This would not have been possible without the successful demonstration and validation of SABRE technology conducted under the Phase 1 Government grant.

Working in collaboration with major government agencies and space/aerospace companies from North America, Europe, and Asia, RE has undertaken a wide range of activities, including:

- Multi-phase studies investigating the utilisation of SABRE Propulsion within multiple space-access applications
- Implementation and collaboration agreements for a wide range of topics
- Concept studies addressing areas such as propulsion and vehicle concepts, flight test vehicles
- Contracts for key components and development support for SABRE
- Test campaigns
- Statements of Interest and support
- Further definition of access-to-space opportunities
- Collaboration on Air-Breathing Rocket technology

4.7 Technological and Scientific Inspiration and Prestige

The UKSA is fostering innovative businesses and high-skilled jobs across the country, enhancing research development and productivity, and ensuring the UK's space capabilities are resilient. The UKSA is launching the first satellites from UK space ports, developing and launching small satellites, and bringing exciting new enterprises to the UK, heralding an exciting future and inspiring kids about the future of the UK space industry. The UK is using space technology and expertise to benefit Earth and its people by opening space up to business, private enterprise, commerce, experimentation, and development to improve the quality of life on Earth. These actions are intended to lay the foundations for careers in space with training and apprenticeships and strengthening the reach and diversity of the UK space industry.

There is a heated race picking up between small- and medium-lift launch companies in the UK. Currently, RE is one of seven launch companies fighting not only to get to space, but also to show who can do so most consistently, cheaply, and repeatedly. However, RE's product offering has some key differentiators including significantly more novel technology compared to the other UK launch systems under development. It is the only UK capability and one of the few globally, looking to compete in the medium lift domain. Its unique attributes such as SSTO, horizontal take-off and landing, and abort capability should transpire to higher reliability, higher cadence of flights and lower cost, to position it well within this future market.

Table 6 was put together using publicly available sources of information to show the variety of potential native UK launch providers. RE appears to have a lot of industry support as evidenced by its total funding raised compared to its UK-based competitors. The UK is also considering hosting launches from US-based small-lift launch providers ABL and Virgin Orbit.

Table 6: Potential Native UK Launch Service Providers

							Orbital Launch Vehicle Mass Class				
Logo	**Provider Name**	**Yr Est.**	**HQ City**	**HQ Country**	**Type**	**Launch Service Vehicles (LVs not yet launched in *blue*)**	**Small-Lift (< 2,000 kg to LEO)**	**Medium-Lift (2,000 - 20,000 kg to LEO)**	**Heavy-Lift (20,000 - 50,000 kg to LEO)**	**Super Hvy-Lift (>50,000 kg to LEO)**	**Total Investment Funding**
	Reaction Engines	1989	Oxfordshire, England	UK	Private	**Skylon TSTO**, **Skylon SSTO**		○			£94,400,637
	Orbex	2015	Forres, Scotland	UK	Private	**Prime**	○				£48,278,772
	Skyrora	2017	Edinburgh, Scotland	UK	Private	**Skyrora XL**, **Third Stage**, **Space Tug**	○				£34,127,238
	Black Arrow Space	2017	Swindon, England	UK	Private	**Black Arrow 2**	○				unknown
	Smallspark Space Systems	2018	Cardiff, Wales	UK	Private	**Frost 1**	○				£1,062,361
	Astraius	2020	London, England	UK	Private	**Air-Launch**, C-17 Globemaster	○				unknown
	Orbit Boy	2021	London, England	UK	Private	**Launcher**	○				unknown

The space value chain can be divided into three components, as illustrated Figure 15. The upstream space sector consists of the scientific and technological foundations of space programmes, manufacturing, and production of space infrastructure. This is where fundamental and applied research occurs along with design and manufacturing of space equipment and subsystems. Midstream operations consist of space launch services and ground support systems. The downstream space sector consists of daily operations of space infrastructure and that directly rely on the provision of satellites to function. It also covers the supply of devices and products supporting consumer markets. The most profitable sectors are the satellite services and supporting ground equipment. In 2020, the global space economy was estimated to be around £284 billion, with £194 billion in revenues generated by satellite services and ground equipment.[21] However, satellite operators rely on the services of the £4 billion launch service industry to get satellite payloads into orbit.

[21] Bryce Tech. "State of the Satellite Industry Report". SIA, June 2021. https://brycetech.com/reports.

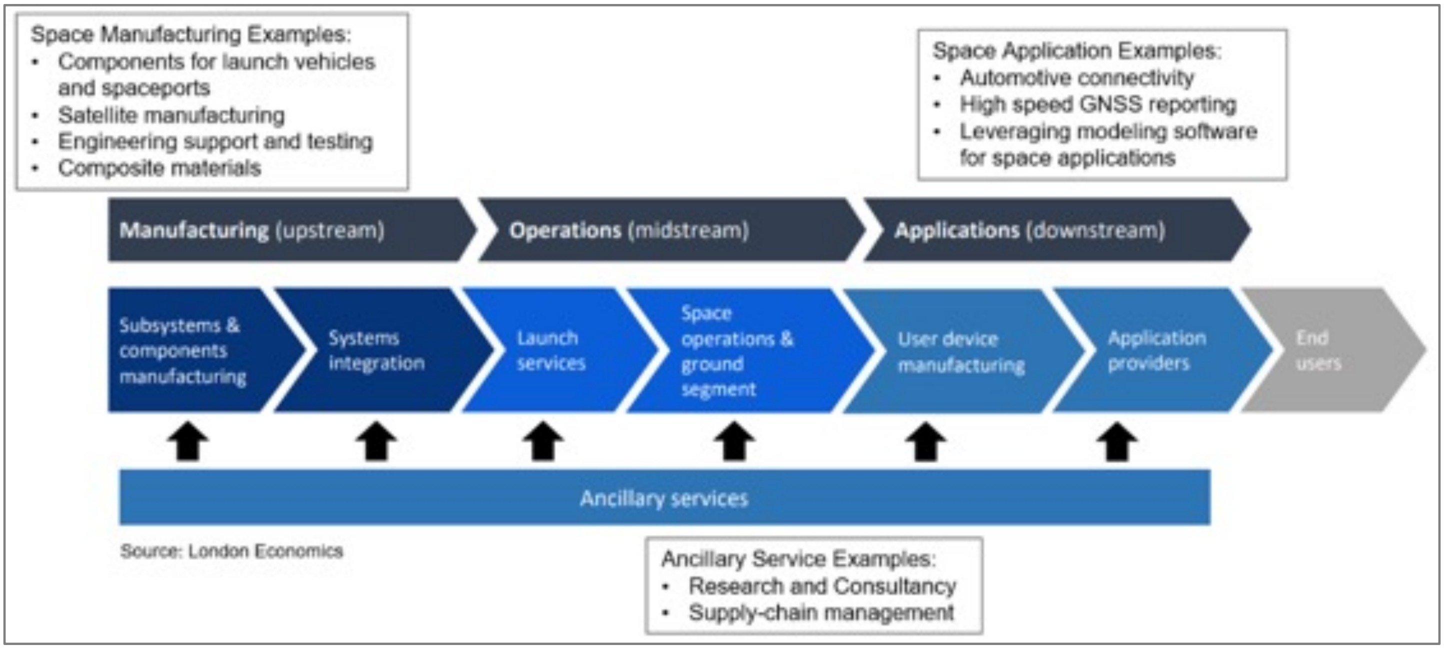

Figure 15: Space Value Chain[22]

The creation of UK spaceports and native launch providers will be a game changer for the current UK space industry in the space value chain. No longer will the UK have to launch polar orbiting satellites from other countries, such as Russia or French Guiana. With RE and others as national launch service providers, the UK would have more resilient launch alternatives, reducing its reliance on foreign launch service providers for access to space.

The Organisation for Economic Cooperation and Development (OECD) views scientific publications as an indicator to track innovation activities.[23] RE actively promotes their profile and company through a variety of communication avenues and participates in events designed to stimulate interest and excitement around space topics. The novel SABRE programme is already inspiring the next generation of engineers and scientists. The inspiring nature of the SABRE results in many publications and invitations to attend conference events within industry. The following list in Table 7 provides an indication of some of these activities.

[22] Sabri, Farooq. "Growth Opportunities Across the Space Supply Chain". London Economics, 2020. https://londoneconomics.co.uk/wp-content/uploads/2020/04/LE_Silverstone-Technology-Cluster_Market-perspective-of-space-sector-opportunities_12th-March-2020_FINAL.pdf.
[23] OECD (2019), The Space Economy in Figures: How Space Contributes to the Global Economy, OECD Publishing, Paris, https://doi.org/10.1787/c5996201-en.

Table 7: Publications and Conference Presentation List, Post 2015[24]

Year	Conference	Paper
2016	IAASS Conference	Dr Andy Quinn, S A B R E Synergetic Air-Breathing Rocket Engine, Plenary Presentation, IAASS Conference 2016
2016	IAASS Conference	Richard Varvill, SABRE – Enabling Single Stage To Orbit, Safely, IAASS Conference 2016
2016	IAC	Dr James Barth and Dr Helen Webber, SABRE Technology Development, IAC, 2016
2016	Space Propulsion Conference	Richard Varvill et al, Pre-Cooler Design and Development for the SABRE Engine, Space Propulsion Conference 2016
2016	Space Propulsion Conference	Robert Bond et al, The SABRE Engine Concept, Space Propulsion Conference 2016
2016	Space Propulsion Conference	Dr James Barth et al, Progress on the Development and Testing of the SABRE Air Intake, Space Propulsion Conference 2016
2017	FAC Annual Conference	Simon Feast and Sophie Harper, SABRE Engine Development Overview, FAC Annual Conference 2016
2018	Royal Aeronautical Society	Dr Helen Webber, The SABRE Engine Development, Royal Aeronautical Society Lecture, 2017
2018	Space Propulsion Conference	Ignacio Duran et al, HTX High Temperature Heat Exchanger Development, Space Propulsion Conference 2018
2018	Space Propulsion Conference	Mike Hood et al, SABRE TF1 – Development of the SABRE Demonstrator Test Facility, Space Propulsion Conference 2018
2018	Space Propulsion Conference	Russ Payne et al, SABRE Demo A – Key Challenges for a Ground Demonstrator, Space Propulsion Conference 2018
2018	Space Propulsion Conference	Dr James Barth et al, SABRE Technology Development – Pathways to Flight, Space Propulsion Conference 2018
2018	Space Propulsion Conference	Shaun Driscoll et al, The SABRE Engine, Concept and Development Status, Space Propulsion Conference 2018
2020	IAC	Cyril Arnono et al, Architecture and Ground Operations Concept for a Two State to Orbit using SABRE engines and launched from the CSG European Spaceport, IAC, 2020
2020	IAC	Simon Feast, The Synergetic Air-Breathing Rocket Engine - Development Status Update, Keynote Address, IAC, 2020
2020	Defence Space Conference	Carrie Lambert, Towards a Future Launch Capability, Defence Space Conference, 2020

[24] Information provided by RE

Accolades can also be used as a means of determining the success of the RE programme in provoking industry. RE's current list of eight accolades are outlined below.

Recent Accolades Demonstrating RE's Industry Recognition
2019

- Large Business of the Year and Employer of the Year Awards at the South and Vale Business Awards.
- Recognised as one of London Stock Exchange Group's 1000 Companies to Inspire Britain 2019 for its innovative work and ability to attract talent.
- Institute of Physics Business Innovation Award for our innovative, high-performance heat exchanger (the precooler) which, in April 2019, successfully achieved all test objectives in the first phase of high-temperature testing representative of high Mach number flight.

2020

- Named top of the BusinessCloud South East Tech 50 list for 2020.
- The Colin Campbell Mitchell Award from the Royal Academy of Engineering for the HTX Programme. This was awarded to the HTX technical team in recognition of their outstanding contribution to the advancement of UK engineering.
- Dr Webber awarded the Sir Ralph Robins Medal for Engineering Leadership for leading the delivery of the HTX design, build, and test programme; the first Mach 5 equivalent ground-based demonstration of a SABRE engine pre-cooler.
- Winner of The Aviation Week Network's Laureate Award for Space: Propulsion. This was awarded in recognition that RE has demonstrated its pre-cooler at temperatures representative of hypersonic speeds, a critical milestone toward development of its air-breathing rocket engine.
- Recognised by 'The Telegraph' 2020 STEM Awards as one of UK's top 10 inspiring projects for graduates to work on.

A company like RE, devoted to the development of new technology, has a positive the impact on the UK economy. RE is a homegrown company that aims to eventually rival incumbent launch providers. The company attracts attention with their numerous publications, presentations, and accolades, which could result in attracting talent from other parts of the world. This benefits the UK space industry in creating a hotspot for big-name business leaders and companies.

5 VALUE FOR MONEY

In 2015, the UK Government provided RE a £50 million grant to aid preparations for the design, manufacture, and testing of SABRE demonstrator engines. That initial HM Government investment catalysed private equity funding and strategic industry investments, attracting some of the world's leading aerospace organisations. RE's strategic backers include BAE Systems, Rolls-Royce, and Boeing, as well as financial investors Baillie Gifford, Artemis, Schroder Adveq, and Elliott Advisors with significant interest from sovereign wealth funds. The SABRE Development Programme has also positioned the company to attract further government investment and commercial contracts covering multiple applications of RE's technology.

The following sections analyse the economic impact of RE's activities on the UK economy, focusing on the 2015-2021 period. It is important to note that traditional measures of economic benefit are not always applicable to space R&D efforts, as quantification of benefit can vary widely and are a function of numerous assumptions, and no standard assumptions or methodologies exist. This analysis represents a maximum, best-case value, based on accepted academic productivity multipliers.[25]

5.1 Direct Impact

The analysis of the direct economic impact of the research, contracts, and investment activities undertaken by RE was based on the activities conducted by the company from 2015 to 2021, including the summarized sources listed in Table 8.

Table 8: Summary of Research Funding, Contracts, and Investment Since 2015 Grant[26]

Initial Value (£M)	
SABRE follow-on funding	4.5
Non-SABRE follow-on funding	0.2
Contracts & other revenue	10.4
Investments	80.9
Total	96

To date RE has received £4.5m in follow-on SABRE funding for work such as coupled subsystem testing and technical studies, to incorporate the learning from Demo A and HTX to refine and further develop the SABRE engine concept. RE's work has also resulted in a spin-out technology of battery pack HXLife cooling foils, which were created with the help of grants from Innovate UK and APC. A patent has been awarded and the technology is currently being tested by potential aerospace and automotive customers. RE has established a dedicated division, Applied Technologies, to identify new markets for its technologies. The division is now generating revenue by developing and providing RE technology across multiple areas including motorsport, aviation, energy production and electric vehicles. Non-SABRE follow-on funding sums to £0.2m, while contracts and other revenues sum to £10.5m.

To date, the UK government's pledge has sparked £81 million in private investment. This includes £22.6m from BAE Systems, who hold an 18% stake in the business. Boeing and Rolls-Royce also invested in 2018 and are shareholders alongside institutional funds including Artemis and Baillie Gifford.

[25] An additional sensitivity analysis could be conducted to account for uncertainties in the assumptions stated here. However, this type of analysis is beyond the scope of this study.

[26] Based on data provided by RE

Aggregating across these sources, the total research-related inflows into RE amounted to £96 million. Approximately 4.7% of this income was received from SABRE follow-on funding (£4.5 million), non-SABRE follow-on funding (£0.2 million, 0.2%), and through contracts and other revenue (£10.4 million, 10.8%), and the majority through investment funding (£80.9 million, 84.3%). Therefore, it is estimated that the direct impact associated with RE's research, contracts, and investment activities in the 2015-2021 period stand at £96 million.

However, the aim of this analysis is to capture the direct and induced economic impacts associated with each of these activities as defined below for a gross economic impact of RE's revenue generating activities.

- **Direct Impact:** The direct economic activity generated by income received by RE as well as the revenue of its spinout company.
- **Spill-over Impact (supply chain and induced wage spending impacts):** RE and its spinout company spend their income on purchases of goods and services from their suppliers, who in turn spend this revenue to purchase inputs to meet RE's orders. This results in a ripple effect of subsequent rounds of spending across industries. Also, the employees of RE and its spinout use their wages to buy consumer goods and services within the economy. This produces wage income for workers in the industries that produce these goods and services, resulting in a cascade of spending across the economy.

5.2 R&D Spill-over Impact

In addition to the direct impact of research and investment activities, academic literature suggests that investments in R&D can induce positive externalities. Externality refers to circumstances in which one market participant's actions have (positive or negative) external consequences on other market participants. Knowledge generated through the R&D activities of one organization enhances the productivity of other organisations.

There are many ways in which R&D can induce positive spill-over effects in the private sector. Spill-overs are enabled through direct R&D collaborations between companies and universities, such as graduate programmes and apprenticeships, the publication and dissemination of research findings, or through university graduates entering the labour market and passing on their knowledge to their employers. Spill-over benefits from space investments can also be significant; RE has actively pursued activities and partnerships that enable spill-over benefits, as described in Section 4.5. RE has established a division within RE specifically to commercialise spin-out technology from the SABRE Programme. RE has achieved early commercialisation of SABRE technology in adjacent and alternative applications and industries such as ammonia heat exchange, battery cooling, green and sustainable applications, and high-speed flight. RE has won contracts for spin-out technologies in these areas with future opportunities for engagement expected. These are the types of activities that would contribute to the estimated R&D spill-over value calculated here.

A 2021 study by London Economics investigated the economic impact of the University of Oxford, including the impact of the University's spinout companies.[27] The authors derived relevant economic multipliers via an Input-Output analysis process in estimating the total direct, indirect, and induced economic impacts associated with the spinout companies. Relevant economic multipliers were assigned to each active spinout company in 2018-2019, based on each firm's industry classification and the region of its main registered office address. Their findings imply that the marginal spill-over effect of turnover accrued by these spinout companies can be modelled using a 1.6 multiplier approximation. Meaning, every £1 earned by university spinout companies generates an additional annual output of £1.6 within the UK economy. This multiplier has been adopted as an analogous approximation of RE output.

Another academic study in 2014 provides estimates for the size of spill-over effects from public research across different UK industries.[28] The study investigated the correlation between the combined research conducted by UK Research and Innovation, the higher education sector, and public research laboratories within the different market sectors. Their findings imply a total rate of return on public sector research of 0.2, i.e., every £1 spent on public R&D results in an additional annual output of £0.20 within the UK private sector.

Further research found no significantly better spill-over estimating methodologies than the existing literature. Therefore, these productivity spill-over multipliers were adopted and applied using engineering best judgement to match the most relevant economic multipliers to the different types of research-related income received by RE to estimate the productivity spill-overs associated with R&D.

A multiplier of 1.6 was assigned to the £4.5 million SABRE follow-on R&D funding that RE received from the UK Government amounting to £7.2 million total. The multiplier of 1.6 was also assigned to the £80.9 million in investments that REL received amounting to £129.4 million total. The multiplier of 1.6 was also assigned to the £50 million in grant funding RE received for the SABRE programme, amounting to £80 million total. A multiplier of 0.2 was assigned to the £0.2 million in non-SABRE follow-on research funding received amounting to £0.04 million total.

An explanation for the large difference in magnitude between these multipliers requires consideration of the differences in scope of R&D efforts. Given that SABRE is an advanced science programme involving large teams of people and a vast supplier network of compounding economic impact, the literature argues that productivity spill-overs from R&D funding directly contributing to SABRE development should be larger. As a result, separate multipliers were applied to the different income strands. To the best knowledge of the authors, there exists no better approach to estimate the aggregate impact of RE's economic spill-overs.

[27] Conlon, Dr Gavan. Et al. "The Economic Impact of the University of Oxford". London Economics, 2021.https://londoneconomics.co.uk/wp-content/uploads/2021/10/LE-Economic-impact-of-the-University-of-Oxford-Final-Report-27-07-2021.pdf.
[28] Corrado, Carol. Haskel, Jonathan. Jona-Lasinio, Cecilia. "Knowledge Spillovers, ICT and Productivity Growth". EPWP, 2014.

Table 9: R&D Spill-over Calculations

	Initial Value (£M)	Multiplier	Spill-over Value (£M)
SABRE follow-on funding	**4.5**	**1.6**	**7.2**
Non-SABRE follow-on funding	**0.2**	**0.2**	**0.04**
Investments	**80.9**	**1.6**	**129.4**
SABRE Programme Grant	**50**	**1.6**	**80**
Total	**135.6**		**216.7**

As seen in Table 9 above, it is estimated that the total £135.6 million invested in RE's R&D activities in 2015-2021 could have generated an additional productivity spill-over economic impact of up to £216.7 million across the UK economy. This analysis represents a maximum, best-case value; RE could have generated more income, or less.

5.3 Contract Spill-over Impact

In addition to its R&D activities, RE generates economic impacts from its contracts through knowledge exchange and licensing of its IP to other organisations and the operations of its spinout company whose activities are based on RE's intellectual property.

These impacts of RE's contract activities were estimated using the same economic multipliers derived by London Economics to measure the impact of the University's spinout companies.[29]

As seen in Table 10 below, it is estimated that the total £10.4 million generated by RE's knowledge exchange and licensing of its IP to other organizations and the operations of its spinout company could have generated an additional spill-over economic impact of up to £16.6 million across the UK economy.

Table 10: Contract Spill-over Calculations

	Initial Value (£M)	Multiplier	Spill-over Value (£M)
Contracts & other revenue	**10.4**	**1.6**	**16.6**
Total	**10.4**		**16.6**

[29] Conlon, Dr Gavan. Et al. "The Economic Impact of the University of Oxford". London Economics, 2021.

5.4 Estimated Total Economic Impact

Table 11 shows an aggregate summary of the £96 million in revenues and £50 million in grant funding and estimates of the £233.3 million in spill-over economic impacts generated by RE in 2015-2021. The total gross economic impact to the UK economy is estimated as £379.3 million, or £54.2 million per year for seven years.

Comparing the £50 million of grants received by RE in 2015 to the £379.3 million gross economic impact from the grant funding and RE's research, contracts, and investment activities, it is suggested that for each £1 million in grants, RE's activities could have generated a gross economic impact of as much as £6.3 million across the UK from 2015 to 2021. This is an upper-bound value and represents a maximum, best-case value, based on academic productivity multipliers.

Table 11: Total Economic Impact of RE's Activities in the UK, 2015-2021

	Initial Value (£M)	Multiplier	Spill-over Value (£M)	Gross Economic Impact (£M) (Initial + Spill-over)
SABRE follow-on funding	4.5	1.6	7.2	11.7
Non-SABRE follow-on funding	0.2	0.2	0.04	0.2
Contracts & other revenue	10.4	1.6	16.6	27.0
Investments	80.9	1.6	129.4	210.3
SABRE Programme Grant	50.0	1.6	80.0	130.0
Total	146.0		233.3	379.3

6 GRANT ADMINISTRATION

This section addresses the processes and activities associated with the administration of the grant. The study team was specifically tasked with evaluating how effectively UKSA administered the grant as well as identifying and documenting any specific lessons learnt or transferable lessons for the administration of similar grants.

This evaluation is based on information collected through interviews with relevant UKSA and RE personnel as well as through the review of relevant documents. Interviewees were sent sample questions ahead of time; the interviews mostly followed these questions but did allow for off-piste discussions as needed.

This section is structured around the three main phases of the grant (Pre-Award, Award, and Post-Award); findings are presented in relationship to these phases.

Findings:

- Pre-Award Phase
    - Proposal was not evaluated against relevant, standard criteria
    - Grant objectives were not clearly stated
- Award Execution Phase
    - Administrative processes improved over time
    - Grant administration included innovation solutions, such as ESA support for technical assurance
    - Administrative overhead was appropriate given the size and scope of the grant
    - The grant structure allowed for sufficient flexibility for all parties to adapt to changing circumstances
    - SABRE Programme lacked a robust risk management process at the initiation of the grant
- Post-Award Phase
    - None

This section also introduces specific lessons learnt or transferable lessons for the administration of similar grants. Some lessons learnt are specific to the findings documented here, while others are more general, and related to the overall grant administration process.

6.1 Pre-Award Phase

This study identified two key findings associated with the administration of the grant in the pre-award phase.

6.1.1 Proposal was not evaluated against relevant, standard criteria

This study determined that the initial SABRE Programme grant proposal from RE was not evaluated against standardised criteria.

The successful administration of a grant begins before it is awarded, with the unbiased and deliberate evaluation of proposals using preferably quantitative selection criteria. According to interviews with UKSA personnel, most grants administered by UKSA are selected through a full and open bid process, which includes proposal evaluations based on standard and documented evaluation criteria. For example, the National Space Innovation Programme (NSIP) uses four weighted criteria to identify proposals that are most relevant to the goals of the NSIP and offer the best Value for Money (VFM). These criteria and their associated weights are publicly available and include Innovation, Relevance, Benefit to the UK, and Management and Planning.[30]

[30] Annex C: NSIP Evaluation Criteria and marking of proposals, https://www.gov.uk/government/publications/call-for-applications-national-space-innovation-programme-nsip, accessed 1 March 2022

It is important to note that these criteria were established and published in 2020; it is not apparent if similar criteria were available and in use by UKSA when the SABRE Programme grant was awarded in 2015.

The SABRE Programme grant was awarded based on a successful European Commission State Aid Decision in 2015. The European Commission found that the grant was in line with EU state aid rules; the assessment was largely based on criteria associated with compatibility under the research and development and innovation framework. The criteria included contribution to a well-defined objective of common interest, need for State intervention, appropriateness of the aid measure, incentive effect, proportionality of the aid, avoidance of undue negative effects on competition and trade, and transparency.[31] While the state aid assessment was robust, it was inherently an economic assessment, and not necessarily tied to the implicit goals of the SABRE Programme grant.

The lack of relevant, standard selection criteria represents a notable shortcoming in the administration of this grant.

6.1.2 Grant objectives were not clearly documented

This study determined that while RE's initial plans were clearly laid out, the government's overall goals and objectives of the UKSA SABRE Programme grant were not clearly documented. This ambiguity did allow for flexibility when modifications were needed.

As part of this study, the study team was tasked with determining whether the overall objectives of the SABRE Programme grant were met. The specific goal of advancing the SABRE technology was obvious through a review of the relevant documentation. However, the study team was never provided with a consolidated list of the other (socioeconomic) goals or objectives of the grant. This information was also not clearly stated in the 2015 European Commission State Aid Decision,[32] the 2015 SABRE Grant Offer letter, the 2015 SABRE Programme Proposal,[33] or the 2017 SABRE Programme Proposal.[34]

Through discussions with relevant UKSA personnel and review of available documentation, the study team was able to assemble a set of appropriate goals and objectives:

[31] SA.39457 (2015/N) - United Kingdom, SABRE – Aid to Reaction Engines Limited, 14 August 2015, ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=3_SA_39457, accessed 1 March 2022

[32] SA.39457 (2015/N) - United Kingdom, SABRE – Aid to Reaction Engines Limited, 14 August 2015, ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=3_SA_39457, accessed 1 March 2022

[33] The SABRE Engine – Phase 3 Development Resource and Implementation Plan, Ref BSDEV-REL-OF-0018, Rev 08, 12 November 2015

[34] Proposal, SABRE Development Programme, Ref SABRE-REL-OF-0022, Rev 03, 14 November 2017

- Advance the SABRE technology
- Stimulate growth in the UK space sector
- Increase the relevant skills and knowledge base in RE and the UK
- Support the development of bilateral agreements between RE and UK and international partners

However, in order to enable a robust evaluation, the goals and objectives of any grant should be clearly documented in the grant solicitation, proposal, and award decision. The lack of clearly documented grant objectives represents a notable shortcoming in the administration of this grant.

6.2 Award Execution Phase

This study identified five key findings associated with the administration of the grant in the award execution phase.

6.2.1 Administrative processes improved over time

This study determined that while the administrative processes that were in place when the SABRE Programme grant was awarded were immature, many of the relevant processes and procedures did improve over time. However, while many relevant processes and procedures did improve over time, some still require additional improvements. Both existing improvements and improvements needed are discussed below.

Skills and Processes

At the time of award, the SABRE Programme grant was the biggest single amount/single entity grant awarded by UKSA. The grant award process was extensive, requiring significant engagement with BEIS, as well as a European Commission State Aid clearance. As the UKSA was a relatively small and young agency in 2015 (established in 2010), there was not yet a robust and mature grant administration process in place within UKSA when the SABRE Programme grant was awarded. However, UKSA personnel were able to draw on grant support from UK Shared Business Services and legal support from BEIS Legal when needed. Since then, UKSA personnel report that there has been significant upskilling, to include an internal commercial team dedicated to supporting grant administration.

The need for improved administrative processes was also captured in a 2015 Government Internal Audit Agency (GIAA) report (see Figure 16). A risk associated with the lack of commercial expertise was documented, with the proposed action that BIS (now BEIS) ensure that the necessary commercial skills and expertise be developed in order to support similar developments in the future.

Throughout the execution of the grant, additional skills were developed, and processes were put in place. For example, RE personnel discussed the informal “processes” initially used by UKSA to change milestones. Initially, there was no documented process – decisions were essentially made based on face-to-face discussions. However, the growth of the commercial team within the UKSA brought some more formality to the change process, and ultimately the SABRE Programme parties began to utilize the formal Grant Change Note process. UKSA also noted an improvement in the change management approach over time but stated that these improvements should have been implemented sooner so that changes could have been monitored more consistently over the duration of the grant.

Additionally, UKSA personnel noted that the general concerns regarding the necessary skills and capabilities within UKSA should have been emphasized and addressed sooner. While the appropriate teams and corresponding rigor and corporate consistency are now in place, valuable time was lost during the early months of the grant administration because the development of necessary skills and processes were not prioritized.

Key Finding 5	Throughout the review, this project has been described as “at the vanguard” and “ground-breaking” in terms of designing commercial mechanisms. However, both Sponsors and UKSA felt that the necessary commercial and legal support/ advice was not readily available, causing them to explore a number of “blind alleys” before decisions could be sufficiently-well evidenced and made. The Commercial functions in place within BIS now were not in place at that time and the ‘procurement’ advice available was not appropriate or sufficient when UKSA were exploring cutting edge payment mechanisms.			
Risk	Lack of the right commercial expertise leads to poor VfM			
Proposed/Agreed Actions:		**Priority**	**Action owner:**	**Target date:**
1	BIS should ensure the necessary commercial capability/ expertise is available to support future developments of this nature.	*M*	Projects and Commercial Director	02/2016

Figure 16: Key Finding 5 from 2015 GIAA Report

Evaluation Metrics

According to HM Treasury Magenta Book (Central Government guidance on evaluation), evaluation metrics should be established before implementing an intervention; in this case, awarding a grant. However, when asked, the UKSA team agreed that a set of standard evaluation metrics were not in place when the SABRE Programme grant was awarded in 2015. Additionally, while there is now a dedicated monitoring and evaluation team within UKSA, a final evaluation indicators document was not available for this study team to review or utilize. While having a dedicated team in place with the relevant skill is a major improvement, the final evaluation indicators document should be finalized as soon as possible, so that current and future grants are evaluated with the appropriate guidance.

Guidance Documents

Based on interviews with UKSA and RE, there was no grant administration guidebook or process document in place when the SABRE Programme grant was awarded in 2015. As of 2022, UKSA personnel reported that there is a standard process for assessing and managing solicited and unsolicited grants funded by the UKSA, involving checks and balances from the Commercial and Financial teams, as well as the Office of the Chief Engineer. However, this process is not documented in a formal Agency reference; this type of document should be developed for all grants administered by UKSA. The UKSA commercial team does offer a course on best practices for grant administration; UKSA personnel stated that they found this course to be helpful, especially for new employees.

The improvements in UKSA's administrative practices over time represent a notable strength in the administration of this grant.

6.2.2 Grant administration included innovation solutions, such as ESA support for technical assurance

In addition to improving processes over time, this study also determined that UKSA utilized innovative solutions to effectively manage this grant; specifically, UKSA relied on ESA to conduct technical assurance of the SABRE Programme Milestones.

According to UKSA personnel, the decision to rely on ESA support was made very early in the SABRE Programme grant award process. As there was no in-house, dedicated engineering function within UKSA at the time, it was recognized that UKSA did not have the right expertise to execute the necessary technical assurance. Per the 2015 GIAA report:

UKSA will rely on ESA to verify when technical milestones have been achieved; this is in recognition ESA are the only other organisation within Europe with the right expertise and with which this type of 'commercial in confidence' information can be safely shared .

This study found that ESA support was an innovative solution and represented a key element in the successful administration of the SABRE Programme grant. Specifically, the partnership with ESA indicated that recognition by UKSA that the SABRE Programme was technical and complex and required a corresponding level of technical support. In addition to having general technical expertise within the ESA team directly supporting the SABRE Programme, ESA personnel were also able to reach back into the organization for technical specialists as needed. UKSA did note that the weekly technical assurance meetings between UKSA and ESA could have been widened earlier to include RE earlier, as this would have reduced the number of weekly meetings being held, streamlined communications, and resulted in a more collaborative approach sooner.

The partnership with ESA for technical assurance represents a notable strength in the administration of this grant.

6.2.3 Administrative overhead was appropriate given the size and scope of the grant

This study determined that the administrative overhead associated with the SABRE Programme grant was appropriate given the size, scope, and ministerial interest of the grant.

During interviews with UKSA and RE personnel, the study team identified multiple administrative activities that occurred on a known, recurring basis.

Weekly

UKSA and ESA met weekly to discuss technical status and the progress of ESA's technical due-diligence activities. These meetings were ultimately expanded to include RE.

The RE project coordinator provided an updated technical milestone tracker to UKSA and ESA on a weekly basis in support of these technical meetings.

Both RE and UKSA personnel agreed that the ESA review process was "rigorous." At the beginning of execution, the review process also took longer than expected, as all parties worked to determine what level of detail ESA required in order to confirm the technical milestones.

Monthly

UKSA was responsible for monthly progress reports to BEIS.

Monthly progress meetings were held at RE. These meetings were an opportunity for UKSA and ESA personnel to thoroughly review the SABRE Programme work packages and discuss status in detail.

Quarterly

The SABRE Project Management Board (PMB) met quarterly. These meetings had a fixed agenda, focused on topics such as financial status, upcoming milestones, international partnerships, and management updates from RE.

RE personnel reported that these meetings required significant preparation and documentation, but that they were able to re-use internal products, so that supporting these meetings was not too burdensome.

Yearly

UKSA was responsible for a yearly financial consolidation. This included an audit of all invoices and payments.

These recurring meetings were also supplemented by ad-hoc discussions between all parties as needed.

These activities are relevant and appropriate to a grant of this size and scope and represent a good balance between scrutiny and accountability and flexibility. The appropriate level of administrative overheard represents a notable strength in the administration of this grant.

6.2.4 The grant structure allowed for sufficient flexibility for all parties to adapt to changing circumstances

This study determined that the grant structure and administration allowed for sufficient flexibility for all parties to adapt to changing circumstances.
As previously discussed, the SABRE Programme experienced several technical and programmatic challenges common to ground-breaking technical development activities. As a result of these challenges, all parties had to make ‘in-flight adjustments’ and adapt to changing goals, schedules, and success criteria. Based on feedback from RE and UKSA personnel, the study team found that the grant structure and administrative processes were flexible enough to support and even bolster these necessary adaptations.

During the interviews conducted by the study team, both RE and UKSA personnel specifically discussed the need to adjust both the content and delivery schedule of technical and non-technical milestones. While major changes required PMB approval, the UKSA Head of Major Projects and Technology Development was able to authorize most changes at their level.

During the initial months of execution, there was no formal process for change requests. Changes were discussed and agreed upon by ESA, BEIS, UKSA, and RE representatives during monthly progress meetings. However, with the support of the UKSA Shared Services Commercial Team, the Programme eventually implemented a change note process in order to formally capture and document milestone changes.

Additionally, because the UKSA Head of Major Projects and Technology Development could authorize changes at their level, the change process appears to have been fluid and dynamic, reacting to changes as they occurred, as opposed to waiting for quarterly review and approval from the PMB. Specifically, when challenges arose, UKSA was able to work with RE to identify multiple alternative plans or off-ramps in order to still achieve as much value as possible. And if an activity was deemed truly unachievable, then UKSA was able to work with RE to identify other funding options or opportunities to realign the work in the future.

The flexible nature of the grant structure and administration represents a notable strength in the administration of this grant.

6.2.5 SABRE Programme lacked a robust risk management process at the initiation of the grant

This study determined that the SABRE Programme lacked a robust risk management process at the initiation of the grant, allowing risks identified by RE in the initial grant proposal to manifest as actual issues.

The need for a robust risk management process was initially documented in the 2015 Government Internal Audit Agency (GIAA) report (see Figure 17). A risk associated with the lack of effective risk management was documented with the proposed action that the PMB manage risks regularly.

The study team found that several risks were documented by RE in the 2015 SABRE Programme Proposal including a risk associated with adequate staffing levels. When asked, UKSA agreed that their staff did not specifically work with RE to develop a mitigation plan for this specific risk. However, risks were formally captured and formally discussed at the quarterly PMB reviews, per the proposed action from the GIAA.

Ultimately, the risk associated with adequate staffing levels did materialize; in the first several months, RE struggled to ramp-up staffing at the necessary rate, which did impact the delivery schedule of some initial milestones.

The lack of a robust risk management process at the initiation of the grant represents a notable weakness in the administration of this grant.

Key Finding 2	Risks were captured at the time of the Business Case being drafted and have not been reviewed since. Some months on from this, these risks would benefit from being refreshed, especially in light of more recent, detailed, technical plans from REL received in November 2015.			
Risk	If the project risks are not captured as they now present, key risks will be missed or will not be managed effectively.			
Proposed/Agreed Actions:		**Priority**	**Action owner:**	**Target date:**
1	The risks should be captured within a Project Initiation Documentation and reflect key risks arising since revised plans received from REL in November 2015. The SABRE Project Management Board should manage those refreshed risks regularly	*M*	Director General, Business and Science	02/2016

Figure 17: Key Finding 2 from 2015 GIAA report

6.3 Post-Award

This study did not identify any key findings associated with the administration of the grant in the post-award phase.

6.4 Lessons Learnt

This study captured multiple lessons learnt, process improvements, and best practices shared by both RE and UKSA. Some of these lessons learnt are discussed above but are also summarized here for completeness.

- The SABRE Programme was selected for and awarded a very significant grant via an ad hoc process. UKSA should consider awarding future grants of this size, scope, and importance through full-and-open competition to ensure proposals are vetted through a more formalized process.
- The SABRE Programme was a very ambitious and technically challenging endeavour. Early technology development activities are inherently difficult, and the criteria for success often must be adjusted as unexpected challenges arise. When administering future technology development grants, the UKSA should endeavour to set realistic expectations with all parties and stakeholders.
- The UKSA should consider scheduling a kick-off meeting before the grant execution period officially begins. The purpose of the kick-off should be to ensure that all parties have the necessary resources in place, that the initial execution schedule is realistic, and that all parties understand the scope and success criteria of the initial work packages. This will help manage expectations during the first several months of execution and help the programme stay on track.
- The SABRE Programme benefited from the robust technical expertise provided by ESA. Ensuring the availability of dedicated technical support, either in-house or through appropriate partnerships, is a best practice that should be replicated on future grants. It should be noted that as of 2022, UKSA now has in-house technical expertise through the Office of the Chief Engineer.
- Over the course of the SABRE Programme grant execution period, reporting was increased, both between the Agency and the core Department and between the project and the Agency. This increased reporting enabled the successful management of the Programme and is a best practice that should be replicated on future grants.
- RE and UKSA personnel reported that face-to-face interactions were very beneficial, especially when addressing a conflict or challenge. Where possible, the UKSA should maximize face-to-face interactions between all parties.
- During the latter part of the SABRE Programme grant execution period, UKSA began taking a more holistic approach to grant administration and worked with other teams across the Agency to address issues and get best results; this best practice should continue with future grants.
- The UKSA should consider implementing more robust feedback mechanisms and dedicated conflict escalation routes, such as formal change boards, on future programmes.

- During the execution of similar grants, an additional emphasis should be placed on strategic and future planning – not just a focus on the tactical execution of the grant itself. This could ensure the continuity of technical development, even if another grant is not awarded.

7 CONCLUSIONS

This section highlights the key findings and conclusions from the evaluation detailed above. It also presents several considerations for improving similar grants in the future.

7.1 On the impact of the programme

Summarizing the economic impact of space activities is challenging. There is a scarcity of economic data that can be compared internationally. Furthermore, identifying all important effects and establishing causal linkages is difficult. Finally, some of the most significant effects of space activities are intangible (e.g., scientific breakthroughs, increased national security) and difficult to quantify. The following summarizes the mostly qualitative impacts RE provides to the UK economy.

Overall, the study team determined that the outputs, outcomes, and impacts of the SABRE Programme grant successfully met the initial grant objectives of advancing SABRE technology, stimulating growth in the UK space sector, increasing the relevant skills and knowledge base in RE and the UK, and supporting the development of bilateral agreements between RE and UK and international partners.

The impact of the SABRE Programme grant funding on the advancement of SABRE technology was mixed. SABRE technology was advanced as a result of grant funding; however, due to the inherent challenges of technology development and maturation, not all the initial technical goals and milestones were achieved. The study team determined that while the realigned (2017) Phase 3 Programme goal of achieving test readiness for DEMO-A and the test facility was not met, the accomplishments achieved to date do fall largely in line with the original 2015 GFA intent of progressing the demonstration engine through the CDKP and CDR. The DEMO-A project achieved all its key design maturity goals whilst also undertaking subscale testing of some subsystems, with focus given to the critical subsystems supplied by RE. These major elements were advanced using a combination of demonstration, trials, and tests with both sub-scale and full-scale articles. The DEMO-R and DEMO-N content was eliminated from the scope and funds allocated elsewhere in the programme. The heat exchanger technology development programme (HTX) achieved the goal of advancing through several critical design reviews as well as test. The successful test campaign, undertaken at the RE purpose built hypersonic ground test facility, enabled the precooler to be tested multiple times at Mach 5 conditions. This was a world first and represents a significant step forward in demonstrating and de-risking a critical element of the SABRE engine. It is noted however that tasks associated with this work invoiced 57% more than the originally allocated GFA amount.

The study team did find that the grant has positively impacted RE's credibility and standing as an integral part of the UK space industry. As a result of the grant funding, RE has made relevant technological advancements as noted above, developed new and strengthened relationships with international and domestic agencies and companies, and received notable accolades and published in relevant forums.

The grant has also positively impacted the relevant skills and knowledgebase within RE and the UK. Since 2015, RE has grown to 204 permanent employees. In addition to the direct impact of the research these employees perform, they also induce positive externalities through positive productivity and knowledge spill-overs, where knowledge generated within RE enhances the productivity of other organisations. The inspiring nature of the SABRE results in many publications and invitations to attend conference events within industry.

Additionally, findings from the recent Size & Health of the UK Space Industry 2020 suggest that every direct employee of RE, supported by the income they receive, should be viewed as a force multiplier delivering 2.6-times greater return on investment to the UK economy over average UK labour. Space industry employment also has indirect and induced supply chain impacts; direct employment in RE thus supports additional UK jobs through indirect and induced effects.

RE has protected its IP with a series of patents. Since 2015, RE has had 12 granted patents, registered in several countries, for an average rate of just under 2 grants per year. It has also logged 35 trade secrets, this being its preferred method of IP protection.RE has used its IP to ease knowledge transfers in industry and develop relationships with other organizations, in addition to protecting it. SABRE is a technology idea with applications beyond space access and the flagship SABRE Programme, and RE has pursued early commercialization of SABRE technology in a variety of adjacent and alternative uses and sectors. RE has been awarded contracts for spin-off technology, with further revenue potential expected. The implementation of these research, contracting, and investment partnerships has a favourable impact on the supply chain, which benefits the UK economy.

Currently, RE is one of seven UK launch companies fighting not only to get to space, but also to show who can do so most consistently, cheaply, and repeatedly. The RE product has some unique characteristics compared to the other UK offerings including more novel technology and higher payload capability, and it appears to have a lot of industry support as evidenced by its total funding raised compared to its UK-based competitors. If SABRE technology advances sufficiently, the UK would have more resilient launch alternatives, reducing its reliance on foreign launch service providers for access to space.

Finally, during the last few years there has been a significant increase in activity relating to high-speed (or high-Mach) and hypersonic technologies, including propulsion. Due to the significant technical crossover between products, RE is already undertaking work in this area and is well positioned to address future opportunities. Due to the unique configuration of SABRE such activities could provide a steppingstone for space access technology development and increase the return on investment. Similarly, net zero applications within aviation and other industries provide further potential opportunities to develop and exploit SABRE technologies.

7.2 On the value of money

The study team analysed the economic impact of RE on the UK economy, focusing on the 2015-21 fiscal years, and determined that the grant had a significant impact.

Aggregating across various sources, the team determined that the total research-related inflows into RE during this time period amounted to £96 million.

Academic literature suggests that investments in R&D can induce positive externalities. Productivity spill-over multipliers were applied to the different types of research-related income received by RE to estimate the best-case productivity spill-over values associated with R&D. Similarly, economic impacts are generated through knowledge exchange and licensing of IP. A contract spill-over multiplier was applied to the contract-related income received by RE to generate the best-case productivity spill-over values associated with contracts and other revenue. In addition to the £96 million in known revenues and £50 million in grant funding, RE could have generated as much as £233.3 million in spill-over economic impacts, for a total of £379.3 million in gross economic impact to the UK economy over the seven-year grant period (~£54.2 million per year).

Comparing the £50 million of grants received by RE in 2015 to the £379.3 million gross economic impact from the grant funding and RE's research, contracts, and investment activities, it is suggested that for each £1 million in grants, RE's activities could have generated a gross economic impact of as much as £6.3 million across the UK from 2015 to 2021. This is an upper-bound value and represents a maximum, best-case value, based on academic productivity multipliers.

7.3 On the administration of the grant

The study determined that the SABRE Programme grant was well administered, especially related to the amount of administrative overhead, flexibility to adjust to changing circumstances, process improvements seen over time, and the use of innovative solutions for technical assurance. RE personnel reported overall satisfaction with the administration of the grant, specifically the balance between scrutiny and support, stating that the bureaucratic burden was appropriate, and that flexibility was balanced with accountability. However, RE did express concerns that UKSA was focused exclusively on the tactical execution of the grant, and that the overall administration of the grant would benefit from a strategic, forward-looking focus as well.

UKSA personnel also reported overall satisfaction with the administration of the grant, but did highlight several weaknesses including an initial lack of consistent change monitoring, concerns regarding performance not being raised soon enough, and not including all parties in technical assurance meetings from the very beginning.

This study identified similar weaknesses. The initial proposal was not evaluated against standardised criteria, and the government's overall goals and objectives of the SABRE Programme grant were not clearly documented. Additionally, prior to awarding the grant, the UKSA did not have a risk management process in place to actively address the risks identified in the initial proposal.

These are notable weaknesses and should be addressed. However, the UKSA should be commended for continuing to improve and institutionalize administrative processes over time; these improvements will help ensure the successful administration of future grants.

The study also captured specific lessons learnt, best practices, and recommendations for improvement associated with the administration of this and future grants. Many of these lessons learnt were also related to continuing to formalize and mature existing processes.

Appendix A Methodological Annex

A.1 Study approach

This study employed a mixed-method approach to this evaluation, organized around three main packages of work:

- Scoping – A short preliminary step, to review initial programme documentation and relevant UKSA guidance documents, and develop an evaluation approach
- Data Gathering – The main phase of the study, including requesting additional data from UKSA and RE, performing open-source research, and conducting interviews with relevant personnel from UKSA and RE
- Analysis – The final phase of the study, analysing the data collected throughout the study and addressing the key evaluation elements
- Reporting – Weekly reporting occurred throughout this study to provide updates on progress. A draft of this report was provided to both RE and UKSA for review and comment in March 2022. The revised final report was delivered to UKSA in December 2022.

A.2 Main Methods

The main methods employed during the evaluation of the SABRE Programme grant were documentation review and interviews.

Significant programme documentation and data was available to the study team, so the evaluation approach was primarily a table-top review of documentation and data. The study also included a series of interviews with relevant personnel within UKSA and RE in order to gather additional primary data. Interviewees were sent sample questions ahead of time; the interviews mostly followed these questions but did allow for off-piste discussions as needed.

A.3 Funding Milestone Details

003 DEMO-A

A total of **10 ACKP review packages** were delivered including Pre-Burner, Air Breathing Hydrogen Turbo Pump (ABHTP), Helium Reservoir, Valves, Regenerator System, Heat Exchanger 3 (HX3), Air Breathing Helium Circulator (ABHC), Air Breathing Air Turbo-Compressor (ABATC) Compressor, ABATC Turbine, and the Throttle Valve. **Total GFA value invoiced was £809,390 and all packages were delivered on schedule.**

A total of **8 BDR review packages** were delivered including Regenerator System, Pre-burner, HX3, ABHC, ABHTP, Duct System AB, Structure, and Valves. A Helium Reservoir BDR review package was originally planned, at a value of £11,508, but was subsequently removed from programme at DI3. **The total GFA value invoiced was £1,282,101 and packages were delivered on average 30 days late.**

A total of **28 PDKP review packages** were delivered including ABATC Turbine ITP On Contract; ABHC Fraser Nash Consulting (FNC) On Contract; ABHC – Preliminary; FNC Interim Review; ABHTP; ABHTP – Ariane Group On Contract for Unmodified Vinci Pump; ABATC Turbine Interim Review; Regenerator System; Duct System AB; Structure; Valves; HX3; ABATC Compressor; ABATC Turbine Document Submission; ABHC; Development of Turbomachinery Toolset; ABATC Turbine; Completion of HX3 Test Concept Design; ABHC Ariane Group Interim Design Review 1 & 2; Pre-Burner; ABATC C1T1 Supplier Selection for Assembly & Integration of Turbomachinery; ABATC C1T1; and ABHC Ariane Group Aluminium Blanks Complete.

A Throttle Valve PDKP review package was initially planned but determined to be Out of Scope and moved to the 007 HTX project. A Helium Reservoir PDKP review package was also planned but removed from the programme at DI3 (originally valued at £35,483). **Total GFA value of the invoiced PDKP packages was £7,175,387 and packages were delivered on average 201 days late.**

A total of **20 MDR packages** were delivered including HX3 Single Module Flow Test Rig Detailed Design Sub Contract; HX3 Start of B1 Full Scale Module Manufacturing Trials; ABHTP, ABHC Rotor Dynamics Sprint; Start-Up System, Engine Instrumentation; Control System; Electrical Supply System; Regenerator System Manufacturing Process Trials Complete; ABHC Ariane Group Design Consultancy Report (Concept Cost & Delivery, plus Commit to Contract); Valves; Duct System AB; Structure; Engine Instrumentation (Release of Long Lead Order Claim); Regenerator System Test Rig Sub Contract Kickoff; Pre-Burner; HX3; Pre-burner Completion of First Full Can Assembly; and the Regenerator System.

A Throttle Valve MDR review package was initially planned but determined to be Out of Scope and moved to the 007 HTX project. A Helium Reservoir MDR review package was also planned but removed from the programme at DI3 (originally valued at £61,376). **Total GFA value of invoiced MDR packages was £4,320,104 and packages were delivered on average 270 days late.**

A total of **27 CDKP review packages** were delivered including HX3 Completion of First Module (Build 2); HX4 -PPM2 Testing Readiness; HX4 - PPM2 Assembly Readiness Review; ABHTP; Duct System AB; Structure; Valves; Start-up System; Engine Instrumentation System; Electrical Supply System; Control System; Regenerator System Rig Test CDR; HX4-PPM3 Testing Readiness; ABATC – C1T1 Design for Manufacture (DFM) - Supplier Review Point; C1T1 Design Handover (CDKP) Readiness Plan to GKN; Regenerator System (Review Document Set Delivered); Pre-burner; HX3 Single Flow Test Rig Commissioning; HX3; ABHC - Review Document submission; Control System Demonstration Build 1B Simulation; Control system software development plans; Hardware-in-the-Loop ECS Test Rig; and ABHC - Ariane Group Release of Long Lead Material.

The ABATC Compressor CDKP Review (£257,321) was initially planned but in August 2019 it was moved to Post-PDR Close-out. An ABHC Assembly Instructions Released CDKP Review was initially planned (£300,000) but in June 2019 was reduced to £0. A Throttle Valve CDKP review package was initially planned but determined to be Out of Scope and moved to the 007 HTX project.

A Helium Reservoir CDKP review package was also planned but removed from the programme at DI3 (originally valued at £76,720). **Total GFA value of the invoiced CDKP packages was £5,491,223 and packages were delivered on average 162 days late.**

A total of **11 PDR packages** were delivered including Development of Team and Models; Development of Robustness Tools (Monte Carlo Analysis); Development of Materials Database for Demo-A Engine; Methodology and Rules for Development of Demo-A Whole Engine Model; Development of Design Process for Integrated Dual-Loop Engine; ABHC Ariane Group Interim Design Review; Completion of DI#7 preliminary design (Delta-PDR); and the Themisto Experiment (Phase 1 & 2). **Total GFA value invoiced was £3,786,240 and packages were delivered on average 29 days late.**

A total of **16 CDR packages** were delivered including Project Management; System Integration (System Requirements, System Design (with Planning), Analysis & Modelling, and System Test Planning); Whole Engine CDR; Design Systems Installation for CAD and Data and Databases Reporting; Preliminary Europa Assembly, Integration, and Test (AI&T) Plan Issued; and Themisto Experiment (Phase 1). **Total GFA value of the invoiced CDR packages £3,027,924 and packages were delivered on average 20 days late.**

A total of **5 FPS review packages** were delivered including the Electrical Supply System, Valves, Release of B1B Long Lead Valve Order, Engine Instrumentation, and Control System. FPS review packages were originally planned for HX3 (£230,189), ABHTP (£85,088), Start-up System, Duct System AB (£207,567), and Structure but were moved to other 003 DEMO-A activities.
Total GFA value of the invoiced FPS packages was £844,165 and packages were delivered on average 16 days late.

Two (2) MRR packages were delivered for System Integration-System Requirements B2 Learning and the Pre-Burner. A review package for ABHC - First MRR for Major Component was originally planned (£300,000) but moved to Post PDR review. **Total GFA value of the invoiced MRR packages was £283,803 and packages were delivered on average 285 days late.**

004 DEMO-R

Project 004 DEMO-R Rocket engine demonstrator project had three milestones: A Scoping Study, a Trade Study, and Concept Design & Requirements Definition. In December 2019 it was determined that DEMO-R was under-resourced due to the focus on HTX and DEMO-A. DEMO-R was declared Out of Scope and the funding transferred elsewhere.

- Original Re-Alignment Amount: £898,722
- As-Invoiced Amount: £0

005 DEMO-N

Project 005 DEMO-N Nacelle subsystems demonstrator has a single milestone for Bypass Burner Development. However, funding was transferred to 003 DEMO-A in July 2020.

- Original Re-Alignment Amount: £1,520,825
- As-Invoiced Amount: £0

006 Test Facility

Project 006 Test Facility for airbreathing core development engines (DEMO-A) was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £8,216,070
- As-Invoiced Amount: £4,924,876

A total of **27 Test Facility milestone packages** were delivered including Test Facility Key Point Review; General Layout Approval – Submission of Planning Application (Phase 3b); Delivery & Review of LH2 Design Study (Phase 3c); Preliminary Site Safety Case; Baseline Design Review of the DDJF (PDR); Planning Consent & Agreement to Lease; Design, Development and Test Concept Silencer Sub-System to Verify Design Model (PDR); Tender Release for Major Work Package; LH2 System - Order Placement; First Cost Certificate for start of Civil Engineering; Assembly Building Construction – Foundations; LH2 System with Supplier PDR; Excess Hydrogen Release System - Detailed Design Review (DDR) of Flare Stack; Gabion Wall Completion; Assembly/Control Buildings Handover to RE; Contracting Data Pack for Flare Stack; CDR for LH2 System with Supplier; Control System PDR; Contracting Data Pack for Compressed Air System; Safety Systems Statement of Work (SoW); Major Update to Safety Case; SCADA PDR; SoW of Water System; Completion of Major Works of Stage 2 Civil; Mixer CDR; Plant Wiring SoW; and SoW for Cable Ducts / Ladder System.

However, there were also **23 planned Test Facility milestone packages** that were eliminated due to “Change of Scope-Not planned to be delivered.” These include the Test Facility Readiness Review Complete; Purge PDR; Install of major Safety Systems; Assembly Building Readiness; Excess Hydrogen Release System -Delivery of Water Tower; Assembly/Control Buildings Handover to RE; Gas Systems - Key Components Delivery to Site; Gas Systems - Mechanical Installation Complete; Gas Systems/Controls - Final Commissioning & Handover; Production Handover; Delivery of Silencer; Control & Instrumentation - Delivery of Electrical Enclosure (Dice); Containment Shelter - Concrete Build of Containment Shelter; Helium System - Key Component Delivery; Mech Install of Flare Stack; Key Component Delivery of Compressed Air System; Water Tower System - Mechanical Installation; Control & Instrumentation Site Enclosure - Mechanical Installation of Lighting Protection; Plant Wiring Completed (Power Distribution); Cryogenic Liquids – Delivery; Contracting Data Pack for Helium System; CDR for LH2 System with Supplier – Mechanical; and CDR for LH2 System with Supplier – Electrical.

Project 006 Test Facility should culminate in facility handover and test facility readiness review.

007 HTX

Project 007 HTX Design, build and test of a high temperature precooler demonstrator, was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £6,154,957
- As-Invoiced Amount: £9,644,627

A total of **25 HTX milestone packages** were delivered including Test Review Board (TRB) – Dry Engine Run; UK Commissioning TRR; Mach 5 & Initial Results; HTX – TA return & investigation Part A; Test Article PDRs (Part 1 & 2); Test Article CDRs (Part 1.1, Part 1.2, Part 2, Part 3, & Part 4 (2)); Delivery Readiness Review Boards (DRRBs) (Part 1 and Part 2); TRRs for TA Delivery, GSE Delivery Readiness, Cold Commissioning, and Hot Test; Completion of Circulator Assembly Development; Pre-cooler Test Article 2 - Stage 1 Module Pack Completion; PDKP Review; Design Review + LLI Procurement (Phase 3c); Module Component MRR (Phase 3c), and the Module Assembly Readiness Review (Phase 3c). The HTX project culminates in a post-test TRB.

008 Pre-Burner Test Rig

Project 008 Pre-Burner Test Rig was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £906,878
- As-Invoiced Amount: £1,006,878

A total of **4 Pre-Burner Test Rig milestone packages** were delivered including the Pre-Burner Test Rig Test Report, Injector Testing, Commissioning, and Module Testing.

009 DEMO-A Microchannel HX Manufacture Development

Project 009 DEMO-A Microchannel HX Manufacture Development was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £292,526
- As-Invoiced Amount: £654,993

A total of **7 milestones** were delivered including Completion of manufacturing trials and pre-production module campaign (BDR), Regenerator Module Manufacturing Process (PDR), Pre-production module development & test status (ACKP presentations on Channel Forming Trials, Manifold Development, Matrix Joint Strength Characterisation, and Hydrogen Embrittlement), and HX4 Production Readiness.

010 Tubular HX Research

Project 010 Tubular HX Research was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £202,197
- As-Invoiced Amount: £215,045

A total of **2 milestone packages** were delivered for High temperature tubular HX research Manufacturing Process and Materials Assessment. A third milestone delivery on Assembly Vibrational Testing was planned but funding was transferred to 003 Demo A.

011 Advanced Nozzle Research

Project 011 Advanced Nozzle Research was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £227,856
- As-Invoiced Amount: £63,928

A single milestone package was delivered on the Nozzle Architecture Study-Interim Report. Another milestone package on the Nozzle Architecture Study was originally planned but funding was transferred to 003 DEMO-A.

012 Intake & Bypass Burner Research

Project 012 Intake & Bypass Burner Research was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £129,426
- As-Invoiced Amount: £129,426

A single milestone package was delivered for Demo-N planning.

013 Nacelle Engineering

Project 013 Nacelle Engineering was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £60,016
- As-Invoiced Amount: £0

A single milestone package was originally planned for to achieve an Interim Key Point (IKP), but in December 2019 it was determined to be Out of Scope and the funding transferred elsewhere.

014 High Temperature Turbine Research

Project 014 High Temperature Turbine Research was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £28,675
- As-Invoiced Amount: £0

A single milestone package was originally planned for Design & Analysis to IKP. However, this milestone was never delivered or paid.

015 Hydrogen Embrittlement Research

Project 015 Hydrogen Embrittlement Research was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £285,131
- As-Invoiced Amount: £326,911

Two milestone reports were delivered.

016 Centrifugal Compressor Test Rig

Project 016 Centrifugal Compressor Test Rig was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £202,130
- As-Invoiced Amount: £0

Originally the Centrifugal Compressor Test Rig project planned to make deliveries on the Centrifugal Compressor Test Rig, Manufactured Compressor Impellers, Test Programme Report, Centrifugal Compressor Design Code Validation Report, and the Validated Centrifugal Compressor Design Code. However, these milestones were never delivered or paid.

017 SABRE Microchannel HX Manufacture Development

Project 017 SABRE Microchannel HX Manufacture Development was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £110,006
- As-Invoiced Amount: £51,703

One delivery was made on the Regenerator Module Manufacturing Process Report.

018 Rocket Design Study

Project 018 Rocket Design Study was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £56,261
- As-Invoiced Amount: £100,000

One delivery was made on the Rocket Engine Design Report.

019 Nacelle Base Drag Research

Project 019 Nacelle Base Drag Research was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £51,147
- As-Invoiced Amount: £0

Nacelle Base Drag Research was originally funded for a Tunnel assessment analysis, NBD brief axi-quasi-3D analysis on SABRE geometry, and CAD designs of model elements and proposals for diagnostics, but delivery delays promoted a transfer of its funding to 003 DEMO-1 in July 2020. Therefore, **the GFA value delivered was £0.**

020 SABRE Re-planning

Project 020 SABRE Re-planning was originally planned and invoiced as follows:

- Original Re-Alignment Amount: £182,000
- As-Invoiced Amount: £182,000

A **single delivery** was made on the SABRE Proposal & Milestones Table.

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