DOI: 10.13009/EUCASS2019-307

SABRE TECHNOLOGY DEVELOPMENT: STATUS AND UPDATE

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Abstract

Reaction Engines' Synergetic Air Breathing Rocket Engine (SABRE™) represents a major breakthrough in aerospace propulsion technology and reusable space access capability. SABRE is a class of hydrogen-fuelled combined cycle engine that operates in air-breathing mode up to speeds above Mach 5, then transitions to rocket mode (burning on-board liquid oxygen) to accelerate to orbital velocity. SABRE's utilisation of unique, light-weight, compact heat exchangers allow the engine to deliver a high air-breathing thrust-to-weight ratio with excellent specific impulse, as well as delivering high performance in rocket operation. This paper provides an overview of two programmes demonstrating key elements of SABRE technology.

1.0 Introduction

The Synergetic Air-Breathing Rocket Engine (SABRE) is a novel combined-cycle engine designed to operate in air-breathing mode and pure rocket mode. Shown in cross-section in Fig. 1, SABRE integrates novel heat exchanger technology with conventional turbomachinery to create an engine that can utilise atmospheric air at flight speeds greater than Mach 5, and cool it prior to its compression [1]. This permits the design of an engine that offers an attractive combination of high thrust-to-weight ratio and high specific impulse.

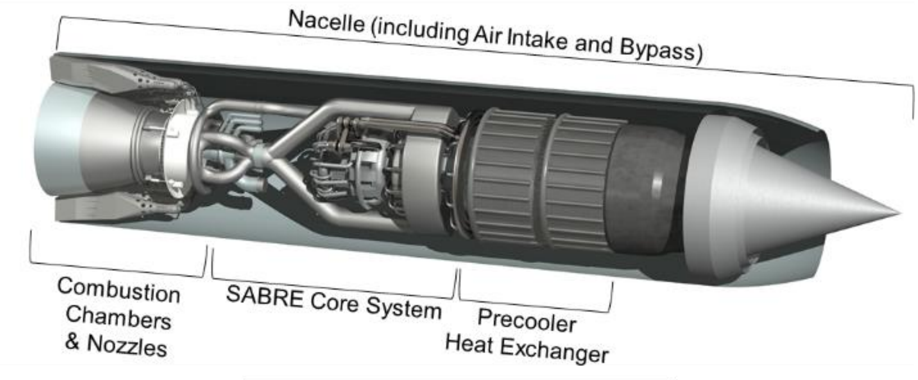

Figure 1: SABRE System Breakdown

In addition to its uniquely high performance, SABRE offers another attractive prospect: It is a modular system that permits concurrent development of each of its major sub-systems. As Fig. 1 shows, SABRE can be divided into four elements:

1. Pre-Cooler (heat exchanger).
2. SABRE Air-Breathing Core.

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3. Combustion Chambers and Nozzle.
4. The Nacelle (including the air intake and bypass).

This paper describes the SABRE development programme currently underway at Reaction Engines Ltd (REL). This programme will culminate in the design, manufacture and demonstration of the first ever SABRE air-breathing core, a flight representative pre-cooler and the test facilities required to develop and validate them. Section 2 describes the SABRE air-breathing core demonstration programme, section 3 describes the pre-cooler development & demonstration programme. Section 4 describes the test facility elements.

The Combustion Chambers and Nozzle and Nacelle programmes are not described within this paper.

2.0 SABRE Core Development

Demo-A is an engineering programme intended to mature the technology required for the SABRE air-breathing core (or SABRE core). During a flight profile, the SABRE core sees near constant sea-level pressure and temperature at the air turbo-compressor inlet. This means that the SABRE core can be tested independently, and at equivalent flight operating conditions on an open-air sea-level static test stand which is advantageous in comparison to hypersonic wind-tunnel facilities.

2.1 Demo-A Programme Objective

The over-arching objective of Demo-A is to demonstrate the operation of an air turbo-compressor driven by a close-cycle helium loop, with liquid hydrogen used as both a fuel and a heat-sink. This ground-based engine is representative of, though not identical to, a space-access SABRE core cycle. This representative cycle has been tailored to maximise the use of Commercial Off-The-Shelf (COTS) components, facilitate the incremental build-up of system complexity, and to minimise overall programme risk. Ultimately, the Demo-A engine will permit demonstration of:

- Controlled start-up/shut-down of the SABRE core;
- Engine throttling;
- Stable steady state operation;
- Cycle tolerance to off-design conditions and component inefficiencies;
- Engine thrust;
- Component technology at a relevant scale.

The successful demonstration of the Demo-A engine on-test will also provide valuable performance data to verify and validate in-house engine models and designs. Demo-A will allow SABRE component technologies to be matured to Technology Readiness Level (TRL) 5, as defined in Ref. [3].

2.2 Demo-A Configuration

The Demo-A programme is designed around two main engine build standards with a number of sub-system experiments. In all builds the sub-systems incorporate flight-like but not flight-weight hardware in order to balance technical risk and cost. Each configuration has been conceived in such a way as to incrementally build experience of the major sub-systems in order to de-risk the engine in stages.

The SABRE core cycle consists of:

- Three major fluid systems (helium heat transfer loop, hydrogen fuel system and the primary air compression system)
- Three separate turbo-machines (helium loop compressor, hydrogen fuel pump and primary air turbo-compressor)
- Two major heat exchanger systems (helium/hydrogen regenerators and air/helium pre-cooler)

REL have considered all sub-systems in turn to identify experimental test requirements and configure experiments using the minimum hardware configuration.

2.3 Demo-A Programme Status

The Demo-A was formally launched in Q4 2016. Since then, six major design iterations have been conducted, resulting in a design configuration that passed Preliminary Design Review (PDR) standard in December 2018. PDR

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was not a single review: it was divided across the engine systems, sub-systems, systems integration activities, and the overall programme. The Critical Design Review (CDR) gate that follows later this year is similarly structured, and will also be conducted across each of the major engine builds.

2.4 Demo-A Major Sub-Systems

While Demo-A itself is a complex system, many of its sub-systems also represent engineering challenges in their own right. The main air turbo-compressor, pre-burner, heat exchangers, regenerators, fuel pump, and start system are all sub-systems that require major engineering efforts, both within REL, and by partner organisations. This section will describe each of these sub-systems, and describe some of the particular challenges they pose.

2.4.1 Main Turbo-Compressor

At the heart of the engine is the core turbo-compressor, which supplies the propelling nozzle with high-pressure air as the oxidiser. The Demo-A programme is designing and building a low pressure-ratio single-spool gas-turbine style compressor as a slave air system to provide a source of compressed air for the pre-burner and to provide a load for the experimental helium turbine. Whilst the flight engine requires a state of the art high-pressure ratio compressor a reduced specification compressor has been selected for Demo-A. The power turbine that drives the compressor however is a different proposition since there are no known turbines that are suitable for this application. The turbine uses the engine's main coolant, helium, as the working fluid. This drives a very different aerodynamic design to that of a conventional gas-turbine. The very high inlet pressure creates a specific problem in balancing the rotor axial thrust load, as well as presenting unique challenges for sealing and tip clearance control.

2.4.2 Pre-Burner

The function of the pre-burner is to provide thermal energy into the helium coolant loop to drive the main turbo-compressor from sea-level static up to a high enough airspeed that it can be powered purely from the intake air enthalpy. Because Demo-A is a static test design using ambient air, the pre-burner is the sole source of heat energy for the thermodynamic cycle.

These units take the full mass flow of the main compressor delivery air but use only a small fraction of the available oxygen to provide the combustion energy for the helium loop. The design of the hydrogen injectors is particularly challenging given the requirement for the combustor to operate over a range of fuel/air ratios whilst delivering a uniform temperature distribution into HX3.

In order to facilitate incremental testing the pre-burner has been modularised to an air flow scale that reduces overall development time, cost and risk.

2.4.3 Pre-Burner Heat Exchangers

Heated compressor delivery air from the pre-burner combustors passes through a number of air/helium heat exchangers. These are designed to REL heat exchanger standards and utilise a matrix of specialised alloy micro-tubes inside a tubular pressure vessel.

2.4.4 Regenerators

One of the key features of the SABRE engine cycle is the use of helium/hydrogen heat exchangers. Microchannel multi-plate heat exchanger design and manufacturing systems are relatively well understood in adjacent industries, however the SABRE requirement for extremely high power density (expressed in kW/kg) is beyond anything commercially available. In addition, heat transfer effectiveness and module efficiency (pressure loss) targets are also very challenging. These requirements drive miniaturisation to the extremes of manufacturing capability. The physical size of these units has been chosen to facilitate manufacturing and testing trials, rather than for an optimal flight configuration.

2.4.5 Hydrogen Fuel Turbo-Pump

SABRE employs liquid hydrogen fuel, which the Demo-A replicates exactly. Liquid hydrogen pumps driven by gaseous hydrogen turbines have been developed by other organisations since the 1940's. There are major European

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aerospace companies that have existing hydrogen turbo-pump systems which can be utilised for Demo-A. Consequently REL has based the Demo-A on the Vinci hydrogen turbo-pump with the cooperation of Ariane Group.

2.4.6 Start-System Combustor

The start-system combustor is required to provide thermal energy to drive the helium compressor before the full regenerative cycle is established, at which point the engine is entirely ‘self-sustaining’ and the start combustor can be turned off. Because it is only used for a short phase of engine operation, fuelling the combustor from gaseous hydrogen and oxygen is acceptable. The actual combustor/injector style chosen is within RELs design experience but nonetheless requires dedicated sub-scale and full-scale testing.

2.5 Systems Integration, Verification and Validation

Systems engineering principles have been embedded in the Demo-A programme from the pre-launch phase in order to maximize team effectiveness and minimise technical and programme risk. A very challenging timeline for delivery of the programme has been set, adding further emphasis on continuous development of design requirements and verification/validation planning at system, sub-system and component levels (essentially the main elements of the ‘V’ model).

Significant effort has been invested in developing a systems integration toolset that meets the needs of the programme, including hierarchical requirements management, structured verification planning, dynamic interface management, whole engine model development and specific systems design tasks.

3.0 Hot Heat Exchanger (HTX) Test Programme

The main objective of the HTX Hot Heat Exchanger programme is to demonstrate the operational, structural and functional integrity of the pre-cooler heat exchanger unit at elevated air inlet temperatures, representative of high Mach number flight conditions. To do so, a hot air test facility (named TF2) has been designed and built in the United States. TF2 can drive the required air mass flow through the heat exchanger, at the correct temperature. The test programme has been designed to incrementally demonstrate the operation of the heat exchanger throughout the flight profile. Fig. 3 shows the air mass flux profile (air mass flow per unit cross-sectional area) as a function of flight Mach number, for the SABRE pre-cooler and the HTX heat exchanger. This shows a close match for most of the Mach number range.

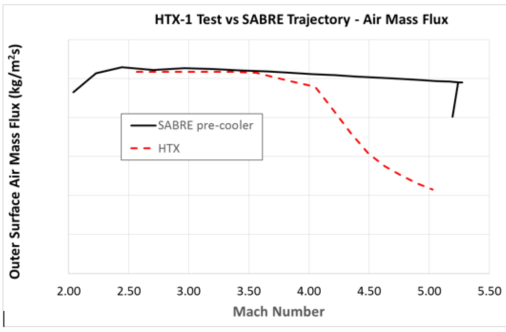

Figure 3: SABRE pre-cooler vs HTX operating conditions

In addition to the primary test objectives, HTX presents a unique opportunity to demonstrate REL design and manufacturing capability. It also proves that such heat exchangers can be realised and meet the stringent performance demands of SABRE and other pre-cooled engines, including effectiveness, mass, reliability and reusability. The HTX test programme also serves to validate the structural, aerodynamic and performance models of the design and manufacturing processes, and also the transient behaviour of the heat exchanger and its support equipment.

3.1 Heat Exchanger Design

Heat exchangers designed for pre-cooled air-breathing engines must meet stringent requirements, due to the nature of their application. The main performance parameter of the heat exchanger is the heat transfer required, which for the SABRE engine is in the order of hundreds of megawatts. This power requirement has to be achieved with a small temperature difference between the fluids, to minimise entropy generation, in combination with a tight pressure drop

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budget, since pressure loss has a negative impact on the thermodynamic cycle and thrust. In addition, there is a challenging mass target typical of space hardware.

A counter-flow heat exchanger arrangement provides the highest thermodynamic effectiveness with minimum system mass and pressure loss. In this arrangement both fluids run in opposite directions maximizing the heat transfer rate through the heat exchanger geometry whilst minimizing the pressure loss through the system. However this flow arrangement presents thermomechanical challenges as the tube wall temperature approaches the air inlet temperature, generating large thermal expansions and stresses.

The SABRE pre-cooler is assembled in an involute spiral arrangement, as shown in Fig. 4. The air stream flows radially inwards through the pre-cooler, while the helium coolant runs spirally outwards from the inner to the outer header. This method combines the benefits of a counter-flow design discussed previously, while maximising the air side heat transfer coefficient by forcing the air in aerodynamic cross flow. This arrangement suits a supersonic vehicle since the pre-cooler frontal area is minimised with attendant benefits of reduced nacelle cross section and external wave drag.

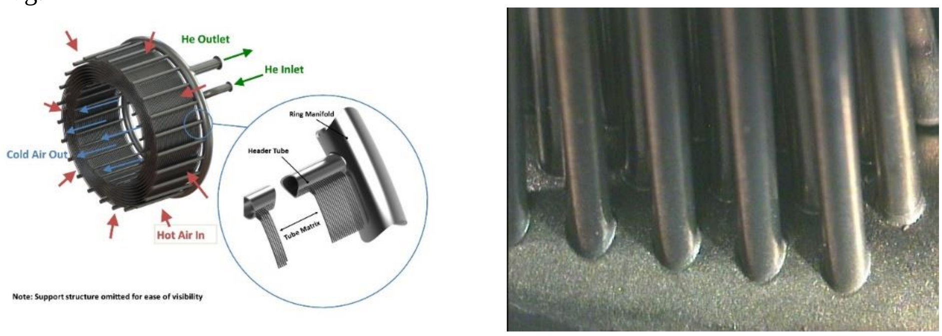

Figure 4: Pre-Cooler arrangement.

HTX is a scaled version of the SABRE pre-cooler for a spaceplane application, nevertheless it is designed to operate with the same temperatures, pressure losses, Reynolds number and mass flux. A total of 16,800 1mm diameter Inconel tubes make up the heat exchanger. HTX contains over 38km of tubes with a total tube mass of only 50kg. The tubes are pressurized with helium at over 200 bar during operation, and subject to temperatures of over 1000K. In order to keep tube wall temperature within material limits, and to provide the heat transfer and effectiveness required, the helium coolant must be distributed uniformly throughout the matrix.

The key challenge of these heat exchangers is the manufacturing process, including the assembly of the 21 modules and their brazing operation where thousands of leak-tight braze joints are effected simultaneously. As discussed previously, the counter-flow arrangement of the heat exchanger implies that this joint will be exposed to the highest metal temperature. The brazing process was specifically developed for this application to ensure that the joint can withstand the loads and operating temperatures, as well as matching thermal expansions. Throughout the HTX test programme, numerous manufacturing trials were performed to verify the integrity of the heat exchanger components, with testing to prove their resistance to pressure and temperature cycling.

3.2 Flow Diffuser, Test Article Enclosure and Instrumentation

As seen in Fig. 5, the air entering the pre-cooler must turn from an axial direction to flow radially inwards. For the SABRE engine this configuration presents itself naturally due to the supersonic intake cone forming an annular upstream flow passage (Fig. 1). For the HTX heat exchanger, a similar flow passage diverts the axial flow from the test facility to an outer plenum feeding the heat exchanger. This flow passage must withstand moderate pressures at temperatures of 1250K. For this reason, a sandwich construction was devised, in which a high temperature non-structural flow liner is enclosed within a low temperature structural pressure vessel, separated by a layer of insulation. Fig. 5 also shows a photo of the test article before integration with the test facility.

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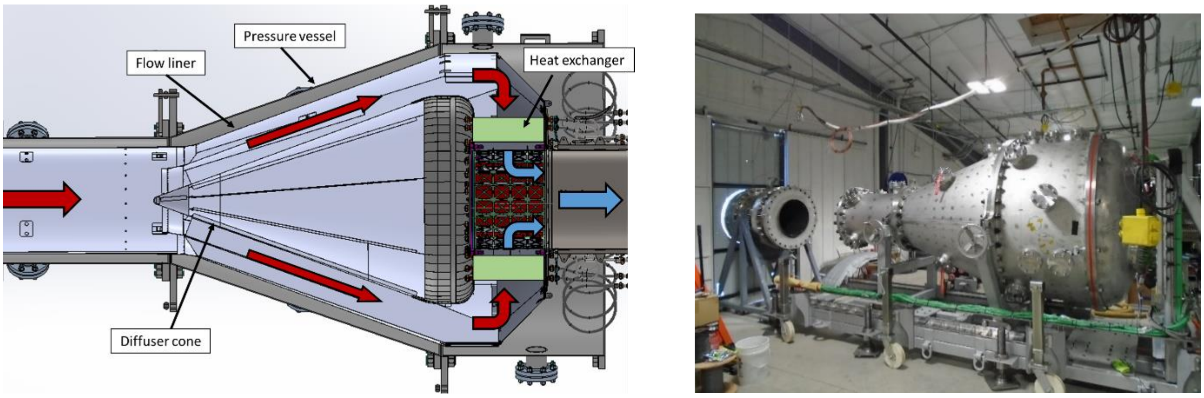

Figure 5: Cut-view through flow liner and containment vessel, with heat exchanger drum marked in green.

Due to the compactness of the heat exchanger, fitting instrumentation to measure pressures and temperatures throughout the matrix was a challenge. In order to monitor the performance of the heat exchanger and ensure the health monitoring of critical components, sufficient numbers of thermocouples and pressure tapings are fitted throughout the test article and around the heat exchanger.

3.3 Ground Support Equipment

During testing the HTX heat exchanger requires flows of hot air and cold helium at the correct pressure and temperature. The Ground Support Equipment (GSE) serves this function by collecting hot helium from the HTX outlet, cooling it using a water boiler and then circulating the cold helium back to the HTX inlet. The GSE is designed to deliver up to 2 kg/s of cold helium at 200 Bar and accept helium up to 950K. Photos of the GSE inside the test facility assembly building, and the water boiler are shown in Fig. 6.

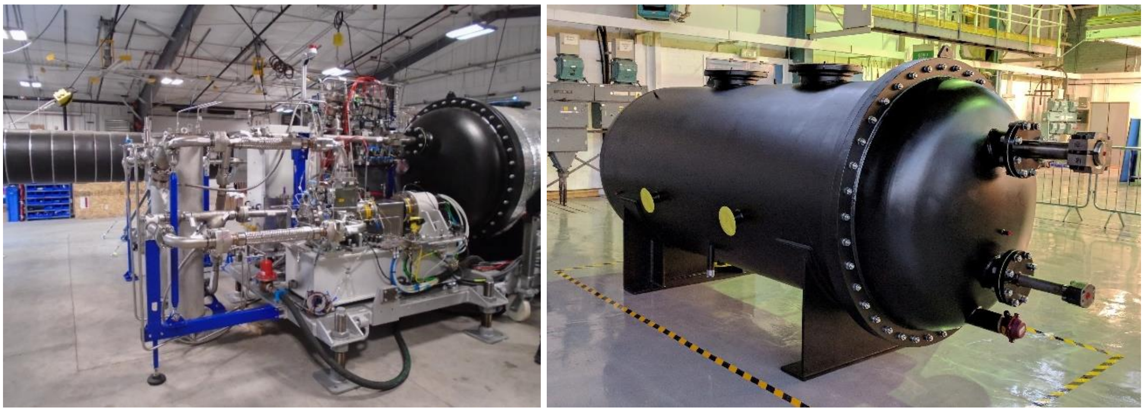

Figure 6: GSE inside the test facility (Left). Heat Rejection System (Right).

Since no COTS equipment was available to service HTX the GSE is custom designed and built. Its design constrains the HTX test envelope, in particular the loop pressure drop and maximum circulator power limit the maximum helium mass flow. This establishes an operational limit of the HTX test programme, by limiting the maximum air mass flux at high temperatures.

The water boiler (or Heat Rejection System) is shown in Fig. 6. It is designed to reject the same power as extracted from the air, approximately 5MW, using boiling water and superheated steam. The water boiler was designed and built by Sterling Thermal Technologies and weighs over 5000 kg, compared to only around 100 kg for the complete HTX heat exchanger (which is intrinsically more difficult due to the low airside heat transfer coefficients).

The GSE is designed to maintain constant helium loop pressure as the temperature changes during a test by using multiple feed and pressure relief valves. Downstream of the water boiler, the helium circulator drives up to 2kg/s of helium around the loop. This circulator is by far the greatest challenge within the GSE, due to the nature of the helium working fluid, stringent leak and low contamination requirements. The circulator is custom-made, operates at 30,000rpm and is driven by a special 120kW electric motor.

A large commissioning campaign was undertaken in the UK between June and November 2018. This proved the operation of the GSE, including the circulator, electric motor and the heat rejection system.

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3.4 Test Campaign and Results

The initial test campaign was carried out between March and June 2019. During this period, numerous tests were carried out at increasing temperatures (i.e. equivalent Mach number).

The first test run, on 25th of March 2019, achieved an air inlet temperature equivalent of Mach 3.3. The heat exchanger performed as expected, with an effectiveness of 99.8%, rejecting 1.6MW of power. Remarkably good agreement has been obtained between measured and predicted performance (generally within 1% of predicted values).

4.0 Test Facilities

4.1 Test Facility 1 (TF1)

To demonstrate SABRE and run the Demo-A engine, a new type of test facility (TF1) is required that combines jet engine air aspiration with rocket engine cryogenic fuel systems.

TF1 consists of a fuel supply system that provides liquid hydrogen with flow rates up to 7 kg/s with delivery pressures up to 6 bar and temperature control from 18 K to 24 K. A maximum of 5T of hydrogen will be stored on site, enough to test the Demo-A engine for a duration equivalent to SABRE's air-breathing trajectory. Two gaseous hydrogen supplies up to 3 kg/s at 75 bar each will also be available for testing. As Demo-A will not feature a main air-breathing combustion chamber, a flare stack will burn excess hydrogen. Helium, nitrogen and oxygen services also form part of the plant delivery systems. Noise from the engine tests will be minimised with the engine in a concrete containment shelter, a high wall surrounding the site, and noise suppression of exhaust. Illustrations of TF1 are shown in Fig. 7.

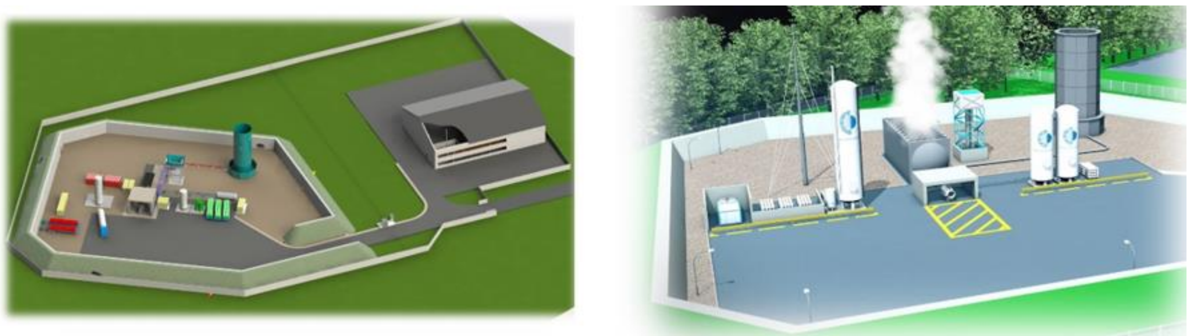

Figure 7: Images of the TF1 facility and test stand.

4.2 Test Facility 2 (TF2)

The HTX test programme requires a large range of air mass flow and high inlet temperatures to simulate Mach 5 flight conditions. This has required the construction of a new facility custom built at Reaction Engines Inc, in Colorado, US (Fig. 8). It features a J79 jet engine, operating with afterburner, to supply pressurized hot combustion products to a downstream plenum. This hot gas source is then modulated in order to supply a wide range of air mass flows, temperatures and feed pressures to the HTX test article.

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Figure 8: A selection of TF2 photos showing main plenum, assembly/test building and J79 jet engine.

5.0 Concluding Remarks

As part of the overall SABRE development programme, REL is undertaking three major development/test programmes to demonstrate SABRE's technology and thermodynamic cycle.

The first of these programmes (Demo-A) has been described in section 2. The second programme (HTX) is described in section 3, and the third programme in section 4 describes the companies test facilities.

The culmination of these programmes will be the first demonstration of the technologies for an air-breathing engine capable of facilitating to high Mach numbers. This represents a major step in testing the systems and sub-systems specified for a full SABRE engine.

Partitioning the programme into a series of experiments, of incremental complexity and technical challenge provides a balanced overall risk and cost path to system and sub-system verification and validation. All of the learning from the design studies and testing will be directly applicable to follow-on bench development and testing of flight engines.

6.0 Acknowledgements

The authors wish to acknowledge the assistance of UKSA, ESA, BAE Systems, and REL's private investors for providing the funding for the work presented, as well as REL's other partners: Ariane Group and Airborne Engineering Ltd.

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