**SABRE Rocket Engine**

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*For other uses, see Sabre (disambiguation).*

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| **Reaction Engines SABRE** | |
| A model of SABRE | |
| **Country of origin** | United Kingdom |
| **Designer** | Reaction Engines Limited |
| **Application** | Single-stage-to-orbit |
| **Associated L/V** | Skylon |
| **Predecessor** | RB545 |
| **Status** | Research and development |
| **Liquid-fuel engine** | |
| **Propellant** | Air and LO2 / liquid hydrogen |
| **Cycle** | Combined cycle precooled jet engine + closed cycle rocket engine |
| **Performance** | |
| **Thrust (vac.)** | Approx. 2,940 kN (660,000 lbf) |
| **Thrust (SL)** | Approx. 1,960 kN (440,000 lbf) |
| **Thrust-to-weight ratio** | Up to 14 (atmospheric) |
| **Isp (vac.)** | 460 seconds (4.5 km/s) |
| **Isp (SL)** | 3,600 seconds (35 km/s) |

**SABRE** (**Synergistic Air-Breathing Rocket Engine**) is a concept under development by Reaction Engines Limited for a hypersonic precooled hybrid air breathing rocket engine. The engine has been designed to achieve single-stage-to-orbit capability, propelling the proposed Skylon launch vehicle. SABRE is an evolution of Alan Bond's series of liquid air cycle engine (LACE) and LACE-like designs that started in the early/mid-1980s for the HOTOL project.

The design comprises a single combined cycle rocket engine with two modes of operation. The air breathing mode combines a turbo-compressor with a lightweight air precooler positioned just behind the inlet cone. At high speeds this precooler cools the hot, ram-compressed air leading to an unusually high pressure ratio within the engine. The compressed air is subsequently fed into the rocket combustion chamber where it is ignited with stored liquid hydrogen. The high pressure ratio allows the engine to continue to provide high thrust at very high speeds and altitudes. The low temperature of the air permits light alloy construction to be employed which gives a very lightweight engine—essential for reaching orbit. In addition, unlike the LACE concept, SABRE’s precooler does not liquefy the air letting it run more efficiently.

After shutting the inlet cone off at Mach 5.14, 28.5 km altitude, the system continues as a closed cycle high performance rocket engine burning liquid oxygen and liquid hydrogen from on-board fuel tanks, potentially allowing a hybrid spaceplane concept like Skylon to reach orbital velocity after leaving the atmosphere on a steep climb.

An engine derived from the SABRE concept called Scimitar has been designed for the company’s A2 hypersonic passenger jet proposal for the European Union-funded LAPCAT study.

In November 2012, Reaction Engines announced it had successfully concluded a series of tests that prove the cooling technology of the engine, one of the main obstacles towards the completion of the project. The European Space Agency (ESA) has evaluated the SABRE engine's pre-cooler heat exchanger, and accepted claims that the technologies required to proceed with the engine's development had been fully demonstrated.

As of July 2013, the United Kingdom has earmarked £60 million for the development of a full-scale prototype of the SABRE engine, citing the viability of its core technologies based on testing performed by the ESA.

As of June 2015, SABRE's development continues with The Advanced Nozzle Project in Westcott, UK. The test engine, operated by Airborne Engineering Ltd, is being used to analyze the aerodynamics and performance of the advanced nozzles that the SABRE engine will use, in addition to new manufacturing technologies such as the 3D-printed propellant injection system.

**History**

The precooler concept evolved from an idea originated by Robert P. Carmichael in 1955. This was followed by the liquid air cycle engine (LACE) idea which was originally explored by General Dynamics in the 1960s as part of the US Air Force's aerospaceplane efforts.

The LACE system was to be placed behind a supersonic air intake which would compress the air through ram compression, then a heat exchanger would rapidly cool it using some of the liquid hydrogen fuel stored on board. The resulting liquid air was then processed to separate the liquid oxygen for combustion. The amount of warmed hydrogen was too great to burn with the oxygen, so most was to be expelled, giving useful thrust, but greatly reducing the potential efficiency.

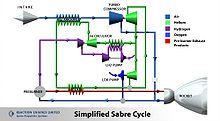
Instead, as part of the HOTOL project the RB545 engine was developed with a more efficient cycle. The engine was given the Rolls Royce name "Swallow".

In 1989, after funding for HOTOL ceased, Bond and several others formed Reaction Engines Limited to continue research. The RB545's precooler had issues with embrittlement, excess liquid hydrogen consumption, patents and the Official Secrets Act, so Bond developed SABRE instead.

As of November 2012[update], hardware testing of the "heat exchanger technology crucial to [the] hybrid air- and liquid oxygen-breathing [Sabre] rocket motor" had been completed. This demonstrated that the technology was viable. The Sabre engine "relies on a heat exchanger capable of cooling incoming air to −150 °C (−238 °F), to provide liquid oxygen (LOX) for mixing with hydrogen to provide jet thrust during atmospheric flight before switching to tanked LOX when in space." The tests validated that the heat exchanger could perform as needed for the engine to obtain adequate oxygen from the atmosphere to support the low-altitude, high-performance operation.

In 2015, the SABRE engine passed feasibility tests conducted by the U.S. Air Force Research Laboratory.

**Design**



Simplified flow diagram of SABRE engine

Like the RB545, the SABRE design is neither a conventional rocket engine nor jet engine, but a hybrid that uses air from the environment at low speeds/altitudes, and stored liquid oxygen at higher altitude.

At the front of the engine a simple translating axisymmetric shock cone inlet slows the air to subsonic speeds using two shock reflections.

Part of the air then passes through a precooler into the central core, with the remainder passing directly through a ring of bypass ramjets. The central core of SABRE behind the precooler uses a turbo-compressor run off the same gaseous helium loop Brayton cycle which compresses the air and feeds it into four high pressure combined cycle rocket engine combustion chambers. The oxygen is also fed to the combustion unit, using a turbopump.

**Precooler**

As the air enters the engine at supersonic/hypersonic speeds, it becomes very hot due to compression effects. The high temperatures are traditionally dealt with in jet engines by using heavy copper or nickel based materials, by reducing the engine's pressure ratio, and by throttling back the engine at the higher airspeeds to avoid melting. However, for an SSTO craft, such heavy materials are unusable, and maximum thrust is necessary for orbital insertion at the earliest time to minimize gravity losses. Instead, using a gaseous helium coolant loop, SABRE dramatically cools the air from 1000 °C down to −150 °C in a heat exchanger while avoiding liquefaction of the air or blockage from freezing water vapor.

Previous versions of precoolers such as HOTOL put the hydrogen fuel directly through the precooler. SABRE inserts a helium cooling loop between the air and the cold fuel to avoid problems with hydrogen embrittlement in the precooler.

The dramatic cooling of the air created a potential problem: it is necessary to prevent blocking the precooler from frozen water vapor and other air fractions. As of October 2012, the cooling solution was demonstrated for 6 minutes using freezing air. The cooler consists of a fine pipework heat exchanger and cools the hot in-rushing atmospheric air down to the required −150 °C in 0.01s. The ice prevention system had been a closely guarded secret, but REL disclosed a methanol-injecting 3D-printed deicer in 2015 through patents, as they needed partner companies and could not keep the secret while working closely with outsiders.

**Compressor**

Below 5 times the speed of sound and 25 kilometers of altitude, which is 20% of the speed and 20% of the altitude needed to reach orbit, the cooled air from the precooler passes into a modified turbo-compressor, similar in design to those used on conventional jet engines but running at an unusually high pressure ratio made possible by the low temperature of the inlet air. The compressor feeds the compressed air at 140 atmospheres into the combustion chambers of the main engines.

The turbo-compressor is powered by a gas turbine running on a helium loop, rather than by combustion gases as in a conventional jet engine. The turbo-compressor is powered by waste heat collected by the helium loop.

**Helium loop**

The 'hot' helium from the air precooler is recycled by cooling it in a heat exchanger with the liquid hydrogen fuel. The loop forms a self-starting Brayton cycle engine, cooling critical parts of the engine and powering turbines. The heat passes from the air into the helium. This heat energy is used to power various parts of the engine and to vaporize hydrogen, which is burnt in ramjets.

**Engines**

Due to the static thrust capability of the hybrid rocket engines, the vehicle can take off under air breathing mode, much like conventional turbojets. As the craft ascends and the outside air pressure drops, more and more air is passed into the compressor as the effectiveness of the ram compression drops. In this fashion the jets are able to operate to a much higher altitude than would normally be possible.

At Mach 5.5 the air-breathing system becomes inefficient and is powered down, replaced by the onboard stored oxygen which allows the engine to accelerate to orbital velocities (around Mach 25).

The combustion chambers in the SABRE engine are cooled by the oxidant (air/liquid oxygen) rather than by liquid hydrogen to further reduce the systems use of liquid hydrogen compared to stoichiometric systems.

The most efficient atmospheric pressure at which a conventional propelling nozzle works is set by the geometry of the bell. While the geometry of the conventional bell remains static the atmospheric pressure changes with altitude and therefore nozzles designed for high performance in the lower atmosphere lose efficiency as they reach higher altitudes. This is overcome in traditional rockets by using multiple stages. The engines at each stage are designed for the atmospheric pressures they encounter. An SSTO engine must use a single set of nozzles. Tests were carried out on an expansion deflection nozzle called STERN that varies the nozzle to overcome the problem of non-dynamic exhaust expansion. The successful experiment recommends this technology for the final SABRE design.

**Bypass burners**

Avoiding liquefaction improves the efficiency of the engine since less entropy is generated and therefore less liquid hydrogen is boiled off. However, even simply cooling the air needs more liquid hydrogen than can be burnt in the engine core. The excess is expelled through a series of burners – "spill duct ramjet burners" which are arranged in a ring around the central core. These are fed air that bypasses the precooler. This bypass ramjet system is designed to reduce the negative effects of drag resulting from air that passes into the intakes but is not fed into the main rocket engine, rather than generating appreciable thrust. At low speeds the ratio of the volume of air entering the intake to the volume that the compressor can feed to the combustion chamber is at its highest, requiring the bypassed air to be accelerated to maintain efficiency at these low speeds. This distinguishes the system from a turboramjet where a turbine-cycle’s exhaust is used to increase air-flow for the ramjet to become efficient enough to take over the role of primary propulsion.

**Performance**

The designed thrust-to-weight ratio of SABRE is up to 14 compared to about 5 for conventional jet engines, and 2 for scramjets. This high performance is a combination of the denser, cooled air, requiring less compression, and, more importantly, the low air temperatures permitting lighter alloys to be used in much of the engine. Overall performance is much better than the RB545 engine or scramjets.

Fuel efficiency (known as specific impulse in rocket engines) peaks at about 3500 seconds within the atmosphere. Typical all-rocket systems peak around 450 seconds and even "typical" nuclear thermal rockets at about 900 seconds.

The combination of high fuel efficiency and low mass engines permits a single-stage-to-orbit approach, with air breathing to Mach 5.14+ at 28.5 km altitude, and with the vehicle reaching orbit with more payload mass per take-off mass than just about any non-nuclear launch vehicle ever proposed.

Like the RB545, the precooler idea adds mass and complexity to the system. The precooler is the most aggressive and difficult part of the design. The mass of this heat exchanger is an order of magnitude lower than has been achieved previously. The experimental device achieved heat exchange of almost 1 GW/m3, believed to be a world record. Small sections of a real precooler, referred to as modules, now exist.

The losses from carrying the added weight of systems shut down during the closed cycle mode (namely the precooler and turbo-compressor) as well as the added weight of Skylon’s wings are offset by the gains in overall efficiency and the proposed flight plan. Conventional launch vehicles such as the Space Shuttle spend around a minute climbing almost vertically at relatively low speeds; this is inefficient, but optimal for pure-rocket vehicles. In contrast, the SABRE engine permits a much slower, shallower climb, breathing air and using wings to support the vehicle, with far lower fuel usage.

Unlike traditional rocket engines, and like other types of air breathing jet engine, a hybrid jet engine can use air to create combustion saving on propellant weight and therefore increasing payload fraction.

Ramjets and Scramjets must spend a significant amount of time within the lower atmosphere to build speed to reach orbital velocity creating issues with extremely high drag leading to intense heating and the subsequent weight and complexity of required thermal protection. A hybrid jet like SABRE needs only reach low hypersonic speeds inside the lower atmosphere before engaging its closed cycle mode, whilst climbing, to build speed.

Unlike ramjet or scramjet engines, the design is able to provide high thrust from zero speed up to Mach 5.5, with excellent thrust over the entire flight, from the ground to very high altitude, with high efficiency throughout.

In addition this static thrust capability means the engine can be easily tested on the ground, which drastically cuts testing costs.

**Sub-scale ground test**

The next stage of the SABRE engine program includes ground testing a sub-scale engine able to demonstrate the entire cycle; ESA declared that a successful test would represent "a critical milestone in the development of this program and a major breakthrough in propulsion worldwide". In June 2013 the United Kingdom government announced further support of the program providing £60M of funding between 2014-16 with ESA providing an additional £7M. The total cost of developing a test rig is estimated at £200M. In 2015, the US Air Force Research Laboratory approved the principles of the SABRE engine.

In August 2015 the European Commission competition authority approved UK government funding of £50 million for further development of the SABRE project. This was approved on the grounds that money raised from private equity had been insufficient to bring the project to completion.

**See also**

* [Single-stage-to-orbit](https://en.wikipedia.org/wiki/Single-stage-to-orbit)
* [Precooled jet engine](https://en.wikipedia.org/wiki/Precooled_jet_engine)
* [Hybrid rocket](https://en.wikipedia.org/wiki/Hybrid_rocket)
* [Liquid-propellant rocket](https://en.wikipedia.org/wiki/Liquid-propellant_rocket)
* [Altitude compensating nozzle](https://en.wikipedia.org/wiki/Altitude_compensating_nozzle)

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