Hypersonic Spy Planes, Civil Transports and Spaceplanes: **Projecting the Future of Transcontinental Flight and Access to Space**

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Can we say with certainty that we are getting closer to revolutionizing transcontinental military and commercial aeronautics? The optimistic side of me responds with a resounding Yes! At the same time, we are aiming even higher. Engineers continue developing scramjet engines that combine synergistically with rockets to propel innovative space launch systems. These launchers are intended to place satellites in low Earth orbit, and even to transport people to the edge of space. Here is a look at some developments in 2016 that show how hypersonic technology is maturing rapidly to achieve those goals.

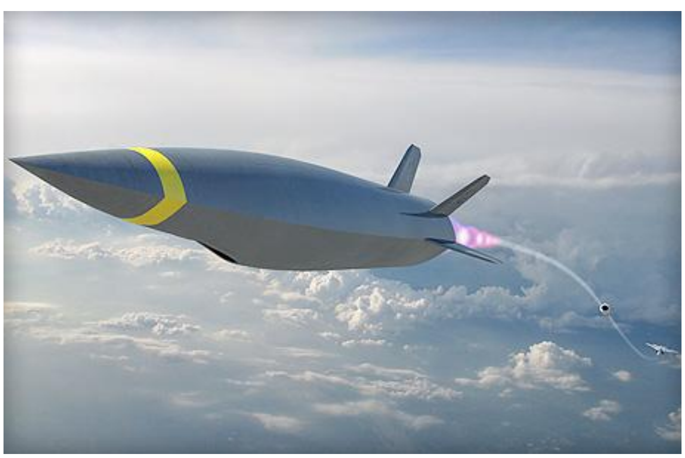
Artistic rendition of the Lockheed SR-72 Hypersonic Aircraft. Image: Lockheed Martin Co.

2016 END OF YEAR HIGHLIGHTS

HAWC Program – High Speed Strike Weapon (HSSW) Hypersonic Missile – SR-72 Spy Plane – LAPCAT-II Program – SABRE – Spartan space launcher – HIFiRE

PROGRESS MADE IN 2016 by leading industry and government groups across the world bodes well for the future of high-speed propulsion. In the military side, the race continues to develop hypersonic weapons, missiles that can reach a target at more than five times the speed of sound. In the USA, for example, most funding now comes from the **Hypersonic Air-breathing Weapon Concept (HAWC)**, a program managed by the Air Force Research Lab (AFRL) and the Defense Advanced Research Projects Agency (DARPA). HAWC is designed to develop the required technologies to achieve hypersonic speed in a cruise-missile-sized platform. It considers a JP-fueled scramjet engine to enable a medium-size rapid response ISR vehicle with operationally-relevant range capability.

In March, Lockheed CEO Marillyn Hewson stated publicly that the company is working on several innovative technologies to enable long-duration, maneuverable, hypersonic flight. Lockheed's breakthroughs include new thermal protection systems, innovative aerodynamic shapes, navigation, guidance and control improvements. Lockheed is now producing a controllable, low-drag aerodynamic plane configuration "capable of stable operations from takeoff to subsonic, transonic, supersonic and hypersonic, to Mach 6," Hewson said.



Lockheed Martin High Speed Strike Weapon (HSSW) Hypersonic Missile Concept. Image: Lockheed Martin

Lockheed's Skunk Works is working with Aerojet Rocketdyne to mature the propulsion technologies for the HAWC program, according to executive vice president Rob Weiss. Just like the very successful X-51A waverider, Lockheed's HAWC concept will use a rocket booster to reach the required altitude and speed, and then it will fire a scramjet engine to fly at Mach 5. What will be the range of the new hypersonic missile? Let us put this in perspective. In its final flight in May 2013, the X-51A demonstrator reached Mach 5.1 traveling more than 230 nautical miles in just over 6 minutes. To date, that is the longest air-breathing hypersonic flight ever.

Raytheon is competing with Lockheed on the HAWC program. The company is considering additive manufacturing for growing exotic components or the entire missile. Raytheon used 3D printing for components of some weapons already in production and now used by the Army. "There have been some fundamental game-changers in that world (of hypersonics), so, not only can you build them, but you can build them affordably," said Raytheon's head of advanced missile systems, Tom Bussing, in a briefing in March.

Perhaps the most intriguing of all is the **SR-72 spy plane**, a hypersonic concept unveiled by Lockheed Martin in 2013. Although I could not get details on its status, the SR-72 is prominent in the company's website. And so although shrouded in secrecy for obvious reasons, I believe that Lockheed engineers are working on the development of the SR-72 at the company's Skunk Works in California. The SR-72 will be a 4,000-mile-per-hour reconnaissance drone with strike capability. As conceived, the future hypersonic spy aircraft will evade assault, take photos from enemy's sites, and attack targets at speeds of up to Mach 6. That's twice as fast as the former SR-71. The new spy plane could reach any location on any continent in an hour!

It is easy to speculate on the required air-breathing engines for the SR-72. In order to be able to take off and reach Mach 6 speeds, the propulsion system may incorporate a turbojet that can take the SR-72 from runway to Mach 3, and a hypersonic ramjet/scramjet that can propel it to hypersonic speeds. The airframe design of such vehicle is also unique, as its aerothermodynamic performance cannot be decoupled from propulsion performance due to shared surfaces and complex flow field interactions.

Moreover, the airframe of the SR-72 must include advanced materials to stay intact while subjected to high dynamic loads, and to withstand the extreme aerodynamic heating of hypersonic flight, as air friction alone would melt conventional materials. Lightweight carbon composites used in hypersonic vehicles can withstand temperatures of up to 2900 degrees Fahrenheit.

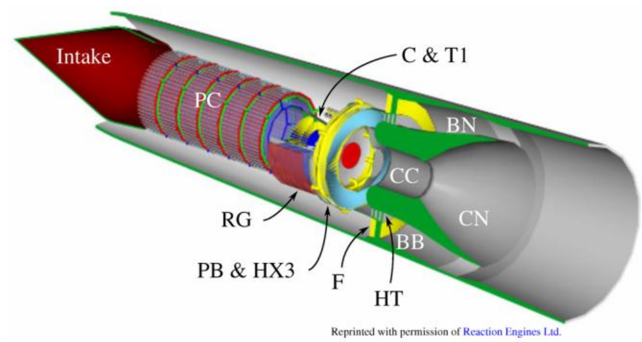
To develop a hypersonic spy plane requires extraordinary engineering and technology advances beyond propulsion and materials. Think about it: a plane moving at Mach 6 will require hundreds of miles to turn around and unique strategies to decelerate and land. It will also require powerful and advanced guidance systems to line up targets, 80,000 feet below. And how do you take photos from that altitude flying at hypervelocity? No question about it, the Lockheed Martin engineers involved in the SR-72 project are developing a truly groundbreaking military vehicle for the future.

Another issue of concern for a hypersonic spy plane is sonic boom. A sonic boom generates a 160-decibel noise that travels to the ground and —aside from the fact that it can permanently damage human ears— it would reveal the presence of the plane. A superboom will develop when the hypersonic airplane changes its speed, turns or maneuvers. In a superboom the ground noise is much louder. Of course, the hypersonic plane will fly at altitudes above 30 km, and so the shock waves are expected to spread out and produce a smaller shock wave on the ground. Nevertheless, I expect the design of the Mach 6 spy plane will incorporate unique features to minimize its boom signature.

Hypersonic Civil Transport

Hypersonic propulsion will also revolutionize transcontinental commercial aviation. Just as going from propeller-driven aircraft to jet planes changed aeronautics, hypersonic air-breathing propulsion is the leap in technology that will transform how we travel across the globe. That is the area where substantial engineering effort is focused in Europe and Japan.

The European Space Agency (ESA) has invested $11 million toward the development of an engine that could one day allow aircraft to fly anywhere in the world in just four hours. In England, Reaction Engines Ltd. (REL) is developing the **Scimitar engine**, a pre-cooled air-turbo ramjet fueled by liquid hydrogen (LH2) that can propel an aircraft to Mach 5 speeds. Scimitar is a derivative the **Synergetic Air-Breathing Rocket Engine (SABRE)**, an air-breathing rocket concept that exploits the unique thermodynamic properties of LH2 by using lightweight heat exchangers. According to REL, the new agreement with the ESA and the UK Space Agency, along with the existing partnership with BAE Systems, means that the first ground demonstrator Scimitar engine could be ready for testing by 2020.



The Scimitar Turbo-Ramjet Engine developed by REL Ltd. Intended for Civil Hypersonic Transports.

The European **LAPCAT-II program** continues advancing the development of a hypersonic civil transport. The program includes a Mach 5 airliner powered by a pre-cooled air-turbo ramjet, and a Mach 8 airplane powered by a ramjet engine, both fueled by LH2. This four-year program is co-funded by the European Commission under the theme of air transportation. It involves 16 partners representing six European member states. LAPCAT II is a follow-up of the previous LAPCAT I program intended to reduce the duration of antipodal flights (flights between two diametrically opposite points on the Earth) to less than two to four hours.

The Mach 5 aircraft will be powered by a pre-cooled turbo-ramjet developed in LAPCAT I. Why pre-cooling is needed for the air-breathing engine? At Mach 5, the stagnation temperature of air approaches 1320 K; this condition is impractical at the inlet to compress the air due to the amount of work required, and because the resulting compressor delivery temperature would be too high.

Artistic Rendition of the Mach 5 LAPCAT A2 concept on the runway.

The design of the Scimitar engine incorporates a high bypass fan into the bypass duct, which encloses the core engine. This is needed to match the intake air capture flow to the engine demanded flow over the supersonic Mach number range. A hub turbine drives the bypass fan, using flow diverted from the core engine nozzle. The flow then discharges into the bypass and mixes with the bypass flow.

The most important technologies that must be matured for the Scimitar engine are the heat exchanger and the contra-rotating turbine, which must operate for extended periods of time, reliably and at the conditions from take-off to cruise and acceleration/deceleration. According to reports from the program, the Scimitar power cycle depends on maintaining a constant top-cycle helium temperature at around 1000 K. A pre-burner is required to heat the helium leaving the pre-cooler during the low flight regime when the enthalpy of the captured air, and therefore the helium temperature, would be low. Advanced materials are thus required for the heat exchanger that can cope with the high temperature part of the engine cycle.

Three years ago, the LAPCAT team determined the feasibility of a Mach 8 aircraft propelled by a scramjet engine. The team concluded that the fuel consumption during acceleration would require a large fuel fraction, and of course this would adversely affect the aircraft's gross take-off weight. They also considered a first stage rocket ejector concept, but predictions indicated that such propulsion system would give low range and large take-off mass. Clearly, for a civil transport, the integrated airframe-engine design should be one that optimizes range, cruise time, and fuel consumption.

Recent reports from the LAPCAT team addressed wind tunnel testing with a 1:120 scale model at Mach 8 speeds. The results were encouraging, as the test model could generate a positive thrust. The European team also reported on hydrogen fuel consumption measurements and aerodynamic heating. Again, acceleration and deceleration at hypersonic speeds are crucial for feasibility of civil transports. These two phases of flight are much more dominant in the propulsion optimization process due to the longer speed-up and slow-down phases, and to the relatively shorter cruise phase. Hypersonic flight optimization requires further work.

There are a number of other issues related to hypersonic flight such as aerodynamic heating, environmental effects, and sonic boom that must be properly resolved. To deal with aerodynamic heating, for example, the LAPCAT aircraft will incorporate ceramic panels and other advance materials. The European team has also stated that hydrogen-fuelled airliners would not emit greenhouse-increasing gases such as carbon dioxide, sulphur oxides or soot like today's subsonic airplanes. However, water vapour produced by hydrogen combustion stays in the stratosphere for a long time, and could be a contributing factor to global warming. This is an issue taken very seriously by the European researchers. The LAPCAT-II program plans for their Mach 8 airliner to fly well above 33 km, expecting that this will minimize the environmental impact. They also consider the use of an alternative fuel such as super-cold liquid methane. When stored as a liquid, it needs far less space than gaseous methane, and thus it would streamline the design of the hypersonic aircraft.

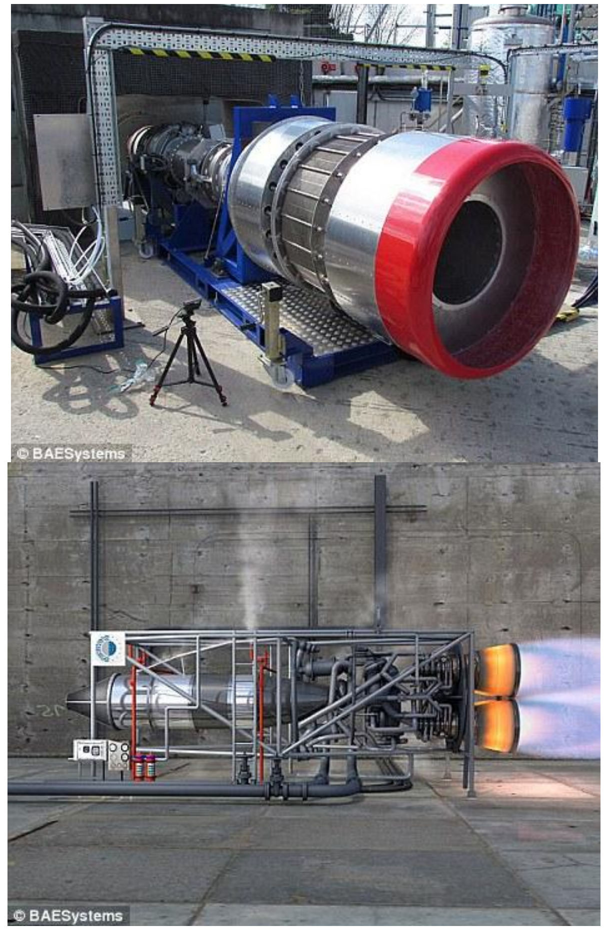
Regarding sonic boom, the European hypersonic aircraft would fly over the North Pole and cross the Bering Strait, avoiding populated land. I also know that NASA is currently working with Lockheed Martin and Boeing to design airplanes that break the sound barrier more quietly. And so I believe that with those improved designs, it is possible that future hypersonic airplanes could then exceed the sound barrier over populated land without causing major disturbances.

In Japan, its Exploration Space Agency JAXA continues working on **Hytex**, a **Mach 5 hypersonic airliner** propelled by a pre-cooled turbojet engine (PCTJ) that uses hydrogen both as coolant for the pre-cooler and as fuel in the combustor. The PCTJ, which has already been demonstrated with ground experiments and a flight experiment up to Mach 1.8, is designed to operate from take-off to Mach 5 continuously. Presently, JAXA is planning a Mach 5 flight demonstration using the hypersonic technology experimental aircraft (HYTEX). I look forward to obtaining their latest results at the upcoming Hypersonics 2017 conference in China. Meanwhile Airbus announced this year that it has patented a delta wing Mach 4.5 hypersonic aircraft concept that could be used to design future business jets.

Propulsion for Access to Space

For space applications, the most prominent effort is the development of reusable launch technology, including the **Skylon single stage to orbit vehicle** developed in England, and Australia's **Spartan launch system**.

In July 2016, Reaction Engines, Ltd. (REL) announced that it secured over $66 million in funding from the British government, and more than $55 million from the UK Space Agency, to continue developing the SABRE air-breathing rocket to power the Skylon spaceplane. The unique Sabre propulsion system is designed to allow Skylon to take off from a runway and accelerate to five times the speed of sound, before switching to a rocket mode, propelling the spaceplane into orbit. REL's launch system has the potential to put satellites into orbit at a fraction of the current cost.



REL's revolutionary Sabre engine could allow a spaceplane to take off from a runway and accelerate to Mach 5, before switching to a rocket mode, propelling it into orbit. An engine with pre-cooler is pictured above at the test area. Photograph: BAESystems.

The air-breathing Sabre rocket is unique. Consider this: atmospheric air must be compressed to about 140 atm before injecting it into the combustion chamber. Such compression raises the air temperature so high that it would melt the material walls. Sabre avoids this issue by first cooling the air to −150 °C (−238 °F), using a pre-cooler heat exchanger, until air is almost a liquid. Then a conventional turbo compressor compresses the air to the required pressure. The development effort in the past few years has concentrated in maturing the pre-cooler heat exchanger.

Researchers in Australia are working on the **multi-stage Spartan launch system**, which they believe could radically reduce the costs of placing satellites into Earth orbit. According to Michael Smart, professor of hypersonics at the University of Queensland in Brisbane, on the launch pad Spartan will look and launch like a conventional rocket vehicle, and it will be launched with a rocket booster. Once it reaches hypersonic speeds, however, the first stage will drop away and "the scramjet will unfurl its wings to blast the spacecraft into the upper atmosphere. When it runs out of air, the scramjet will separate and a small conventional rocket will carry the satellite into space."

Australia's space launch system. Credit: University of Queensland.

What makes the Spartan concept more attractive is the reusability of the first two stages. Once completing their operation, both the scramjet stage and the rocket booster will fly back to a runway landing by deploying aerodynamic wings and a small propeller. Only the final third rocket stage of the launch vehicle will burn up in the atmosphere after releasing its payload into orbit.

Another interesting hypersonic technology development is the spaceplane concept by China Aerospace Science and Technology Corporation (CASTC). Although no details of the hypersonic propulsion system have been made public, I assume the engine will be a combined cycle concept since, according to public reports, the vehicle would take off from a runway like an aircraft, and for the hypersonic velocity range, it would use a scramjet engine, which will propel the vehicle to almost 100 km above sea level. Rocket boosters will then provide the additional thrust, giving the Chinese spaceplane enough power to reach low Earth orbit.

Supersonic Civil Transports

In mid-November, Boom Technology showcased its future **supersonic passenger jet**, which is expected to achieve top cruise speeds of Mach 2.2. The company's CEO Blake Scholl made the announcement. He unveiled the XB-1 Supersonic Demonstrator, a 1/3-scale version of the Boom supersonic aircraft, stating that the airliner will be ready by 2023.

No propulsion system has been selected for the full-scale Boom plane. However, three General Electric J85-21 turbojet engines will power the 68-ft long **XB-1 demonstrator**. The J85 is a small single-shaft afterburning turbojet engine that has a military version delivering up to 2,950 lbf (13.1 kN) of thrust dry. With the afterburner on, it can deliver up to 5,000 lbf (22 kN). However, it is very likely that the three engines in the full-scale Boom airliner will not have afterburners.

The full-scale airliner will be 170 feet long and have a wingspan of 60 feet. It is expected to carry 45 to 55 passengers, and have a maximum range of 9,000 nm (4,500 nm unrefueled). To address the sonic boom problem, the aircraft will only fly at top speeds over-water, unless flying in a supersonic corridor.

Artistic rendition of Boom Technology's prototype SST. Image: Boom Technology.

U.S. Activities on Hypersonics

Let us close this review with developments in the U.S. The Hypersonic Combined Test Force at Edwards AFB is also working at developing flight-testing technology to support the HAWC program. The driving requirement is the long distance test flight profiles of the hypersonic vehicle that will also require range assets able to deliver telemetry data across long ranges.

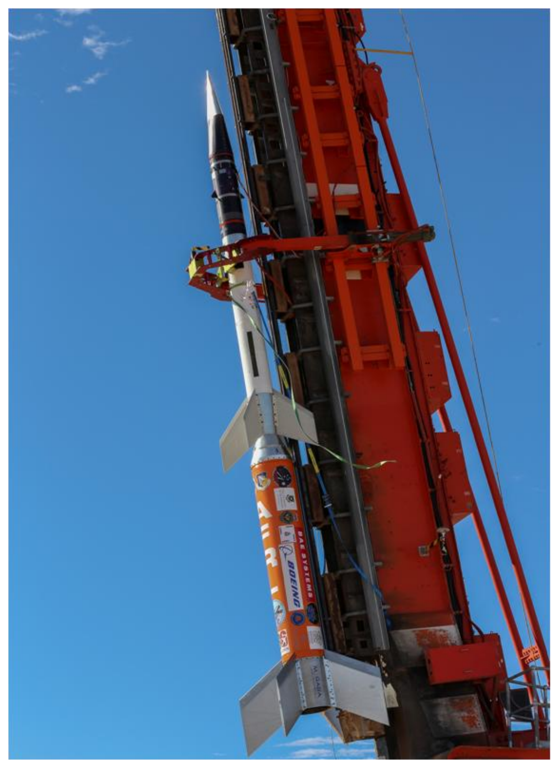
In February, researchers at NASA Glenn Research Center (GRC) and AFRL completed phase 3B testing of the **Combined Cycle Engine-Large Scale Inlet Mode Transition Experiment (CCE-LIMX)** to characterize mode transitions at speeds less than Mach 3.5. They validated autonomous mode transition control laws/algorithms to enable smooth and stable inlet operation. The NASA/AFRL team investigated distortion mitigation strategies during mode transition.

In July, a task order was issued by NASA for the Preparation to Integrate the WJ38-15 Turbine Engine with CCE-LIMX. This task has the objective to demonstrate/validate mode transition sequences and inlet operation strategies to insure their compatibility with the Williams International's WJ38-15 turbine engine, and to develop corresponding engine control sequences. Phase 3C of the CCE-LIMX is underway with the main goal of reducing risks in Phase 4 testing, which is scheduled for 2018.

NASA Langley Research Center (LaRC) continued work to develop numerical methods, ground testing, and systems analysis to support the advancing of hypersonic propulsion technologies. The team is formulating the new Hypersonic Technologies Project (HTP), which is scheduled for FY17. To advance modeling and simulation of hypersonic aerodynamics, LaRC researchers added hybrid structured-unstructured grid capabilities to the VULCAN-CFD code. The LaRC team also began experiments on the Enhanced Injection and Mixing Project (EIMP) in the Arc-Heated Scramjet Test Facility (AHSTF) to better understand the physics of injection, and to develop mixing enhancement strategies.

Arnold Engineering Development Complex (AEDC) is modifying its Aerodynamic and Propulsion Test Unit (APTU) in preparation for the first direct-connect tests of larger scale scramjet engines. Once upgraded, the facility will be capable of supporting AFRL's Medium Scale Critical Components (MSCC) direct-connect test program. The engines tested will have 10-times the airflow rate of an X-51A Waverider.

In May, a successful test brought the **Hypersonic Flight Research (HIFiRE)** experimental vehicle to an altitude of 172 miles, reaching a maximum speed of Mach 7.5. Identified as HIFiRE 5B, this test was used to measure heat on the outside of the vehicle in hypersonic flight. After the successful flight test, Douglas Dolvin from the High Speed Systems Division at the U.S. Air Force Research Laboratory (AFRL) addressed the status of the HIFiRE Program and reviewed plans for 2017. He reported on previous flights, and completion of the Flight Vehicle CDR for Flight 8.



HIFiRE 5B Vehicle ready to launch. Image: University of Queensland (Australia)

The first HIFiRE test was conducted in 2009, and it was planned then to complete the project in 2018. The next HIFiRE test is Flight

4, which will be launched from Woomera Test Range in South Australia in March 2017. The objective of HIFiRE 4 is to evaluate multiple control strategies for hypersonic reentry and cruise of shock-on-lip waverider design. The test will involve the scramjet engine separating from the rocket booster and flying on its own. The HIFiRE Program includes researchers from University of Queensland, the Australian Defence Science and Technology Group, the U.S. Air Force Research Laboratory, and Boeing.

Based on those developments and many more highly guarded industry-government programs related to high-speed propulsion technologies, I am convinced that the future of hypersonic flight is assured.

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