SCRAMJET: ISRO'S FUTURISTIC TECHNOLOGY TO REDUCE COSTS OF SPACE TRAVEL

What are Scramjet engines? How are they different from conventional one time use-and-throw rocket launch vehicles? This article introduces readers to this new technology, exploring its use in providing low cost space launch in low earth orbits.

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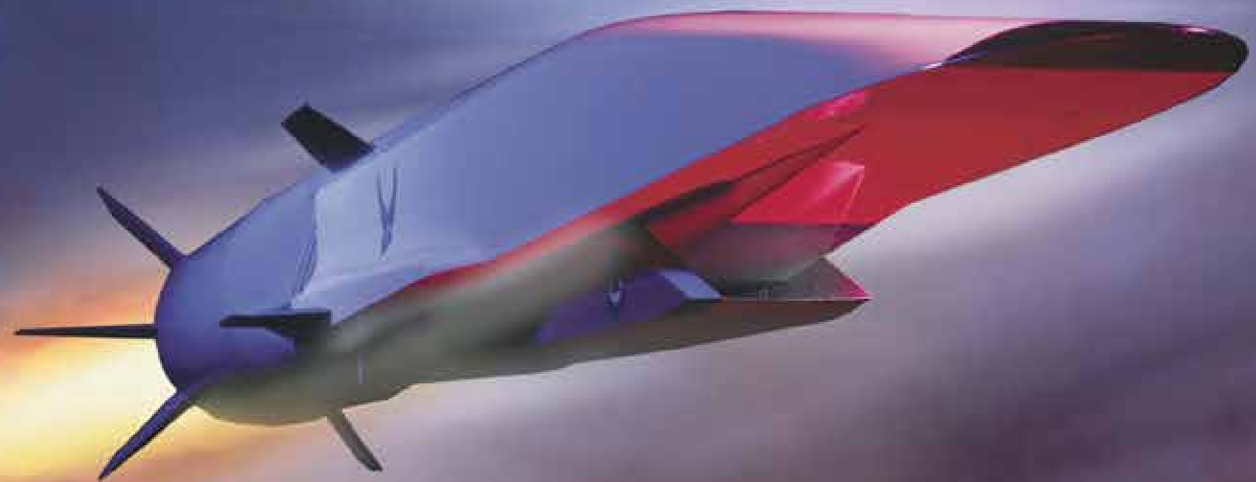

On 28th August, 2016, the Indian Space Research Organisation (ISRO) successfully demonstrated its indigenously produced Dual Mode Ramjet (DMRJ) ScramJet engines in-flight. India now belongs to an elite club – with USA, Russia and Europe – leading the quest to design reliable, safe, affordable and reusable space launch vehicles to place space assets, like satellites, in a low earth orbit.

Box 1. What is a low earth orbit?

Most communication satellites are placed in what is known as the Geosynchronous Orbit (GSO), about 36,000 km above the surface of the Earth. A satellite at that height would take approximately 23 hours 56 minutes and 4 seconds to complete one revolution around the Earth, matching the Earth's sidereal rotation period.

In contrast, the Global Positioning System (GPS), Russian Glonass and a few other space environment research satellites are placed in what is called the Medium Earth Orbit (MEO), about 1200 – 35790 km from the surface of Earth. The orbital periods of MEO satellites range from about 2 to nearly 24 hours.

However, if you wanted to build a space station and ship people to and fro, you'd prefer its location to be much nearer to the Earth. This would also be true for a remote sensing satellite, if you were planning to use it to take close-up pictures of the Earth's surface. Thus satellites such as these are typically placed in what is called the Low Earth Orbit (LEO), which is about 200 – 1200 km from the surface of Earth. These satellites take about 80 to 130 minutes to go around Earth once.

Limitations of current technology

Current launch vehicles are mainly multi-stage, expendable, and carry oxidiser, making them costly, risky and bulky.

About 85-90% of rocket mass before lift-off is propellant, and only about 1% is the mass of the satellite that orbits the earth. The rest, which includes the supporting structure, tanks, pumps, engines etc. are useless once the fuel is burnt. To avoid having to carry all that excess weight into space, rockets often have several stages, or sections, each of which drops away after use. Typically, once the fuel in one stage-section is consumed, that stage of the rocket, its shell and motors are jettisoned into the ocean.

As each stage burns out, it has to be de-coupled from the vehicle, and the next stage has to ignite. This must occur with each stage, in sequence, without fail or delay, making current technology both expensive and risky. The greater the number of stages, the higher the chances of failure – even a tiny lag or mishap in this sequence can spell disaster. The accident, in Jan 1986, on NASA's space shuttle – Challenger – that killed seven astronauts and shocked the world, was caused because the rubber-O-rings joining two stages failed to seal properly.

Except during its final stages, when a rocket travels to the edge of Earth's atmosphere, it is surrounded by abundant oxygen. In spite of this, many rockets carry both their own fuel and an oxidiser for burning it. This makes their design bulky and inefficient, with more than half of the thrust generated by the rocket going into lifting the oxidiser.

If we could build a launch vehicle with a re-usable engine that could somehow use atmospheric oxygen, at least during most of its flight inside the Earth's dense atmosphere – the cost of space travel would be reduced considerably. Little wonder then, that space-faring nations around the world are in quest of such a technology.

What is a dual mode Ramjet-Scramjet engine?

An ordinary jet engine works on the same principle as a rocket – with two important exceptions. Jet engines are re-usable, and use atmospheric oxygen to burn fuel.

The design of a jet engine is quite simple. Atmospheric air, rich in oxygen, is compressed by rotary blades and brought to the combustion chamber. Fuel is injected into the hot compressed air to make it burn, causing the whole mixture to expand considerably. This gas comes out of the exhaust nozzle at high speed, generating thrust (based on Newton's third law) that pushes the jet upward.

Ramjet and scramjet are advanced models of jet engines that can be used for space travel. The fastest jet plane can cruise at speeds of about 0.8 km per second, while space travel requires one to achieve speeds of 8 km per second. Jet engines that can provide such an impulse are called ramjets. In other words, ramjets are more advanced air-breathing engines that do not need rotary blades to ingest compressed air into the combustion chamber. Instead, compressed air is sucked in through specially designed inlets, even as the vehicle moves at supersonic speeds. A scramjet, or a "supersonic combusting ramjet", is an improved novel variant of velocity required to compress air, their scramjet/ramjet engines can be ignited. This ignition is quite tricky – it must

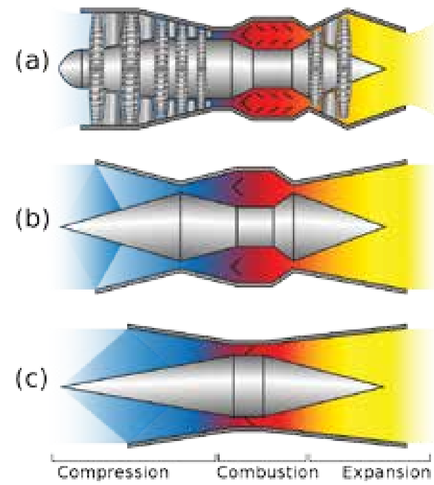

Fig. 2. Ramjet and scramjet are two types of advanced jet engines. Unlike a jet engine, ramJets and scramJets have no movable parts and, hence, are safe. All three types of jet engines use atmospheric oxygen for combustion.

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a ramjet that uses the same principle, but operates optimally at hypersonic speeds.

The challenge of a scramjet!

Although the design of a scramjet seems pretty simple, operationalizing it is difficult and technologically demanding.

In the absence of rotary blades to compress the air, both ramjet and scramjet engines use their relative velocity to compress the air entering through their inlets. On ground, the air entering the inlets will not have any appreciable relative velocity. Therefore, much like the way we start the engine of a car whose battery is down by giving it a push, we use conventional rockets to propel scramjet/ramjet crafts into space. These rockets help the crafts quickly achieve an initial velocity greater than Mach 4. Once they reach the relative

Fig. 1. Launch of the ScramJet engine

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occur within the next few milliseconds. Given the riotous flow of air into the combustion chamber of a spacecraft moving at a velocity of Mach 5 or 6, experts liken this ignition to lighting a matchstick in the midst of a hurricane.

Even if the mixture can be ignited, sustaining the flame for the duration of time taken to burn the fuel is an arduous task – almost like holding a lighted candle in your hand while running at top speed!

This is not all. As a scramjet moves through the atmosphere at hypersonic speeds, the relative velocity of the air is high enough to interfere with its ability to continue ingesting air. Imagine putting your face through a fast moving bus window –the gush of wind blowing across your nose will leave you breathless. The design of the scramjet has to ensure that the inlets continue to suck in air, even at such velocities.

These challenges were addressed by developing, testing and perfecting the design of ramjet-scramjet engines stage-by-stage. ISRO chose to use its time-tested, indigenously designed, three tonne Rohini class rockets RH 560 for the initial propulsion. First tested in March 2010, and designated ATV-D01, this rocket maintained a Mach 6 velocity for seven seconds. While this analysis was conducted with scramjet modules strapped on to the rocket, these modules were not ignited. The test showed that Rohini class rockets could provide the dynamic pressure of around 80 kilopascals required to initiate ignition of ramjet/scramjet engines. Then, in the wee hours of 28th August 2016, two indigenously built dual mode ramjet-scramjet engines were strapped on to the Rohini class two-stage RH-560 rocket, along with a solid booster. Once the rocket attained an altitude of 20 km, the scramjet engines were ignited, and the flame sustained for five seconds. A preliminary examination of the test showed that the propulsion system maintained the desired flight condition, both in terms of Mach number (6+0.5) and dynamic pressure (80+35kPa). Also, as planned, the burn out of booster rocket stage and activation of scramjet engines took 5 seconds, occurring between the 55th-60th seconds of flight and at 20 km height. This was followed by a burn out of the second stage. Together, these imply that ISRO's dual mode ramjet-scramjet engines can be expected to function well in flight mode.

Box 2. Mach number

Mach number is defined as the ratio of the speed of a body to the speed of sound in the surrounding medium. It is often used with a numeral (as Mach 1, Mach 2, etc.) to indicate the speed of sound, twice the speed of sound, etc.

Supersonic speed is a rate of travel of an object that exceeds the speed of sound (Mach 1).

Hypersonic speed is highly supersonic – since the 1970s, this term has generally been assumed to refer to speeds of Mach 5 and above.

What lies ahead?

Although this test has been successful, we have miles to go before these ScramJet engines are used to carry payloads to space.

Some key challenges facing ISRO include the design and development of a supersonic combustor, computational tools to simulate hypersonic flow, and new materials capable of withstanding the huge oscillations and the very high temperatures likely to happen at higher speeds. Others involve ensuring hypersonic engine air intake, performance and operability of the engine across a wide range of flight speeds, proper thermal management, and ground testing of the engines. For example, while analysis of the current test was done only at about Mach 6 speed, the engine needs to be tested at various speeds between Mach 2-12. Also, with computational fluid dynamic tools having matured only recently, improvements in the design of scramjets have to be tested by trial-and-error. This is complicated by the fact that other countries are unwilling to share their technical knowledge of scramjets, as it is thought of as strategic technology. This means that ISRO has to embark upon an indigenous programme to develop its own reusable launch vehicle.

An ISRO project called AVATAR is aimed at developing a rocket to launch the scramjet engine into space. This rocket should be able to lift off vertically from a launch pad (with the assistance of conventional chemical booster rockets), soar at supersonic speeds, initiate a scramjet engine and propel it to low earth orbits to deliver space

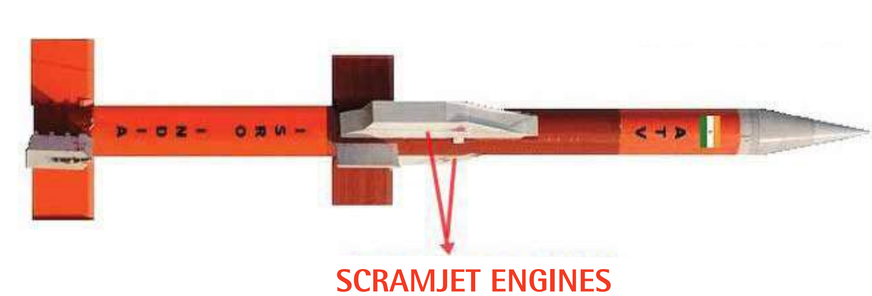

Fig. 3. Two ScrameJet engines were strapped to Rohini Class rockets and test fired by ISRO.

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payloads, and then land on a runway like an ordinary plane. The estimated development cost of this entire project is 35 cores, of which about three cores were spent on the test conducted in August 2016.

While ISRO aims to use a single-stage-to-orbit (SSTO) launch vehicle ultimately, it is settling for a two-stages-to-orbit (TSTO) launcher in the interim, with an air-breathing first stage. In the second stage, a cryogenic motor will be used to take the payload to the desired low earth orbits. ISRO proposes to make the first stage of the TSTO re-usable, halving the costs of launching satellites.

On 23rd May 2016, ISRO conducted a Hypersonic Flight Experiment or HEX1 in which the performance of a Reusable Launch Vehicle (RLV), dubbed 'Swadeshi space shuttle', was experimentally launched, and the performance of guiding computers on-board and heat-resistant tiles affixed to the RLV were tested. At the end of the test-flight, the spaceship splashed down into the Bay of Bengal. In the next experiment, named landing experiment (LEX), ISRO will attempt to land an RLV on a custom runway, to be constructed at SHAR (Sriharikota High Altitude Range). Thereafter, RLV and Rohini-Scramjet modules will be integrated into a single mission, and actively powered by the scramjet engines for Return Flight Experiment (REX)s. For propulsion beyond the atmosphere, the RLV will be fitted with five semi-cryogenic engines. It is only after all these different stages have been tested and integrated flawlessly that the system will be used for commercial launch. Estimates by ISRO indicate we will be ready for space missions using a TSTO launch vehicle with scramjet engines, around the year 2030.

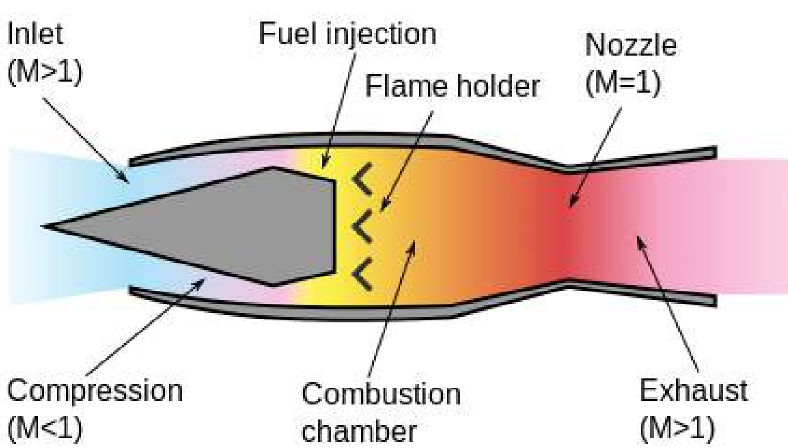

Fig. 4. Ignition, sustaining the flame, and ensuring compressed air inflow are some of the major technological challenges of ScramJet design.

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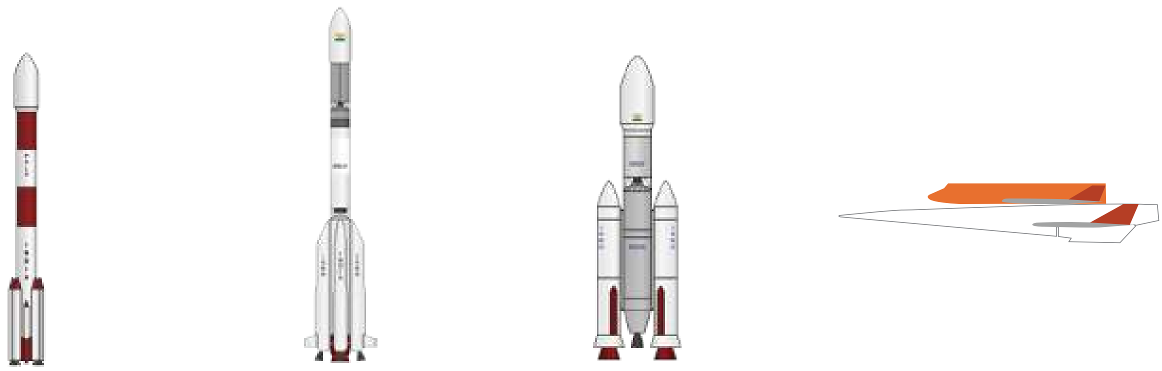
Box 3. Cryogenic Rocket Engines

A cryogenic rocket engine is one that uses a cryogenic fuel or oxidizer, that is, its fuel and/or oxidizer are liquefied gases stored at very low temperatures.

A scramjet-fired RLV can take a payload of about 10,000 – 20,000 kg to low earth orbit; while the most advanced conventional ISRO launch vehicle GSLV Mk-III is designed to take only 8,000 kg, and SpaceX's rival Falcon 9 rocket is expected to lift 13,000 kg to the same orbit. These futuristic re-usable launch vehicles, with their air-breathing propulsion will enable cost-efficient space launch. While the launch of one kg of payload currently costs about US$ 5000; ISRO estimates that its RLV will cause a drop in rates to US$ 2000 per kg.

However, some experts question ISRO's elation, and claim that the cost-benefit analysis is not that clear. A 2006 NASA technical document warns that "The general conception is that the choice between a reusable and an expendable launch vehicle is essentially a trade-off between lower recurring costs of the former and lower non-recurring costs of the latter". On average, the reliability of throwaway launchers is about 95% – which means that on average, 1 in every 20 launches fails. However, the reusable launcher has to be fail-safe if it has to justify the higher investment needed to develop and build it. Also, as the RLV will take-off, cross into space and re-enter the Earth's atmosphere many times, it will require advanced heat shields – making the project technologically more challenging. The NASA document goes on to assert that a "decades-long debate over reusable launch vehicles (RLVs) versus expendable launch vehicles (ELVs) has been less a reasoned debate than a sustained argument for the building of reusable launchers instead of the standard throwaway rockets."

The economics of developing reusable hybrid vehicles that use expendable boosters and a reusable vehicle, like the one proposed by ISRO, is rather different. A.S. Kiran, the ISRO chief, remains optimistic, stating that, "in principle, even if the cost comes down by 50%, it is worth it. After factoring in the logistics of recovering it, etc., whatever it can bring down is worth it."



PSLV	GSLV	GSLV MK3	ABLV-TSTO (FULLY REUSABLE)
TIME FRAME	TODAY	10 YEARS	40-50 YEARS
LAUNCH COST	20,0000 $/kg	5,000 $/kg	500 $/kg
FLIGHTS/YEAR	4-6	20-30	300
TURN AROUND TIME	FEW MONTHS	FEW WEEKS	FEW DAYS
.... UP TO 2010 + ...		2010 +	2040/50

Fig. 5. The Scramjet engine is a worthy addition to ISRO's slew of existing launch vehicles.

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