Propulsion System for Low Cost Approach to Space

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Abstract

This paper argues for a single stage to orbit (SSTO) vehicle based on air-breathing engines in the atmospheric regime of flight and rocket engines for trans-atmospheric flight to low earth orbit (200 km) for reducing the cost of payload delivery. Consistent with some earlier thoughts, it is suggested that the only route available to reduce the costs of space transportation is to handle space transportation much like aircraft fleet operations - take off from an airstrip like an aircraft, reach the useful end of the atmospheric flight at about 25 km with minimum fuel consumption in air-breathing engines, both turbofan and ramjet and use rocket for space journey to LEO, the rocket itself must be the most safe and user-friendly with a little demand for detailed checkout. It is suggested that this can be based on a hybrid rocket to meet the just mentioned objective of safe operation and low costs of propellants which will become the driving factor for reducing the cost of operation. It is suggested that the current cost of payload delivery to low earth orbit (LEO) from rocket engine based vehicles, typically around 6500 to 10000 US $/kg, should be capable of being reduced by a factor of 50 to 100, this value depending on the amount of use that the vehicle will be subjected to. It is also suggested that these concepts will become the reality of the future and those who concretize them first stand to gain more than the others.

1. Background

To appreciate the importance of attempting to look for newer approaches, it is useful to briefly examine the developments that have taken place in the field of aerospace. It is the work of Wright brothers which led to the exploration of the environment near the earth. The ninety years that have gone by have caused a revolution in the life of the inhabitants on earth. Travel around the world needing months together (eighty days, according to Jules Verne!) can be accomplished in just 24 hours. Till the forties, the speed limit was less than of sound. Research into transonic flow problems and shooting past them (literally) led to exploration of supersonic flight regime. Flight speeds nearly six times that of sound (X15 aircraft) and operational altitudes as high as 20 km that have been achieved with aircraft (SR71). Very efficient air-breathing engine based subsonic passenger transport has been achieved and has created the most extensive world transportation system today.

Reaching for the outer space was begun in the mid-fifties based on the German work during the Second World War and has incessantly been pursued towards several valuable societal goals of global communication, natural resources assessment and television apart from military applications over the last forty years or more.

Both in the case of aircrafts and rocket launch vehicles, military applications have spurred significant developments and honed the aerospace technology in immeasurable ways.

Both these areas have grown in their own ways with weak points of interaction along-way. Both the areas have reached virtual saturation in terms of performance and single engines of very high thrust/power have been built. The recently built GE-90, P & W PW 4000 and RR Trent 800 class air breathing engines on a single engine basis produce 0.4 to 0.45 MN thrust and the SSME liquid rocket engine produces 1.6 MN thrust. All these are high pressure engines and exhibit a high level of performance. Many other interesting ideas in both air-breathing and rocket engines are being thought of and development pursued but the benefits are likely to be incremental and the cost-to benefit ratio not small at all. Societal emphasis has undergone change. Man-to-the-moon galvanized the entire American nation in the sixties. New York-to-Tokyo-in two-and-a-half-hours did very little to stir the imagination of the same nation in the late eighties. Priorities changed from imaginative goals to the more mundane economic issues.

In India, investments into space activities were a subject of hot debate in the sixties and the seventies. In the eighties, they were taken for granted and demands on the services from this sector for various social needs have been and are being made continuously. However, financial limitations still turn out to be a constraint.

The most major development in the access to space started in the seventies consists of the space shuttle system aimed at increasing the reusability of as many elements of the total system as possible. While the vehicle and its performance are commendable, one of the aims left unfulfilled is the extent of reusability (and therefore the number of launches per year which is much smaller than expected).

It is in this light that one should view the possible new developments to be worked on in the coming decade.

2. The primary issues

It is necessary to first understand what the current costs of putting a vehicle into space are. An ARIANE 44 L vehicle launch to geo-stationary orbit costs about 120 million US $ for a payload of 4.5 tonnes. This performance can be translated to a low earth orbit (200 km circular) into a payload of 9.5 tonnes. Thus the cost of placing a payload into a 200 km circular orbit is 12,600 US $/kg. The costs for a DELTA vehicle launch work out at 10000 US $/kg a value comparable to the ARIANE launch. Correspondingly, Indian PSLV vehicle can place one tonne payload into a 1000 km circular orbit at 750 million Rs. Translated to 200 km orbit, the payload capability is about 3.5 tonnes. This implies that the cost of placing a payload into 200 km circular orbit is 6000 US $/kg. These values are indeed smaller than values for other vehicles in the free world.

We should next look at the payload fractions. The launch vehicle mass for putting a certain amount of payload is an important parameter describing the efficiency of the launch vehicle. The launch vehicle masses for ARIANE, DELTA 7920 and PSLV are 470, 230 and 280 tonnes. Thus the payload fractions for launch into 200 km circular orbit are 2.0, 2.2 and 1.25 % for the three vehicles. From this, it appears that there is a possibility to increase the payload capability of PSLV substantially. A weight analysis of the different elements of the vehicle and the contemporary vehicles of the day shows that the first stage inert weight can be reduced to a certain extent. It also appears that the cost of realization can also be brought down by another 15 % compared to the current cost of the vehicle if the currently available technologies like cryo-engines are also deployed in the vehicle. The basis of the last statement is that one obtains a substantially higher efficiency in terms of realized specific impulse in the upper stage, a feature which contributes to payload enhancement more significantly than the improvement in the lower stages.

In the case of Space Shuttle, a vehicle designed in the early seventies with the idea of lowering the cost of space transportation by using the idea of reusability of components, the cost of delivering a payload into 200 km circular orbit is again about 10,000 US $/kg payload. Thus the aim of reducing the cost of access to space was not achieved despite the fact that many elements of the system are technological marvels in the contemporary engineering practice, particularly, the liquid engine. The launch campaign for the flights is much like expendable vehicles each time. The extent of reusability of components became much more than originally anticipated largely due to refurbishment time and cost. Thus there has been a wide spread feeling that reusability in the rocket engine mode has not been established adequately.

Even though there is no universal acceptance of the modes of achieving reusability, it is understood that the important way by which costs of access to space can be reduced is to use concepts in air breathing engines. A point stressed on reusability by Heald (1995) very succinctly and effectively is that "such concepts should use a new attitude which believes that good flight data precludes complex flight check-out before the next flight." If we analyze the cost break-up of PSLV, of the total cost of launch amounting to Rs. 65 crores, the cost of integration is about 9 crores and that of launch campaign 6 crores. These together amounts to 25 % of the launch cost. In a typical air fleet operation, the cost of "integration and flight preparation" is about 2 to 5 % because the number of flights is very large compared to satellite/missile launches (typical ratio is 106 to 108 world over). Other costs including hardware and fabrication (Rs. 24 crores), and electronics (Rs. 12 crores) constitute 60 % of the launch vehicle cost lends itself for a reduction by 10-15 % when the mode of fabrication is made into manufacture at reasonable numbers and some issues of more efficient design are implemented. The cost of the propellants whether it is high energy solid (AP-HTPB based) or storable liquids is about 550 to 650 Rs/kg. The total cost of propellants for PSLV is Rs. 10-12 crores (15-18 % of the launch vehicle cost). All the propellants used belong to the high cost category. The only solids and liquids which qualify for low cost are polymeric fuels based on rubbers, kerosene and liquid oxygen. These can be taken to cost about 5 to 10 % of the cost of the presently used propellants. The two reasons why the cost of the propellants becomes important are that (a) if the concepts of reliability need to dispense with large integration and launch campaign costs for each flight and also cut down on the vehicle realization costs by larger volume manufacture with appropriate redesign, the costs of propellant turn out to be a significant fraction of the total launch costs (about 30 to 40 %), and (b) the only non-reusable component of the vehicle, even in air-breathing engine based fleet is the propellant.

Thus it appears that one needs to integrate air-breathing engines to the extent possible for flights within atmosphere, and use rocket engines which are SAFE, CHEAP and RELIABLE for trans-atmospheric flights in an SSTO mode. The reason for thinking of air-breathing engines in terms of reliability and the absence of long flight readiness check is due to the well known fact that even international flights with stop-overs will need to stay on ground for no more than an hour before take-off and this period is used more for ground operations unconnected with the flight readiness. On these matters there is not only technical appreciation and approval, but public acceptability as well. A technical point in support of the use of air breathing engines is that they leave behind exhaust at lower velocities than in the case of rockets. Therefore they provide fuel efficiency of a high order. While one conceives a booster rocket with a specific impulse of 2900 N.s/kg, the lowest achievable specific impulse with a turbo-jet in a partial after-burning mode is 30,000 N.s/kg nearly ten times as large as for a rocket. If one uses a turbofan with a bypass ratio of 0.5, say one can increase the specific impulse to 40,000 N.s/kg. Thus there is significant potential to increase the performance of the total vehicle with the use of air-breathing engines.

3. What is therefore the strategy?

It has been suggested that a 200 km circular low earth orbit is an appropriate target for a trans-atmospheric mission. Such a mission could be for the purposes of space tourism, and/or delivering satellite payloads for civilian or military applications. An average round the world trip will cost about 2500 US $/person. Translated to units of mass, one could view this as transportation of 120 kg and therefore, the cost of air transportation is about 20 US $/kg payload. One can conceive that an average tourist will undertake a journey twice an year and this translates to transportation costs of 400 US $/kg. Because of the specialty of space journey, it may possible to set the demands of a reliable flight to space at 80-100 $/kg (10000 US $/person on an average) payload and perhaps, double this value at least in the early stages of the operation. This implies the need to reduce the current costs by a factor of fifty to hundred, something which calls for drastically different approaches, and may be possible only if we recognize that the use of reusability nearly completely is the "mantra" for reducing the costs.

The flight to 200 km altitude has three segments. The first segment is from ground to an altitude of 10 to 15 km and the Mach number achieved being 2 to 2.5. This can be accomplished by using a turbojet/low bypass turbofan. The suggestion of low bypass turbo-fan arises from the need to have a high thrust to unit total mass flow rate, a parameter indicating the compactness of the propulsion unit. If one looks for the current experience in this segment, the Anglo-French Concorde and the Russian Tupolev constitute commercially tested and operating systems. Though more expensive than the high subsonic large transport carriers, they are still used by business community who intend reducing the time of travel. The atmospheric segment of the flight can be extended upto an altitude of 30 km involving high speeds - Mach 5. This can be handled by using ramjets which are known to be efficient in this Mach number range and arranged to take over from turbojets because of the high stagnation pressures (at these Mach numbers) recovered from appropriately designed air inlets. It must also be stressed that this propulsion unit is perhaps one of the simplest to design and realise in comparison to other air-breathing engines. Both these propulsion units are reusable and the turbojet/turbofan can also be used in the landing segment, permitting the vehicle to in an autonomous mode during the entire flight.

The remaining segment of the flight - from 30 km to 200 km is to be accomplished using a rocket engine. The possible propellant combinations are LOX/Kerosene, LOX/LH2, and LOX/Rubber systems. The first two are semi-cryogenics and full cryogenic liquid systems and the third, a hybrid rocket system. LOX/Kerosene system qualifies on the ground of being cheap and can use kerosene from a single source in the vehicle with LOX being loaded separately. LOX/LH2 system qualifies on the grounds of being very efficient (Specific Impulse), clean exhaust without problems of nitrogenous or chlorine compounds both of which are considered undesirable for the Ozone layer in the stratosphere. LOX/Rubber system is a cheap system both from the point of view of cost of propellants and development. Also it will qualify perhaps as the best in terms of safety considerations. Handling LOX in an airport like environment needs care not practiced till now. Since India does not currently have either the semi-cryogenic or full cryogenic engines needed for such applications off-the-shelf and therefore need independent development, it may be just as well that all the knowledge base in the country can be deployed in a fast development of high thrust hybrid propulsion systems. Such a path will be new in comparison to any contemplated elsewhere till now and will therefore provide a leading edge in space development efforts.

4. Features of aircraft and space vehicles

Typical payload ratio (payload to take-off mass) is about 19 to 23 % for heavy long distance passenger transport and 28 to 30 % for heavy cargo transport. The difference, of 7 to 9 % is the typical overhead on auxiliaries required for passenger seating and comfort. The average payload density for passenger aircraft is about 35 to 50 kg/m^3 and for cargo aircraft is 150 to 200 kg/m^3.

For supersonic transport, the payload ratio is 6 to 7 % (Concorde aircraft weighing 185 tonnes carries 11.3 tonnes of useful payload and Tupolev weighing 180 tonnes carries 14 tonnes of payload). In both cases, the fuel carried is about 100 tonnes. These fuel loads are needed for transportation distances of 6000 km. The fraction of fuel used for reaching cruise altitude is all that needs to be accounted for in the present case. This constitutes about 6 tonnes. In these commercial operations the flight path is chosen for minimizing the fuel consumed. If we examine how much of payload is being transported by the aircraft to cruise altitude allowing it to carry the fuel required to reach the cruise altitude instead of the total fuel load, then the payload ratio will be 11.3/(185x0.9 – 94) x 100 = 15.5% -a not too small a value.

Payload fraction for space transportation is 1.5 to 3 % at present. The payload density for space craft is bout 200 to 300 kg/m^3.

These indicate that the crucial point at which space transportation is weak is with respect to payload ratio. Thus use of as many aircraft elements as possible will enhance the payload ratio. A value of 10% should be a reasonable value to aim at atleast for satellite payloads. A lower bound which can be taken with greater certainty is 5%.

5. Some typical parameters

If the vehicle is to employ aircraft elements as discussed above, it is a good strategy to take advantage of lifting characteristics by employing a wing like structure. Typical weight to thrust of several high speed aircraft show values as follows (from Janes the World Aircraft series):

Aircraft	Engine	Thrust kN	Isp N.s/kg
Concorde	Olympus 593(TJ)	4 * 170 (with 17% AB)	29700
Tupolev	Kuznetsov (TF . 1) Nk 144	4 * 127 , 196(AB)	
F15	F-100-PW	2 * 64; 111.2 (AB)	52000
Sukhoi 27	Saturn/Lyulka	2 * 122.6	14000

AB = After burner; UR = Uprated

The value of lift to drag ratio at take-off conditions is about 4.9 for Space Shuttle. Though Space Shuttle is designed for vertical take-off, there is significant advantage to be gained by horizontal take-off since the thrust that needs to be provided is only a fraction of the total vehicle mass. For a vehicle with 130 tonne mass, thrust required for take-off can be set at 390 kN at a conservative estimate of the thrust for take-off.

The aircraft engines that can provide the thrust are again those powering the above aircraft. These are as follows.

Aircraft	Engine	Thrust kN	Isp N.s/kg
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The required thrust can be obtained by two engines of Olympus or several others. The operation with continuous after-burning is a specific feature of Concorde design and need not be followed; depending on the demand for thrust one can modulate the after-burning. One can get at afterburning a specific impulse of about 25000 to 35000 N.s/kg and without after-burning about 35000 to 50000 N.s/kg.

The first phase of the flight should occupy about 8 to 10 minutes and burns up fuel of 4 and takes the vehicle to about 10 km altitude. The whole craft is 3.0 % lighter at this stage.

The second phase of the flight intended to be accomplished by a ramjet producing a similar thrust level (~170 kN) for another 3 minutes or so. During this period, the vehicle has to accelerate from Mach 2 to 5. The fuel used up during this flight is 3 tonnes.

The third phase of the flight is based on a hybrid rocket based on liquid oxygen and rubber. The specific impulse is expected to be about 3000 N.s/kg and the average density a little over 1000 kg/m^3. There are other alternates which must be looked for in hybrids, like the one to be possibly based on solid oxidizer and liquid fuel. While it is simple to suggest the liquid (kerosene of the same grade as for gas turbine engine), it is very difficult to conceive of a solid oxidizer which has good mechanical integrity, and does not have the obnoxious oxides of nitrogen or chlorine in the list of products.

The return path of the flight has the usual elements of reentry choice of the trajectory towards the landing airport and the landing which can be helped by the turbojet/turbofan used for the first phase of the flight.

The turbojet/turbofan takes the vehicle to 10 km and a speed of 0.6 km/s. The ramjet takes the vehicle to 1.5 km/s. The rocket has to take the vehicle to 7.8 km/s to get a near circular orbit of 200 km. The incremental velocity to be provided by the rocket is still large, 6.3 km/s. This calls for a mass ratio (Initial to final) of 8.2 if storable propellants (3000 Ns/kg of specific impulse) are used. If cryogenic system at a specific impulse of 4500 N.s/kg are used, the mass ratio is reduces to 4.1. Admittedly, the advantage of cryogenic propellants in improving the performance is remarkable. However, if reusability has to support commercial operations at low cost of transportation, the number of missions to be completed every year needed is so large, say one every few days, that one has to include passenger transport. The amount of user confidence in reliability, safety of passengers in the cryo-system in case of an accident is still so low that the possibility of using this system in the near future appears remote, particularly if it is noted that the vehicle sizing is still controlled by rocket rather than air-breathing engine.

To get an idea of the total vehicle, very simple calculations of the overall weights and sizes have been made. A total vehicle weight of 135 tonnes is composed of 100 tonnes of rocket propellants, 7 tonnes of kerosene for the turbojet/turbofan and the ramjet, 10 tonnes of rocket hardware including the engine, 13 tonnes of aircraft hardware including the air breathing engines, and 5 tonnes of payload. Since the payload is obtained essentially as a consequence of subtracting a large number (130 tonnes) from a slightly larger number (135 tonnes), a less than accurate calculation may reveal either negative payload or a very large payload capability. The only reassuring feature is that calculations on rocket engines for SSTO of the Delta-Clipper class show positive payload fractions even upto 15 %. Therefore, there is need to validate the numbers through rigorous flight path calculations.

6. Comparison with other ideas

Concepts involving the improvement of the rocket engine per se through improvements in the choice of propellants, and propulsion system elements are all in progress. Perhaps these will contribute to the improvement in the performance of rocket based propulsion system by itself and benefits will be drawn by the rocket community. In addition to these, in the last several years, countries like France, Russia, Japan and USA are conducting large number of studies and large scale investments into hardware development are being made in Japan. The concepts being tried out are: combining rocket engine with air breathing engine in an ejector based rocket-ramjet mode (Siebenhaar and Bulman, 1995), integrating a turbofan into a combined cycle engine (Escher, 1996), attempting to use an existing aircraft for providing air-launch facility (Anderson and Lopata, 1996), improving the performance using in-flight collection of air, liquifying it and separating oxygen from it while operating the scramjet at Mach numbers from 6 to 10 for use in rocket engine subsequently (Venugopalan, Gollakota and Gopalaswamy, 1996), operation and development of specially suited turbojet like air turbo-rocket (Japanese development).

While each one of these developments is arguably in the right direction, it is not obvious that they can result in substantial benefits in terms of costs of access to space. To repeat the "mantra", reusability should be used in the form of time tested air breathing engines to the extent atmosphere can be used and then the rocket engines. The development of some concepts will inevitably contribute to the "mantra", but alternate ones proposed here should be pursued for an early realisation of a bold conceptual framework. Amongst change in mindset called for are also aspects which will affect the design. As Thode (1995) has put it across succinctly, "... If one is launching an expendable rocket, one criteria for design might be to minimise the dry mass of the vehicle to reduce the fabrication costs-a strategy that can lead to a design completely different than that for a reusable vehicle, where dry mass cost may be of less concern". Amongst the concepts around SSTO discussed by several people, one by Bekey (1994) (the present author's attention was drawn to it after the draft article was set out) seems very instructive. It is very important to note his observations on Delta-Clipper experimental program that many criticise as being useless. He states "... What it did demonstrate is the feasibility of radical new operations technologies and techniques. The truth of the matter is that the DC-X actually represents a revolution.

Consider that it is the first hydrogen--oxygen launch vehicle in which the crew can walk to the pad, with the vehicle empty and the power off overnight, and throw switches, load propellants, checkout the vehicle including hardware and software, and be ready to launch one hour later. There is no other launch vehicle in the world that has achieved anything like that, except perhaps the Zenit, which is designed for automated launch but is not even hydrogen--oxygen vehicle. That's a revolution".

The details of the thinking process presented here are somewhat different from those expressed in the earlier articles; airbreathing engines and rockets are combined and deployed only where they are most effective. A further point about the robustness of the proposal is that the use of air breathing engine concepts should be around operational systems so that realisation is fast enough and public acceptability becomes much simpler. Those who make it first will obviously reap benefits. In this venture, combining of international forces is an excellent possibility, since, commercial operations devoted to airline fleet and space launches have become competitive and newer greener pastures are being looked for.

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