Future Space Launch Vehicles

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Introduction

Space technology plays a very substantial role in the economical growth and the national security needs of any country. Communications, remote sensing, weather forecasting, navigation, tracking and data relay, surveillance, reconnaissance, and early warning and missile defence are its dependent user-technologies. Undoubtedly, space technology has become the backbone of global information highway. In this technology, the two most important sub-technologies correspond to spacecraft and space launch vehicles.

Spacecraft

The term spacecraft is a general one. While the spacecraft that undertakes a deep space mission bears this general terminology, the one that orbits around a planet is also a spacecraft but called specifically a satellite — more strictly an artificial satellite, moons around their planets being natural satellites. Cassini is an example for a spacecraft. This was developed under a cooperative project of NASA, the European Space Agency, and the Italian Space Agency. Cassini spacecraft, launched in 1997, is continuing its journey to Saturn (about 1274 million km away from Earth), where it is scheduled to begin in July 2004, a four-year exploration of Saturn, its rings, atmosphere, and moons (18 in number). Cassini executed two gravity-assist flybys (or swingbys) of Venus — one in April 1998 and one in June 1999 — then a flyby of Earth in August 1999, and a flyby of Jupiter (about 629 million km away) in December 2000, see Fig. 1. We may note here with interest that ISRO (Indian Space Research Organisation) is thinking of a flyby mission of a spacecraft around Moon (about 0.38 million km away) by using its launch vehicle PSLV.

In the Indian scenario, among many artificial satellites that the Country built, two most recent-ones are the remote sensing polar Sun-synchronous satellite, IRS-P4 (1050 kg), and the geo-synchronous communications satellite, INSAT-3B (2070 kg). While the Indian built space launch vehicle PSLV launched the former to an orbit of 727 km altitude, the latest launch vehicle of Arianespace, Ariane 5 (see Fig. 2), launched the latter to reach the geo-synchronous altitude of 35786 km. The ability to place a satellite using its own launch vehicle to the geo-synchronous altitude makes a nation a full pledged space faring one. In March/April 2001, ISRO is planning to launch a geo-synchronous satellite using for the first time the indigenously built space launch vehicle GSLV.

Space Launch Vehicles

There are a large number of countries that own satellites, orbiting around Earth. However, there are only nine countries/consortia that possess space launch vehicles, demonstrate space-launch capability, and/or currently active in space-launch operations. These are the erstwhile USSR and now the Commonwealth of Independent States (hereafter let us denote these two under one name, Russia), the United States, the European consortium [(Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom); let us denote this consortium as Europe], China, Japan, India, Israel, Brazil, and North Korea. Australia, after its first space launch that was a success, has not entered into space-launch activities after 1967.

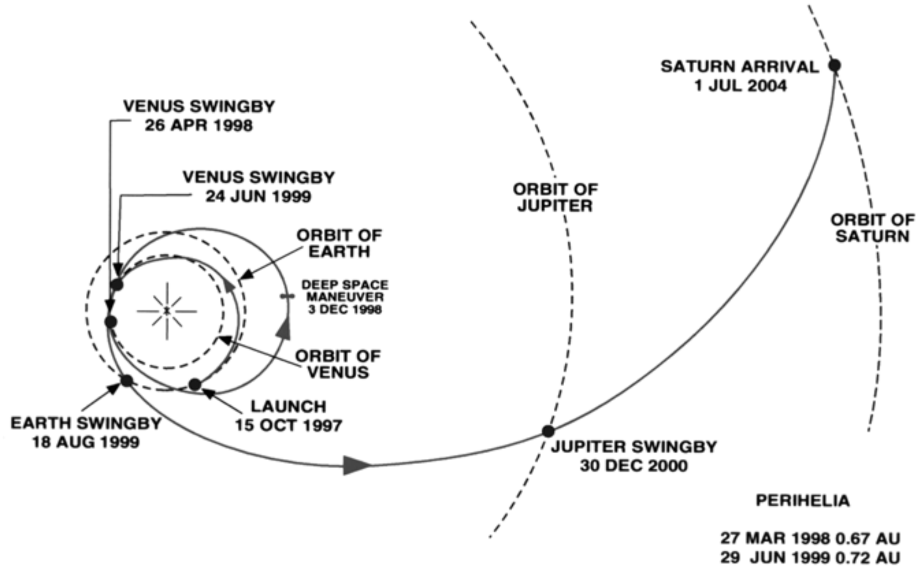

Fig. 1 Cassini interplanetary trajectory (adopted from www.jpl.nasa.gov/cassini/Mission).

Most space launch vehicles have their pedigrees in ballistic missile technology. Therefore if a country possesses space vehicles to launch spacecraft/satellites at great distances beyond Earth, the country is supposed to have the technology to carry massive weapons to large ranges beyond its borders. Having vehicles to launch satellites in the low and medium Earth-orbits (usually in the corridor above 200-km and below 1000-km altitude) and geo-synchronous orbits (at the altitude of 35,786-km) is invariably taken as possessing capabilities respectively of IRBMs (Intermediate Range Ballistic Missiles) and ICBMs (Intercontinental Ballistic Missiles) — for example the Indian SLV-3 has in a way led to the IRBM Agni. Therefore the technology to build space launch vehicles is always considered as "critical" one. We can buy communications or remote sensing satellites (evidently, not a military type) made by another country as per our requirements. But, it is almost impossible to procure space launch vehicles built by another country — you may recall the problems and delays that we have-faced in getting the cryogenic upper stage from Russia for the GSLV!

Impediments for Growth

The important issues that affect faster long-term growth in the space industry are related to the technology of space launch vehicles. Firstly it is the minimal improvement in the launch-success rate over the last two decades. And secondly, it is the high launch cost. A study led by the accounting firm, KPMG Peat Marwick, lists the frequent launch failures as the most important issue to be addressed under the space-technology-improvement issue. General H. M. Estes, retired from the U. S. Air Force and the former head of the U. S. Space Command, said, “Getting good, reliable launches and also getting costs down are huge issues for the U.S. Government. We can't even get the first one right! We have to fix this launch problem — get the reliability up and the cost down.”

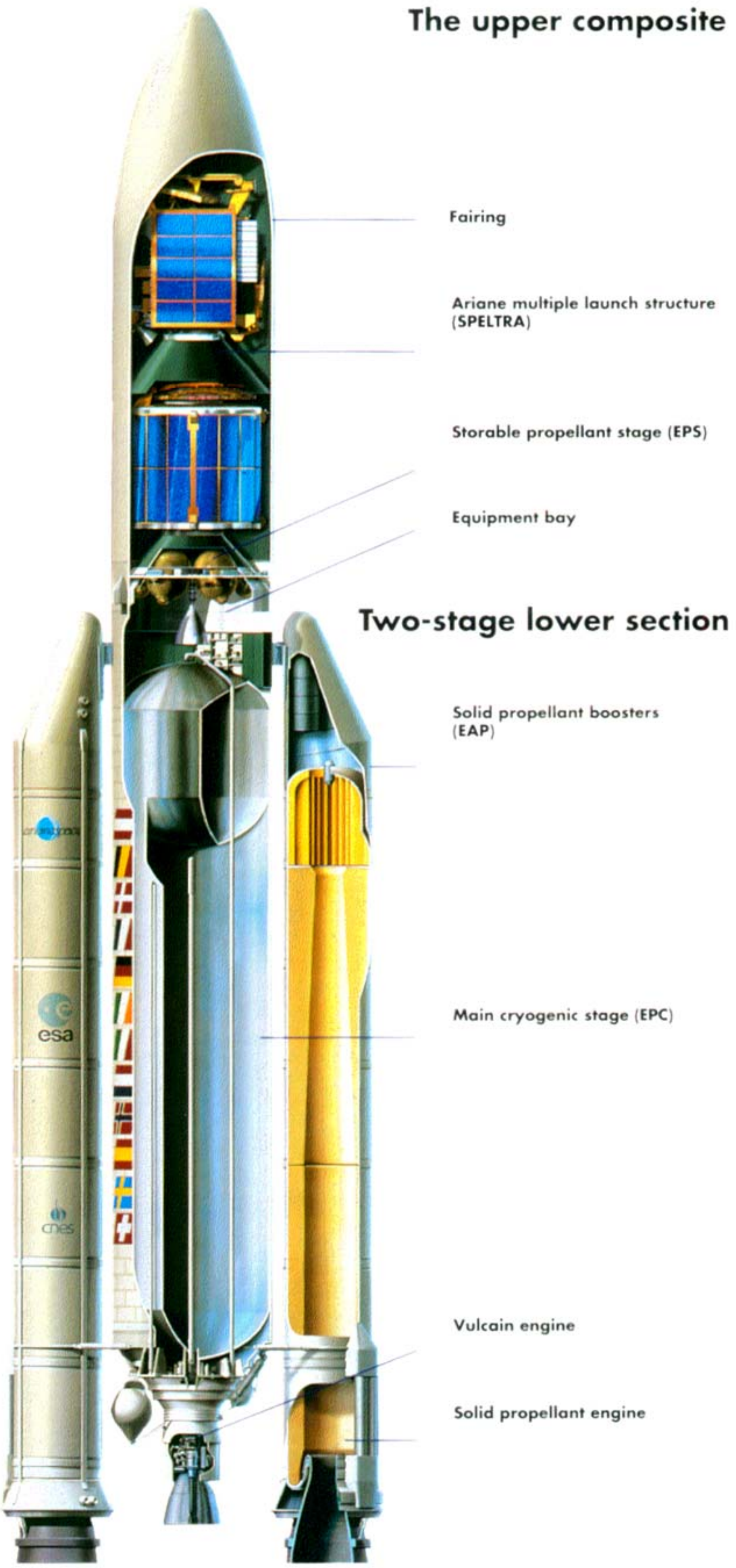

Fig. 2 Space launch vehicle Ariane 5 (adopted from "Space Transportation for the World Ariane 5," Arianespace, Evry, France, © ARIANESPACE 1996).

Launch Failures

There were totally 4377 space launches worldwide from 1957 to 1999. Out of these there were 389 failures, Table 1. Usually a space launch failure is defined as an unsuccessful attempt to place a payload into the *intended* orbit. For any technology at its embryonic stage it is natural to expect the success rate to be low. When the same technology matures the success rate improves to reach a "steady value" for the chosen concept. The success pattern in the last four decades for space launches, from 1959-'98, is given in Table 2. Looking at the trend for the recent two decades (1979-'88 and 1989-'98), it appears as though that the success rate for the current concept of launch-vehicle technology has reached a steady value of around 95%.

A space launch vehicle has many subsystems such as propulsion, avionics, separation/staging, electrical, structures, etc. For the period from 1985 to 1998, there were 85 space-launch failures. A critical review of the causes for these failures by the Aerospace Corporation (USA) has revealed that the propulsion subsystem is the Achilles' heel of the space programme (Chang, I., Journal of Propulsion and Power, Vol. 16, Sept.-Oct. 2000, pp. 853-866.) — out of the 85 failures, 53 were identified to be due to the propulsion subsystem alone, whereas the next highest number of failures was just 10 and it was due to the avionics.

Table 1 Space launches up to the end of 1999[a]

Country/ Consortium	Year of first launch	Total launches until the end of 1999	Number of failures	% Success
Russia	1957	2769	180	93.5
USA	1957	1316	164	87.5
Europe	1965	143	15	89.5
Japan	1966	61	9	85.2
China	1970	67	11	83.6
India	1979	13	6	53.8
Israel	1988	4	1	75.0
Brazil	1997	2	2	0.
North Korea	1998	1	1	0.
Australia	1967	1	0	100.
Total	**--**	**4377**	**389**	**91.1**

[a] Compiled from the data by (1) Chang, I., Journal of Propulsion and Power, Vol. 16, Sept.-Oct. 2000, pp. 853-866; and (2) Encyclopedia Astronautica, www.friends-partners.org/~mwade/ .

The propulsion subsystem includes solid motors, and liquid/cryogenic engines and their propellant tanks with propellants. Solid motor means the system that includes the combustion chamber, the solid propellant stored within the combustion chamber, and the nozzle. The terms solid motor and solid rocket mean one and the same. Liquid/cryogenic rocket means the system comprising the combustion chamber (or combustor), the liquid propellants (oxidizer and fuel), the tanks in which the two propellants are separately stored, the nozzle, and the propellant feed system. Traditionally the term liquid/cryogenic-engine (not liquid/cryogenic motor) includes all the above components of liquid/cryogenic rocket except the propellants and their tanks. The propulsion subsystem is the heaviest and the largest subsystem of a launch vehicle, and hence the most expensive part — note most of the two stage lower section and some of the upper composite of Ariane 5 are of propulsion subsystem, Fig. 2.

Table 2 Success pattern in the last four decades from 1959-'98 for space launches[a]

Country/ Consortium	1959-'68			1969-'78			1979-'88			1989-'98			**Total**		
	T[b]	F[c]	%S[d]	T	F	%S	T	F	%S	T	F	%S	**T**	**F**	**%S**
Russia	372	58	84.4	904	58	93.6	976	38	96.1	480	21	95.6	**2732**	**175**	**93.6**
USA	514	90	82.5	305	25	91.8	160	11	93.1	282	15	94.7	**1261**	**141**	**88.8**
Europe	5	1	80.0	13	6	53.8	27	4	85.2	88	4	95.5	**133**	**15**	**88.7**
Japan	3	3	0	16	3	81.3	23	0	100	18	2	88.9	**60**	**8**	**86.7**
China	--	--	--	12	4	66.7	16	2	87.5	35	5	85.7	**63**	**11**	**82.5**
India	--	--	--	--	--	--	6	4	33.3	6	2	66.7	**12**	**6**	**50.0**
Israel	--	--	--	--	--	--	1	0	100	3	1	66.7	**4**	**1**	**75.0**
Brazil	--	--	--	--	--	--	--	--	--	1	1	0	**1**	**1**	**0**
North Korea	--	--	--	--	--	--	--	--	--	1	1	0	**1**	**1**	**0**
Australia	1	0	100	--	--	--	--	--	--	--	--	--	**1**	**0**	**100**
Total	**895**	**152**	**83.0**	**1250**	**96**	**92.3**	**1209**	**59**	**95.1**	**914**	**52**	**94.3**	**4268**	**359**	**91.6**

[a] Compiled from the data by Chang, I., Journal of Propulsion and Power, Vol. 16, Sept.-Oct. 2000, pp. 853-866. [b] Total number launches. [c] Total number of failures. [d] Percentage of successful launches.

The propulsion subsystem operates under high pressures and extreme temperatures. As per the current design concept, it is always made to operate at its maximum power *all the time* resulting in very low margins on performance and safety. The situation is similar to a car engine pulling *all the time* in first gear a fully loaded vehicle against an extremely steep gradient with its accelerator completely pressed.

Among the three types of rockets under the propulsion subsystems (solid-, liquid-, and cryogenic-rockets), the cryogenic propellant rockets are the most complicated ones. And, they are invariably required in the space launch vehicles designed to place large satellites/spacecraft at great distances — heights corresponding to geo-synchronous orbits and above. In addition to the high pressures (70 to 100 times the atmospheric value in the combustion chamber) and extreme temperatures (very high temperature of about 3,000^{o}C in the combustion chamber and very low temperatures of -200 to -256^{o}C in the propellant tanks), these rockets have turbines rotating at a few tens of thousands of revolutions per minute. The turbines are run by expanding high pressure and usually high temperature combustion gases at about 900^{o}C. The propellant pumps, run by the turbines within a few centimeters away, pressurize the cryogenic propellants at about -250^{o}C to values much higher than the combustion pressures.

Launch Cost

The current rates of launch cost are estimated to be varying from 10000$ to 18000$ per kg for a low Earth-orbit, and 18000$ to 33000$ per kg for a geo-transfer orbit (a relatively lower orbit to be reached before going to the geo-synchronous orbit). The lower rates may pertain to Chinese, Russian, and European launches (in that order) while the highest ones are believed to be for the U. S. A typical passenger aircraft flying long distances costs about the same as a typical launch vehicle. It has a similar number of parts and is built to similar tolerances. The amount of propellant a launch vehicle burns to reach a low Earth-orbit is about the same as an aircraft burns to go from North America to Australia. And, the cost of single airline-ticket for this travel is about 1,500 $. Looked at this way, it would seem that the cost of getting into a low-Earth orbit should be much less than 15 $ per kg! The reason for the three orders of magnitude higher cost to reach a low-Earth orbit is the "use and throw away" concept applied to space launch vehicles — the technical jargon for such launch vehicles is expendable launch vehicles (ELVs).

Reusable Launch Vehicle (RLV) Technology

We have seen that the high launch cost (because of the "use and throw away" concept) and the frequent launch failures (due to the low margins on performance and safety) are the two principal impediments for faster long-term growth in space technology. These two obstacles point to, as solutions, the component reusability and enhanced margins on performance and safety. Consequently there have been efforts in the last ten years or so to develop (1) fully or partially RLV of two-stage-to orbit (TSTO) category and (2) fully RLV of single-stage-to-orbit (SSTO) category. All these RLVs have the common mantra, viz., *reusability*. No doubt that the company that develops the first successful RLV is sure to get a large number of space launch contracts and hence huge profits. In view of this market force many groups, principally in the US, are engaged in the RLV development. Also, interestingly, there is a prize of 10 million dollars announced by St. Louis based X-PRIZE Foundation. The "X-PRIZE" condition is that the company should be a non-governmental one, and the RLV should launch a manned spacecraft into sub-orbital flight and the launch should be repeated within the next two weeks (www.discovery.com). The RLV-race situation is similar to the one humorously depicted in the 1965 box-office hit, "Those Magnificent Men in their Flying Machines" or "How I Flew from London to Paris in 25 hours 11 minutes," Fig. 3. Centred around a London-to-Paris air race early in the 1900's, this wonderful English comedy spoofs national characteristics! Although the plot outlines how sabotage efforts damage an international air race, as an aerospace enthusiast one enjoys noting in the movie, how the different design concepts with the common mantra that "it should fly" result in a fantastic array of aircraft.

In this RLV race, many cost- and time-overruns, company closure, and contract termination have been there and these will continue to happen. But every one is clear of the fact that the reusability of launch vehicles is the key to the faster long-term growth of space technology. Definitely before 2010, if not by mid-decade as claimed by developers, a few of these RLV-concepts should become operational.

Astroliner

Astroliner (Kelly Space & Technology, Inc., San Bernardino, California; www.kellyspace.com) is a piloted, towed and air launched, horizontal landing, turbofan jet engine and rocket engine based, sub-orbital, aircraft like, reusable launch vehicle with an expendable second stage. From a conventional runway, a modified Boeing-747 aircraft using a patented tether tows the launch vehicle Astroliner as a glider to a launch point, 6 km up in the air, Fig. 4. At this point, the Astroliner, on the ignition of its three semi-cryogenic liquid-oxygen (LOX)/kerosene rocket engines (Russian RD-120) and the release from the tow, climbs to about 110 km before the rocket engines shut down. On a subsequent coasting to about 120-km, the nose door of Astroliner is opened and the expendable second stage with its satellite is released, Fig. 5. The second stage ignites its LOX-kerosene rocket engine and carries the satellite (from 5000 kg for low Earth-orbits to 2100 kg for geo transfer orbits) into the desired orbit. The Astroliner, after coasting to an apogee of 180 km, reenters to land at a designated airport using its two turbofan engines (Pratt and Whitney F100). The second stage after deploying its satellite will be de-orbited to either get burned in the atmosphere or fall into an ocean area.

The Company’s philosophy is to rely exclusively on proven and simple technologies to achieve the low cost access to space. So the means adopted to achieve this objective are:

(1) the recovery of the sub-orbital Astroliner alone for reuse — the largest and usually the most expensive part of a launch vehicle is the first stage (here, the Astroliner minus the second stage), and from a reentry-heating standpoint the recovery of a sub-orbital vehicle is significantly easier than that of an orbital one; and (2) the use of an in-production expendable second stage and the adoption of existing and well proven hardware for the main components of the first stage — air frame, landing gear, rocket engines, and turbofan jet engines. The tow-air-launch technique is much safer than other air-launched techniques. During World War II pilots used to tow cargo gliders behind their planes.

Fig. 3 A 1965 box office hit where in a fantastic array of aircraft is displayed.

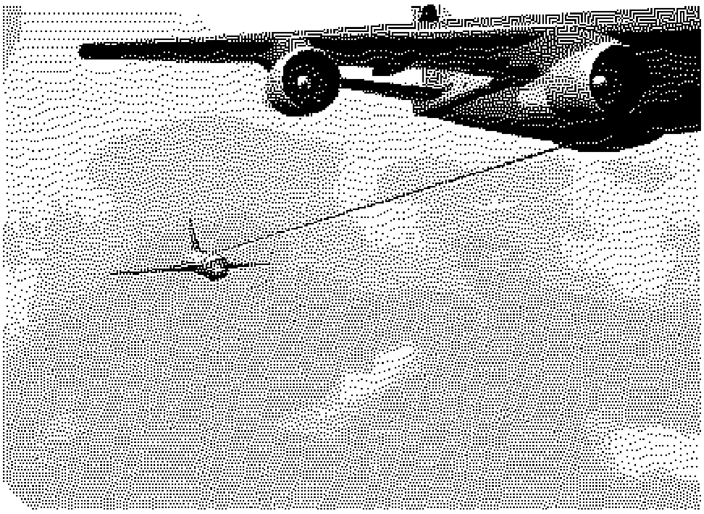

Fig. 4 Astroliner being towed (adopted from www.kellyspace.com).

The Company is well into a testing program and plans to have the Astroliner operational by mid-2002 with an ability carry out nine to eighteen launches per month. The low-cost Astroliner is claimed to reduce the launch cost to less than 4500 $ per kg for low Earth-orbit. The company has been working in close collaboration with NASA and has been receiving grants and awards from NASA for its work in the area of future space launch systems.

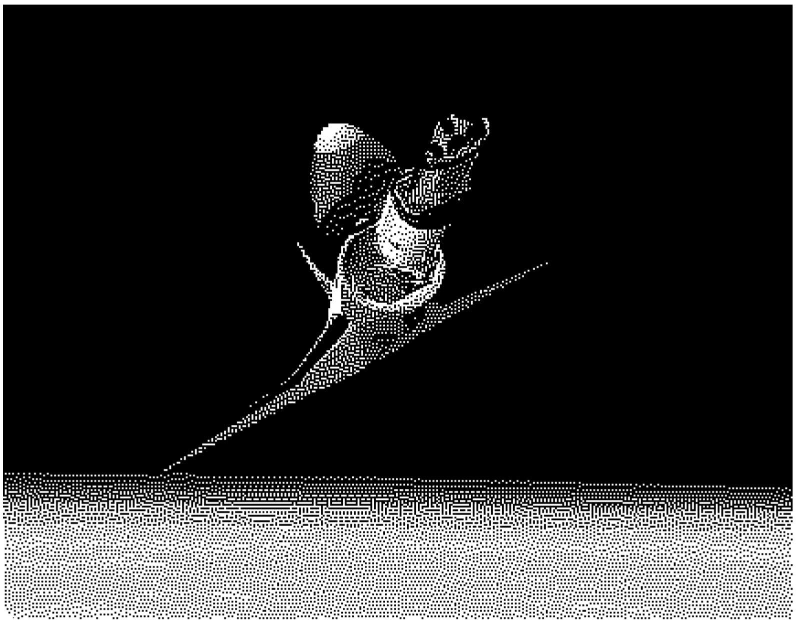

Fig. 5 At about 120-km, the nose door of Astroliner is opened and the expendable second stage with its satellite is released (adopted from www.kellyspace.com).

BA-2

The BA-2 space launch vehicle (Beal Aerospace Technologies, Inc., Frisco, Texas; www.bealaerospace.com) of 68 m height and 6.2 m diameter is a three-stage vehicle weighing 950,000 kg at lift-off. The vehicle uses only one engine per stage. The first-stage engine is to produce 13.4 million Newton thrust. Stages one and two utilize liquid injection thrust vector control for steering and stage-3 has a gimbaled engine with the ability to restart multiple times. Kerosene and hydrogen peroxide is the propellant combination. Propellant tanks are of composite filament wound structures. Propellants are fed to the combustion chambers using helium pressure-fed system against the usually adopted turbo-pump one, which is complicated and costly. All combustion chambers use composite ablative material. Stages 1 and 2 will ultimately employ reusable technologies for complete recovery at sea. The standard ascent trajectory launches 17000-kg satellite to a 200-km altitude. For geo transfer orbit and Earth escape missions, a second burn is executed by the third stage to inject a spacecraft of about 5800-kg.

The design of BA-2 vehicle adopted many sweeping concepts: the uncommon propellant combination of hydrogen peroxide and kerosene, single engine per stage, simple pressure-fed-system, no igniter since the decomposed hydrogen peroxide automatically gets ignited with kerosene, ablative combustion chambers, and liquid injection thrust vector control. The design axioms were "make it big, make it simple, and make it inexpensive." Because of the design simplicity the launch cost was projected to be substantially lower than the current charges.

Beal Aerospace Technologies was formally incorporated early in 1997. The founder of the Company Andrew Beal is a Texas multi-millionaire. He had founded one of the most profitable banks in Texas, Beal Bank. The BA-2 project-cost was projected to be about 500 million dollars. After spending from his personal resources many millions of dollars in building large test facilities and designing and demonstrating the operability of the upper stage engine, Beal suddenly announced in October 2000 that he was closing down the activities of Beal Aerospace, as he had found impossible to compete with the private aerospace companies developing RLVs, that enjoyed subsidies from the US Government and NASA. Currently the assets that he purchased under the project are for sale!

K-1

K-1 (Kistler Aerospace Corporation, Kirkland, Washington; www.kistleraerospace.com) of height 36.9m and diameter 6.7m weighs totally 382,300 kg at liftoff with the first stage mass of 250,500 kg. It is a TSTO with full reusability for both the stages. This is a privately financed project. The TSTO K-1 will lift off using the two NK-33 and one NK-43 LOX/kerosene Russian engines of the first stage. At 121st second after lift-off, at an altitude of about 41-km the first and second stages separate. NK-43, one of the three engines of the first stage, restarts and places the separated first stage on a controlled return trajectory. Parachutes are deployed at an altitude of 3 km and air bags are deployed just before touch down for the returning first stage, Fig. 6. The second stage, on igniting its single NK-43 engine, proceeds to the desired 800 km LEO with its payload of 2,600 kg. After orbit injection, the K-1 payload-bay is opened and the payload deployed. Thereafter, the second stage does a pitchover maneuver and fires the maneuvering engines to de-orbit. It re-enters Earth's atmosphere nose first on a controlled trajectory to the launch site. Parachutes are deployed at an altitude of 3-km braking the descent velocity of the second stage. Airbags are deployed just prior to touchdown for soft landing at the launch site, Fig. 7. The stages are quickly refurbished and can be flown again in less than two weeks.

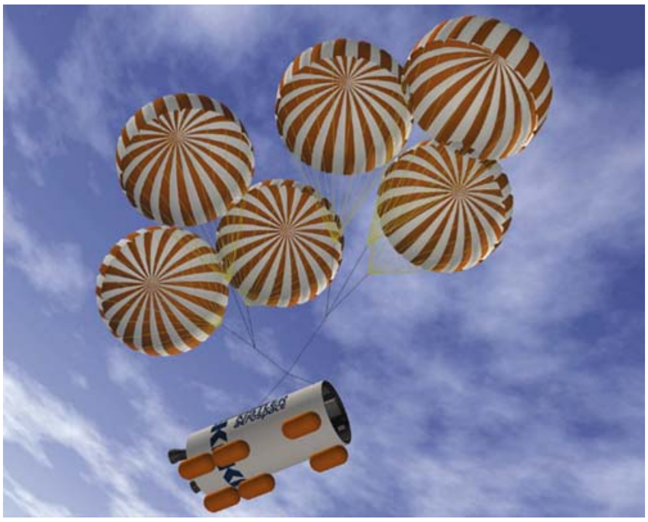

Fig. 6 Artist rendering of the return of K-1 first stage with airbags and parachutes deployed (www.kistleraeropace.com).

The NK33 and NK43 engines were developed by Russia in mid 1970's but never flown. The US Aerojet Corporation is modifying these engines for adoption in K-1 with 100-times reuse capability. Although the original configuration of K-1 is for the launch of payloads in the low Earth-orbits of maximum 1000 km altitude, the Company is engaged also in the development of an expendable third stage, known as Active Dispenser, to inject payloads in medium Earth-orbits, geo synchronous orbits, or inter planetary mission trajectories (Kohrs, D., Knowles, S., Cochran, D., Curtis, R., and Lai, G., "Beyond LEO: The K-1 Active Dispenser," Space Technology and Applications International Forum, Albuquerque, New Mexico, Feb. 11-14, 2001). In February 2001, the Company announced that the fabrication of the first K-1 vehicle was 75% complete. It did not specify any date for the first launch.

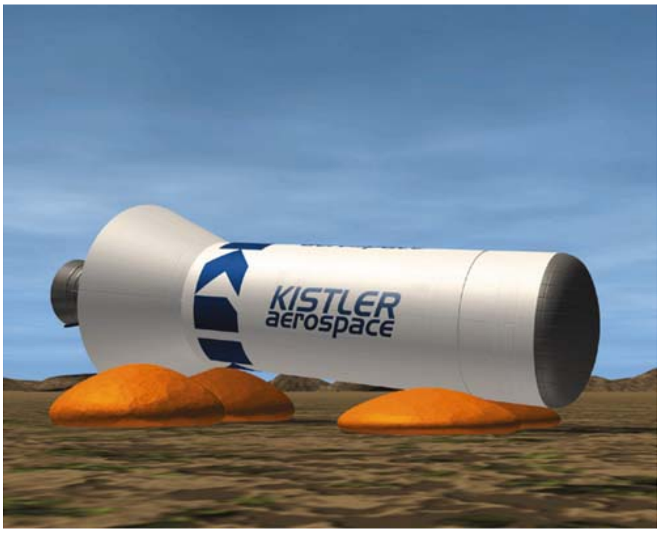

Fig. 7 Artist rendering of K-1 second stage landing on airbags (www.kistleraeropace.com).

Pathfinder

Pathfinder (Pioneer Rocketplane, Vandenberg AFB, California; www.rocketplane.com) is a piloted, horizontal take off and horizontal landing, aerial propellant transfer, sub-orbital, turbofan engine and rocket engine based, reusable launch vehicle with an expendable second stage. Like an aircraft, the Pathfinder takes off from a regular airport using its two-turbofan jet engines, Pratt & Whitney F100, Fig. 8. At an altitude of 9 km a tanker aircraft, KC-135, transfers to Pathfinder 59000 kg of LOX within 15 minutes. Lighting then its semi-cryogenic rocket engine, Russian RD-120, the Pathfinder undertakes a sub-orbital ballistic trajectory to release at about 130-km altitude its expendable upper stage that launches the satellite at the required LEO. Pathfinder then lands at the airport using its jet engines. An entire mission, from takeoff to touchdown, takes just a few minutes under two hours. "Maximizing the use of off-the-shelf technology, innovate to achieve low-cost access to space" is the underlying design philosophy. Existing engines, existing avionics and subsystem components, and existing thermal-protection-system materials are to be used.

For the launch of a 900-kg satellite in a polar sun-synchronous-orbit using Pathfinder, the cost is claimed to be as low as 7 million dollars. This works out to 7700$ per kg as against the current rate varying from 10000$ to 18000$ per kg to LEO.

There are many similarities between Astroliner and Pathfinder. However, the former is towed and air launched but the latter is one of aerial propellant transfer. Towing and air launching is a well-proven concept. Although the aerial transfer of Earth-storable fuel from one aircraft to another is a proven concept, in Pathfinder it is the transfer of cryogenic-propellant, LOX, and this will definitely pose challenges.

As per the news release in Feb 1999, Pioneer Rocketplane was continuing negotiations to raise the funds needed to build its Pathfinder.

Roton

Roton Space Vehicle (Rotary Rocket Company, San Bruno, California; www.rotaryrocket.com) is a piloted, vertical takeoff and vertical landing, rocket based, and conical shaped SSTO-RLV. It also has the cargo return capability from orbit. This is a privately financed project. With the crew of two, the conical Roton vehicle (of 6.7 m diameter at the base, about 19.2 meters tall and less than 180,000 kg mass) will lift off like a conventional launch vehicle, powered by a novel semi-cryogenic "rotary" rocket engine burning LOX and kerosene and delivering 2.2 million Newton thrust, Fig. 9. Once its payload of 3200 kg is delivered to a low Earth-orbit, the Roton returns to Earth via a nose-mounted rotor, which is deployed in space and used during reentry to help stabilize the craft. Once in the atmosphere, the vehicle will glide like an autorotating helicopter and land vertically, assisted by rotor tip thrusters.

Fig. 8 Sequence of events after Pathfinder launch (Courtesy Pioneer Rocketplane).

The unusual item in Roton is its rotary engine. The engine assembly, located at the base of the vehicle, consists of 72 small high-pressure combustors placed equally around the perimeter of a disk. To generate the necessary centrifugal force required to pump the propellants to the high-pressure combustors, this 6.7-m diameter engine disk rotates at 720 revolutions per minute (rpm). The combustors are mounted with their exit nozzles flush to the outer surface of the bottom of the vehicle and each is slightly tilted in the direction of rotation of the disk to provide the power to rotate the engine. A small number of approximately 450-Newton-thrust engines are used to control vehicle attitude in flight, to provide the impulse necessary to circularize the initial injection orbit, to maneuver in space, and to provide the thrust necessary for de-orbit. These engines are mounted on the side of the vehicle and are arranged to provide pitch, yaw, and roll forces to the vehicle as well as axial thrust for orbital modification and retro maneuvers. At the very top of the vehicle is the rotor hub assembly. The four metal rotor-blades in the assembly will deploy during reentry. Like the rotor hub of an autogyro, the hub is unpowered and freely rotates on its shaft. The rotor hub assembly provides a slow, pilot-controlled approach to the landing site. At an altitude of about 8,500 meters the vehicle starts to glide at 83 km per hour for a distance of about 8500 meters — that is at a glide ratio of 1:1. Small rockets are mounted at the tip of each rotor blade and will be fired 150 meters above the landing site to enable the vehicle to hover and precisely land at the desired spot. The Roton's propellant tanks, cargo bay, aeroshell, and most other airframe components will be made of carbon fiber-epoxy composites to take advantage of the material’s high strength and light weight property.

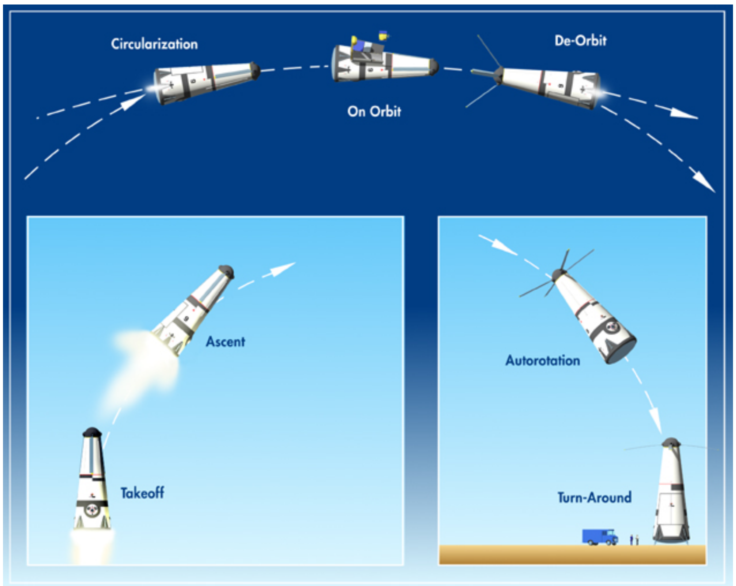

Fig. 9 Space launch trajectory of the reusable launch vehicle, Roton.

Fig. 10 Roton atmospheric test vehicle in the translatory flight and vertical landing demonstration in October 1999.

The unique concepts in Roton are two. First is the use of the centrifugal force created by the 6.7-m engine disk rotating at 720 rpm to pressurise the propellants and feed them into the combustion chambers. And the second is the mounting of small rocket engines at the tips of the rotor blades. In the conventional liquid propellant rocket engines this pressurisation is achieved by the turbo-pumps run by turbines. Essentially the large disk rotating at 720 rpm replaces the smaller mass turbine-disk and pump-impellers rotating at a few tens of thousands of rpm. In fact this concept had been proposed before the rocket engineers adopted the present day turbo-pumps. Regarding the second concept too, this idea had been proposed for the rotation of helicopter blades by mounting the ramjets (a type of airbreathing jet engines that start working efficiently only at speeds sufficiently above sonic value) at the blade tips. But the concept never saw the light.

In March 1999 Rotary Rocket Company unveiled a full-scale demonstrator of Roton atmospheric test vehicle. This preliminary vehicle did not have launch engines. In October 1999, the Company demonstrated for this vehicle the operational viability of translational (forward) flight and vertical landing using a tip thruster powered rotor blade landing system, see Fig. 10.

Being a privately financed project, the progress is seen with many time overruns. Although the promoters indicate that the Roton will enter into commercial service in 2002, the immediate issue appears to be the fund raising. Thereafter lies the mighty challenge in developing the rotary rocket engine technology.

X-33 and VentureStar

The X-33 advanced technology *demonstrator* (Prime Contractor: Lockheed Martin Skunk Works, Palmdale, California; Program Manager: NASA Marshall Space Flight Center, Huntsville, Alabama) is a vertical takeoff and horizontal landing, cryogenic rocket based, reusable, winged and wedge-shaped, sub-orbital, single stage, Mach 13+ (more than 13 times the speed of sound) hypersonic vehicle, Fig. 11. The X-33 Program is to demonstrate the key design and operational aspects of SSTO RLV VentureStar. VentureStar is being developed by Lockheed Martin.

A typical flight of the X-33 consists of a vertical takeoff, an ascent-acceleration to the planned Mach number and altitude, and a cruise phase followed by re-entry and horizontal landing. Although X-33 is a sub-orbital vehicle, its flight path simulates environments of VentureStar. X-33 is a bridge between the Mach-8 X-34 demonstrator and Mach-25 VentureStar RLV. The primary technology objective is that by pushing the limits of current construction techniques build an airframe and key subsystems using the same composites, structures, and component weights that scale-up to follow-on the VentureStar. Furthermore, X-33 will by actual operations demonstrate the feasibility of rocket powered "aircraft/airliner-like" operations, support, reliability, and associated recurring flight costs of an RLV.

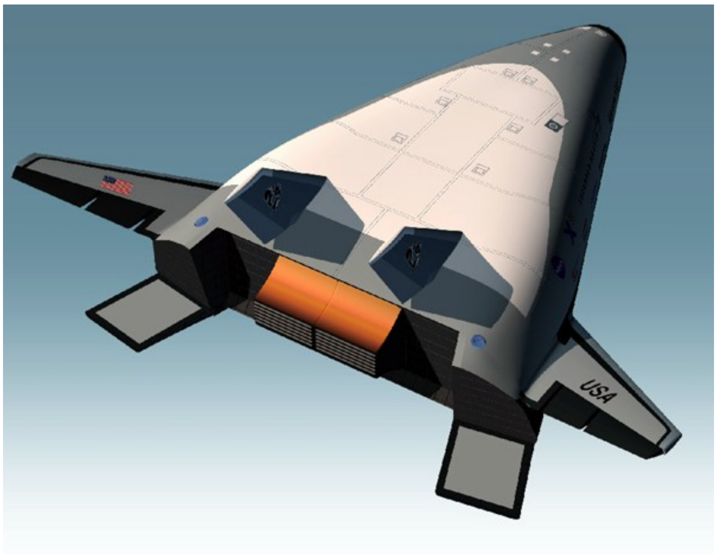

Fig. 11 Artist rendering of X-33 back view (adopted from www.venturestar.com).

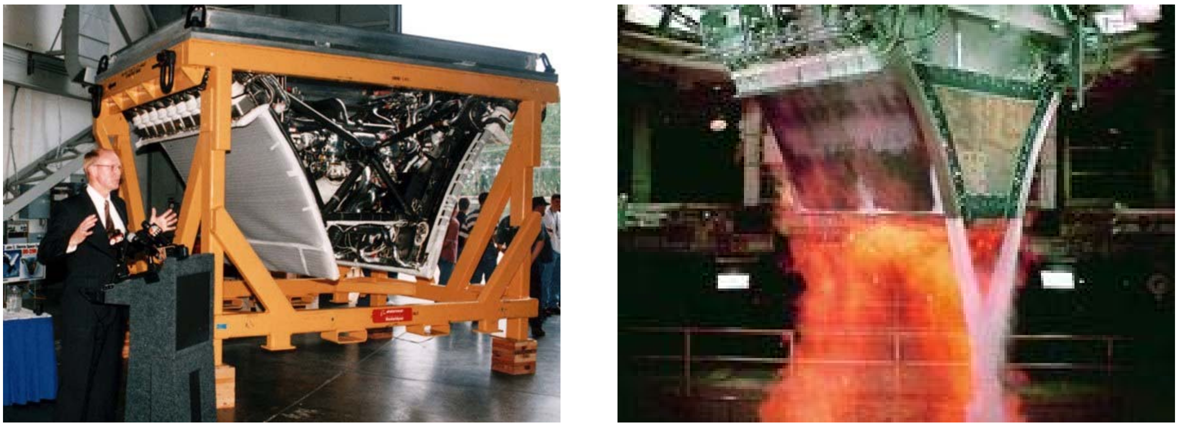

Fig. 12 Photographs of XRS-2200 Boeing Rocketdyne aerospike-engine that will power X-33 (adopted from www.venturestar.com). The right side photograph shows the engine being tested at its 100% power.

The X-33 is VentureStar’s half-scale version at one-ninth weight. The fully automated, lifting body, 21-m long, and 23.5-m wide X-33 vehicle weighs 130,000 kg at lift-off. To withstand very high temperatures experienced during hypersonic flight and still be fully reusable the entire external surface is constructed with high-temperature-resistant materials — elevons, leading edges, and nose cap are of carbon/carbon-silicon composites, and rudders and windward-surface are of advanced high temperature metallics to withstand temperature up to about 1000^{o}C.

X-33 and VentureStar are to use a new type cryogenic rocket engine, known as linear aerospike engines developed by Boeing Rocketdyne, Fig. 12. X-33 has two XRS-2200 linear aerospike cryogenic engines that use simple and low risk gas generator cycle and store 96000 kg of liquid hydrogen (LH2) and LOX propellants (74% of lift-off mass resulting in a mass fraction of 26%) to deliver totally about 1.82 million Newton thrust at lift-off. X-33 will fly with a single LOX-tank of about 73000 liters storing 82200 kg of LOX and two LH2 tanks of about 195000 liters total-capacity storing 13800 kg of LH2. All the tanks are of aluminium. In cryogenic rocket hardware, the mass of propellant tanks is the heaviest and between LOX tank and LH2 tank, the latter is substantially heavier; in the present case it should be at least 1.4 times heavier than the LOX tank of 2700 kg.

The difference between the linear aerospike and conventional rocket engines is the shape of the nozzle. The new nozzle concept was originally developed by Rocketdyne in the 1960's but never actually used in a launch vehicle — during this period an Indian born US scientist Gadicherla V. R. Rao played a significant role in designing the optimum nozzle contours. The bell shaped nozzle of a conventional engine expands the hot combustion gases on its inside surface. But the aerospike nozzle, shaped “like a bell turned inside out and upside down,” expands the hot gases along the outside surface of the two ramps resulting out of the “inside out and upside down” turning, see Fig. 12. And, the thrust is produced in a spike shaped plume — hence the name “aerospike.” The plume is open to the atmosphere on one side and free to move to the extents appropriate to local pressures. This altitude compensating mechanism with the decreasing atmospheric pressure as the vehicle ascends keeps the engine performance very high throughout the entire trajectory. The aerospike engine allows the small, low-cost RLV to be developed because the engine fills the base, reducing base drag, and is integral to the vehicle, reducing installed weight when compared to an engine with bell-shaped nozzle. The two XRS-2200 engines have ten thrusters each and these thrusters are aligned equally in segments along the forward end of each nozzle ramp. The X-33 vehicle will be steered by using differential thrust — that is, varying the thrust of the aerospike engine segments to produce pitch, roll, and yaw — opposed to moving or gimballing the entire engine to change direction. This feature also reduces mechanical systems and contributes significantly to a lighter weight vehicle when compared to the one with engines using bell-shaped nozzles. The X-33 engine can throttle from 40 to 119 percent of its designed thrust level. The ramp is composed of a copper sheet milled with internal cooling passages, which is brazed onto a steel backing.

X-33 will lift-off, reach a maximum altitude of about 80 km, cover a total distance of some 1500 km at speeds more than Mach 13, and land horizontally. The whole mission will last about 24 minutes. The X-33 is scheduled to make 15 test flights from Edwards Air Force Base, to Dugway Proving Ground, and Malmstrom Air Force Base.

In July 1996 Lockheed Martin Skunk Works had been selected by NASA to build and fly within 42 months the X-33 advanced technology demonstrator. NASA investment in the X-33 program totaled 912 million dollars, staying within its 1996 budget projection for the program. No profit is to be made by Lockheed-Martin and its teammates. Lockheed Martin originally committed to invest 212 million dollars in the X-33, and during the life of the program increased that amount to 357 million dollars. There have been many time overruns. In September 2000, NASA projected a target launch date in 2003.

That X-33 eventually will lead to VentureStar is the primary goal, but the road to that end will continue to be littered with many more challenges. X-33's mass fraction is going to be more than 26%. VentureStar's is to be 10%, so a 62% reduction is required. VentureStar's RS-2200 engine is to have a thrust-to-mass ratio of 785 N/kg, compared to a ratio of 345 N/kg for X-33's XRS-2200. In effect, a 56% weight reduction is required. Originally, two lightweight multilobed carbon-composite LH2-tanks were planned to be used. A developed composite LH2 tank structurally failed after a series of tests in November 1999. Consequently it was decided to replace composite LH2 tanks with the aluminum ones. However, in March 2001, after a thorough review of the project NASA decided not to include X-33 project under the Space Launch Initiative funding. As a result, the current X-33 program will come to completion when the cooperative agreement between NASA and Lockheed Martin expires on March 31, unless Lockheed Martin chooses to go forward with the program with its own funds.

March 15, 2001