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Heavy Satellite Launch Vehicles: An Assessment

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Summary

This brief has carried out an assessment of the launch vehicles used globally for launching of heavy satellites into the geostationary orbit. This assessment is mainly based on the comparison of the various features of different launch systems and the characteristics of the propellants put in use.

Introduction

A satellite launch vehicle (rocket) is designed to lift a satellite from the earth and to deliver it to the desired orbit. The strength of such a vehicle depends on the weight of the satellite and the nature of the orbit in which it is to be placed. With advancing rocket technology, capability to put the heavy satellites into different orbits has increased significantly. Recently, India joined the coveted club having capacities to launch around 2 tonnes of payload into the geostationary orbit. This Issue Brief makes an assessment of the existing global capabilities to launch heavy satellites into the space.

Technically, launch vehicles could be categorised based on various features. It could be based on the number of stages the vehicle use for launching a satellite like single stage, twin stage, etc. It could also be based on method of assembly like vertically or horizontally assembled. However, the most common approach of classification could be based on the payload carrying capacity. There could be further sub-classifications in this category based on the orbits in which the payload is to be delivered.

In relative sense for rocket scientists' development of technology for delivering less than 2000-kg payload satellites in the low earth orbit (LEO) has been an easier task than putting heavier satellites in higher orbits. Currently, every space-faring state is not in a position to put heavy satellites into the geosynchronous orbit. Interestingly, even states like India with much advanced space programme has not been able to successfully undertake Moon and Mars missions but could achieve success in this field only at a later stage.

On January 5, 2014, India conducted a successful launch of GSLV-D5 under its Geosynchronous Launch Vehicle programme. With this launch India, has for the first time, succeed in demonstrating its indigenous cryogenic technology. For India mastering this technology is extremely important because without cryogenic/semi-cryogenic technology it is not in a position to further develop its rocket programme for launching heavy satellites. What India has achieved with the successful launch of GSLV-D5 on January 5, 2014 (approximately two tones payload) could be viewed as a first step in the direction of developing a reliable launch system for the delivery of heavy satellites into different orbits. For all these years India has been depending on outside agencies to launch its communication/weather satellites (normally of four tonne variety) at cost. With the Indian system being available the cost of such exercises will not only be significantly less but could attract business by offering launch facilities using GSLV vehicle.

India's cryogenic engine development programme was in making for many years. In fact during early 1990s India was denied this technology. Russia was then supposed to transfer this technology to India but was pressurised by the US not to do so owing to the nuclear and missile related policies prevalent then. Since 2001, the Indian Space Research Organisation (ISRO) has been involved in the development of cryogenic engine.

TYPE	PROTON M	DELTA IV	ATLAS V	ARIAN 5[1] ECA	H IIB/H2B	LONG MARCH 3B/E	FALCON 9 HEAVY (V1.1)	GSLV MK II
COUNTRY	*Russia*	United Launch (Lockheed Martin and The Boeing) in alliance with ***US govt.***	United Launch ***United States (US)***	Arianespace EADS[2] ***Europe*** (Private sector)	JAXA (and Mitsubishi Heavy Industries ***Japan***	***China***	***Space X***	***India***
MASS (METRIC TONNES)	712	733.4	334	780	531	458	505	402
PAYLOAD TO LEO (METRIC TONNES)	22	22	29	20	19	12	13.15	5
PAYLOAD TO GTO (METRIC TONNES)	6.7	13	13	10	8	5.5	4.8	2
STAGES (NUMBER)	3-4	2	2	2	2	3	2	3
PROPELLANT	1st-Liquid (N2O4/UDMH) 2nd- Liquid (N2O4/UDMH) 3rd- Liquid 4th- Semi-Cryogenic (RP-1/LOX)	1st- Liquid (LOX/LH2) 2nd- Cryogenic (LOX/LH2)	1st- Semi-Cryogenic 2nd- Cryogenic	1st- Liquid (LOX/LH2) 2nd- Cryogenic	1st- Semi-Cryogenic 2nd- Cryogenics	1st- Liquid (N2O4/UDMH) 2nd-Liquid (N2O4/UDMH) 3rd Cryogenics	1st- Semi Cryogenic 2nd- Semi Cryogenic	1st- Solid (HTPB) 2nd- Liquid (LOX/LH2) 3rd- Cryogenic

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1 Arianespace. "Ariane 5 - Overview", http://www.arianespace.com/launch-services-ariane5/ariane-5-intro.asp, accessed January 25, 2014

2 Arianespace. "User Manual Issue 5", http://www.arianespace.com/launch-services-ariane5/Ariane5_users_manual_ Issue5_July2011.pdf, accessed on February 1, 2014

ENGINE	1st- RD-253-14D14 2nd- RD-0210 3rd- RD-0212 4th-RD-58M	1st- RS-68 2nd- RL10-B-2	1st- RL10 2nd- RL10A	1st-Vulcain 2 2nd- HM7-B	1st LE-7A 2nd- LE-5B	1st -YF-20C 2nd- YF-22E (Main) YF-23C (Vernier) 3rd- YF-75	1st- Merlin 1D 2nd-1 Merlin Vacuum (1D)	1st- S139 2nd- GS2 Vikas 4 3rd – CE 7.5
ISP (SEC)	1st- 285 2nd-327 3rd-325 4th-352	1st – 420 2nd -462	1st- 337 2nd- 422	1st- 431 2nd-446	1st- 440 2nd-448	1st- 255 2nd-292 3rd-431	1st-282 (Sea level) 2nd- 375	1st- 166 2nd-255 3rd- 454
THRUST (KN)		1st-3,312 2nd-112	1st- 4,152 2nd-99.2	1st- 1,340 2nd- 64.7	1st- 2,196 2nd- 137	1st- 2,961 2nd-742 3rd-157 (78.5*2)	1st- 5,885 2nd- 801	1st- 4,700 2nd- 720 3rd-73.5*
LAUNCHES • **SUCCESS** • **FALIURE** • **PARTIAL FALIURE**	**70** • 62 • 6 • 2	**7** • 6 • - • 1	**43** • 42 • 1	**42** • 41 • 1	**4** • 4	**15** • 8 • 7	**3** • 3	**2** • 1 • 1
SUCCESS RATE (ESTIMATED)	88%	90%	97%	97%	100%	53%	100%	50%
ESTIMATED LAUNCH PRICE (US$ IN MILLIONS)[3]	95-105	96	110	120		70[4]	56.5	40[5]

3 “Atlas V - Specifications.”. http://www.spaceandtech.com/spacedata/elvs/atlas5_specs.shtml. Last modified February 3, 2014

4 Encyclopedia Astronautica. “CZ-3B.”. http://www.astronautix.com/lvs/cz3b.htm. Accessed February 4, 2014

5 “GSLV-D5 rocket launch delayed, countdown clock stopped due to leak.” NDTV (Hyderabad), August 19, 2013. accessed February 4, 2014. http://www.ndtv.com/article/india/gslv-d5-rocket-launch-delayed-countdown-clock-stopped-due-to-leak-407446.

CRYOGENIC ENGINES

VARRIANT	DELTA IV AND ATLAS V	ARIAN 5 ECA	JAPAN HIIB[6]	LONG MARCH 3B/E	GSLV MARK II	FALCON 9
ENGINE	RL10A-4-2 variant of RL10	HM7-B variant of HM7	LE-5B VARIANT OF LE 5	YF 75 variant of YF 73	CE 7.5	MERLIN 1D
DEVELOPER	US and Pratt & Whitney	Earlier as part of Europe program currently by Snecma (Safran)	JAPAN (JAXA)	China	India (ISRO)	Space X
TIME FOR DEVELOPMENT	11 years (1950-1961)	8 years (1973-1979)	15 years (1975-1990)		14 (1994-2008)	

6 Japan Aerospace Exploration Agency. "Level with the world and efforts to date of liquid hydrogen engine technology in Japan". http://www.rocket.jaxa.jp/rocket-engine/engine/finish/. accessed January 18, 2014

It witnessed one failure on April 15, 2010 when the launch using indigenously developed cryogenic engine failed. The failure to develop cryogenic technology appears to be almost universal.

In order to understand where India stands globally in respect of developments into lift vehicles capable of carrying more than two tonnes of payload following paragraphs compares and contrasts the available global launch systems in this category. This could allow for a better understanding about how these vehicles are similar and diverse.

Equating the Vehicles

The above table making a broad comparison of vehicle characteristics indicates that:

1. Mostly cryogenic engine technology has been at heart of development of various launch vehicles designed for launch of more than 2 tonnes weight into GTO and other orbits.

2. Vehicles of Russian, Chinese and Indian origin are three/four stage vehicles while that of Western and Japanese origin are two stage vehicles. Except India in all other cases the combination constitutes of stages with liquid and semi cryogenic or cryogenic propellants. For Indian vehicle the first stage is with solid propellant. The specific details about the propellant are discussed in next section.

3. Participation of private sector towards the overall development of the launch vehicle family is evident barring India and China where no major involvement of the private sector is evident.

4. The payload capacity of GSLV-MK II is comparatively very low in comparison with other vehicles. However, GSLV-Mk II is the first variant of GSLV family and further modifications of this system are in the pipeline. Currently, GSLV-Mk III launch vehicle is under development and is expected to launch payload weighing 4500 to 5000 kg. The vehicle envisages multi-mission launch capability for GTO, LEO, Polar and intermediate circular orbits. GSLV-Mk III is designed to be a three stage vehicle. First stage comprises two identical S200 Large Solid Booster (LSB) with 200 tonne solid propellant, which are strapped on to the second stage, the L110 re-startable liquid stage. The third stage is the C25 LOX/LH2 cryo-stage.[7]

5. The time taken for the development of cryogenic engine technology appears to be quite significant in each case mostly more than ten years. ISRO took about fourteen years for this development and it appears that they had no late starter advantage.

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7 Indian Space Research Organisation. "Launch Vehicles :: GSLV Mark III." http://www.isro.org/launchvehicles/GSLVMARKIII/mark3.aspx. accessed February 6, 2014.

One of the reasons for this could be the cryogenic haves club been tight-lipped about the technological knowhow. One another important aspect could have been that during 1994 two important ISRO scientists working on cryogenic project were falsely named in some scam and by the time their innocence was proved their careers and India's cryogenic programme suffered significantly.[8]

6. The success rate for India and China is lowest, hovering around 50%. In case of India it may be noted that number of launches are two, one failure and success. Therefore critical assessment is foreseeable only by their future launch record.

7. In the Indian case, the thrust produced by CE7.5 GSLV MKII cryogenic engine is comparatively less. However, it also needs to be considered that the GSLV-D5 launch was with small payload.

For any assessment of launch vehicles it is important to recognize the importance of the propellants used for the rocket system. The history of research, design and manufacture of rocket systems indicate that correct handling of propellants has always been a challenge for the scientific community. Particularly for heavy launch vehicles mostly cryogenic engine technology has been found put in use. Mastering the cryogenic technology has proved to be the most challenging task for the rocket scientists. One of the complex challenges in this field has been the handling of the propellants.

The various propellants put in use has certain limits in terms of their overall composition and energy characteristics. Hence in order to understand the best option available in terms of propellant selection it is important to analyse the composition on certain vital parameters and their impact on the performance of the propellant.

Propellant

Propellant is the chemical mixture burned to produce thrust in rockets. Presently, most rockets operate with either solid or liquid propellants or combination of both. The propellant does not mean simply fuel; it means both fuel and oxidizer. The fuel constitutes of the chemical the rocket burns but, for burning to take place; an oxidizer (oxygen) is required to be present. Jet engines draw oxygen into their engines from the surrounding air. However, the rockets do not have the luxury that jet planes have; they need to carry oxygen with them into space, where there is no air.[9] It may be noted that cryogenic is low

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8 Rajeev Srinivasan, ""Who killed the ISRO's cryogenic engine? India News." http://www.rediff.com/news/column/who-killed-the-isros-cryogenic-engine/20131118.htm,. accessed February 6, 2014.

9 braeunig. "Basics of Space Flight: Rocket Propellants." accessed February 5, 2014. http://www.braeunig.us/space/propel.htm., and NASA Quest. "Practical Rocketry." accessed February 5, 2014. http://quest.arc.nasa.gov/space/teachers/rockets/rocketry.html.

temperature physics and propellants used for cryogenic stage in the overall rocket assembly usually involves a combination of liquid hydrogen and liquid oxygen or methane and liquid oxygen.

For understanding the importance of cryogenic engine in heavy launch vehicles it is essential to examine various important propellant characteristics of such system. Relevant discussion in this regard has been carried below.

The major components of rockets are rocket motor or engine, propellant as a fuel, control system and payload such as satellite. Typically of total mass, 91 percent is shared by propellant and 6 percent is that of payload[10]. Therefore, the propellant plays significant role in the success of a mission. Following table indicates the amount of propellants put in use for various stages of rocket. The values presented below are under ideal conditions and do not cater for the reduction in efficiency of rocket owing to losses due to atmospheric drag and heating:

Propellant	**Percentage Propellant for Earth Orbit**
Solid Rocket	96
Kerosene-Liquid Oxygen	93
Hypergolic[11]	94
Methane-Liquid Oxygen	90
Liquid Hydrogen-Liquid Oxygen	83

Table 1: Mass fractions (given as percentage of the total rocket mass).
Source: Expedition 30/31 Flight Engineer Don Pettit, NASA[12]

The above table indicates that to carry same payload, solid rocket has to carry 96 percent of propellant to the total mass leaving small margin for payload. It is also notable that this value reduces to 83 percent for cryogenic stage which leaves wide leeway of higher mass and payload integration.

Thrust is a force that moves rocket through air and space. Thrust is generated by the propulsion system of the rocket through the application of Newton's third law of motion

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10 About.com Inventors. "Rocket Engine and Mass." Accessed February 1, 2014. http://inventors.about.com/library/inventors/blrocketmass.htm.

11 In Hypergolic propellants when fuel and oxidizer come in contact they burn rapidly without the use of igniter.

12 NASA. "The Tyranny of the Rocket Equation." http://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny_prt.htm. accessed February 1, 2014.

(for every action there is an equal and opposite reaction).[13] The amount of thrust produced is directly associated with kind of propellant used on basis of its performance. For instance to produce 1 tonnes of thrust, Vikas liquid engine used in PSLV and GSLV, require 3.4 kg of propellant per second. Same thrust can be produced by cryogenic engine with only 1.85 kg of propellant per second.[14]

In order to appreciate the physics and chemistry of propellants it is important to compare few important features. Four explicit features like specific impulse, mixture ratio, oxidizer to fuel ratio and density are discussed below.

Oxidizer	**Fuel**	**Type**	**Specific Impulse (s, sea level)**	**Mixture ratio**	**Oxidizer to fuel ratio**	**Density (g/cc)[15]**
Ammonium Perchlorate (solid)	Aluminium + HTPB	Solids	277	2.12	-	1.21
	Aluminium + PBAN	Solids	274	2.13	-	-
Liquid Oxygen	Liquid Hydrogen	Cryogenic	391	5.0	6.0	1.48
	Kerosene (RP-1)	Semi-Cryogenic	352	2.30	2.56	1.02
Hydrazine	-	Monopropellants	303	-		-
Nitrogen Tetroxide	Kerosene	Hypergolic	267	1.08	1.34	
	Hydrazine	Hypergolic	286			1.22
	MMH	Hypergolic	280	1.73	2.52	1.20
	UDMH	Hypergolic	282	2.10	2.61	1.18

HTPB stands for Hydroxyl Terminated Poly-Butadiene and PBAN for Polybutadiene acrylonitrile

MMH and UDMH is Mono methyl hydrazine and Unsymmetrical dimethyl hydrazine

***Source:** Compiled, edited and written in part by Robert A. Braeunig, 1996, 2005, 2006, 2008*

***Source:** Compiled by authors from Robert A. Braeunig study and Encyclopaedia Astronautica*

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13 Space Flight Systems Mission Directorate. "Rocket Thrust.". http://exploration.grc.nasa.gov/education/rocket/rktth1.html. accessed February 7, 2014

14 Raj, Gopal. *Reach for the Stars: The Evolution of India's Rocket Programme*. New Delhi: Viking, 2000. pp 234

15 Encyclopedia Astronautica. "Index", http://www.astronautix.com/props/index.htm, accessed on February 9, 2014

The Specific impulse (Isp) is an important factor to measure efficiency of rocket. Specific impulse is defined as the thrust divided by the mass of propellant consumed per second. The result is expressed in seconds. The higher the specific impulse, the less propellant is needed to gain a given amount of momentum. Isp depends on combination of propellant and medium in which they are employed. In general trend propellant gives less Isp at sea level than vacuum.

The above table indicates that cryogenic engines are much more efficient in delivering high Isp. Liquid Oxygen and liquid Hydrogen combination is one of most energetic chemical reaction to produce high Isp used by rocket industry so far. However, due to its complex storage systems (it may be noted that Hydrogen remains liquid at temperatures of -253^{o}C and Oxygen remains in a liquid state at temperatures of -183^{o}C) high overall cost of propellants and highly corrosive nature makes it less attractive option to be used in all stages of rocket. Majority of the heavy lift vehicles use cryogenic in its upper stage, while for other stages there is a shift for semi-cryogenic propellants. This includes combination of liquid oxygen as oxidizer and kerosene (RP-1) as a fuel. Kerosene offers less Isp than cryogens, but due to its other properties like earth storable, no requirement of handling of any extremely low temperatures and ease in fabrication of the propellant chamber, they are preferred over other propellant combinations.

Mixture ratio is another important factor which explains the importance of the type of propellant put in use. Mixture Ratio is the ratio of oxidizer mass to fuel mass. We define the optimum mixture ratio as that which will produce the highest specific impulse for the given reactants. An engine with a high combustion chamber pressure and a low nozzle exit pressure, i.e. a large section ratio, will have the highest optimum mixture ratio. A propellant's optimum mixture ratio is a function of the pressures at which the rocket engine will operate. Higher mixture ratio means the propellant have fuel rich mixture and burn much more efficiently by producing higher thrust. This mixture ratio is also extended to oxidizer to fuel ratio (O/F). It is similar to air to fuel ratio in combustion engine[16]. This means that the amount of oxidant present in the reaction is just enough to completely burn the fuel. Therefore higher ratio indicates complete combustion hence better efficiency. Following table indicates the mixture ratio and O/F ratio to various compositions.

It is obvious that cryogens is undoubtedly has edge over other propellants. Semi-cryogens have higher O/F and mixture ratio, hence performs better than hypergols and solids.

Density of the propellant affects the design, manufacture and the efficiency of rocket engines. Propellant's density depends on the nature for fuel (like solid, liquid etc.) being

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16 University of Tulsa, Moeckel, W. E., and Weston, Kenneth C. "Introduction to combustion." Fuel and Combustion. http://www.personal.utulsa.edu/~kenneth-weston/chapter3.pdf. and Braeunig. "Propellant Combustion Charts", http://www.braeunig.us/space/comb.htm, accessed on February 2, 2014

used. It is important to note that both high and low density of any propellant has both advantages and limitations. For a given weight, dense propellant can be carried in smaller and lighter tanks, resulting in low overall weight of rocket[17]. Beside, higher density also implies higher mass flow, resulting in high exhaust velocity.

Lower density propellant can results in complication related to their storage. Liquid hydrogen for example has a very low density (0.071 g/cc) and, therefore, requires a storage volume many times greater. Nevertheless the overall density could be enhanced and compensated with high mixture ratio, resulting in reduction of storage volume. Hypergolic has better overall density, thus can be stored in smaller tanks. Hence, normally for a heavy lift vehicle the last stage is a cryogenic stage and earlier stages are hypergolic stages.

Conclusion

This brief has carried out an assessment of the launch vehicles used globally for launching of heavy satellites into the geostationary orbit. This assessment is mainly based on the comparison of the various features of different launch systems and the characteristics of the propellants put in use.

India has recently joined the club of countries capable of launching of satellites weighing more than 2 tonnes. The above assessment indicates that India has taken a long route develop the technology for heavy launch vehicles. Particularly, development of cryogenic technology has been a major challenge for India. However, the overall assessment indicates that other states too have undergone a longer gestation periods. India's trajectory for the technology development is similar to that of other agencies. However, presently India is a nascent player in this field and is required to make quick progress. India current launch vehicle has three states namely solid, liquid and cryogenic. In order to increase its payload carrying capability India needs to change this configuration and opt for semi-cryogenic stage as one of the stages in its GSLV programme. Since, now India has developed cryogenic engine technology it should not take much of a time to evolve a system with semi-cryogenic and cryogenic stages.

The current configuration for launch vehicles of major space agencies is based on semi-cryogenic and cryogenic approach. The futuristic porgrammes of various space agencies are also found revolving around advancing the semi-cryogenic technology. Presently, Russia has plans to advance its next version of Proton rockets for lifting 80 metric tons into low Earth orbit in a single launch. Subsequently, this system could be upgraded to launch 160 metric tons. The primary fuels for such heavy launches are proposed as semi-cryogenics. For India also it is essential to develop semi-cryogenic engines to launch heavy payloads in future.

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17 NASA. "GENERAL FEATURES OF ROCKET PROPELLANTS", history.nasa.gov/conghand/propelnt.htm, accessed February 7, 2014.