CURRENT AND NEAR-FUTURE SPACE LAUNCH VEHICLES FOR MANNED TRANS-PLANETARY SPACE EXPLORATION: Phobos-Deimos mission architecture case study

Abhishek Jain[1] and Nejc Trost[1]
Sasakawa International Center for Space Architecture, University of Houston, Houston, TX, 77004

This paper summarizes the initial study based on the Phobos-Deimos Explorer project, which was conducted at the Sasakawa International Center for Space Architecture (SICSA), Houston, USA. Safest and cheapest possible access to low Earth orbit were key mission architecture drivers for our manned Mars vicinity exploration project. The first part of the study investigates present and future launch vehicles, determining their capabilities and capacities in terms of fairing size, payload capacity and cost. The main challenge was to select the most suitable launch vehicle(s) for the mission with minimum number of launches and maximum efficiency. Heavy lift launch vehicles are needed mostly for trans-planetary exploration and also some larger satellites, which do not represent a major business prospect at this time. Despite this fact, some private companies anticipate future space exploration opportunities and are investing R&D funds to develop cheaper and safer access to space. In addition, commercialization of space and general public interest are essential for further space technology development. This paper summarizes options for safe, modular and efficient heavy lift launch vehicles for future space exploration and compares current mission proposals.

Acronyms and Abbreviations

BNTR = Bimodal Nuclear Thermal Rocket
DRM5 = Mars Design Reference Mission 5
ELV = Expendable Launch Vehicles
FH = Falcon Heavy
FXH = Falcon X Heavy
GTO = Geostationary Transfer Orbit
HAB = Habitation Module
IMLEO = Initial Mass in Low Earth Orbit
LEO = Low Earth Orbit
LVs = Launch Vehicles
MT = Metric Tons
PRLV = Partially Reusable Launch Vehicle
RLV = Reusable Launch Vehicle
SICSA = Sasakawa International Center for Space Arch.
SLS = Space Launch System
MPO = Mars Parking Orbit
TMI = Trans Mars Injection
TRL = Technology Readiness Level

I. Introduction

SINCE the beginning of space exploration, launch vehicles (hereinafter LVs) have been the most essential space components. They must resist huge stresses and heat produced by massive engines in order to escape the boundary of Earth's gravity and thus they are the most expensive and risky part of the space mission. The first segment of the study investigated present and future LVs to determine capabilities and capacities in terms of fairing size, payload, costs and Technology Readiness Level (hereinafter TRL). The central purpose was to design a mission to explore the vicinity of Mars, including a manned excursion to Phobos and unmanned exploration of Deimos, the moons of Mars. Main mission objectives are to send 3 astronauts to Phobos, stay 14 days on the surface and conduct various experiments. The main design challenge is to reduce fuel payload/mass required by delta-v budgets, and in turn, reduce the cost and complexity of the mission also considering alternative mission trajectories

[1] MS-SpaceArch student, SICSA, 122 College of Architecture bldg. University of Houston, Houston, TX 77204, AIAA Member.

and redesigning the habitat to minimum but still comfortable living conditions. SICSA investigated multiple mission architectures, various payloads and LV options, and then compared them with other mission proposals to estimate feasibility and cost factors. The comparison and selection criteria is briefly summarized in this paper and illustrated in tables and bar charts.

II. An overview of current and near future launch vehicles

An overview of existing and in development types of LVs was performed as an initial stage of the study. Expandable Launch Vehicles (hereinafter ELVs) and Reusable Launch Vehicles (hereinafter RLVs) were compared based upon status, lift capacity to LEO and GTO, shroud diameter, price per launch and TRL. Comparison tables are presented below (See Table 1 and Figures 5-7 in Appendix). The double line in Table 1 marks a distinction between operational and non-operational LVs. The Russian Proton-M is currently the largest operating vehicle after Shuttle's retirement but it does not enjoy the highest launch success rate. A major launch failure in the beginning of July 2013 has left this LV option in doubt. Despite this fact it is important to highlight that the largest operational LVs can currently launch to LEO only about a 22MT payload (Proton-M/Delta IV Heavy/Ariane5). In contrast, trans-planetary manned missions would require multiple vehicles with more than 100MT capacity. This section provides an overview of the LVs and technology demonstrators - both past and present.

A. ELVs are designed for one-time use. They usually separate from their payload, and may break up during atmospheric reentry. An ELV is made up of one or more rocket stages. After each stage has burned its compliment of propellant is expended (jettisoned from the vehicle) and left to land back on Earth. Their components are not reused after recovery [2].

B. RLVs are designed to be recovered and used again for subsequent launches (e.g. Skylon). No true reusable vehicle currently exists. Even the Space Shuttle was only a Partly Reusable Launch Vehicle (hereinafter PRLVs). SpaceX is currently developing a reusable rocket launching system designed for use on both the Falcon 9 and Falcon Heavy LVs [3].

Vehicle name	Producer	Country	Status	Type	Payload to LEO (kg)	Payload to GTO (kg)	Fairing diameter (m)	Price per launch (MIL US$)
Falcon XX	SpaceX	US	In develop.	PRLV	**140,000.00**	/	10.0	$ 300
Falcon X Heavy	SpaceX	US	In develop.	PRLV	**125,000.00**	/	10.0	$ 280
Saturn V	NASA	US	Retired	ELV	**118,000.00**	/	6.6	$ 1,160
Long March 9	CALT	China	In develop.	ELV	**100,000.00**	/	8.0	$ 350
Energia	NPO Energia	Russia	Retired	ELV	**100,000.00**	20,000.00	8.0	$ 764
SLS	Alliant Lockheed	US	In develop.	ELV	**100,000.00**	/	8.0	$ 1,000
Falcon 9 Heavy	SpaceX	US	In develop.	PRLV	**53,000.00**	12,000.00	4.6	$ 123
Angara A7	Khrunichev	Russia	In develop.	ELV	**40,500.00**	12,500.00	5.1	$ 140
Long March 5	CALT	China	In develop.	ELV	**25,000.00**	14,000.00	5.0	$ 105
Angara A5	Khrunichev	Russia	In develop.	ELV	**24,500.00**	7,500.00	4.3	$ 105
Space Shuttle	NASA	US	Retired	PRLV	**24,400.00**	/	4.6	$ 300
Proton-M	Khrunichev	Russia	Operational	ELV	**23,000.00**	6,920.00	4.4	$ 75
Delta IV Heavy	BLS/ULA	US	Operational	ELV	**22,977.00**	13,399.00	5.0	$ 330
Ariane 5	ESA (Astrium)	EU	Operational	ELV	**21,000.00**	9,000.00	5.4	$ 220
Atlas V	LM CLS/ULA	US	Operational	ELV	**20,520.00**	8,900.00	4.2	$ 128
H-IIB	Mitsubishi Heavy Ind.	Japan	Operational	ELV	**19,000.00**	8,000.00	4.6	$ 114
Angara A3	Khrunichev	Russia	In develop.	ELV	**14,600.00**	3,600.00	3.8	$ 70
Zenit 2	Yuzhnoye D. Bureau	Ukraine	Retired	ELV	**13,740.00**	5,000.00	3.3	$ 45
Zenit 3 SL	Yuzhnoye D. Bureau	Ukraine	Operational	ELV	**13,600.00**	5,250.00	4.1	$ 75
Delta IV	BLS/ULA	US	Operational	ELV	**13,360.00**	7,020.00	5.0	$ 250
Falcon 9	SpaceX	US	Operational	PRLV	**13,150.00**	4,850.00	5.2	$ 50
Skylon	Reaction Engines Lim.	UK	In develop.	RLV	**12,000.00**	5,000.00	4.8	$ 35
Long March 3B	CALT	China	Operational	ELV	**12,000.00**	5,700.00	3.3	$ 50
Soyuz-FG	TsSKB-Progress	Russia	Operational	ELV	**7,800.00**	4,500.00	4.1	$ 50
Antares	Orbital Sciences Corp.	US	Operational	ELV	**6,120.00**	/	3.9	$ 80
Strato Launch	Scaled C. & Orbital S.	US	In develop.	PRLV	**6,100.00**	/	5.0	$ 15
Delta II	BLS/ULA	US	Operational	ELV	**6,097.00**	2,171.00	2.9	$ 37

Table 1. List of current/past and near future launch vehicles [4].

Cost analysis of current and near future LVs shows us that PRLVs and RLVs are essential for further mission cost reduction. The current LVs are partially reusable or not at all. The technical challenges of designing a system to fly multiple missions to orbit and back are monumental. For example, the entire Saturn V rocket was expended while sending humans to the Moon. On the other hand, the Space Shuttle, which transported astronauts to LEO and back, was reused repeatedly but the cost was high. A number of government research projects, most notably the X-33, X-34, X-37 and X-38, were initiated to develop and test next generation RLV technologies. At the same time, a number of entrepreneurial companies have developed their own RLV concepts (e.g. Scaled Composites, Xcor, Stratolaunch, etc) in an effort to reduce launch costs and undercut established LV providers, but their lift capacities are limited at this time to suborbital operations or small LEO satellites.

C. Cost reduction on launch systems

A LV or carrier rocket is used to carry payload from the Earth's surface into outer space. LVs are the most important drivers of the cost of any space mission and hence are the major factor responsible for its success (or failure). Every mission has certain budget limits and controlling LV costs represents a major priority. Reducing launch expenses makes more funds available for other aspects of a mission. Cost overruns may result in long mission delays or even cancellations. There are a couple of ways to reduce the launching expenses:

a. With currently operating ELVs:

1. Reduction in the number of launches for particular mission would drastically affect the cost of overall mission and increase the launch safety;
2. reducing the size of the mission (e.g. habitat with just the most essential components) but this approach may present risks in terms of mission success, or even crew safety;
3. selecting vehicles in compliance to the mission with maximum payload capacity and minimum cost. This may involve the use of variety of LVs, depending upon the mission requirements, launch windows and delta-v budgets.

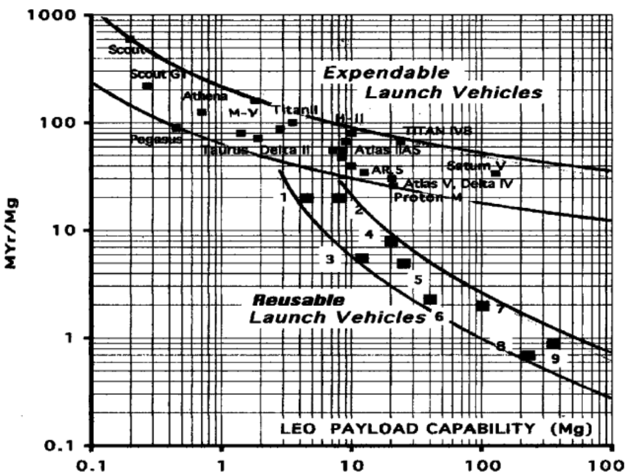

Figure 1. Cost comparison of ELVs and RLVs [1].

b. With future RLVs:

1. Development of technologically advanced RLVs initial cost of investment may be high, but economical in the long run (in case of higher launch frequency);
2. reusability will allow using the same vehicles/components for different/multiple missions, and thus result in minimalized production cost and increased reliability/safety.

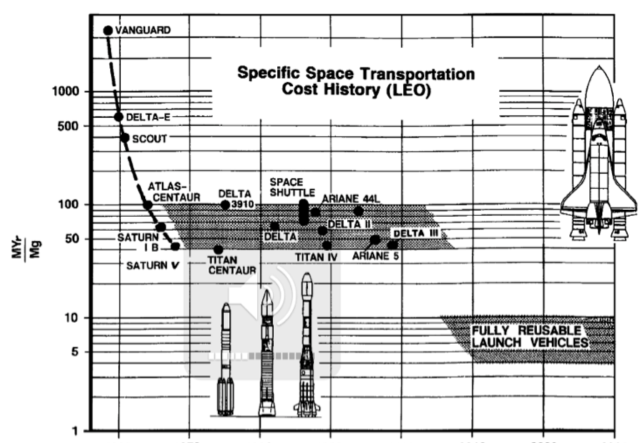

Figure 2. Specific space transportation cost history (LEO) [1].

General considerations:

- Space transportation cost is generally viewed as the biggest growth obstacle of the space commercialization and exploration;
- Space transportation represents typically 25-70% of a specific space program [1];
- Rapid cost decrease took place in the 1960's due to growth of LV size/capability (Figure 2);
- LEO transportation costs remained constant over 40 years: between 40 and 100 MYr/Mg or 10,000 and

25,000 USD/kg (2007) (Figure 2);
- Additional cost decrease would occur after RLVs start their operations (Figure 2);
- Reusability is only justified for vehicles with more than 10MT LEO payload [1];
- Significant cost reduction is only achievable with fully RLVs [1] or new, yet unknown revolutionary propulsion, which would replace expensive and heavy chemical engines.

III. Launch vehicle selection

The launch vehicles list was further analyzed to compare payload to LEO capacity and the ratio between payload capacity and cost/kg (see Figure 3 bellow). LVs were then listed upon highest to lowest payload capacity and cost/kg ratio. Further selection was made based upon multiple transplanetary human exploration reference missions that requires min 40MT lift capacity (all vehicles bellow that number in Figure 3 were eliminated but are still shown as a cost analysis reference). In addition, we also excluded retired LVs from further selection such us: Energia, Saturn V, Zenit 2 and Space Shuttle.

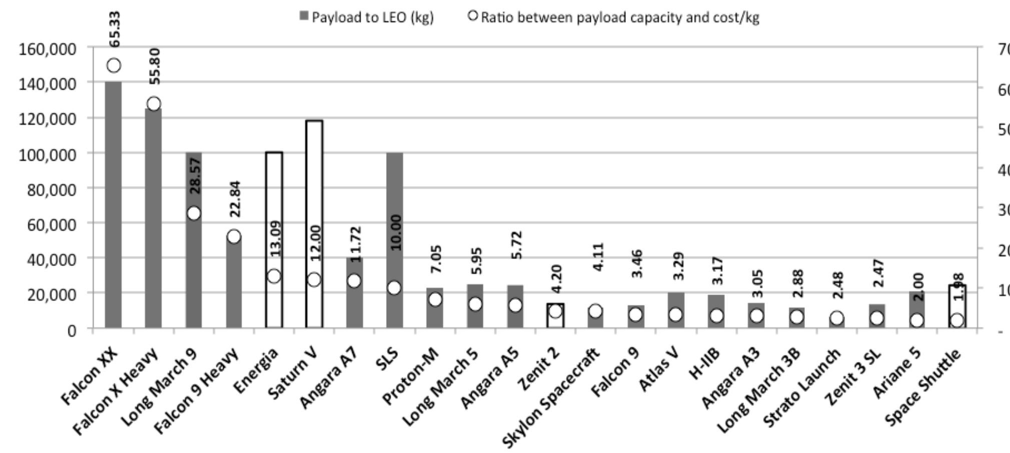

Figure 3. Ratio between payload capacity and $/kg.

Final selection (see Figure 4 below) consists of various vehicles developed in different countries, both private and government funded. According to our analysis, the SLS (Space Launch System) meets the requirements but its price per kilogram is the highest from selected vehicles. However, due to the fact that it is a government supported project, it might still be one of the most plausible realization in the future. Both foreign projects, Long March 9 and Angara A7, have good lift capacities and fairly reasonable launch price. Nevertheless, ITAR restrictions and lack of heavy-lift development experiences should be considered. On the other side, privately funded SpaceX offers perspective heavy-lift boosters with very high ratio between payload capacity and $/kg and makes it most efficient selection for our Phobos-Demos mission.

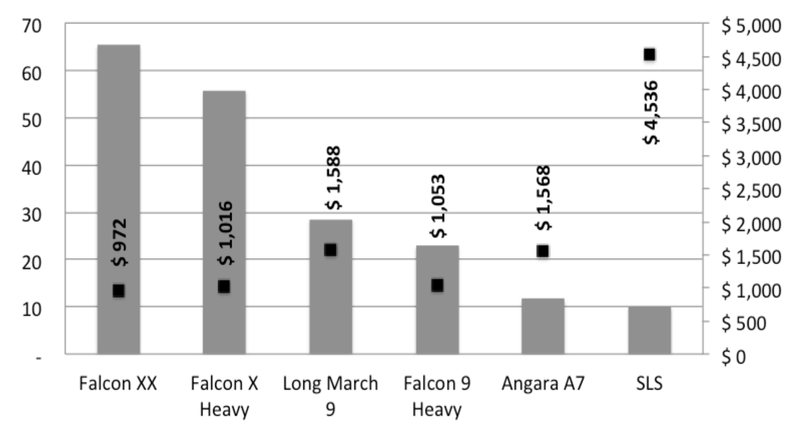

Figure 4. Final selection ratio and cost/lb.

A. Limitations of Existing Launch Systems

Current LVs have certain limitations that need to be addressed and are important for assessment to improve the future generation of LVs. Few limitations and ways to improve them are listed:

- **A lack of "resiliency"** – Resiliency is the ability of a launch fleet to maintain schedules despite failures. The resiliency of existing launch fleets was in question by the ELV and Shuttle launch failures in 1986. In order to increase space transportation resiliency, nations could develop new, reliable launch systems or make existing vehicles more reliable [5].
- **High launching costs** – Current launch costs are between $3,000 and $6,000 per pound delivered to LEO. Such high costs limit the amount of civilian, military, and commercial space activity that a nation can reasonably afford. "For example, payload sizes in some SDI mission models are compatible with today's LVs, but launch costs using current vehicles would be unacceptably high because too many launches would be required" [5].
- **Limits on payload size** - Current LVs have the ability to launch payloads up to 48,000 to 117,000 pounds into LEO, or about 20,000 pounds into geosynchronous orbit. Future space missions could benefit from a LV with a greater lift capacity [5].

To increase the resilience of launch systems, nations could pursue one or more of the following alternatives:

- Develop new, more reliable launch systems by incorporating the technology into the designs for new LVs. However, developing a new space LV is a challenging task involving significant technical and financial risk. The efforts underway are the development of reusable launch systems like the Grasshopper from SpaceX with vertical takeoff and landing [5];
- Increase the reliability of current launch systems by replacing some subsystems on existing vehicles with new, more reliable subsystems, increasing the systems' overall reliability and resilience [5];
- Increasing current ground facilities and by acquiring more of the existing LVs and payloads – In case of a failure more ground facilities would help in improve resiliency by reducing the time it takes to fly off the backlog and return to normal operations instead of interrupting the launch activities [5].

B. A Sustainable Solution?

A mix of launch alternatives; existing ELVs, new expendable and reusable vehicles and low-cost cargo launchers, doesn't offer an integrated solution that a heavy lift vehicle that could send crew to the Moon in one or two launches can. Instead, the various components of such a mission would be launched on different vehicles: major spacecraft components on ELVs like Falcon X Heavy in SICSA's mission, crews on ELVs or perhaps small RLVs, and consumables on cargo launchers. "This alternative sounds far more complex, and, in many respects, it is. However, this same infrastructure can be used for far more than just human missions to the Moon: it can serve as the basis for journeys to Mars and other destinations in the solar system. The same infrastructure could conceivably support commercial and other government applications" [6]. This architecture could end up being far more affordable and sustainable in the long run than any system that relies on a new heavy lift launch vehicle [6].

V. Current trans-planetary mission proposals

To identify common needs for heavy lift LVs for future trans-planetary manned exploration we looked at four recently proposed missions to Mars or its vicinity and compared them with SICSA's Phobos-Deimos mission proposal (see Table 2 on following page for further details):

A. NASA's DRM 5:

DRM5 is proposing conjunction class (900 days, also referred as "long stay") mission to Mars surface. Total mission duration and total IMLEO were the largest within our study cases. Fairly large-scale architecture suggests pre-deployment missions and consequently crew launches with approximately nine SLS launch vehicles. NTR is considered as main TMI/TEI propulsion system. Despite the size, mission offers increased safety redundancy and supports long-term human Mars exploration on a larger scale.

B. Dr. Fred Singer's PH-D proposal:
Singer's proposal was initially published in 1981, revised 2013, and proposes opposition class (also referred as short stay) Mars mission with pre-deployment and manned landing on Deimos. Total duration of mission would be 545 days, with the surface stay of 2-4 weeks. In comparison to other proposals this mission suggests proven chemical engines instead of NTR resulting in more required TMI fuel tanks (due to lower engine Isp's). Lift to LEO considers both SLS and Falcon family LVs.

C. Tito's Mars Inspiration:
Recently announced Tito's Mars Inspiration mission suggests extremely minimal approach using free return trajectory (launch window in 2018). Complete Mission will be 501 days long and it would swing by Mars for about 10 hours already on its way back to Earth. The project differs from others due to direct injection from Earth towards Mars (without assembly in LEO) using Falcon's heavy excess delta-V. Single launch volume and mass limitations (10MT for HAB) makes this mission extremely challenging regarding crew comfortability.

D. SICSA Phobos-Deimos Explorer v2:
SICSA's Phobos-Deimos mission v2 suggests opposition class mission (545 days) and landing on Phobos for four weeks before returning to Earth. Its efficient and modular design enables this mission to be fitted in two FXH's and additional F9 for crew resulting in low total IMLEO=141MT. Scenario purposed also as a Mars precursor mission.

	NASA DRM 5	**Dr. Fred Singer PH-D Proposal**	**TITO's Mars Inspiration**	**SICSA Phobos-Deimos v2**
Year of study	2009	1981/ rev.2013	2013	2013
Crew	10	5-8	2	2-3
Mission duration	≈ 900 days	≈ 545 days	≈ 501 days	≈ 545 days
Venus swing-by	NO	YES (both directions)	NO	YES (outbound)
Total IMLEO	≈ 848 MT	≈ 400 MT (est.)	≈ 10 MT	≈ 141 MT
Payload mass	?	≈ 50 MT + 50 MT	≈ 10 MT	≈ 40 MT
Fairing diameter	8.0 m (26.2 ft)	8.0 / 8.5 m (26.2 / 27.8 ft)	5.2 m (17 ft)	8.5 m (27.8 ft)
Pre-deployment at Mars vicinity	YES	YES (nuclear reactor)	NO	NO
Starts in LEO	YES	YES	NO	NO (GTO)
Number of deployments from LEO	3	2	1	1
TMI propulsion	NTR	Chem / Solar	Excess Delta-V	BNTR
H-Lift launches (≈ 125 MT) SLS or FXH	9 x SLS	5-6 x SLS/FXH	0	2 x FXH
Crew launch (Falcon 9 or FH)	0	1-2 x FH	1 x FH	1 x F9
International cooperation	YES	NO	NO	NO
Coop. with private companies	NO	YES	YES	YES
HAB parking position	MPO	Deimos orbit (4 weeks)	NO	MPO
Stay at moons/ Mars	500 days	2-4 weeks	10 h	4 weeks
Assembly in LEO	YES	6 months	NO	IN GTO, SHORT
Total Mission duration	min 5 years (pre-deploy)	min 3 years (pre-deploy)	1.4 years (direct)	1.5 years (direct)

Table 2. Mars missions comparison [7-10].

In current scenario of launch systems when there are no specific LVs for particular mission, the missions should be designed according to LVs availability in present or near future. The SICSA's Phobos-Deimos mission is one example of this approach. The idea is to use maximum fairing diameter of a LV selected for the mission. Mission components such as HAB, Phobos explorer, LH2 fuel tanks for TMI and other components are designed specifically to fit into LV fairing. This helped in utilizing the maximum payload capacity and fairing volume resulting in reduced number of launches (2xFXH + 1xF9). Major consideration was given to SpaceX's Falcon family and NASA's SLS, both suitable for the mission.

SICSA's general mission considerations were:
1. Travel safe and light with minimum required equipment;
2. Land on Phobos and safely return crew to Earth;
3. Utilize COT's for different vehicle/HAB subsystems;
4. Ergonomic/flexible interior architecture for maximum crew comfort.

VI. Conclusion

The research conducted during this project suggests that:

- A minimalistic approach to mission planning and design leads to cost reduction and therefore more affordable manned mission space exploration;
- crew comfort and safety has to be considered as one of the main challenges associated with reduction of e.g. HAB size/volume;
- utilizing the maximum LV fairing size, volume and lift capacity;
- development of new launching/propulsion technologies (alternative to chemical engines) is essential for rapid commercialization of space and manned space exploration;
- more the cost is reduced, more can be achieved in terms of mission success and more research and funds can be invested in other pursuits of the mission;
- there is a lack of heavy lift LVs in the market for reasonable launch price as the satellite business is going "smaller" every year with more sophisticated communication and sensor technologies;
- good and cost effective mission can be designed by using a combination of LVs depending upon the type of payload (e.g. in SICSA's Phobos-Deimos mission Falcon X heavy is chosen for transportation of big payloads such as fuel tanks and HAB, crew was transported with Falcon 9);
- the contribution of private sector in developing new LVs leaves more resources for big organizations like NASA to focus on other R&D priorities;
- Trans-planetary missions will be non-profitable during first years of operations but they will eventually become profitable with the involvement of private companies such as SpaceX, etc;
- the private sector has already recognized this new, emerging market and started pursuing it;
- private companies like SpaceX, with much better cost-effective production and some novel tech solutions are already competing with government-funded projects. (For instance best commercial airliners are run by private companies - more flexible, adaptable company organization.);
- future of Space missions greatly depends on the development of new launching systems those completely reusable and cost effective.

Acknowledgments

We would like to express our deep gratitude to Professor Larry Bell and Professor Olga Bannova, our research supervisors, for their patient guidance, enthusiastic encouragement and useful critiques of this research work. We would also like to thank SICSA lecturer Bob Sauls for his guidance in the early stages of this project.

References

1. Koelle, D. E. "Specific transportation costs to GEO — past, present and future," *Acta Astronautica* Vol. 53, No. 4–10, 2003, pp. 797-803.
2. Technology, A. S. "Expendable Launch Vehicles." Andrews Space & Technology.
3. Technology, A. S. "Reusable Launch Vehicles." Andrews Space & Technology.
4. "2011 U.S. Commercial Space Transportation Developments and Concepts: Vehicles, Technologies, and Spaceports," January 2011, p. 111.
5. DalBello, R. "Launch Options for the Future: A Buyer's Guide." Washington, DC 20402-9325, July 1988.
6. Powell, J., Powell, J., Maise, G., and Paniagua, J. "NEMO: A mission to search for and return to Earth possible life forms on Europa," *Acta Astronautica* Vol. 57, No. 2, 2005, pp. 579-593.
7. Group, M. A. S., and Headquarters, N. "Human Exploration of Mars Design Reference Architecture 5.0," *Human Exploration of Mars Design Reference Architecture 5.0*. NASA Johnson Space Center, Houston, Texas, 2009.
8. Singer , S. F., and Emeritus. "Manned Space Goals: Science and Adventure to Mars via its moon Deimos," *Science & Environmental Policy Project*. Pasadena, CA, 2012.
9. Tito, D., MacCallum, T., Carrico, J., and Loucks, M. "Feasibility Analysis for a Manned Mars Free-Return Mission in 2018 - FISO," *Future In-Space Operations (FISO) telecon colloquium*. Wilshire Associates Incorporated, 2013.
10. Drake, B. G., Baker, J. D., Hoffman, S. J., Landau, D., and Voels, S. A. "Alternative Strategies for Exploring Mars and the Moons of Mars." Houston, Texas, 2012

Appendix

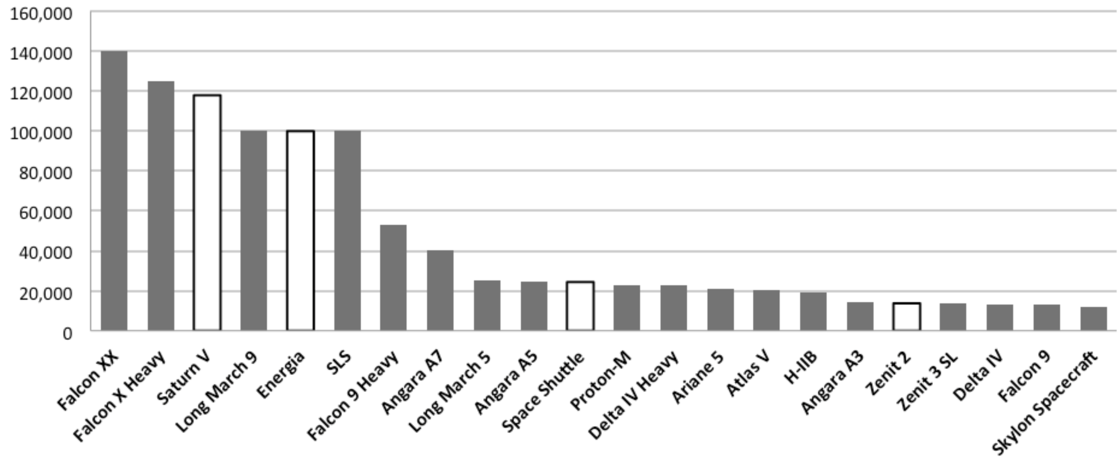

Figure 5. Payload to LEO(kg).

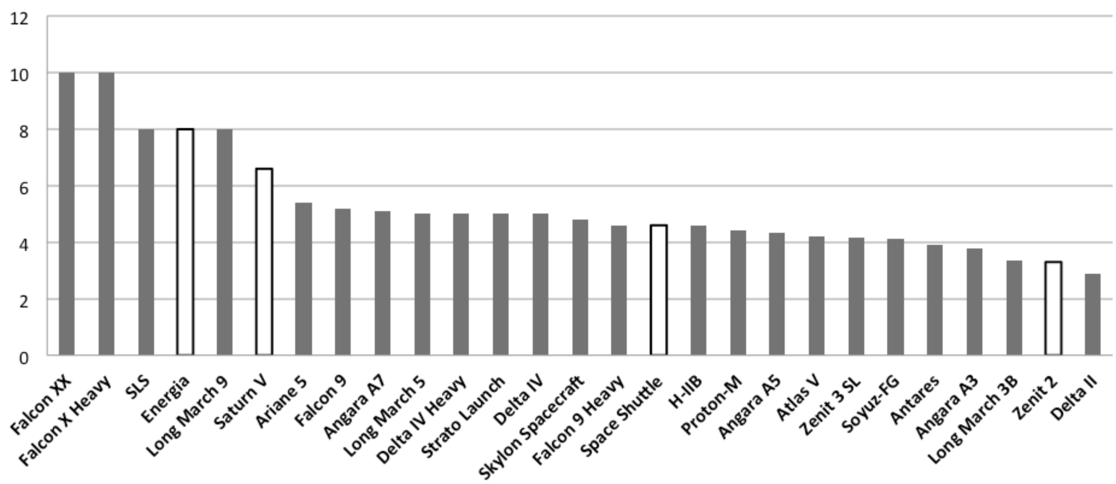

Figure 6. Fairing diameter(m).

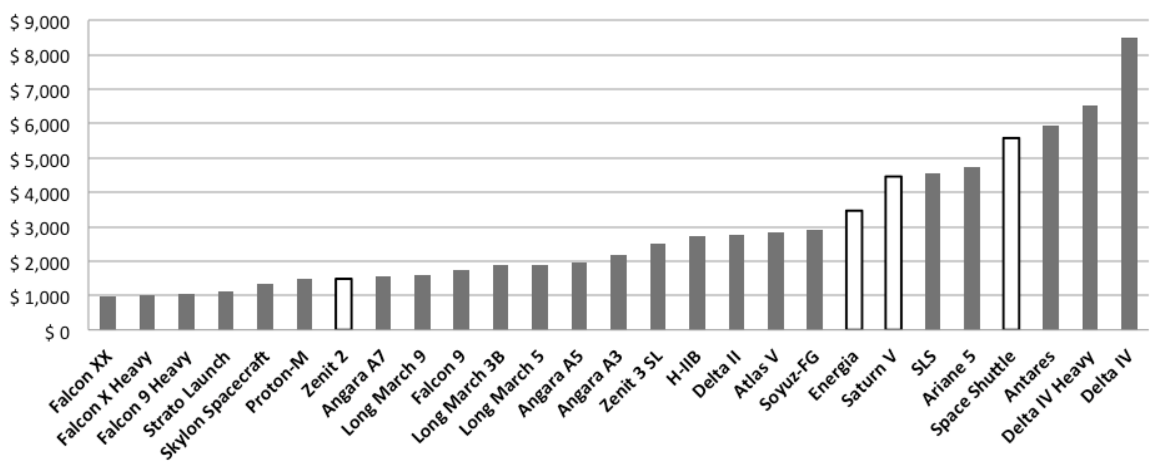

Figure 7. Cost comparison $/lb.