DEVELOPMENT AND TRANSPORTATION COSTS OF SPACE LAUNCH SYSTEMS

D. E. Koelle[1], R. Janovsky[2]
1: TCS-TransCostSystems, Ottobrunn, Germany
2: OHB-System AG, Bremen, Germany

DGLR-WORKING GROUP "SPACE TRANSPORTATION"

The **DGLR S4.1 Working Group on Space Transportation Systems** (Fachausschuss S4.1 Raumtransportsysteme) is a forum for members from agencies, institutions, industry and universities. Gathering and analysing information and argumentation on space transportation systems' past, status and future is the objective of the group.

The analysis and documentation is coordinated around the topics

– Demand / Market
– System Concepts & Subsets
– Propulsion, Structures & Subsystems (System related aspects)
– Missions & Operations (incl. Ground infrastructure)
– Cost (Development, Production & Operation)
– Projects / Programmatic (Development & Demonstration)

Subject of this paper is to give an overview on the cost aspects of space transportation.

INTRODUCTION

In the past 20 years quite a number of detailed studies and technology development programs for fully reusable space launch systems have been performed, in order to implement a major reduction of the cost for the "access-to-space" and increase of reliability and safety in the area of space transportation. These have been the German Sänger Hypersonic Technology Program, the ESA FESTIP studies, the US NASP effort, the X-33 (Venture Star) and DC-X experimental vehicles as well as the HOPE project in Japan. However, none of these efforts resulted in the development of an operational reusable launch vehicle (RLV). The paper analyzes what has prevented up to now and for the foreseeable future a major progress in cost reduction. The paper will discuss the historical cost evolution for LEO and GEO missions as well as the important impact of payload size and launch frequency on the transportation costs.

1. THE COST HISTORY OF SPACE ACCESS

The transportation of a payload into space is still a very expensive venture. Unfortunately due to the use of the same expendable launch vehicle technology and techniques as in the 60ies of the last century, there has been no reduction of space transportation costs to LEO (Low Earth Orbit) since more than 40 years. FIG 1 shows that the lower limit of specific transportation cost (SpTC) to LEO in the year 1968 using Saturn V was about the same as for the more recent Delta IVH vehicle in 2007:

– 35 MYr/Mg (Man-Year per ton) or 9000 US Dollars per kg (2007)

without the additional insurance cost.

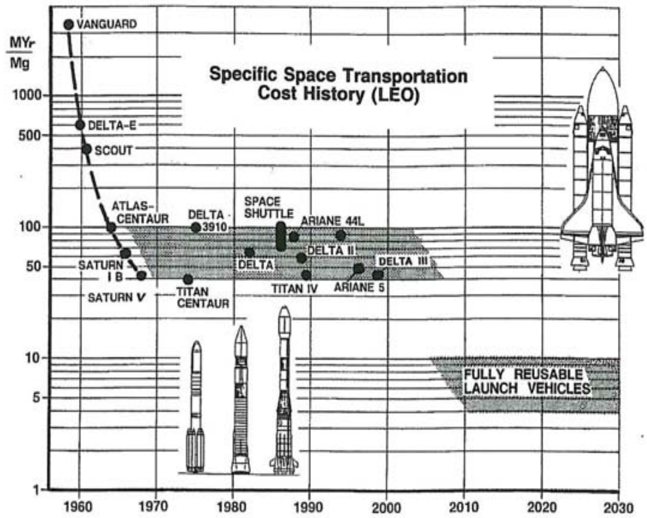

FIG 1. Historic development of specific transportation cost to LEO (US and European LVs)

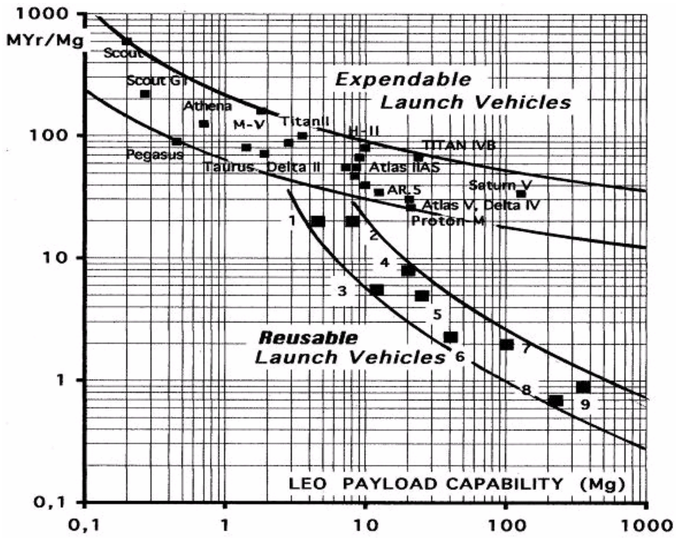

FIG 2. Specific transportation costs to LEO versus vehicle payload capability (US and European LVs)

FIG 2 also illustrates not only the costs of existing ELVs, but also the expected SpTC of Reusable Launch vehicles (RLVs). These are the result of detailed studies on different RLV concepts and performed by different companies. Two conclusions can be drawn:

- For payloads below some 10 tons ELVs are the most cost-effective means of transportation.
- The RLV cost advantage grows with size: For a 20-t-P/L vehicle it may be a factor 2, for a 100-ton-P/L vehicle it may be more than a factor 10 (depending on the launch frequency).

The impact of the annual launch rate on the Cost-per-Flight is illustrated in FIG 8 for an ELV and RLV example.

The SpTC are calculated with 100% utilization of the launch vehicle payload capability. The actual average utilization, however, is only in the order of 80 %.

For GTO/GEO missions the historic development is somewhat different compared to the LEO situation: In this case a real cost reduction has taken place for two reasons:

- the improved performance of the upper stages (LH2/LOX propulsion instead of solid motors), and
- the substantial increase of the GEO satellite mass (from 250 kg in the 60ies to 3600 kg in 2007 kg BoM - Begin of Mission).

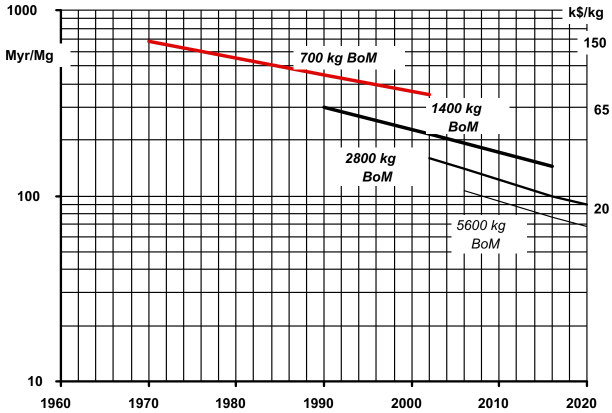

FIG 3. Historical development of SpTC for satellite launches to GEO with impact of spacecraft mass

FIG 3 shows both: the specific cost reduction effect by technology improvement for the same satellite mass, as well as the cost reduction by the satellite mass growth. Together it is one order of magnitude: from 300 000 USD/kg (2007 value) in the 60ies for a small satellite to some 30 000 USD/kg for a large GEO satellite in 2007.

2. PRICE AND COST DEFINITIONS

The price for a payload launch the customer has to pay depends on many factors:

- the customer payload requirements (payload mass and size),
- number of payloads (bulk buy),
- special launch services required,
- world market competitive situation
- financial and economic conditions (currency exchange rate, company hour rate in the country of launch vehicle production) plus
- insurance fee for launch and payload (in case of ELVs)

Depending on the past launch reliability, the insurance fees can reach 10 to 20 % of the launch price plus payload cost. This is a substantial factor which is not included in the values of FIG 1 to FIG 3.

The launch price should normally cover the "Cost-per-Flight" (CpF) of the launch vehicle provider which are consisting of

- Vehicle Production Cost (taking into account the "Learning Factor") in case of ELVs or the vehicle cost amortization in case of RLVs,
- the Direct Operations Cost (DOC) including propellants and materials, ground and flight operations, mission planning, transport (and recovery, if applicable), refurbishment in case of RLVs, fees and public damage insurance,
- the Indirect Operations Cost (IOC) including program administration and system management, technical system support, launch site support and maintenance,
- Company profit and amortization fees.

The mainly constant annual IOC are the reason that the CpF become very expensive in case of only 2 or 3 launches per year. A quantitative example of this effect can also be seen in FIG 8.

The following chart (FIG 4) provides a survey about the actual specific launch prices for LEO missions, including Russian and Chinese vehicles which can offer lower prices due to the economic situation in these countries. Some of the launch vehicles are out of service today and are shown for comparison.

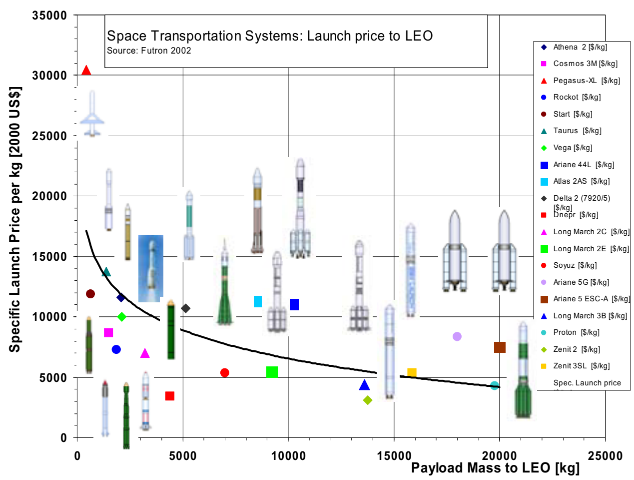

FIG 4. Survey about specific launch prices to LEO including Chinese and Russian vehicles [3]

A size-effect with a decrease of the specific launch price per kg with the payload capacity of the launch vehicle is clearly observable. Further, the Russian and Chinese launch vehicles represent the lower end of the launch prices in all payload mass categories. The same overview is presented in FIG 5 for GTO missions. To compare these prices with the GEO SpTC the actual mass in GEO at BoM has to be calculated (Factor 1.85 for launches from ETR/Cape Kennedy, and factor 1.65 for launches from Kourou).

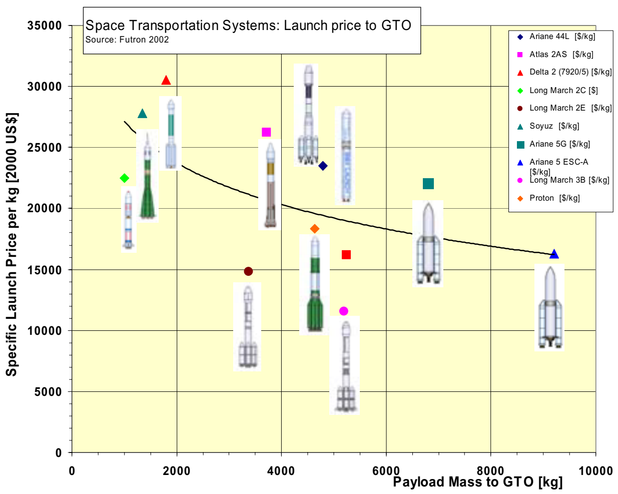

FIG 5. Survey of launch prices to GTO including Chinese and Russian Launch Vehicles [3]

Also here a size-effect is observable, however it is not as pronounced as for LEO. In the category of heavy launch vehicles, the Ariane-V is competitive with regard to its specific launch price.

3. COST OF REUSABLE LAUNCH SYSTEMS VS. EXPENDABLE VEHICLES

In order to analyse and compare the cost constitution of expendable and re-usable launch vehicles, a life-cycle cost comparison was set-up, based on the following assumptions and constraints:

ELV: Cost model assumptions & constraints

– 9t payload capacity to GTO
– 6 flights per year, 30 years of operation (180 vehicles produced)
– Cost of theoretical first unit (TFU) 220 M€
– Learning curve factor 0.875
– Fixed Cost launch site 300 M€/year (IOC)
– Insurance rate 10% of average vehicle production cost

No re-financing of the development cost was included. With these assumptions and constraints, one can calculate average CpF of approx. 153 M€ or specific cost 17 k€/kg of payload. These costs are constituted as shown in FIG 6. Roughly 53% of the CpF are the cost-share of the vehicle production. This average value takes into account, that due to learning effects during the series production the cost decrease from 220 M€ for the TFU to approximately 65 M€ for the last one (#180). The next major cost share are the IOC, which contribute roughly 1/3 to the overall CpF. These cost basically include all efforts to provide and operate the launch site and its facilities. It is obvious, that this cost share is strongly dependent on the annual launch rate. Flight operations costs contribute roughly 10% to the overall CpF. Also here a learning factor of 0.875 was assumed, reducing these cost from flight to flight. Insurance costs are in the order of 5% of the CpF

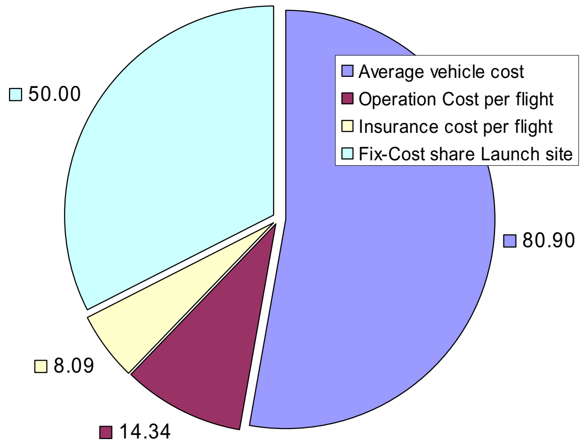

FIG 6. Constitution of ELV-cost (cost in M€)

From FIG 6 it is obvious, that the main factors influencing the CpF and thus also the competitivness of an ELV are the production cost, followed by the IOC.

A similar analysis was performed for a RLV. Here, the following assumptions and constraints were applied:

RLV: Cost model assumptions & constraints

– 4t payload capacity to GTO
– 12 flights per year, 30 years of operation (fleet of 5 vehicles produced)
– Cost of theoretical first unit (TFU) 600 M€
– Learning curve factor 0.875
– Fixed Cost launch site 300 M€/year (IOC)
– Insurance rate 1% of average vehicle production cost

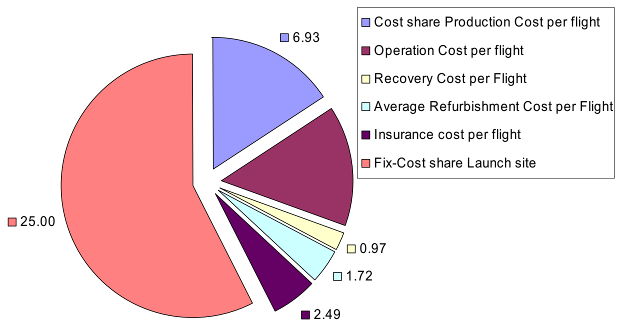

FIG 7. Constitution of RLV-cost (cost in M€)

This theoretical RLV has exactly half of the payload capacity to GTO as the ELV shown previously. However, it was assumed, that it transports the same annual payload mass to GTO, thus requiring the double of the ELV annual launch rate. As for the ELV, no re-financing of the development cost was assumed. The same fixed costs for the launch site operations (300 M€/year) as for the ELV were assumed, whereas the insurance is only 1% of the average vehicle production cost per flight, taking into account the inherently higher reliability of RLVs. With these assumptions and constraints, one can calculate average CpF of approx. 43 M€ or specific cost 9.7 k€/kg of payload. These costs are constituted as shown in FIG 7. Roughly 58% of the CpF are the cost-share of the IOC. The vehicle production cost share is only ~7M€ per flight or 16%. This average value takes into account, that due to learning effects during the series production the cost decrease from 600 M€ for the TFU to approximately 360 M€ for the last one (#5), with an average cost of ~500 M€ for the fleet of five vehicles. The operation costs per flight are approximately 6.8 M€, whereas the cost for insurance, recovery and refurbishment and maintenance are lower by approximately one order of magnitude. Due to the large share of the indirect operations cost it is obvious, that the CpF of an RLV is even more dependent on the annual launch rate than the ELV. This effect is clearly observable in FIG 8, where this rate is varied between one and ten flights per year for the ELV&RLV.

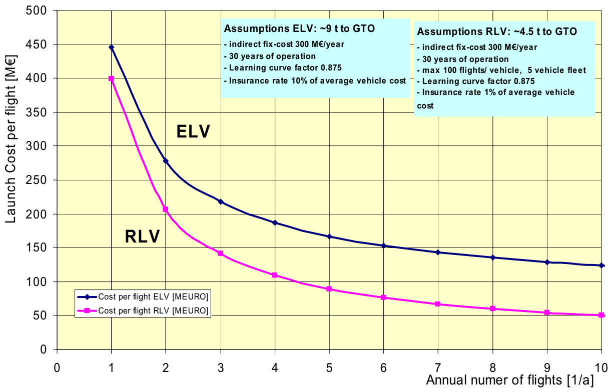

FIG 8. Influence of annual launch rate.

At very low annual launch rates (one flight per year), the CpF increase dramatically, by a factor of three for the ELV and a factor nine for the RLV, compared to their "nominal" launch rates of 6&12 flights per year. Beyond a certain threshold the influence of the annual launch rate decreases, the difference in the CpF between ELV and RLV is approximately constant at 70 M€ cost advantage for the RLV. It is to be re-called, that the ELV has the double payload capacity of the RLV.

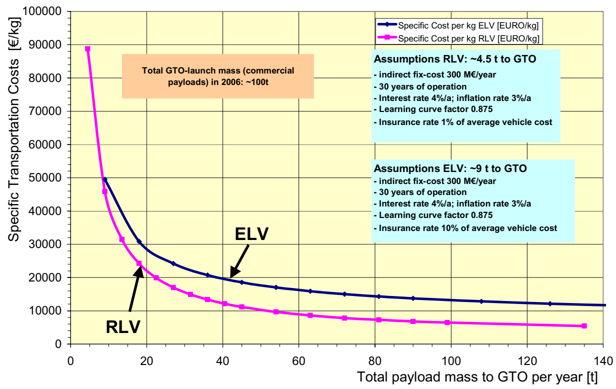

FIG 9. Influence of annual launch mass

The influence of the annual launch mass to GTO on the specific transportation costs for both vehicle types is shown in FIG 9. The starting points of each curve are representing one flight per year, which means 9 tons to GTO for the ELV and 4.5 tons to GTO for the RLV. At these small transportation rates, the specific transportation costs increase dramatically to 50 k€ per kg respectively 90 k€ per kg for the ELV and the RLV. It is to be noticed, that reusable LVs are even more costly than using expendable ones. With increasing transportation demand, the specific transportation costs decrease dramatically for both types of vehicles, but, due to the effects described before, more for the RLV. For an annual mass to GTO of 9 tons, which is equal to two RLV-flights and one ELV-flight, the specific costs are roughly the same. With further increasing transportation demand, the RLV gets cost advantages of approximately 6-8 k€/kg or 20-50%. A cost advantage by orders of magnitude for the RLVs is not to be expected, since the specific ELV-cost also decrease with the transportation demand.

4. FUTURE COST REDUCTION POTENTIAL OF REUSABLE LAUNCH SYSTEMS

Although several attempts have been made in the past to initiate the development of reusable launch vehicles, such as the German Sänger Hypersonics Technology Program, the NASP Program, the NASA "Venture Star" Project, the Kistler K-1 Vehicle, no such vehicle was finally realized.

The major impediment for the development of a larger RLV are the high development cost in the range of 5 to 25 Billion Dollars. Cost reductions (up to 50 %) would be feasible compared to the historical "Business-as-Usual" (BaU) approach if cost engineering principles and modern management methods (less multiple supervision, reduced bureaucracy, less paperwork) and rapid prototyping (less computational analyses, instead actual testing) are applied; see [1].

The private commercial ventures undertaken in the USA to develop more economic small launch vehicles based on conventional technology and straight-forward development strategies cannot be considered as a substitute, since the relatively high development effort for a larger reusable launch system including new technologies and new operational procedures can only be financed by a governmental space agency. But this has been avoided by NASA even in case of the new US Manned Lunar Exploration program, instead relying on expendable launch vehicles. In a longer-term lunar program, however, the transportation costs with such vehicles will sum up to such a high level (up to 80 % of the total program cost) that at some point the whole program continuation will be endangered.

The large number of studies in the past 40 years about all possible concepts of reusable space transportation systems as well as different technology developments have revealed large development cost differences between the various RLV concepts (FIG 10):

– Winged vehicles with airbreathing propulsion in the first stage and horizontal take-off require by far the highest development costs - in the range of 20 to 25 Billion USD (2007). This is no surprise since such projects combine the problems of advanced aircraft and space vehicles with the related propulsion.

– Winged vehicles with rocket propulsion and vertical take-off have a reduced complexity but are still very expensive to develop (10 to 15 Billion USD, 2007) for the same reason as mentioned above.
– The lowest costs have ballistic reusable vehicles with vertical take-off and landing, in the order of 4 to 8 Billion USD. The small Kistler K1-vehicle as a reusable two-stage ballistic launch vehicle was started as a private venture with a development cost goal of less than 1 Billion USD. Unfortunately only some 50 % of this amount could be found as venture capital. All major components of the vehicle are existing, including the engines. Only the assembly and test phase is missing.

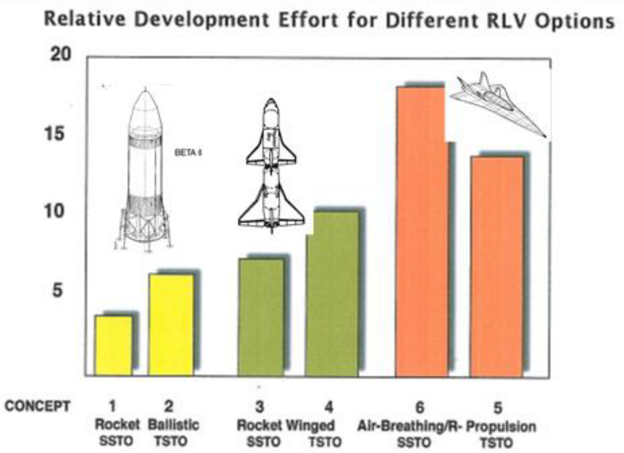

FIG 10. Development comparison of the major RLV concepts: Ballistic Rocket Vehicles, Winged Rocket Vehicles and Vehicles with Air breathing Propulsion

It is to be noticed, that these estimates do not include the cost for the development and verification of the enabling technologies. The trend for RLV studies in the past was towards winged vehicles like the German “Sänger-concept” as shown in FIG 11.

FIG 11. The two-stage German SÄNGER Concept, representative for HTOL RLVs with airbreathing propulsion (turbo-ramjet)

The cost situation and the past experience has changed this towards the preference of ballistic vehicles (see the "Orion" Vehicle of NASA). McDonnell Douglas has demonstrated the feasibility of a ballistic vehicle, its maneuverability and vertical landing by several test flights of the DC-X vehicle, see FIG 12 (the pneumatically extended telescope landing legs were contributed by MBB/Dasa).

FIG 12. The DC-X Test Vehicle at the vertical landing approach, landing legs extended

Regarding the situation in Europe any new vehicle must allow a transportation cost reduction by at least 50% compared to the existing ARIANE 5 and potential improved versions (FIG 13). Otherwise the development effort cannot be justified. Recent studies about semi-reusable advanced concepts, such as the "Hopper" or Flyback-Boosters with expendable upper stages do not fulfil this requirement, as a comprehensive review by DLR has shown.

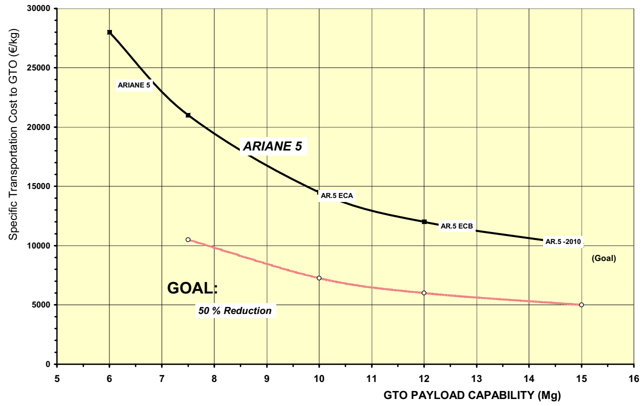

FIG 13. ARIANE 5 SpTC trend versus GTO payload capability and the cost reduction goal for the next generation European launcher

The great chance for Europe and probably the only possibility to continue as a player in the space transportation field seems to be to consider the development of a ballistic reusable launch system as the most cost-effective approach with the lowest development cost of any RLV. This is also important with respect to the international competition of launch services from Russia, India and China. With such a relatively simple RLV Europe would be able to offer launch prices which are competitive to those from low-cost countries with expendable vehicles. In addition, this type of reusable vehicle is the optimum means for realization of orbital space tourism. It would allow to offer space adventures which comprise several Earth orbits with view over large parts of the planet, in addition to the experience of "real" weightlessness.

FIG 14 shows the comparison of the actual and expected Cost-per-Flight of different launch vehicle options:

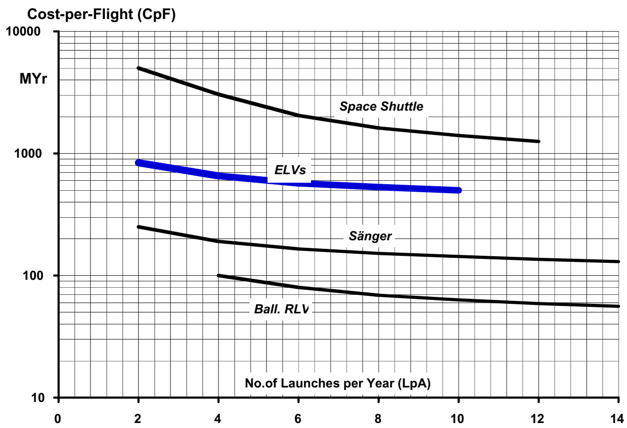

FIG 14. Cost-per-Flight (CpF) Comparison for ELVs and different reusable launch systems vs. number of flights per Year (Costs are shown in logarithmic scale!)

The Space Shuttle as a semi-reusable manned system is far above the ELV fleet due to the large "standing army" or high operations cost. A winged reusable HTOL launch system like Sänger could decrease the cost by a factor 2, but the most cost-effective solution is a relatively simple Ballistic VTOL "space lift" which would allow a cost reduction to one third of the ARIANE 5 transportation cost. However, it is to be mentioned, that investments in new technologies for expendable vehicles reducing especially their production costs would be made in the same order of magnitude as required for the enabling technologies of any RLV, the ELV would also benefit significantly.

REFERENCES

[1] Handbook of Cost Engineering for Space Transportation Systems, Ref,2, 2007, including the TRANSCOST-Model Version 7.2, D. E. Koelle, TCS Ottobrunn

[2] D. E. Koelle: Cost Efficiency as Design and Selection Criterion for Future Launch Vehicles, Paper at the International Astronautical Congress Vancouver, Oct.2004, published in "Acta Astronautica", Vol.57, No.2-8, July-Oct.2005, pp.623-629

[3] Space Transportation Costs: Trends in Price Per Pound o Orbit 1990-2000, Futron Corporation, September 2002