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D. KOELLE : DEVELOPMENT COSTS OF REUSABLE LAUNCH VEHICLES

1.ABSTRACT :

The paper deals first with the definition and understanding of "Development Costs" in general. Usually there is large difference between initial "development cost guesses", "Proposal Cost Estimations" and the final "Cost-to-Completion". The reasons for the usual development cost increases during development are discussed. The second part discusses the range of historic launch systems' development costs under "Business-as-Usual" (BaU) - Conditions and potential cost reductions for future developments of RLVs, as well as the comparison to commercial. industrial development cost.

Part three covers the potential reduction of development cost by application of "Cost Engineering Principles". An example of the large potential cost range (between 6 and 17 Billion USD) for the development of the same winged rocket-propelled SSTO launch vehicle concept is presented. Finally the tremendous development cost differences are shown which exist for the different potential Reusable Launch System Options which are under discussion. There remains an unresolved problem between the primary goals of the national space agencies with emphasis on new technology development/national prestige and the commercial market requirement of a simple low-cost RLV-System.

1. Development Costs - Different Definitions

There are great differences in the definition of „development cost" as mentioned in the literature. At least five different versions can be found:

(1) *Effective Cost-to-Completion (CTC)*
Total cost after completion of the program, including inflation, respectively the increase of annual hour-rate or ManYear (MYr)-cost

(2) *Most Probable or Realistic Development Cost,*
which include a margin for unforeseeable technical problems and delays

(3) *Ideal or Theoretical Development Cost,*
assuming that everything goes as planned, without technical or schedule problems (this is the standard proposal basis)

(4) *Minimum Credible Development Cost*
Unrealistic cost estimate in a competitive situation in order to win a contract (some cost items neglected or excluded by proper wording of the contract conditions)

(5) *Unrealistic Development Cost*
Cost figures based on „believing" without cost studies and lack of experience, in order to sell a pet concept.

Type (1) Costs are the only „real" cost, although they include inflation over a longer period which drives cost up by 5 to 15 %, depending on the program duration. This cannot really be considered as a „cost increase" since it is outside the influence of program or project management.

TYPE (2) Costs are about 15 to 20 % higher (in average)[1] than the „Ideal Cost" TYPE (3), which are normally derived by a „bottom-up" cost estimate through addition of subsystem costs or by use of a subsystem-based cost model. A system-based Cost Estimation Model, such as the TRANSCOST-Model (ref.1) does include the average cost increase by unforeseen technical problems and/ or schedule delays.

TYPE 3 Costs represent the STANDARD INDUSTRIAL PROPOSAL cost, not

[1] Statement of ESA's Director General, A. Rodota (Space News, 31.1.2000): In the past, programs were routinely 15% over their budgets"

including margins for unforeseen problems and delays. This would be required in fact, since this always happens but it cannot be added for competitive reasons.

TYPE 4 development costs can be as low as 80 to 85 % compared to Type 3 cost, since some development tasks are excluded for good reasons or only due to contractual clauses which allow later to negotiate a cost increase.

TYPE 5 Costs sometimes are just 15 to 30 % of any realistic cost estimate since such values are invented without any experience in this area mainly to sell a new pet launch vehicle concept.

Therefore, talking about „development cost" it should be made clear what kind of development cost are meant really.

2. „Business-as-Usual" Development Costs vs. Commercial Development Costs

The reference for development costs of launch vehicles are the government-financed development programs of the past. The requirements and conditions were similar in the USA (NASA, USAF), in Europe (ESA, CNES) and Japan (NASDA).

It is understood now that it is possible to reduce this historic development effort which is called „Business-as-Usual" by some 30 to 50 % for future government-financed projects. This is based on an analysis of NASA's Comptrollers Office (ref.2) as well as on a study by NASA's Langley Research Center with Lockheed (ref.3). Accordingly the cost reduction can be achieved by avoiding the following cost drivers which have been identified in past programs:

(1) Duplication of management teams at customer and contractor side (engaging each other largely), requiring more personnel on the contractor's side in order to „cover" the government oversight

(2) Micromanagement Procedures:
- -- Overspecification (unnecessary requirements),
- -- Regular (weekly) Progress Reports,
- -- Excessive project reviews[2] and documentation,
- -- Preoccupation with traceability, and other „...ilities",
- -- High bureaucratic effort for contract changes and supplements

(3) Aversion to risk,
- -- instead of a step-by-step approach and verification, individual test programs for each component

(4) Extended Schedule by
- -- Long acquisition cycle with „dead periods" in between
- -- Frequent „stops and starts" by funding fluctuations
- -- Design changes / Approval process

(5) „One of a kind" designs, according to the preference of the project manager(s) instead of using existing (may-be non-optimum) systems and hardware

(6) Sequencial small quantity production contracts
- -- instead of one longer-term contract/ order

Slogans like „Rapid Prototyping", „Skunk Works Principles" or „Concurrent Engineering" have been used for this revised development approach.

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2) ESA Newsletter „On Station", Dec.1999 proudly reports that for the X-38 CRV contributions by ESA, 22 design reviews have been held within 21 month.

3. Commercial Development Costs

Commercial industrial project development is generally associated with lower cost than government-contracted and controlled project development. This is due to a more extensive application of the cost-reducing measures decribed before and the lack of customer-induced changes.

This can be observed in commercial aircraft development (vs. military transport aircraft), as well as in commercial communication satellite development vs. dedicated or military satellites (taking into account the somewhat higher technical requirements).

The development costs for purely commercial projects can be as low as 20 to 40 % of the traditional BaU-cost. The key reasons for this somehow surprising fact are

- reduction of project bureaucracy and paperwork (reporting, reviews),
- reduction of theoretical analyses in favour of „rapid prototyping" and testing,
- Minimum project team size and development schedule.

The problem in case of launch vehicles, especially future RLVs (Reusable Launch Systrems), however, is the fact that commercial financing seems almost impossible due to the large amount (billions of USD) and the long payback period. Launch vehicle development requires 6 to 10 years and this is unacceptable for a satisfactory ROI (Return On Investment).

4. Development Cost Reduction by the Application of „Cost Engineering Principles"

Substantial development cost reductions are feasible if „cost engineering" is applied in the very early phase of vehicle design. In the past decades only one principle was guiding launch vehicle design: maximum performance, minimum weight. As long as the performance of rocket engines was mediocre and conventional materials and construction methods prevailed, performance indeed was a critical issue.

However, things have changed: Minimizing weight or pushing performance to the maximum possible has always been an expensive approach. Present priority is on MINIMUM COST. Future launch vehicles are no more national prestige projects but subject of commercial operations and international competition.

"Cost Engineering" is the third level of launch vehicle design and engineering: in the initial phase cost were of no concern. This was true, by example, for the SATURN-Program, or in Europe for the ELDO-I / Europa I vehicle development. The second step was the "Design-to-Cost"-rule which means to keep to a pre-determined budget. In case of "Cost Engineering" the goal is the minimum cost vehicle design concept. This means that costs have to be taken into account as a criterion for each technical decision. By example, using less advanced technology and /or existing components will lead to lower development cost (and lower risk !), as well as to lower fabrication cost.

„Cost Engineering" requires not only technical design expertise but also technical judgement and understanding of cost issues and cost drivers. Unfortunately no University provides an education in "Cost Engineering". This goes far beyond cost accounting procedures and spread-sheet organization :

- The first step towards „Cost Engineering" is the understanding of the importance and the serious intention to strive for a cost-optimized vehicle concept and design.

--- The second step is the familiarization with cost engineering principles and its potential. This implies the use of a cost data base and a parametric cost model (such as *TRANSCOST*)

It is important - and this is the distinct different to the past methodology - to start cost analysis at the very beginning of a vehicle design process, and NOT after a detailed design has been established. The usual „bottom-up"- cost estimation with detailed costing of each component and each activity is expensive and time consuming. It also may lead to a cost result which is not acceptable - and the complete process must start again.

Cost Engineering, however, provides the possibility to offer realistic lower cost since all potential means of a cost-efficient design can be identified such as

(1) Optimum vehicle size (payload capability) and launch frequency for minimum transportation cost

(2) Consideration of a larger vehicle size (propellant mass) with conventional technology, instead of an expensive high-tech vehicle with minimum launch mass (GLOW).

(3) Use of existing engines, subsystems, components

(4) Optimum thrust level, number and type of rocket engines

(5) Optimum number of engine qualification tests to achieve the maximum vehicle system reliability, etc.

By application of such measures it must be expected that the total vehicle size or weight (GLOW) is growing somewhat, however, a 10% increase in size (propellant mass) for the same payload capability - caused by application of less advanced technology - does NOT increase the development cost, instead it leads to a cost reduction of 10 to 15 %. This is the trade-off to be made with weight-saving technology options.

Another cost engineering task is to take into account maintainability and refurbishment requirements already in the early design phase: this means not only to take care of inspection and exchangeability of all components (including propellant tanks !), but also of such operational design features as to overdesign the rocket engines so that they can be operated at 5 to 8 % below the nominal (maximum) thrust level. This improves engine design life and reliability .

A further application area of cost engineering is the verification of new technologies: it should be made sure before investing into an expensive technology development program that the new technology is a contribution to better cost efficiency. Examples for the contrary are the proposals for tripropellant rocket engines/ systems, or inflight air-liquifaction, leading to higher cost and risk, instead of cost reduction.

5. Potential Development Cost Range for a Winged Orbital Launch Vehicle

Development Cost for the same launch vehicle, resp. a launch system with the same performance, can vary in a wide range. For a more detailed analysis the example of a Winged VTO Rocket Vehicle was chosen as depicted in FIG. 1. The reference vehicle (FSSC-1, ref. 5) has a launch mass (GLOW) of 916 Mg and a dry mass of 97 760 kg inclusive the engines' mass of 25 400 kg. New rocket engines were included: a 150 bar staged-combustion cycle engine with 1450 kN SL thrust level. Four of the 8 engines were equipped with larger nozzles to achieve an I_{sp} of 448 sec in vacuum. The total propellant mass (LH_2/LOX) amounts to

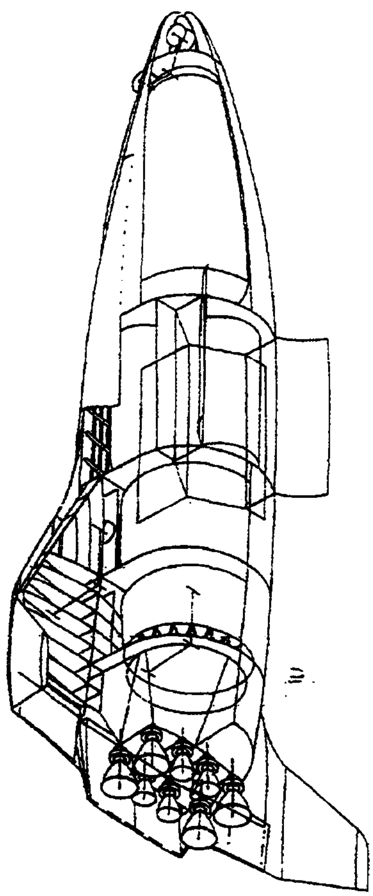

FIG. 1: **Reference Launch System**

794 Mg (+ 6.8 Mg residuals, margin, RCS propellants). The LEO mass for payload, a CTV or OTV is 17.5 Mg in a 250 km/ 5°-orbit.

The TRANSCOST-Model CERs establish the „most probable development cost" under BAU (Business-as Usual) conditions. This means the cost include 15 to 20 % cost for unforeseen techncial problems and delays which is usually the case for such vehicle programs (This does not mean that the cost can't be higher: that occurs in case of catastrophic incidents or a major change of specifications).

The application of the TRANSCOST CERs results in the „most probable development cost" of 98 000 MYr = 15.8 B.Euro(1995) for a European program.

Taking into account that the TRANS-COST-values are 15 to 20 % above the „Ideal development cost", the comparative nominal development cost would be 12.6 to 13.4 Billion Euro('95), which is also the expected result of a „bottom-up" cost estimation. Therefore, the value of **<u>13 Billion Euro (1995)</u>** has been adopted as reference value. This refers to the traditional approach of an ESA Program with controlled development and minimum risk. The NASA Langley estimate for a similar winged SSTO vehicle with BaU-methodology was 14.3 B.$(94) - ref. 6.

FIG. 2 shows the whole range of potential development costs: realistically one has to expect technical changes and unforseen problems which may add 10 to 15 % to the nominal cost. Also the inherent schedule delay - like in almost all programs - will add 5 to 10 % or more if there are funding delays. This means that realistic development cost must be expected to be in the **15 to 16.5 Billion Euro** range.

On the other hand there are a number of potential cost reduction options by application of cost engineering principles.

The first one is <u>the use of existing systems and components</u> instead of a completely new development. The most expensive item in this respect are the rocket engines. In fact, instead of new engines the Russian RD-0120 fulfils the thrust and performance requirements. The somewhat higher specific impulse balances the higher engines mass, compared to a new design. The engines have been qualified by some 800 tests (ref. 7). It is assumed that ca.200 additional tests are required to qualify the modifications required for reusability. The total vehicle development cost could be reduced by this

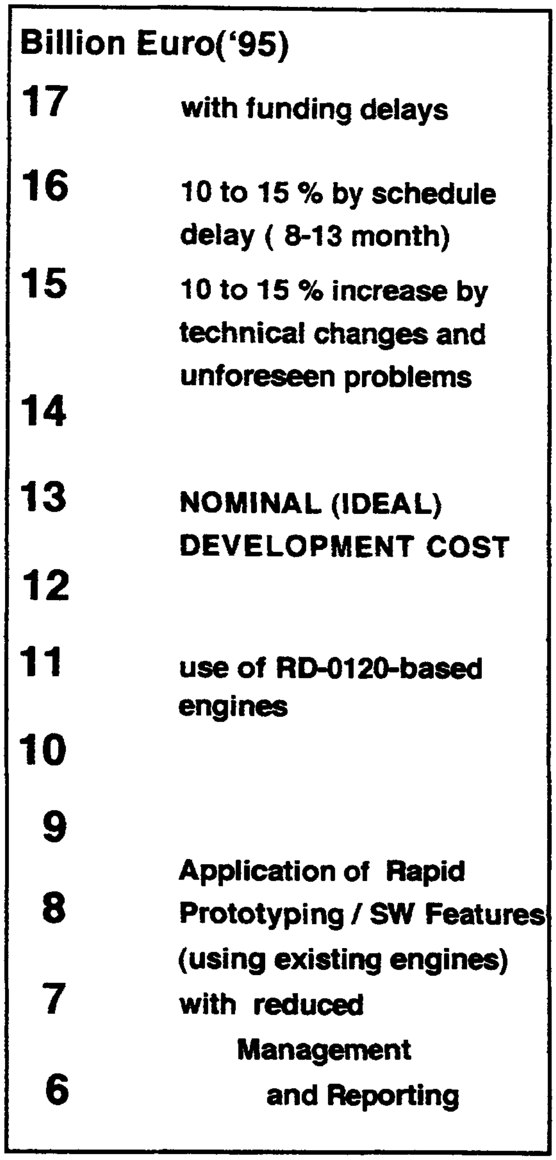

FIG. 2 : **Total Development Range for the Winged SSTO- Vehicle Concept**

measure by some 2.5 B.Euro, or 20 % to a nominal reference value of **10.5 B.Euro.** The engine reliability after some 200 additional tests has been estimated by Aerojet to be 0.994 (ref. 7).

The next area of cost engineering is the optimization of the vehicle net mass, i.e. cost trade-offs for components or elements technology and weight. This results in a variation of the lift-off mass and nominal propellant mass. The design net mass of the vehicle with 914 Mg GLOW is 104 Mg or 13.1 % of the nominal propellant mass of 794 kg. For this propellant mass the Net mass Fraction (NMF) is 13.6 % as median value (ref.1, Fig.2-36). The lower NMF is a cost driver factor in the CER and an increase could lead to a cost reduction.

The third area of cost engineering is the scope of testing and verification. Some features of the "Rapid Prototyping" approach and - generally speaking - taking into account progress and modern development tools and experience from the past programs should allow to reduce the development effort in terms of time and money: Especially the sometimes overdone computerized structural design analysis (requiring years with still never definite results) must be checked carefully whether it is required or could be replaced by a simple test of a complete structural element. (This, by example, was done for the complete carbon-composite structure of the PEGASUS first stage). In contrast, more extensive use of computational 3-dimensional assembly verification (as used by Boeing for the B-777 development) can indeed reduce the number of mistakes during the vehicle integration, saving time and cost. These measures could reduce the total development cost further by some 2 B.Euro to a reference value of **8.5 B.Euro.**

Another potential cost reduction is the area of Project Management with the limitation of technical reporting and reviews to the necessary minimum. This results in an effective reduction of technical personnel both on the prime contractors' as well as on the customers side . In this case, which had been successfully implemented in the DC-X development, the nominal development cost in our RLV example could be reduced to some **7 B.Euro** or less.

6. Potential RLV Options and Development Cost

As mentioned before, a cost- effective RLV -technology program should define the anticipated launch vehicle concept before starting major technology activities. It must also be clear that tremendous development cost differences exist for the different vehicle options.

The main RLV options based on present or near-term technology are:

(A) **Winged Rocket Configuration** (VT-HL) - with vertical take-off and horizontal landing, similar to the Space Shuttle Orbiter

(B) **Ballistic Rocket Configuration** (VTOL) - with vertical take-off and landing, as tested by the DC-X, the Delta Clipper Demonstrator Vehicle,

(C) **Parallel-staged Winged TSTO** Rocket Configuration - sometimes with equal-sized stages, VTO-HL, (FSSC-9) and

(D) **Horizontally launched TSTO** with airbreathing propulsion in the first stage and rocket propulsion for the second stage - with the German SÄNGER Concept as an example.

The concepts are shown in FIG.3 to about the same scale for a payload of 7000 kg to the ISS-orbit. Since most missions are going to higher orbits than just LEO two stages are required normally. Therefore, it is not a question of SSTO vs. TSTO, but whether the first stage should have

- orbital capability,
- suborbital capability (with flyback provisions), or
- only boost capability.

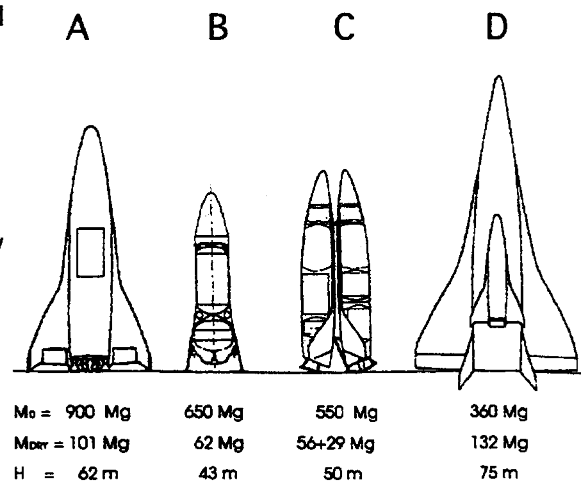

FIG. 3: **Major RLV Concepts**

CONCEPT A: The winged RLV with rocket propulsion and orbital capability has an external similarity with the Shuttle Orbiter and implies horizontal landing which is a well demonstrated mode. Wings and the related power supply for the aerodynamic surfaces results in the highest launch mass of all concepts, as shown in FIG.1. A vehicle with suborbital capability would require additional turbojet engines and design for cruise flight, adding substantially to the dry mass, but reducing the total vehicle size.

CONCEPT B: The ballistic reusable vehicle concept as such is not new - it has been conceived already in 1963/64 by Krafft Ehricke (NEXUS) and Phil Bono (RHOMBUS). The technology level at that time, however, resulted in vehicle sizes of several thousand tons, as did the Chrysler Shuttle option of 1972 (SERV). Nowadays with existing technology a ballistic SSTO Launch Vehicle can be built with 500 to 900 tons launch mass, depending on the payload and mission orbit. In 1994/95 the technique of vertical takeoff and landing, as well as a short turnaround time with a minimum ground staff was demonstrated by the DC-X experimental vehicle. The ballistic SSTO Vehicle basically has a lower launch mass and a lower dry mass than Concept A.

CONCEPT C: The two-stage winged rocket vehicle has been studied in many variations. Shown is a special design with externally equal-shaped stages which are non-optimum from the performance standpoint, but may reduce development cost. Internally the vehicles have to be different. The first stage in this case has a low suborbital velocity capability, allowing for a glide-back to the launch site. However, two complete systems have to be developed, plus the mechanical and dynamic interstage problems. The total launch mass is relatively low; however, not the combined dry mass.

CONCEPT D: The launch sytem with horizontal take-off using an advanced aircraft design with turboramjet engines, plus a relatively small winged orbital rocket vehicle as second stage minimizes the total launch mass, but not the vehicle size: due to the use of hydrogen in the first stage with its low density the vehicle is the largest one. The combined dry mass is the highest of all concepts, but it has the greatest mission flexibility by take-off from conventional airfields and its inherent cruise capability of few thousand kilometers.

It is important - but rarely being done - to perform a cost comparison of different launch vehicle options with the same costing methodology and assumptions, before making a concept selection/ decision.

The TRANSCOST-Model (ref.1) allows to perform such a cost estimation process of different launch systems without a detailed subsystem design. The Model has system-based CERs (Cost-Estimation Relationships) for different launch vehicle configurations and engines. It is kind of a

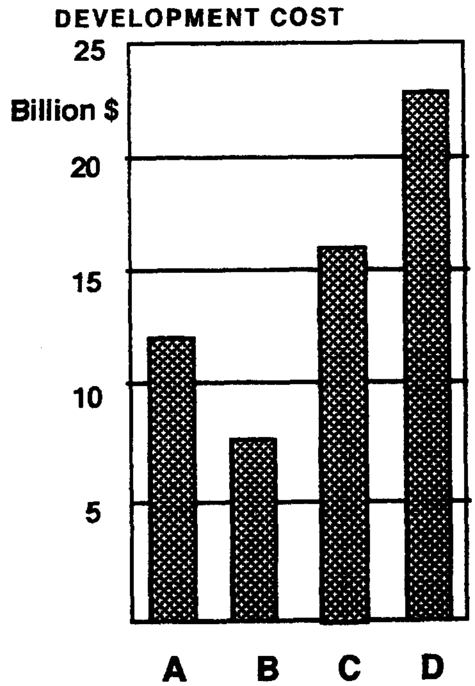

FIG.4: **Development Cost of four RLV Concepts**

„transparent" cost model with references indicated, so that the user can apply his own independent judgement.

FIG.4 shows the resulting nominal or „ideal" development costs of the four launch systems of FIG.3 if those are developed under the usual government agencies' contract conditions („Business-as-Usual").

The cost differences between the vehicle concepts - between 7 and 23 Billion US $ are substantial and should normally be a major decision factor instead of (only) personal preferences. A careful analysis is required what investment if affordable to fulfil the future requirements.

There remains an unresolved problem between the primary goals of the national space agencies with emphasis on new technology development/national prestige and the commercial market requirement of a simple low-cost RLV-System.

7. Conclusions

1) There are many types of development cost estimates for different purposes, and you must know which type you are dealing with and the assumptions behind each of them before using the cost estimate as an absolute number or in comparisons of estimates and RLV system options;

2) The development cost estimate is only as good as the input data and underlying assumptions. The farther one departs from the historical database and processes, the greater the uncertainty in the cost estimate. This includes the satisfaction of the at times conflicting requirements and goals between the commercial market and the various national space agencies; and,

3) Cost engineering principles should be applied early and continuously throughout the design, development and test program to control costs and arrive a at a more cost optimized system design.

Thanks to Allen E.Goldstein for his comments and the formulation of the conclusions.

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Author's Address:

Dr. Dietrich E. KOELLE
TCS - TransCostSystems
Liebigweg 10
D-85521 Ottobrunn/ Germany
Phone/Fax: +4989-6091677
e-mail: dekoelle@transcost.com