5. COST-PER-FLIGHT (CpF) and Pricing, Specific Space Transportation Costs, Life Cycle Cost

5.1 Cost-per-Flight (CpF) Definition and Pricing

5.11 The International Cost-per-Flight Standard

What is often called „Launch Cost" in reality is a complex subject : the major components are (1) launch operations cost, (2) vehicle production cost - or amortization cost in case of reusable vehicles, and (3) the indirect operations cost. For this reason the term „launch cost" is wrong or at least misleading: it should read „Cost-per-Flight" (CpF), resp. "Price-per-Flight" (PpF). From the launch provider's viewpoint it is a PRICE, including profit and eventual development cost amotization charges, while it is a COST item for the payload customer.

Previously in studies on future launch systems different costing schematics were used by the various companies - resulting in not comparable cost data. Especially the IOC (Indirect Operations Cost) were often disregarded, often also the vehicle amortization cost. But it is simply not correct to arrive at low „launch cost" just by neglecting some major cost items. Instead of the somewhat misleading term „launch cost" the expression „Cost-per-Flight" (CpF) has been introduced.

Since there was no standardized format existing for the definition of the cost-per- flight of launch systems, the author conceived a draft proposal which was submitted, discussed and after some improvements accepted in Sept. 1992 by the AIAA (American Institute of Aeronautics and Astronautics) Space Transportation Technical Committee. The following year also the „Committee on Economics in Space Operations" (CESO) of the International Academy of Astronautics (IAA) approved the updated version of the standardized „Cost per Flight" definition (ref. 104) which is presented in the following chapter.

5.12 CpF Format for Expendable and Reusable Launch Vehicles

5.121 The Basic Scheme

The basic CpF structure is common to expendable and reusable launch vehicles:

1. VEHICLE COST
2. DIRECT OPERATIONS COST (DOC)
3. INDIRECT OPERATIONS COST (IOC)
4. BUSINESS CHARGES

(5. INSURANCE COST).

There are differences, however, between expendable and reusable launch systems which requires separate formats.

For *Expendable Launch Systems* the vehicle hardware costs are 65 to 80 % of the total CpF. The second-largest cost share are the Direct Operations Cost (DOC) with 10 to 25 %. The third-largest share are the Indirect Operations Cost with 10 to 20 %.

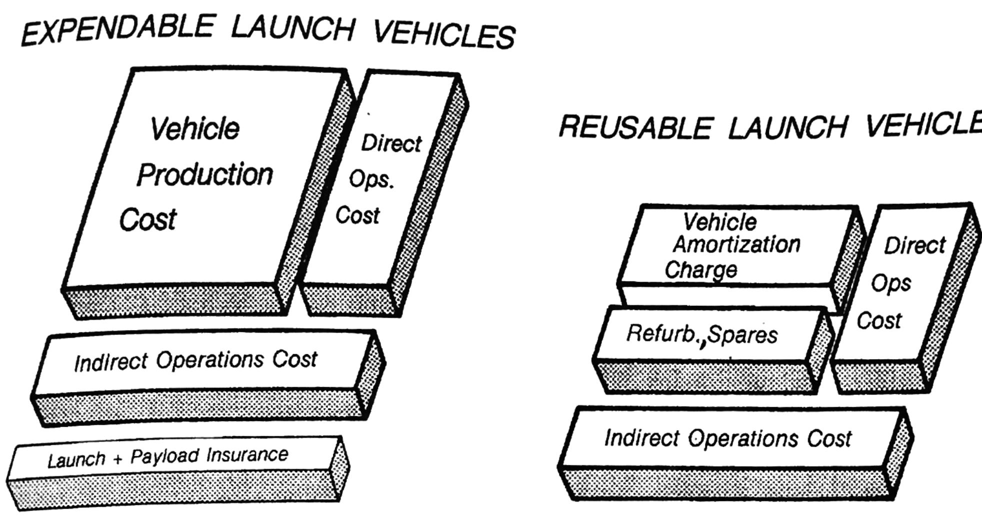

FIG. 5-01: **Major CpF-Cost Elements of Expendable and Reusable Launch Vehicles**

The launch frequency, the number of flights per year, has a major impact on the cost distribution: low launch rates increase the direct and indirect operations cost per flight. In addition to the Cost-per-Flight, or better Price-per-Flight as charged by the launch provider, there is normally for commercial customers the insurance fee to be paid as an expensive add-on cost item: Depending on the demonstrated launch vehicle reliability and the insurance record, the insurance fees are between 7 and 25 % of the CpF plus the payload value. With payload cost as high as the CpF or up to twice that cost the insurance fee is a major cost item.

In case of *Reusable Launch Systems* the situation in different in several aspects: First, the recurring cost consist of a vehicle cost amortization charge - depending on the number of flights in the vehicle lifetime - and refurbishment cost. Secondly, insurance is no more an additional cost item for the customer, but becomes an inherent part of the DOC. It must be covered by the launch operator as owner of the vehicle, but is much lower than in case of ELVs. Reason is the inherently much higher reliability or success rate of reusable systems caused by their higher redundancy and the emergency landing capability. This relieves also or eliminates the need for a payload loss insurance.

TABLE 5-I shows the CpF elements of expendable vehicles, and TABLE 5-II for reusable systems. In addition, definitions and explantions are provided as they have evolved from discussions and contributions by many experts worldwide.

TABLE 5-I : **Complete „Cost-per-Flight" (CpF) and „Price-per-Flight" (PpF) Definition for Expendable Launch Vehicles**

EXPENDABLE LAUNCH VEHICLES	
A. **VEHICLE COST (VRC)**	(1A) Vehicle Recurring Cost (Fabrication, assembly, verification)
B. **DIRECT OPERATIONS COST (DOC)**	(3) Ground Operations Cost
	(4) Flight and Mission Operations Cost
	(5) Propellants, Gases & Consumables
	(6) Ground Transportation Cost
	(7) Launch Facilities User Fee
	(8) Public Damage Insurance Fee
	(9) Vehicle Failure Impact Charge
	(10) Other Charges (Taxes,Fee
C. **INDIRECT OPERATIONS COST (IOC)**	(11) Program Administration and System Management
	(12) Marketing, Customer Relations and Contracts Office
	(13) Technical Support
	(14) Launch Site Cost
TOTAL COST-PER-FLIGHT (CPF) :	***Σ (1A to 14)***
D. **BUSINESS CHARGES**	(15) Development Cost Amortization Charge (in case of a commercial project, incl. cost of financing)
	(16) Nominal Profit (on items 1 to 14)
PRICE-PER-FLIGHT (PPF) :	***Σ (1A) to (16)***
E. **INSURANCE COST** (OPTIONAL)	(17) Insurance for Launch Failure
	(18) Insurance for Payload Loss
COMPLETE USER COST :	***Σ (1A) to (18)***

TABLE 5-II : **Complete „Cost-per-Flight"(CpF) and „Price-per-Flight" (PpF) Definition for Reusable Launch Systems**

REUSABLE LAUNCH SYSTEMS

A. **VEHICLE COST (VRC)**	(1B) Amortization Share of the Vehicle Recurring Cost (fabrication, assembly, verification) (1C) Expendable Elements' Cost (2) Refurbishment and Spares' Cost
B. **DIRECT OPERATIONS COST (DOC)**	(3) Ground Operations Cost (4) Flight and Mission Operations Cost (5) Propellants, Gases & Consumables (6) Ground Transportation /Recovery Cost (7) Launch Facilities User Fee (8) Public Damage Insurance Fee (9) Mission Abort and Premature Vehicle Loss Charge (10) Other Charges (Taxes,Fees)
C. **INDIRECT OPERATIONS COST (IOC)**	(11) Program Administration and System Management (12) Marketing, Customer Relations and Contracts Office (13) Technical System Support (incl. Spares Administration) (14) Launch Site and Range Cost (Annual Fee)
TOTAL COST-PER-FLIGHT (CPF)	***Σ (1A) to (14)***
D. **BUSINESS CHARGES**	(15) Development Cost Amortization Charge (in case of a commercial project, incl. cost of financing) (16) Nominal Profit (on items 1 to 14)
PRICE-PER-FLIGHT (PPF)	***Σ (1A) to (16)***
E. **INSURANCE COST** (OPTIONAL)	(18) Insurance for Payload Loss
COMPLETE USER COST	***Σ (1B) to (18)***

5.122 Cost Items' Definitions and Explanations

(1A) **Vehicle Recurring Cost :**
Fabrication cost of all vehicle elements plus assembly, checkout and verification/ testing, including profit, product liability insurance and eventual financing costs.
Learning Factor cost reduction to be applied to the reference cost of the no.1 unit - if applied to a batch of vehicles - or to a specific vehicle out of a running production line (including profit and eventual financing cost).

(1B) **Vehicle Amortization Cost Share :**
Total cost of vehicle production, integration and verification, divided by the total number of flights anticipated for the reusable vehicle. This number may be different for the vehicle system and the engine(s): i.e.100 to 300 for the vehicle, and 30 to 60 for the rocket engine(s);

(1C) **Cost of Expendable Elements** in case of reusable vehicles, such as additional kick stages, or the ET (Expendable Tank) in case of the Space Shuttle

(2) **Refurbishment and Spares Cost** :
Cost of manpower, operations and spares required to keep the same technical standard, quality and reliability (essentially scheduled parts and elements replacement), comparable to the major aircraft overhaul.

(3) **Ground Operations Cost :**
Costs of vehicle assembly, maintenance in case of reusable vehicles, checkout, mating of multistage vehicles, payload integration (without payload preparation itself), launch pad operations including fuelling. Launch pad refurbishment after launch.

(4) **Launch and Flight Operations Cost :**
Cost of mission planning and preparations, launch, flight control and range monitoring crew and facilities, communications, on-orbit tracking and monitoring throughout the mission, flight data assessment and synthesis. This covers the flight period from take-off to payload separation, or until docking with a space station, as well as the return flight until landing for reusable vehicles. It excludes payload-related mission operations in orbit .

(5) **Cost of Propellants, Fluids, Gases and other Consumables:**
Cost of all propellants, gases and other required fluids: including boil-off losses in case of cryogenic propellants (Exception: Solid propellants are not accounted separately, but are part of the motor or booster cost).

(6) **Ground Transportation and Recovery Cost:**
Cost of ground/ air / sea transportation of the vehicle (stages) to the launch site, including transport insurance, as well as applicable direct and indirect recovery operations including eventual emergency landing sites.

(7) **Launch Facilities User Fee:**
Launch sites are normally operated by government agencies and a certain fee per launch has to be paid by commercial launch services providers, including the cost of launch facilities' maintenance and refurbishment after each launch. Military and National Space Agency launches are exempted from this fee.

(8) **Public Damage Insurance Fee :** Governments require frequently commercial launch providers to take an insurance against potential public damage due to a launch failure. In the USA this responsibility is limited to 100 M$ per launch. Insurance Cost are ca.100 000 $. Governmental and military launches are exempted from this requirement.

(9A) **Vehicle Failure Impact Charge:** (Expendable Vehicles)
In case of expendable vehicles a launch failure will require comprehensive failure analysis efforts and technical changes. Those cases as well as the indirect impacts of the vehicle's "down time" must be accounted for by a special reserve fund, fed by a fee as part of the DOC. The amount depends on the demonstrated or expected mission success rate (reliability).

(9B) **Mission Abort and Vehicle Loss Charge**: (Reusable Vehicles)
Reusable systems have the inherent capability of an emergency landing or even return to the launch site. The cost of an aborted mission cannot be charged to the customer but must be taken care of by a special charge as part of the DOC. For a premature vehicle loss either an insurance fee or a special contribution to a reserve fund has to be planned for.

(10) **Other Charges (Taxes, Fees)**
All other charges and fees which have not yet been mentioned before.

(11) **Program Administration and System Management**
The launch system operator needs a certain staff for administration, launch system management and procurement. This also includes the related office cost, as well as travel, etc. and general financing costs (interest payments, if applicable)

(12) **Marketing, Customer Relations and Contracts Office:**
A certain staff is required for customer relations and launch contract negotiations, plus cost for advertisement campaigns, press material, exhibits, etc., including related office and travel cost .

(13) **Technical Support / Improvements**
A certain engineering staff is required for technical performance survey, implementation of technical vehicle improvements, technical supervision of deliveries, etc. For reusable vehicles the additional task of spares' administration and storage has to be taken into account. In the special case of *piloted vehicles* the costs of pilots and the related support (including training) have to be accounted. This excludes mission and/ or payload specialists .

(14) **Launch Site Cost**
Independent from the Launch Equipment user fee per launch a basic (annual) fee may have to be paid by the launch service provider company if using a government-owned or commercial launch site. In case of a private commercial launch site the complete site cost may have to be taken into account.

(15) **Development Cost/ Investment Amortization**
In case of a commercial development the full non-recurring costs (plus interest) need to be distributed over the total expected number of launches. Normally, however, the NRC of a larger vehicle are covered by contract of a governmental

agency, but in some cases a royalty may be requested as a partial payback. A third case is the amortization of commercial add-on developments or modifications. The development cost should include the eventual cost of financing.

(16) **Profit**
An essential item for the final Price-per-Flight is the profit the Launch Provider is adding to the total cost. This is normally in the 5 to 12 % range and allows also a certain flexibility regarding the final price, taking into account the competitive situation.

(17) **Insurance against Launch Failure**
User organizations often take insurance against launch failure which in case of *expendable* launch vehicles means also loss of the payload. Either the launch only, or launch and payload are insured which adds between 10 and 30 % of the CpF (insuring the launch and the payload cost), depending on the type of launch vehicle and the situation on the insurance market. In case of *reusable* launch vehicles the situation is different since the inherent emergency landing and return capability will reduce catastrophic failures (loss of vehicle and payload) substantially - probably by one order of magnitude.

(18) **Insurance against Payload Loss**
In case of expendable vehicles a launch failure automatically leads to the loss of the payload; therefore normally for commercial launches the full or partial payload cost are insured. The case is different for reusable launch vehicles with their inherently higher reliability and emergency landing capability. Therefore, the insurance against payload loss at launch can be considered as no more necessary or will require only a relatively low fee.

5.123 Applications of the CpF Scheme / Spread Sheets

For the cost comparison of different launch vehicle configurations within the same study it is sufficient to use the level 1 CpF, consisting of items A + B. For a complete Cost-per-Flight value, resp. the expected realistic market *Price*, items C and D have to be added. This makes the cost/ price comparable to existing vehicles and allows the evaluation of the competitiveness.

For the user's convenience two Spread Sheets are added, one for Expendable Launch Vehicles (ELVs), and one for Reusable Launch Vehicles (RLVs).

In a highly competitive situation the profit can become negative, resulting in a price which is lower than the cost. In the first quarter of the year 2000 three ATLAS launches have been priced more than 10 M.$ below cost as reported in the press[1]. This can make sense economically if the interruption of a production line

[1] Space News, 21.7.2000

TABLE 5-III : **Standardized Cost-per-Flight (CpF) Spread Sheet for Expendable Launch Vehilces**

EXPENDABLE LAUNCH VEHICLES	VEHICLE DESIGNATION:				
	Reference	Conditions,Assumptions No. LpA: No.produced	Learning C.R.	MYr	Currency Year:
VEHICLE COST (VRC) A1a First StageVehicle Recurring Cost A1b First Stage Engines' Recurring Cost (No.of) A2a Second Stage Vehicle Recurring Cost A2b Second Stage Engine(s) Recurring Cost (No.of) A3a Third Stage Vehicle Recurring Cost A3b Third Stage Engine(s)' Cost (No.of) A4 Other Items					
DIRECT OPERATIONS COST (DOC) B 3 Prelaunch Ground Operations B 4 Mission and Flight Operations/ Range Cost B 5 Propellants and other Consumables B 6 Ground Transportation B 7 Launch Facilities User Fee per Launch B 8 Insurance Fees and other Charges					
INDIRECT OPERATIONS COST (IOC) C 9 Program Administr. and Management C10 Marketing, Customer Relations, Contracts C11 Technical Support C12 Royalties, Techn.Improvements Amortization C13 Taxes, Fees C14 Launch Site Cost (Fixed Annual Fee)					
CpF COST-per-Flight	MYr				
D15 Development Amortization Charge D16 Nominal Profit					
PpF PRICE-per-Flight	MYr				

TABLE 5-III : **Standardized Cost-per-Flight (CpF) Spread Sheet for Reusable Launch Vehicles**

REUSABLE LAUNCH VEHICLES	VEHICE DESIGNATION:				
	Reference	Conditions, Assumptions No.LpA:		MYr	Currency Year:
VEHICLE COST (VRC)		No.of Reuses			
A1-1a First StageVehicle Rec. Cost Amortization					
A1-1b First Stage Engines' Rec. Cost Amortization					
A1-2a Second Stage Vehicle Rec.Cost Amort.					
A1-2b Second Stage Engine(s) Rec. Cost Amort.					
A2-1a First Stage Vehicle Refurbishment Cost					
A2-1b First Stage Engine(s)' Refurbishment Cost					
A2-2a Second Stage Vehicle Refurbishment Cost					
A2-2b Second Stage Engine(s) Refurb. Cost					
DIRECT OPERATIONS COST (DOC)					
B 3 Prelaunch Ground Operations					
B 4 Mission and Flight Operations/Range Cost					
B 5 Propellants					
B 6 Ground Transportation					
B 7 Launch Facilities User Fee per Launch					
B 8 Mission Abort and Vehicle Loss Charge					
INDIRECT OPERATIONS COST (IOC)					
C 9 Program Administration and Management					
C10 Marketing, Customer Relations, Contracts					
C11 Technical Support					
C12 Royalties,Techn.Improvement Amort.					
C13 Taxes, Fees					
C14 Launch Site Cost (Fixed Annual Cost)					
CpF COST-per-Flight					
D15 Development Amortization Charge					
D16 Nominal Profit					
PpF PRICE-per-Flight					

can be avoided and/ or the lay-off of a specialized team. In an alternative scenario the production of one additional unit could be accounted for without the indirect cost charges, if the indirect costs are already covered by the „standard" production number.

5.13 Production Cost Amortization (RLVs and Engines)

In case of reusable vehicles a recurring cost charge applies as „vehicle cost" which is defined by the unit cost (or recurring cost) of the new vehicle, divided by the number of planned, resp. the expected total number flights. No experience exists yet but the assumptions for orbital vehicles are between 100 and 300 flights, depending on the type of vehicle. For winged first stage vehicles up to Mach 6.5 the number of potential flights is much higher (500 to 1000) since no re-entry maneuver has to be made. As already discussed in chapter 4.34 the required refurbishment costs also play a role in the determination of the optimum number of flights. As an example, the „Space Tug" refurbishment strategy from FIG. 4-24 is shown together with the vehicle amortization charge vs. number of flights in FIG. 5-02 (Vehicle unit cost = 230 MYr without engines). If this refurbishment strategy is realistic, then the resulting number of flights per vehicle should be limited to 20, when the combined cost. reach the minimum. However, this cannot be generalized, it depends strongly on the specific refurbishment strategy and effort in each case.

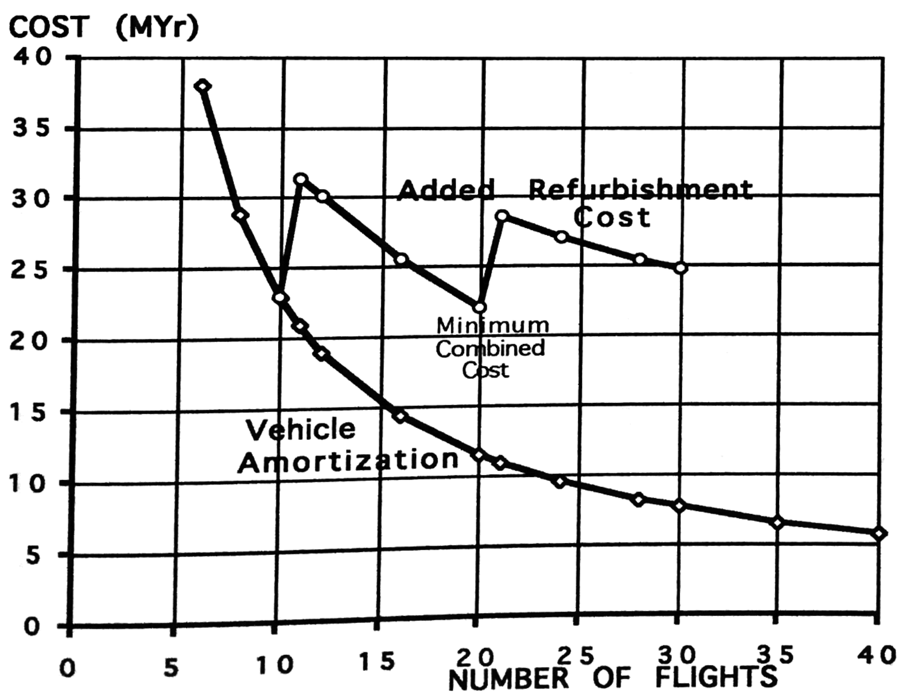

FIG. 5-02: **The Combined Cost of Vehicle Amortization and Refurbishment may Limit the Total Number of Flights**

For rocket engines the problem is the same, but the number of flights per engine is much smaller than for the vehicle system : 30 to 80 are usually assumed.

FIG. 5-03 illustrates the impact of the total number of vehicle flights and rocket engine flights on the total CpF charge: For the example of a winged orbital upper stage vehicle with 4100 MYr recurring cost + 183 MYr for the main engine plus 85 MYr for the OMS engines, the decrease of the CpF charge with increasing number of flights is shown. It is interesting to note that there is a steep cost decrease until some 100 flights but levelling out for higher flight numbers.

Also for the number of engine reuses it seems that it is not necessarily worthwile to plan for more than 30 to 50 flights per engine since the CpF effect is small, but the impact on engine development cost may be high.

In the case shown in FIG. 5-03 some 120 vehicle flights have been assumed, with 30 flights per engine. This means that 4 engine sets are required during the lifetime of the vehicle.

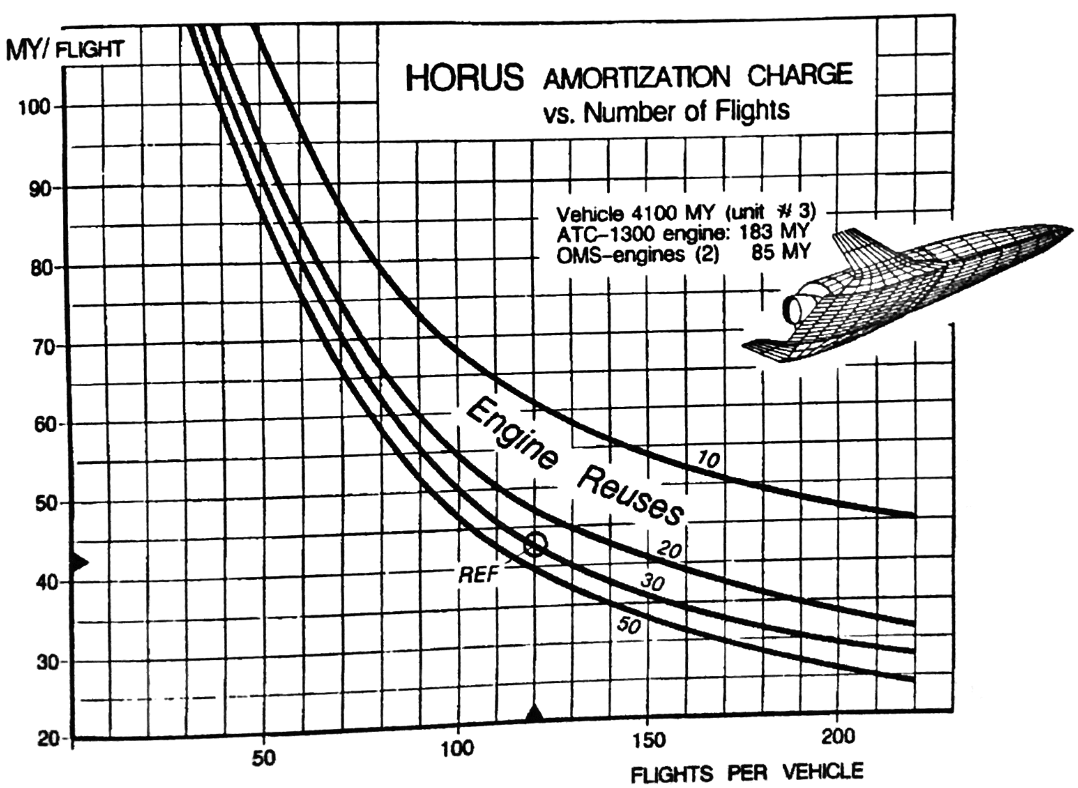

FIG. 5-03: **Impact of Vehicle Number of Flights and Engine Reuses on the Cost per Flight (CpF) for a Winged Orbital Vehicle**

5.14 CpF vs.Vehicle Size and Launch Frequency (LpA)

Both the launch vehicle size in terms of GLOW, resp. payload capability, as well as the launch frequency (LpA) have a major impact on the Cost-per-Flight (CpF).

5.141 Impact of Flight Rate (LpA = Launches per Annum) on the CpF

FIG. 5-04 shows the Space Shuttle CpF as constructed from NASA FY budget allocations and number of actual or planned flights. The reference points fit a curve with a fixed amount (hardware) plus the related share of the „standing army" of some 13 600 people, equivalent to some 12 000 MYr capacity. The actual curve fits a relation of (300 + 12000 / LpA).

The cost reduction between 1991 and 1998 was essentially the result of process improvement and learning curve effects (ref.85). The 9 % cost reduction between flights no.38 and 92 indicates the effect of a 90 % Learning Curve, as well as the further CpF reduction until 2002 (FIG. 5-04). This further reduction is implemented by the new automated Checkout and Launch Control System (CLCS), as stated in ref. 85.

The cost level as well as the sensitivity vs. the annual number of launches is relatively high due to the share of expendable hardware, the high refurbishment

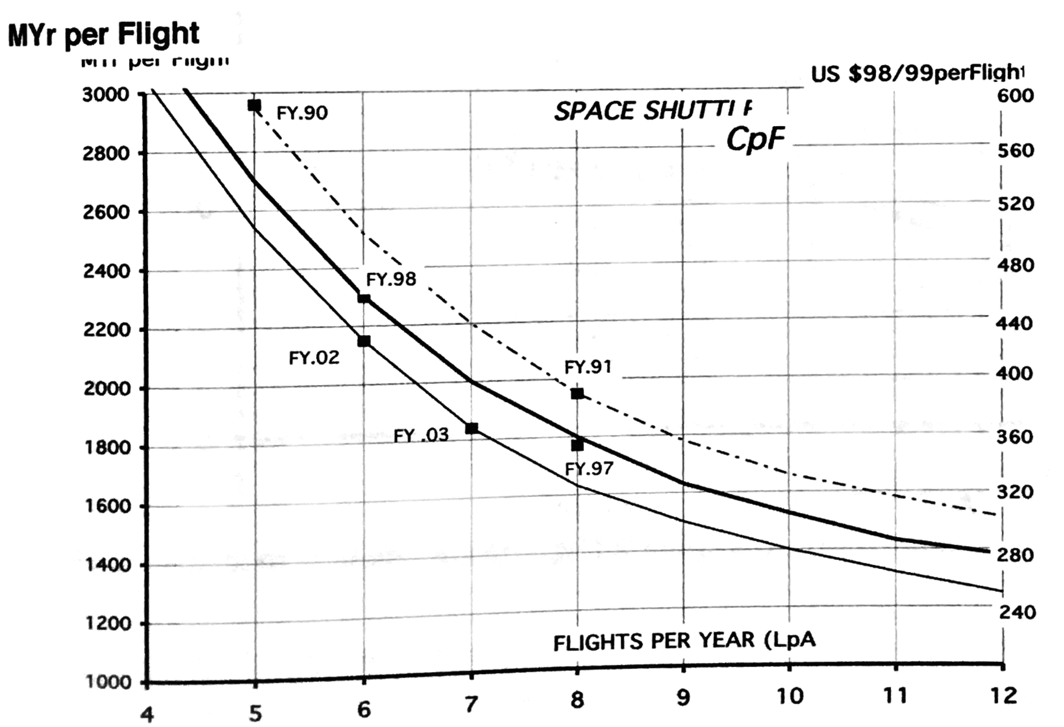

FIG. 5-04: **Space Shuttle Cost-per-Flight (CpF) vs. Launch Frequency (LpA)**

cost and due to the fact that the system was designed originally for a much higher launch rate (65 LpA !)

A somewhat different trend can be expected for fully reusable launch systems with little or no new hardware required per flight. As an example, the CpF assessment for a two-stage winged vehicle concept (*MBB* -SÄNGER, 400 Mg GLOW, turboramjet propulsion in the first stage, horizontal take-off and landing) is shown in FIG. 5-05. Compared to the Shuttle with 2000 Mg GLOW and 24 Mg payload, the SÄNGER payload capability to the ISS-orbit is only 7 Mg unmanned and 3 Mg with a crew of three , but the CpF value is more than one order of magnitude lower. Also the cost sensitivity vs. launch rate is much lower due to the fact that both the IOC and the DOC are relatively low by aircraft-like operations. FIG. 5-05 shows also the difference of CpF for unmanned and piloted flights since the SÄNGER upper stage - FIG. 2-39 - was conceived for either option: the crewed option (SÄNGER-M) increased the CpF in this case by some 11 % (exluding any crew activities in orbit) compared to the automated version SÄNGER-C.

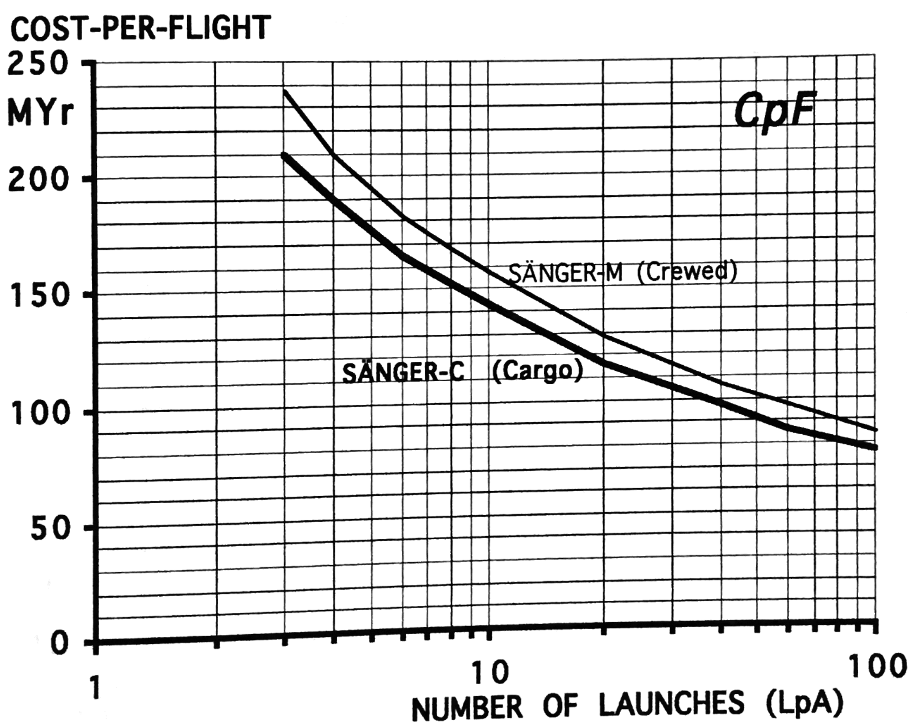

FIG. 5-05: **Impact of Launch Rate on CpF for Fully Reusable Systems**

5.142 Impact of Vehicle Size (Launch Mass or Payload) on CpF

The launch vehicle size in terms of either launch mass (GLOW) or LEO payload mass is the other major impact factor on the CpF. The impact is different for ELVs

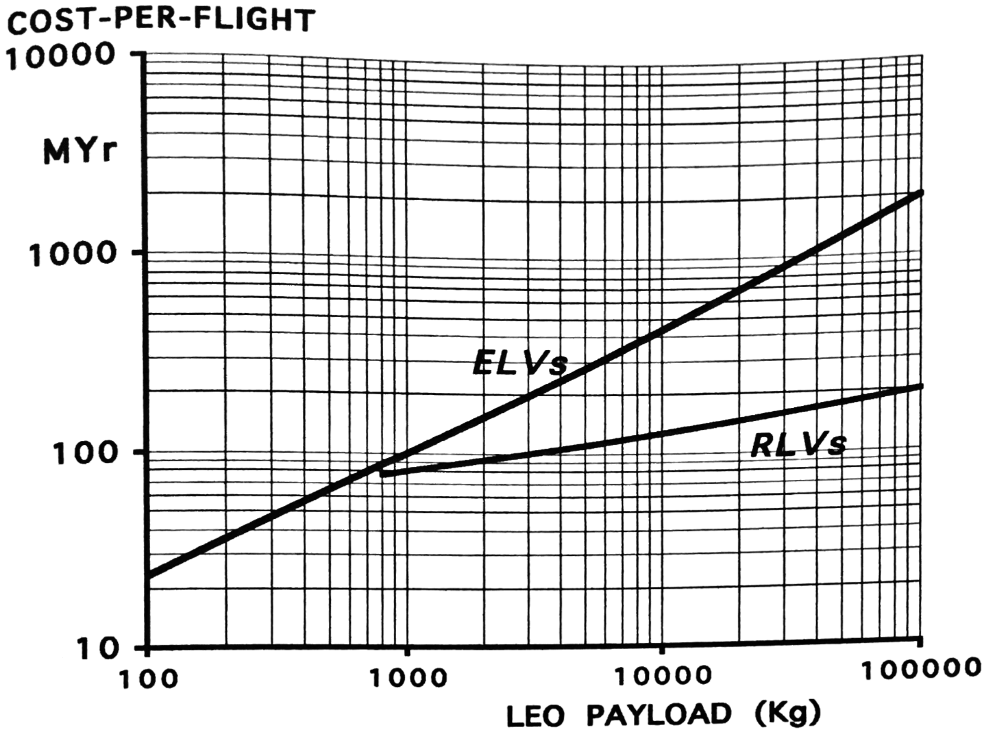

FIG. 5-06: **Impact of Vehicle LEO Payload Capability on the CpF for ELVs and RLVs at about 10 LpA**

and RLVs as visible in FIG. 5-06: The larger the vehicle the greater is the difference between ELVs and RLVs. The reason for this difference is the high hardware share in case of ELVs, while the RLV cost are mainly determined by the operations cost which are less sensitive to vehicle size. As it is evident from the charts the crewed Space Shuttle has about twice the CpF as an ELV with the same payload capability, while the RLV Cost-per-Flight are about 25 % of the ELV cost at a launch rate of 6 LpA.

FIG. 5-07 shows the example of a Ballistic SSTO Vehicle CpF vs. GLOW, with the launch rate as parameter. A better insight provide the specific transportation cost (SpT-Cost) showing the high cost sensitivy of smaller vehicles (see chapter 5.4).

From the controversial fact that increasing vehicle size reduces the SpT-Cost while at the same time the cost are growing due to a reduced number of flights (given a constant total payload mass per year) an optimum vehicle payload capability can be determined which delivers the lowest SpT-Cost; see chapter 5.43.

5.15 Development Cost Amortization

Development or non-recurring cost of launch systems previously have been funded by governmental agencies. In this case the cost do not need to be amortized by a CpF surcharge. Commercial (industrial) development of launch

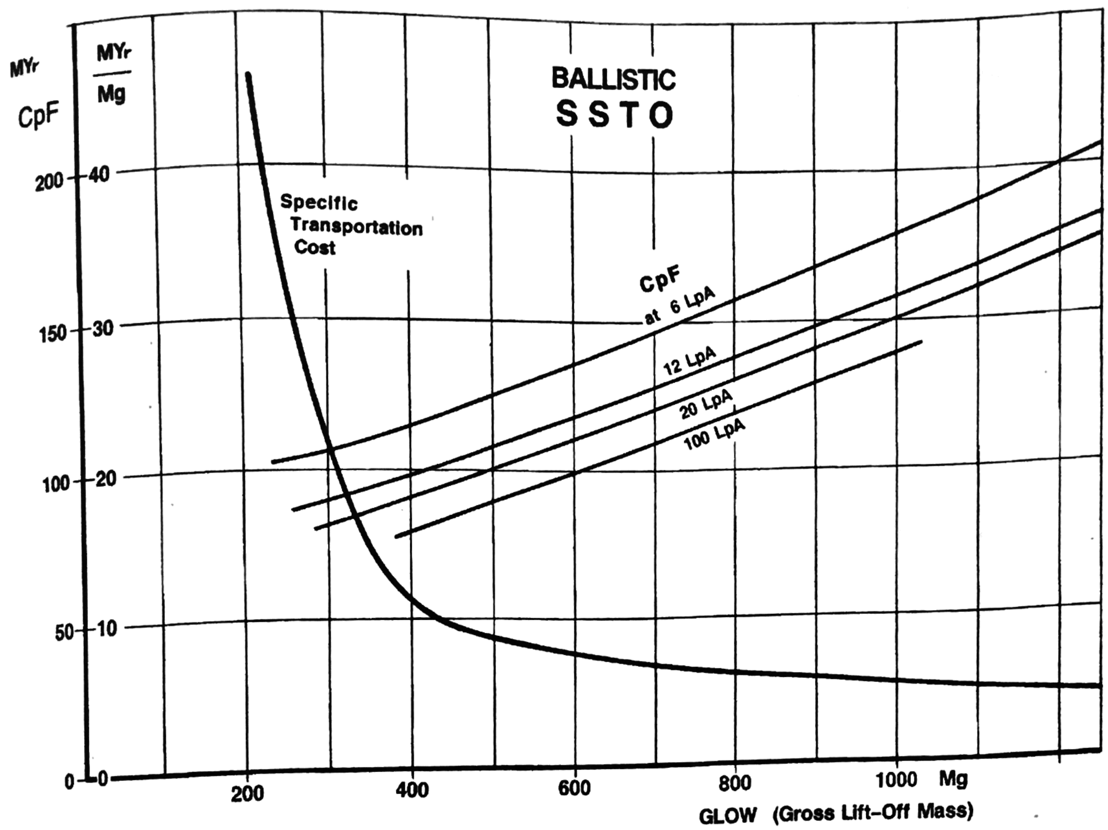

FIG. 5-07: **CpF and SpT-Cost Trends for a Ballistic RLV vs.Launch Mass**

vehicles has been restricted to small launch vehicles (like ATHENA by Lockheed Martin) composed of existing and qualified solid-propellant rocket motors, or to vehicle improvements (DELTA family by Boeing). ARIANESPACE has an investment plan for 400 M.Euro for improvements of ARIANE 5 and expansion of ground facilities in the period 2000 to 2005[2] which must be amortized partially by the AR.5 CpF.

The development costs for larger and more advanced launch systems are so high (5 to 15 Billion $) that it is almost impossible to provide commercial funding especially if the government does not provide a long-term guarantee for a minimum number of launches. This was also the conclusion of the „Commercial Space Transportation Study" (CSTS) performed by the US Industry in 1993/94 under NASA Contract (ref. 56).

While it will be almost impossible to get commercial funding for a project which requires some 10 years before the credit payback can be started, the amortisation

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charge which has to be added to the CpF seems acceptable for an ELV, but would probably kill the competitiveness of a new RLV. The reason for this is the fact that the ratio between development cost and CpF for ELVs is between 50 and 100 (or 1 to 2 %). For reusable launch systems this ratio is 500 to 1000 (0.1 to 0.2 %) because the development costs are higher and the CpF lower compared to expendable systems.

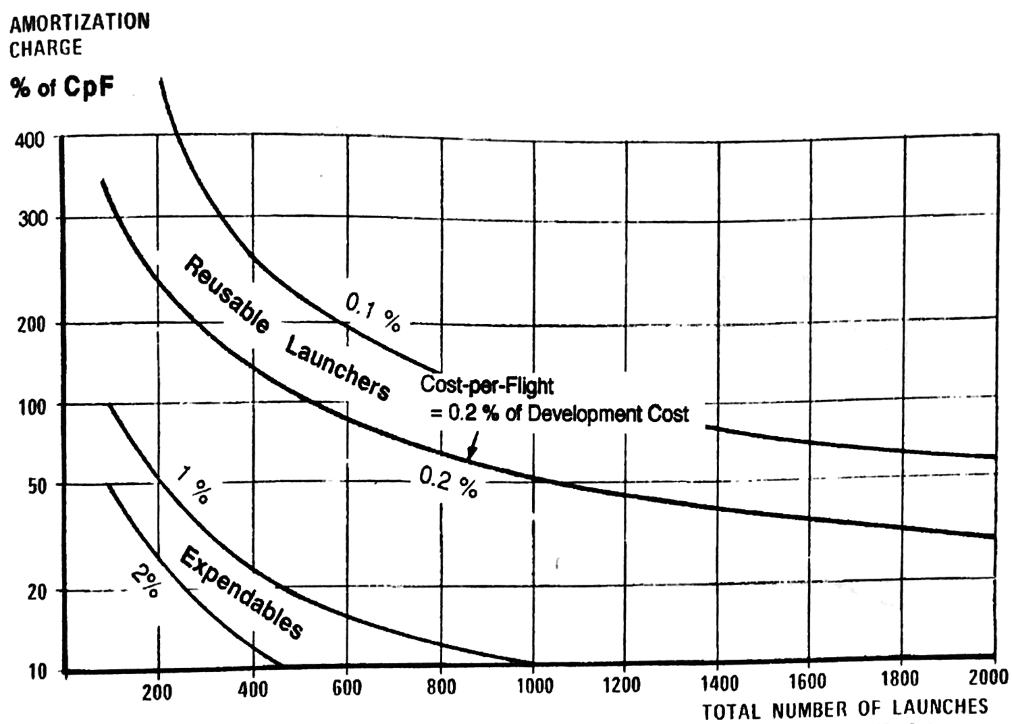

FIG. 5-08: **Full NRC Amortization Surcharge vs. Total Number of Flights**

For a new _expendable launch vehicle_ (ELV) the CpF would require a 15 to 40 % surcharge in case of 200 to 400 flights assumed for its life-cycle (cf. FIG. 5-08). The resulting price would, however, probably not be competitive with the presently existing launch market prices.

For a newly developed _reusable launch vehicle_ (RLV) the add-on amortization charge would be even 200 to 400 % assuming the same 200 to 400 flights in total. But - surprisingly - the resulting CpF could be competitive and would probably allow to offer launch services at lower prices than the present expendable vehicles (ELVs).

FIG. 5-09 demonstrates this fact by using an example comparing a typical ELV with some 120 Mio.$ CpF and a RLV costing about 35 Mio.$ per flight (without NRC amortization). Both vehicles have about the same LEO payload of 8 Mg.

When the NRC surcharge is added to the basic CpF, which is a large overhead for the RLV and a smaller one for the ELV, then the diagram shows that the total RLV price decreases rapidly and crosses the ELV line between 40 and 90 launches.

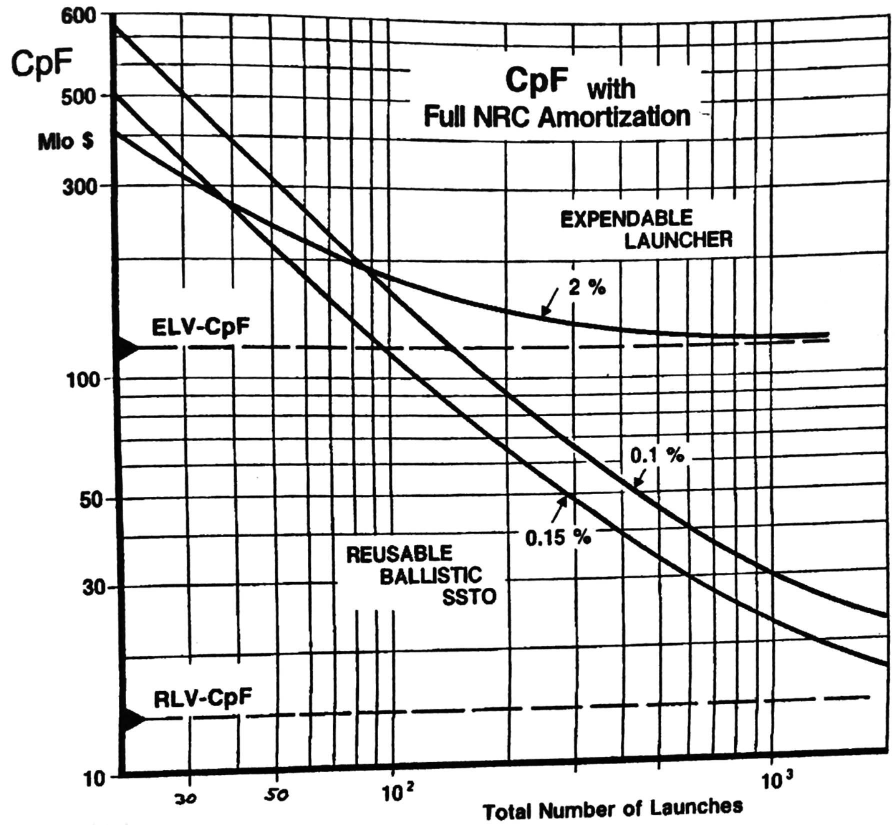

FIG. 5-09: **ELV and RLV Total Cost per Flight vs.Number of Launches**

The example shown in FIG. 5-09 does not include cost of financing. However, the conditions could be improved by application of commercial approaches for development (cf. chapter 2.5) and airline-type operations. This situation provides a chance for the commercial development of a small reusable automated launch system, provided a way for funding the up-front development cost can be found. Kistler Aerospace has been pioneering this approach by its commercial development of the reusable two-stage ballistic K-1 launch vehicle.

A potential solution for the development of larger reusable systems has been described by Ivan Bekey (ref. 59) for a Space Shuttle successor. The strategy is a commercial vehicle development approach supported by the government with a guarantee for a minimum number of later government launch orders. Such an innovative plan for a Multi-Billion $-Project is probably unavoidable in order to implement a new reusable launch vehicle development.

The chances for the historic approach where the government pays for the complete development effort appear very poor for the foreseeable future even though the US Government could save some 1.5 Billion USD annually by replacing the present ELV operations by RLVs.

5.16 Pricing Strategies

5.161 Standard Pricing

The standard pricing for a satellite launch is based on the actual cost of the launch vehicle and the ground/ flight operations, plus an amortization charge (for company-funded investments if applicable) and the nominal profit, as shown in TABLES 5-I and 5-II. Both these business charges depend also on the actual launch market . The competitive situation will define the maximum charges possible to be included in the price per launch. The launch risk lies only with the customer who normally takes an insurance for the launch, the satellite cost and eventually for the lost profit from the satellite operations in case of a launch failure.

5.162 Pricing below Cost

The market situation as well as the required vehicle production continuity (for ELVs) and/ or the launch frequency may require sales priced below the nominal CpF. This can result in a reduced or even negative profit. However, this strategy could be justified economically if

(a) an additional launch can be done without the indirect cost burden, assuming that the IOC are already covered by the „nominal number" of launches, or

(b) if an interruption of the production line or a layoff of a specialized team can be avoided.

The US Space Shuttle provides a good example: With the fixed cost of the large „standing army" of ground operations personnel the CpF for a Shuttle flight are about 460 M$ (98/ 99) per flight at 6 LpA, while an additional 7th flight would cost only in the order of 100 M$.

5.163 Pricing according to Payload Mass

In case of multiple payload launches with one launch vehicle the pricing issue becomes more complex. In principle, the dual launch strategy provides the great advantage that smaller payloads can be launched at the reduced costs of larger satellites, according to the law of scale (cf. FIGs. 5-17 and 5-21). However, there are also negative factors which reduce the theoretical advantage:
First, the vehicle's maximum payload capability will be reduced by the required additional payload support structure. Secondly, the average utilization of the vehicle's payload capability will be lower than for single payload launches. It is already difficult to achieve an average payload utilization factor (actual payload

mass flown vs. vehicle maximum payload capability) of 90 % with single payloads. For multiple payloads the utilization factor decreases further since it is difficult to find two satellites at the same time the combined mass of both filling exactly the maximum vehicle capability. Launch operations are also hampered by the dual launch strategy since often one of the two satellites has a schedule problem or a technical problem so that the chances for a launch delay are twice as high as in case of a single payload.

The first practical application of a pricing policy for dual launches was due for the ARIANE 4 vehicle family with its dual payload as standard case. FIG. 4-10 shows the pricing strategy from the initial ARIANE 4 operations: Up to 2500 kg satellite mass GTO pricing per kg was applied while for satellites above 2500 kg the dedicated launch with one of the AR.4 Versions was applicable. This pricing policy prevented excessive specific costs for smaller satellites in case of a dedicated launch with AR.40 or 42P.

By example, the launch of a 2000-kg-satellite (GTO) as a shared payload was priced to only 570 MYr instead of the 720 MYr for a dedicated AR.42P launch, but higher than the the half price of an AR.44L which would have been 430 MYr. Accordingly, the reduced payload utilization for dual payloads as discussed above resulted in some 34% higher cost (but still 20 % lower than for a dedicated launch).

A similar pricing strategy is used for ARIANE 5: the satellite INSAT IIIC with a mass of 2750 kg or 45 % of the AR.5 GTO payload capability was contracted for a

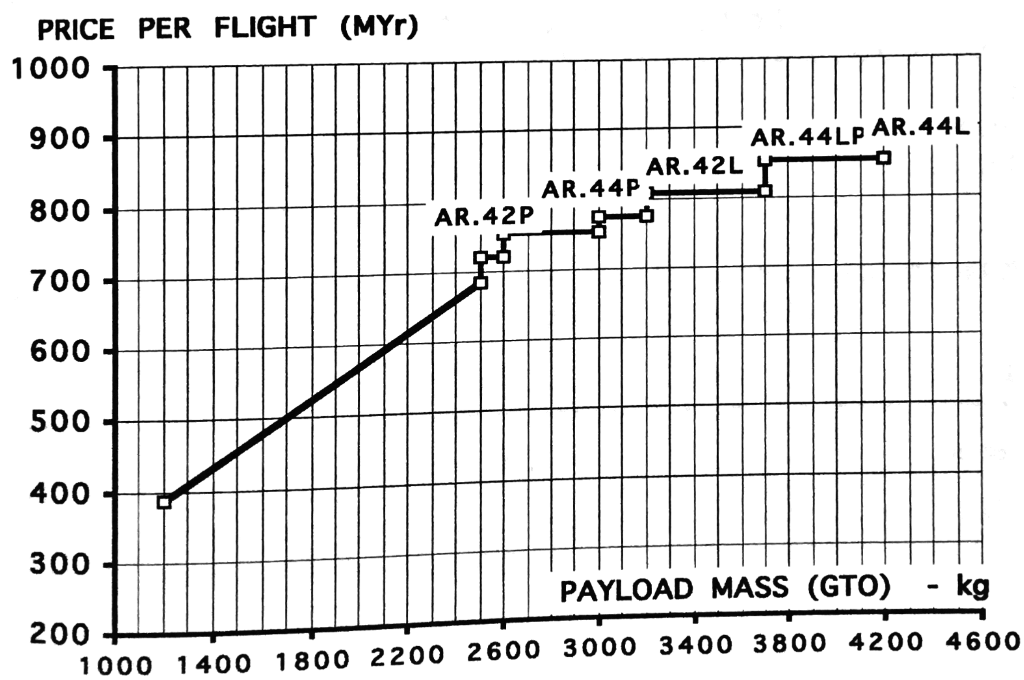

FIG. 5-10 : **Initial Pricing Strategy for ARIANE 4 Launches** price of 77 M$ [3], or 70 % of a dedicated AR.5 launch. The satellite finally was launched as a single payload on an ARIANE 42L Vehicle in Jan. 2002.

5.164 Pricing for Mini-Satellites (Piggy-back Payloads)

Small satellites below some 100 kg are accepted by some launch providers as „piggy-back" payloads. They can make up part of the residual payload capability if the volume and the target orbit are compatible with the main payload. The launch prices are negotiable (between few thousand and some 10 000 US$). This is far below any dedicated small launch vehicle and it does provide a small additional revenue for the launch provider.

5.165 Pricing per kg for Equipment Transportation to and from the ISS

For transportation of equipment to or from the ISS by the Space Shuttle NASA has quoted cost of 22 000 USD per kg for pressurized and 26 500 USD per kg for unpressurized passive cargo each way (ESA, Sep. 2001).

5.2 Cost of Unreliability / Insurance

5.21 Failure Rates of Expendable Launch Vehicles

Reliability is an inherent problem of multistage expendable launch vehicles since each vehicle is a new product which cannot be tested in a flight-representative mode. Even if designed for high reliability by redundancy of important systems, the production process involves changes of materials, processes, component suppliers and - unavoidably - new people over the time. For these reasons even a vehicle with a proven long-term reliability can fail on the next flight. Also a new cause for failures has shown up more recently: software errors.

A study by space insurance underwriter AGF (Paris) has shown that the reliability of new commercial rockets has changed little in the past 20 years[4]:

	1980-85	1985-90	1990-95	1995-00
Failure Rate	60 %	50 %	55 %	65 %

The failure rates shown are the percentage of new launch vehicles that failed at least once in the first five missions. Fortunately the reliability normally increases with the

3) BIS Spaceflight, Vol.43, 2001

4) Arianespace Newsletter Nr.155, June 2000

number of flights (cf. FIG. 5-11) as long as there are no major changes of the vehicle configuration.

Launch vehicle failures have been attributed to about 50 % to poor workmanship or human mistakes, and about 50 % to design and random failures. The analysis of 447 launch attempts in the USA resulted in 413 successes, or an average of 92.4 %. Liquid boosters' success ratio has been 0.988 for first stages and 0.984 for second stages.

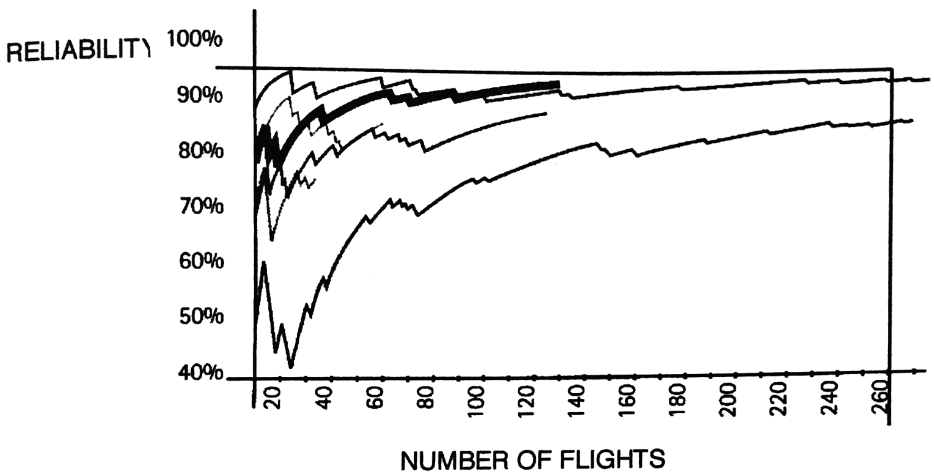

FIG. 5-11 : **Reliability vs.Number of Flights of 6 Major Launch Vehicles**[5]

Solid boost propulsion had a 0.988 reliability level. Thus solid and liquid boosters have demonstrated the same reliability[5].

Regarding the technical failure areas the following statistics from the evaluation of 69 failed launches is given in ref. 84:

Engine failures	11	(16 %)
Propellant system failures	7	(10 %)
Attitude control /TVC	17	(25 %)
Electrical system faults	6	(9 %)
Mechanical faults	7	(10 %)
Guidance failures	6	(9 %)
Solid motor failures	12	(17 %)
Others	3	(4 %)

The statistical reliability values or failure rates quoted for expendable launch vehicles differ sometimes for the same vehicle. The reason is that they are related either to the total of all vehicles launched, or only to the most recent

[5]) Aerospace America, July 1990

version, or to the number of launches performed in the past 10 years, or only of the past 10 or 20 or so number of launches. TABLE 5-V provides a survey of the mostly used launch vehicles' failure rates for the complete family lifetime until the end of 2006 and for launches in the past 5 years (2002 to 2006)
.

5.22 Cost of ELV's Unreliability / Insurance Fees

Launch vehicle failures do not only have an impact on the insurance rates for commercial launches but are also a severy cost penalty for the launch provider. Failure analysis, resulting technical improvements and validation, revision of procedures are expensive. In addition, the down-time period with no launches and schedule recovery
are an additional problem with cost impacts.

TABLE 5-V : **Failure Rates of Present Launch Vehicles** (Status: Jan.1, 2007)

VEHICLE		ALL FLIGHTS (L/ V Family)		LAST 5 YEARS (2002-2006)		Versions
Ariane	(Europe)	**6 %**	(11/174)	**3 %**	(1/29)	AR.4, AR.5
Atlas	(USA)	**12 %**	(39/334)	**0 %**	(0/19)	II, IIA, IIAS, III, V
Delta	(USA)	**6 %**	(18/321)	**0 %**	(0/32)	Delta-II, -III
H-Series	(Japan)	**12 %**	(3 /26)	**10 %**	(1/10)	H-I, H-II, H-IIA
Long March	(China)	**9 %**	(8/ 93)	**0 %**	(0/24)	2C,3A,3B,4B, 2F
Proton	(Russia)	**12 %**	(38/321)	**6 %**	(2/32)	DM-2, DM-3, -M
Sojus/Molnya	(Russia)	**5 %**	(90/1714)	**4 %**	(2/50)	-U,-Ikar, 2BL
Space Shuttle	(USA)	**2 %**	(2/117)	**10 %**	(1/10)	
Titan	(USA)	**11 %**	(24 /221)	**0 %**	(0/8)	-II, IVA, IVB
Tsyklon	(Ukraine)	**3 %**	(8/252)	**0 %**	(0/2)	
Zenit	(Ukraine)	**15 %**	(9/62)	**6 %**	(1/18) incl.Jan.07	-M, -3SL

The commercial launch vehicle customer, however, normally takes an insurance for covering the launch itself and the potential loss of the payload. The insurance market is highly volatile, depending strongly on the launch failure record and the amount of the insurance industry revenues and loss/ profit situation.

The cost impact of the launch vehicles' unreliability is tremendous: In the period 1984 to 91 insured launch vehicle and payload losses reached a volume of 1410 Mio.$[6]) or about 180 Mio.$ as annual average. In 1994 two launch failures (AR 63 and AR 70) and one satellite failure (Telstar 402) created

[6] according to „Assicurazioni Generali di Trieste"

insurance claims of not less than 757 Mio. $ while the total revenues from all space insurance contracts was only 550 Mio.$. This was followed by another launch failure in Jan.1995 (Apstar on Long March 2E) which was insured for a value of 160 Mio.$. The consequence of this situation: the insurance rates were increased substantially to the level shown in FIG. 5-11 in 1994. Until 1997/ 98 the rates decreased again to the relatively low level of some 7 %. Then 1998 became the worst single year for the insurance companies. Premiums collected totalled 850 M$ while the claims paid reached a value of 1450 M$, as shown in FIG. 5-12.

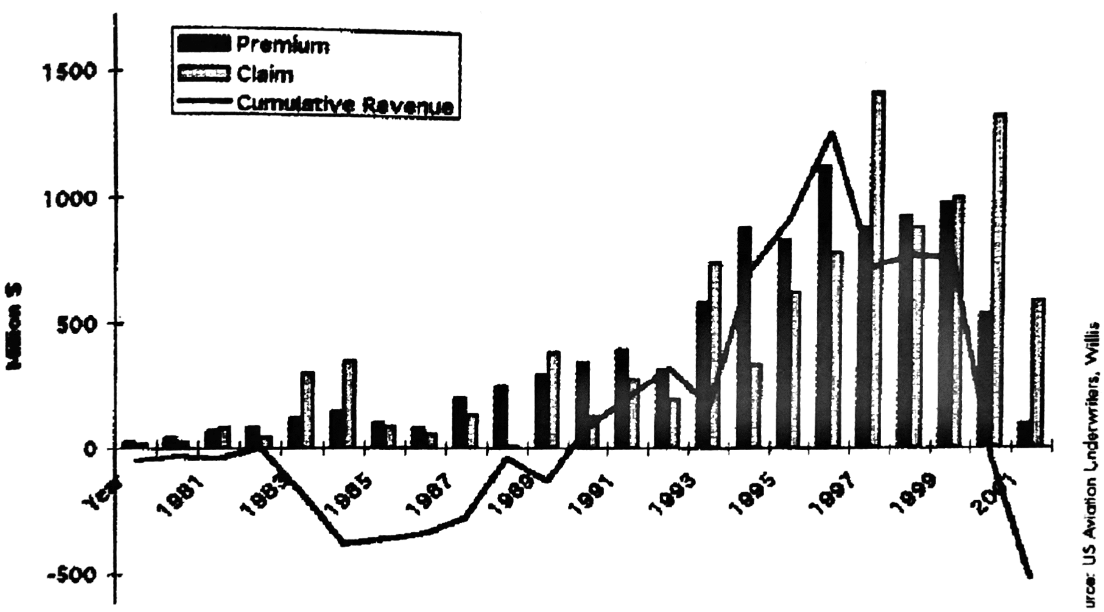

FIG. 5-12: **Premiums and Claims and Cumulated Revenues** (ref.139)

FIG. 5-13 also shows another impact of the high losses: the reduction of available insurance capacity. Several companies dropped out of this business. The capacity in the year 2002 was marginal with 800 Mio.$.

This led to a major increase of the insurance rates from 1999 to 2002, depicted in FIG. 5-13. DirektTV Co. paid 1999 a premium of 20.5 % to cover the launch of its 1-R Satellite with the ZENIT Rocket plus one year of operation. The Space Imaging Co. paid a premium of 27.5 % for the launch of its Ikonos Observation satellite with the ATHENA rocket[7]. EUTELSAT paid a 25% premium for the first ATLAS-III launch in May 2000 with a partial refunding in case of a successful launch[8].

[7] Space News, 15.11.1999

[8] Space News, 24.7.2000

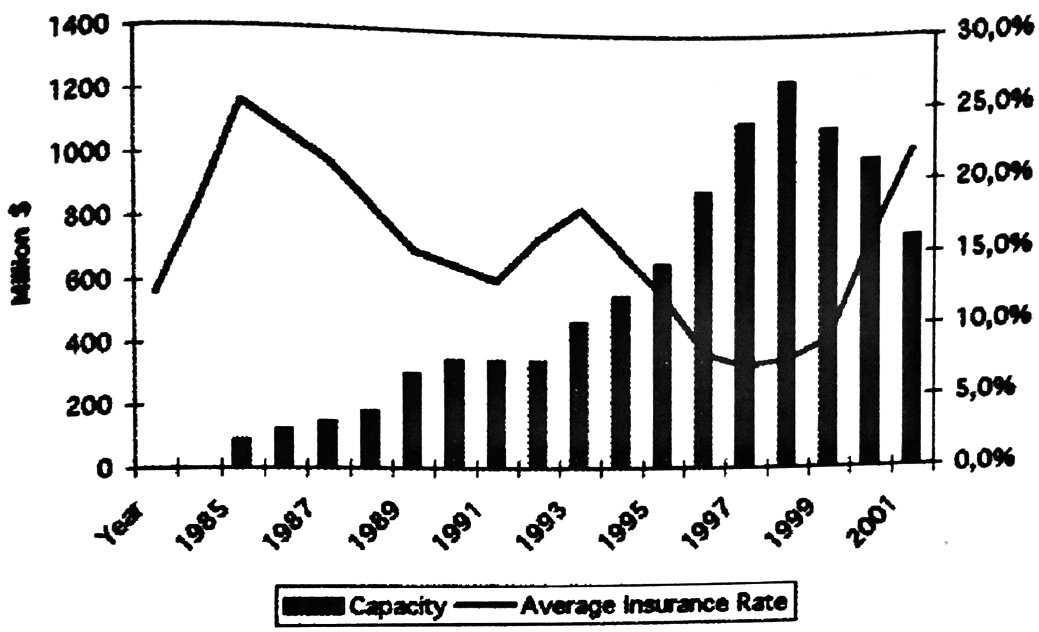

FIG. 5-13 : **Volatility of Insurance Rates and Capacity vs. Time** (ref.139)

It must be mentioned that the insurance rates refer to the cost the launch plus the value of the satellite which normally has an equal or higher value than the cost of the launch service as such. This means that the price per launch grows through insurance by some 20 % under most favourable conditions, but eventually up to 50 %.

5.23 Cost of Unreliability of Reusable Launch Systems

In case of reusable launch systems the situation is rather different compared to ELVs:

(1) The reliability of reusable vehicles will be much higher than for present ELVs because it is cost-effective to employ a higher degree of redundancy and to include a built-in health control system.

(2) Even in case of a technical problem the flight normally can be aborted and the vehicle will return either to the launch site or to an emergency landing site. In each case the payload is saved.

(3) The reusable vehicle must be insured by the launch service company and is part of the DOC (cf. chapter 4.26).

For these reasons there is no need for a customer to take a launch insurance, nor a payload insurance. If he wishes to cover the small risk of a catastrophic failure for his payload then the insurance fee would be at a very low level.

Referring to chapter 4.263, depending on the type of reusable vehicle and the degree of redundancy and advanced technology used, the vehicle loss charge should be in the order of 0.1 to 0.2 % of the vehicle recurring cost (VRC) taking into account that part of the required replacement cost have been acquired already by the vehicle amortization charge (depending of course on the number of flights accomplished before the accident).

The coverage of vehicle flight abort cases depends on the vehicle system design as well as on the operational maturity. If one assumes an initial abort rate of 1 out of 30 to 50 flights, then 6 to 3 % of the CpF should be taken into account as an add-on charge for each flight.

It can be expected that the total losses by launch vehicle unreliability can be reduced by reusable launch systems by more than one order of magnitude. However, reliability is only part of the problem: extrinsic factors (acts of God, sabotage, maintenance or management errors) are more likely to produce a loss at RLV levels of reliability (the Challenger accident is an example of this)[9] .

5.3 Status of Launch Services' - Cost / Price-per-Flight

5.31 Commercial Launch Providers

After industrial restructuring and international market consolidation there are the following launch provider companies left:

(1) ARIANESPACE,

the European Company located in F-91006 Evry/France,Blvd.de l'Europe,
BP 177 Fax: xx331-6087-6304 e-mail:webmaster@arianespace.fr
Internet Web pages: www.arianespace.com
Launch vehicles operated:
ARIANE 5G and version AR.5 ECA
VEGA (under development), to be operational 2007/8
Launch operations are performed at the Guiane Space Center, Kourou/ French Guiana, S.A.

[9] W.Claybaugh (NASA Hq.), 1998

(2) BOEING LAUNCH SERVICES

with Headquarters in Huntington Beach, CA, 92647-2099, USA
e-mail: launchservices@boeing.com
Internet Web Pages: www.boeing.com/ delta
Launch vehicles operated:

DELTA II
DELTA IV

and by the Joint Venture Company „SeaLaunch":

ZENIT 3SL.

The DELTA Vehicles are launched from Cape Canaveral (GTO and inclined orbits) and the Western Test Range (Polar orbits). The Ukrainian ZENIT Vehicle is launched from a sea-going platform in the Pacific Ocean, leaving from its home port Long Beach, CA, USA

(3) LOCKHEED MARTIN CO.

Space Systems Company, 12257 S.Wadsworth Blvd.
Littleton, CO 80125-8500 USA
Internet: www.lockheedmartin.com/wms/
Launch vehicles operated:

ATLAS II (IIA and IIAS)
ATLAS III (IIIA and IIIB)
ATLAS V - 400 und -500 Series

The ATLAS-vehicles are launched from Cape Canaveral (GTO and inclined orbits) and the Western Test Range (Polar orbits).

(4) INTERNATIONAL LAUNCH SERVICES (ILS)

a joint venture of the Russian Companies Khrunichev and RSC Energia
Headquarters: 1660 International Drive, Suite 800, McLean, VA 22102 USA
Fax: 571-633-7500
Internet Web Site: www.ilslaunch.com

PROTON-M/Breeze

The PROTON Vehicle is launched from the Baikonur Cosmodrome in Kazakhstan.

(5) EUROCKOT GmbH,

a joint venture of ASTRIUM (DE) and KHRUNICHEV (RU).
Headquarters: Airport Center, 28361 Bremen, P.O.Box 286146
e-mail: eurockot@astrium.eads.net
Internet Web Page: www.eurockot.com
Launch vehicles operated:

ROCKOT (with Breeze Upper Stage)

Launch Sites: Plesetsk (63° N) and Baikonur(46° N)

(6) STARSEM, The Sojus Company
a joint venture of EADS, Arianespace, RKA(Russian Aeropace Agency) and Samara Space Center.
Headquarters: F-75755 Paris/France, 33 Ave.du Maine, BP 30
e-mail: communications@starsem.com
Internet Web Pages: www.starsem.com
Launch vehicles operated:
SOYUZ (incl.Soyuz-Icare and Molnya-Versions)
Launch Sites: Baikonur (46° N) and Plesetsk (63° N)

(7) CHINA GREAT WALL INDUSTRY - Long March International Launch Services
Headquarters: No.30, Haidian Nanlu, Beijing 100080, CHINA
e-mail: cgwic@cgwic.com
Internet Web Pages: www.cgwic.com
Launch vehicles operated:
LONG MARCH LM-3A, LM-4B (LEO)
LONG MARCH LM-3B (GTO)
Launch Sites: Xichang, Taiyuan/China

(8) ROCKET SYSTEM CORP.
Headquarters: 1-29-6 Hamamatsu-cho, Central Building, 4F, Minato-ku, Tokyo 105-0013, Japan
e-mail: h2a@rocketsystem.co.jp
Interrnet Web Pages: www.rocketsystem.co.jp
Launch vehicles operated:
H2A, H2B
Launch site: Tanegashima Island, Japan

The total revenues of the launch industry were 8.5 Billion USD in 2000, 5.0 B.$ in 2001 and **9.4 B.$ in 2002**, according to ref. 138.

5.32 Price/Cost and Payload Capability of US Launch Vehicles

This chapter shows a compilation of the costs, resp. „Price-per-Flight" (PpF) for the actual and past major launch systems in the USA. It must be noted that the PpF are in fact prices negotiable to a certain extent and influenced by the scope of non-standard „Special Services" (cf. chapter 5.32 for „Ariane"). Insurance costs have to be added if applicable.

TABLE 5-VI: **Performance and Prices (Costs) of US Launch Vehicles**

LAUNCH VEHICLE	Launch Service Provider	GLOW Launch Mass Mg (mt)	PAYLOAD LEO kg	Polar kg	GTO kg	PRICE per Flight M.US$	MYr
ATHENA-I	Lockheed- Martin	66	700	300	----	18-20	80-90
ATHENA-II	dto.	121	1900	1200	450	24-26	110-120
ATLAS- IIAS	dto.	237	8600		3700	85-92	380-420
ATLAS-III	dto.	225	10700	6500	4500	90-100	400-450
ATLAS-V-401	dto.	337	12500	7300	4950	75-80	330-350
ATLAS V-551	dto.	540	20500	12400	8670	130-150	530-610
DELTA-II 7320	Boeing Launch Services (BLS)	152	2690	1580	---	55-70	230-290
DELTA-II 7925	dto.	232	---	3200	1840	80-90	350-400
DELTA-III	dto.	302	8300		3800	75-85	340-385
DELTA IV-M	dto.	250	8100		4200	70-75	320-340
-M+(4.2)	dto.	329	10400		5800	75-80	340-360
DELTA IV-H	dto.	733	23000		12 750 (GEO 6275)	150-200	600-800
FALCON I	Space-X	27	650	420	---	6.7	30 - 35
FALCON-5	Space-X	180	4100	2000	1050	18	75 -85
FALCON-9	Space-X	300	9 300		3400	35	140 - 160
PEGASUS XL	Orbital Science Corp.	23	450	200	---	18-22	80-100
TAURUS XL	dto.	73	1450	1050	500	20-22	90-100
SATURN IB	NASA	583	15000	---	----	43 (1963)	1500
SATURN-V	NASA	2850	127000	---	45000	220 (1974)	4280
SCOUT	NASA	22	150	----	------	16	77
SPACE SHUTTLE	NASA	2040	24000	---	----	cf. FIG.5-04	(2200)
TITAN-II	US Air Force	155	3500	1100	-----	50-55	250-270
TITAN IVB	US Air Force	930	24000	-----	-----	300	1400
TITAN-IVB-IUS	US Air Force	943	-----	---	GEO 3000	400-460	1800-2000
TITAN-IVB-CENTAUR	dto.	955	-----	---	GEO 6100	450-500	2000-2300

The prices shown in TABLE 5-VI are subject of inflation and as well influenced by the competitive situation. For this reason there are measures of internal cost reduction at all launch providers, which may reduce the PpF. The same effect can be caused by the „Learning Factor" in series production and maturing operations. The PpF are also indicated in MYr. With help of TABLE 1-II these can translated in each year's cost level, taking into account the actual conversion rate for other currencies.

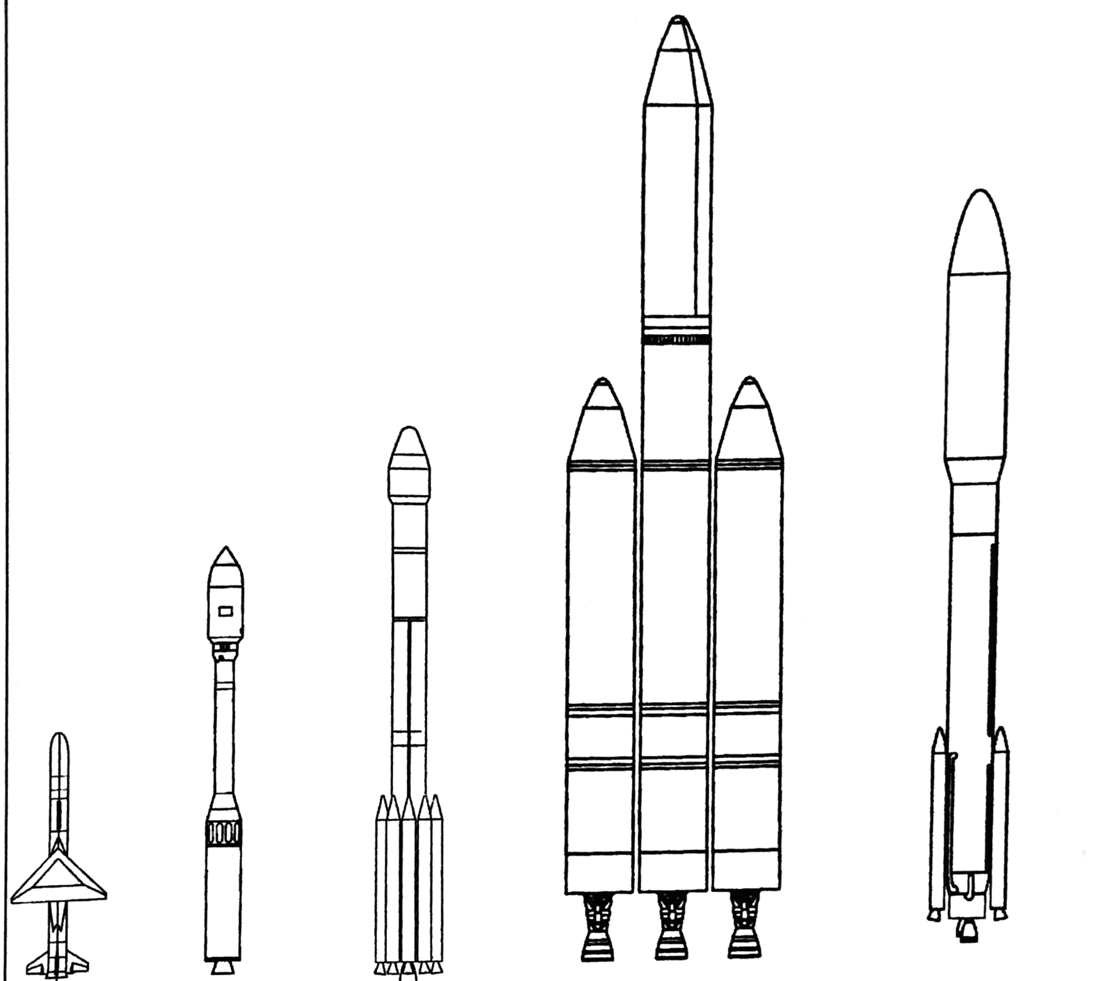

FIG. 5-13: **Survey of US Expendable Launch Vehicles**

The Polar Orbit performance in TABLE 5-VI refers to a 200/ 800 km Sun-synchronous orbit. The SPACE SHUTTLE costs (not prices in this case) depend strongly on the number of launches per year (LpA) as shown in FIG. 5-04.

The range of US Launch Vehicles is shown in FIG. 5-13 (except the Space Shuttle).

5.33 Price/Cost and Payload Capability of International Launch Vehicles

FIG. 5-14 provides a survey of the major non-US launch vehicles to be used in the post-2000 period. The performance and cost data are summarized in TABLE 5-VI.

TABLE 5-VII: **Performance and Prices (Costs) of International Launch Vehicles**

LAUNCH VEHICLE	Launch Service Provider	GLOW Launch Mass Mg (mt)	PAYLOAD LEO kg	PAYLOAD Polar kg	PAYLOAD GTO kg	PRICE/COST per Flight Currency	PRICE/COST per Flight MYr
ARIANE-40	Arianespace	240	4350	3380	2200	86-90 M.Euro	430-450
ARIANE-44L	dto.	470	9000	7500	4800	108-114 M.Euro	540-570
ARIANE 5G	dto.	746	21000	10000	7340	120-125 M.Euro	600-625
ARIANE 5ECA	dto.	777	25000	14200	10050	135-145 M.Euro	650-700
COSMOS-3M	Kosmos Intl.GmbH		109	1400	760	12 M.USD	
CYCLONE-4						10 M.USD	
CZ-2C	China Great	213	2800		1400	20-25 M.USD	
CZ-3A	Wall Company	240	----		2500	30-35 M.USD	
CZ-2E/ HO	dto.	461	8800		4800	55-65 M.USD	
CZ- 2F	CNSA						
DNEPR	ISC Kosmotras	209	3700	300	-----	11 Mio.USD	
H-II (Japan)	NASDA	260	10050	4200	4100	19-21 B.Yen	800-920
H-IIA202	Mitsubishi	285	9900	3600	4100	10-11 B.Yen	380-410
H-IIA204	dto.	443	(17000)		5800	12-13 B.Yen	450-500
ISRO-GSLV	Antrix Corp.	401	4500	1800	2000	35-40 M.USD	
ISRO-PSLV	dto.	294	3500	1350	1050	26-28 M.USD	
M-5 (Japan)	ISAS	140	1850	600	----	6.5-7 B.Yen	280-300
PROTON-M	Internatl.Launch Services (ILS)	690	21000	3700	5500	60-70 M.USD	270-320
ROCKOT	Eurockot GmbH	107	1850	1300	----	14 M.Euro	65
SOYUZ/ Molnya	Starsem Baik	305	6200	2700	1450	25-30 M.USD	
SOJUZ-2	STARSEM KOUROU					40 M.EURO	160
TSYKLON-3	KB Yuzhnoye	190	3600	2100	----	22-25 M.USD	
VEGA	Arianespace	130	2150	1500	----	21 M.Euro	100
ZENIT-3SL	NSA Ukraine	472	----	----	5000	80-90 M.USD	360-410
ZENIT-M	dto.	460	15	6,5	---	45-55 M.USD	200-250

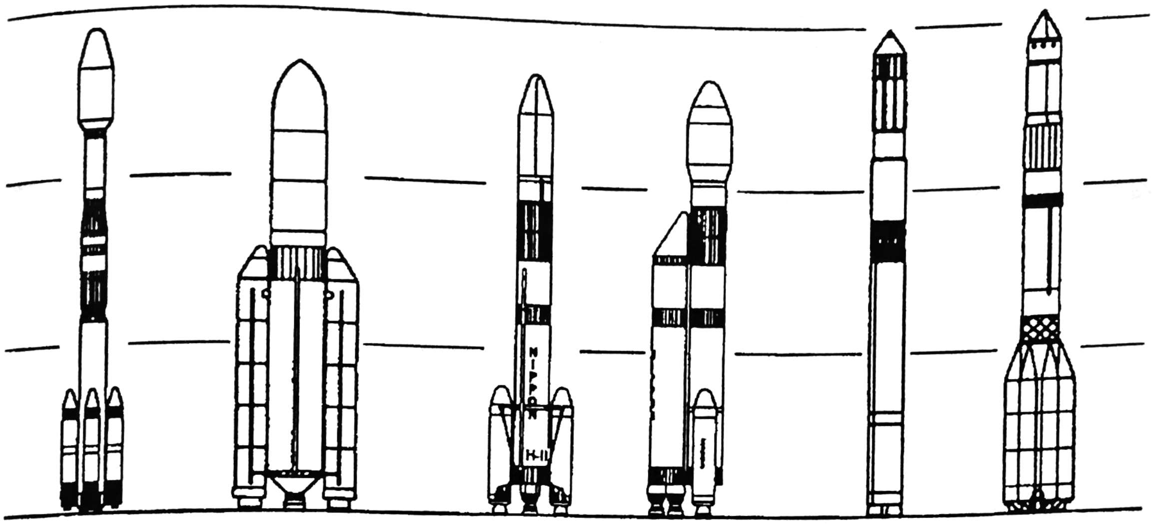

FIG. 5-14: **Survey of International Expendable Launch Vehicles**

The remarks made in the previous chapter are also valid for the international launch vehicles listed in TABLE 5-VII.

Regarding the „Special Services" which are charged by the launch service company separately in addition of the standard CpF the Arianespace Users Manual is helpful in the definition of those services (page 206) :

Special Services (to be paid in addition to the basic price):

- -- Satellite telemetry during launch and data processing,
- -- Pyrotechnical and other electrical signals to the satellite,
- -- Additional access doors in the shroud and / or radio-transparent windows,
- -- Special analyses for the satellite during flight (trajectory, separation),
- -- Loan or purchase of spacecraft adapter and clampbands,
- -- Separation shock tests, random noise or acoustic tests,
- -- Spacecraft transportation Cayenne-Kourou CSG,
- -- Special satellite guard services,
- -- Supply of satellite propellants, gases and fluids, chemical analyses.

5.34 L/V Payload Ratio Comparison and Trend vs. GLOW

A good measure of the specific launch vehicle performance is the ratio of (LEO) payload mass to launch mass, respectively the payload percentage of GLOW.

This is shown in FIG. 5-15, indicating also the great impact of vehicle size, again an effect of the „law of scale": Due to the better mass efficiency of larger vehicles the payload ratio is improving substantially with size. The higher values within the band are achieved by vehicles with cryogenic upper stages. This is well illustrated by the ARIANE-5 example: with its small storable propellant third stage the payload ratio is only 2.8 %, with the new cryogenic third stage it grows to 3.9 %, and with a new larger third stage and the Vinci engine (ARIANE 5-ECB) the payload ratio would reach some 4.3 %.

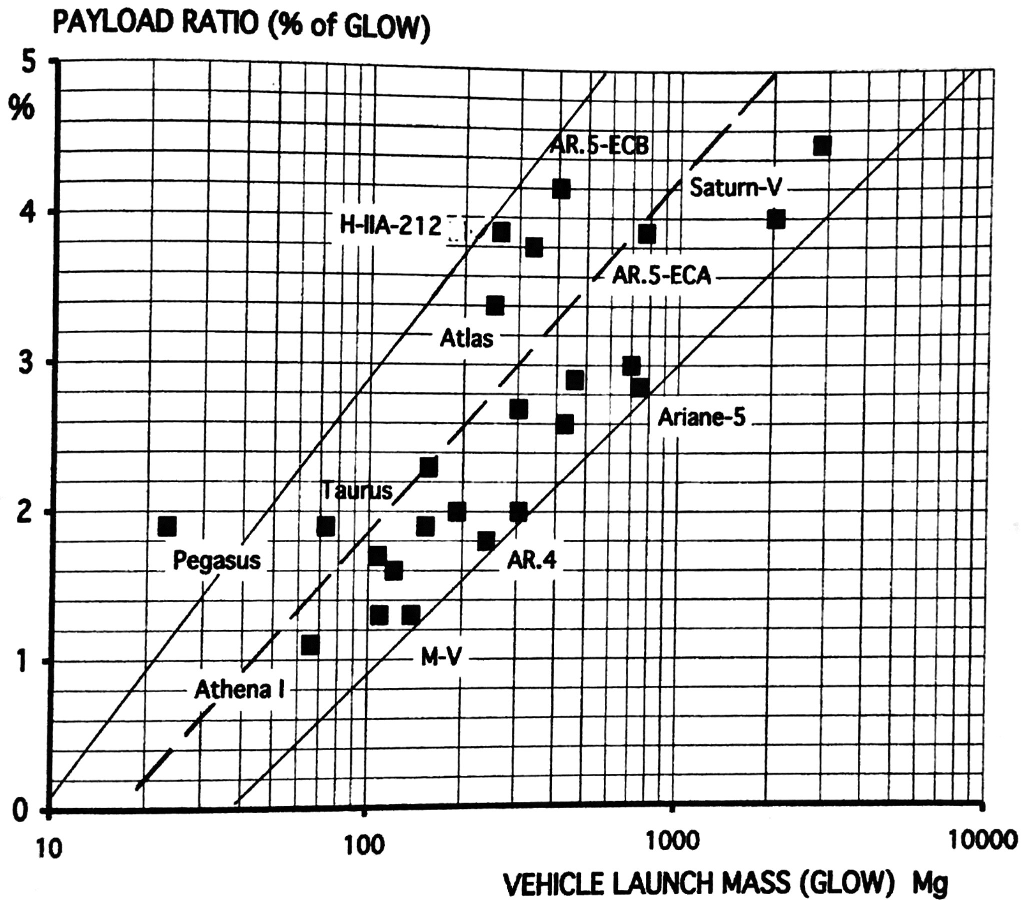

FIG. 5-15: **LEO Payload Ratio Trend (% of GLOW) for Expendable Launch Vehicles (ELVs)**

The relatively high performance of the Pegasus launch vehicle although using solid-propellant stages is achieved by the air-launch mode.

The over-proportional payload growth with vehicle size (20 % higher GLOW = + 30 % payload !) is due to the share of vehicle elements which are widely independent from vehicle size - such as guidance equipment, telemetry, etc. - and the improved volume efficiency of larger propellant tanks.

5.4 Specific Space Transportation Cost (SpTC)

5.41 Specific Cost to LEO (Low Earth Orbits)

5.411 Historic Overview: Cost vs. Time

The historic trend of specific space transportation costs to LEO is illustrated in FIG. 5-16. The cost value used is MYr/ Mg in order to avoid the problem of inflation. The actual year costs can be obtained by using the values of TABLE 1-II. The cost data shown in FIG. 5-16 are *theoretical* specific costs, related to the maximum launch vehicle LEO payload capability.

The initial steep decrease in the 60ies by two orders of magnitude was caused by improved technology (introduction of cryogenic upper stages with LH_2/LOX propulsion) and the rapid increase of vehicle size and payload capability within one decade: from 40 kg payload of the VANGUARD vehicle to 127 000 kg of SATURN V. However, after 1970 the specific transportation cost to LEO have not been reduced for some 40 years. They are still between 40 and 100 MYr/ Mg (equivalent to 10 000 to 24 000 $/ kg in the year 2006).

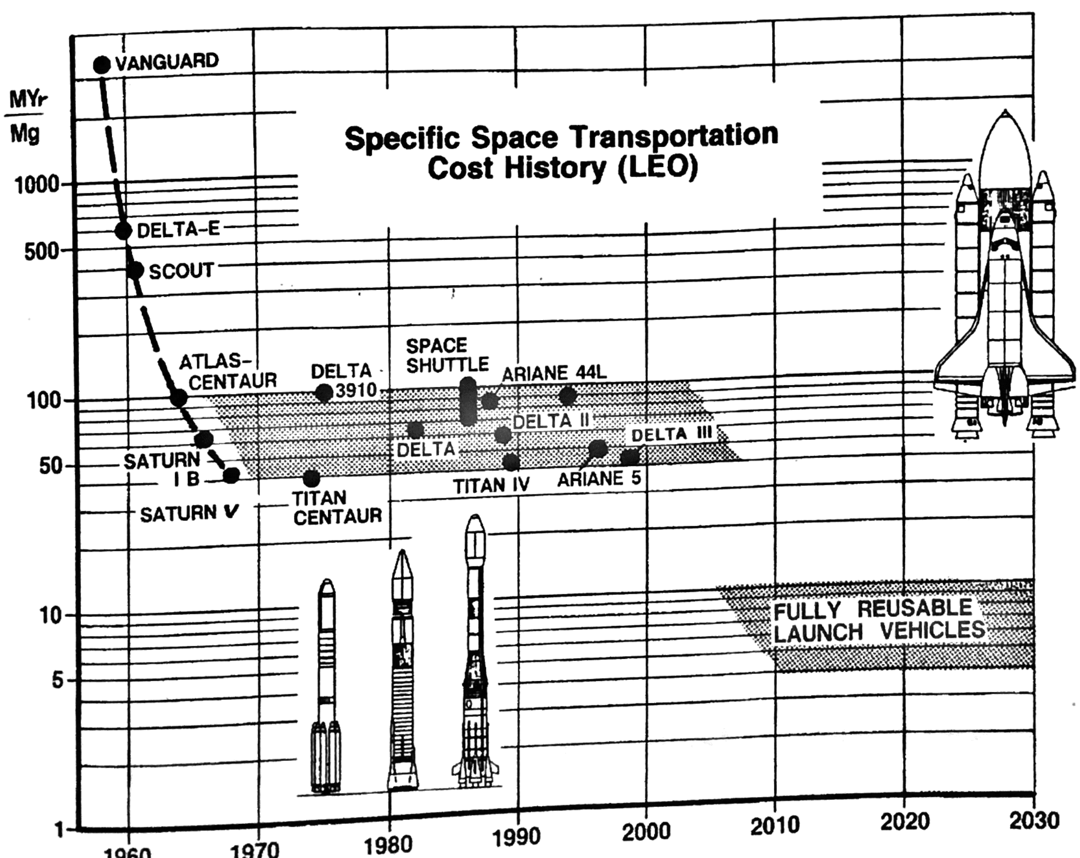

FIG. 5-16: **Historic Trend of Theoretical Specific Transportation Cost to LEO (Low Earth Orbit)**

The variations within this region are due the vehicle size / payload capability, respectively the different launch frequency (LpA). Only the development of the more recent new vehicle generation of ARIANE 5-ECA, ATLAS V and DELTA IVH with increased performance and application of several cost reduction features (such as reduced number of engines, simplified ground operations) as well as overcapacity and increased competition promises eventually the reduction of the theoretical specific transportation costs to LEO to the range of 25-30 MYr / Mg (= 6000 to 7300 $/ kg) for large payloads.

A further reduction of specific transportation cost cannot be expected for expendable launch vehicles, except by another major increase of payload capability and/ or much higher flight rates (launches per year).

5.412 Specific Cost vs. Payload Size (L/V Performance)

The specific transportation cos are decreasing with increasing vehicle size, respectively payload capability . This „law of scale" (valid for all kinds of transportation systems on ground, on sea and in the air) is evident in FIG. 5-17 with a large number of reference points ranging from SCOUT to SATURN V. The reference specific cost data are those from the launch vehicles shown in TABLES 5-VI and 5-VII. Specific cost reductions have been made in the different launch vehicle families like ARIANE, DELTA and ATLAS over the time but only due by increasing the payload capability.

Some projected RLV cost values are also shown in FIG. 5-17. The data are for different vehicle concepts and they originate from different sources, using different cost estimation methods. They indicate a clear trend of reduced transportation cost by RLVs. The cost reduction compared to ELVs is becoming larger with increasing vehicle size, resp. payload capability. The reason is evident : For ELVs the vehicle fabrication costs are dominant, for RLVs the operations costs which are less sensitive to vehicle size than production costs.

The specific cost trend in FIG. 5-17 also indicates that for small vehicles (LEO payload less than 2000 kg) reusability probably does not pay off. For 5 Mg-payload-vehicles a cost reduction to one quarter can be expected while for 30 to 40 Mg-payload-vehicles a cost reduction by one order of magnitude should be feasible and for larger vehicles even more (depending on the number of launches per year).

5.413 Specific Cost to and from the ISS (International Space Station) by the Space Shuttle

For transportation of equipment to or from the ISS by the Space Shuttle NASA has quoted costs of 22 000 USD per kg for pressurized and 26 500 USD per kg for unpressurized passive cargo each way (ESA, Sep. 2001).

5.414 Mini-Satellites / Piggyback-Payloads

Eurocket has offered the launch of Piggy-back payloads of 1 to 2 kg with the Rockot Launcher into an 800 km-Orbit for 25 000 US$ per satellite[1].

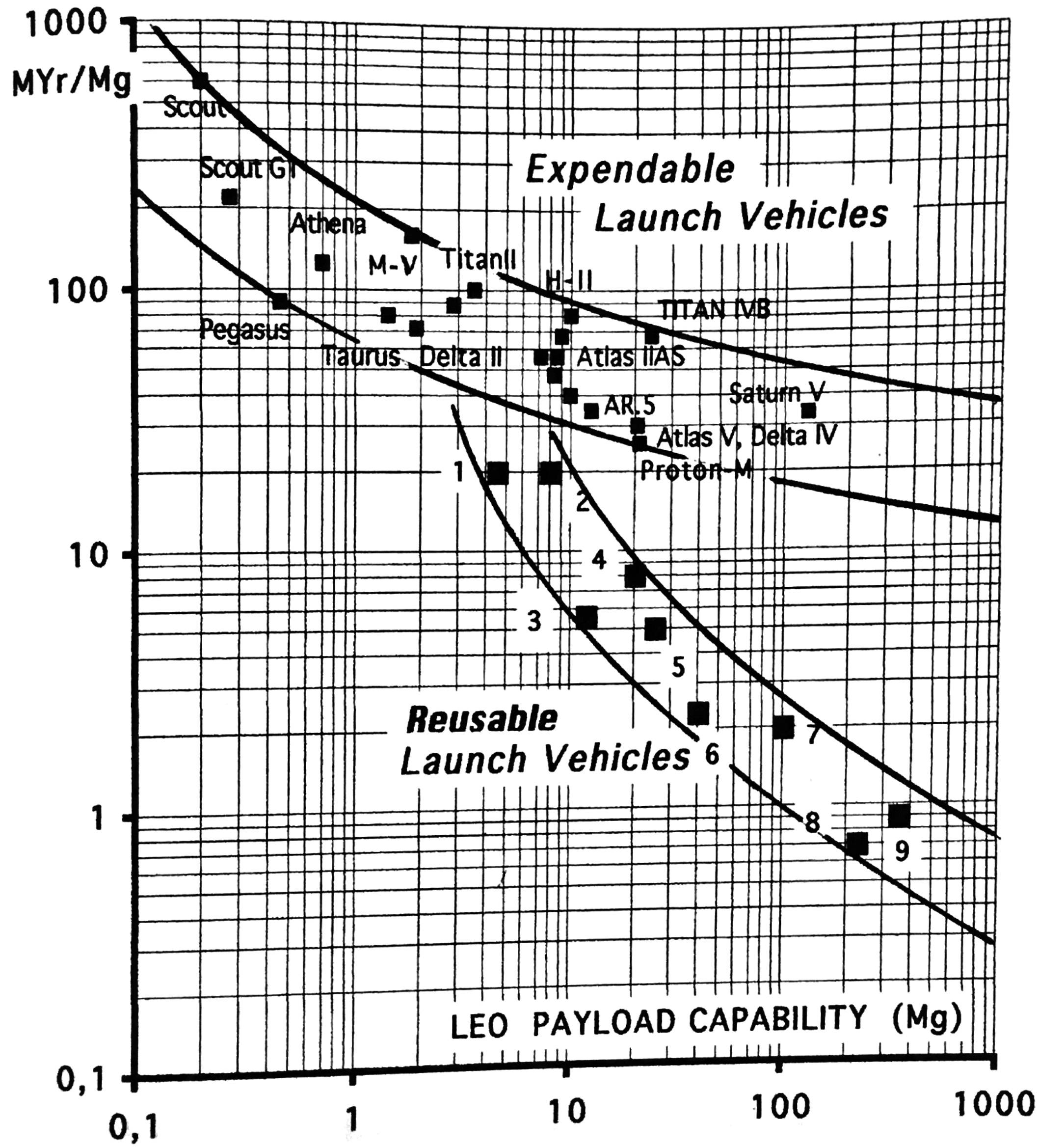

FIG. 5- 17 : **Theoretical Specific Transportation Cost of Expendable and Reusable Launch Vehicles vs. Payload Capability to LEO**
(RLV-Projects: 1 = Kistler K-1, 2 = Sänger TSTO, 3 = *MBB* BETA II, 4 = Lockheed Martin „Venture Star", 5 = BETA III, 6 = Chrysler SERV, 7 = BETA IV, 8 = Boeing SSTO'76, 9 = TUB NEPTUNE) - No NRC amortization

[1] AW, 3.2.2003

5.42 Missions to the Geostationary Orbit (GEO)

5.421 Historic Cost Trend

The payload and accordingly the specific transportation costs in case of GEO missions are influenced by the launch site latitude, taking into account the required apogee maneuver including the plane change to zero degree inclination. For this reason the payload in GEO is being used after insertion, instead of the GTO payload.

The historic development must be related to the same spacecraft mass in GEO, as shown in FIG. 5-18. The cost decrease is about a factor 2 from 1970 to 2002 for a 700 kg-satellite (BoM-GEO). This reduction is mainly due to a higher launch rate and improved ground operations. A more dramatic cost specific cost reduction resulted from the payload mass increase from 36 kg in 1963 (Sycom II) to 2860 kg in 2001(Intelsat 9). This growth is illustrated well by the example of the DELTA Launcher GTO payload capability as shown in FIG. 5-19. A similar performance increase was developed in the ATLAS- and ARIANE- launcher families.

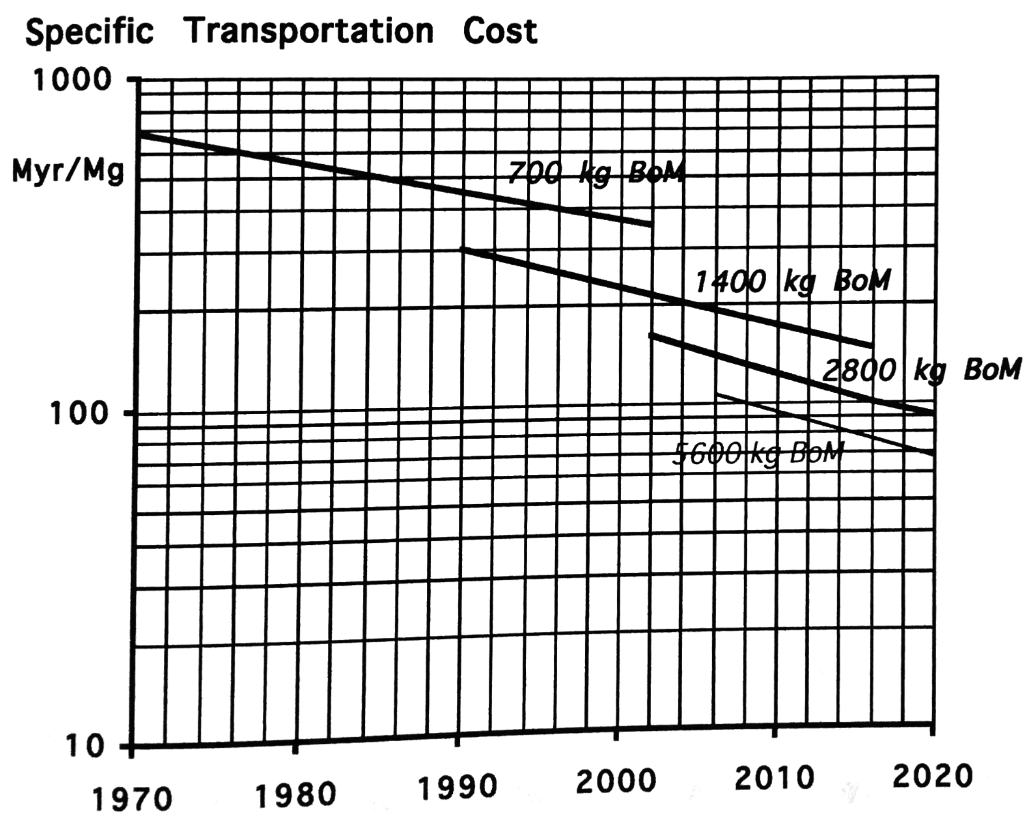

FIG. 5-18: **Historic Trend of Specific Transportation Cost to GEO vs. Payload Size**

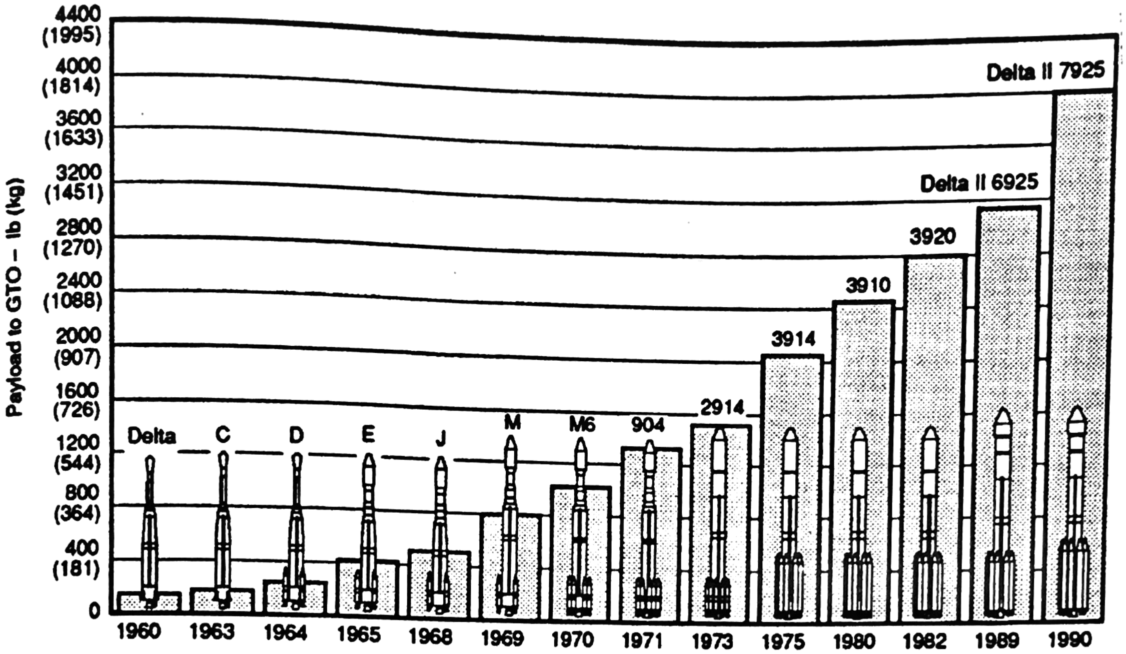

FIG. 5-19 : **Historic GTO/GEO Payload Growth of the DELTA Launch Vehicle**
(Bars and Figures at left indicate Payload to GTO in lb and (kg)

As shown in FIG. 5-20 the *average mass* of all satellites in GEO has grown from 300 kg in 1970 to 1600 kg in the year 2000. The related specific transportation costs are 460, resp. 180 MYr/ Mg according to FIG. 5-21, showing the cost reduction by the larger launch vehicle payload capability. This is the major cost reduction trend, as illustrated in FIG. 5-18. The last step were the improved AR.5, DELTA-4M and Atlas-5 vehicles reducing the specific costs to the new level of some 150 MYr/Mg to GEO. Further payload growth to some 5600 kg in GEO (ARIANE 5-ECB and DELTA-IVH) may result in costs of some 100 MYr/Mg.

A new generation of reusable launch vehicles could reduce the transportation costs to GEO by the year 2020 further by 30-50 % of the ELV costs with an expendable Perigee Stage, and by 50 to 70 % by the combination of an RLV with reusable Perigee Stage (ref. 134).

5.422 Specific Costs vs. Payload Size / Launch Vehicle Capability

The theoretical specific transportation costs to GEO are shown in FIG. 5-21. They show a strong sensitivity to the ELV payload capabiity. The cost values are related to the *maximum* launcher capability and do *not* include the apogee propulsion system costs (or cost share in case of unified satellite propulsion systems). For a fair comparison with the direct GEO injection mode by the launch vehicle itself the related share of the satellite propulsion system cost should be added. This would add 5 to 7 % to the specific costs shown in FIG. 5-21 for commercial launches.

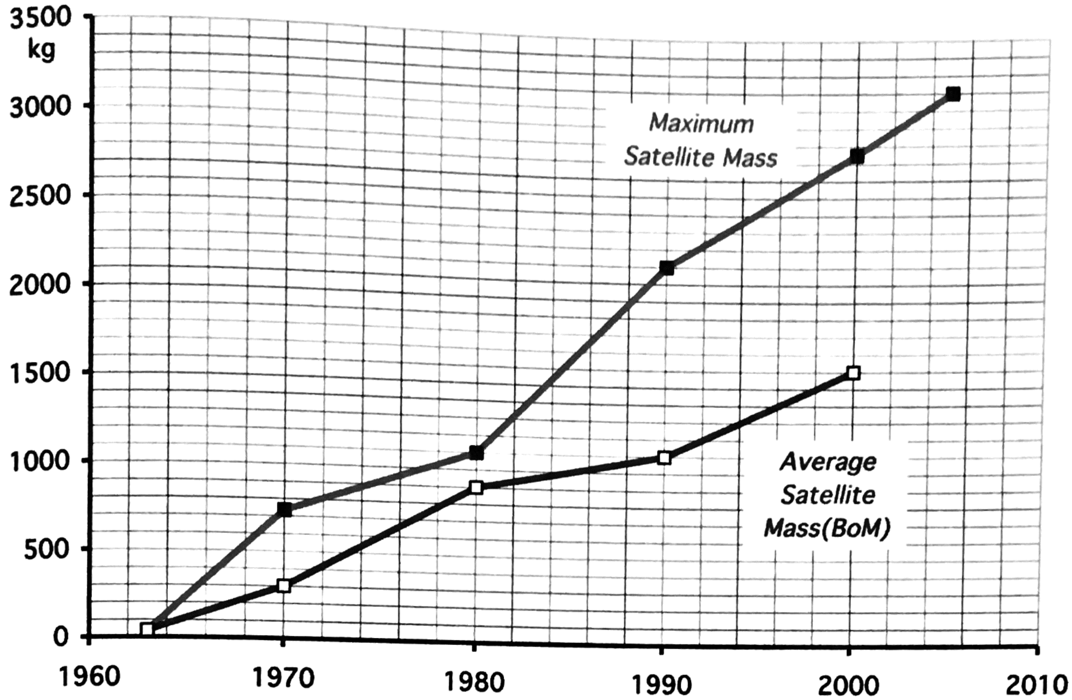

FIG. 5-20: **Historic Growth Satellite Massin GEO (BoM)**

There seems to be a major cost difference between injection via GTO with subsequent apogee injection by the onboard satellite propulsion system, and the ELV injection into GEO by a re-ignitable transfer stage. This is, however, only related to the TITAN IVB which was more than twice as expensive than other vehicles (cf. FIG. 5-17). Insofar the new EELV systems ATLAS V and DELTA IV H with the same performance as TITAN IVB reduce the transportation costs essentially, down to the commercial vehicles' level.

For realistic specific GEO transportation *prices* related to the satellite BoM mass 15 to 20 % must be added to account for the vehicle's payload utilization which is 80 to 85 % in average. Also insurance costs (both for launch and satellite costs) have to be added in case of commercial missions, increasing the effective costs by another 10 to 25 %. The chart also shows that the dual launch capability of some ELVs (such as ARIANE) results in a generic cost reduction of 25 to 35 % due to the lower costs of larger payloads compared to single smaller payloads. Dual launches, however, mean a lower launch rate (LpA) which reduces the theoreticall cost advantage by 10 to 15 %. Also the risk of schedule delays is increased in case of two satellites.

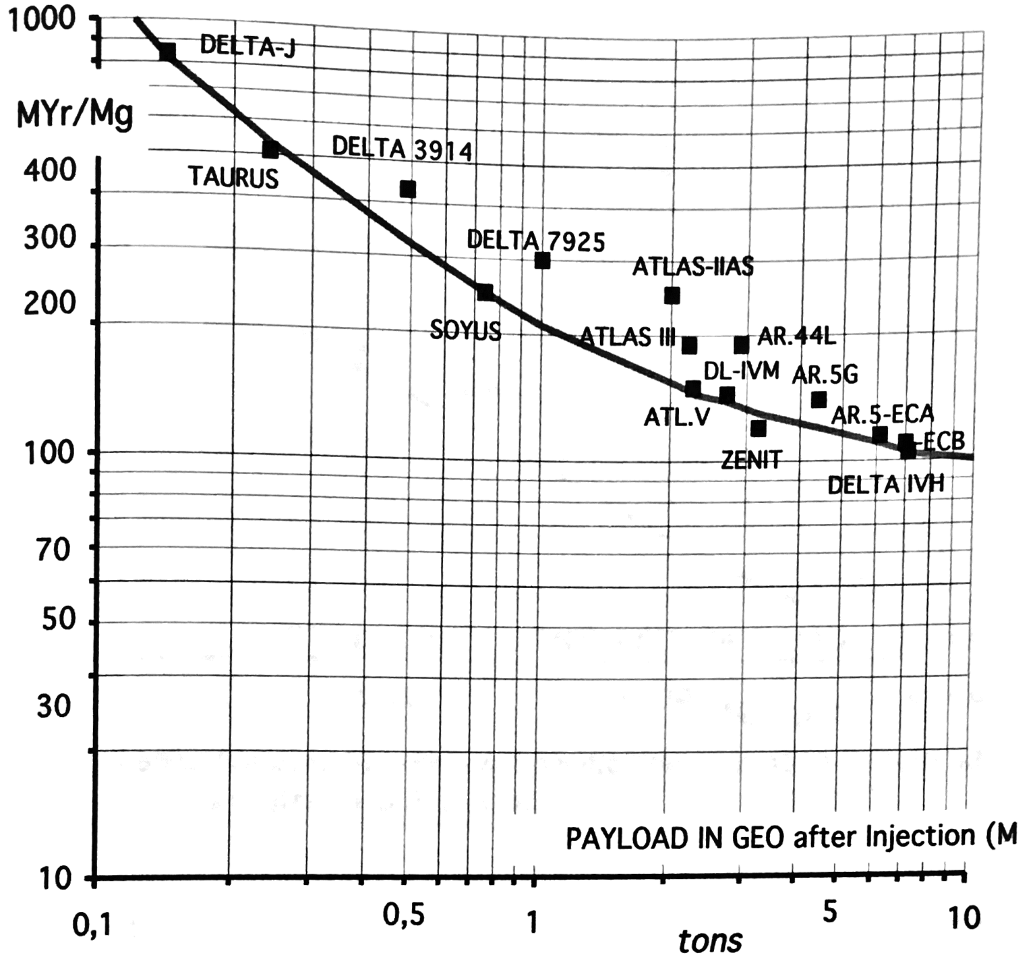

FIG. 5-21: **Theoretical Specific Transportation Cost to GEO vs. Launch Vehicles' Payload Capability**

5.43 Specific Costs vs.Total Annual Transportation Mass (Market Size) and Optimum RLV Payload Capability

An increase of the annual transportation demand (or market size) leads to a higher launch frequency and to the use of larger launch vehicles, i.e. to larger average individual payload size. Also the incentive is growing for vehicle improvements and the development of more cost-effective (re-usable) launch systems. All these factors have an impact on the average specific transportation cost.

The space launch activity in **1999** comprised 83 launches (including failures), using 24 different vehicle types. The total theoretical LEO payload capability represented by these vehicles was 700 Mg, composed of the following launch vehicle payloads:

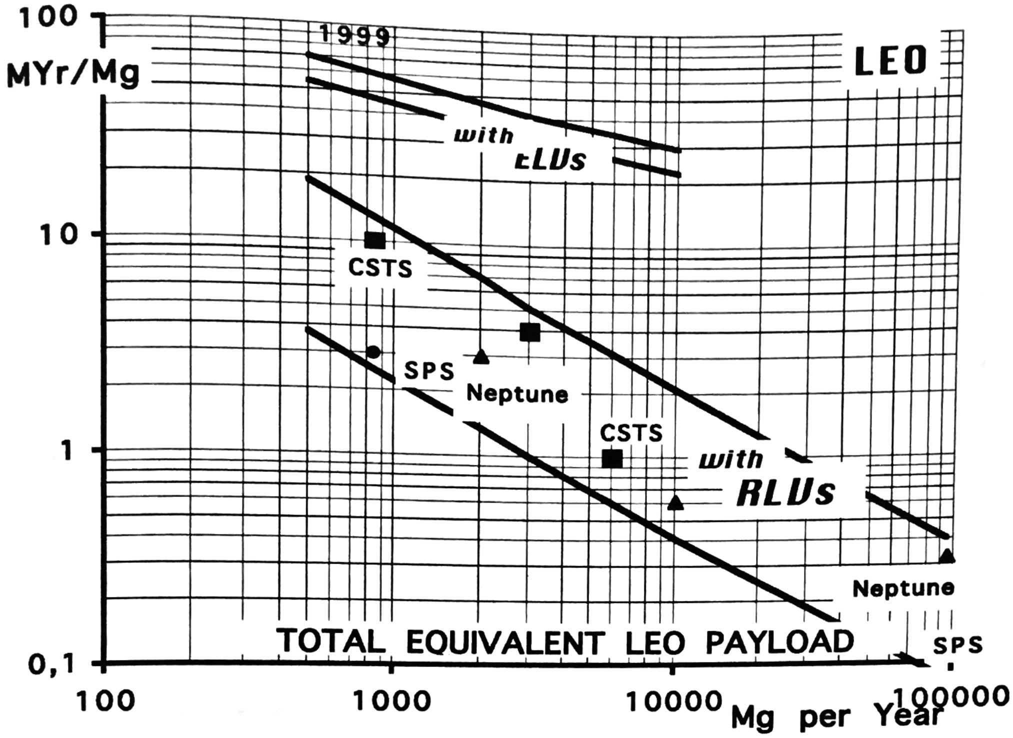

FIG. 5-22: **Relation Between Theoretical Specific Transportation Cost to LEO and Market Size** (LEO Equivalent Mass, no Development Cost Amortization)

295 Mg Russian launch vehicles,
235 Mg US launch vehicles,
80 Mg European launch vehicles,
55 Mg Ukrainian launch vehicles (Zenit), and
35 Mg L/V from Japan, China and India.

The effectively used capability, however, assuming a utilization factor of some 82 %, is only about 575 Mg., or an average of 6.9 Mg per launch. This value is the *equivalent LEO payload* , i.e. including the real payload plus all upper stages required for missions beyond LEO. The 83 launches in 1999 did cost 39 400 MYr, resulting in average values of 475 MYr per launch, or 68,5 MYr / Mg specific transportation cost (= 15 300 $/ kg in 2003), or 56,3 MYr / Mg „theoretical specific cost", related to the launch vehicle capability.

This result is in good agreement with FIG. 5-22, taking into account that the graph shows the *theoretical* specific costs (assuming 100 % utilization) while the 68,5 MYr/Mg-value takes into account the realistic vehicle utilization.

The interdependency of specific costs and market size was subject of the CSTS Study (ref. 56). The CSTS-derived values for a potential future market volume of 850, 3000 and 6000 Mg per year have been combined with previous

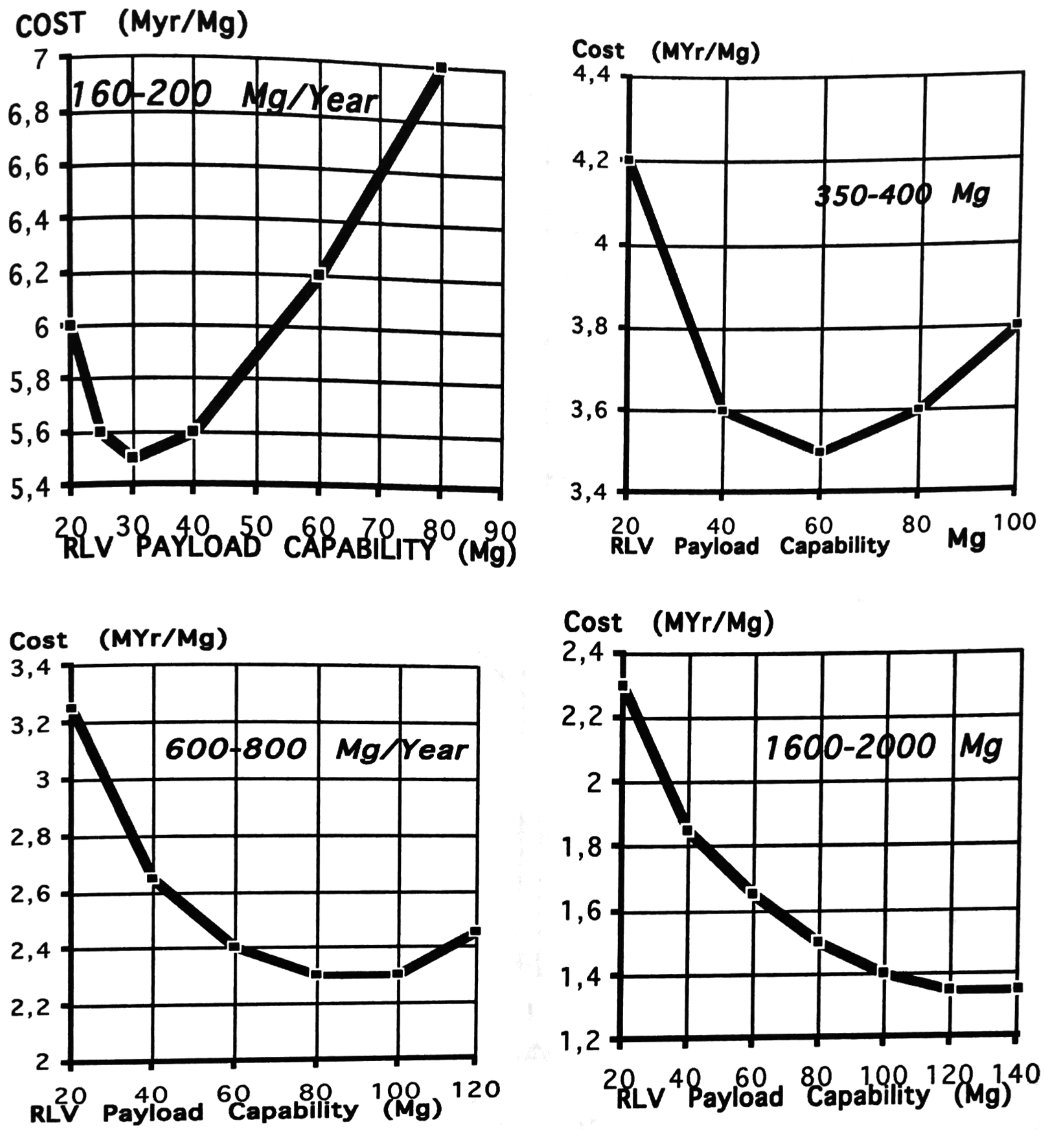

FIG. 5-23 : **Optimum RLV-Size for a Given Annual Transportation Demand**

data from the SPS studies (Space Power Station) and a NEPTUNE Case Study in FIG. 5-22. The resulting specific cost reduction trend is shown for both expendable and reusable launch vehicles. The cost data result from a mixed fleet of different vehicles and depend both on the vehicle type and size (payload capability) as well as on the launch rate.

There exists, however, an ideal case for each given transportation demand with minimum specific transportation cost, since a larger launch vehicle reduces the specific cost (cf. FIG. 5-17), but this means also a reduced launch rate which increases the specific cost. Therefore, there must exist an optimum combination of vehicle size and launch rate. This is shown in FIG. 5-23 by the variation of vehicle

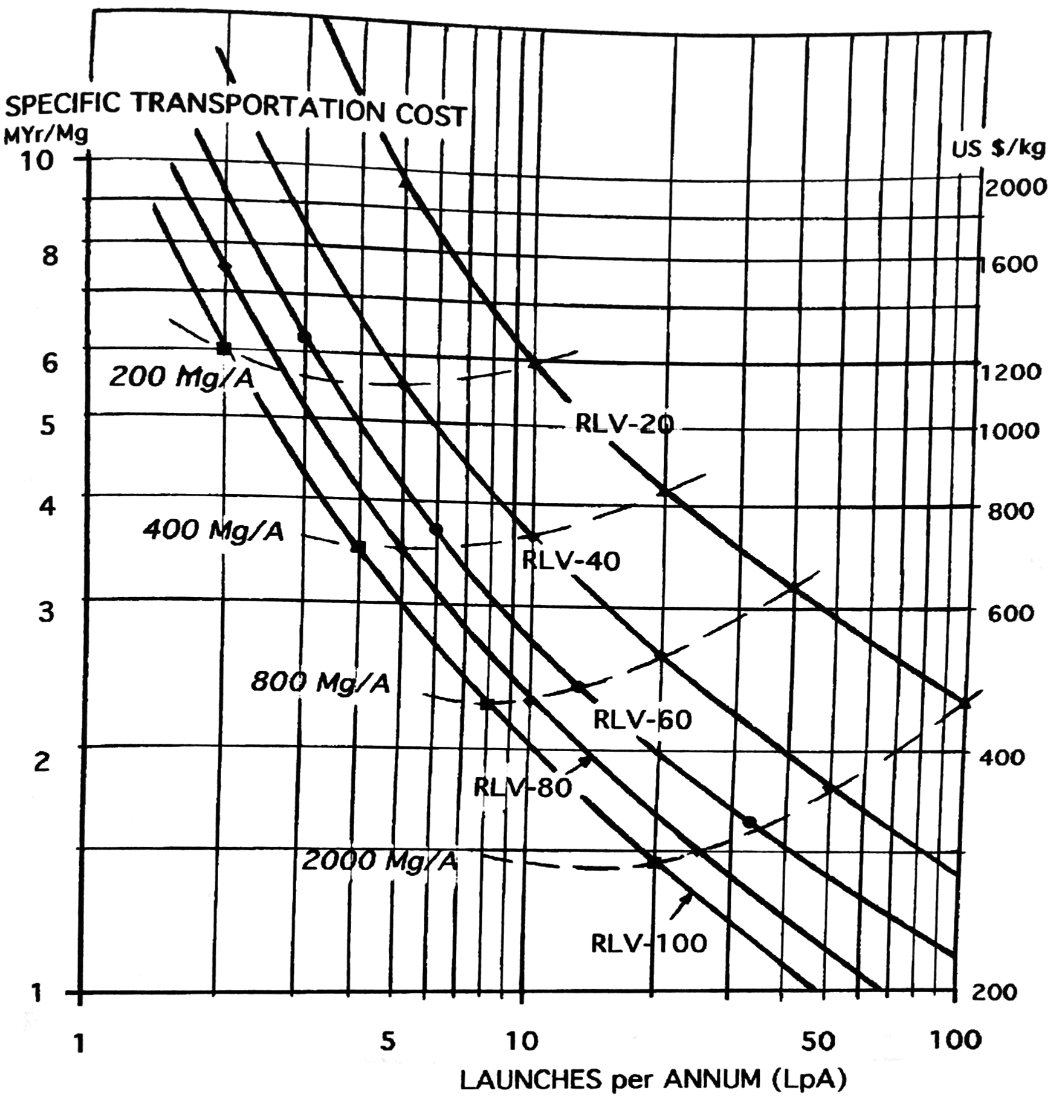

FIG. 5-24 : **Design Chart for the Optimum Ballistic RLV-Size and Launch Rate with Annual Transportation Demand to LEO as Parameter** (1998/99 $)

payload capability for four different transportation demands to LEO. The RLV type used in this example is the ballistic reusable SSTO vehicle without development cost amortization.

The results of this analysis (ref. 110) has been compiled in a design chart which illustrates both the impact of vehicle LEO payload capability and launch rate on the specific transportation cost (FIG. 5-24). The calculated minimum specific cost in the four cases confirm the cost-vs.-payload-trend of the statistically derived RLV-curves in FIG. 5-23. The cost values are lower than the indicated range because they represent the optimum case, while FIG. 5-22 represents a fleet of RLVs with different payload capabilities.

5.44 Human Transportation Cost / Space Tourism

5.441 Short Flights to > 100 km Altitude

Based on the successful demonstration of a two-stage winged vehicle built at Burt Rutan's Scaled Composites Workshop (X-Prize Winner), Richard Branson plans with his Virgin Galactic Company to offer commercial flights for 190 000 USD per person from 2007/2008.

5.442 Orbital Human Missions

Initial space flights for tourists have beeen offered by the Russian Soyuz-Vehicle, and 5 persons took this chance since 2001 for a price of some 20 M$. However, for public access to space (space tourism) in a larger scale then essentially lower cost are required. Several market analyses about the public interest in spae tours have been made in different countries (ref. 105). They shows that a price of 0.7 M$/1994 would only attract some 100 people (FIG. 5-25). In order to make space tourism a profitable business ticket prices must be 50 000 $ or less, in order to attract at least 10 to 20 000 passengers per year. It must be taken into account for this market analysis that there is a difference between saying „I would like to make a trip into space" and the actual payment for a ticket. Therefore, a more realistic relation or market model has been prepared as FIG.5-26 which can be used for economic studies. The price threshold of 50 000 $ is a tremendous challenge for a space transportation system: it means that for a 50-passenger-

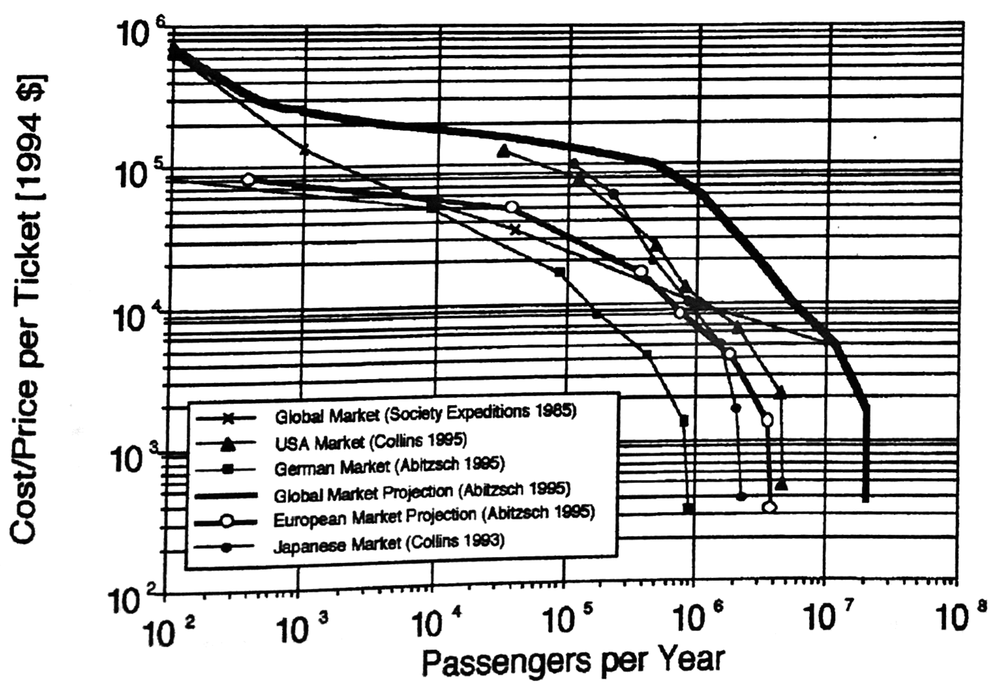

FIG. 5-25 : **Expected Number of Passengers per Year vs.Ticket Price**

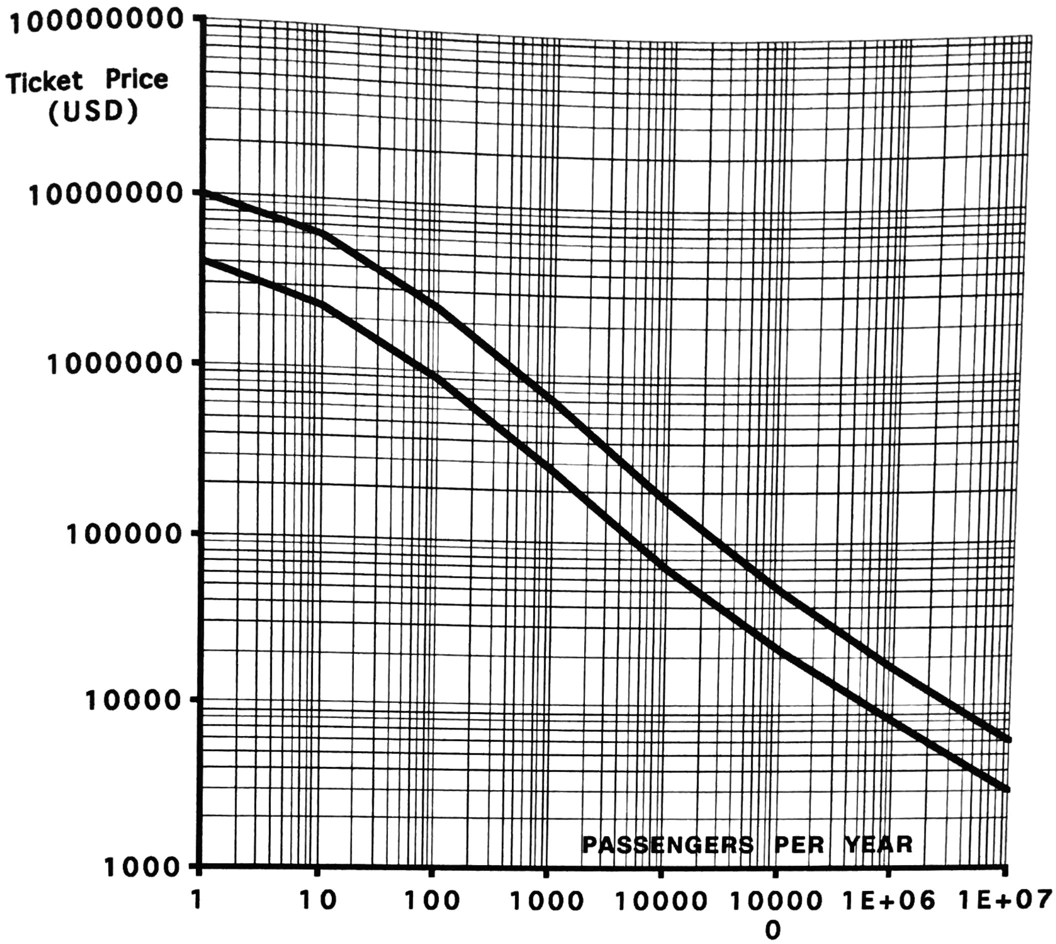

FIG. 5-26: **Space Torism Market Model: Number of Annual Passengers vs. Ticket Price**

vehicle the cost-per-flight may not be higher than 1.65 M$ or less than 8 MYr per flight, taking into account the usual business charges (development cost amortization and profit of the launch service provider). As shown in an example in chapter 6.7 the situation can be improved by using larger launch vehicles with at least 100 passengers.

A typical space tourism mission could last 12 hours allowing for 7.5 orbits around the Earth in 250 to 400 km altitude with 65° inclination, providing great views on a large part of the surface, as well as time for a personal zero-g experience, both the major objectives of a space tourist.

The main impediment to space tourism is the fact that no suitable launch vehicle exists yet. The development of a new reusable launch vehicle with high reliability has to be implemented as acommercial venture with a long payback period for investors. The total investment required is in the 2 to 4 Billion $ range, and it will take some 8 years until the flight operations can start. In addition, a build-up phase of several years has to be taken into account until the tourist business can reach mature operations with hundred or more flights per year. A first business assessment how space tourist operations could develop, has been made by Bob Citron in 1997 (ref.109).

The launch vehicle size, respectively its passenger capability, has an important impact on the economics of the space tourism business. Uncertainties are the business charges (company profit, development cost amortization, ROI, etc.) and the actual level of specific transportation cost - in this case the cost-per-seat - which finally can be implemented. The relative results, however, are representative: the smaller the launch vehicle, the higher is cost-per-seat and accordingly the market size. A larger vehicle increases the initial investment, but offers much better business opportunities. As an important side-effect, the implementation of space tourism with a large number of flights would also reduce the cost of satellite launches and transportation into orbit, thus opening new markets of space applications.

FIG. 5-27 shows the concept of a passenger cabin for a ballistic RLV. It has been conceived for 100 persons on three levels, plus plus a pilot and a tour guide. Each passenger has a convenient viewing port and there is a cylindrical space in the center that provides the opportunity for „zero-g floating", both the most important requirements for space passengers. The seats can be adapted to a flat position for launch and re-entry / landing. Only the ballistic RLV - using the rear re-entry mode - provides the same acceleration vector both at launch and at re-entry, an important aspect for designing the passenger accomodations. The diameter is 6.5 m, allowing for the accomodation of 34 deployable flat seats in a circular arrangement (ref. 107).

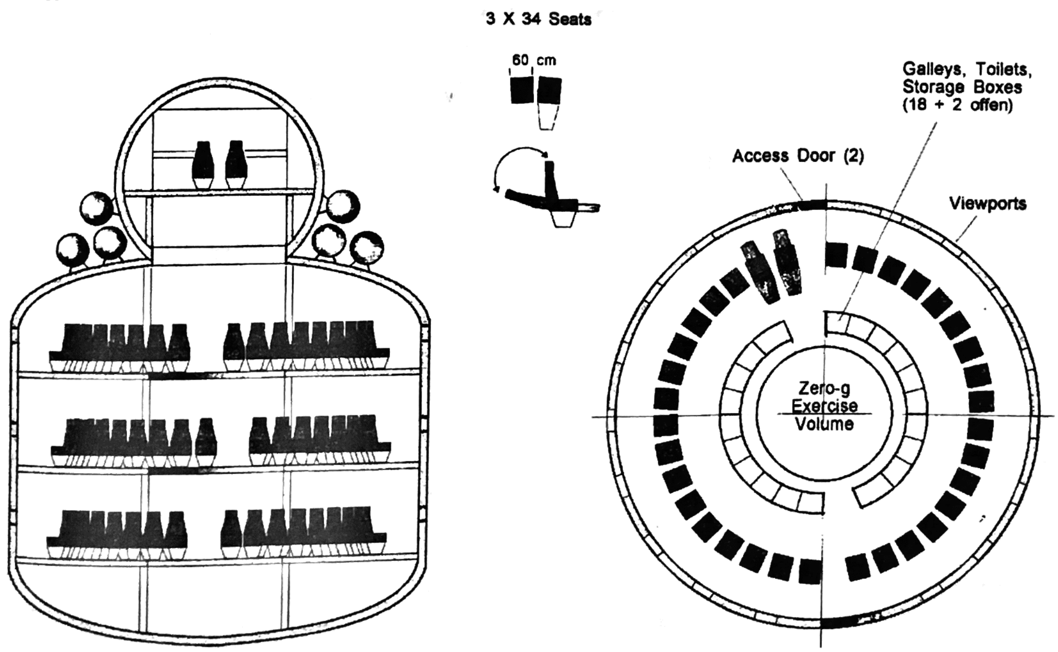

FIG. 5-27: **Design of a Passenger Cabin for a Ballistic RLV (100 Paxe)**

The total mass of the pressurized passenger/ crew cabin as shown in FIG. 5-27 is estimated to 11.6 Mg plus 8.4 Mg for the passengers and their small luggage (ref. 107). The LEO payload equivalent (for the same launch vehicle to be used for conventional cargo launches) in this case would be about 17 Mg, plus 3 Mg shroud weight .

5.5 Life-Cycle-Cost (LCC) of Launch Systems

5.51 Definitions

Life-Cycle-Cost add the programmatic element to vehicle cost analysis. This means that a certain program duration (10, 20, 30 years) and the annual or total number of launches has to be assumed. Only in special cases a certain transportation demand can be established, by example for the launch of a space power station (SPS). In contrast to military missile or aircraft programs there is (normally) no program requirement, it is an open-end business.

Life-Cycle-Cost comprise the main phases of a flight system:

(1) Detailed Design and Development (Phases C and D)
(2) Production of n vehicles in z years,
(3) Flight Operations over z years
(4 Disposal).

Disposal is only applicable in case of military projects, however, not in case of launch vehicles: ELVs are used up normally, and the limited number of RLVs would find easily a retirement place in one of the aerospace museums. Not included in the LCC are the initial definition studies (Phases A and B), technology pre-development, and eventual technology demonstrators / flight test vehicles.

5.52 CpF vs. Program Duration

The Life-Cycle analysis is useful to show the variation of CpF, by example, over the program duration. The Cost-per-Flight (CpF) are not constant but decrease with time, respectivley with the number of launches due to the learning effect both in vehicle production as well as in prelaunch and flight operations. Therefore, it is important to define whether given CpF are start-up cost, or average cost of a defined program, or actual cost of a mature program.

By example, the CpF of ARIANE 44L (without development cost amortization) have been 877 MYr at the time of its introduction (1988), and only 580 MYr twelf years later after some 100 vehicles have been built and launched. This means a cost reduction by 34 % which can be allocated as follows:

Unit Production Cost : - 36 % of 658 MYr = - 27 % of CpF
Direct Operations Cost: - 34 % of 132 MYr = - 5 % of CpF
(in line with a reduction of the launch preparation time from 29 to 18 d)
Indirect Operations Cost : - 25 % of 61 MYr = - 2 %
(in line with the increase of the launch rate from 7 to 11 LpA, but taking into account the staff increase of the ARIANESPACE Company).

The cost reduction had the effect that the price per launch could be kept almost constant over the 10-year period, while the MYr-cost in Europe increased by some 37 % from 1989 to 1998.

In a LCC assessment for the NEPTUNE RLV Concept (ref. 15) with 350 Mg payload in LEO the CpF -reduction is even more pronounced - as to be expected: the calculated CpF decrease is some 66 % between flight 30 and flight 150, excluding development cost (NRC) amortization. If the development cost need to be taken into account, then the CpF are initially much higher (factor 3 at 30 flights), but decreases by ca. 65 % after some 150 flights. FIG. 5-28 illustrates this situation.

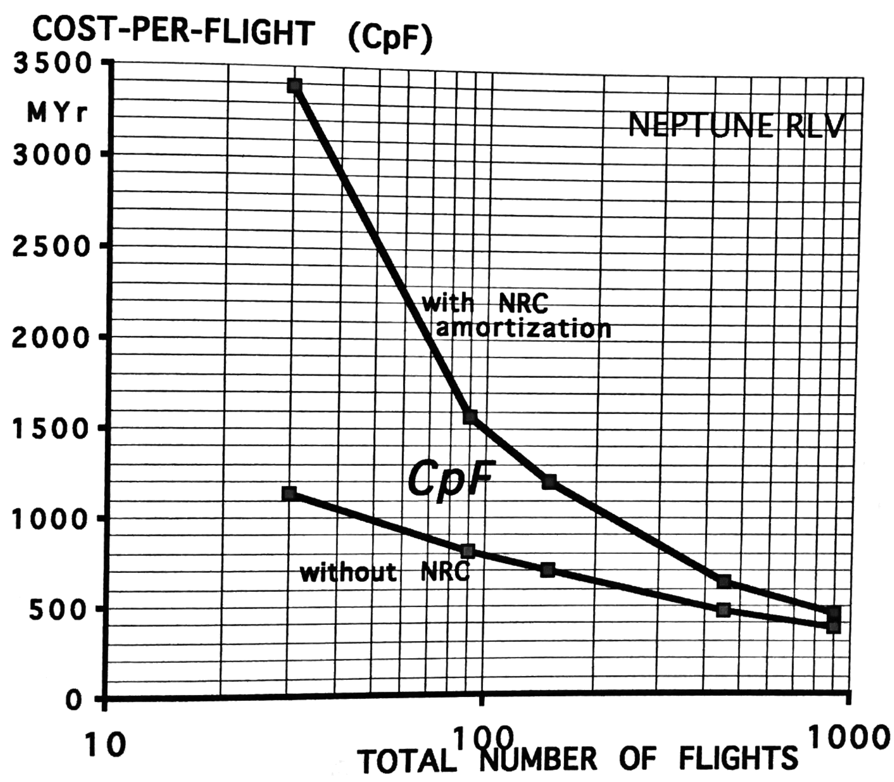

FIG. 5-28: **Cost-per-Flight vs.Total Number of Flights for a Ballistic Reusable Launch Vehicle (NEPTUNE)** with and without Development Cost Amortization

5.53 Life-Cycle-Cost as a Comparison Criterion

The comparison of launch systems' development cost is an important criterion but it does not provide a complete view of the system economics. Here life-cycle-calculations are the better solution in principle. The problem, however, in space launch vehicle business is the fact that the life-cycle duration, respectively the total number of launches has to be assumed, and that this assumption influences the results essentially.

This is demonstrated in FIG. 5-29 with the comparison of three representative cases (launch systems with 20 Mg payload to LEO):

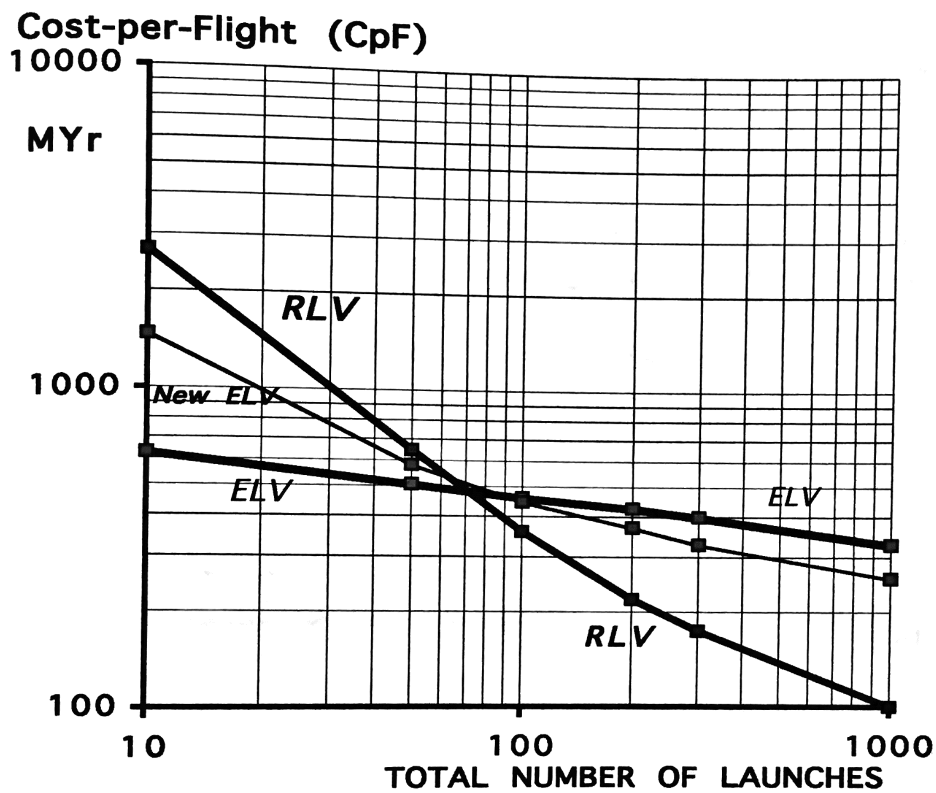

FIG. 5-29: **Cost-per-Flight vs. Life Cyle (Total No. of Launches)**

Case (1) : Existing ELV with initial (TFU) 129 M$ vehicle cost

Case (2) : Improved ELV with 2 B$ development cost and initial 90 M$ vehicle cost (reduction of 25 %)

Case (3) : New RLV with 5 B$ development cost and 250 M$ vehicle unit cost.

For vehicle production and the operations cost a Learning Factor of 0.90 has been taken into account in all three cases. The resulting CpF vs. number of launches leads to interesting results:

The use of an existing ELV is the best solution if not more than 80 launches are planned in the future. However, already at some 68 launches the new RLV (with the assumptions made here) results in lower CpF inspite of the high development cost investment. Surprisingly the improved ELV does not show superiority at any flight number. Its implementation does only pay off after more than 90 launches in comparison to an existing ELV, and it is only more cost-effective than a new RLV at up to 60 launches.

5.54 Discounted Life-Cycle Cost Analysis

For the planning and evaluation of commercial/ industrial development activities the discounted LCC is important since it reflects the investment vs. the Net Present Value (NPV).

FIG. 5-30 compares the significance of LCC costing for typical RLV program phases: The technology and system development cost - some 30 % in Example 1 - Constant Currency Value (discount rate zero) - can grow to almost 80 % of the NPV in case of an industrial equity financing (case 5). The nominal discount rates used in FIG. 5-30 (ref.135) are

Case (3) :	US Government	7 %
Case (4) :	Commercial Lender	15 %
Case (5) :	Equity Financing	25 %

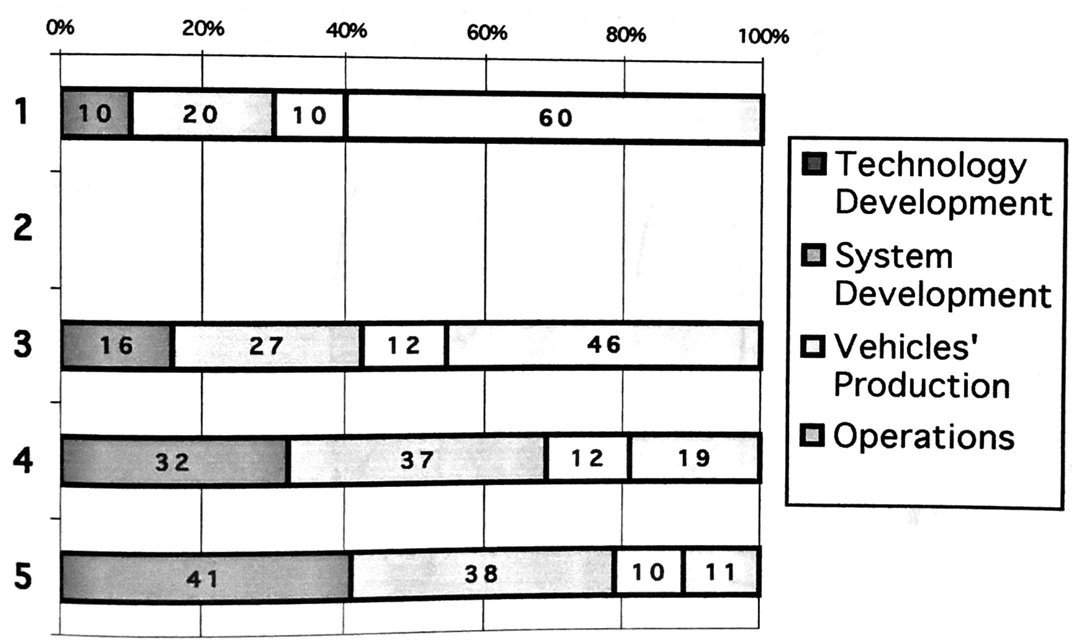

FIG. 5-30: **Comparison of Discounted LCC Cases with the Constant Value LCC**

assuming an inflation rate of 3 % per year. Only expenditures are shown here. For the complete NPV definition the (discounted) revenues during the operational period also have to be taken into account.

The ROI - Return-on-Investment - is the metric that allows to compare the expected benefits to investment cost. ROI represents the the ratio (as percentage) of the present value of the investment, both calculated at the firm's cost of capital.

Given the time schedule for launch vehicles' development and testing, i.e. the late start of revenue cash flow, the ROI has to be very high to justify a commercial investment in this business area.

5.6 Cost of Earth-Moon Cargo Transportation

5.61 Lunar Flight Mode Options

For lunar transportation different flight profiles and related vehicle system options are feasible. FIG. 5-31 illustrates some cases such as direct transfer with expendable and reusable systems, application of orbital operations in LEO (Space Operations Center, SOC) with propellant and payload transfer to a Lunar Transfer Vehicle (LTV), or the option with one single vehicle which after launch from Earth is refueled at the SOC and continues to a landing on the Moon. This is feasible, in principle, because the delta-V requirement for lunar transfer, orbit injection, descent and landing, ascent and return to Earth is about the same as for ascent from Earth to LEO.

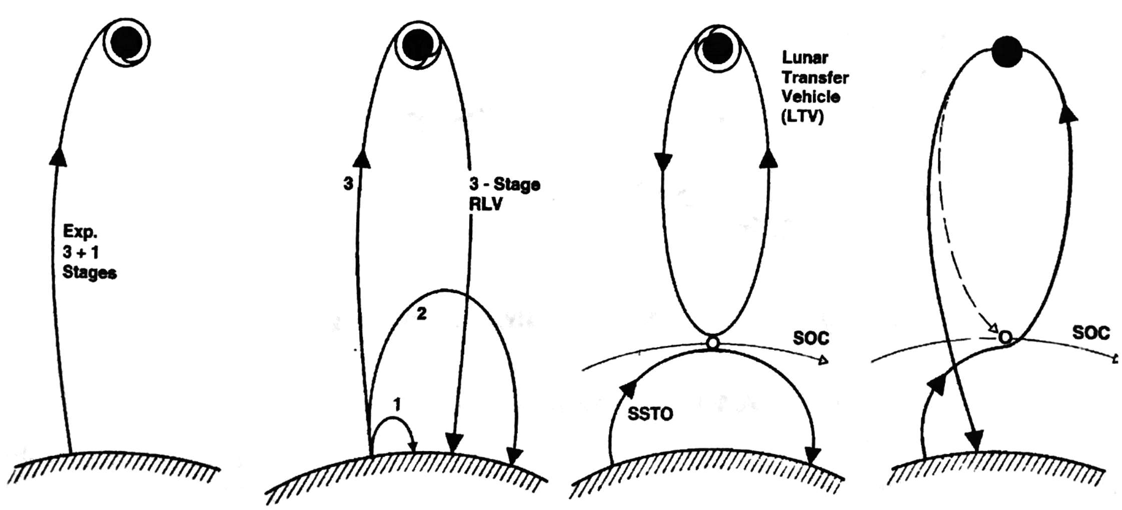

FIG. 5-31 : **Flight Profiles for Earth-Moon Transportation**

For LTVs and LLVs the following typical mission velocity requirements have been used :

- Injection from LEO into lunar transfer orbit 3100 m/s
- Lunar orbit insertion 1050 m/s
- Descent from LLO and landing 2100 m/s
- Ascent to LLO 1900 m/s
- Injection from LLO into Earth transfer orbit 1100 m/s
- Braking and phasing for SOC-RdV 900 m/s
  (for vehicles with aerobraking)
- Braking for SOC orbit without aerobraking 3200 m/s
- Braking and phasing for direct return to Earth 300 m/s

Resulting are different vehicle systems and operational requirements which are discussed in the following chapters, with assessment of the specific transportation cost to be expected for transportation of cargo to the lunar surface.

5.62 Lunar Transfer Vehicles (LTVs) and Lander Vehicles (LLVs)

For the injection into lunar orbit (LLO) and also for injection into the transfer orbit - if Earth orbit departure is being used - a dedicated LTV = Lunar Transfer Vehicle (also called OTV = Orbital Transfer Vehicle, or „Space Tug") is required. For larger payloads LOX and LH_2 are the preferred propellants. FIG. 5-32 depicts typical cryogenic Orbit Transfer Vehicle concepts with aerobraking equipment .

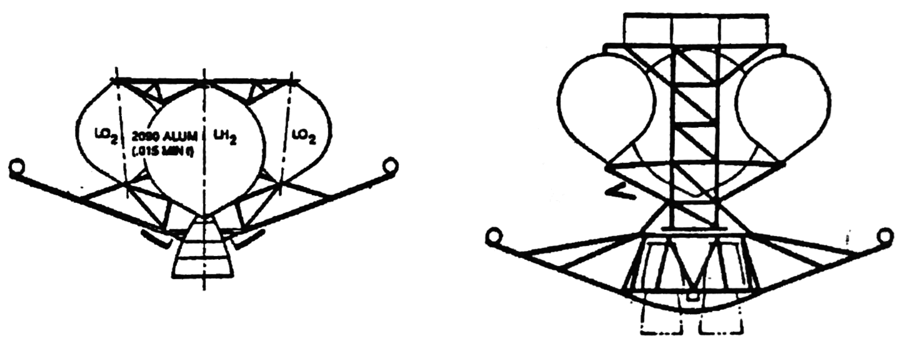

FIG. 5-32 : **Orbit Transfer Vehicles with Aerobraking Device** (ref. 112)

FIG. 5-33 shows a dry mass fraction model for LTVs / OTVs based on some reference design points and analogy to similar systems such as cryogenic launch vehicle stages. In comparison, LTVs require a lower dry mass than launch vehicle stages with the same propellant mass. This is due to the lower aerodynamic and thrust loads of such vehicles which operate in space only.

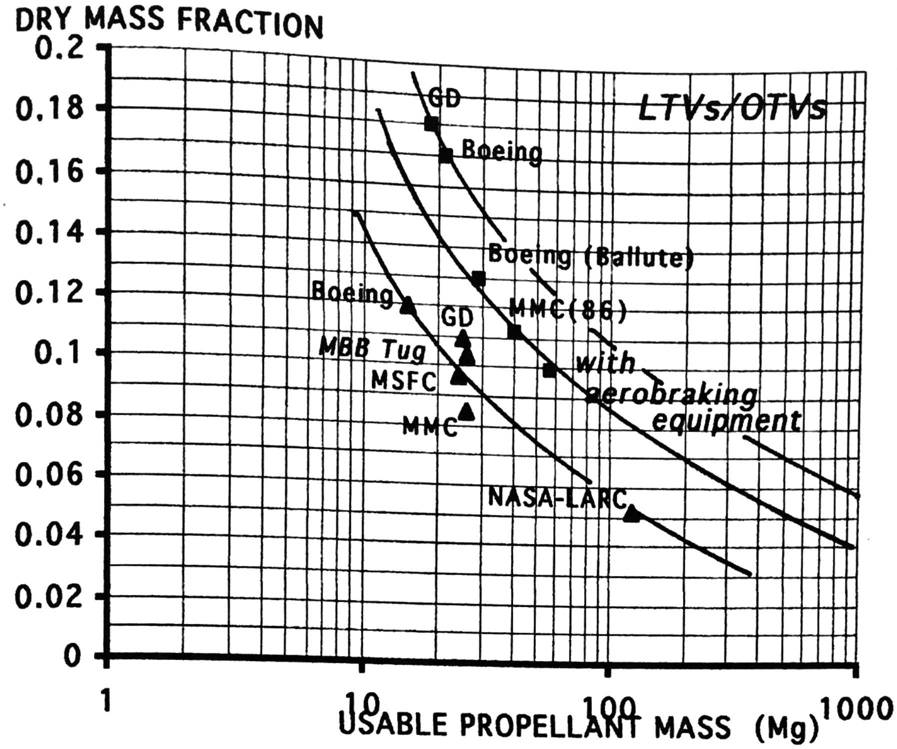

FIG. 2-33: **Dry Mass Fraction Model of Reusable Orbit Transfer Vehicles**
(Dry Mass / Propellant Mass)

A modular LTV with payload and attached LLV is shown in FIG. 5-34. The LTV is equipped with a heat shield for aerobraking. This device reduces the propellant mass

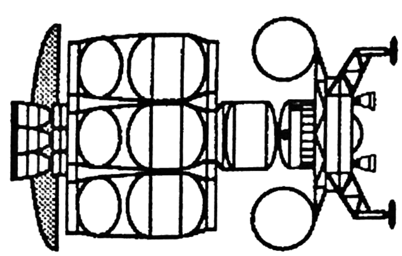

FIG. 5-34: **Modular LTV-Payload-LLV-Assembly**

required for the retro maneuver to enter the SOC Earth orbit (- 2300 m/s) but it increases the vehicle dry mass. It needs several atmospheric braking orbits (with atmospheric density variations of +/ - 30 %) thus extending the mission time and operations. In addition to the heat shield mass there remains the requirement for refurbishment or exchange of the heat shield or ballute system after each flight. From the cost engineering standpoint it does not seem to be a cost-effective method.

The second dedicated vehicle required for transfer from LLO to the lunar surface (and back to LLO for reusable systems) is the Lunar Shuttle. FIG. 5-35 shows another typical LLV design. Only few reference

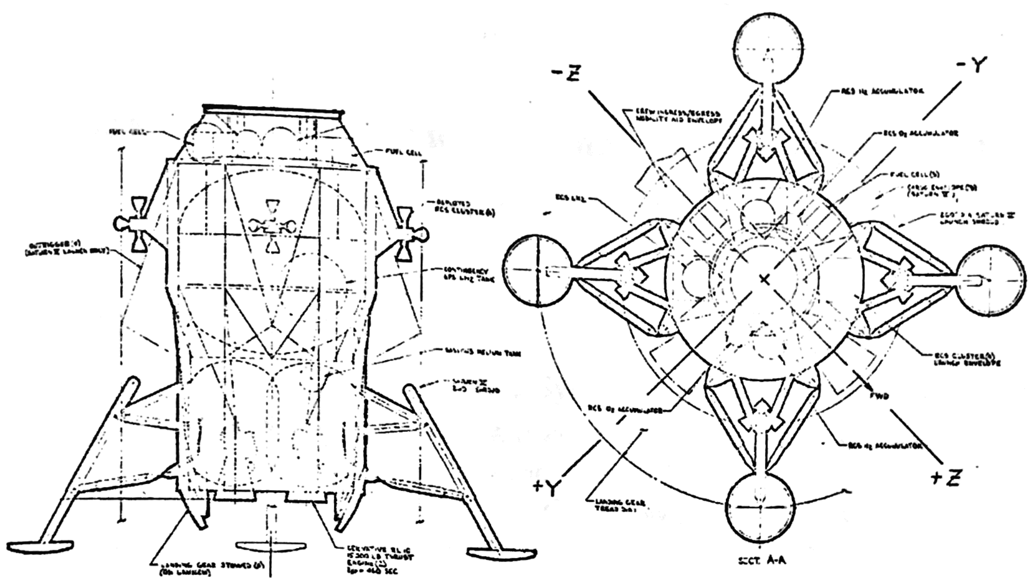

FIG. 5-35: **Typical Lunar Lander Vehicle Design**

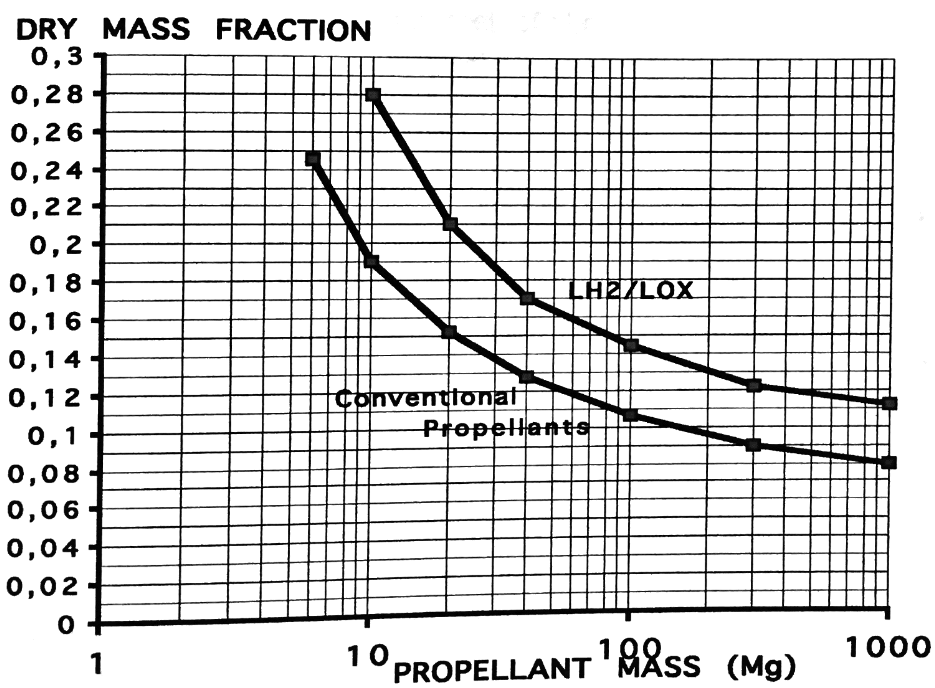

FIG. 5-36: **Dry Mass Fraction Model - including engine(s)' Mass - for Lunar Landing Vehicles (LLVs)**

projects have been designed in detail. Nevertheless, a provisional Dry Mass Model has been conceived (FIG. 5-36) in order to allow cost estimations. The upper curve is more representative for LOX/LH_2-vehicles and/ or reusable LLVs while the lower curve relates to landers with conventional propellants and / or expendable vehicles.

5.63 Direct Cargo Flights to the Lunar Surface with ELVs and RLVs

The first phase of a lunar exploration program will be the transportation of automated laboratories to the lunar surface, with subsequent supplies of equipment (power supplies) and finally habitats for the human return to the Moon, establishing a lunar outpost.

CASE 1: Expendable Launch Vehicle System Specific Transportation Cost

The historic SATURN V launch vehicle does no more exist, but it still can serve as a good example : As a three-stage vehicle with 127 Mg payload in LEO it was able to place 30 Mg cargo in LLO (Low Lunar Orbit). With a new LTV for orbit injection and a dedicated Lander Vehicle (LLV) the payload on lunar surface would be about 12 Mg (LLV = 15 Mg propellants, 3 Mg net mass when arriving on the Moon).

This results in specific transportation cost of about **390 MYr / Mg,** or 86 000 $/kg (2002), taking into account the additional costs of the LTV and LLV as well as the related mission operations cost (total CpF of the SATURN V for this lunar landing cargo mission = 4650 MYr at 3 LpA).

CASE 2: Reusable Launch Vehicle System Specific Transportation Cost

The second option for direct lunar cargo transportation would be a new reusable launch vehicle, with the same mission profile as described above. As an example, the NEPTUNE Vehicle is used, a concept conceived at the Technical University of Berlin (ref. 15), depicted in FIG. 5-37. It is a heavy space freighter with 6000 Mg launch mass, designed for sea landing / recovery with modular shipbuilding technology. The third stage is able to deliver 100 Mg payload to lunar orbit, and has sufficient propellant left for returning to the Earth (Mode 2 in FIG. 5-31). The main data of this vehicle with low-cost simple technology are summarized in TABLE 5-VIII.

The total arrival mass in LLO is 165 Mg which is subdivided as follows :

Boiloff losses in LLO	3 Mg
Payload shroud	8 Mg
Propellants for the LTV return to Earth	25 Mg
Third stage (LTV) net mass	43 Mg

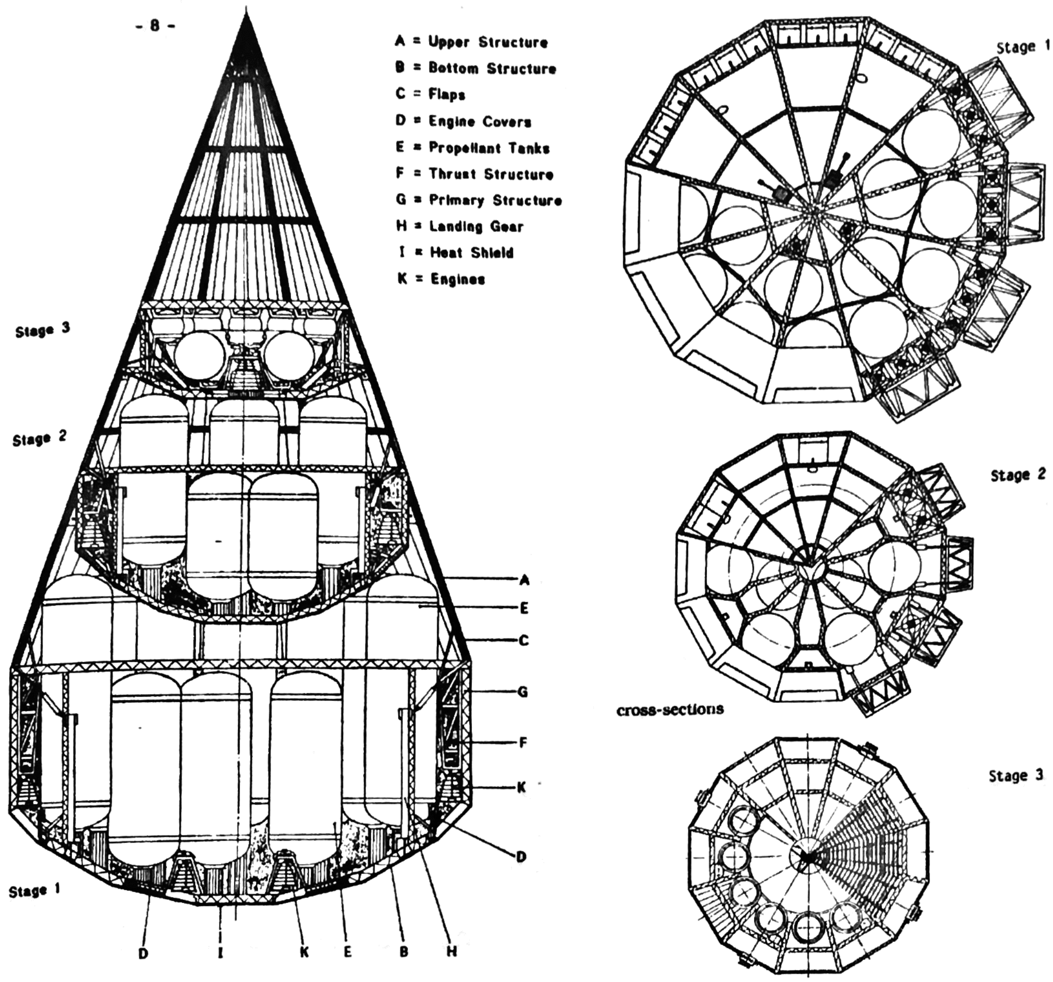

FIG. 5-37: **The NEPTUNE RLV Concept with 86 Mg Payload in LLO**

TABLE 5-VIII : **Main Data of the NEPTUNE-RLV** (ref. 15)

Mg (metric tons)	Stage I	Stage II	Stage III
Launch Mass	6 000	1 658	426
Stage Mass	4 342	1 232	320
Prop.Mass (ascent)	3 762	1 072	249 (+12)
Net Mass	580	160	45 (+35)
Dry Mass	486	133	40 (w.shroud)
Number of Engines	40 SSME-der.	9 SSME-der.	8 RL-10
Total Engine Mass	80	25	2.5
Specific Impulse (sec)	400/451	469	469 s
Thrust per engine (MN)	1.85/2.08	2.2	0.2

Lunar Landing Vehicle:	Expendable	Reusable(LuBUS)
Lunar Payload	45 Mg	38 Mg
Propellant Mass for descent (+ascent)	32 Mg	43 Mg
LLV Dry Mass	6 Mg	(8.3 Mg)
Reserve props., boiloff, residuals	3 Mg	5 Mg
TOTAL	86 Mg	86 (94,3) Mg

The expendable LLV could place a payload of 45 Mg on the lunar surface. The E-LLV would have a dry mass of 6 Mg plus 3 Mg boiloff, residuals and reserves at a nominal propellant mass for descent of 32 Mg. Assuming the same unit production costs like launch vehicle stages and a total batch of 30 units, then the cost per unit amounts to about 240 MYr, and with operations cost about 300 MYr at 3 LpA (185 MYr, resp. 215 MYr at 10 LpA).

For the reusable LLV operations it is assumed that the LuBUS vehicle is waiting in LLO and docks with the third stage for propellant and payload transfer. The LuBUS needs a higher propellant mass due to the re-ascent after de-loading on ground which reduces the payload to 38 Mg. The LLV-CpF also are reduced, assuming 25 flights per unit to 120 MYr for 3 LpA, resp. 60 MYr for 10 LpA.

The resulting specific transportation costs to the lunar surface are about the same for expendable and reusable LLVs (50 MYr/ Mg at 3 LpA and 27 MYr/ Mg at 10 LpA). The lower total CpF of the reusable LLV is balanced by the smaller payload. An expendable LLV, however, is simpler to operate than a reusable lander vehicle since it avoids the complex docking maneuver in LLO as well as the payload and propellant transfer to the reusable LLV (LuBUS) in lunar orbit. Reusable LLVs are, however, definitely required as soon as human operations begin.

The CpF of the three-stage NEPTUNE Vehicle for lunar missions have been estimated to 1362 MYr at 3 LpA and 595 MYr for 10 LpA (without development cost amortization, taxes and profit). Comparing these results to the expendable SATURN-V-type vehicle (CASE 1) with 50 vs. 390 MYr/Mg, the cost reduction is essential: factor 8 at 3 LpA, and increasing with higher launch rates.

5.64 Flights via Space Operations Center (SOC) in LEO

In the following cases it is assumed that a space station in LEO exists which serves as a flight base for lunar and planetary flights (SOC = Space Operations Center). It must be equipped with propellant storage tanks and vehicle maintenance facilities so that it can accomodate lunar and planetary transfer vehicles, designed for operations in space only.

CASE 3: A reusable Lunar Transfer Vehicle (R-LTV) is used for the transfer of payload and Lunar Lander to the LLO (low Lunar Orbit). The R-LTV is space-based at a SOC. So it has not to be designed for re-entry loads and does not need a payload shroud. This mode does increase the performance, resp. the payload efficiency but also makes the operations more complex (payload and propellant transfer in orbit).

In principle one could assume a similar orbital operations center in lunar orbit but this is not yet considered here because it would only make sense for a second or third phase of a lunar exploration program with a large number of flights including crewed operations.

Fig. 5-38 shows the possible cargo payload on the lunar surface plus the related mass values of the reusable LTV (including the propellant for return to the SOC in LEO, without aerobraking) and the expendable LLVs as a function of the total departure mass in LEO (SOC): In order to place a 6.0 Mg cargo payload on the lunar surface it needs an LTV (R) with 86 Mg total mass (61 + 14 Mg propellants plus 5.5 Mg dry mass, plus 10.5 Mg residuals, boil-off and reserve propellants).

The E-LLV (expendable lunar lander), designed for the payload of 6.0 Mg, has a propellant mass of 5.3 Mg, a dry mass of 2.0 Mg, and residuals, boil-off and reserve propellants of 0.7 Mg (= 2.7 Mg net mass). All vehicles use LOX/LH_2 -propellants and RL-10-type engines.

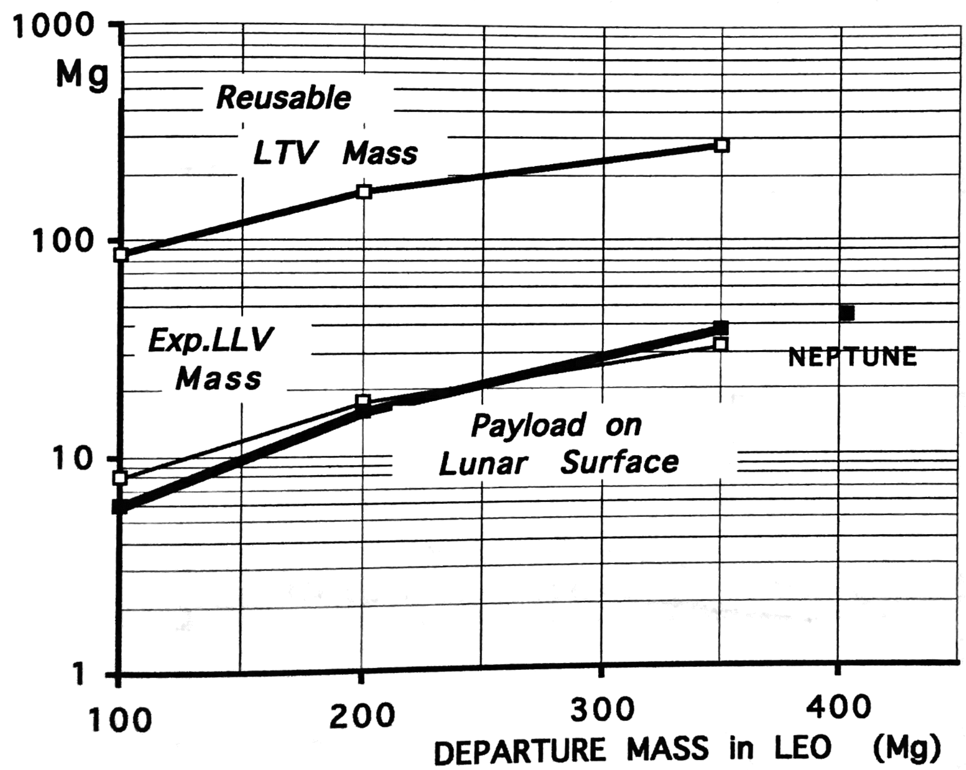

FIG. 5-38: **Payload on Lunar Surface, Mass of Reusable RTV and Mass of Expendable LLV vs. LEO Departure Mass**

The CpF and the specific transportation cost for the CASE 3 are composed of three elements:

(1) the cost to LEO (SOC),
(2) the LTV and its operations cost, plus
(3) the LLV and operations cost.

The cost to LEO (SOC) depend on the vehicle size and launch frequency. FIG. 5-22 is used for the LEO cost.

The mass to be transported into LEO consists of

-- the lunar payload,
-- the Lunar Lander Vehicle (LLV),
-- the propellant for the LTV (incl.boil-off losses).

Using the same three examples as before, then the following total mass values are resulting:

	Payload	LLV	Propellants	TOTAL Mass	CpF
(a)	6 Mg	8 Mg	81 Mg + 20 %	111 Mg	222 MYr
(b)	16 Mg	18 Mg	157 Mg+20 %	223 Mg	446 MYr
(c)	38 Mg	32 Mg	265 Mg +20 %	388 Mg	776 MYr

The specific transportation cost to LEO (SOC) depend on the vehicle payload capability as well as on the annual number of flights (LpA), as shown before. Using

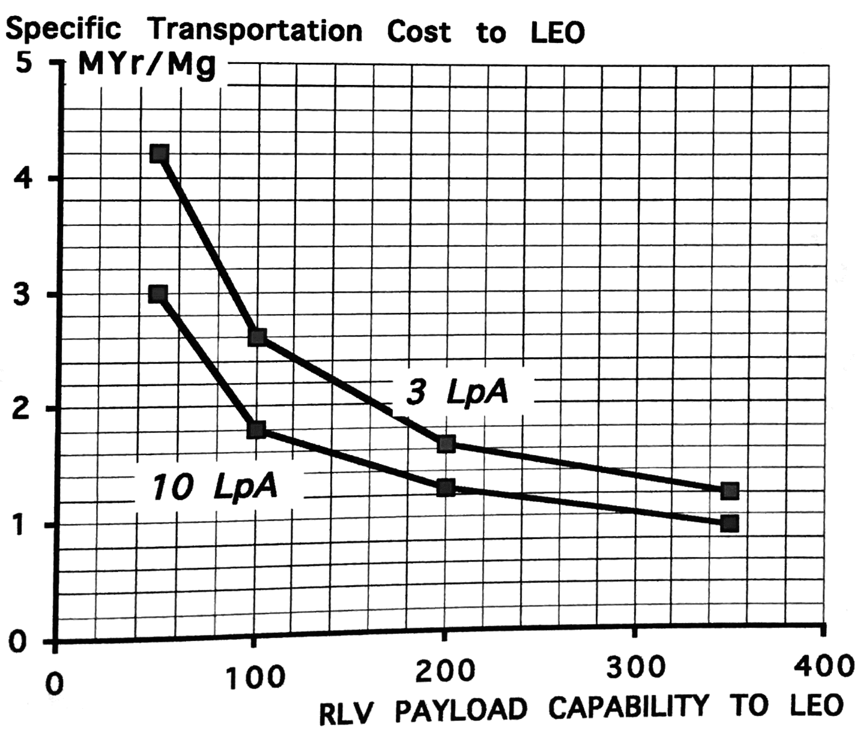

FIG. 5-39: **Specific Transportation Cost to LEO - Model based on FIG.5-22**

FIG. 5-22 as reference, a representative cost spectrum can be established for RLVs with 50 to 350 Mg payload capability for 3 and 10 LpA, as shown in FIG. 5-39.

For the Reusable Lunar Transfer vehicle (R-LTV) the vehicle unit cost share is based on (only) 30 flights per vehicle, plus maintenance and direct operations cost. However, no indirect operations cost are included, especially no overhead resulting from SOC operations. For the expendable Lunar lander (E-LLV) the full unit production cost, assuming a series of 30 vehicles over 10 years (resp.100 vehicles in case of 10 LpA) have been taken into account, plus operations cost.

The detailed results are shown in FIG. 5-40 for the case of 3 LpA. For a launch rate of 10 LpA the specific cost decrease to 70-75 % of the values shown in FIG. 5-40.

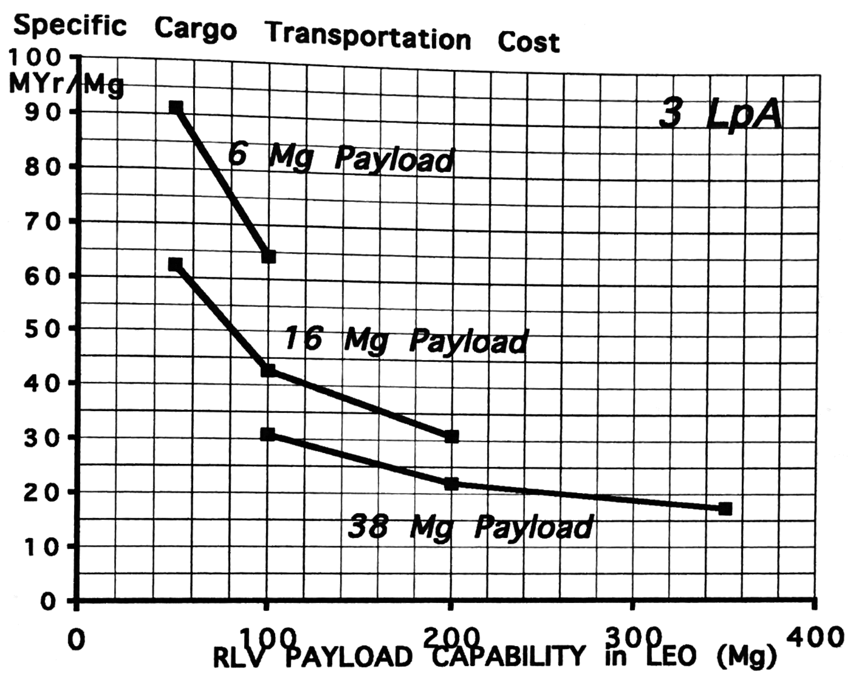

FIG. 5-40: **Specific Transportation Cost to the Lunar Surface, using RLVs to LEO, Reusable Transfer Vehicles to LLO, and Expendable Lunar Landers vs. Lunar Cargo and RLV- Payload Mass**

Conclusions:

The specific cargo transportation cost to the lunar surface depend strongly on the LEO launch vehicle size, resp. its payload capability. It seems highly desirable for economic reasons to have a RLV available with 100 to 150 Mg payload capability available for Earth-Moon cargo transportation. Larger launch vehicles are required if payload assembly and operations cost at the SOC would be very expensive.

The specific cost level for Earth-Moon cargo transportation resulting from this analysis (between 30 and 70 MYr/ Mg) is comparable to the present specific cost of LEO transportation with expendable launch vehicles

CASE 4 : Refuelling of a Ballistic RLV at the SOC with Continued Flight to the Lunar Surface and Back to Earth (cf. FIG. 5-25d)

The other option of using an SOC is unique insofar as it required no dedicated LTVs and LLVs, as well as no payload transfer between the different vehicles. A ballistic reusable launch vehicle (such as shown in FIG. 2-29) is launched with the lunar payload to the SOC where it is refulled, then it continues to a direct landung on the lunar surface. Since the vehicle is designed for vertical landing on Earth, it can do so also on the Moon. After removal of the payload it is relaunched, flying back directly to the Earth spaceport, using aerodynamic breaking. This is feasible since the delta-V demand for the lunar flight section is about the same as for the ascent from Earth to LEO (SOC).

For the cost assessment a ballistic SSTO Launch Vehicle is assumed which can deliver 100 Mg payload to the SOC. The launch mass (GLOW) is about 1850 Mg and the propellant mass 1600 Mg. The vehicle data are summarized in TABLE 5-IX.

Refuelling of the initial vehicle which has placed a lunar landing payload of about 50 Mg into LEO would require 18 to 20 tanker flights to the SOC, taking into

TABLE 5-IX : **Main Data of 100 Mg Payload SSTO Launch Vehicle (BETA IV)**

Launch Mass	1 850 Mg
Vehicle Mass	1 750 Mg
Propellant mass (for ascent)	1 600 Mg
Vehicle Net Mass	152 Mg
Vehicle Dry Mass	120 Mg
Number of Engines	24 x 1060 kN Thrust (SL)
Total Engines' Mass	32 500 kg (1354 kg/ engine)
Specific Impulse	350 s (SL), 455 s (vac) with plug effect

account the required 1600 Mg propellants for the lunar flight, plus 200 to 400 Mg boiloff losses during transfer and storage. Three lunar missions per year would result in a launch rate of 57 to 63 LpA with specific transportation cost of about 1.4 MYr/ Mg (cf. FIG. 5-38). The total transportation cost for one lunar mission are accordingly

1900 to 2100 x 1.4 = 2660 to 2940 MYr,

plus the estimated lunar mission cost SOC-Moon-Earth (DOC) of about 60 MYr.

The resulting specific transportation cost for the 50 Mg payload would be 54 to

60 MYr/ Mg. (SOC operations cost are not taken into account, as in the previous Case 3).

The specific cost are about twice as high as in CASE 3, but it must be considered that the development costs of an R-LTV and the E-LLV are saved. Further no mission optimization has been made. It seems feasible to reduce the total propellant mass and / or to increase the lunar payload. By example, a conservative gross value of 1000 m/s has been assumed for phasing orbit maneuvers around the Earth at the return flight which may well be reduced.

The inherent round-trip capability of this lunar flight option allows a payload of 20 Mg to the Moon and back to Earth for this size of launch vehicle which is sufficient for a crew capsule.

5.65 Cost Reduction by Lunar Propellant Production

An essential reduction of the specific transportation costs for lunar operations can be achieved by a lunar propellant production plant. The cargo capability to the Lunar surface could be increased by a factor 5 (saving the transportationof of LOX from the Earth to the lunar surface for the return flight) respectively allowing the use of smaller vehicles and enabling crewed roundtrip missions .

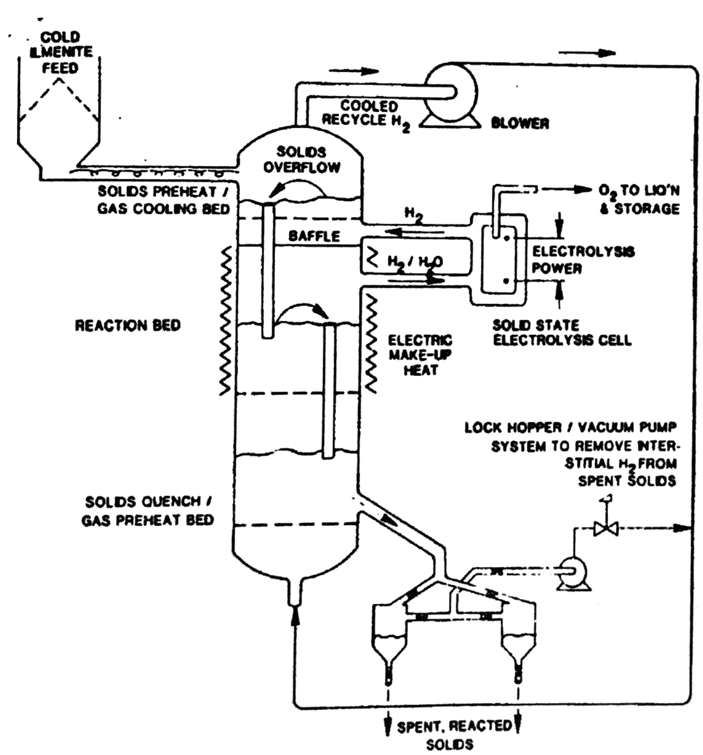

FIG. 5-41: **Schematic Production Process for LOX from lunar Imenite**
(Gibson and Knutsen, Carbotek inc.)

Liquid oxygen could be produced from lunar soil (Ilmenite) and / or from lunar ice if the existence near the pole is verified, liquid hydrogen as well. In ref. 145 an estimate is presented about the required production facility for 33, 65 and 130 tons LOX per year. Accordingly, the total facility mass required would be 8, 14.5 and 26 tons with radiation cooling assumed. The required power demand would be 93, 178 and 340 kW.

For a permanent lunar basis the LOX production will certainly be a requirement, primarily for the lunar lab and the astronauts, but also for the refueling of the return vehicles. The processing of Ilmenite ($FeTiO_3$) will also allow the production of iron and titanium.