3. UNIT PRODUCTION COSTS (Manufacturing, Integration and Verification of Flight Hardware)

3.1 Production Cost Basics

Production costs include material cost, processing and manufacturing cost, assembly and verification and/ or acceptance testing costs as well as engineering support and quality assurance costs. The largest share of the production cost is caused by the support functions as shown in FIG. 3-01, but these are no constant percentages; they vary from project to project and from company to company. The direct touch-labour is relatively low, and the smallest share represent the material cost in most cases (5 to 10 %) even if expensive materials are used.

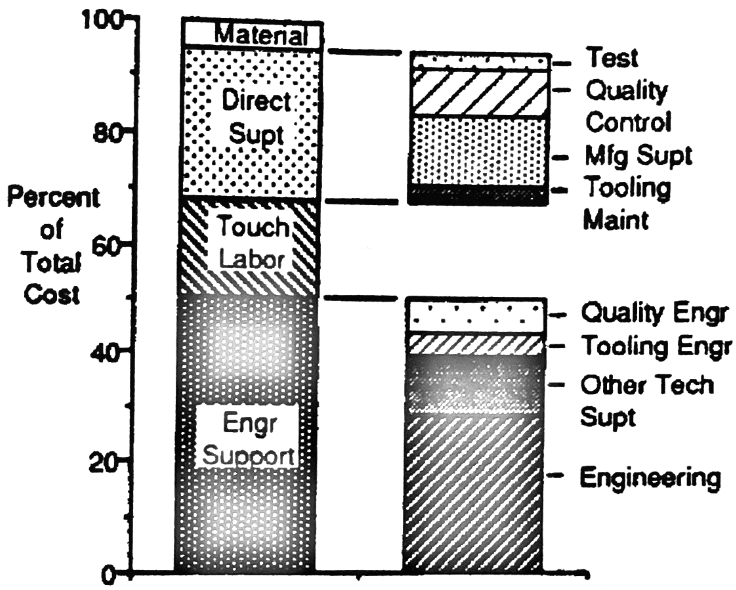

FIG. 3-01: **Typical Launch Vehicle Production Cost Breakdown** (ref. 99)

The cost of special (large) rigs and tools is assumed to be part of the development cost, since the first flight unit is being built and tested as the final activity of a development program.

The difference between development cost and production cost for a launch vehicle is substantial : it is a factor of 55 to 65 related to BAU development cost. In other words, the production cost of an expendable vehicle are only 1.5 to 2 % of the development cost. An example of sub-system cost distribution for an attached liquid-propellant booster (ALS-Concept) is shown in FIG. 3-02 , excluding the main engines' cost.

The cost-effectiveness of advanced (expensive) materials depends of course on the specific application. FIG. 3-03 shows a comparison for an aircraft fuselage section.

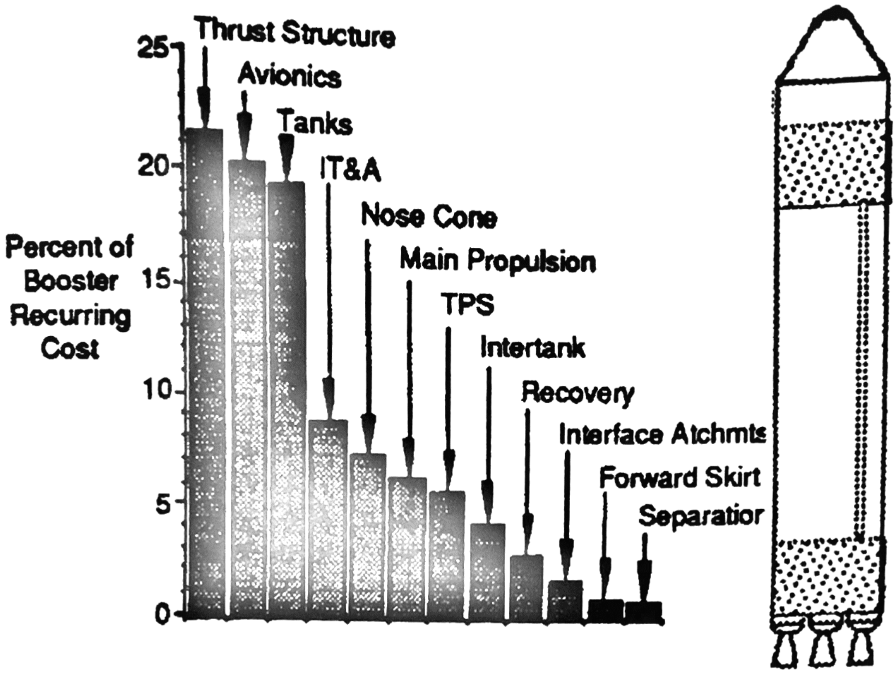

FIG. 3-02: **Subsystem Cost Distribution of a Liquid-Propellant Booster - without Main Engines** (from ref. 99)

The use of an Al-Li-alloy would reduce the weight by 9 % but increase the cost by 38 %. In case of a CFRP structure there would be a weight reduction of 26 % at about the same cost - even though the material cost are the highest.

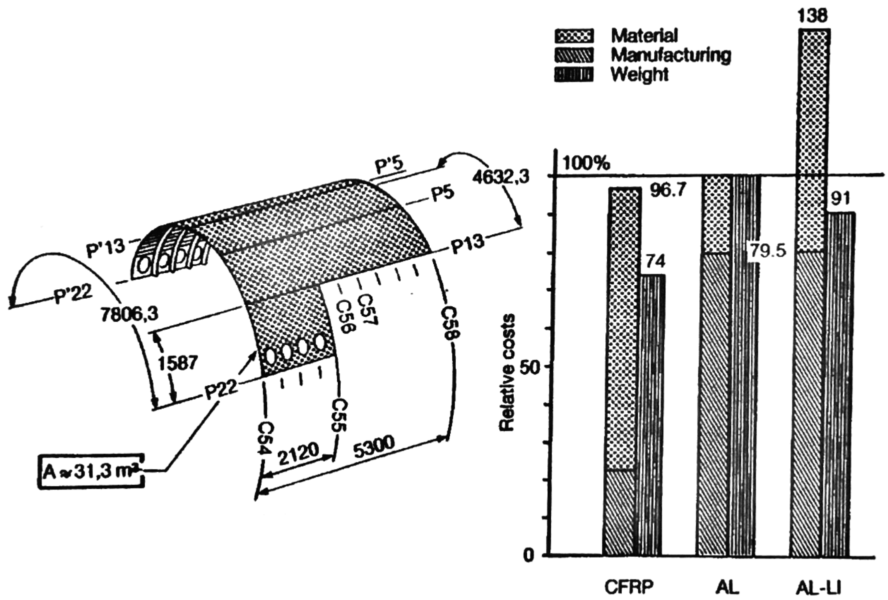

FIG. 3-03: **Cost and Weight Comparison of Alternative Structure Materials (Example: Airbus Fuselage)**

The key factors in the production cost area are the „First Unit Cost" or „Theoretical First Unit Cost" (TFU) and the „Learning Factor" (p) which is important for the cost reduction in case of larger production numbers.

3.2 The „Learning Factor" p / Production Quantity Impact

The so-called „Learning Factor" was defined by T.P. Wright in 1936 and takes into account the reduction of effort required for the fabrication of follow-on units compared to the no.1 unit. The Learning Factor p = 0.80 or 80 % says that each doubling of the number of units produced will reduce the cost to 80 %. This means that the no.2 unit will cost 80 % of the first unit (or better: will require only 80 % of the original manhour effort), the fourth unit will require only 80 % of the number 2 unit, the number 8 unit only 80 % of the no. 4 unit, etc.

For an easy application FIG. 3-05 presents this cost reduction as an f_4- chart for Learning Factor values p = 0.95 to 0.70 for the two cases:

a) The average total cost reduction for a batch of n units starting with unit no.1, and

b) the cost reduction for the n_{th} unit produced, compared to the no.1 unit. This applies also to cases where i.e. the cost of units no. 20 to 30 is to be determined.

The applicable Learning Factor values for space systems are between 0.80 and 1.0. The specific value depends on the unit size (mass) as well as on the learning effect (p ⇨ 1).

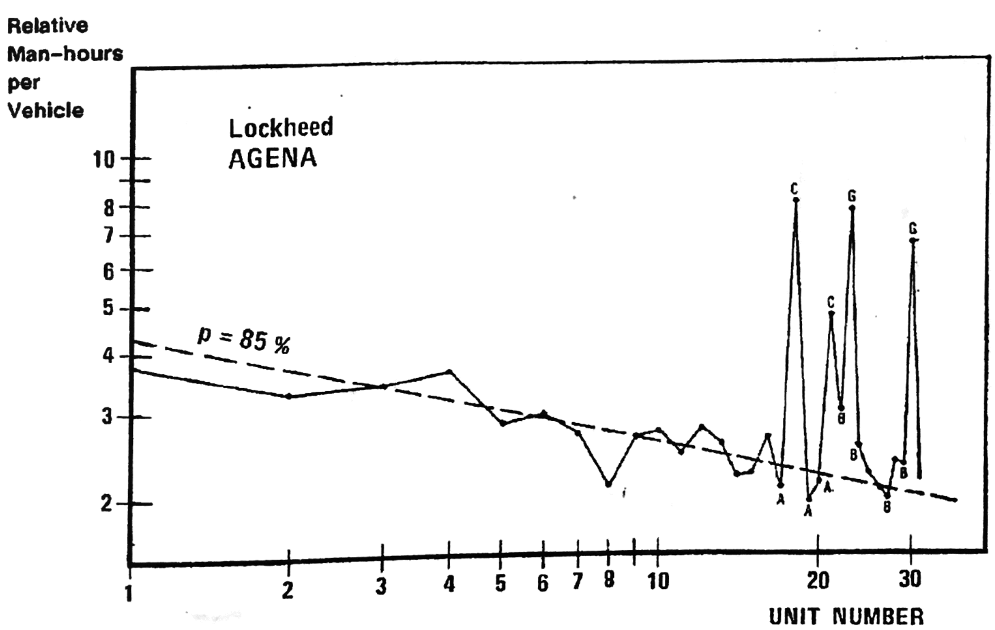

FIG. 3-04: **Example of Actual Cost Reduction vs. Number of Units Built**
(Production and Assembly Manhours Lockheed AGENA Upper Stage)

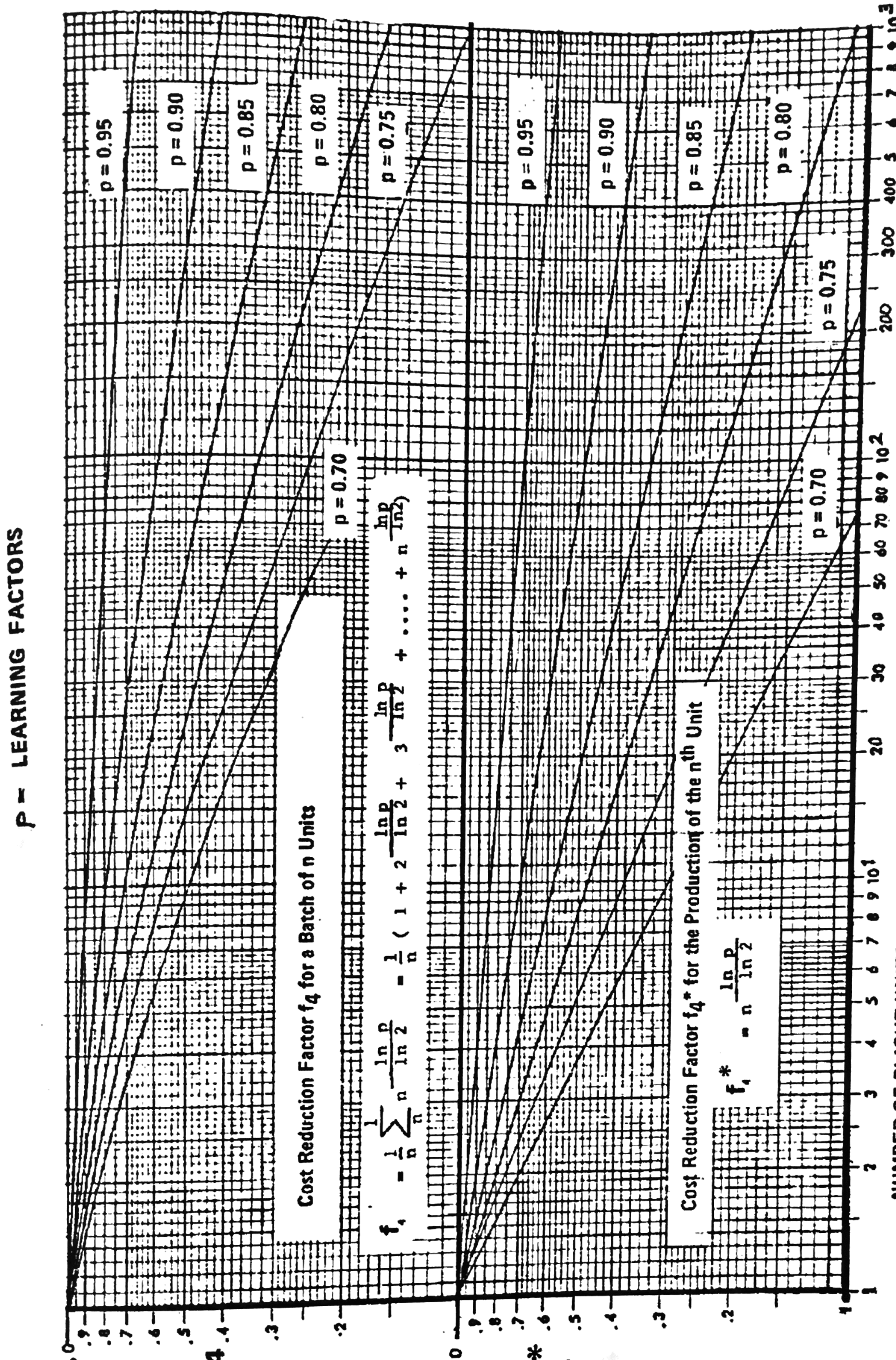

FIG. 3-05: LEARNING FACTOR CHART : **Production Cost Reduction Factor f_4 vs.Number of Units Built with Learning Factor p as Parameter**

FIG. 3-04 (ref. 14) shows for the Lockheed AGENA-A upper stage vehicle (1959/60) both the actual learning factor of 85 % or 0.85, and the increase of hours required for the AGENA-C and -G Versions due to the technical changes. Another more recent example cames from EADS regarding the production of stages 1 and 3 of ARIANE 4 , the L.220 and H.10 vehicles (ref.125). 150 units have been built in the period 1989 to 1997. The resulting combined p-value is 0.875 for an average production rate of 17 units per year.

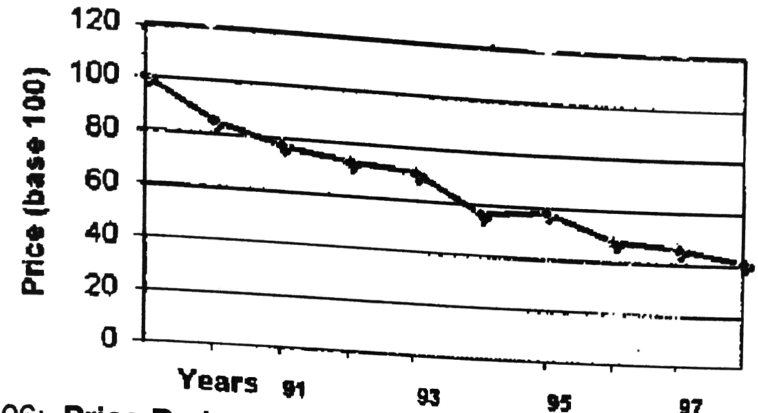

FIG. 3-06: **Price Reduction of ARIANE-4 Stages vs. Production Number**

Based on these examples for past production learning experience an empirical chart has been prepared for launch vehicles stages including some reference points (FIG. 3-07). Of special interest are the two ATLAS reference points: one for the

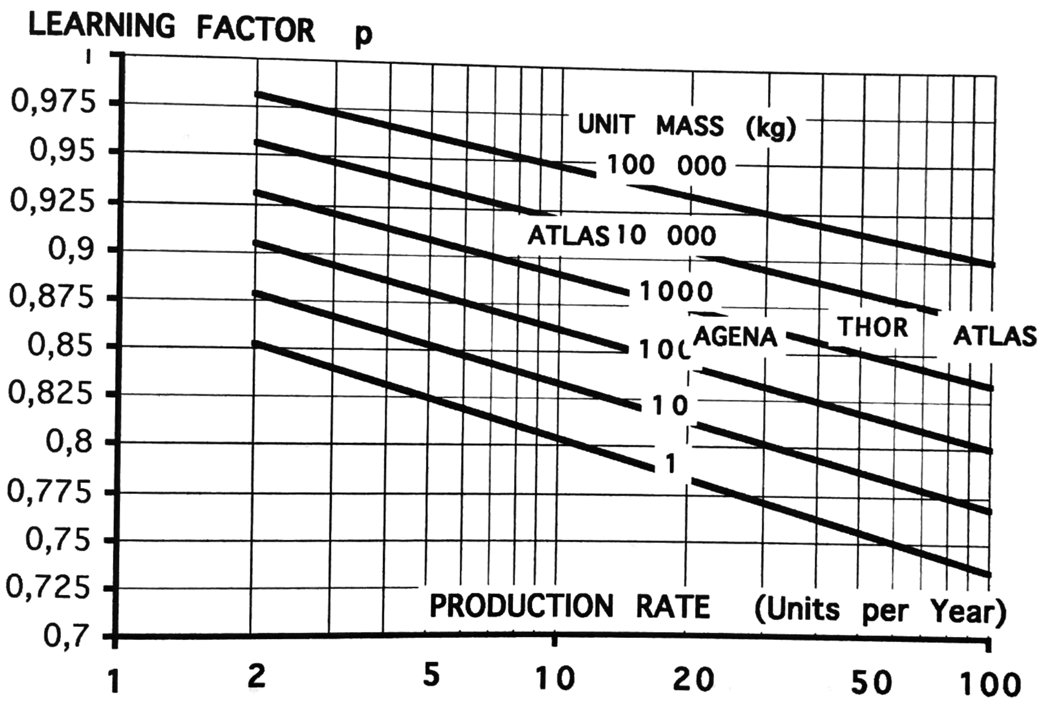

FIG. 3-07: **Empirical Chart for p-Values of Launch Vehicle Stages**

missile production line with 100 vehicles per year, and the other for the later satellite launch vehicle with only some 10 units per year.

Complete multistage launch vehicles' production shows a Learning Factor of about 0.9 or 90 %. The ARIANE 4 vehicle with a total production number of 116 units showed a cost reduction of only 35 % compared to the ideal reduction potential of 50 % for the last batch of 10 vehicles. This was caused by the model variants (AR.40 to 44L) and the modifications/ improvements during the production phase of 16 years (1986 to 2001).

The full Learning Factor effect can only be expected for the production of *identical* units, without modifications. If any technical changes are applied the cost reduction by learning is being reduced.

In the same way, the change of the *annual production rate* has an essential effect on the Learning Factor, respectively the cost reduction factor f_4 : When the production rate of the J-2 engine was reduced in 1969 from 36 to only 12 per year the price per engine increased by 10 % (ref. 66). The same is apparent in FIG. 3-07: At

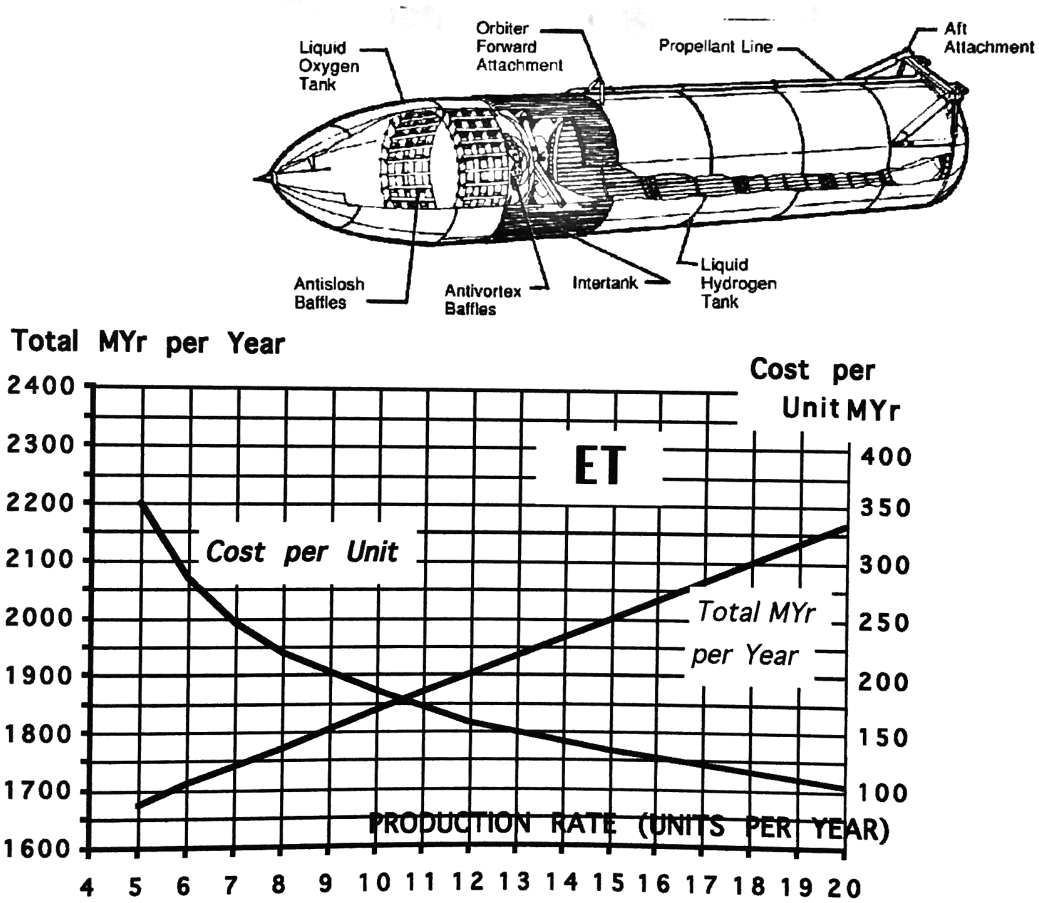

FIG. 3-08: **Initial Cost per Unit for the Shuttle Expendable Tank (ET) and Total Cost per Year vs.Production Rate**

the peak production rate of the ATLAS ICBM the Learning Factor was less than 0.85, decreasing to over 0.90 when the production rate was reduced to 10 per year. In some cases, when large units are built in a special facility as the only product, as in case of the Shuttle Expendable Tank (ET) the total cost per year are almost constant, independent of the number of tanks produced. FIG. 3-07 shows this situation with the initial production cost vs. number of units built per year, as well as the total number of MYr. If the ET production, by example, is reduced from 12 units per year to 6 p.a. then the total costs are reduced by some 200 MYr - essentially the material costs - but the cost per unit are growing from 170 to 270 MYr (or from 38 to 61 M.$/ 2003) per unit. However, there remains a learning cost reduction over the years with the growing total number of units built. For the ET a learning factor of 0.90 resulted over the time. In the ideal case this could have been about 0.85, but technical changes/ improvments did reduce the learning effect.

The Learning Factor as such does not only apply to launch vehicle recurring costs but also for the launch operations costs as shown later (ch. 4.225).

3.3 *TRANSCOST* Production Cost Submodel

3.31 Submodel Scope and Structure

This *TRANSCOST*-Production Submodel deals with vehicle system and engine manufacturing, integration and verification cost estimation. The development cost submodel includes only test units and one complete flight test vehicle with launch operations. Additional flight test vehicles and the subsequent production need to be costed with dedicated CERs which have the same basic structure, but are different in each case.

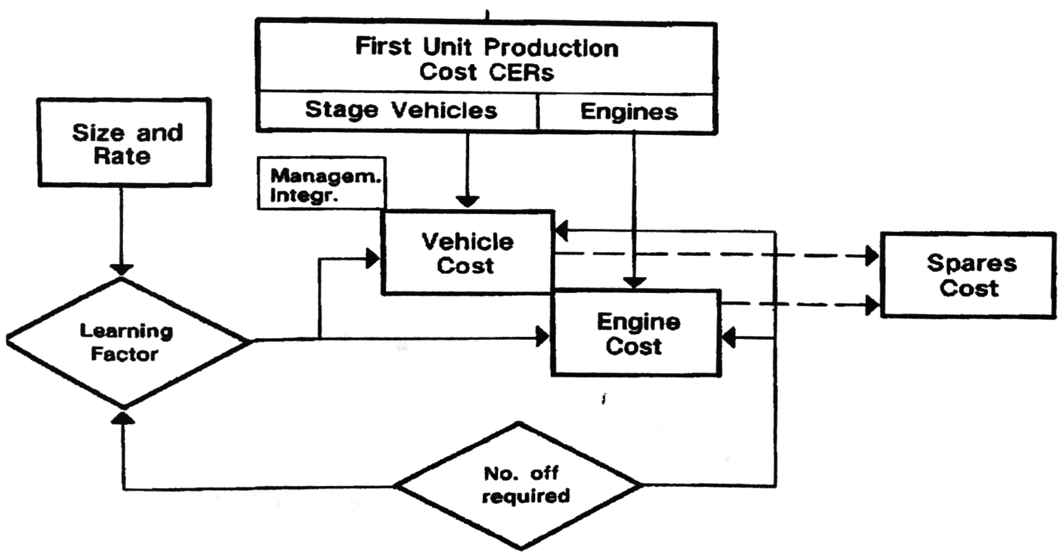

FIG. 3-09: **Production Cost Submodel Structure**

The structure of the Production Cost Submodel is shown in FIG. 3-09. It is subdivided in vehicle systems and engines, plus management and integration - the same as the Development Cost Submodel.

Rigs and tools required for fabrication are already - by definition - included in the development cost submodel since normally at least a prototype unit (if not the first flight unit) are part of the development program, requiring the tools and rigs. Only in case of large-scale production (which, however, did not yet occur in space transportation projects) additional tooling cost must be taken into account.

In case of reusable launch vehicles (RLVs) also the cost of spares have to be considered. The TRANSCOST-Model, however, does not provide subsystem and components' costs - except engines. The spares' cost are included in the refurbishment cost (cf. chapter 4.3).

The basic recurring cost CERs are structured as follows:

$$\boxed{F = n \cdot a \cdot M^{x} \cdot f_4} \quad \text{MYr}$$

with

F = total effort in MYr, n = number of units to be built, x = specific cost/ mass sensitivity value for each hardware group, M = reference mass (kg) f_4 = cost reduction factor for series production

No other correction factors are required in this case.

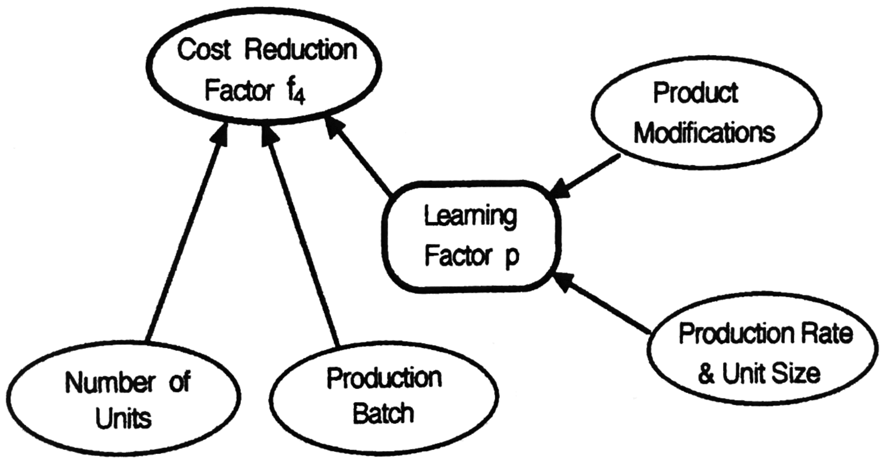

FIG. 3-10: **Criteria Influencing the Cost Reduction Factor Value**

The cost reduction factor value depends on the applicable Learning Factor, the number of units to be produced, and the fact whether these are inital units (no.1 to x) or a certain batch out of a series (i.e. no. 20 to 30), cf. FIG. 3-10 and 3-04.

Recurring Cost CERs have been established for the following engine and system species:

(1) SOLID-PROPELLANT MOTORS AND BOOSTERS
(2) CRYO ROCKET ENGINES (WITH LIQUID HYDROGEN)
(3) ROCKET ENGINES WITH STORABLE PROPELLANTS
(4) MONOPROPELLANT ROCKET ENGINES
(5) AIRBREATHING TURBOJET ENGINES
(6) PROPULSION MODULES
(7) BALLISTIC VEHICLES (EXPENDABLE AND REUSABLE)
(8) CREWED SPACE VEHICLES
(9) AIRCRAFT AND WINGED FIRST STAGE VEHICLES
(10) WINGED ORBITAL VEHICLES

3.32 Complete Launch Vehicles' Production Costs

The total industrial fabrication, assembly and test cost of a complete launch vehicle are defined by the sum of the single elements cost multiplied by a factor f_0 for system management, vehicle integration and checkout:

$$\boxed{C_F = f_0^N \left(\sum_1^n F_S + \sum_1^n F_E \right) f_8} \qquad \text{MYr}$$

N is the number of stages or system elements of the vehicle, while n is the number of identical units per element (number of engines or boosters, by example). This can also apply to tank modules if the vehicle design is of higly modular nature. f_0 is between 1.02 and 1.03, depending on the vehicle and program complexity.

EXPENDABLE Launch Vehicles have the advantage of a continuous production line with cost reductions vs. time due to the learning effect.

In case of REUSABLE Launch Vehicles the situation is different since only few vehicles are required. Since production cannot be switched on and off according to program requirements , there are only two options:

(1) All vehicles and spares required for the planned operational period are produced in an optimum time period (for minimum cost) and put into storage until they are needed. The production facilities are then closed, resp. converted to be used for other projects.

(2) A continuous production activity is maintained which means the scheduled introduction of new vehicles into the program. This, however, requires either a continuous growth of operational capability and/ or a limited lifetime for each vehicle.

3.4 Engine Production CERs

3.41 Solid Propellant Rocket Motors and Boosters

Solid-propellant rocket motors for launch systems cover a wide range from small kick motors to simple boost motors (as in case of the DELTA-Vehicle) to large-size motors with thrust vector control, representing a full first stage, as in case of ARIANE 5, TITAN IV and the US Space Shuttle.

The CER has been conceived from the relatively large number of 19 reference projects from USA, Europe and Japan, covering 4 orders of magnitude as shown in FIG. 3-11. Although the motors' inert mass is used as reference the costs indicated include the propellant and are valid for the complete motor assembly.

The resulting CER for Solid-Propellant Motors and Boosters is

$$\boxed{F_{ES} = 2.3 \cdot n \cdot M^{0.399} \cdot f_4} \quad \text{MYr}$$

The CER can also be applied to boosters with special equipment like shrouds, attachment / separation mechanisms and / or recovery equipment since this is

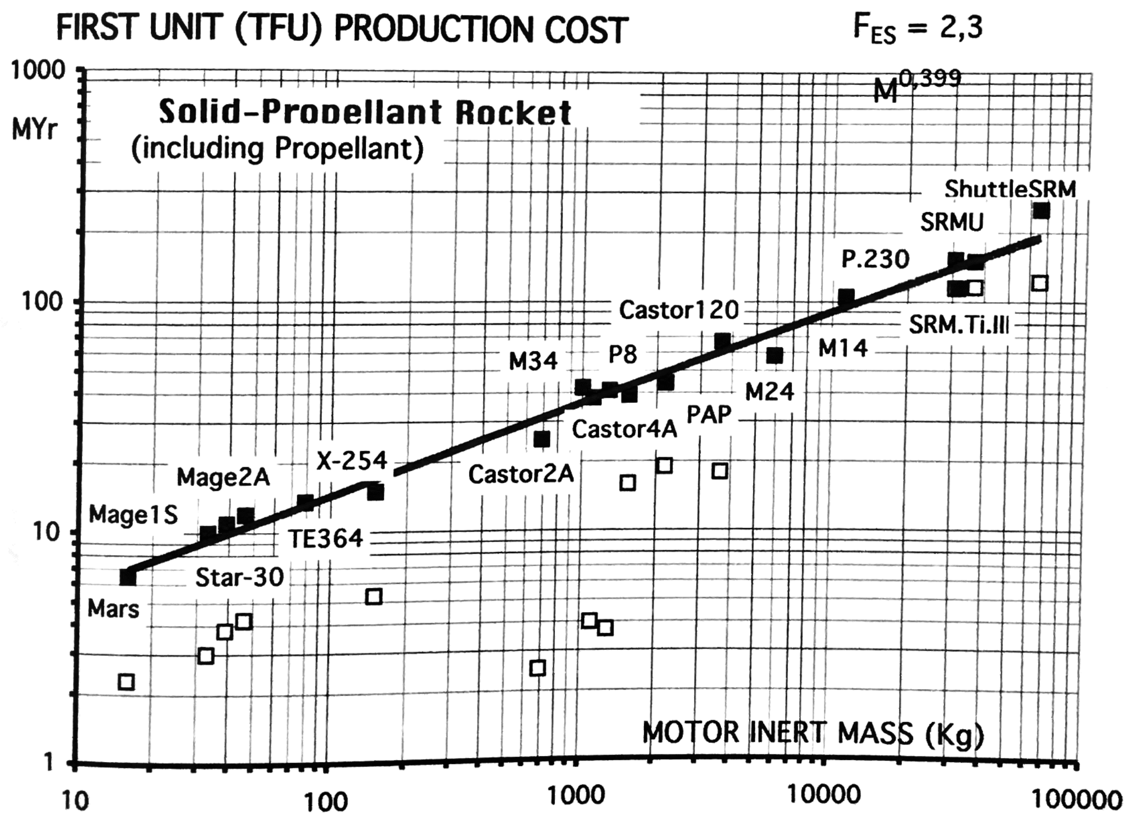

FIG. 3-11: **Solid Rocket Motor Reference Projects and the Resulting Basic CER**

reflected in the increased net mass. Net mass values vs. propellant mass are shown in FIG. 2-05.

Propellant cost are included in the unit production cost. They represent 10 to 20 % of the total unit cost. Solid propellants are relatively expensive compared to liquid propellants. The solid propellant price depends on the motor size and the total annual production rate (cf. chapter 4.233).

3.42 Liquid-Propellant Rocket Engines

Already in 1965 the first evaluation of rocket engine production cost has been performed in order to find out what provides the best cost correlation (ref. 67): engine dry mass, thrust level, or mass flow rate / specific impulse. The result was in favour of the engine dry mass, which is also used for the *TRANSCOST* CERs.

Because there have been publications advocating low-pressure engines for cost reduction (ref. 68), an analysis was performed regarding the impact of chamber pressure on cost. In agreement with own results, in ref. 40 it is shown that low chamber pressure does not reduce engine costs, but pressures higher than 120 bar result in cost growth (cf. FIG. 3-14). Indeed, very high pressures demand more advanced material and processing technologies and increase fabrication costs (for a 200 bar engine by some 9 % according to ref. 40). The SSME (222 bar chamber pressure) TFU cost value clearly is above the reference CER trend but it must be recognized that this was the first engine *designed for reusability* featuring a very complex design with a large number of components. This can be illustrated best by a comparison of the SSME with the later STME (Space Technology Engine) design of 1991 for the NLS (National Launch System Program), as shown

TABLE 3-I : **Engine Cost Reduction by Minimum Number of Components**

Engine :	SSME	STME
Combustion chamber parts	60	6
Combustion chamber no. of welds	96	4
Main injector parts	3200	1641
Main injector no. of welds	360	13
LOX turbopump parts	153	78
LOX TP no. of welds	128	0
LH_2 Turbopump parts	198	60
LH_2 TP no. of welds	810	1
Nozzle no. of parts	1600	580
Nozzle no. of welds	113	15

in TABLE 3-I. This dramatic reduction of components and welds resulted, by example, for the turbopump assembly in a cost reduction by a factor 3.5 compared to the original SSME turbopumps. Since the turbopump cost are about one quarter of the total engine unit cost, the latter should be reduced by 18 to 23 %. With reductions of chamber pressure, injector head and nozzle complexity as planned for the STME (177 bar, 4000 kg dry mass) the TFU cost have been estimated to some 220 MYr. The same principles and a chamber pressure of only 104 bar led to further cost reductions in case of the Rocketdyne **RS-68** engine as used on the DELTA IV launch vehicle. The unit cost of this engine have been quoted to be

SSME Unit Fabrication Cost

Fuel and LOX Turbopumps	24.1 %
Combustion Chamber with Injector head	18.2 %
Nozzle	14.5 %
Preburner	3.0 %
Accessories / Control Systems	6.5 %
Management, Assembly, Test, Profit	33.8 %
	100 %

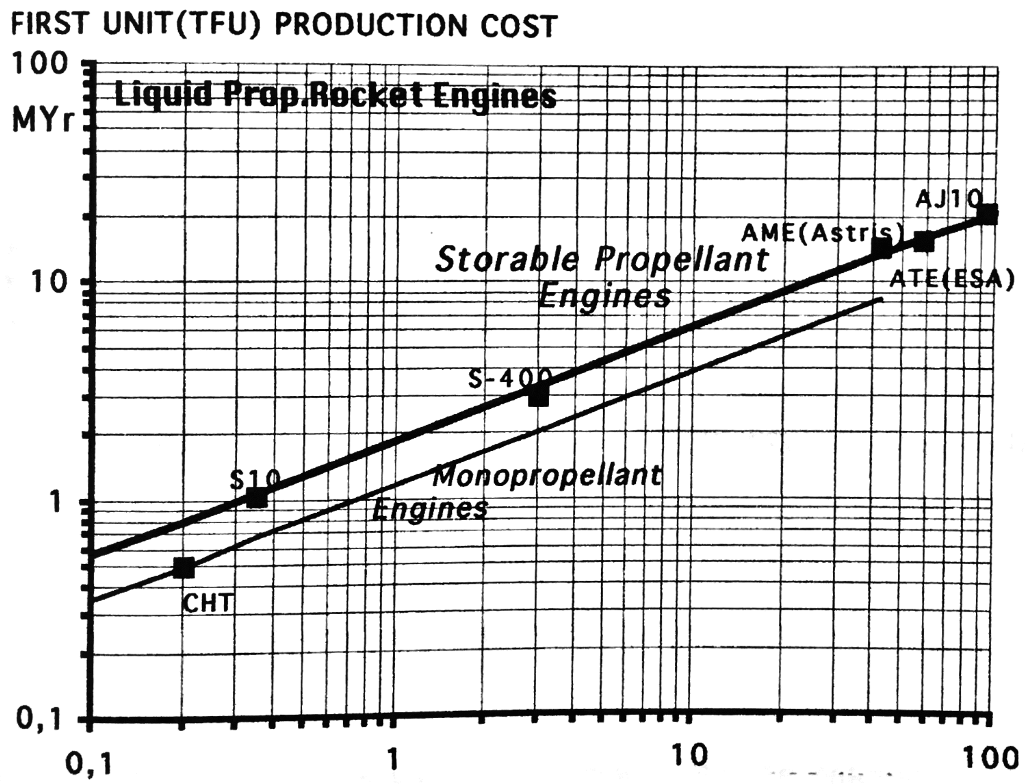

FIG. 3-12: **Reference Projects and Resulting Basic CERs for Storable- and Mono-Propellant Engines**

some 20 M$[1] which would be a cost reduction of more than 50 % compared to the *TRANSCOST*-CER- value based on the cost of the historical relatively complex rocket engines. The RS-68 engine, developed by Rocketdyne in the period 1996-2002, was the first large rocket engine with the prime requirement of low production cost, instead of high performance and low mass. The engine configuration (FIG. 3-13) shows the simple design concept. This proves that a major enine cost reduction is feasible by relaxed performance requirements, reduced number of components and modern fabrication techniques.

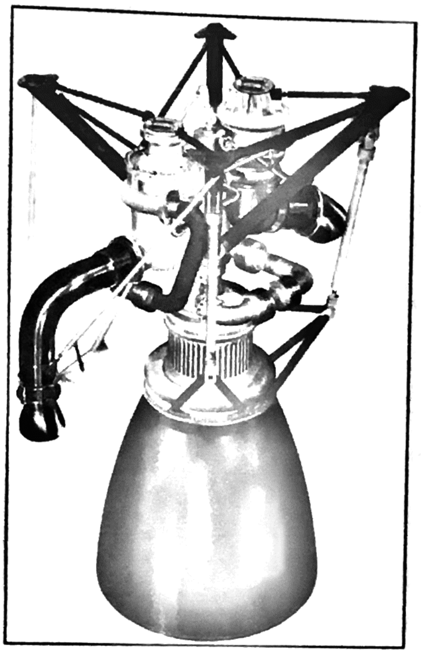

FIG. 3-13: **Rocketdyne RS-68 as Example for Cost-Optimized Design**

Another important item is the impact of the propellant combination on engine production cost: While in case of development costs the engine type and propellant combination did not prove to have a major impact on the required development effort, in case of the recurring costs the situation is different: Rocket engines featuring liquid hydrogen as fuel exhibit higher production costs than engines with other fuels, while monopropellant thrusters can be built for lower costs.

The large number of engine reference projects and the range over five orders of magnitude required the subdivision into two CER charts. The 23 reference projects shown in FIG. 3-12 and -14 led to three different basic engine groups and CERs:

(1) Rocket engines with the cryogenic propellant combination Hydrogen/ Oxygen), pump-fed

(2) Conventional rocket engines with storable propellants (pressure-fed and pump-fed),

[1] Aviation Week, 22.5.2006

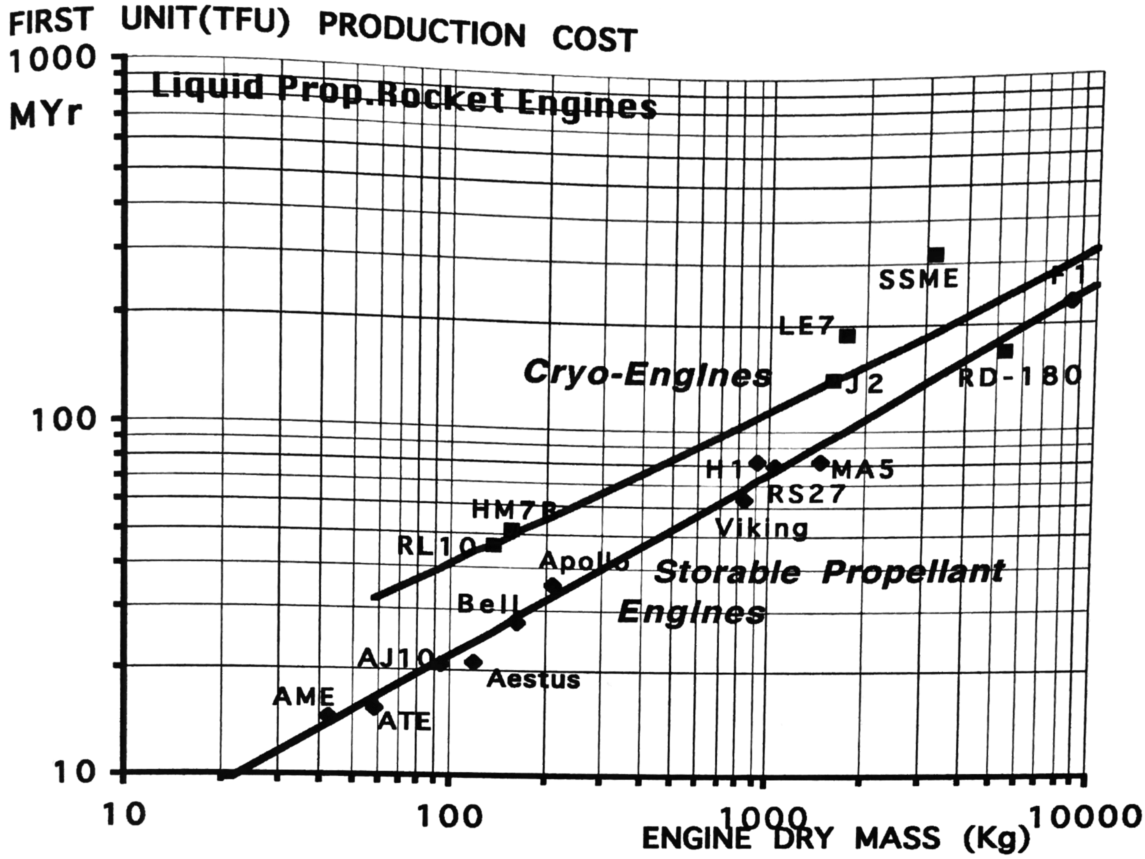

FIG. 3-14 : **Reference Projects and Resulting Basic CER for Storable-Propellant Engines (black) and LOX/Hydrogen Propellant Engines (blue)**

and (3) Monopropellant rocket engines.

The engine production cost CERs have been derived as follows:

(1) Cryo Engines with LH_2 (pump-fed) :

$$\boxed{F_{EL(c)} = 5.16 \cdot n \cdot M^{0.45} \cdot f_4} \quad \text{MYr}$$

(2) Engines with Storable Propellants (pressure-fed and pumpf-fed) :

$$\boxed{F_{EL(s)} = 1.9 \cdot n \cdot M^{0.535} \cdot f_4} \quad \text{MYr}$$

(3) Monopropellant Engines (Preliminary CER) :

$$\boxed{F_{EP(m)} = 1.13 \cdot n \cdot M^{0.535} \cdot f_4} \quad \text{MYr}$$

These CERs are valid for engines with regenerative cooling. Using ablative chambers and nozzles reduces the fabrication cost but also the engine's lifetime.

The statistical results lead to the conclusion that the recurring costs of cryo-engines presently are 60 to 30 % higher (decreasing with size and future simplification) than for engines with storable propellants, while Monopropellant engines seem to require some 40 % lower costs.

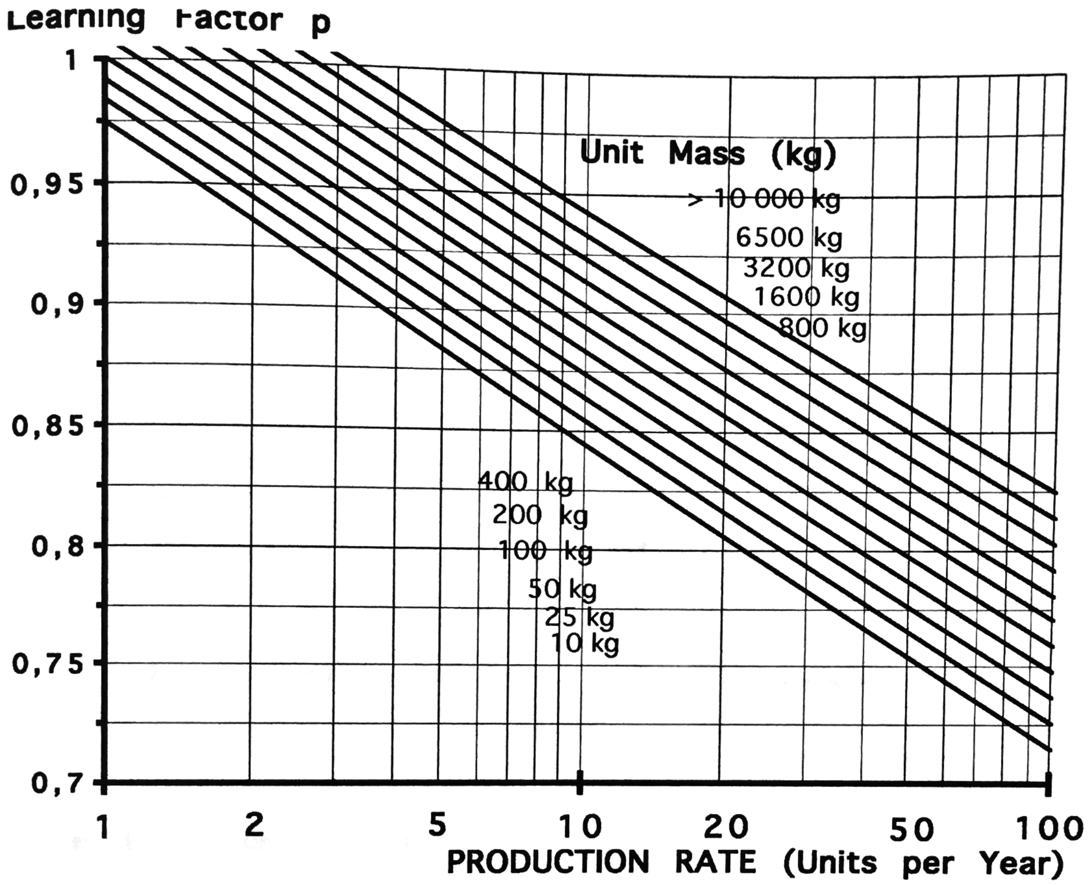

FIG. 3-15 : **Empirical Learning Factor Model Chart for Rocket Engines LF (p) vs. Unit Size (Mass) and Production Rate**

LEARNING FACTOR for Rocket Engines:

Regarding the applicable Learning Factor for rocket engines, an empirical chart has been prepared as shown in FIG. 3-15 which allows to select a representative p-value according to the engine mass and the annual production rate. It is mentioned here again that changes in the production rate as well as technical modifications do change also the applicable Learning Factor, reducing it in some cases to 1. Only a continuous production line will result in the optimum learning factor cost reduction.

3.43 Airbreathing Turbojet Engines

This group of airbreathing engines is of interest for winged first stage vehicles which require cruise flight and / or return flight capability to the launch site. Only for turbojet engines a recurring cost CER can be established since, by example, no operational ramjet engines have been developed yet.

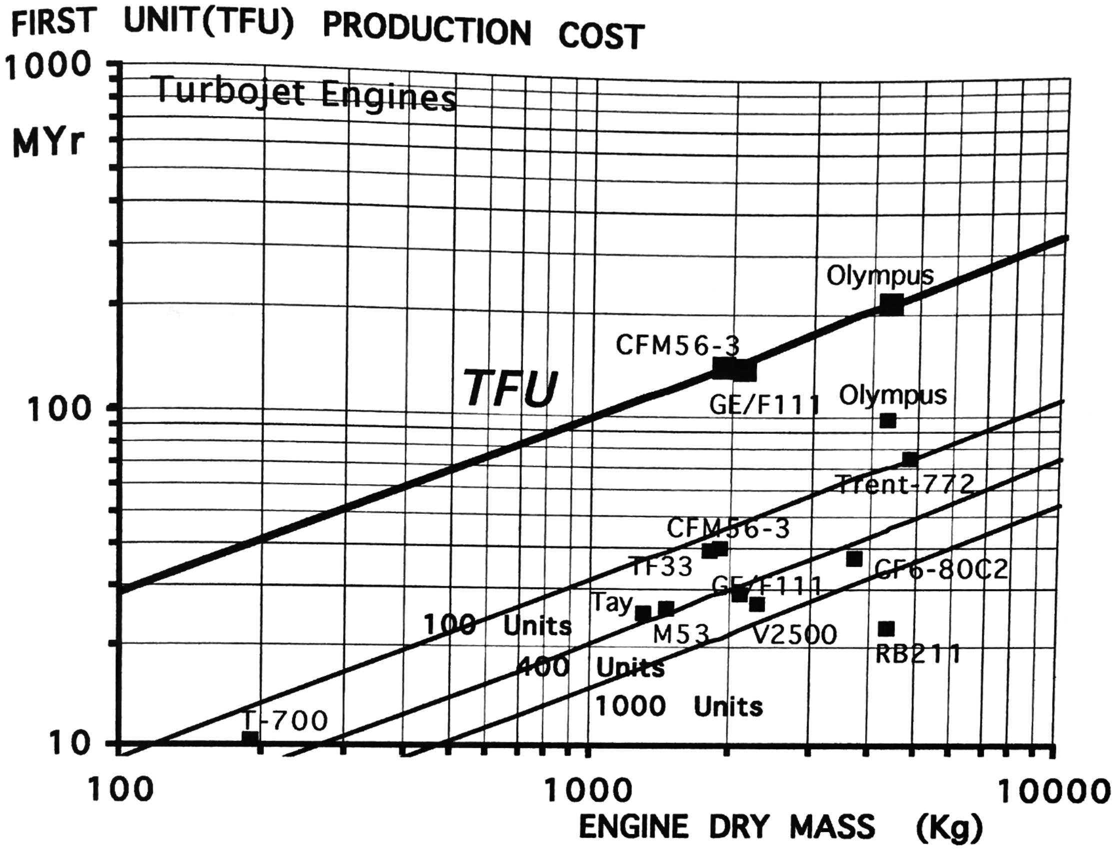

FIG. 3-16: **Reference Projects and Resulting CER for Turbojet Engines**

For turbojet engines there exists a competitive price situation - in contrast to rocket engines where only one supplier exists for each type or size of engine - which makes it more difficult to establish a CER for the TFU (Theoretical First Unit). The engine prices are influenced by the market situation and the anticipated total number of engines which can be sold. Also the development cost have to be amortized normally over the engines' sales price.

Nevertheless, based on some 11 reference projects and estimated production numbers a preliminary CER has been established (FIG. 3-16). The CER for the Theoretical First Unit (TFU) - as a very appropriate definition here - is close to the rocket engines' production CER , a fact which supports its credibility:

$$\boxed{F_{ET} = 2.29 \cdot n \cdot M^{0.545} \cdot f_4} \qquad \text{MYr}$$

The engine sales prices depend strongly on the production numbers which are indicated in FIG. 3-16 for a typical Learning Factor of about 0.8. Due to the similarity of several engines and engine families the Learning Factor can vary as well as the definition of the total number of engines built.

3.5 Launch Vehicle Systems' Production CERs

3.51 Propulsion Modules

Propulsion Modules cover a wide range of applications: from kick-stages of launch vehicles to apogee and orbit modules of large communication satellites (TV-SAT, INTELSAT VI, VII) , as well as for planetary spacecraft (GALILEO; CRAF). The design of a special propulsion module instead of a completely integrated, resp. distributed system, has shown to be a cost-efficient concept.

Propulsion modules are - by definition - complete propulsion systems with its own structure but no equipment like attitude control electronics, telemetry, power supply, etc. A typical propulsion module is the GALILEO-RPM (Retro

FIRST UNIT (TFU) PRODUCTION COST

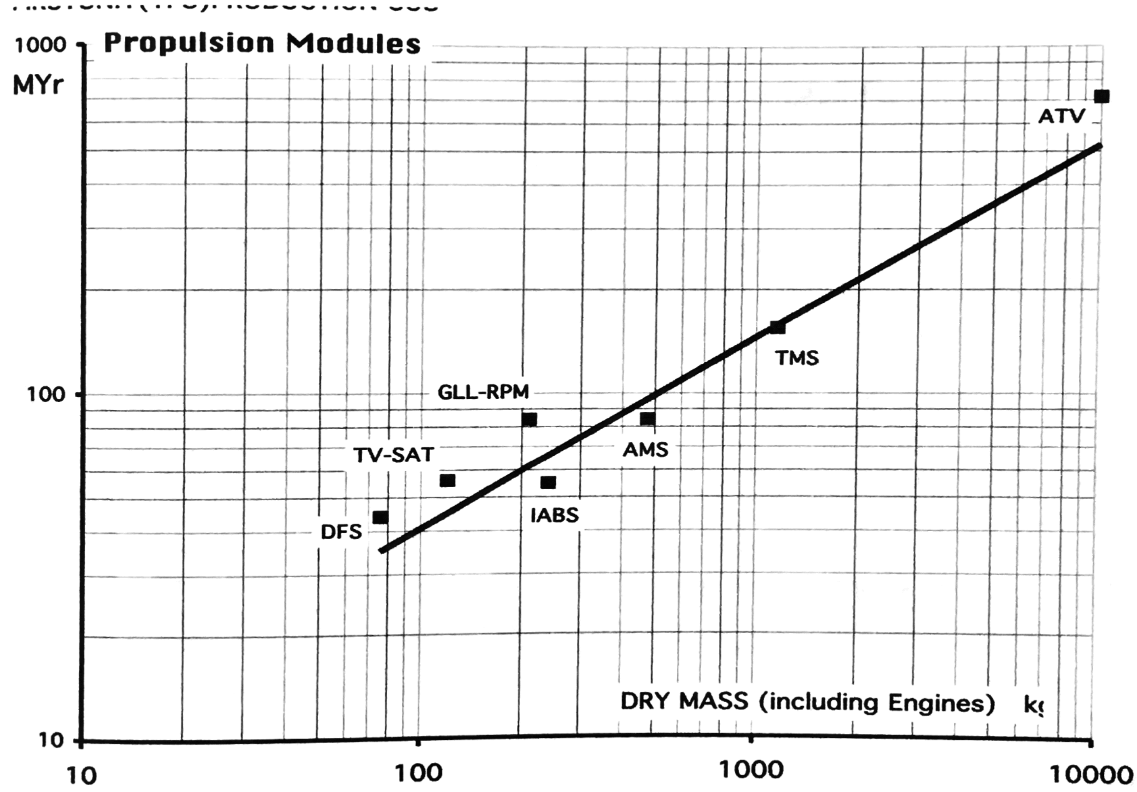

FIG. 3-17: **Reference Module Projects and the Resulting CER Graph**

Propulsion Module) built by MBB for NASA-JPL (FIG. 2-22) The net mass is 210 kg, containing 930 kg propellants in four tanks, plus two Helium vessels, 12 small 10N thrusters and one 400 N engine. The RPM flight unit fabrication and assembly took place in the period 1981- 83 and did cost some 13.5 Mio. DM or 65 MYr. Due to the high degree of redundancy it is more expensive than a satellite propulsion module. The European ATV (Ariane Transfer Vehicle) is another very different example, including docking equipment and solar arrays. Although this is an independent flight vehicle the ATV has been placed in this group of vehicles since it has only a maneuvering propulsion system, consisting of small engines. The projected cost fit well into this group of reference projects which is shown in FIG. 3-17 together with the resulting basic CER:

$$\boxed{F_{VP} = 4.65\ n\ M^{0.49}\ f_4} \quad \text{MYr}$$

The reference mass for Propulsion Modules - in contrast to other CER's - includes the mass of the engines, as well as the engines' cost. Storable propellants are used for this type of vehicles. The slope of the curve as well as the cost level is higher for propulsion modules than for stage vehicles (next chapter) which makes sense due to the lack of large - relatively low-cost structure elements.

3.52 Ballistic Vehicles / Stages (Expendable and Reusable)

A relatively large number of 16 reference projects exists for this group of vehicles built in the past four decades in different numbers. This requires the careful cost regression to the number one flight unit, the TFU (Theoretical First Unit) taking into account the Learning Factor effect, in order to make the data comparable and to create a coherent CER.

FIG. 3-18 with the reference data points shows the same cost difference between vehicles with storable propellants and cryogenic system with LH_2 as the related rocket engines (cf. FIG. 3-14). The only exception in the coherent data set is the ASTRIS vehicle (third stage of the ELDO/Europa I Launcher). The high vehicle cost can be explained, however, by its unique titanium sandwich structure. This required no less than 350 000 welding points for the fabrication of the external structure, made of 0.1 mm titanium sheet metal.

The CERs are applicable for expendable and reusable systems. Since reusable vehicles require some 40 % higher dry mass, they are more expensive to build. The following CER has been derived for rocket vehicles with <u>storable propellants</u>:

$$\boxed{F_{VP} = 0.83\ n\ M^{0.65}\ f_4} \quad \text{MYr}$$

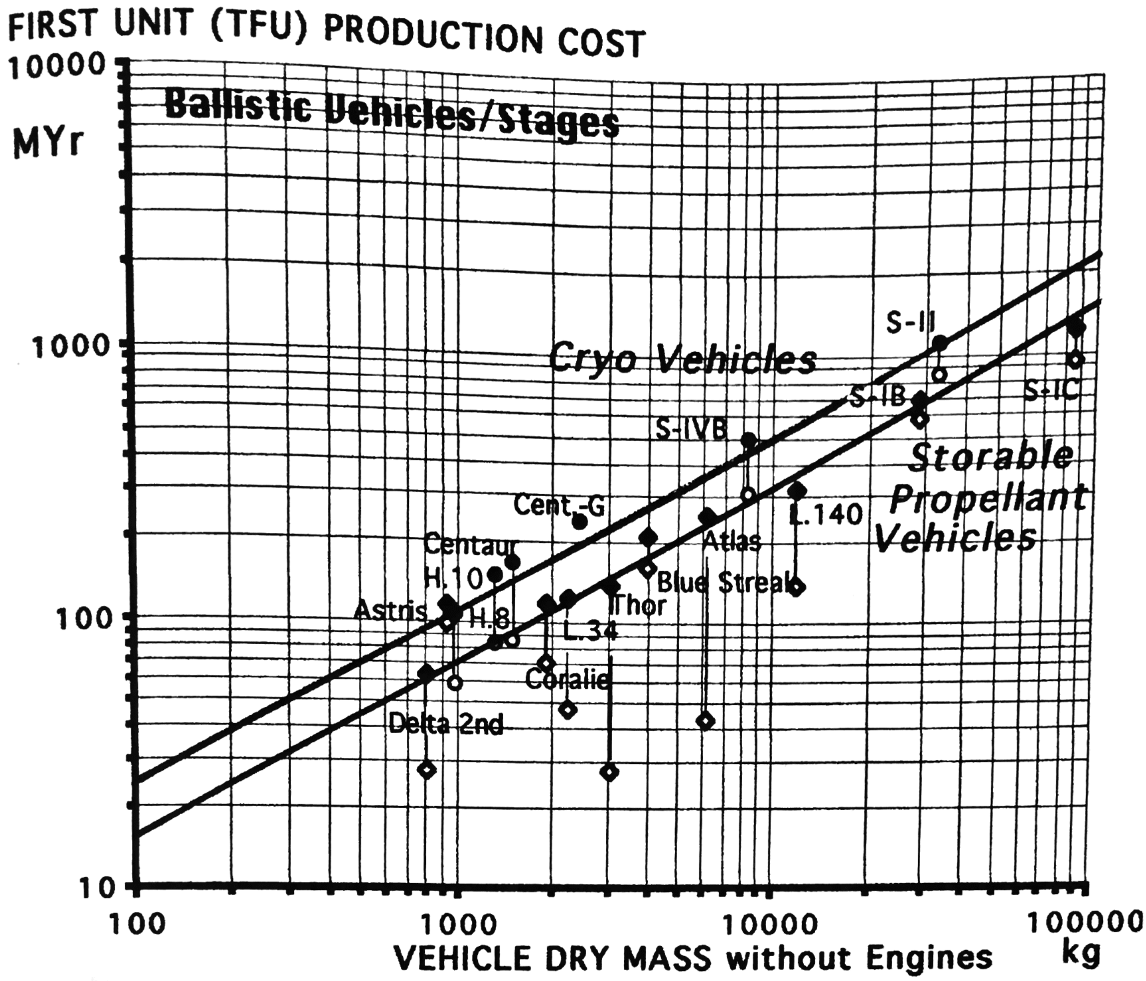

FIG. 3-18: **Reference Projects and Resulting CER for Ballistic Vehicles**
(Solid Points = Reference Values after Degression)

For vehicles with cryogenic propellants (LH_2) the following CER applies:

$$\boxed{F_{VP} = 1.30 \; n \; M^{0.65} \; f_4} \quad \text{MYr}$$

The reference mass is the vehicle DRY mass without engines (other CER applicable) but including inter-stage adapters or payload shroud (if applicable) as well as the telemetry and attitude control equipment.

The CERs indicate that vehicle systems with hydrogen fuel are about 60 % more expensive than those using storable propellants. In addition, due to the larger tank volume required for the same propellant mass the dry mass is some 60 % higher. Due to this fact a reusable vehicle needs to be larger for the same performance (delta-V). This is balanced, however, largely by the 40 to 50 % higher total impulse of the LOX/LH_2 propellant combination, resulting in a smaller propellant mass demand.

The cost / mass sensitivity of the CER shows that a vehicle with 10 times larger dry mass requires only four times higher cost; or, increasing the dry mass by some 15 % as margin or to make up for more conventional technology employed, increases the vehicle production cost only by few percent.

3.53 High-Speed Aircraft / Winged First Stage Vehicles

The broad data base of commercial aircraft production cost provides also the basis for potential future winged first-stages or so-called Flyback Vehicles. The TFU cost and basic CER is based on the CONCORDE and other advanced aircraft production, including the X-15, but it is also in accordance with the series production of subsonic commercial aircraft with production quantities of over 400, resulting in a learning cost reduction factor of 0.25 to 0.2 at learning factors p = 0.8 to 0.85.

FIG. 3-19 provides a survey about the reference projects and cost data used to establish the basic CER. In this case the vehicle dry mass including engines, resp. the „Operating Weight Empty“ (OWE) in aircraft terminology, is being used as reference. The CER for aircraft and flyback launch vehicle first stages TFU

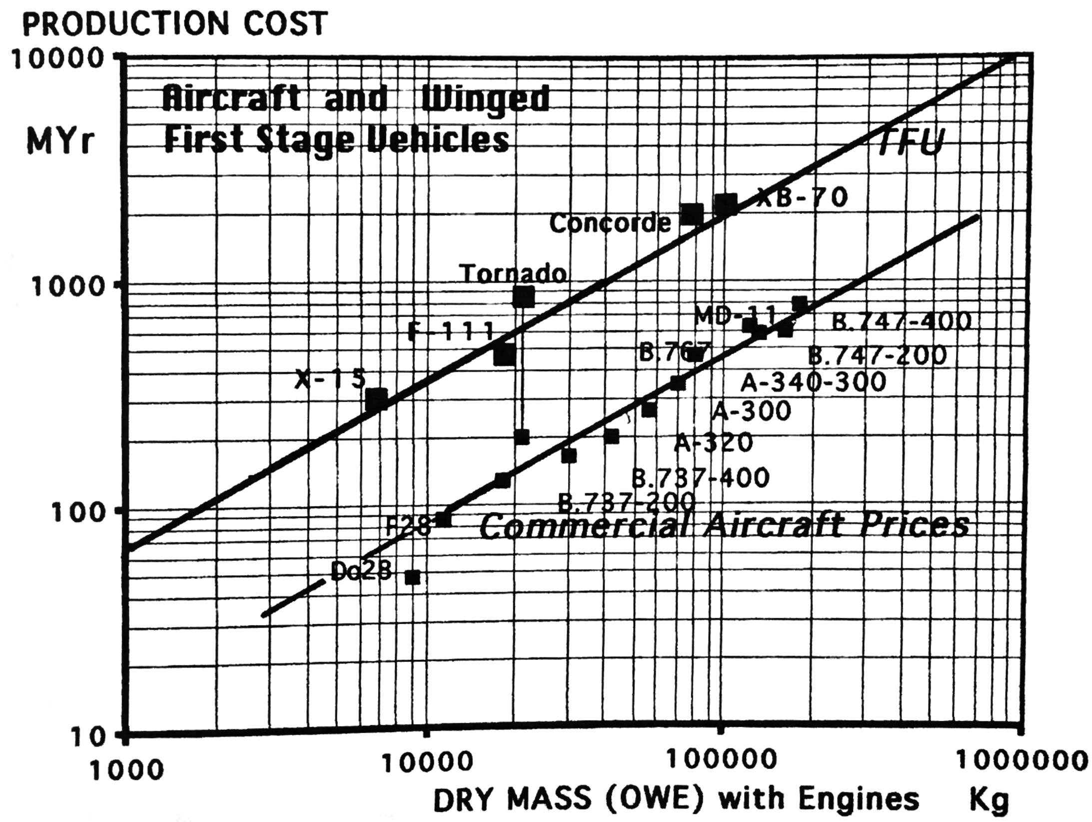

FIG. 3-19: **Reference Projects and Basic CER for Aircraft and Winged First Stage Launch Vehicles**

cost is

$$\boxed{F_{VF} = 0.367\ n\ M^{0.747}\ f_4} \quad \text{MYr}$$

In case of commercial aircraft the data are not production costs but prices, strongly influenced by the market and the competitive situation, but also by the production number and the development cost amortization share. In average the unit prices are 20 to 30 % of the TFU cost.

3.54 Winged Orbital Rocket Vehicles

This group of vehicles comprises winged SSTO Vehicles as well as Winged Upper Stages with re-entry and flyback capability. Although the Shuttle ORBITER has a similar external configuration it is *not* a typical example due to the lack of integrated propellant tanks and its internal design with cockpit and as manned laboratory for extended stay times in orbit.

Many detailed studies have been performed on such vehicle concepts but very few on detailed production cost estimates. The most recent ones are the FESTIP analyses (ref.101) with detailed subsystem-based production cost estimates using the PRICE-H Model. Due to the lack of actual vehicle production cost data only a provisional CER can be established with respect to the great interest in this vehicle concept.

The basic cost/ mass trend is taken from the Ballistic Cryo Vehicles (chapter 3.52 and the cost level from the calculated concepts FSSC-9/ II, the upper stage of a TSTO Launch Vehicle, and FSSC-1, a Single-Stage Vehicle, both with vertical launch mode:

FSSC-9/ II : Vehicle Mass 27 200 kg (w/ o engines); TFU Cost = 2 820 MYr

FSSC-1 : Vehicle Mass 72 500 kg (w/ o engines); TFU Cost = 5 130 MYr

FIG. 3-20 shows the situation: the cost level of the provisional TFU-CER is in between the cost of ballistic vehicles and the crewed Shuttle Orbiter which is plausible. Whether the cost factor of almost 3 between the ballistic and winged vehicles is realistic remains to be seen, however, the cost level is just some 50 % higher than for aircraft , and that seems to be quite realistic. On the other hand, the Space Shuttle Orbiter fabrication cost are higher by a factor 2.5 compared to the TFU cost for unmanned winged vehicles.

The provisional production CER for Winged Orbital Vehicles accordingly has the form of

$$\boxed{F_{VW} = 3.75\ n\ M^{0.65}\ f_4} \quad \text{MYr}$$

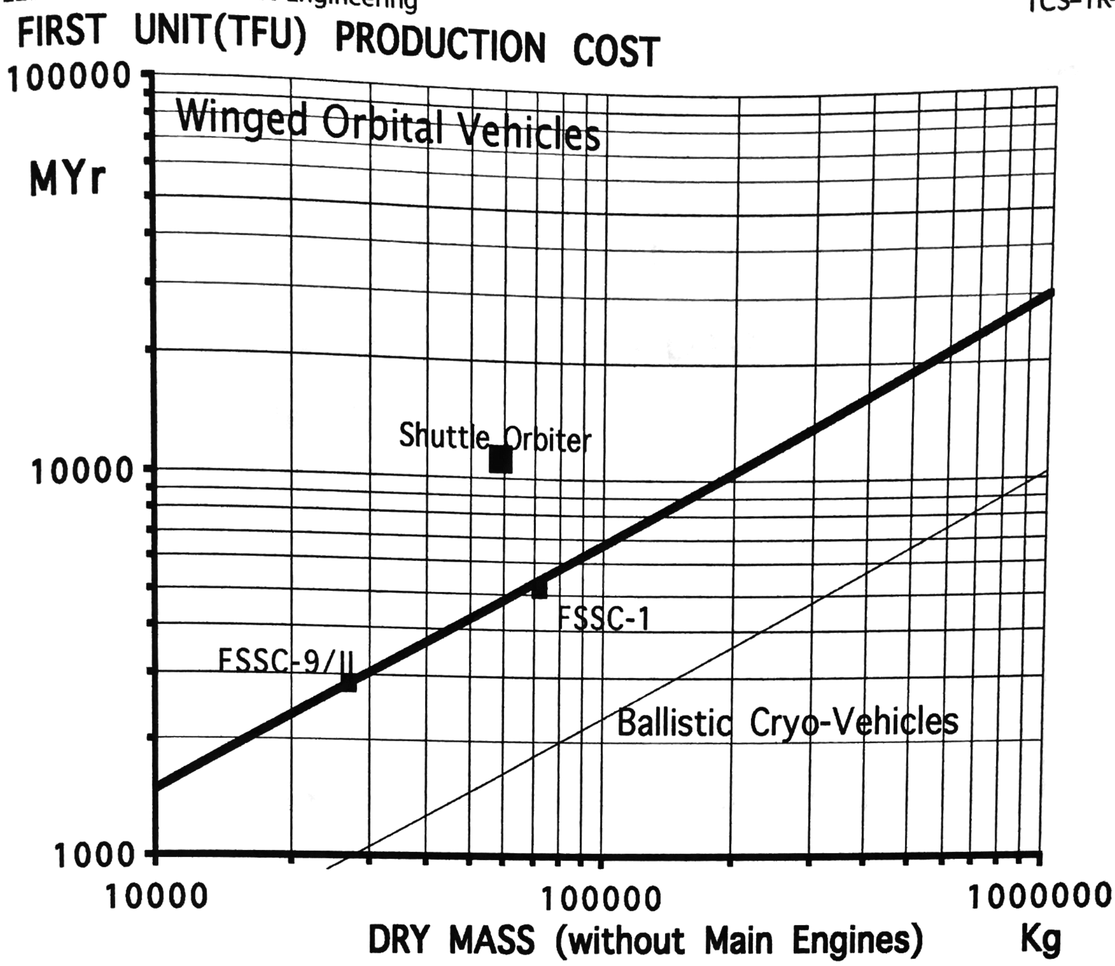

FIG. 3-20: **References for Provisional CER for Winged Orbital Vehicles**

This needs to be confirmed or corrected as soon as a vehicle of this type has been built.

3.55 Crewed Space Systems

This group of space systems is described in chapter 2.38. It covers a wide range of vehicles from crewed re-entry capsules, lunar transfer and landing vehicles and the Shuttle Orbiter (without engines). It is also unique insofar as the mass/cost exponent in the CER approaches the value 1: this means that the fabrication cost in this case are almost proportional to the vehicle mass.

The other - less surprising - fact is that the production cost are the highest of all systems. This can be explained by the complex life support system with the power supply and the electronic equipment (communications) required for crewed space systems.

The seven reference projects shown in FIG. 3-21 make a good fit for the basic CER which has the form of

$$\boxed{F_{VS} = 0.16\ n\ M^{0.98}\ f_4} \qquad \text{MYr}$$

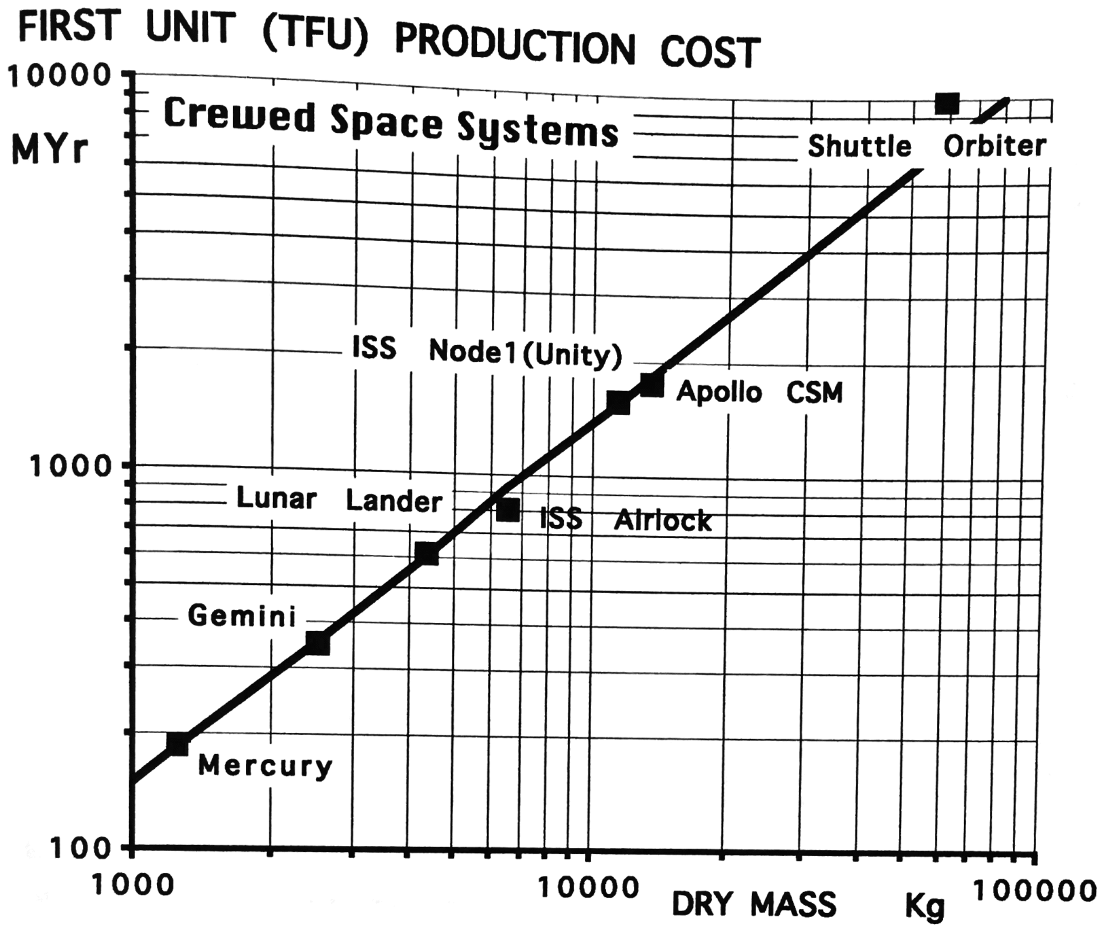

FIG. 3-21: **Reference Projects and the Resulting Basic CER for Crewed Space Systems**

3.6 Production Cost Uncertainties and Risks

The cost estimating accuracy in case of production costs is relatively high since the strong programmatic impacts as in case of development costs do not exist.

3.61 Technical Cost Criteria

(1) On the technical side a major impact on the production cost has the NUMBER OF COMPONENTS. This criteria has to be taken into account already in the design phase since the fabrication costs are strongly influenced by the number of components which have to be built and assembled. This has been demonstrated by the example of rocket engines (TABLE 3- I).

(2) Another major impact factor on production costs is the scope of VERIFICATION / ACCEPTANCE TESTING. There is a trade-off between component testing vs. testing of sub-assemblies or systems, and finally complete systems tests, such as in case of rocket engines.

(3) It is also evident that a technical MODIFICATION of the product or a process change can increase the learning factor and, accordingly, increase the production cost per unit (cf.FIG. 3-05) if the modification does not have clear cost reduction advantages.

3.62 Non-Technical Cost Criteria

(1) The major uncertainty is related to the PRODUCTION QUANTITY. It is evident that the unit production cost depend strongly on the number of units ordered as one batch, as well as on the total production number already realized or planned. For achieving the maximum cost reduction by learning it is also necessary to ensure a continuous production at - if possible - a constant production rate (per month or year).

(2) The next major impact on the production cost has the ACTUAL HOUR-RATE or MYr-Cost of the specific company, factory or workshop. While the *TRANSCOST*-Model uses an average MYr-value related to the aerospace industry, the specific costs may well be different, depending on the size of the workshop / factory and their accounting method regading overhead costs. If the production can be related to a specific workshop it is worthwhile to get the actual MYr-cost for an improved production cost estimate.

(3) Another critical factor is the personnel EXPERIENCE. It has happened repeatedly that new people, not completely familiar with special production features, have caused problems and cost growth.

3.7 Applications of the Production Cost Submodel
(Examples, Comparison of Results with Actual Costs)

3.71 Launch Vehicle Stage Production Cost (SATURN S-II Stage)

In Sep. 1967 a Contract to North American Aviation (NAA, then Rockwell, now Boeing) was issued by NASA for the production of 5 additional S-II Stages for the SATURN V L/ V at a value of 159.716 M$[2].

These stages were production no. 11 to 15 built in the 1968 to 70 period at a rate of 2 to 3 per year.

With the TRANSCOST CER of chapter 3.52 the cost estimate would result in

$$\begin{aligned} F_{VP} &= 1.3 \ n \ M^{0.65} \ f_4 \quad \text{(MYr)} \\ &= 1.3 \cdot 5 \cdot 29\,700^{0.65} \cdot 0.86 \\ &= 4515 \ \text{MYr} \times 0.036 = \underline{162.6 \ \text{M\$(69)}} \end{aligned}$$

(0.036 M$ is the average MYr-cost for the 1968-70 period)

The stage dry mass without the 5 J-2 engines was 29 700 kg. The Learning Factor for this stage mass and production rate is about 0.96, leading to a cost reduction factor of $f_4 = 0.86$ for vehicles no.11-15.

The difference between the estimate and the contract value is + 2 %. Eventually an incentive fee was added to the contract value.

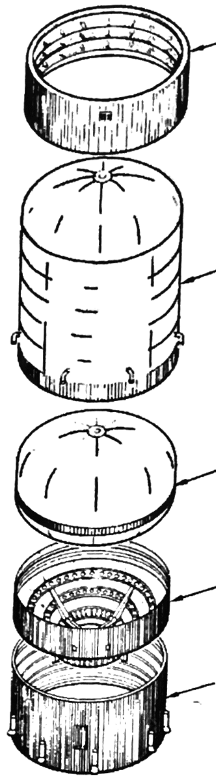

FIG. 3-22:
S-II Structure Assembly

3.72 Rocket Engine Production Cost (F-1 Engine)

As an example, the F-1 engine has been selected, 5 of which have been used as propulsion system for the SATURN V - S-I Stage. The NASA Contract awarded to Rocketdyne for the second batch of 30 engines (no.76 to 106) in 1966 amounted to 141 M$[3] + 4.1 M$ addendum in 1969, or 4.83 M$ per engine. The engine dry mass is 8 452 kg.

According to the TRANSCOST -CER (chapter 3.42) the resulting average cost per engine would be

$$F_{ES(s)} = 1.9 \cdot 8452^{0.535} \cdot f_4 \qquad \text{(MYr)}$$

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[2] NASA Press Release 67-244, dated 19 Sep.1967

[3] according to NASA Press Release 66-297, dated 21 Nov.1966

The learning factor for an engine of this mass and a production rate of 14 per year (derived from the total quantity of 106 engines built in the period 1963 to 1970 = 8 years) would be about 0.92 according to FIG. 3-07. With the lower chart of FIG. 3-03 a cost reduction factor of 0.58 can be found as average for engine production numbers 76-106 at p = 0.91. The resulting cost value can be calculated by using the average MYr-cost for the production period 1967-69 from TABLE 1-I = 0.0343 M$/MYr :

$$F_{ES(s)} = 1.9 \cdot 126.2 \cdot 0.58 \quad \text{MYr}$$

$$= 139.1 \cdot 0.0343 = \underline{4.77 \text{ M\$ per engine (1968)}}$$

This is almost too good a fit; the difference between the TRANSCOST- CER result and the actual cost could well be plus/ minus 10% or so. Reason is that the actual ManYear cost of the manufacturer can differ from the industry's average used here, and /or that the learning factor cost reduction factor is not equivalent to the „ideal one" if changes in the production rate and/ or the manufacturing process or technical modifications took place.

3.73 Production Cost Comparison of Solid-Propellant Launch Vehicle Options

The TRANSCOST-Model CERs can also be used for comparing the production cost of different configurations of a small launcher composed of solid-propellant rocket motors (ref. 102) in order to make a decision on the most cost-effective configuration.

FIG. 3-22 (next page) shows the basic launch vehicle options which have the same LEO payload of 500 kg:

CONCEPT A is a typical performance-optimized vehicle with minimum total launch mass (53 Mg), similar to the Taurus Vehicle, consisting of a P.38 (38 Mg propellants) plus a P.7 (7 Mg propellants) motor.

CONCEPT B is a simplified building-block version with two same-size motors (as the Athena-2 vehicle). The use of two P.32 motors is far from the optimum staging rule and results in a high launch mass of 70 Mg.

CONCEPT C is a modularized vehicle, using one single standardized motor size (P.10) trying to meet optimum vehicle staging conditions by clustering four motors as first stage. The resulting launch mass of 60 Mg is in between the two previous vehicle configurations.

All three vehicle configurations are equipped with a small third stage or apogee motor (EBM with 1622 kg propellants) for injection into high orbits.

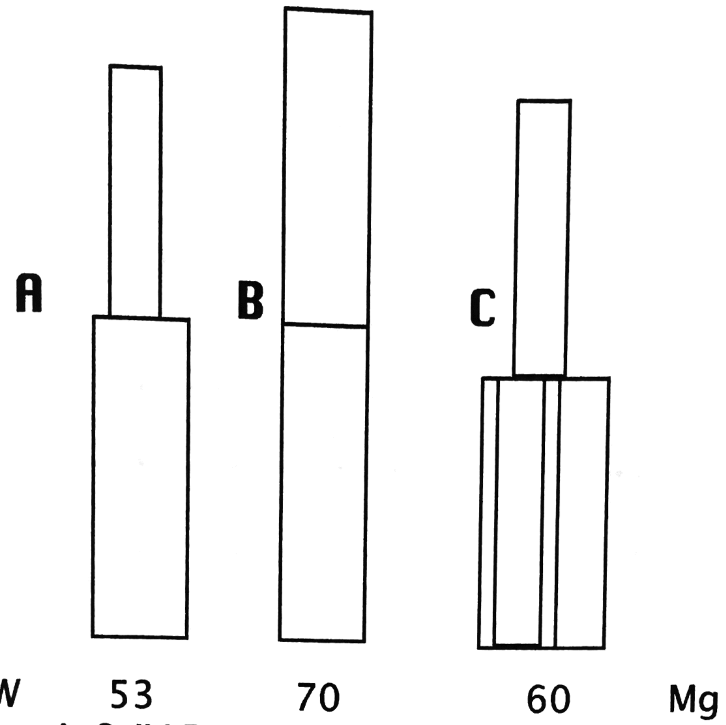

FIG. 3-23: **Generic Solid-Propellant Launch Vehicle Configurations**

For the vehicle cost comparison an assumption is required on the program scope, i.e. how many motors are required. Assuming a 10-year period and 4 LpA (launches per annum) then the number of motors can be derived, with the associated cost reduction factors by applying a Learning Factor of 0.85 or 85 %. For the unit cost determination the relevant TRANSCOST-CER (Cost Estimation Relationship) for Solid-Propellant Motors is applied which is shown as FIG. 3-11 in chapter 3.41. The results for the rocket motors of the three reference vehicles are shown in TABLE 3-II including the resulting development cost amortization charge per motor.

TABLE 3-II : **Motor Production and Development Costs**

Motor Size (Prop.Mass)	P.38	P.32	P.10	P.7	EBM
Net Mass (kg)	3200	2600	830	600	141
Total Number required	40	80	200	40	40
Cost Reduction Factor	0.54	0.46	0.38	0.54	0.54
UNIT COST (M.Euro)	6.0	4.7	2.5	3.1	1.8
DEV. COST (NRC) M.Euro	300	265	147	125	58
Amortization Charge M.Euro	7.5	3.3	0.73	3.1	(0.3)

TABLE 3-III : **Complete Launch Vehicle Unit Cost**
(Program with 40 Launches) in M.Euro(96)

VEHICLE CONCEPT	A	B	C
Basic Motor Cost	10.9	11.2	14.3
Basic Vehicle System	2.4	2.6	3.2
Third Stage with Electronics	3.5	3.5	3.5
TOTAL	**16.8**	**17.3**	**21.0**
+ Motor Dev.Charge	10.6	6.6	3.7
TOTAL with Motor Dev. Amort.	**27.4**	**23.9**	**24.7**

Based on the motor cost data of TABLE 3-III the total vehicle cost (VRC) can be assembled, using representative values for the stage eqipment and assembly from the ATHENA-2 and TAURUS launch vehicles.

CONCLUSIONS:

(1) A solid-propellant launch vehicle should be composed of existing motors with high production numbers (since the motor cost represent 46 to 60 % of the total vehicle cost).

(2) Motor size optimization for a minimum GLOW launch vehicle does NOT provide a cost advantage. In the contrary, if new motors must be developed this is the most expensive approach (cf. TABLE 3-III).

(3) The number of motors used for a vehicle should be minimized nevertheless. This means that the the Athena-2 approach with two (existing) equal-sized motors (Concept B) is about the most cost-effective concept even though being the worst one from the performance criterion and having a relatively high launch mass (GLOW).

(4) The vehicle with a clustered first stage (Concept C) is not cost- competitive if existing motors are available for Concept type A or B. However, if new solid motors have to be developed this is the optimum vehicle configuration since the CpF are comparable to Concept B but the development cost are much lower: 147 M.Euro vs. 265 M.Euro for Concept (B) and 425 M.Euro for Concept (A).

This example shows that a performance-optimized launch vehicle is an expensive approach. The configuration of a cost-optimized launch vehicle looks much different.