Systems Engineering Studies of On-Orbit Assembly Operations

George W. Morgenthaler

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S5-31

p 26

Center for Space Construction

The Theory of Space Construction

Progress Report

George W. Morgenthaler

PART I: DEFINITION AND SCOPE OF SPACE CONSTRUCTION

PART II: ORBITAL ASSEMBLY AND CONSTRUCTION

PART III: LUNAR BASE CONSTRUCTION

PART IV: MARS BASE CONSTRUCTION

(11/23/91)

Constructability Definition

"Constructability is defined as the optimum use of construction knowledge and expertise in the conceptual planning, detail engineering, procurement, and field operations phases to achieve the overall project objectives."

N. Eldin, "Constructability Improvement Of Project Designs", Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE), Vol. 114, No. 4, pp. 631-640, December 1988

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Theory of Space Construction

- Construction is Old; Construction Theory is young.
- The literature is filled with construction "war stories" and "Sea Bee" epics, but little quantitative analysis and optimization of construction.
- Strong parallels exist between Manufacturing and Construction:
  - — Requirements are critical (confused requirements lead to waste)
  - — Good design is critical; concurrent engineering requires iterations between Engineering and Manufacturing.
  - — Material selection is critical (failure, weight, hazards)
  - — Procurement (logistics) is critical
  - — Manufacturing Engineering is critical
  - — Inspection, QC, NDE are critical
  - — Cost and schedule analysis is critical
  - — A Systems Approach is required for success
- Analytical tools have been developed for terrestrial manufacturing and construction, but not for Space-based applications. (Synthesis tools do not as yet exist for either domain)
- We need to approach a Theory of Space Construction in the same way

(Space construction is not as forgiving as manufacturing)

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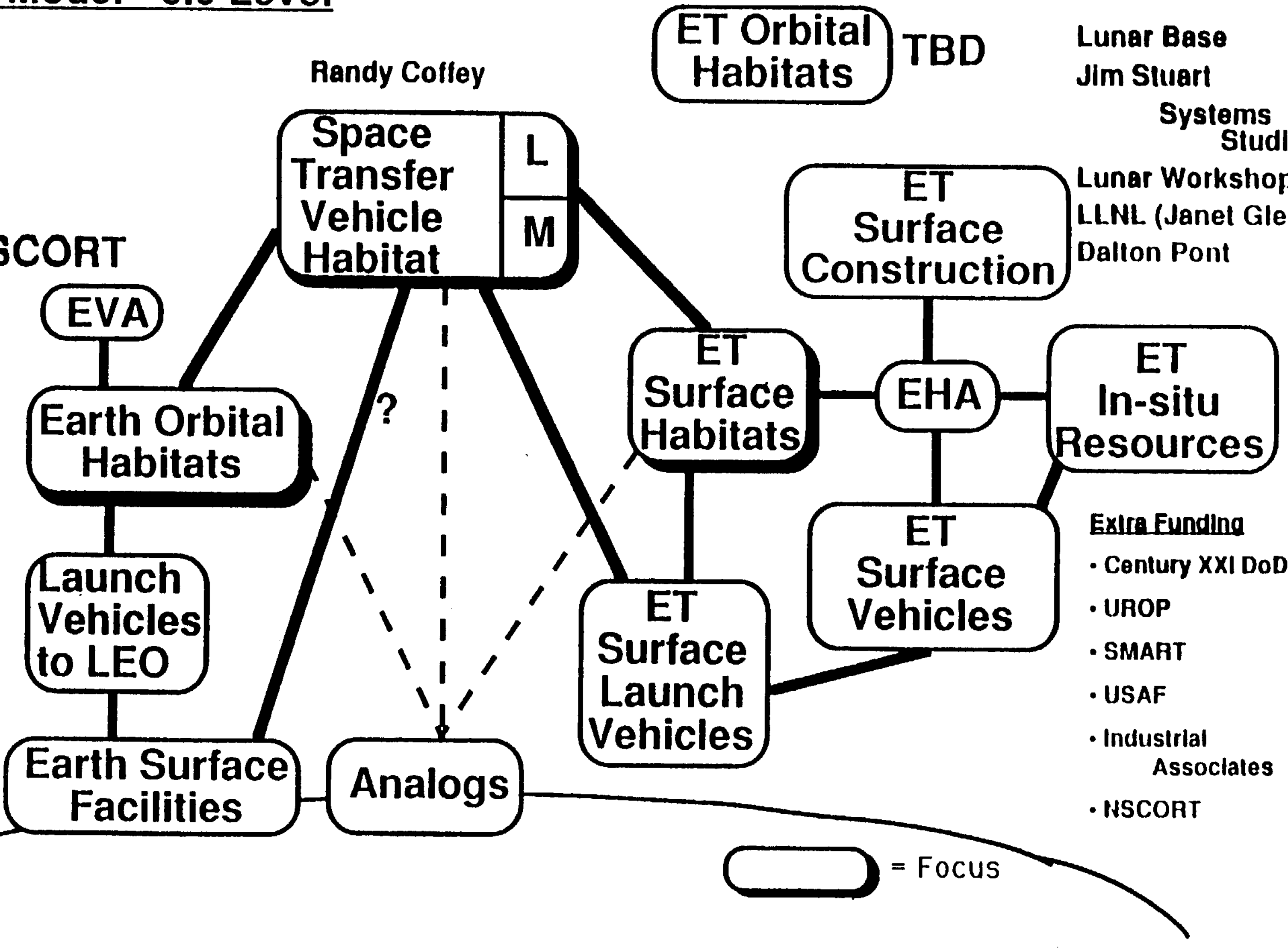
Theory of Space Construction

System Model - 0.0 Level



Randy Coffey

Space Transfer Vehicle Habitat

L

M

ET Orbital Habitats

TBD

NSCORT

EVA

Earth Orbital Habitats

Launch Vehicles to LEO

Earth Surface Facilities

Analogs

?

ET Surface Habitats

ET Surface Launch Vehicles

ET Surface Construction

EHA

ET In-situ Resources

ET Surface Vehicles

= Focus

Interruptability

DYCAM 1.0

DYCAM 2.0

Simulation

Launch-On-Time'

Vehicle Selection

Lunar Base

Jim Stuart

Systems Studies

Lunar Workshops

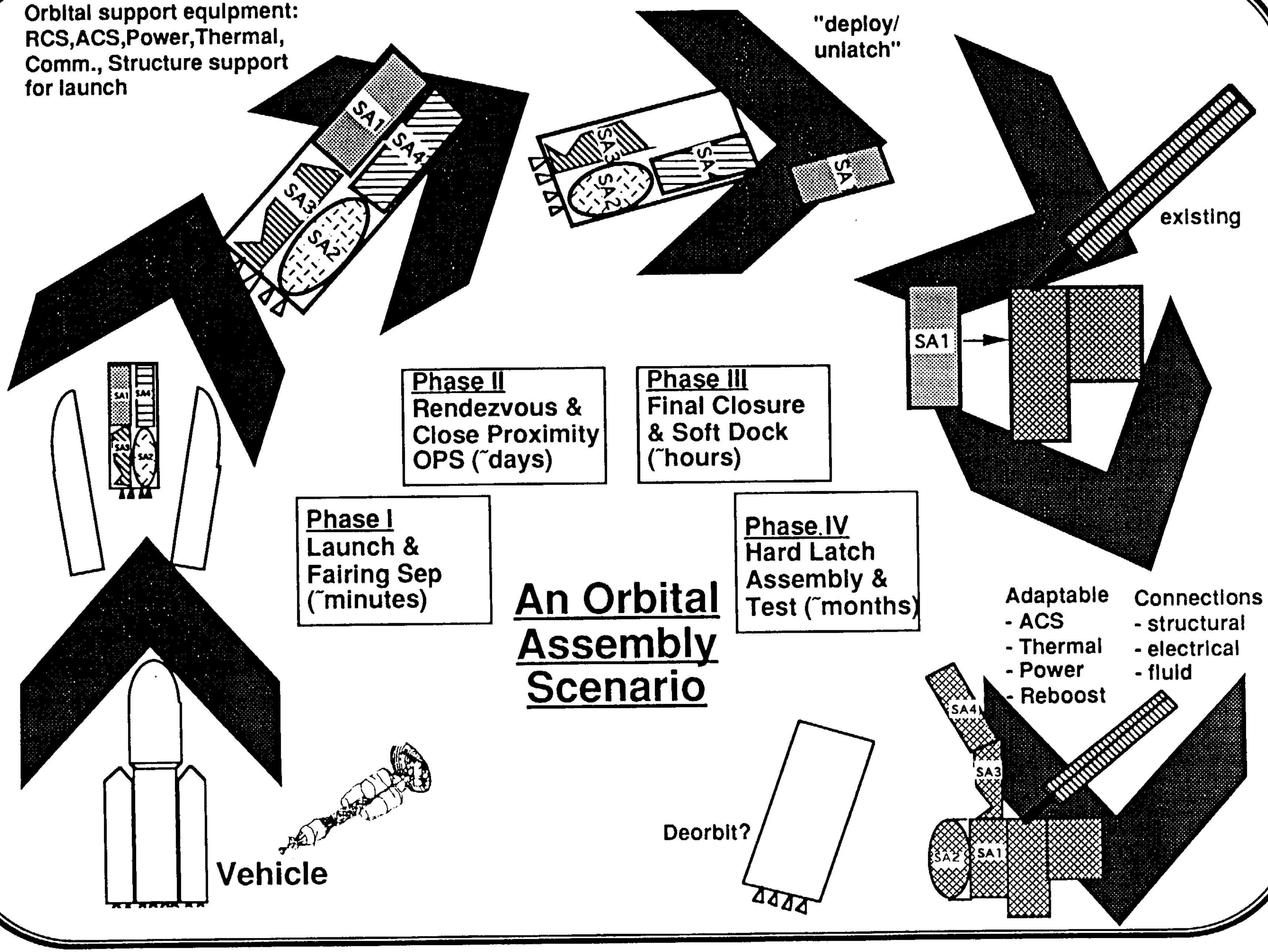
LLNL (Janet Gleave)

Dalton Pont

Extra Funding

- Century XXI DoDE
- UROP
- SMART
- USAF
- Industrial Associates
- NSCORT

An Orbital Assembly Scenario



Orbital support equipment: RCS,ACS,Power,Thermal, Comm., Structure support for launch

Phase I
Launch & Fairing Sep (˜minutes)

Phase II
Rendezvous & Close Proximity OPS (˜days)

Phase III
Final Closure & Soft Dock (˜hours)

Phase.IV
Hard Latch Assembly & Test (˜months)

Adaptable
- ACS
- Thermal
- Power
- Reboost

Connections
- structural
- electrical
- fluid

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In-Space Construction Research (AY 1990-1991)

Introduction

- Theory of Space Construction
- A Systems Approach
- Develop Construction Model Theory of CAE/Constructability Tools

Logistics to LEO

- Launch-on-time- GWM, K.Nii (Compound Distribution)
- Vehicle Selection Model- GWM, A. Montoya
- Simulation Models- K. Chan, K .Nii
- System Study: Need HLLV- GWM

Interruptability

- NASA Requests , Early Work
- The General Model - (Network Theory + Stability Matrices) J. Wade, H. Sato, K. Chan (Ph. D Thesis)

DYCAM

- Early Definition- U. Racheli
- DYCAM 1.0 (IDEAS**2 + resource allocation)-H. Schroeder (Ph. D Thesis)

Orbital Assembly

- Problem Definition- S. Jolly, M. Loucks, GWM
- Simulation Model- M. D'Amara (Simulation + Monte Carlo)
- Rendezvous + Docking D. Mackison, K. Nii, D. Lawrence, GWM

Logistics to SEI Destinations

- Optimal Supply of GEOS- R. Coffey (Ph. D Thesis)
- Lunar/ Mars Cyclers C. Uphoff, M. Loucks

Joining, Test and NDE

- Joining- K. Nii, B. Nguyen
- Test and NDE- R. Nici

On-Orbit Assembly

- Evaluation of Logistics Supply Needs
- Evaluation of Assembly Sites
- Evaluation of On-Orbit Assembly Operations
- Evaluation of On-Orbit Assembly Support Equipment Designs and Performances
- Evaluation of Space Transfer Vehicle Designs

A COST TRADE-OFF MODEL FOR ON-ORBIT ASSEMBLY LOGISTICS

George W. Morgenthaler

(11/23/91)

All is not well with SEI logistics

- Ability to deliver on-time constrains space construction — logistics trade-offs limit specialized construction equipment.
- Data analysis of US LEO launch capability shows:

  - Reliability high; L.O.T. low; need L.O.T. improvement model
  - Incapable of supporting existing missions plus SEI

$$\frac{2{,}100{,}000 \text{ Lbs/yr to LEO for SEI}}{50{,}000 \text{ Lbs/Shuttle launch}} = 42 \text{ Shuttle launches/yr}$$

  - Need HLLV

$$\frac{2{,}100{,}000 \text{ Lbs/yr to LEO}}{330{,}000 \text{ Lbs/HLLV launch}} = 6.4 \text{ HLLV launches/yr}$$

- Need HLLV Vehicle Requirements Model

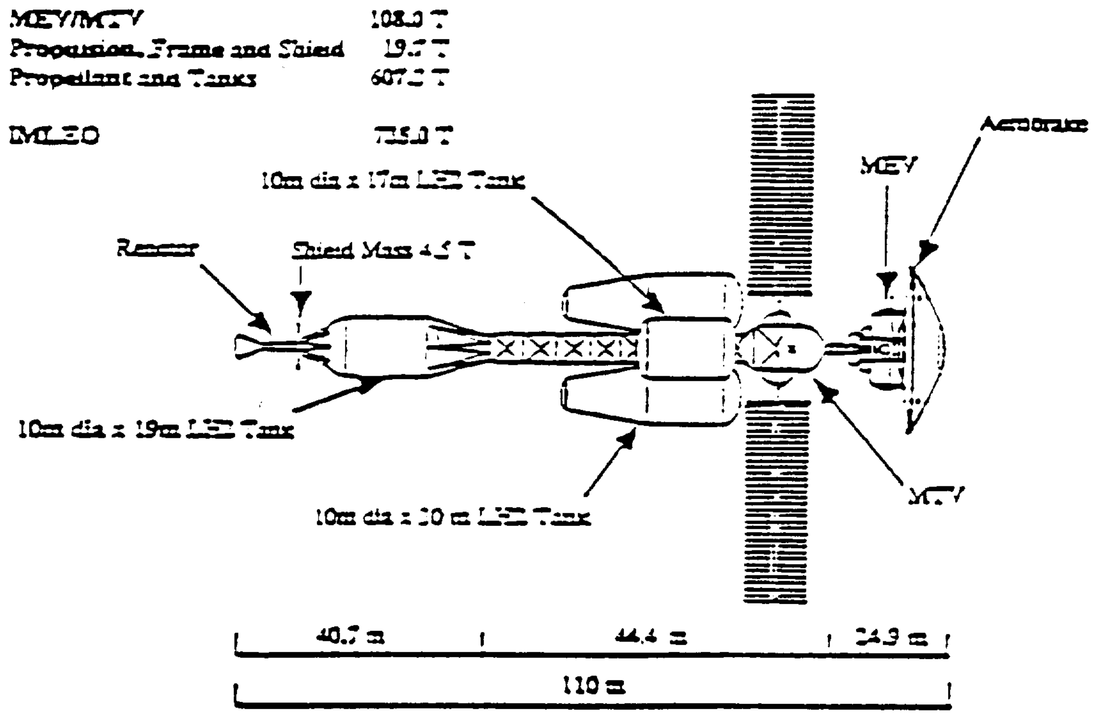


Figure 2-1 Reference Boeing NTR Vehicle

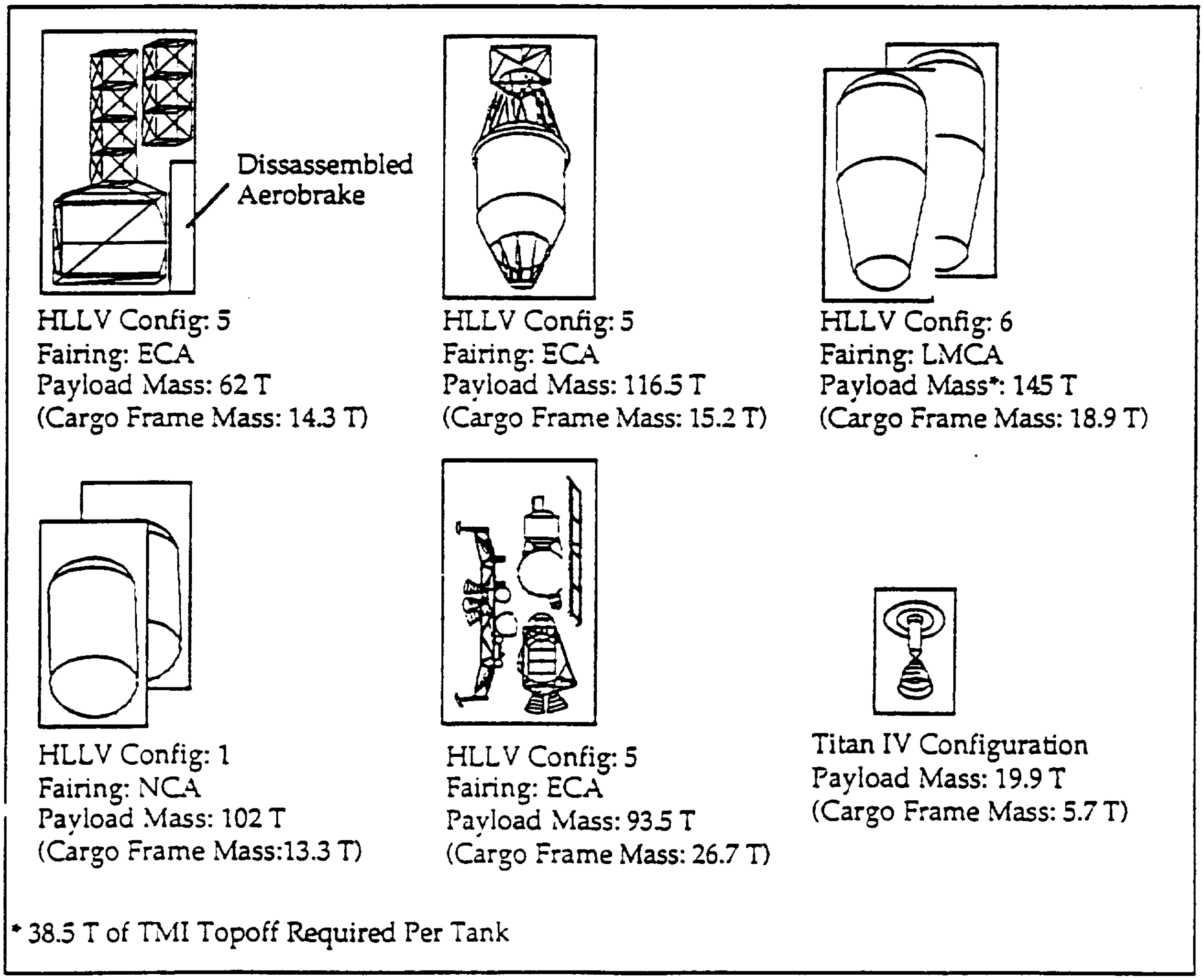


Figure 3-5 Initial HLLV Cargo Delivery Manifests

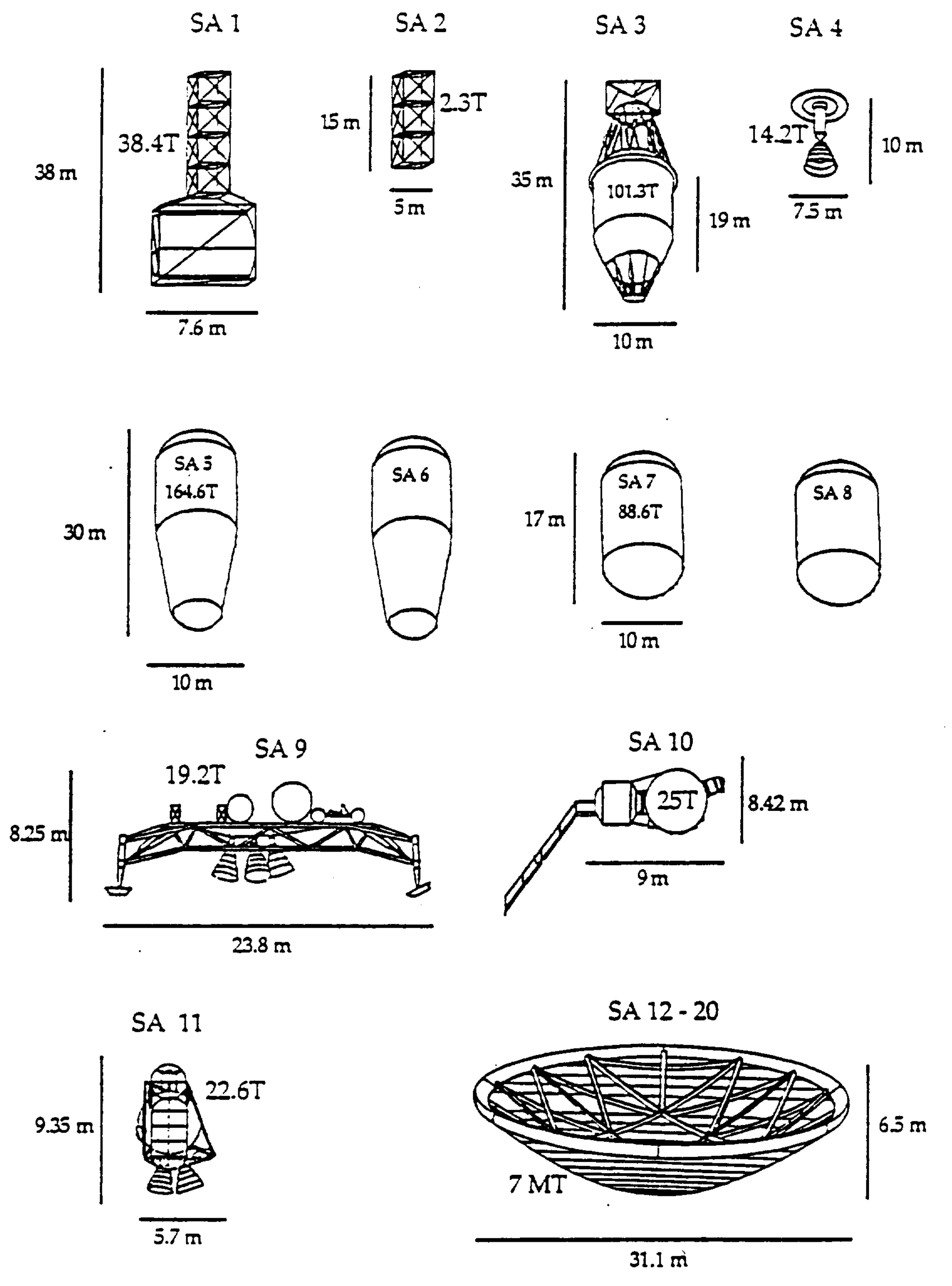


Figure 3-6 Subassemblies for Delivery to Low-Earth Orbit

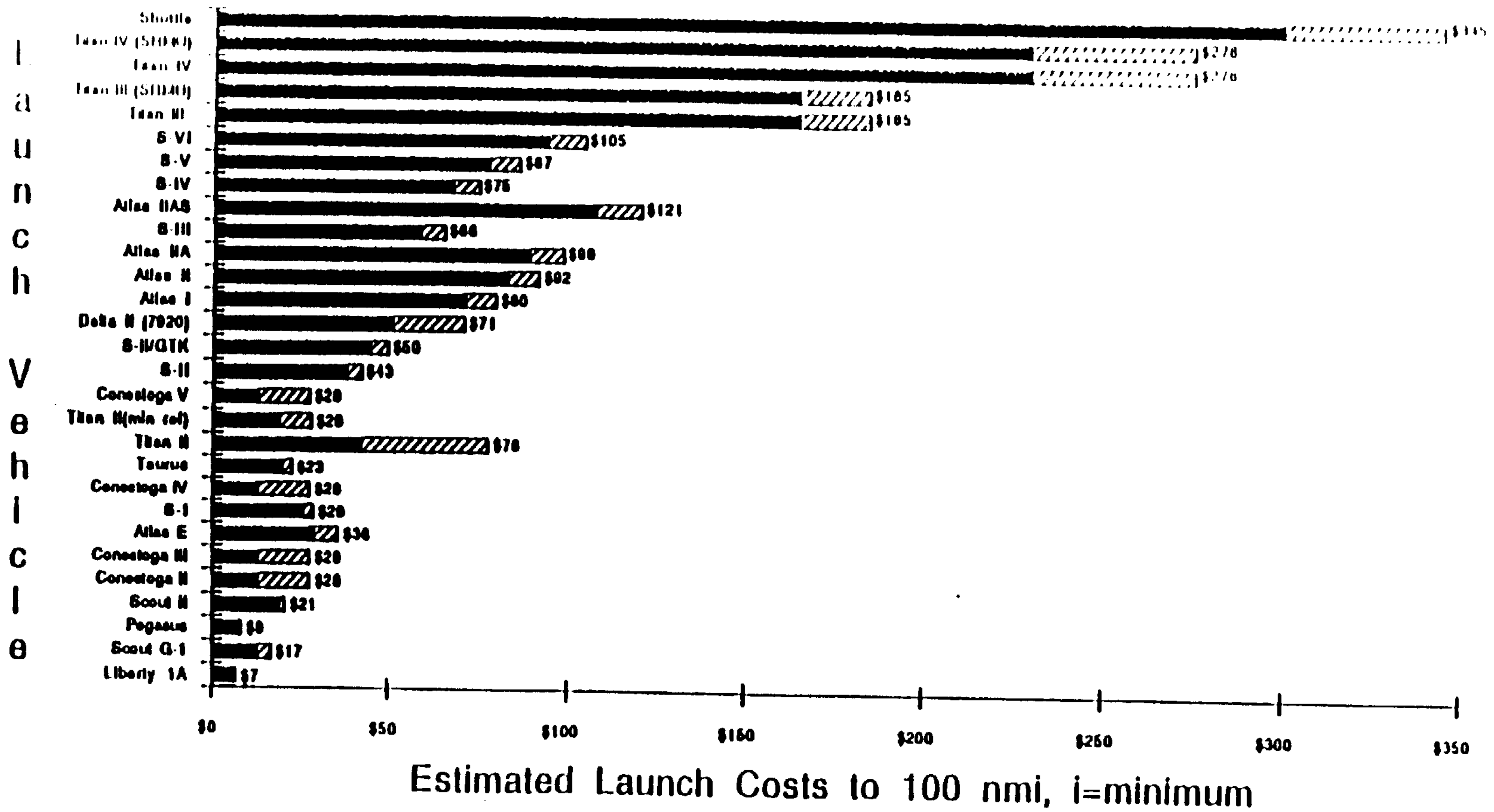
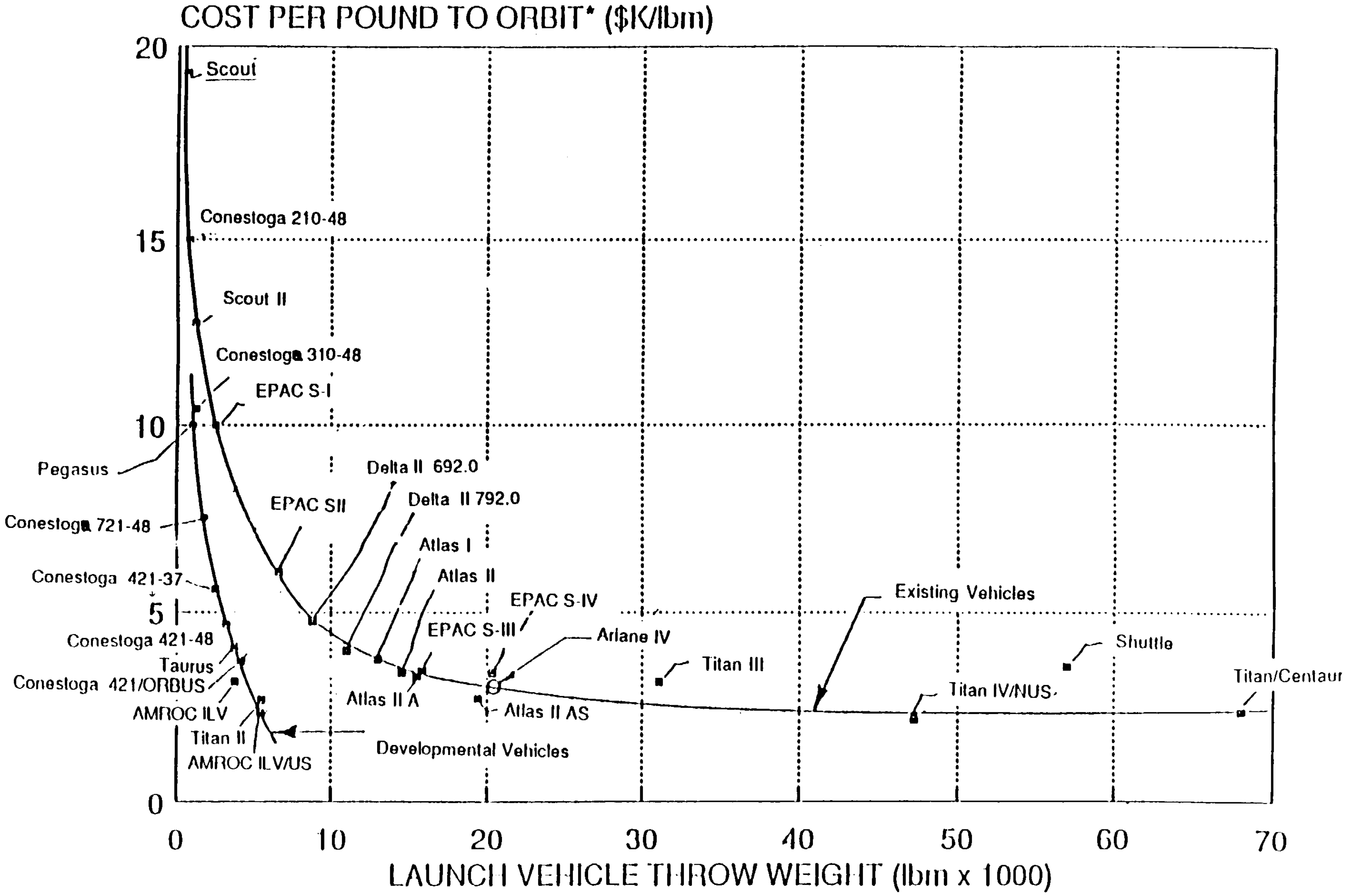


Figure 1 Launch Costs in Order of Performance (U.S. Launch Vehicles)

From Reference 10.

Figure 3

U.S. LAUNCH VEHICLES

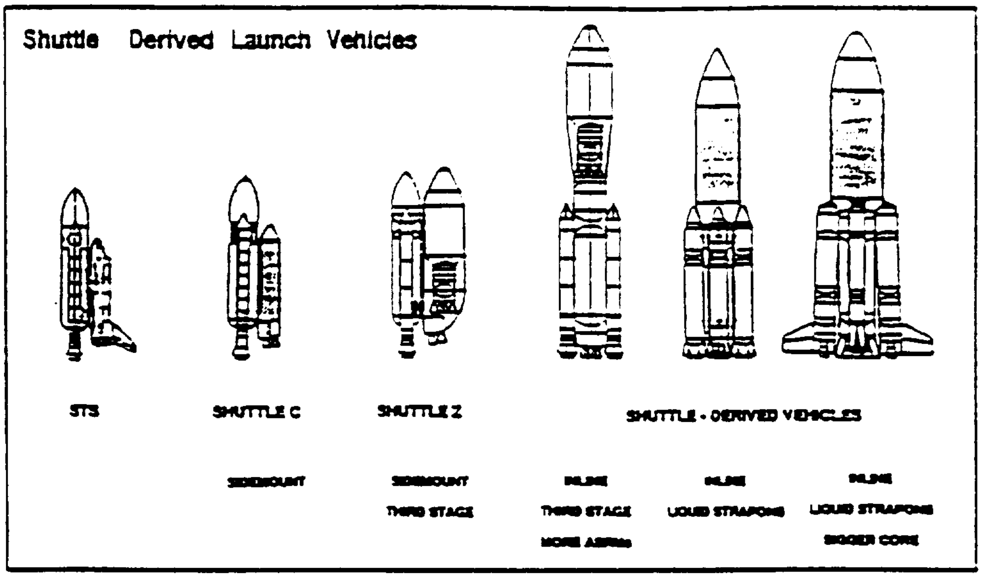


* REF ORBIT: 100 n.mi. CIRC @ 28.5 deg

From Reference 10.

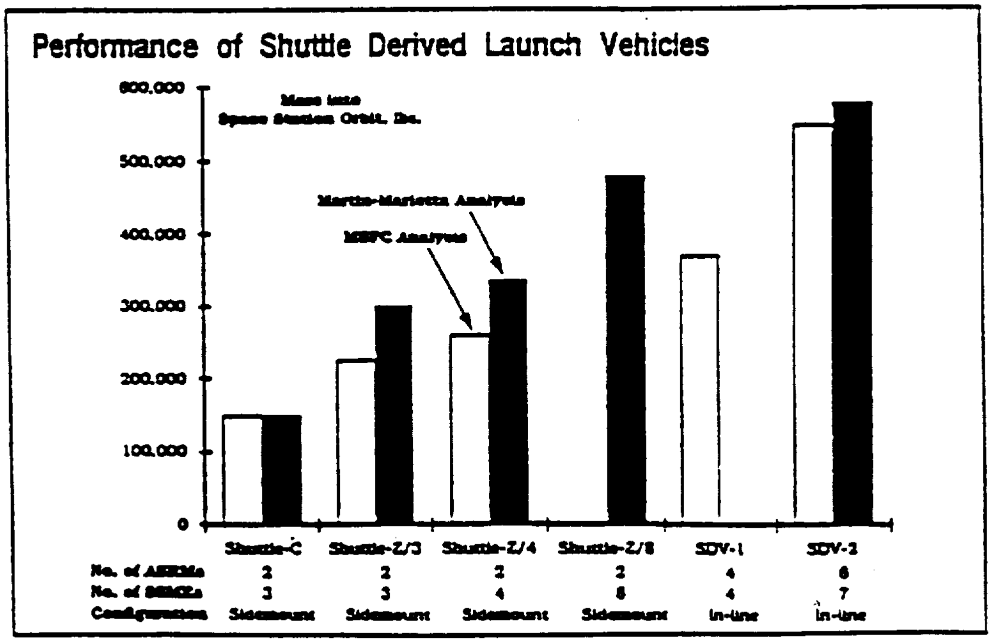
Shuttle C Performance

Figure 5



SPACEFLIGHT, Vol. 31, September 1989

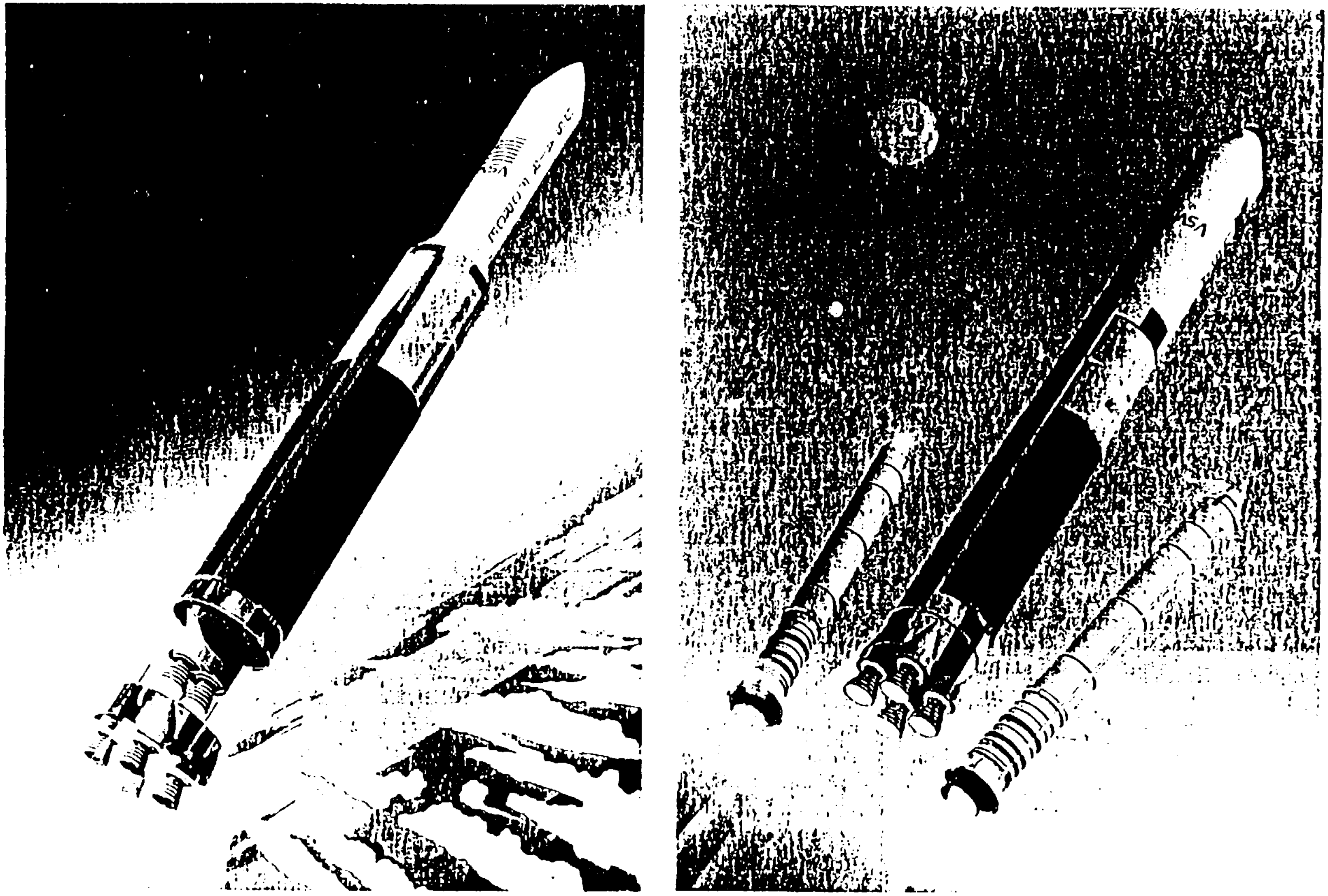
Figure 6



SPACEFLIGHT, Vol. 31, September 1989

From Reference 10.

NLS - SHUTTLE E.T. CORE



These are two configurations envisioned for the National Launch System that use the Martin Marietta space shuttle external tank as the vehicle core. Concept at left is of the One and One-Half Stage Vehicle and at right is the concept for the Heavy-Lift Launch Vehicle.

AVIATION WEEK & SPACE TECHNOLOGY/August 26, 1991

Table 1. Vehicle Cost Performance (Thousands of 1990 dollars)

Vehicle	Cost (Millions)	Pounds to LEO	Kg to LEO	Cost/Kg (thousands)
Scout	17	574	261	65.13
Conestoga	28	1397	635	44.09
Scout II	21	1184	538	39.03
EPAC S-I	29	2499	1136	25.53
EPAC S-II	43	6600	3000	14.33
Delta II 6920	42	8700	3955	10.62
Delta II 7920	71	11086	5039	14.09
Atlas I	80	12980	5900	13.56
Atlas II	92	14916	6780	13.57
EPAC S-3	66	15862	7210	9.15
EPAC S-4	75	20328	9240	8.12
EPAC S-5	87	24640	11200	7.77
EPAC S-6	105	29920	13600	7.72
Atlas IIa	99	15664	7120	13.90
Atlas IIas	121	18942	8610	14.05
Ariane IV	65	20500	9318	6.98
Titan III	185	32432	14742	12.55
Titan IV	276	46900	21318	12.95
Shuttle C	240	150000	68182	3.52
Shuttle Z	343	250000	113636	3.02
Titan IV/Cent	276	68000	30909	8.93
Saturn V	600	308000	140000	4.29

Shuttle 1	345	54386	24721	13.96
Shuttle 2	200	54386	24721	8.09
Shuttle 3	345	303600	138000	2.50
Shuttle 4	200	303600	138000	1.45

Note: There are four Shuttle data entries here because the Shuttle is the only one of these launch vehicles whose payload compartment, the Orbiter, is recoverable and reusable. This makes it difficult to compare it with expendable launch vehicles. Saturn V data are from Ref. 11.

Shuttle 1 this is the data entry for the standard Shuttle from Ref. 10.

Shuttle 2 this entry shows a reduction of the cost of the Shuttle "launch vehicle" by an estimate of the cost of the Orbiter, which is assumed to be replaced by a fairing. The amortized cost used was the $4.1 billion Orbiter cost divided by a 28 launch utilization lifetime, i.e., approximately $145 million per launch, reducing the $345 million to $200 million per launch.

Shuttle 3 this entry keeps the $345 million cost per launch of the Shuttle but assumes that the Orbiter is replaced by a payload bay. The LEO delivery weight is thus (24,721 + 113,279) = 138,000 kg.

Shuttle 4 this entry shows a reduction of the per launch cost by $145 million and an increase of the payload delivered to LEO to 138,000 kg.

Figure 7 includes a "rectangle of uncertainty" with the Shuttle entries at the four corners.

Figure 7: Cost vs. Pounds to LEO (100 nmi @ 28.5 deg)

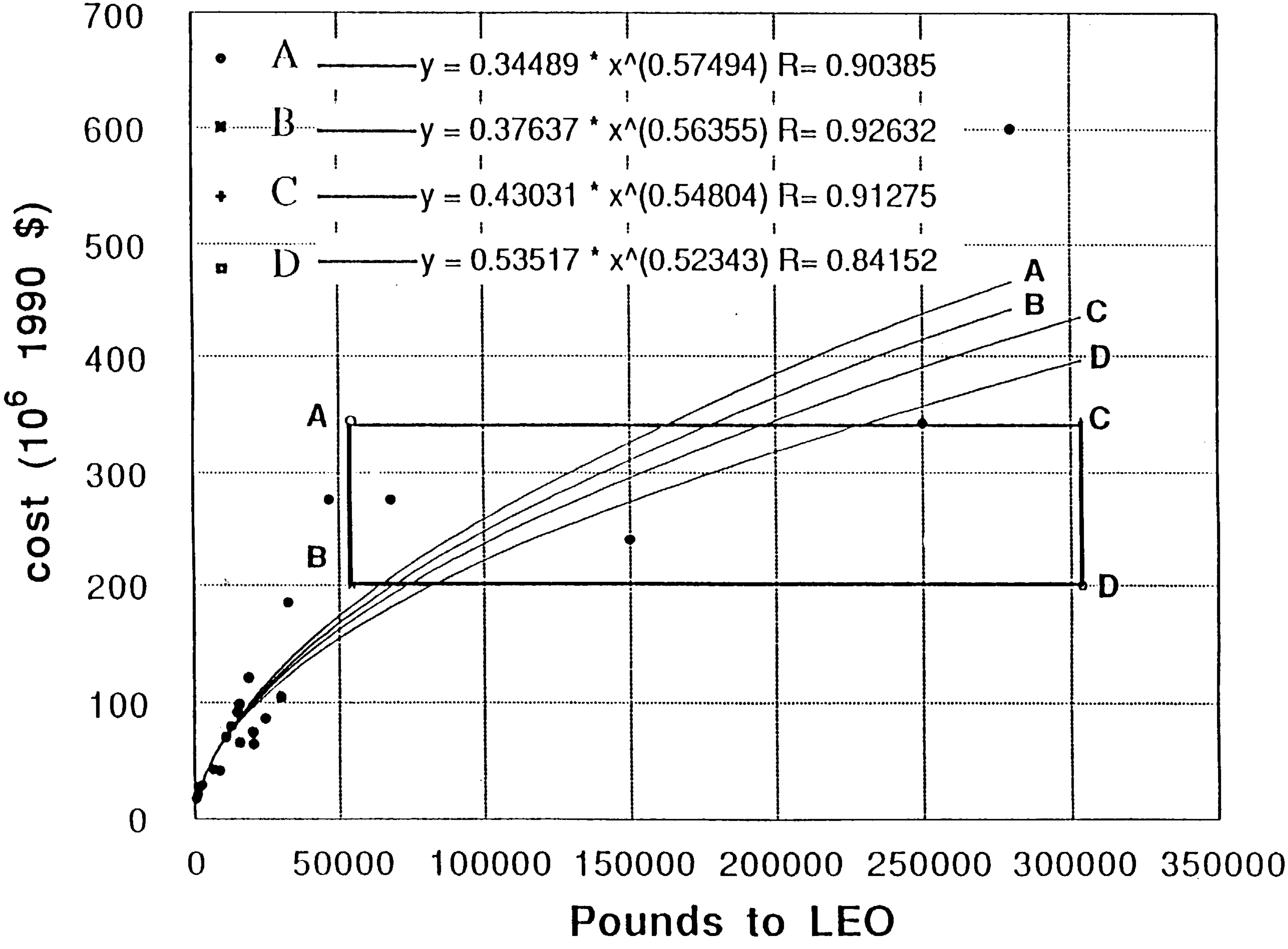


Figure 8: Cost/kg vs. kg to LEO

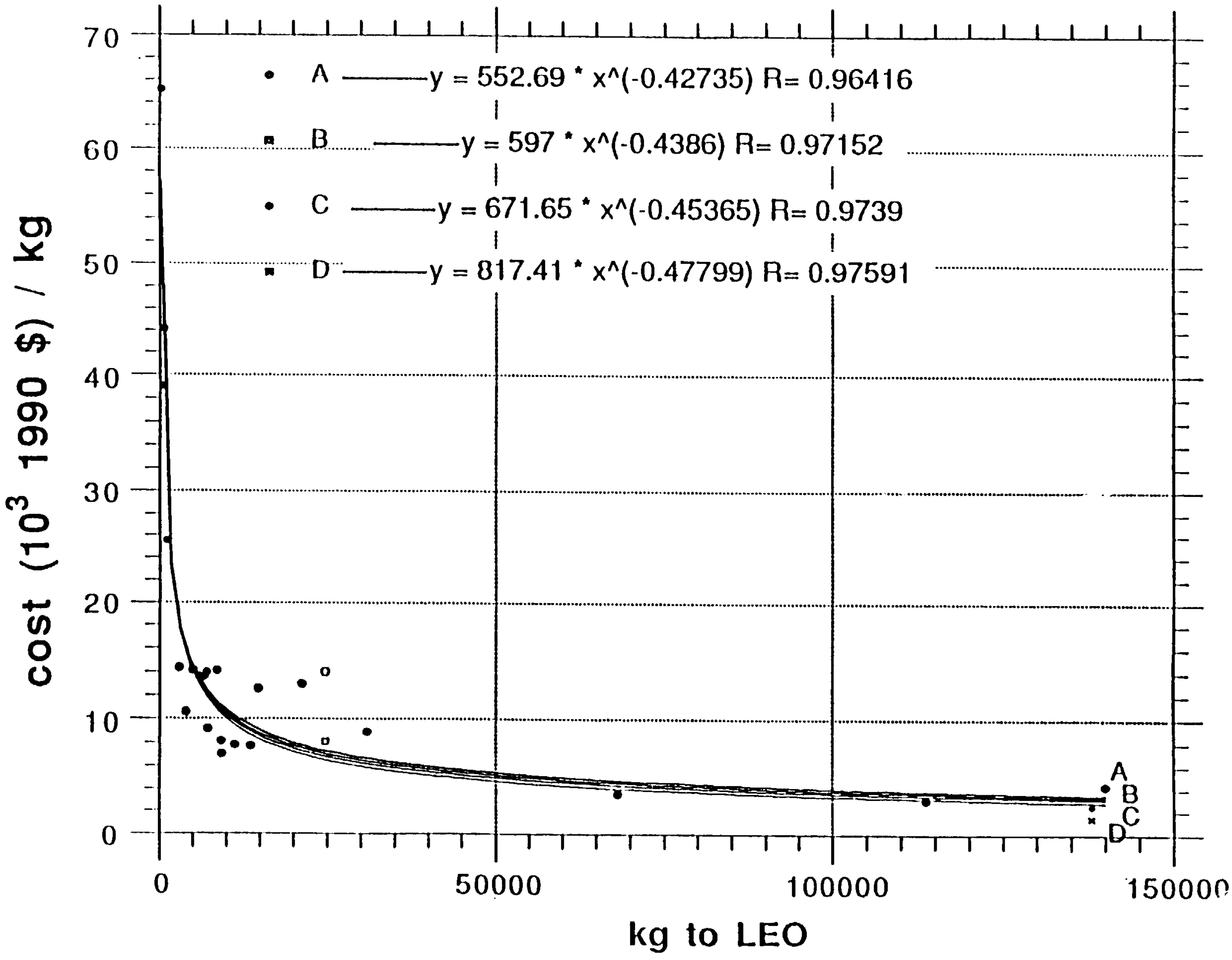
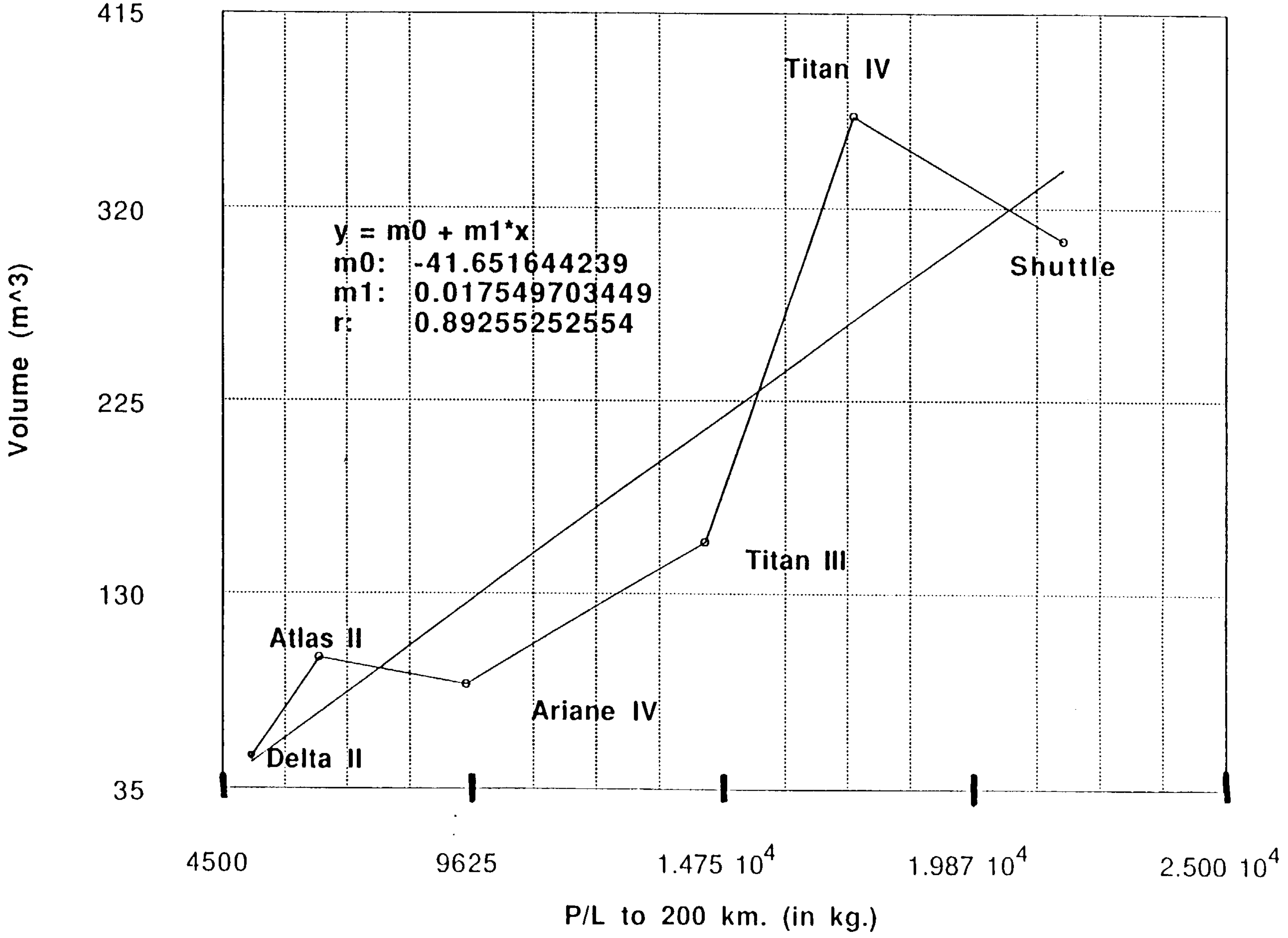


Figure 9: "Useful" Volume vs. Payload



NUMBER OF PAYLOADS NEEDED

$$N_L(w) = [W_o/w] + (1/2)\{1 + \mathrm{sgn}(W_o/w - [W_o/w])\}\, \mathrm{sgn}(W_o/w - [W_o/w])$$

$$N_V(w) = [V_o/V_H(w)] + (1/2)\{1 + \mathrm{sgn}(V_o/V_H(w) - [V_o/V_H(w)])\} \times \mathrm{sgn}(V_o/V_H(w) - [V_o/V_H(w)])$$

$$N(w) = \mathrm{Max}\,\{N_L(w), N_V(w)\}$$

LAUNCH VEHICLE RELIABILITY

Then the probability of a successful launch to LEO, i.e. not more than h units out of n failing, is

(12) $$P_n(n-h) = \sum_{j=0}^{h} (n!/(n-j)!j!)p^{n-j}q^j,$$

If we let r be the conditional probability that an engine fails catastrophically, given that it fails, then

(13) $$q = qr + q(1-r),$$

where $q(1-r)$ = probability of that an engine fails, but not catastrophically.

Hence,

(14) $$P_n(n) = p^n q^0 (1-r)^0 = p^n$$
$$P_n(n-1) = np^{n-1}q(1-r) + p^n$$
$$P_n(n-2) = (n(n-1)/2)p^{n-2}q^2(1-r)^2 + np^{n-1}q(1-r) + p^n.$$

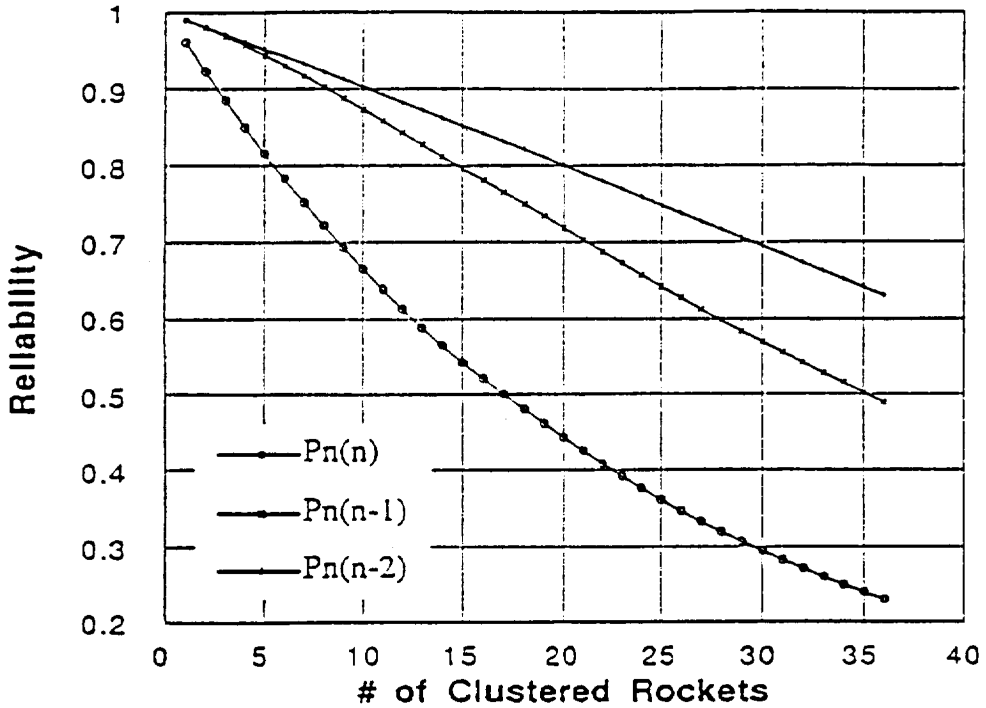


Figure 10. Launch Vehicle Reliability as a Function of Clustered Rockets (p = 0.96, r = 0.25)

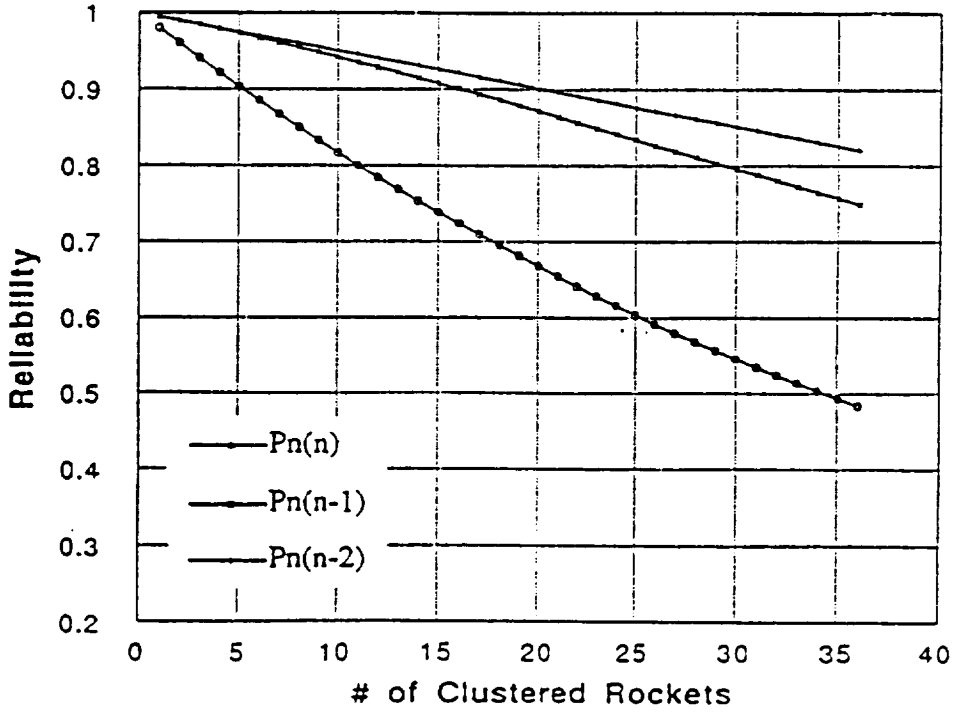


Figure 11. Launch Vehicle Reliability as a Function of Clustered Rockets (p = 0.98, r = 0.25)

MAKING THE LAUNCH WINDOW?

If $N = N(w)$ payload deliveries are needed to assemble the spacecraft and if time for up to j additional launches is included in the schedule to compensate for up to $(j - 1)$ launch failures, then, assuming no political launch hiatus after any failure,

$$P^* = P\begin{bmatrix}\text{make launch window}\\ \text{in } j \text{ extra launches}\end{bmatrix} = p^N + C_1^N p^N q + C_2^{N+1} p^N q^2 + \ldots + C_j^{N+j-1} p^N q^j$$

where

$$C_i^{N+i-1}\, p^N q^i = \frac{(N+i-1)(N+i-2)\ldots(N)}{i!} p^N q^i$$

is the negative binomial density which gives the probability that the Nth success is achieved precisely at the $(N + i)$th launch.

LIMITATIONS ON HLLV SIZE

1. Limitations on the usable size and shape of payload bays and the limited deployability of space structures;
2. Limitations on the size of propellant tankage domes (currently around 10 to 15 meters in diameter) that can be built with current methods of metal forming, spinning, welding, etc;
3. Limitations on the size of loads that can be transported by air, rail, truck, and barge;
4. Limitations on the size of facilities and handling ability of cranes, transports, and "strongbacks" at launch sites;
5. Limitations on the safety considerations for handling and launching very large quantities of cryogenic or hypergolic propellants, particularly with respect to the population living in the local abort zone;
6. Limitations on the reliability of HLLVs that are made of a large number of clustered tanks;
7. Limitations of cost and risk in concentrating too many resources in a single launch of the HLLV.

ORBITAL ASSEMBLY EXPECTED COST MODEL

$$C(w) = [\text{Expected Cost}] = \overbrace{N(w)C_H(w)/P_H(w)}^{\text{HLLV Costs}} + \overbrace{(SC)_{\$} + (SC)_{\$}/N(w)\left\{N(w)/P_H(w) - N(w)\right\}}^{\text{Spacecraft Costs}} \tag{15}$$

$$+ \overbrace{(N(w)-1)(k)(C_{\$c})}^{\text{Connection Costs}} + \overbrace{(N(w)-1)(C_s/P_s)}^{\text{Crew Transport Costs}} + \overbrace{(N(w)-1)C_{\$D}}^{\text{Docking Costs}} + \overbrace{\left\{1 + [N(w)/15]\right\}C_{\$F}}^{\text{Facility Costs}}$$

$$C^*(w) = \{\text{Expected cost including probability of missing one launch window}\} \tag{18}$$

$$= C(w)\,[1 + (1 - P^*)R],$$

where $C(w)$ is found in (15).

Table V: Parameter Values Used with Equations (15) and (18) for Figure 14.

HLLV Payload (lbs.)	h	N(w)	# Cluster	PH(w)	k	C$c	Ps	Cs ($10^6)	C$D ($10^6)	FH(w) ($10^9)	# Bases	P*	R	C*(w) calc ($10^9)	CH(w) list ($10^6)	C* list ($10^9)
$75 BILLION CASE																
1620000	2	1	36	0.82	100	0		0	0	2	1	.9676	0.5	96.3		
810000	2	2	18	0.91	100	100000	0.98	170	10	2	1	.9771	0.5	87.2		
550000	2	3	14	0.93	100	100000	0.98	170	10	2	1	.9733	0.5	86.1		
440000	2	4	10	0.95	100	100000	0.98	170	10	2	1	.9774	0.5	84.7		
330000	1	5	6	0.97	100	100000	0.98	170	10	2	1	.9875	0.5	82.9		
220000	1	8	5	0.98	100	100000	0.98	170	10	2	1	.9869	0.5	83.4		
110000	1	15	3	0.99	100	100000	0.98	170	10	2	1	.9891	0.5	84.7		
68000 Titan IV/Cent		24		0.98	100	100000	0.98	170	10	2	2	.9114	0.5	93.6	276	95.8
55000 Shuttle		30		0.98	100	100000	0.98	170	10	2	3	.8723	0.5	93.9	345	99.6
46900 Titan IV		35		0.98	100	100000	0.98	170	10	2	3	.8382	0.5	102.3	270	107
32432 Titan III		50		0.98	100	100000	0.98	170	10	2	4	.8220		109	185	112.2
$30 BILLION CASE																
1620000	2	1	36	0.82	100	0		0	0	2	1	.9676	0.5	96.3		
810000	2	2	18	0.91	100	100000	0.98	170	10	2	1	.9771	0.5	37.2		
550000	2	3	14	0.93	100	100000	0.98	170	10	2	1	.9733	0.5	37		
440000	2	4	10	0.95	100	100000	0.98	170	10	2	1	.9774	0.5	36.8		
330000	1	5	6	0.97	100	100000	0.98	170	10	2	1	.9875	0.5	36.3		
220000	1	8	5	0.98	100	100000	0.98	170	10	2	1	.9869	0.5	37.1		
110000	1	15	3	0.99	100	100000	0.98	170	10	2	1	.9891	0.5	38.9		
68000 Titan IV/Cent		24		0.98	100	100000	0.98	170	10	2	2	.9114	0.5	45.7	276	47.8
55000 Shuttle		30		0.98	100	100000	0.98	170	10	2	3	.8728	0.5	45.1	345	50.8
46900 Titan IV		35		0.98	100	100000	0.98	170	10	2	3	.8382	0.5	52.7	276	57.3
32432 Titan III		50		0.98				170	10	2	4	.8220	0.5	59.3	185	62.4

Figure 14: Total Expected Cost vs. LEO Payload Capability