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HYBRID DEVELOPMENT PLANNING MANUAL

MARCH 1968

Prepared under Contract No. NAS 1-7289
by Douglas Aircraft Company
Missile and Space Systems Division
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By M.B. ADAMS, P.H. BIALLA, and R.H. MICHAELIS

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CONTENTS

Section 1
INTRODUCTION

The usefulness of hybrid propulsion is, in most cases, strongly related to its cost effectiveness as compared with other types of propulsion systems. Although vehicle performance can usually be estimated with reasonable accuracy, system costs, which are of equal importance in cost-effectiveness comparisons, frequently cannot or are not accurately estimated. This document, then, aims to fulfill this need for cost data, because much less is known of the hybrid system than of solids and liquids.

This document presents parametric data which will enable the user to estimate the development cost, first-unit cost, and development schedule for hybrid propulsion systems. The propulsion-system-development program costs and schedules were evaluated for several types of subsystems over a large range of mission-imposed design criteria. These criteria, their ranges, and the subsystems, shown in Table 1-1, were selected to encompass the potential hybrid upper-stage mission requirements for the next decade.

The cost estimates reported in this manual are of a budgetary planning nature and are based on a propulsion-system development program that is initiated after mission analysis and propulsion-system definition have been completed. Further, the program is defined to conclude when the propulsion system has been developed to a status where it is available for integration into a flight-test program.

Table 1-1 (Page 1 of 2)

HYBRID PROPULSION SYSTEM DESIGN CRITERIA
AND CANDIDATE SUBSYSTEMS

	Design Criteria					
	Propulsion System Size	Propellant Selection	No. of Restarts	Throttle Ratio	Accel. Limits	Stay Time
Baseline selection	$W_p = 3,200$	FLOX/HFX 2086	0	1:1	10g	0 Day
Range	$3,200 \leq W_p \leq 50,000$	Cryogenic or storable oxidizers	0 - 10	1:1 - 15:1	0g - 30g	0 to 500 Days

Table 1-1 (Page 2 of 2)

System	Candidate Subsystems: Subsystem Class	Baseline Selection	Alternates
Oxidizer feed system	Tankage	Single sphere	Cylinder Torus Sphere cluster
	Expulsion system	Heated helium	Ambient helium Solid charge augmented helium Gas generator augmented helium Turbopump
	Propellant settling	Ullage rockets	Screen Positive expulsion
	Insulation	None	NRC-2 Dimplar
Fuel system	Combustion chamber	Fiber glass	High-strength steel Titanium
	Fuel grain	Compression molded	Castable
	Injection system	Head end injection	Head + aft end injection Head end injection + turbulator
	Nozzle	Ablative	None
Airframe	Thrust structure	Skin and stringer	Sandwich
	Tank support	Cone	Multiple A-frame
	Payload support	Skin and stringer	Sandwich Truss
	Interstage adaptor	Skin and stringer	Sandwich Truss
Control system	Thrust vector control	Hydrazine reaction control	Bipropellant RCS Gimballed nozzle N_2O_4 secondary injection Oxidizer secondary injection

To formulate this manual, detailed development costs and schedules were first prepared for a specific (baseline) hybrid propulsion system then broadened to accommodate a variety of potential hybrid design concepts and mission criteria. The characteristics of the baseline propulsion system* are shown in Table 1-1, under Baseline Selection, and are further described in Section 3. These estimates were used as a point of departure in evaluating the effects of the design criteria on the development program. Separate detailed cost estimates were also prepared for each of the alternate subsystems. In Section 2, instructions are presented in use of the manual. This is followed by a definition of the subsystem options available and the data needed to estimate development and unit costs. Methodology and data for formulation of the development schedule are then shown.

It should be understood that although design optimization and costs are closely coupled in cost-effectiveness analyses, no such attempt to do so has been made here. Cost and schedule data are presented without the inference that specific subsystems be included in a development program. Rather, it is assumed that the potential user will be in a better position to make selections based upon his understanding of his design and program requirements.

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*The detailed development cost and schedule estimates for the baseline propulsion system are reported in: M. B. Adams, P. H. Bialla, and R. H. Michaelis. Development Requirements for a High-Energy Hybrid Propulsion System. Douglas Report No. DAC-58080, Douglas Aircraft Company, March 1968.

Section 2
INSTRUCTIONS AND GUIDELINES

2.1 GENERAL

The approach taken to estimate propulsion-system development costs is structured around a baseline stage from which perturbations can be made to reflect desired subsystem changes or variations in design criteria. The method is general enough to allow cost estimates to be made of a hybrid propulsion system that bears little or no resemblance to the baseline. Consequently, the baseline serves more as a starting point for cost analysis than as a model which possesses characteristics in common with the particular system of interest.

To illustrate the basis of this approach, development costs are shown to be divided into three major levels of effort in Figure 2-1. The lowest level is the subsystem, as exemplified by the tankage in the figure. All subsystems are subsequently integrated into the next higher level, system development, and continuing with the example, this would be the feed system. A total of four major systems constitute the stage; these systems are the feed system, fuel system, thrust vector control system, and structure. The final level is overall propulsion system integration or all-systems testing. Total development costs are, in essence, the sum of each of these levels of development.

Within the framework of this approach are provisions for alternate subsystems and design criteria. Alternate subsystems are directly substituted for equivalent baseline subsystems on the subsystem development level. The influence of alternate design criteria, which include the effects of system size, expressed in terms of propellant weight, is felt on all levels.

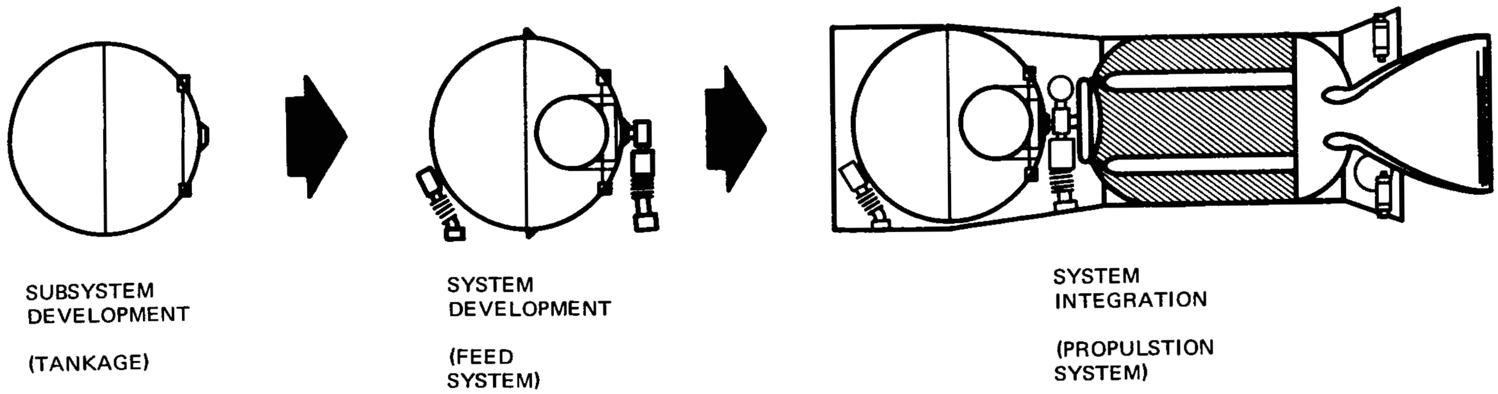


Figure 2-1 Stage Development Progression

Data sheets are provided in an envelope at the back of this manual. These sheets, together with the information in the following sections, will enable the user to estimate hybrid propulsion-system development costs.

Data Sheet No. 1 is simply a reference sheet which summarizes the system requirements of the propulsion system of interest. Subsystem selections must be made from among those listed in Table 1-1, but can be either baseline or alternates, as desired. Drawings or schematics of all candidate subsystems are presented in Section 3. Design criteria and size should be within the range of those in Table 1-1, although, if not, the cost data provided can generally be extrapolated to some extent.

Data Sheet No. 2 is a summary sheet for subsystem development costs. Subsystem cost data appear in Section 3. In the Development Cost column on the data sheet should be entered the value for the appropriate propellant weight and subsystem from the large curve on the left side of Figures 3-1 through 3-14 in Section 3. This value represents development costs of each subsystem for the baseline design criteria. The right sides of the figures represent the effects of alternate design criteria expressed as functions of the baseline design criteria. The value for subsystem Unit Costs are obtained from Figures 3-15 through 3-28 in Section 3 and are independent of design criteria.

Data sheet No. 3 is a summary sheet for system development costs. Only feed system and fuel system development costs are shown; the two other major systems, thrust vector control and structure, are treated on the subsystem level. As seen on the data sheet, system development costs are the sum of hardware, special test equipment, test operations, and design engineering costs.

Hardware costs are a function of the number of singular tests and commonality tests as defined in Section 4. For the feed system, the total number of sets of hardware, N_{sets}, is one; for the fuel system, N_{sets} is the sum of the commonality tests divided by f, a reusability factor, plus the singular tests. The cost of a single hardware set, C_{set}, is the sum of the unit costs of its subsystems. This sum will have already been tabulated on Data Sheet No. 2.

Special test equipment costs are a function of subsystem complexity and the special test equipment for the baseline system, $C_{STE\ B/L}$, which is shown in Figure 4-3. Subsystem complexity is expressed in terms of complexity factors, f_1, in Table 4-1.

Test operations costs are obtained similarly. Baseline system test operations cost rates, $\dot{c}_{T.O.\ B/L}$, are shown in Figure 4-4 of Section 4. The effects of subsystem alternates are expressed as factors, f_2, found in Table 4-1 of Section 4. Another factor, k, reflects the type of oxidizer selected, cryogenic or storable. The remaining terms show the effects of the test program on schedule, and total test operations costs, $C_{T.O.}$, are obtained from the equation shown on the data sheet.

Design engineering costs, C_{DE}, and subcontractor management costs, C_{SM}, are determined from the equations in the data sheet; total system development costs are then obtained by addition of the elemental costs.

Data Sheet No. 4 is a summary sheet which combines system integration, or all-system test costs with all other development costs previously defined to yield total development program costs. All system test hardware costs are obtained from the Unit Cost column of Data Sheet No. 2. All system test operations costs, are based upon those of a baseline rate, $\dot{c}_{T.O.\ B/L}$. The system complexity factors, $\Pi(f_3)$, are products of the subsystem factors which comprise the system of interest and are found in Table 4-1 of Section 4. The appropriate oxidizer k-factor is then noted and an expression, $W_p^{0.14}$, calculated to account for system complexity arising from system size. All-system test-program length, L, in months, is found as a function of system size in Figure 4-5 (Section 4). Test operations costs are then found from the equation in the data sheet.

Aerospace ground equipment (AGE) costs are obtained by factoring the baseline AGE costs, $C_{AGE\ B/L}$, shown in Figure 4-6 (Section 4). The AGE complexity factors, f_4, are found in Table 4-1 of Section 4 and total AGE costs are simply the product of all f_4 factors and $C_{AGE\ B/L}$. System design engineering costs (C_{SDE}) are found similarly. System integration costs then represent the sum of $C_{hardware}$, $C_{T.O.}$, C_{AGE}, and C_{SDE}.

The following paragraphs present instructions in the use of the data sheets, as well as a sample cost analysis.

2.2 DATA SHEET INSTRUCTIONS

The following instructions are keyed by number to the appropriate blanks in subsequent sheets. Blank data sheets are contained in the envelope at the back of this manual.

(1) See Table 1-1 for candidate subsystems and design criteria.

(2) See curves on left side of Figures 3-1 through 3-5 in Section 3.

(3) See curves on left side of Figures 3-6 through 3-8 in Section 3. If the TVC system selected is monopropellant hydrazine or bipropellant liquid, use Figure 3-9 (Section 3) for Nozzle/TVC; if the TVC system is gimballed nozzle or secondary injection, use Figure 3-10 in the same section.

(4) See curves on left side of Figures 3-11 through 3-14 in Section 3.

(5) If the TVC system selected is monopropellant hydrazine or bipropellant liquid, use lefthand curves of Figure 3-10 of Section 3. If the TVC system is gimballed nozzle or secondary injection, leave this entry blank.

(6) For the selected design criteria and each subsystem of interest, add the additional development costs under item A and curves B, C, D, and E of Figures 3-1 through 3-14 of Section 3. This represents a cost increment to be added to the development costs of a system designed to the baseline criteria ((2), (3), (4), and (5)). To make the mathematics workable, divide this sum by 100 (to obtain its functional equivalent) then add 1.00.

(7) (2) x (6)

(8) (3) x (6)

(9) (4) x (6)

(10) (5) x (6)

(11) See Figures 3-15 through 3-28 of Section 3; select unit costs for selected subsystems at appropriate propellant weight. Select entries for nozzle and thrust vector control in same manner as explained under (3) and (5).

(12) See Figure 4-1 of Section 4. Add the baseline test requirements, $N_T = 4$, to the total number of integration tests required to satisfy the selected design criteria.

(13) Enter subtotal of feed system unit costs from Block (11), Data Sheet No. 2.

(14) Enter value of Block (13).

(15) See Figure 4-2 of Section 4. Add the baseline test requirements, $N_T = 10$, to the total number of singular integration tests, found by taking the difference between the clear curves and the cross-hatched curves.

(16) See Figure 4-2 of Section 4. Find the total of the commonality tests from the cross-hatched curves in the figure.

(17) Divide the commonality tests, (16), by 2; round off the result to the next higher whole number.

(18) (15) + (17)

(19) Enter subtotal of fuel system unit costs from Block (11), Data Sheet No. 2.

(20) (18) x (19)

(21) (14) + (20)

(22) See Figure 4-3 of Section 4.

(23) See Table 4-1 of Section 4. Enter the factors for the appropriate subsystems from Column f_1.

(24) Enter the product of the four values of (23)

(25) (22) x (24)

(26) Enter the product of the four values of (23)

(27) (22) x (26)

(28) (25) + (27)

(29) See Figure 4-4 of Section 4.

(30) See Table 4-1 of Section 4. Enter the factors for the appropriate subsystems from column f_2 .

(31) Enter the product of the four values of (30)

(32) Enter 0.92 or 1.0, in accordance with the type of oxidizer selected.

(33) Enter the value from Block (12) - 4.

(34) (33) x 0.2

(35) 6.0 + (34)

(36) (29) x (31) x (32) x (35)

(37) See Figure 4-4 of Section 4.

(38) Enter the value from Block (18) - 10.

(39) Enter the value from Block (38)

(40) 15.0 + (39)

(41) (37) x (31) x (40)

(42) (36) + (41)

(43) Solve the equation shown on the data sheet.

(44) Enter the value from Block (43)

(45) Solve the equation shown on the data sheet.

(46) Solve the equation shown on the data sheet.

(47) (45) + (46)

(48) (44) + (47)

(49) (14) + (25) + (36) + (44)

(50) (20) + (27) + (41) + (47)

(51) (49) + (50)

(52) Enter value from Block (13) , Data Sheet No. 3.

(53) 2 x (19)

(54) If TVC system selected is hydrazine or bipropellant RCS, enter TVC system subtotal from Block (11) , Data Sheet No. 2. If TVC system is gimballed nozzle or secondary injection, leave this item blank.

(55) Enter airframe subtotal from Block (11) , Data Sheet No. 2.

(56) (52) + (53) + (54) + (55)

(57) See Table 4-1 of Section 4. Enter product of appropriate factors under column f_3 for tankage, expulsion system, propellant-settling system, and insulation.

(58) See Table 4-1 of Section 4. Enter product of appropriate factors under column f_3 for combustion chamber, injection system, and nozzle.

(59) See Table 4-1 of Section 4. Enter the f_3 factor for TVC.

(60) See Table 4-1 of Section 4. Enter 1.00 in block.

(61) (56) x (57) x (58) x (59)

(62) Enter 0.96 or 1.00, in accordance with type of oxidizer selected.

(63) Solve expression in data sheet.

(64) See Figure 4-5 of Section 4.

(65) 27,000 x (61) x (62) x (63) x (64)

(66) See Figure 4-6 of Section 4.

(67) See Table 4-1 of Section 4. Enter product of appropriate factors under column f_4 for tankage, expulsion system, propellant-settling system, and insulation.

(68) See Table 4-1 of Section 4. Enter product of appropriate factors under column f_4 for combustion chamber, injection system, and nozzle.

(69) See Table 4-1 of Section 4. Enter the f_4 factor for TVC.

(70) See Table 4-1 of Section 4. Enter 1.00 in block.

(71) (67) x (68) x (69) x (70)

(72) (66) x (71)

(73) Enter the product of values of Block (6), Data Sheet No. 2, for tankage, expulsion system, propellant-settling system, insulation, and fill, feed and vent system.

(74) Enter the product of values of Block (6), Data Sheet No. 2, for combustion chamber, fuel grain, injection system, and nozzle/TVC.

(75) Enter value of Block (6), Data Sheet No. 2, for thrust vector control system.

(76) Enter product of values of Block (6), Data Sheet No. 2, for thrust structure, tank support, payload support, and interstage adaptor.

(77) (73) x (74) x (75) x (76)

(78) 519,000 x (77)

(79) (56) + (65) + (72) + (78)

(80) (7) + (8) + (9) + (10)

(81) 1.15 x (80)

(82) Enter value from Block (51)

(83) 1.15 x (82)

(84) (79) + (81) + (83)

(85) 0.06 x (84)

(86) 0.16 x (84)

(87) (84) + (85) + (86)

(88) 1.10 x (87)

DATA SHEET NO. 1
SYSTEM REQUIREMENTS

Size	Subsystem Selection	Design Criteria
W_p = ___(1)___ lb.	Tankage: ___(1)___	Type of oxidizer: ___(1)___
	Expulsion system: ______	Number of restarts: ______
	Propellant-settling system: ______	Throttle ratio: ______
	Insulation: ______	Max. acceleration: ______
	Combustion chamber: ______	Stay time: ______
	Fuel-grain type: ______	
	Injection system: ______	
	Nozzle: Ablative	
	Thrust structure: ______	
	Tank support: ______	
	Payload support: ______	
	Interstage adaptor: ______	
	Thrust vector control: ______	

DATA SHEET NO. 2

SUBSYSTEM COST SUMMARY

System	Subsystem	Development Cost (Baseline Criteria)	Total Additional Development Cost x 10^{-2} + 1.00	Total Development Cost	Unit Cost
Feed system	Tankage Expulsion system Propellant-settling system Fill, feed, and vent system Insulation	(2)	(6)	(7)	(11)
Subtotal					
Fuel system	Combustion chamber Fuel grain Injection system Nozzle/TVC*	(3)	(6)	(8)	(11)
Subtotal					
Air-frame	Thrust structure Tank support Payload support Interstage adapter	(4)	(6)	(9)	(11)
Subtotal					
Control system	Thrust vector control*	(5)	(6)	(10)	(11)
Total					

*Enter TVC Subsystem under Fuel System, in place of nozzle, if gimballed nozzle or secondary injection alternates are selected. If either hydrazine or bipropellant RCS is selected, enter under Control System.

DATA SHEET NO. 3
SYSTEM DEVELOPMENT COST SUMMARY

System	Hardware Costs		Special Test Equipment Costs			Test Operations Costs						Engineering and Subcontrac or Management		Total
Feed system	$N_{commonality\ tests}$	(12)	$C_{STE\ B/L}$		(22)	$\dot{c}_{T.O.\ B/L}$		(29)	k {Storable = 0.92; Cryogenic = 1.0}		(32)			
	f	☒	f_1	Tankage	(23)	f_2	Tankage	(30)	$L_{B/L}$		6.0	$C_{DE} = 92,300\ W_P^{0.05}$		
	$\frac{N_{commonality\ tests}}{f}$	1		Expulsion system	(23)		Expulsion system	(30)	N_{tests}	(33)	ΔL (34)			
				Prop.-settling system	(23)		Prop.-settling system	(30)	k_1 (test)	0.2		C_{DE}	(43)	
	N_{sets}	1		Insulation	(23)		Insulation	(30)						
	C_{set}	(13)	$\Pi\ f_1$		(24)	$\Pi(f_2)$		(31)	$L_{B/L} + \Delta L$		(35)	C_{SM}	0	
	$C_{hardware}$	(14)	C_{STE}		(25)	$C_{T.O.} = \Pi(f_2)\ k\ \dot{c}_{T.O.\ B/L}(L_{B/L} + \Delta L)$					(36)	$C_{E\&SM}$	(44)	(49)
Fuel system	$N_{singular\ tests}$	(15)	$C_{STE\ B/L}$		(22)	$c_{T.O.\ B/L}$		(37)	k		1.0			
	$N_{commonality\ tests}$	(16)	f_1	TCA	(23)	f_2	TCA	(30)	$L_{B/L}$		15.0	$C_{DE} = 142,000\ W_P^{0.05}$		
	f	2		Fuel grain and Insulation	(23)		Fuel grain and Insulation	1.0	N_{Tests}	(38)	ΔL (39)	$C_{SM} = 46,700\ W_P^{0.25}$		
	$\frac{N_{commonality\ tests}}{f}$	(17)		Injection system	(23)		Injection system	(30)	k_1 (Test)	1.0				
	N_{sets}	(18)		Nozzle/TVC*	(23)		Nozzle/TVC*	(30)				C_{DE}	(45)	
	C_{set}	(19)	$\Pi\ f_1$		(26)	$\Pi(f_2)$		(31)	$L_{B/L} + \Delta L$		(40)	C_{SM}	(46)	
	$C_{hardware}$	(20)	C_{STE}		(27)	$C_{T.O.} = \Pi(f_2)\ k\ \dot{c}_{T.O.\ B/L}(L_{B/L} + \Delta L)$					(41)	$C_{E\&SM}$	(47)	(50)
Total	$C_{hardware}$	(21)	C_{STE}		(28)	$C_{T.O.}$					(42)	$C_{E\&SM}$	(48)	(51)

*If gimballed nozzle or secondary injection are used for TVC, enter their f_1 and f_2 values in place of nozzle entry.

DATA SHEET NO. 4
SYSTEM INTEGRATION AND TOTAL COST SUMMARY

All-System Test Hardware Costs		All-System Test Operations Costs					AGE Costs			System Design Engineering Costs			Subtotal
Feed system	(52)	$\hat{c}_{T.O.\ B/L}$	27,000		k $\begin{vmatrix} \text{Storable} = 0.96 \\ \text{Cryogenics} = 1.00 \end{vmatrix}$	(62)	$C_{AGE\ B/L}$		(66)	$C_{SDE\ B/L}$	519,000		
Fuel system x 2	(53)	$\Pi(f_3)$	Feed system	(57)	$W_P^{0.14}$	(63)	$\Pi(f_4)$	Feed System	(67)	$\frac{C_{Dev}}{C_{Dev\ B/L}}$	Feed system	(73)	
TVC system*	(54)		Fuel system	(58)				Fuel system	(68)		Fuel system	(74)	
			TVC system	(59)				TVC system	(69)		TVC system	(75)	
Structure	(55)		Structure	(60)	L	(64)		Structure	(70)		Structure	(76)	
		$\Pi(f_3)$		(61)			$\Pi(f_4)$		(71)	$\Pi(C_{Dev}/C_{Dev\ B/L})$		(77)	
$C_{Hardware}$	(56)	$C_{T.O.} = \Pi(f_3)\ \hat{c}_{T.O.\ B/L}\ k\ W_P^{0.14}\ L$				(65)	$C_{AGE} = \Pi f_4 C_{AGE\ B/L}$		(72)	C_{SDE}		(78)	(79)

			(79)
System integration costs	(80)	x1.15	(81)
Subsystem development costs (See Data Sheet No. 2)	(82)	x1.15	(83)
System development costs (See Data Sheet No. 3)			(84)
SUM_1 = System integration + system development + subsystem development			(85)
System engineering: $C_{S.E.} = 0.06 \times SUM_1$			(86)
Program management: $C_{P.M.} = 0.16 \times SUM_1$			(87)
Development program costs (less contractor fee): $C_{Dev} = SUM_1 + C_{S.E.} + C_{P.M.}$			(88)
Total program costs: 1.10 x Development program costs			

*Enter TVC system costs only if the hydrazine RCS or the bipropellant RCS system is selected.

DATA SHEET NO. 1
SYSTEM REQUIREMENTS

Size	Subsystem Selection	Design Criteria
W_p = 10,000 lb.	Tankage: Torus	Type of oxidizer: Storable
	Expulsion system: Ambient He	Number of restarts: 2
	Propellant-settling system: Ullage Rockets	Throttle ratio: 5:1
	Insulation: None	Max. acceleration: 5g
	Combustion chamber: Steel	Stay time: 100 days
	Fuel-grain type: Castable	
	Injection system: Head & Aft End	
	Nozzle: Ablative	
	Thrust structure: Skin/Stringer	
	Tank support: A-Frame	
	Payload support: Skin/Stringer	
	Interstage adaptor: Skin/Stringer	
	Thrust vector control: Gimballed Nozzle	

DATA SHEET NO. 2

SUBSYSTEM COST SUMMARY

System	Subsystem	Development Cost (Baseline Criteria)	Total Additional Development Cost x 10^{-2} + 1.00	Total Development Cost	Unit Cost
Feed system	Tankage	650,000	1.03	670,000	6,800
	Expulsion system	920,000	1.10	1,012,000	62,000
	Propellant-settling system	110,000	1.00	110,000	38,600
	Fill, feed, and vent system	2,000,000	1.16	2,320,000	92,500
	Insulation	---	---	---	---
Subtotal				4,112,000	199,900
Fuel system	Combustion chamber	64,000	1.01	64,600	10,000
	Fuel grain	310,000	1.03	319,300	56,500
	Injection system	108,000	1.02	110,200	15,900
	Nozzle/TVC*	480,000	1.33	639,000	102,000
Subtotal				1,133,100	184,400
Air-frame	Thrust structure	156,000	1.01	157,600	16,500
	Tank support	95,000	1.00	95,000	2,500
	Payload support	160,000	1.01	161,600	19,200
	Interstage adapter	195,000	1.01	196,900	8,200
Subtotal				611,100	46,400
Control system	Thrust vector control*				
Total				5,856,200	430,700

*Enter TVC Subsystem under Fuel System, in place of nozzle, if gimballed nozzle or secondary injection alternates are selected. If either hydrazine or bipropellant RCS is selected, enter under Control System.

DATA SHEET NO. 3
SYSTEM DEVELOPMENT COST SUMMARY

System	Hardware Costs		Special Test Equipment Costs			Test Operations Costs					Engineering and Subcontractor Management		Total
Feed system	$N_{commonality\ tests}$	9	$C_{STE\ B/L}$		26.500	$\dot{c}_{T.O.\ B/L}$		167,000	$k \begin{bmatrix} Storable = 0.92 \\ Cryogenic = 1.0 \end{bmatrix}$	0.92			
	f	☒	f_1	Tankage	1.06	f_2	Tankage	1.05	$L_{B/L}$	6.0	$C_{DE} = 92,300\ W_P^{0.05}$		
	$\frac{N_{commonality\ tests}}{f}$	1		Expulsion system	0.95		Expulsion system	0.90	N_{tests} (ΔL)	1.0			
				Prop.-settling system	1.00		Prop.-settling system	1.00					
	N_{sets}	1		Insulation	---		Insulation	---	k_1 (test) 0.2 (ΔL)		C_{DE}	146,200	
	C_{set}	199,900	$\Pi\ f_1$		1.007	$\Pi(f_2)$		0.9[illegible]5	$L_{B/L} + \Delta L$	7.0	C_{SM}	0	
	$C_{hardware}$	199,900	C_{STE}		26,700	$C_{T.O.} = \Pi(f_2)\, k\, \dot{c}_{T.O.\ B/L}(L_{B/L} + \Delta L)$				1,015,000	$C_{E\&SM}$	146.200	1,387,800
Fuel system	$N_{singular\ tests}$	13	$C_{STE\ B/L}$		102,[illegible]00	$\dot{c}_{T.O.\ B/L}$		48,500	k	1.0			
	$N_{commonality\ tests}$	3	f_1	TCA	1.00	f_2	TCA	0.98	$L_{B/L}$ 5	15.0	$C_{DE} = 142,000\ W_P^{0.05}$		
	f	2		Fuel grain and Insulation	1.0		Fuel grain and Insulation	1.0			$C_{SM} = 46,700\ W_P^{0.25}$		
	$\frac{N_{commonality\ tests}}{f}$	2		Injection system	1.15		Injection system	1.10	N_{Tests} / k_1 (Test) 1.0 (ΔL)	5.0			
	N_{sets}	15		Nozzle/TVC*	1.15		Nozzle/TVC*	1.20			C_{DE}	225,000	
	C_{set}	184,400	$\Pi\ f_1$		1.322	$\Pi(f_2)$		1.291	$L_{B/L} + \Delta L$	20.0	C_{SM}	467,000	
	$C_{hardware}$	2,766,000	C_{STE}		135,000	$C_{T.O.} = \Pi(f_2)\, k\, \dot{c}_{T.O.\ B/L}(L_{B/L} + \Delta L)$				1,252,000	$C_{E\&SM}$	692,000	4,845,000
Total	$C_{hardware}$	2,965,900	C_{STE}		161,700	$C_{T.O.}$				2,267,000	$C_{E\&SM}$	838,200	6,232,800

*If gimballed nozzle or secondary injection are used for TVC, enter their f_1 and f_2 values in place of nozzle entry.

DATA SHEET NO. 4
SYSTEM INTEGRATION AND TOTAL COST SUMMARY

All-System Test Hardware Costs	
Feed system	199,900
Fuel system x 2	368,800
TVC system*	---
Structure	46,400
$C_{Hardware}$	615,100

All-System Test Operations Costs		
$\hat{c}_{T.O.\ B/L}$		27,000
$\Pi(f_3)$	Feed system	0.958
	Fuel system	1.050
	TVC system	1.100
	Structure	1.000
$\Pi(f_3)$		1.105
k [Storable = 0.96, Cryogenics = 1.00]		0.96
$W_P^{0.14}$		3.63
L		14.4
$C_{T.O.} = \Pi(f_3)\ \hat{c}_{T.O.\ B/L}\ k\ W_P^{0.14}\ L$		1,498,000

AGE Costs		
$C_{AGE\ B/L}$		1,670,000
$\Pi(f_4)$	Feed System	0.960
	Fuel system	1.010
	TVC system	1.060
	Structure	1.000
$\Pi(f_4)$		1.027
$C_{AGE} = \Pi f_4\ C_{AGE\ B/L}$		1,715,000

System Design Engineering Costs		
$C_{SDE\ B/L}$		519,000
$\frac{C_{Dev}}{C_{Dev\ B/L}}$	Feed system	1.314
	Fuel system	1.411
	TVC system	---
	Structure	1.030
$\Pi(C_{Dev}/C_{Dev\ B/L})$		1.910
C_{SDE}		991,300

			Subtotal
System integration costs			4,819,400
Subsystem development costs (See Data Sheet No. 2)	5,856,200	x1.15	6,734,600
System development costs (See Data Sheet No. 3)	6,232,800	x1.15	7,167,700
SUM_1 = System integration + system development + subsystem development			18,721,700
System engineering: $C_{S.E.} = 0.06 \times SUM_1$			1,123,300
Program management: $C_{P.M.} = 0.16 \times SUM_1$			2,995,500
Development program costs (less contractor fee): $C_{Dev} = SUM_1 + C_{S.E.} + C_{P.M.}$			22,840,500
Total program costs: 1.10 x Development program costs			25,124,600

*Enter TVC system costs only if the hydrazine RCS or the bipropellant RCS system is selected.

Section 3
SUBSYSTEM COSTS

Subsystems are identified and subsystem costs are estimated for all baseline and alternate subsystems. Costs include development (nonrecurring) as well as unit (recurring) costs. Development costs are expressed as a function of system size and reflect the effects of design criteria on development requirements. Unit costs are expressed only as a function of system size because the influence of design criteria upon hardware manufacture is negligible.

3.1 DEVELOPMENT COSTS

Subsystem development costs are shown in Figures 3-1 through 3-14 along with sketches and schematics of the subsystems, each figure summarizing a different subsystem class. The large graph on the left side of each figure shows subsystem development costs as a function of size, expressed in terms of propellant weight, for each subsystem within the class. It should be noted that these curves are for subsystems developed to the baseline design criteria, defined in Table 1-1. The effects of changes in design criteria are accounted for on the right side of the figures under Item A and Curves B, C, D, and E. These changes are expressed as incremental additions to the basic subsystem development costs. Total subsystem development costs for any subsystem and any combination of design criteria can then be found from the following equation.

$$C_{SD} = \sum C'_{SD} \left(1 + \sum_{i=A}^{E}\right) \frac{C_{AD_i}}{100}$$

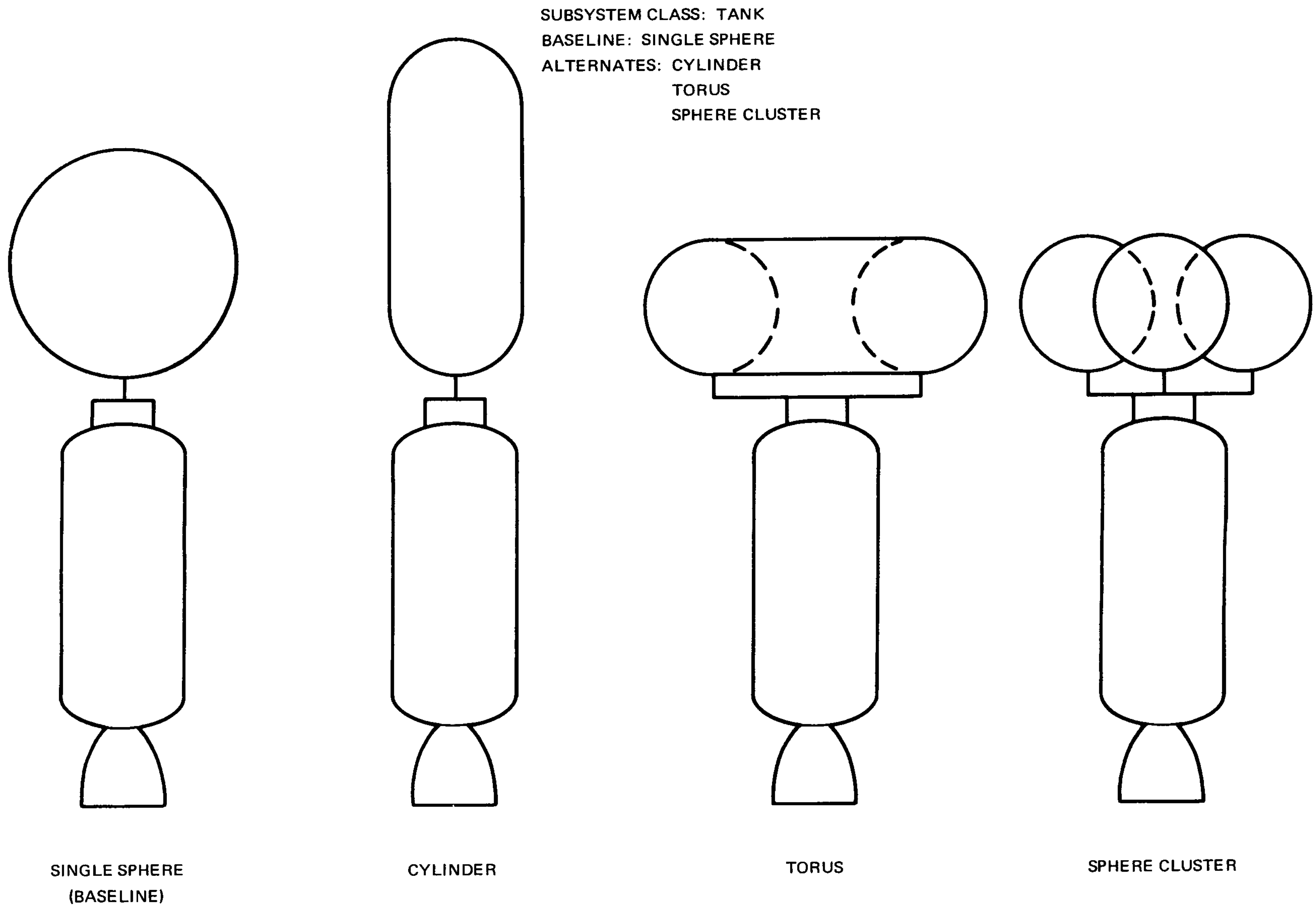
where

C_{SD} = Total subsystem development costs

C'_{SD} = Development costs of each subsystem to meet the baseline design criteria and for a specific propellant weight

C_{AD_i} = Additional costs, expressed as a percent, required to develop the subsystem to satisfy each of the five design criteria

The cost increments for Items A through E of Figures 3-1 through 3-14 are seen to be represented by both a band and a line. The band indicates the expected range of additional development costs imposed by the design criteria, while the line indicates the current best estimate of what those costs would be. Therefore, the user has the option of adjusting the current estimate to any value within the band.


SUBSYSTEM CLASS: TANK
BASELINE: SINGLE SPHERE
ALTERNATES: CYLINDER
TORUS
SPHERE CLUSTER
SINGLE SPHERE
(BASELINE)
CYLINDER
TORUS
SPHERE CLUSTER

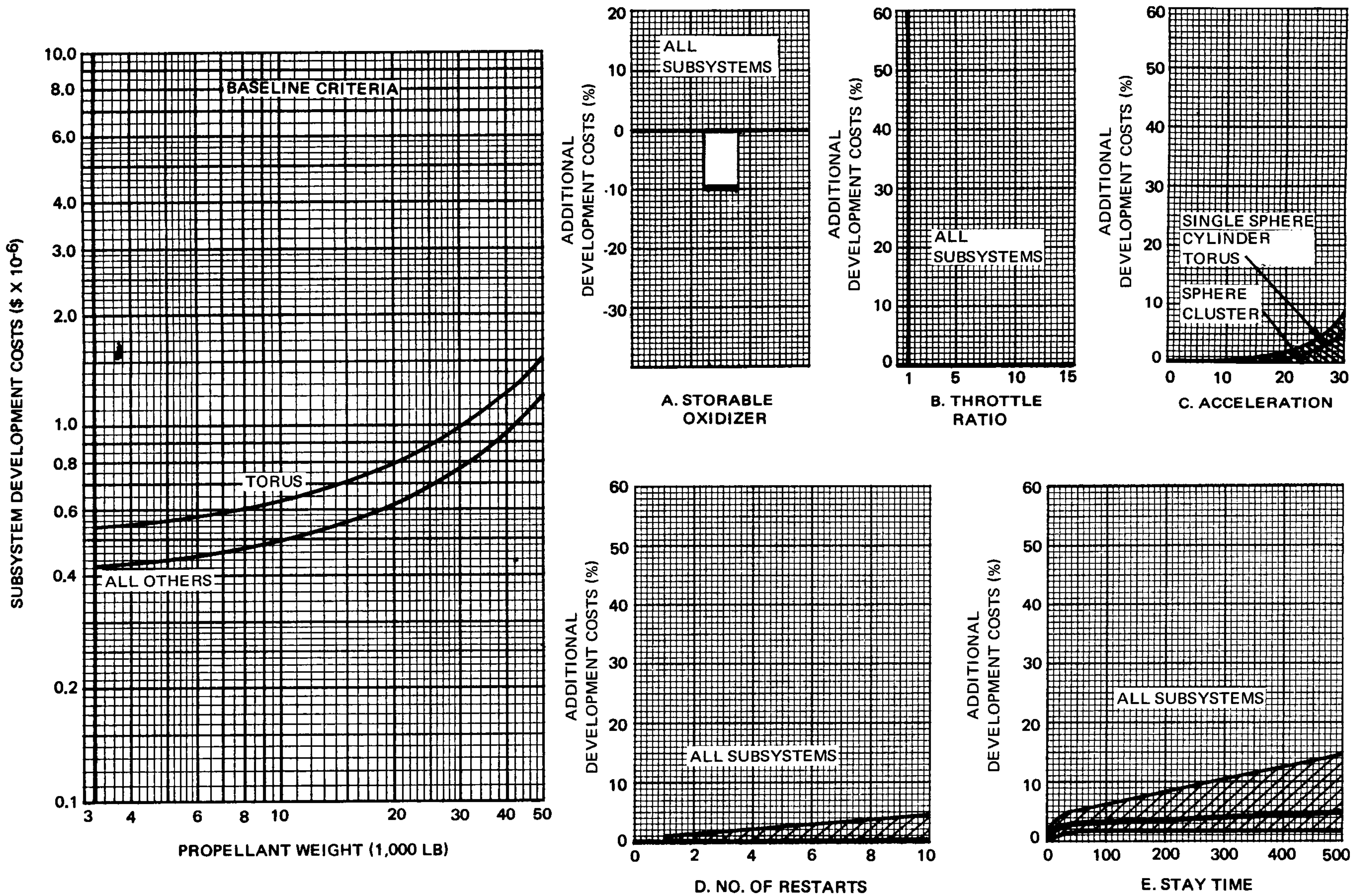
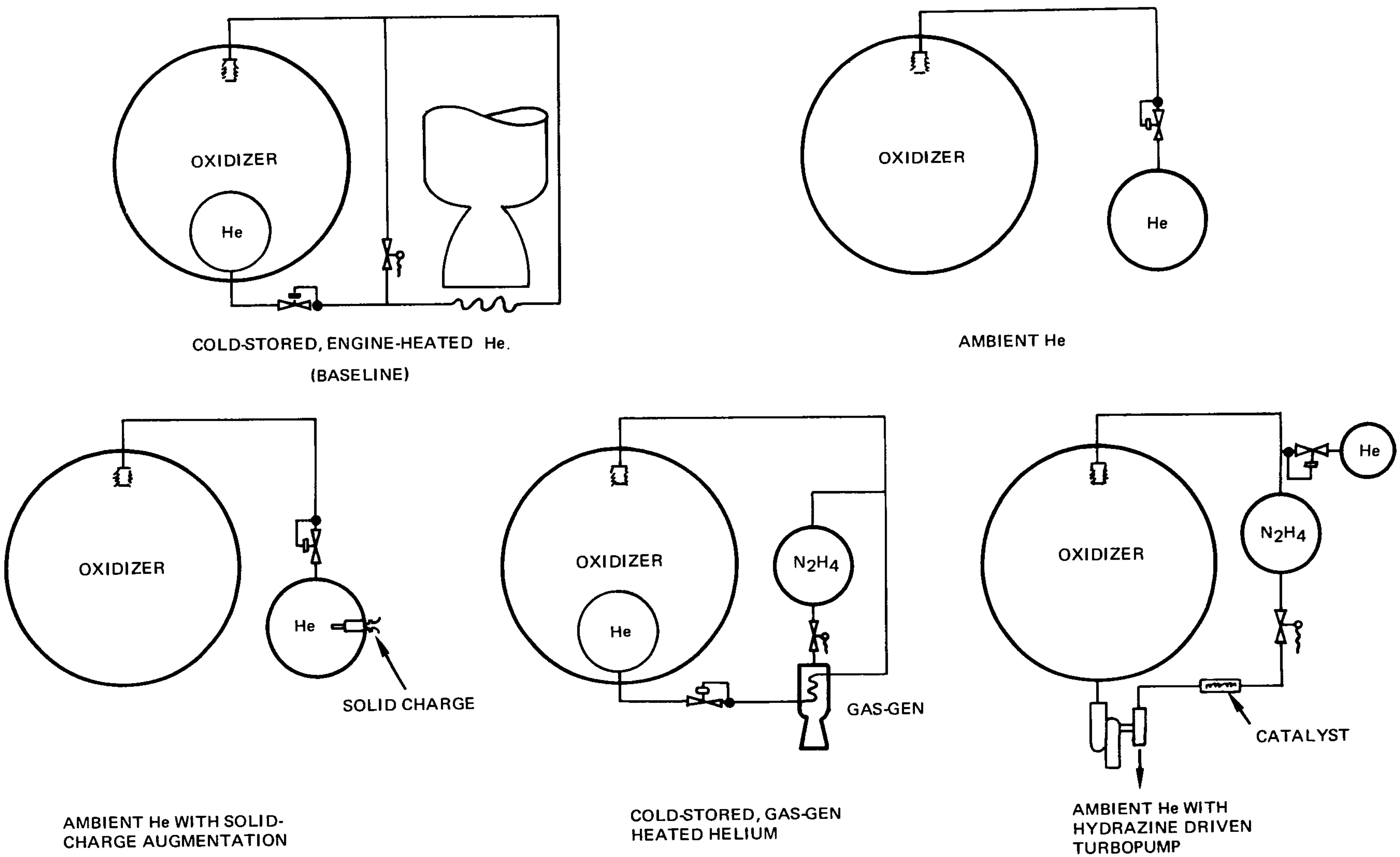


Figure 3-1 Subsystem Development Cost Summary -- Tank

SUBSYSTEM CLASS: EXPULSION SYSTEM
BASELINE: HEATED HELIUM (NOZZLE HEAT EXCHANGER)
ALTERNATES: AMBIENT HELIUM
CARTRIDGE - AUGMENTED He
GAS - GENERATOR - AUGMENTED He
TURBOPUMP



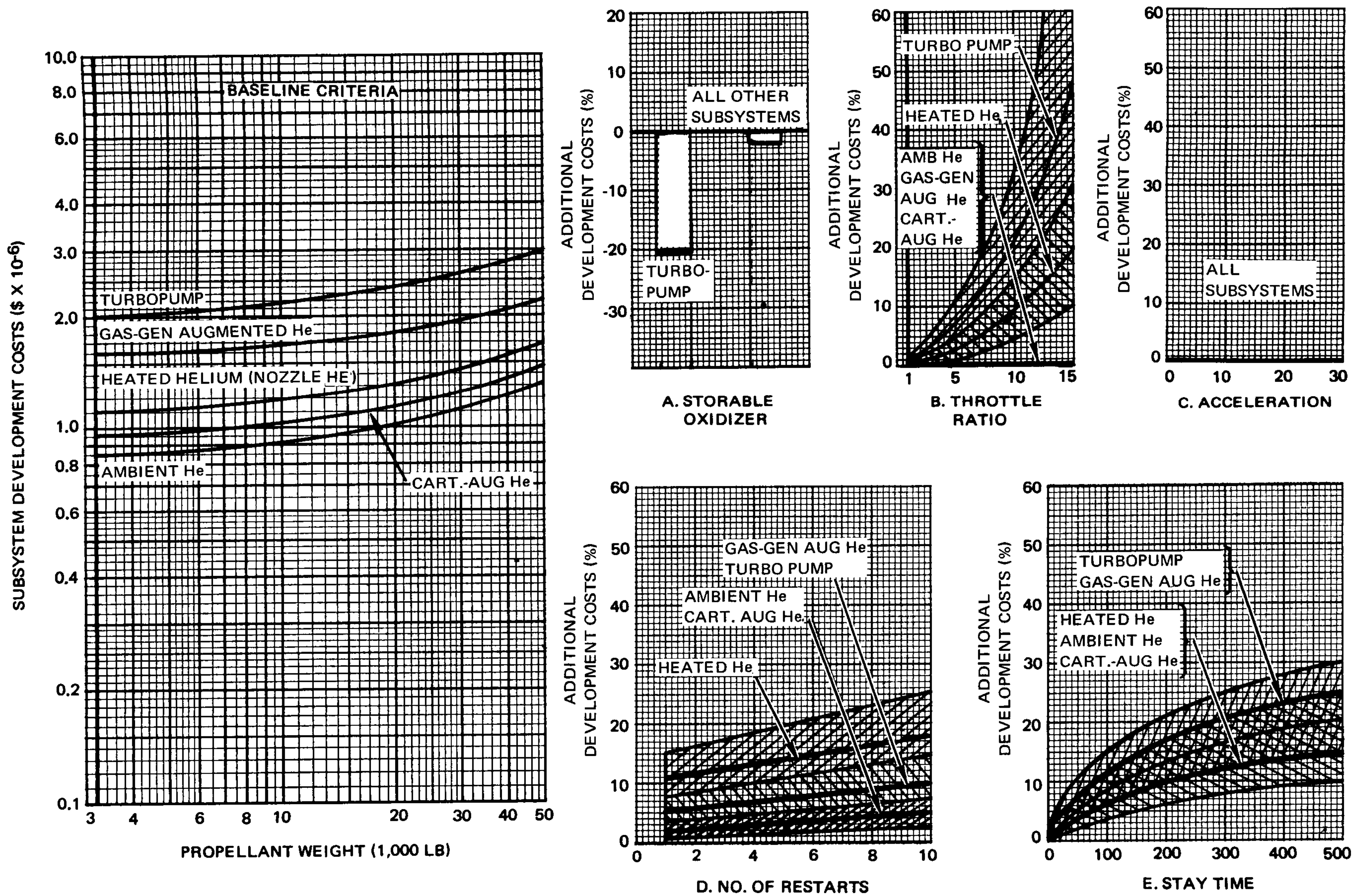
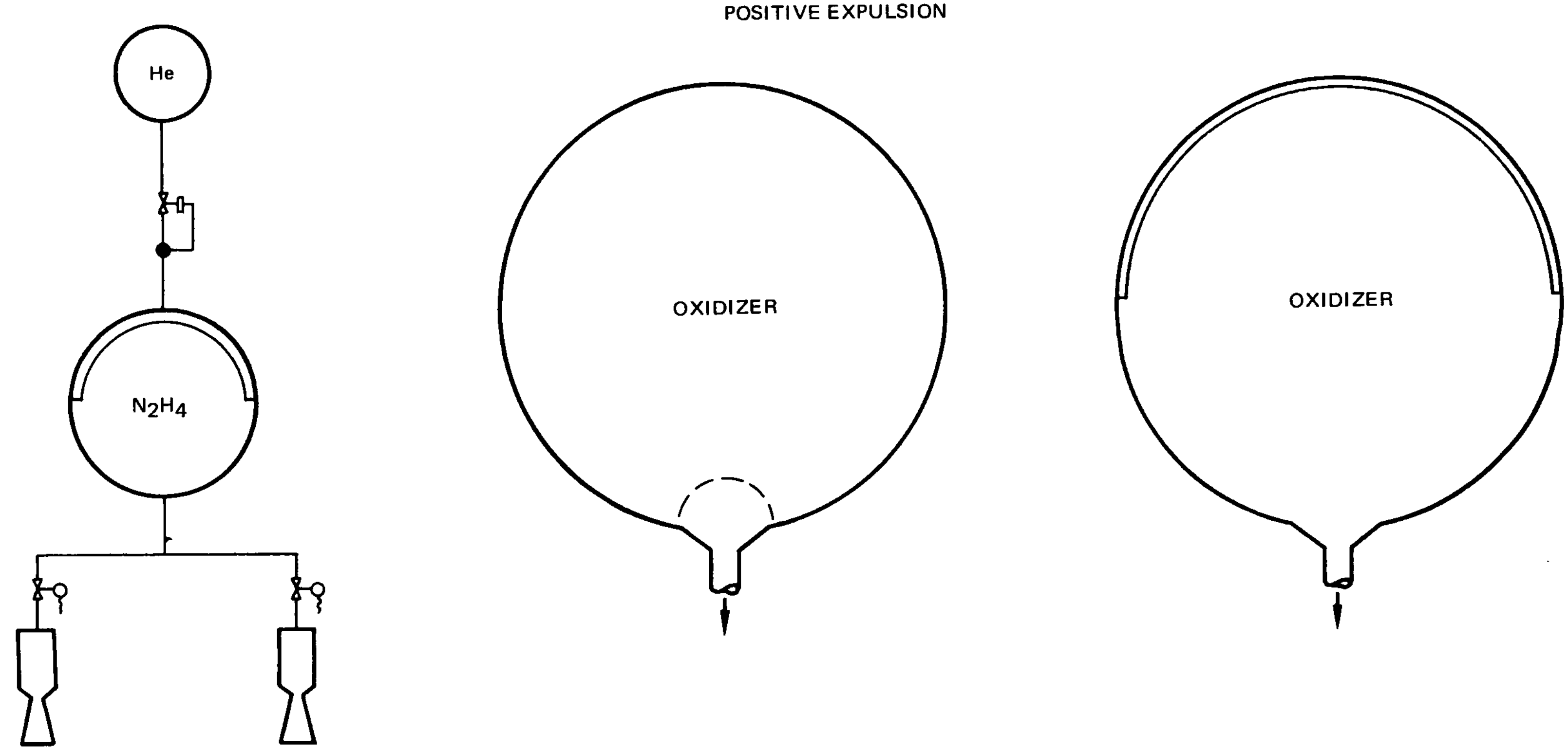


Figure 3-2 Subsystem Development Cost Summary -- Expulsion System

SUBSYSTEM CLASS: PROPELLANT SETTLING
BASELINE: ULLAGE ROCKETS
ALTERNATES: SCREEN
POSITIVE EXPULSION



HYDRAZINE SETTLING MOTORS

(BASELINE)

SCREEN IN TANK SUMP

MAIN TANK EXPULSION DIAPHRAGM

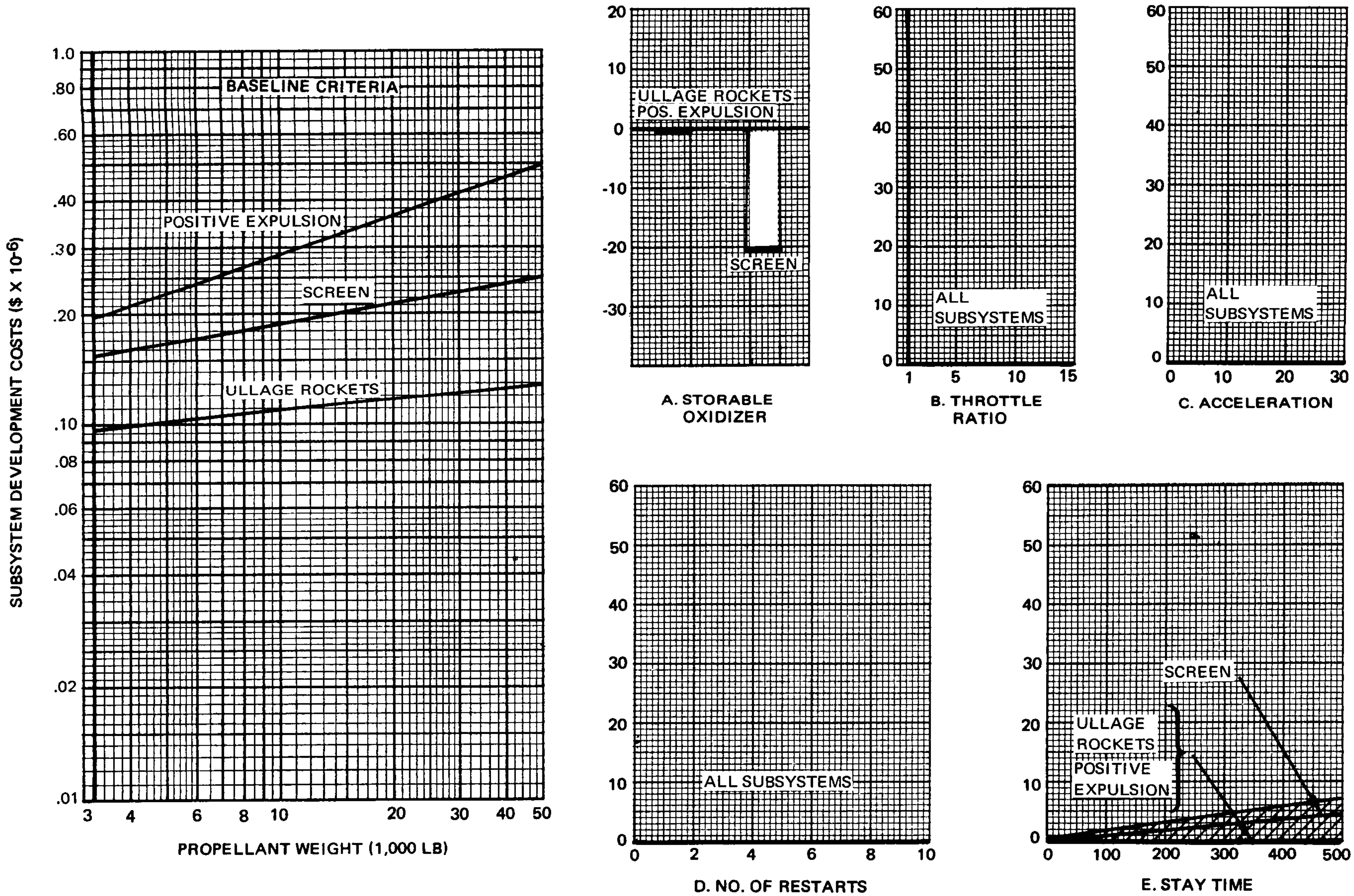
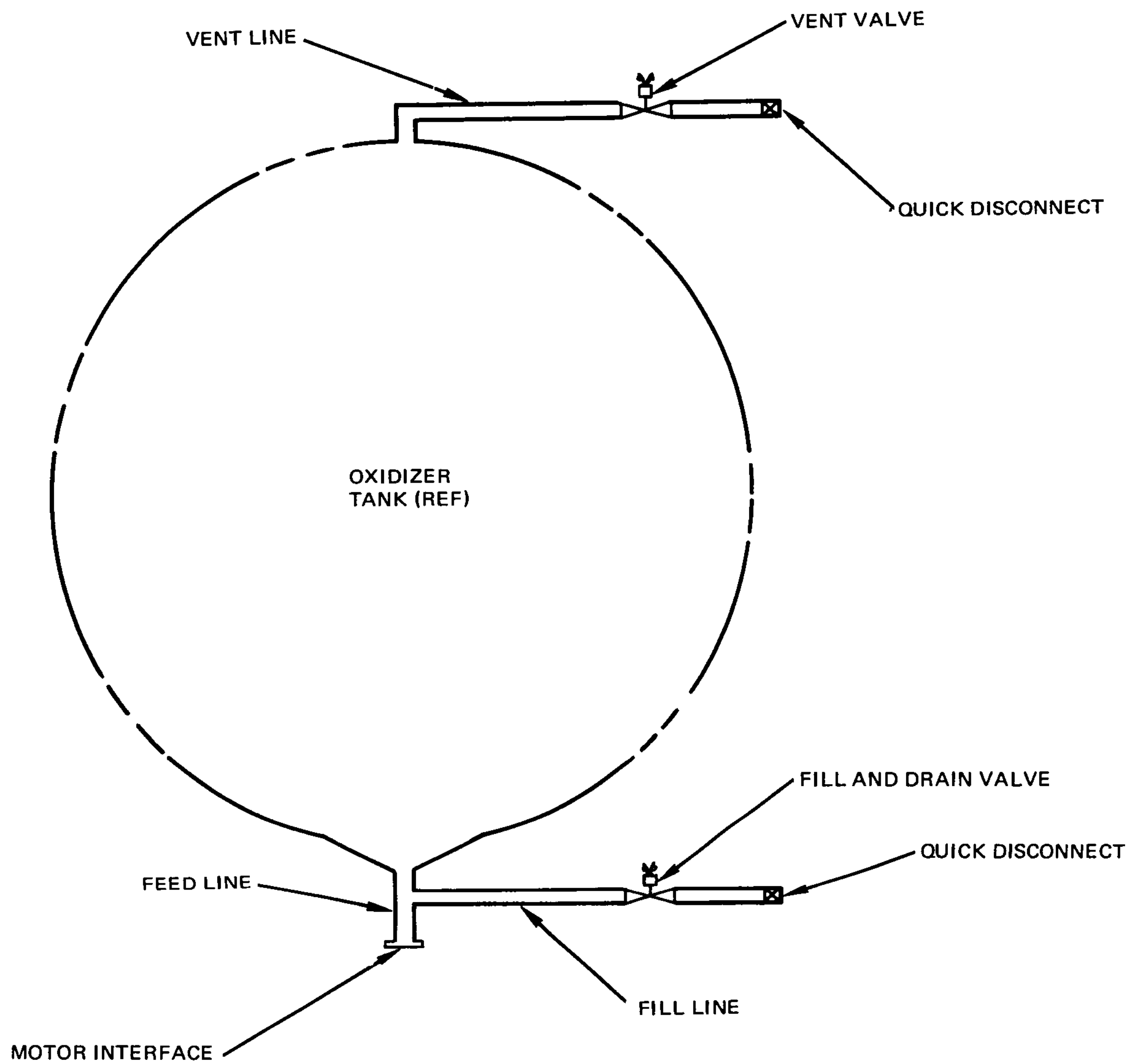


Figure 3-3 Subsystem Development Cost Summary -- Propellant Settling

FILL, FEED AND VENT SYSTEM



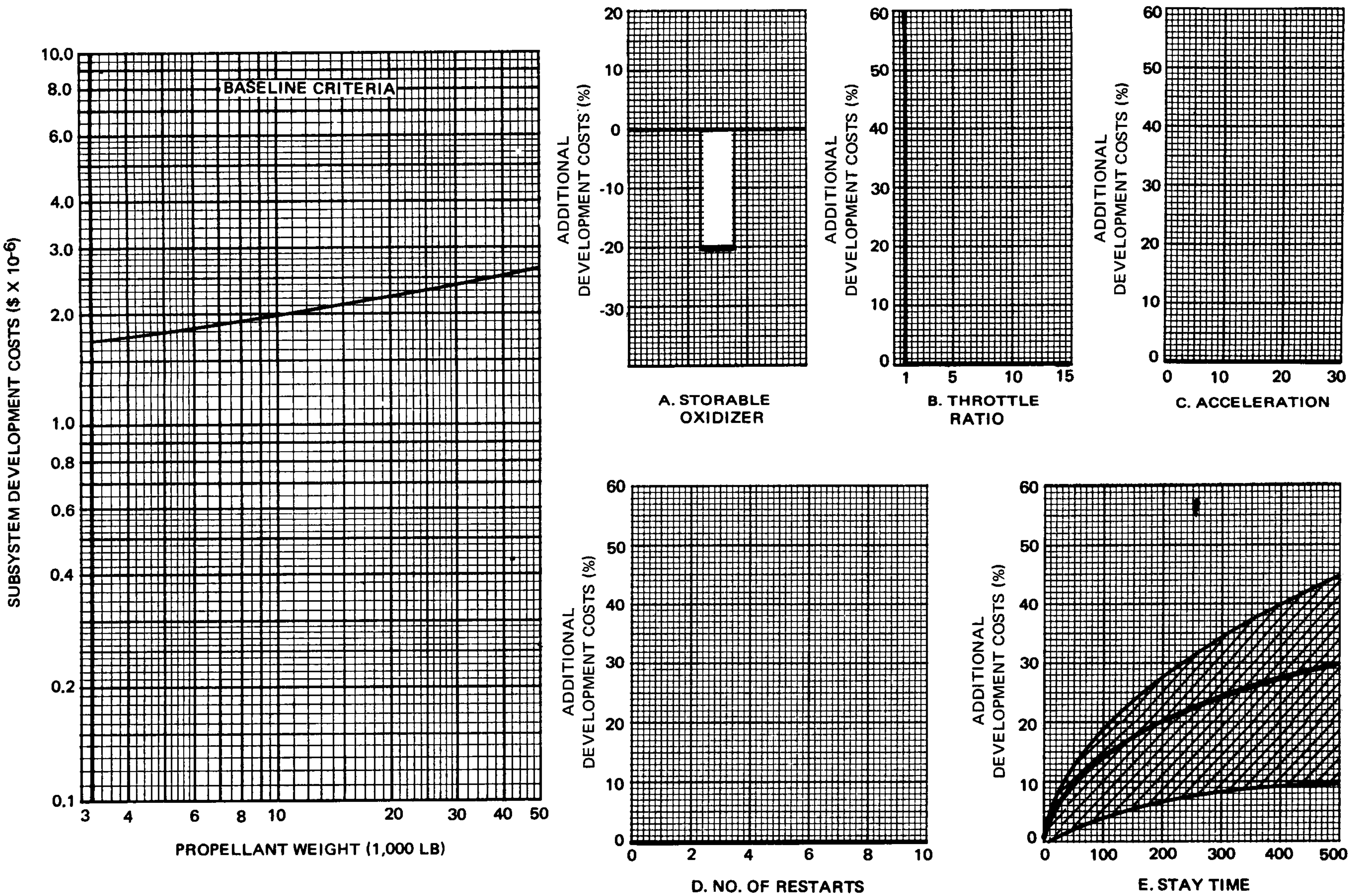
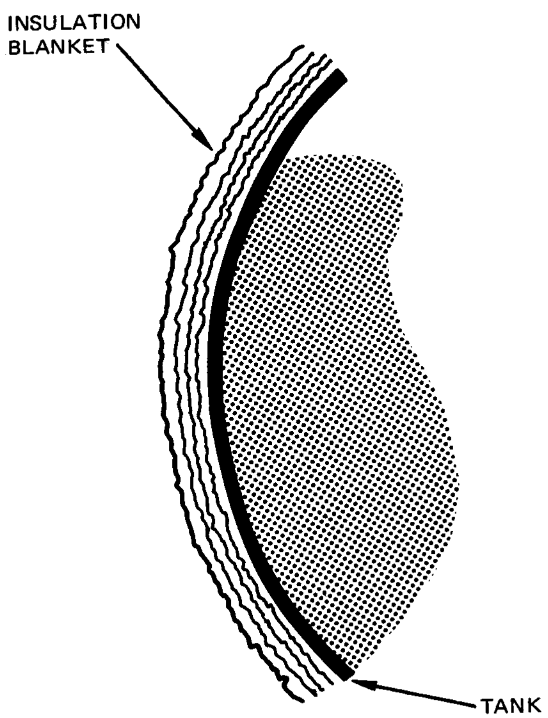
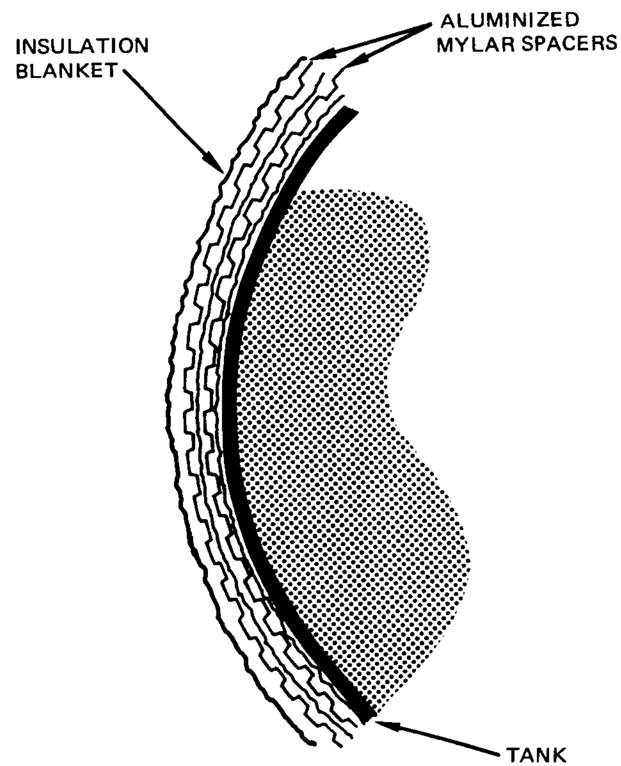


Figure 3-4 Subsystem Development Cost Summary -- Fill, Feed and Vent

SUBSYSTEM CLASS: INSULATION
BASELINE: UNINSULATED
ALTERNATES: TANK-MOUNTED NRC-2
TANK-MOUNTED DIMPLAR



TANK-MOUNTED NRC-2



TANK-MOUNTED DIMPLAR

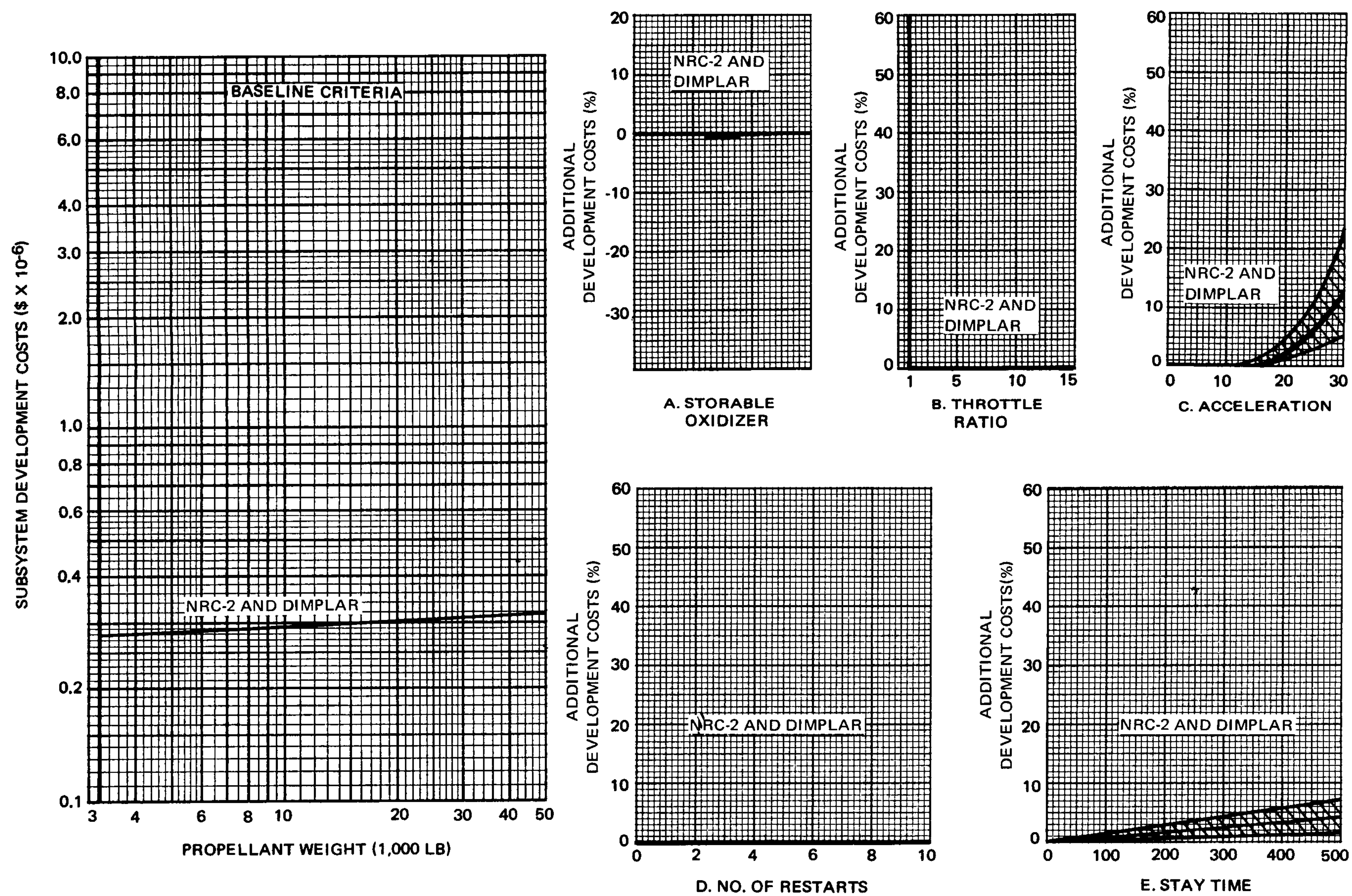
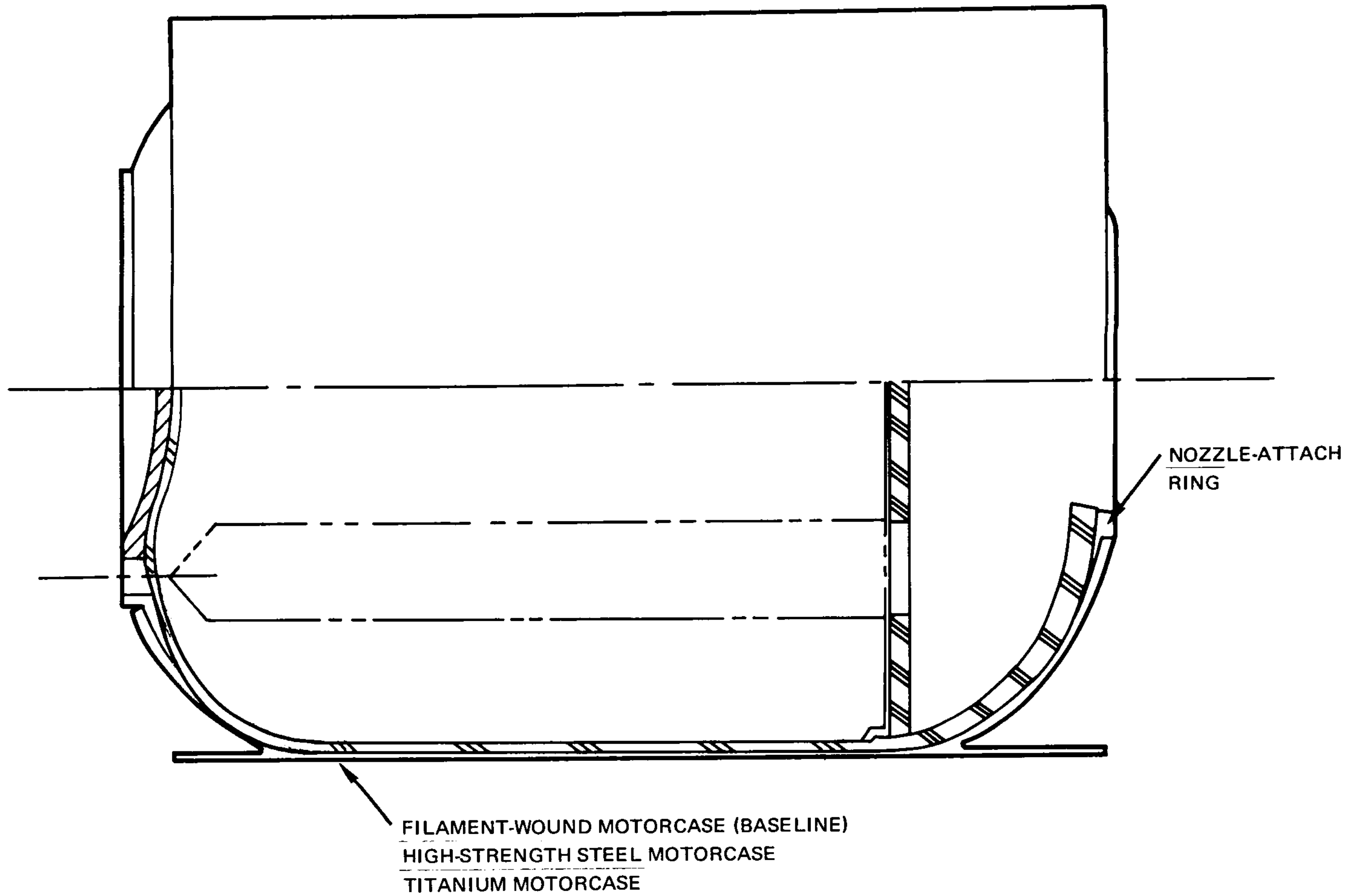


Figure 3-5 Subsystem Development Cost Summary -- Insulation

SUBSYSTEM CLASS: COMBUSTION CHAMBER
BASELINE: FIBER GLASS
ALTERNATES: HIGH-STRENGTH STEEL
TITANIUM



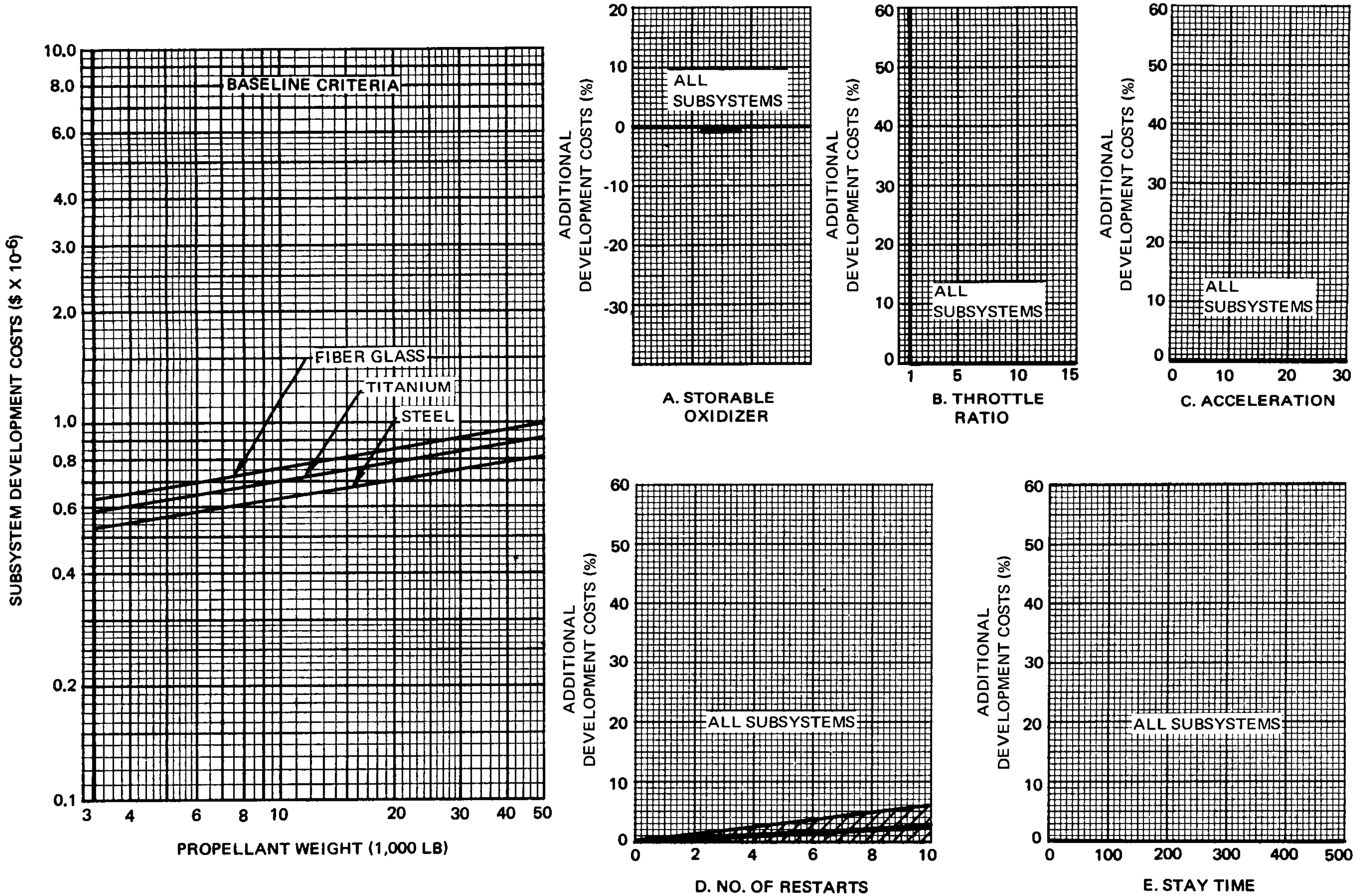
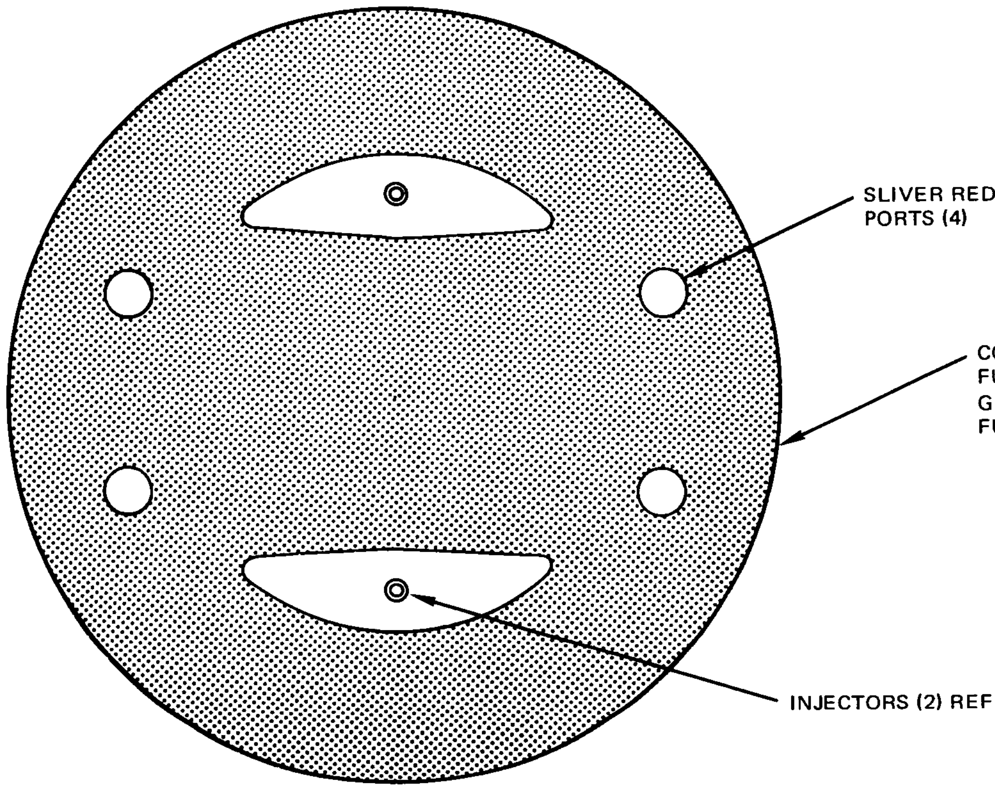


Figure 3-6 Subsystem Development Cost Summary -- Combustion Chamber

SUBSYSTEM CLASS: FUEL GRAIN
BASELINE: COMPRESSION MOLDED
ALTERNATES: GRAVITY CASTABLE



NOTE: REPRESENTATIVE GRAIN DESIGN ILLUSTRATED. REASONABLE CHANGES IN GRAIN DESIGN WILL NOT SIGNIFICANTLY AFFECT COSTS.

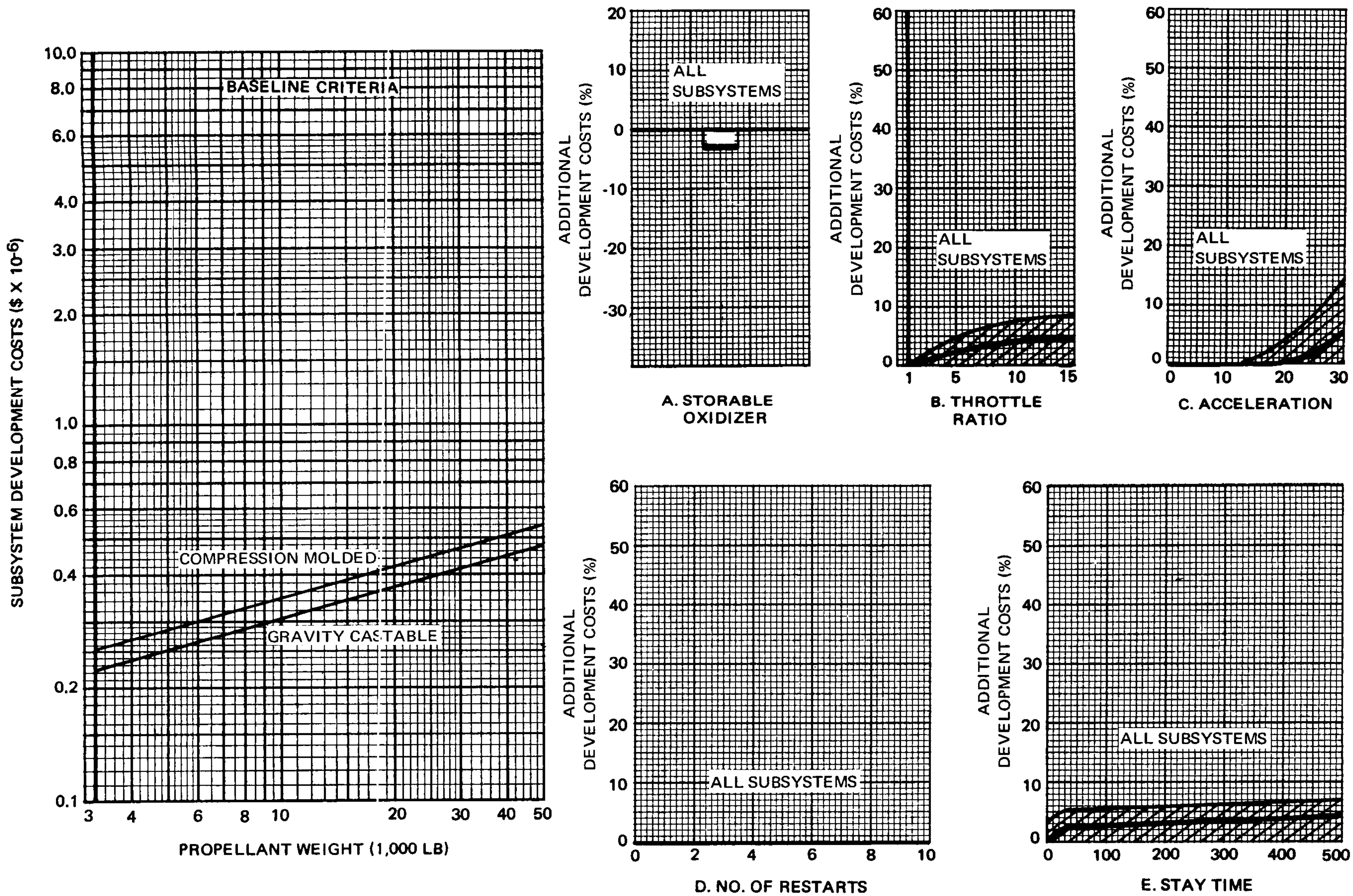
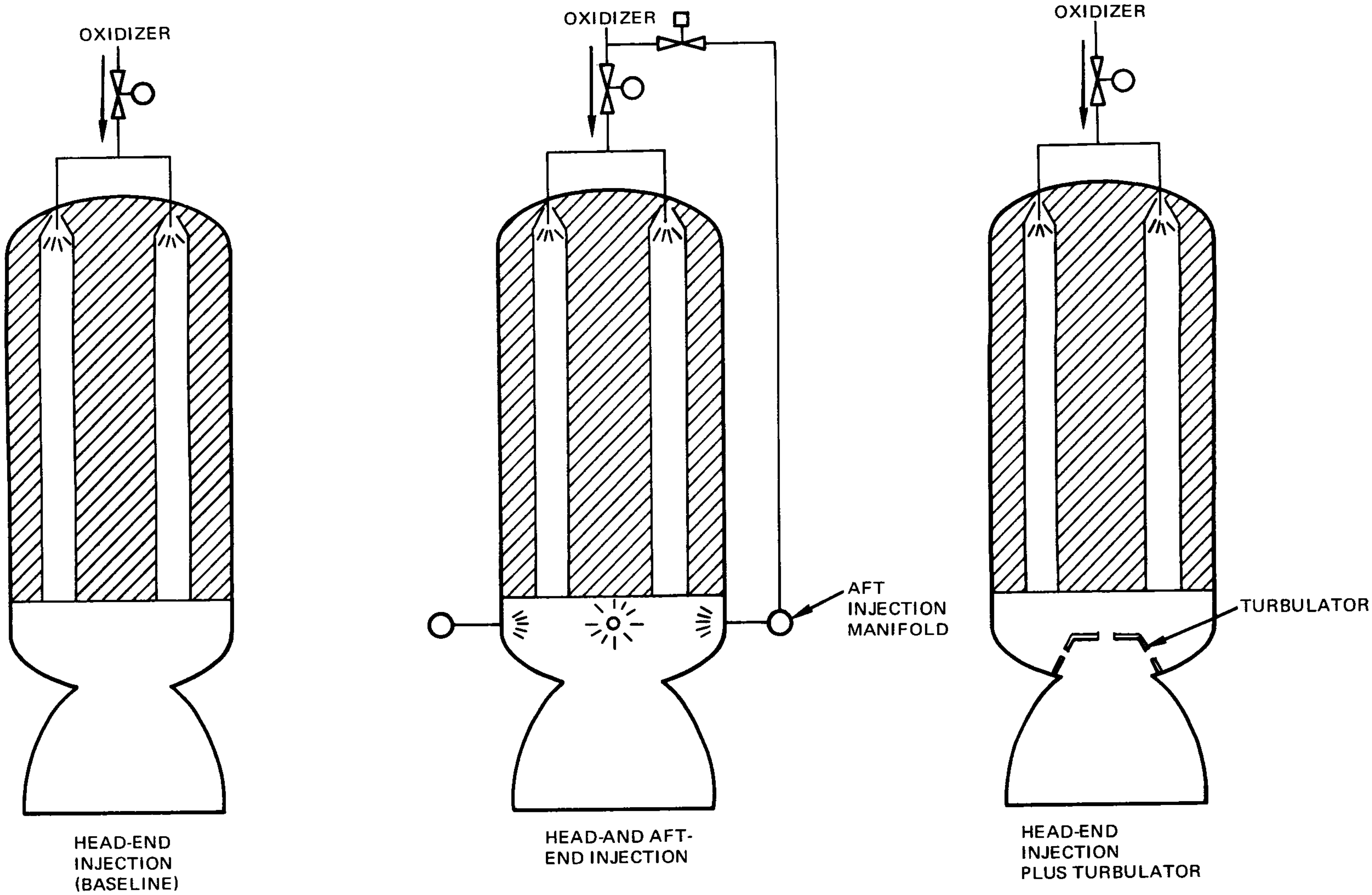


Figure 3-7 Subsystem Development Cost Summary -- Fuel Grain

SUBSYSTEM CLASS: INJECTION SYSTEM
BASELINE: HEAD END - ONLY
ALTERNATES: HEAD END + AFT END INJECTION
HEAD END INJECTION + TURBULATOR



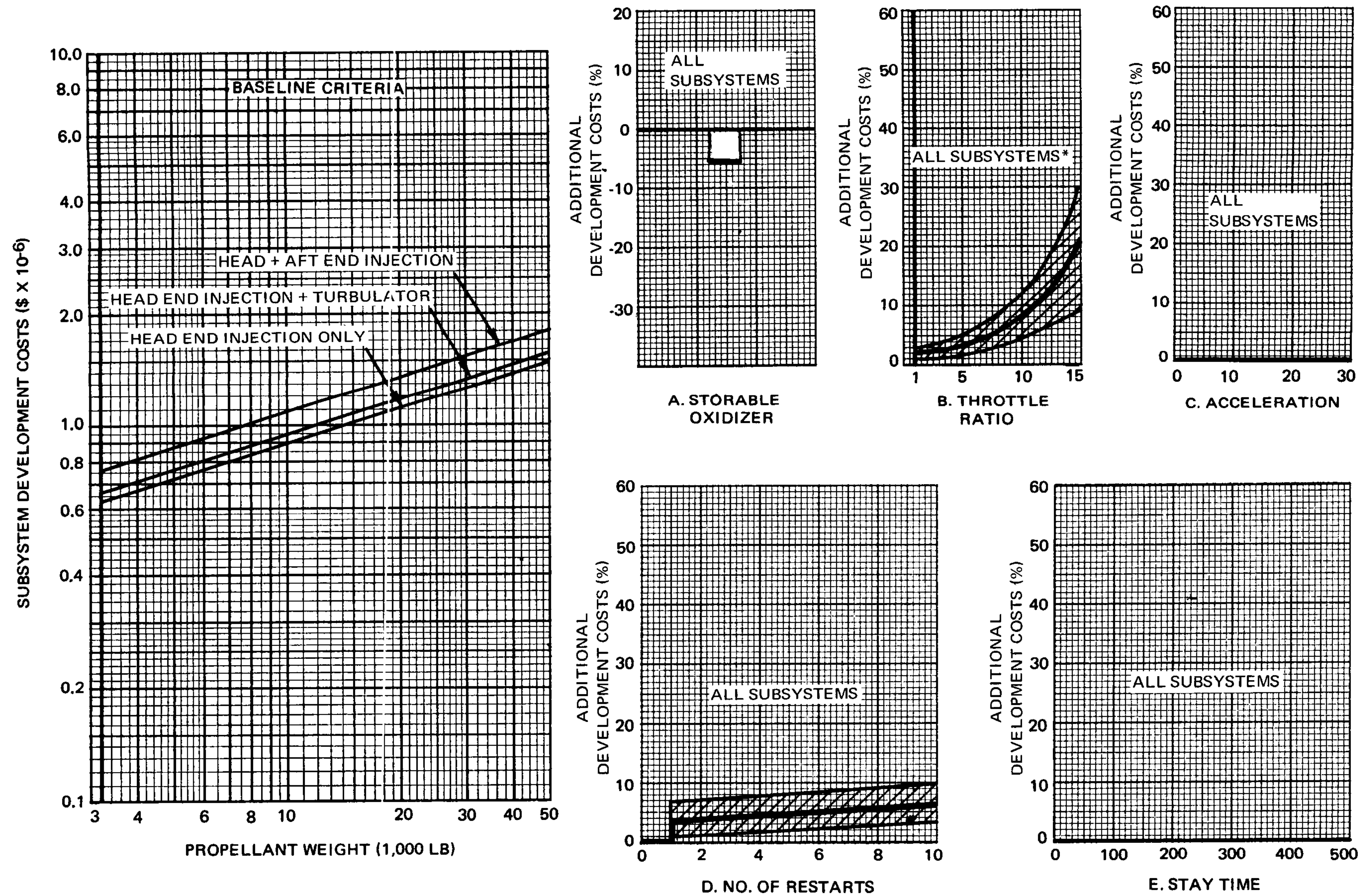


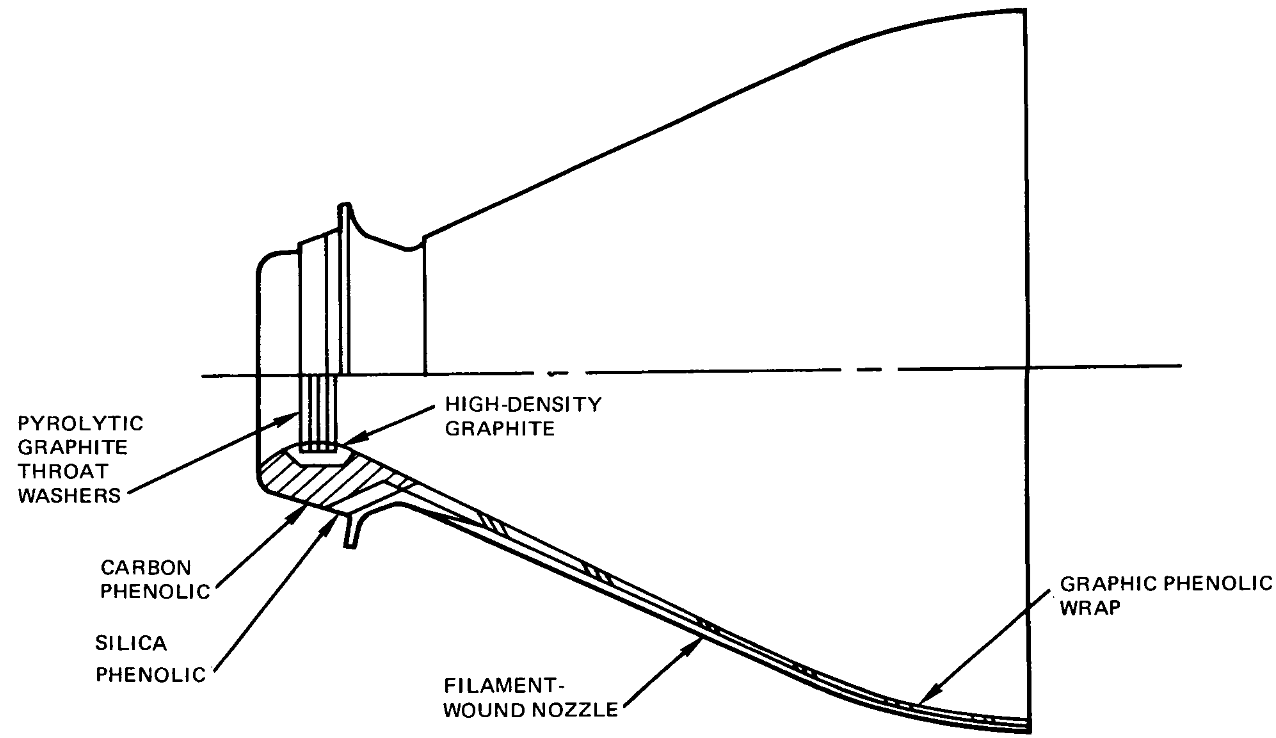
Figure 3-8 Subsystem Development Cost Summary -- Injection System

*NOTE: HEAD END INJECTION ONLY *AND* HEAD END INJECTION + TURBULATOR *CAN BE USED ONLY TO THROTTLE RATIO OF 3.*

SUBSYSTEM CLASS: NOZZLE

BASELINE: ABLATIVE

NO ALTERNATE CONFIGURATIONS



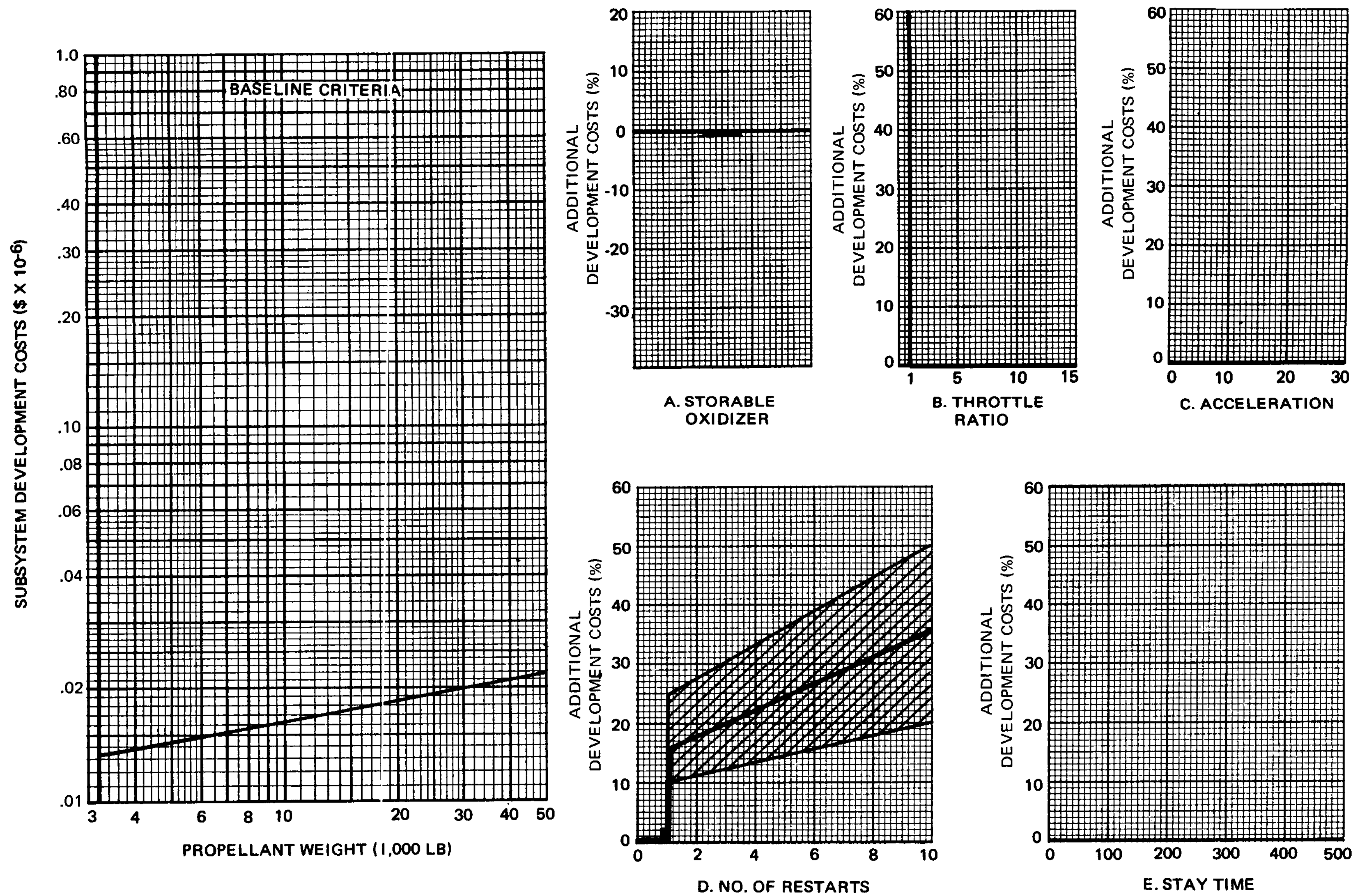
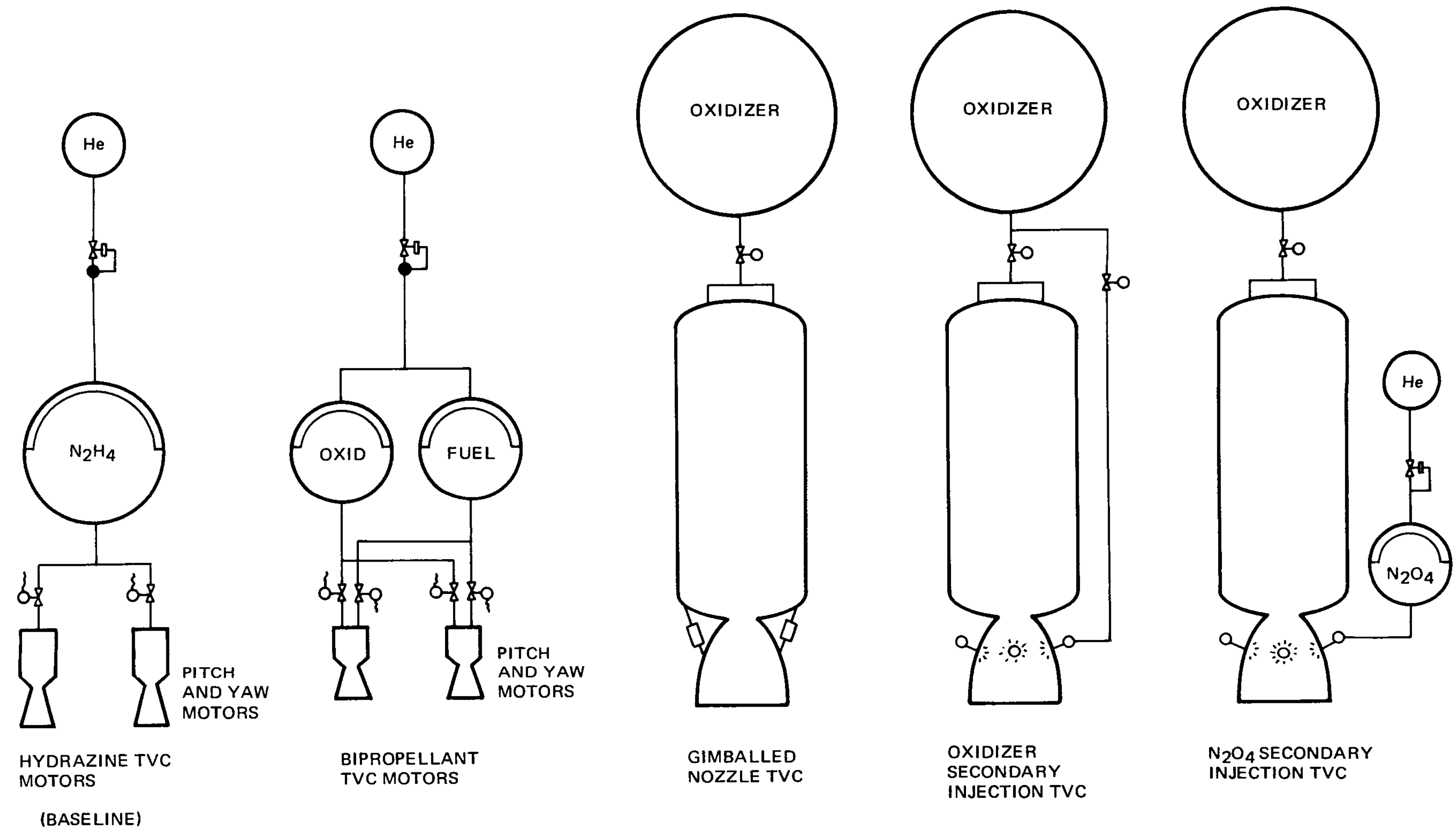


Figure 3-9 Subsystem Development Cost Summary -- Nozzle

SUBSYSTEM CLASS: THRUST VECTOR CONTROL

BASELINE: MONOPROPELLANT RCS

ALTERNATES: GIMBALLED NOZZLE
N_2O_4 SECONDARY INJECTION
OXIDIZER SECONDARY INJECTION
BIPROPELLANT RCS



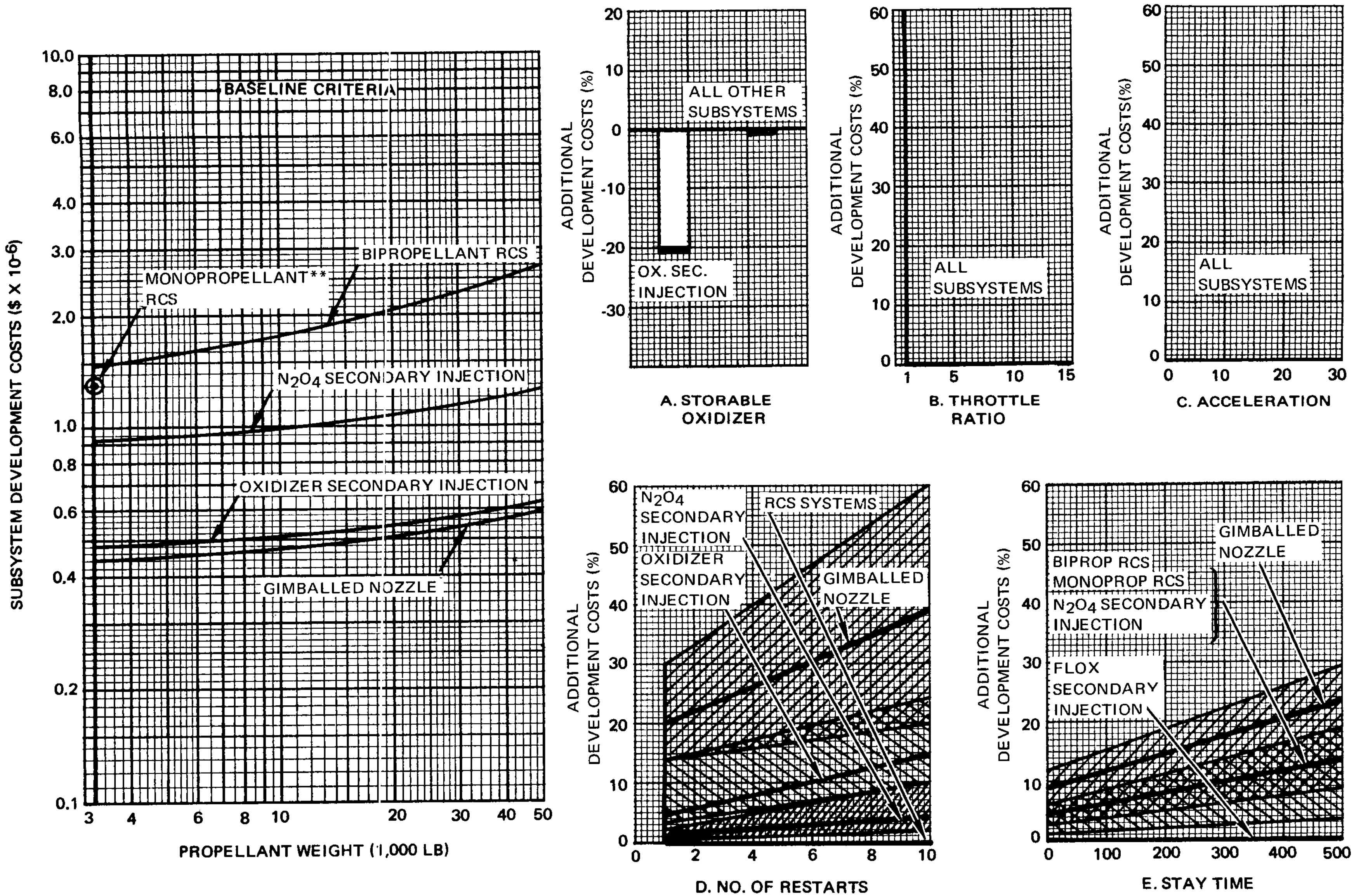
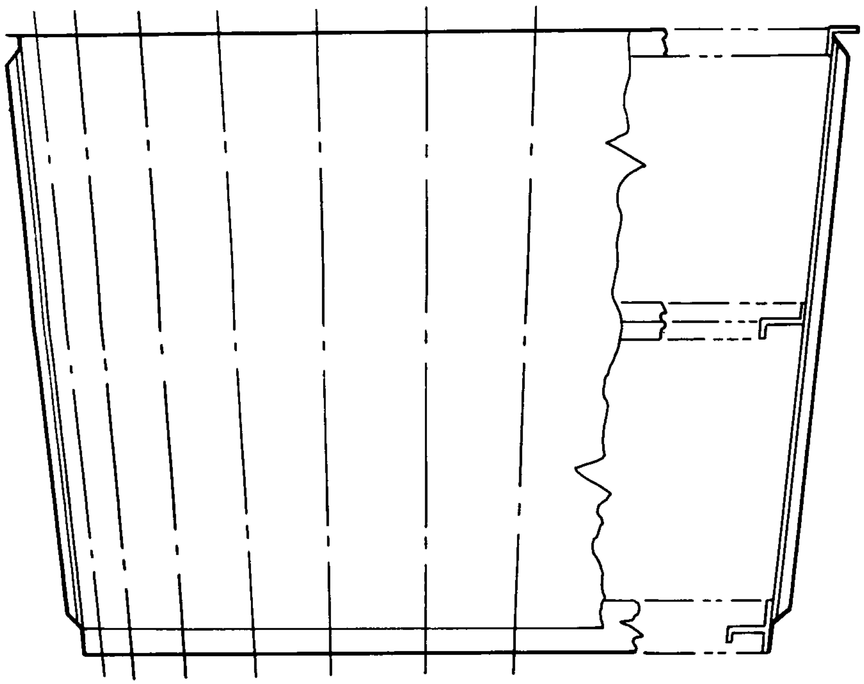


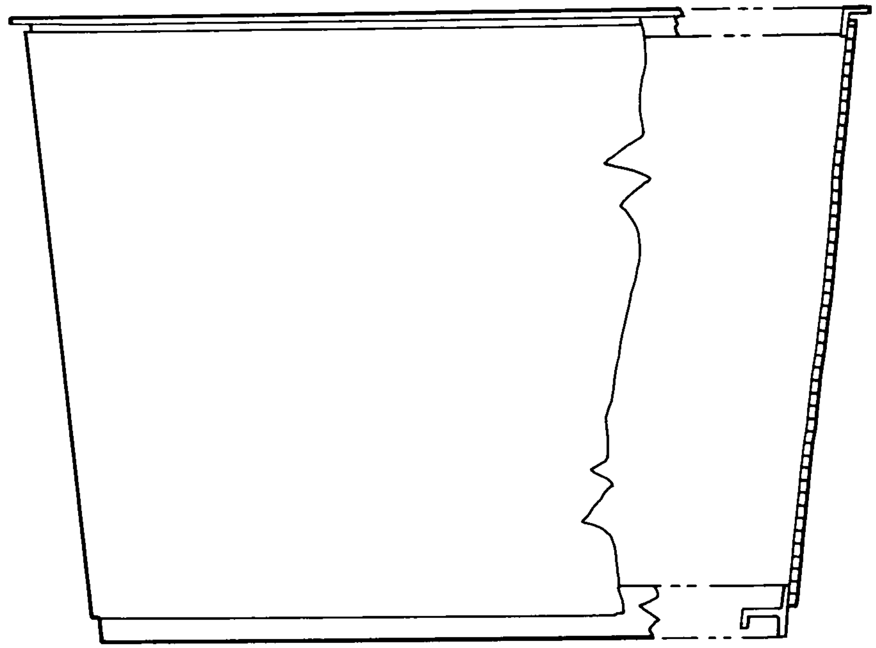
Figure 3-10 Subsystem Development Cost Summary -- Thrust Vector Control

**MONOPROPELLANT RCS NOT AVAILABLE IN SIZES LARGER THAN BASELINE

SUBSYSTEM CLASS: THRUST STRUCTURE
BASELINE: SKIN AND STRINGER
ALTERNATES: SANDWICH CONSTRUCTION



SKIN AND STRINGER
(BASELINE)



SANDWICH

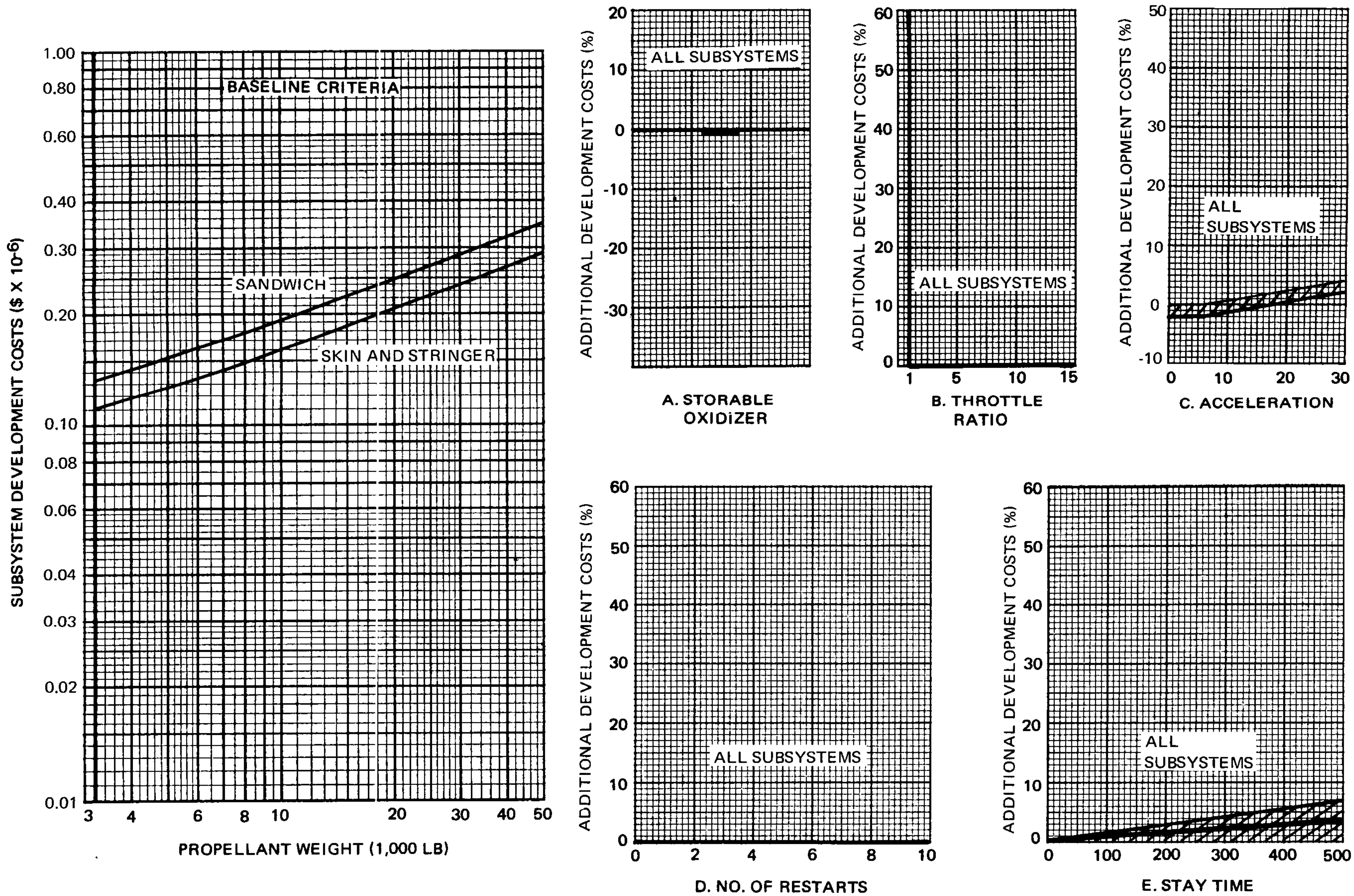
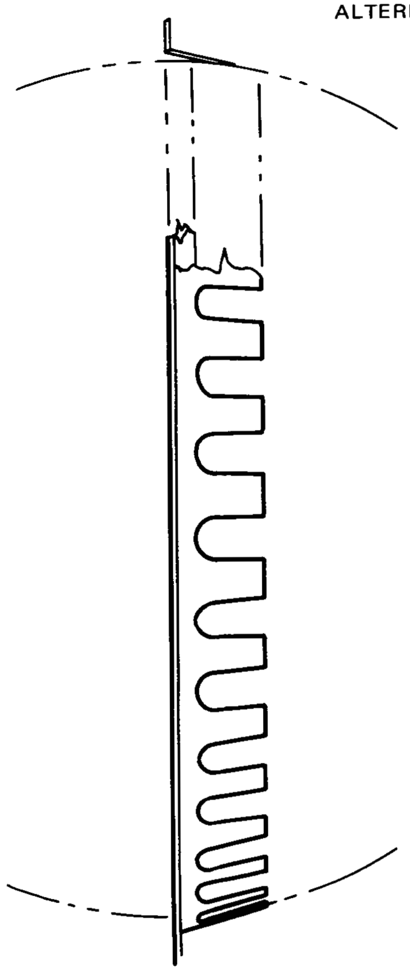


Figure 3-11 Subsystem Development Cost Summary -- Thrust Structure

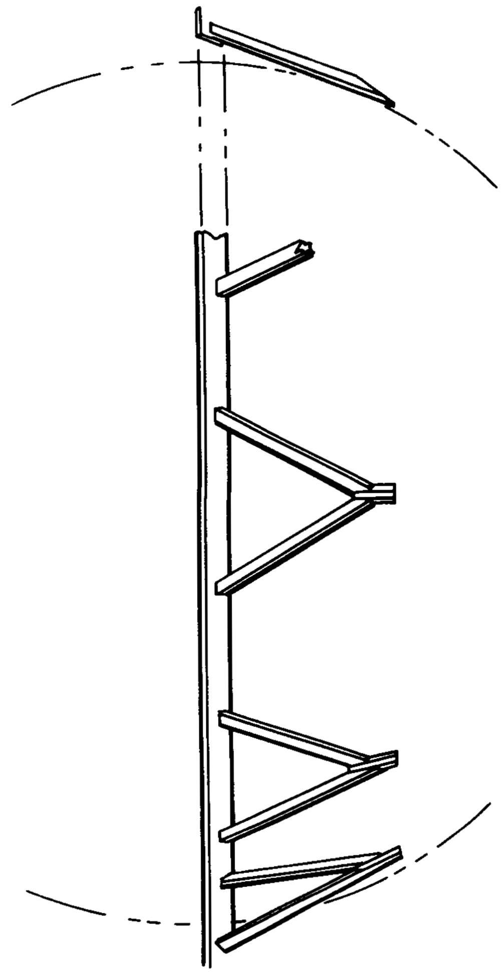
SUBSYSTEM CLASS: TANK SUPPORT STRUCTURE

BASELINE: CONE

ALTERNATES: MULTIPLE A-FRAMES



CONE
(BASELINE)



MULTIPLE A-FRAME

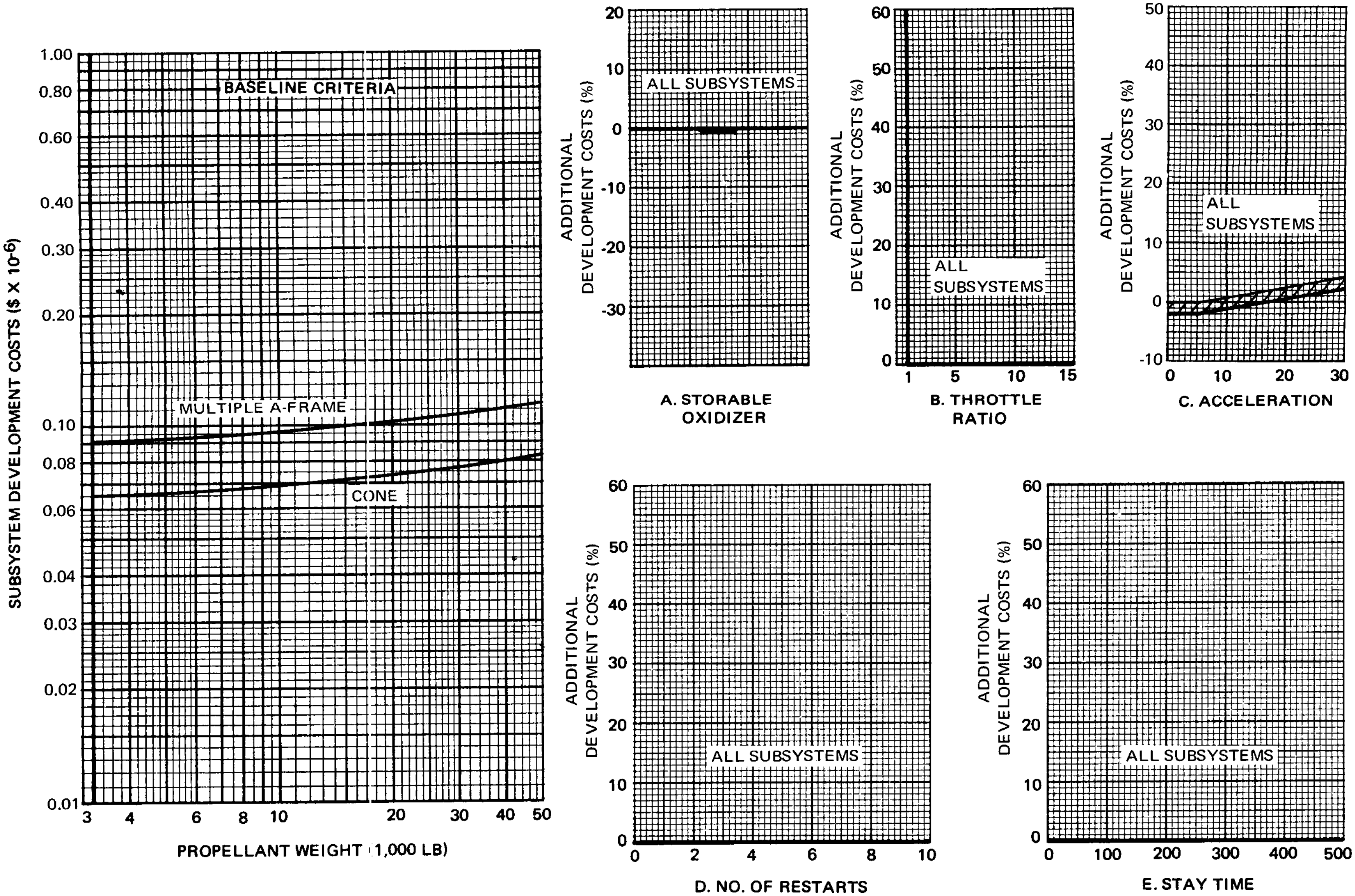
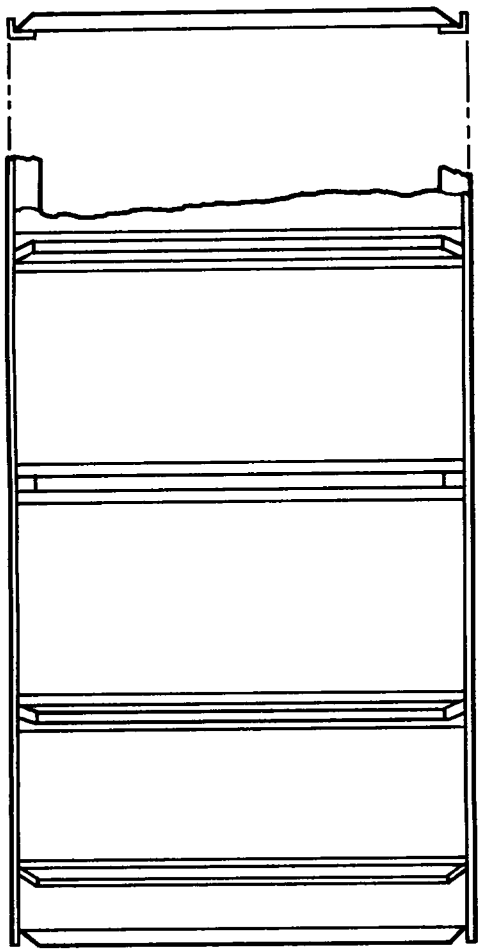
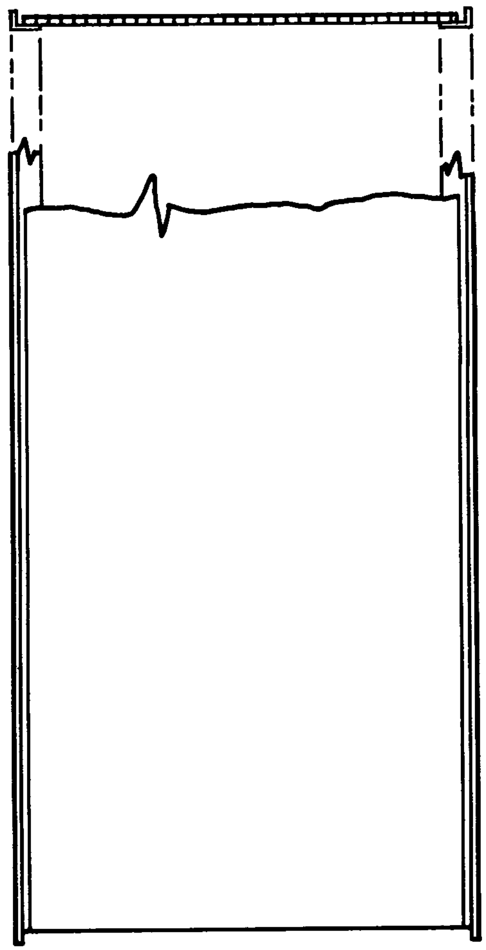


Figure 3-12 Subsystem Development Cost Summary -- Tank Support Structure

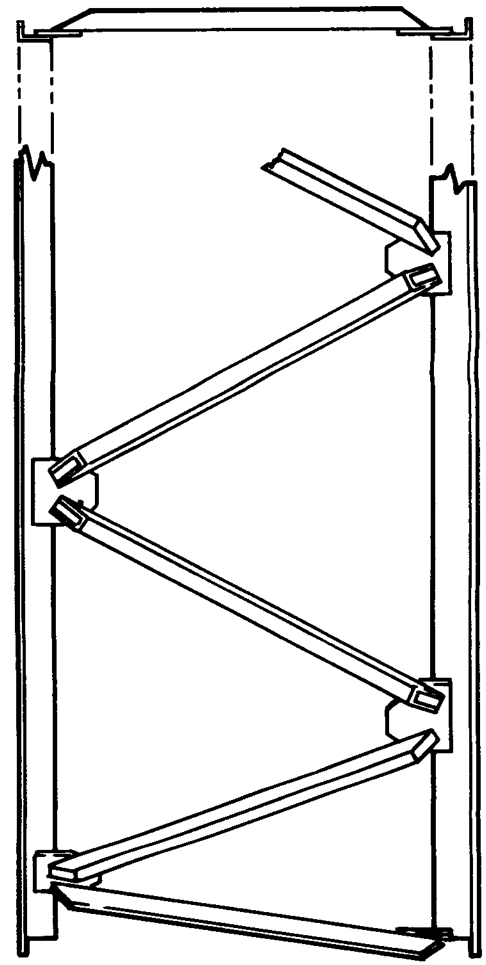
SUBSYSTEM CLASS: PAYLOAD SUPPORT STRUCTURE
BASELINE: SKIN AND STRINGER
ALTERNATES: SANDWICH CONSTRUCTION;
TRUSS CONSTRUCTION



SKIN AND STRINGER
(BASELINE)



SANDWICH



TRUSS

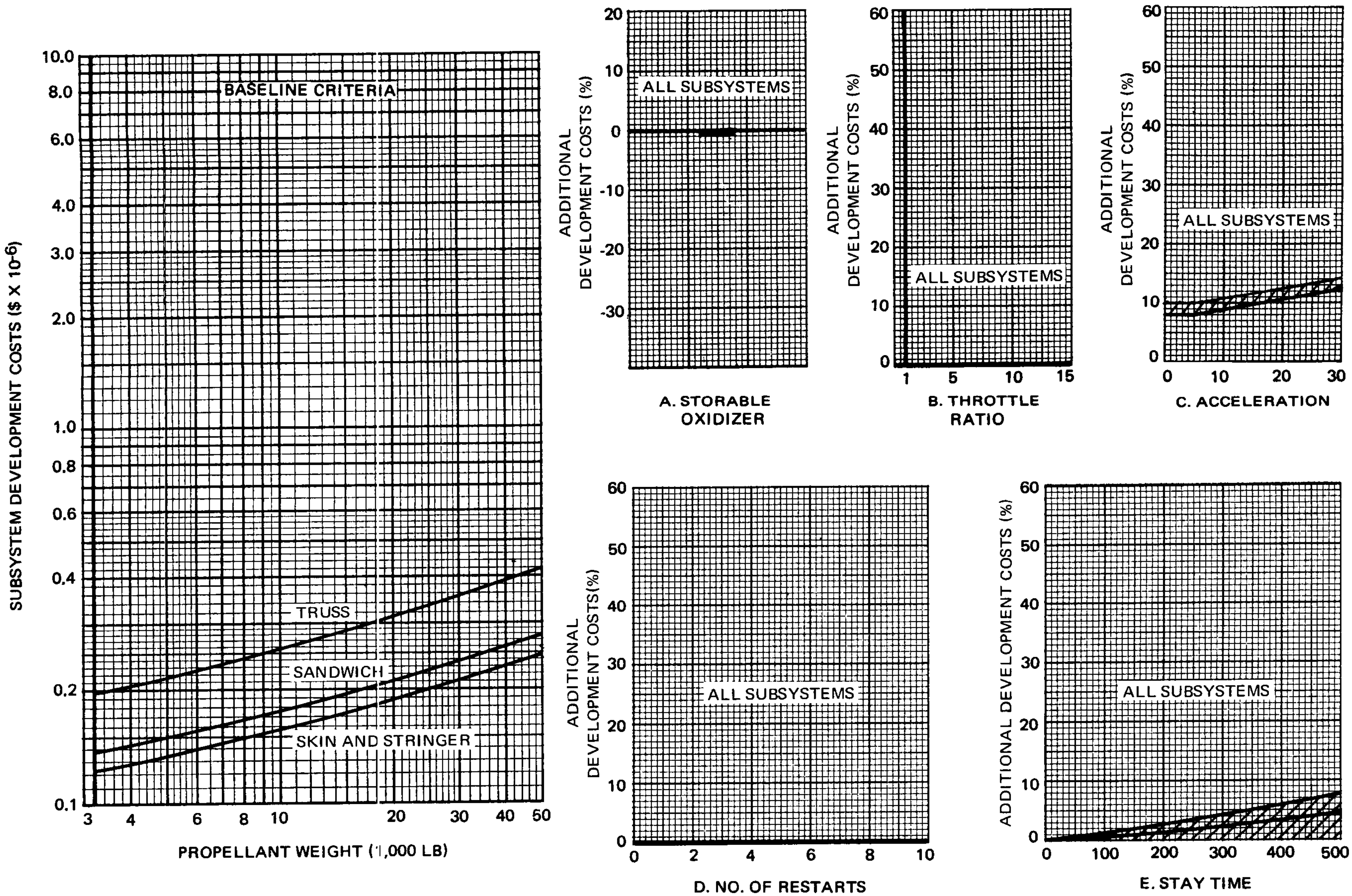
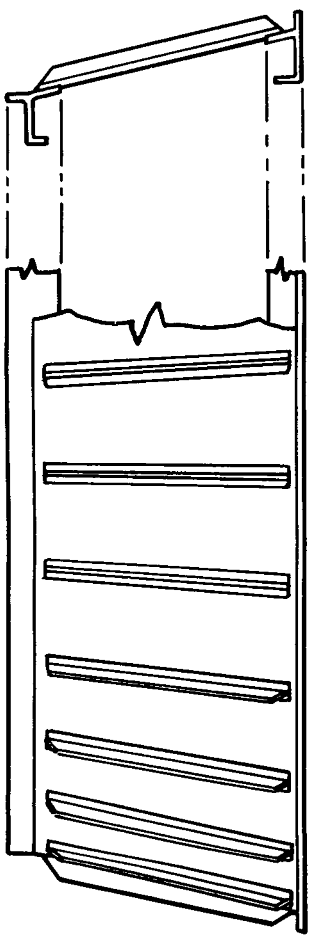
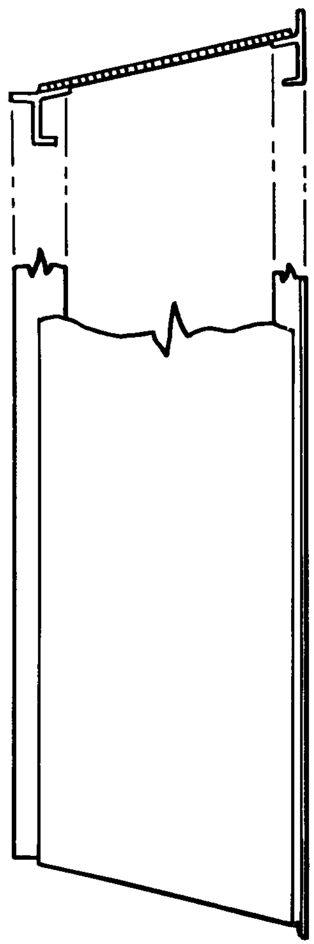


Figure 3-13 Subsystem Development Cost Summary -- Payload Support Structure

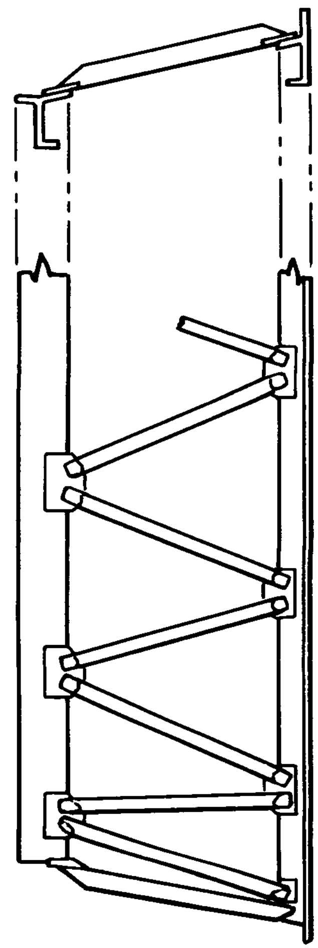
SUBSYSTEM CLASS: INTERSTAGE ADAPTOR
BASELINE: SKIN AND STRINGER
ALTERNATES: SANDWICH CONSTRUCTION;
TRUSS CONSTRUCTION



SKIN AND STRINGER
(BASELINE)



SANDWICH
CONSTRUCTION



TRUSS
CONSTRUCTION

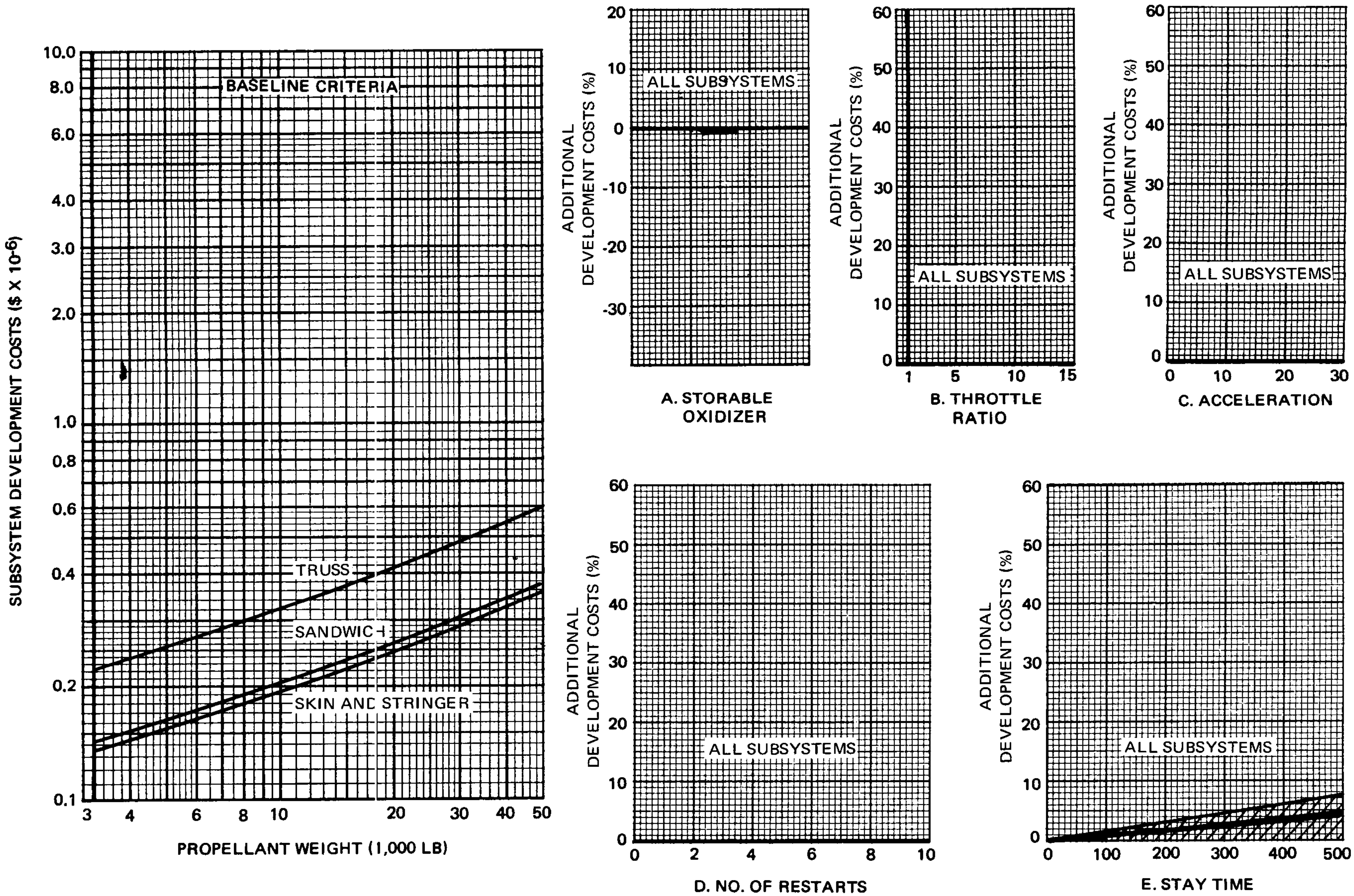


Figure 3-14 Subsystem Development Cost Summary -- Interstage Adaptor

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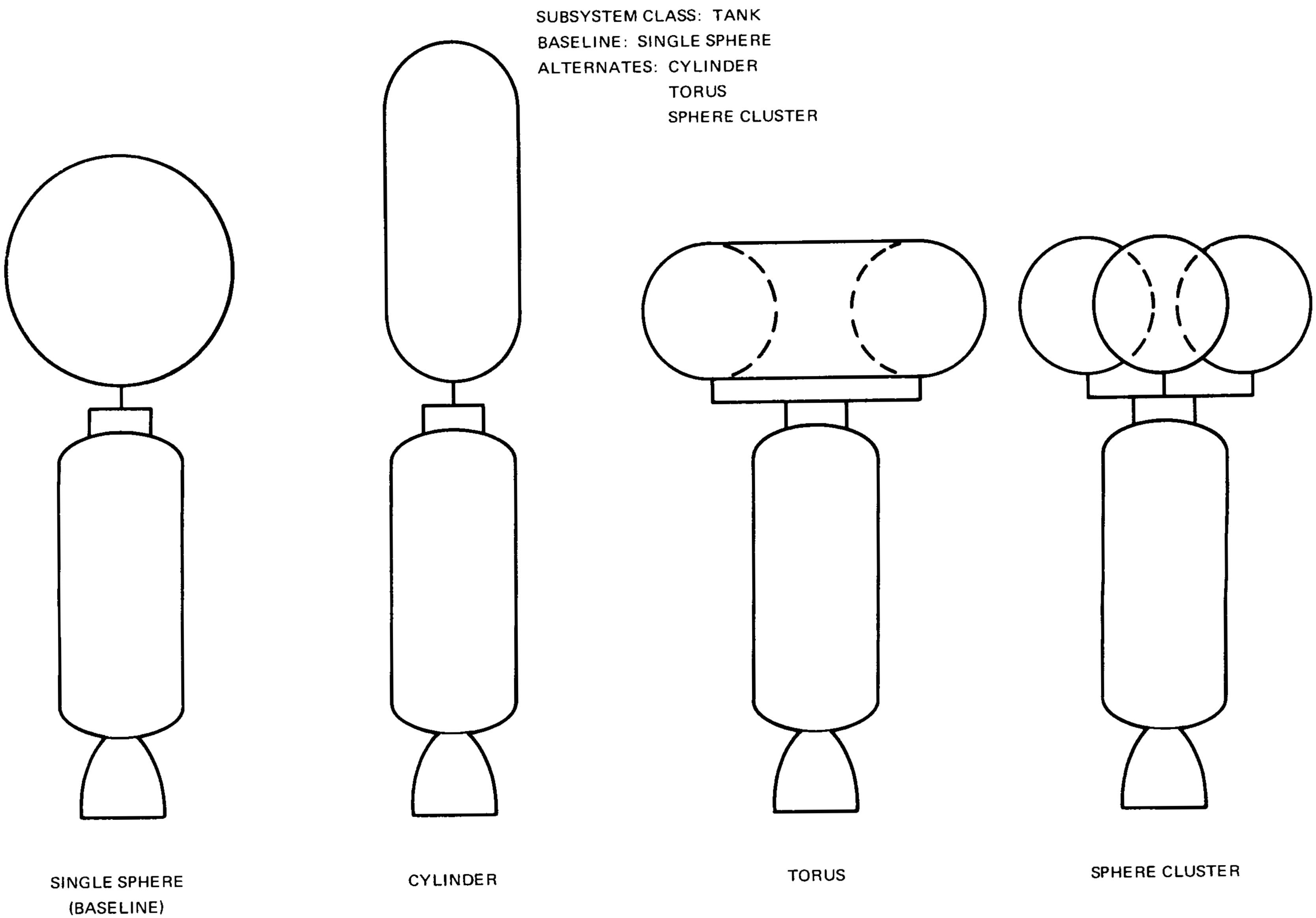
3.2 UNIT COSTS

Subsystem unit costs, shown in Figures 3-15 through 3-28, reflect the costs associated with procurement of developed hardware. Although such information is of prime importance in production cost estimates, the data also play a role in the system development phase where production type subsystems are used for system integration tests.

Unit costs were obtained from empirical data where fabricated subassemblies, such as structure and tankage, were estimated. For purchased parts, such as valves and pressure regulators, costs were obtained from records of purchase orders for similar parts.


SUBSYSTEM CLASS: TANK
BASELINE: SINGLE SPHERE
ALTERNATES: CYLINDER
TORUS
SPHERE CLUSTER
SINGLE SPHERE
(BASELINE)
CYLINDER
TORUS
SPHERE CLUSTER

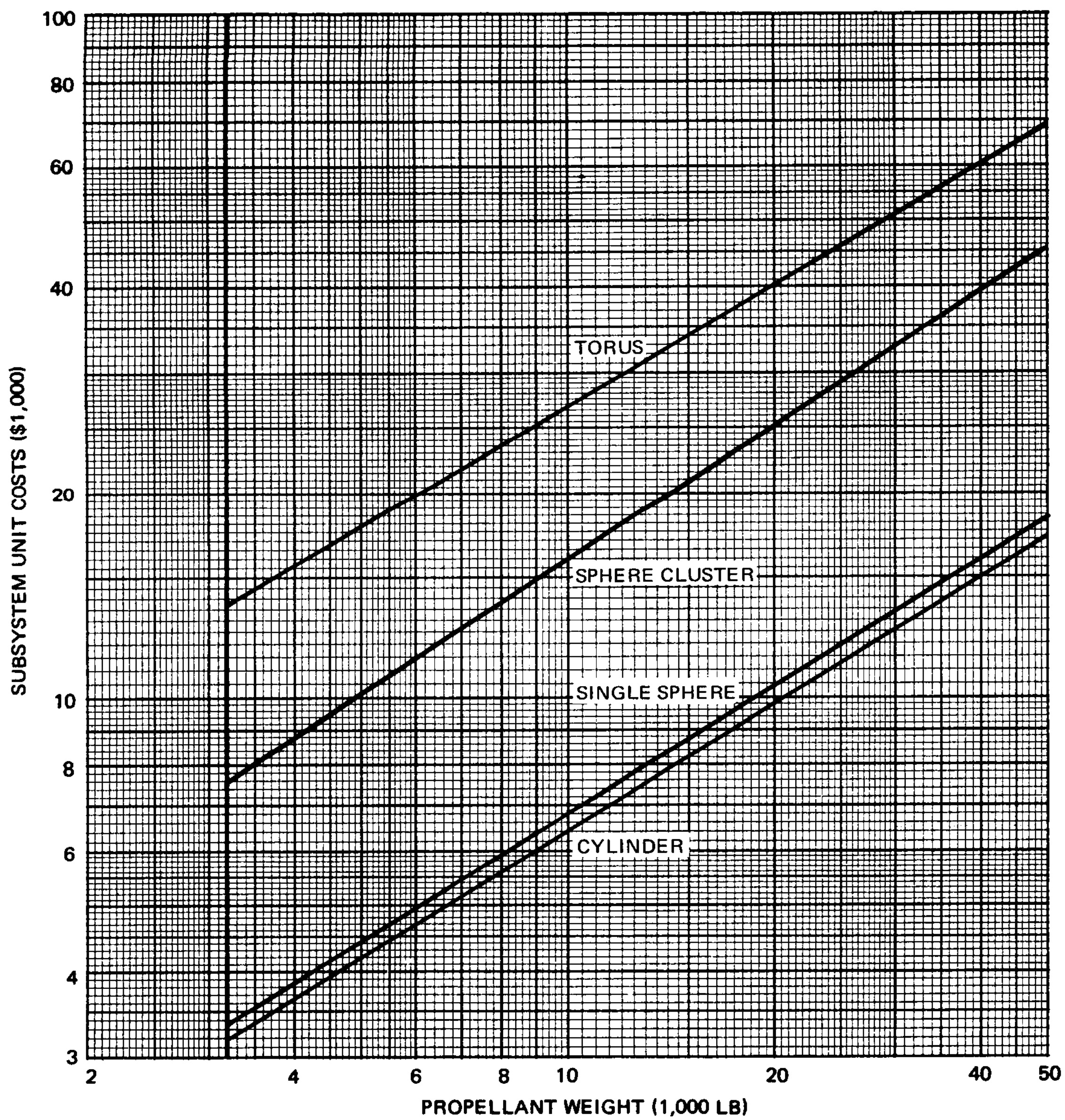
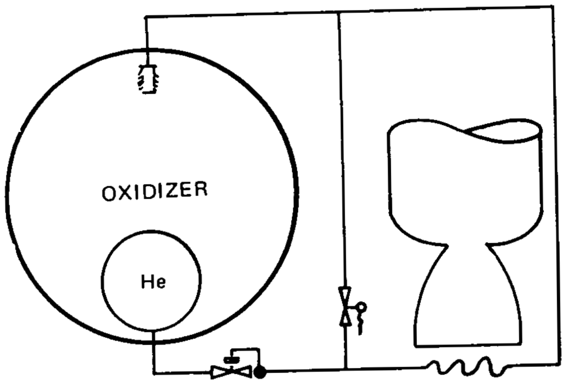
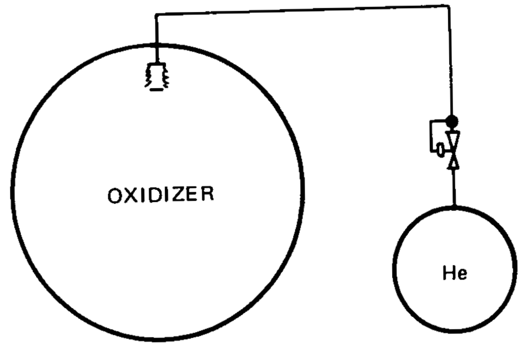


Figure 3-15 Subsystem Unit Cost Summary -- Tank

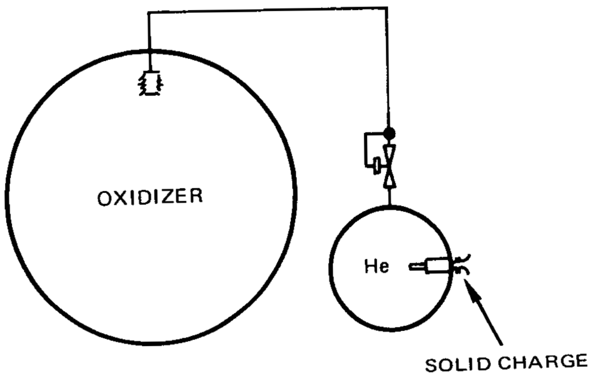
SUBSYSTEM CLASS: EXPULSION SYSTEM
BASELINE: HEATED HELIUM (NOZZLE HEAT EXCHANGER)
ALTERNATES: AMBIENT HELIUM
CARTRIDGE - AUGMENTED He
GAS - GENERATOR - AUGMENTED He
TURBOPUMP



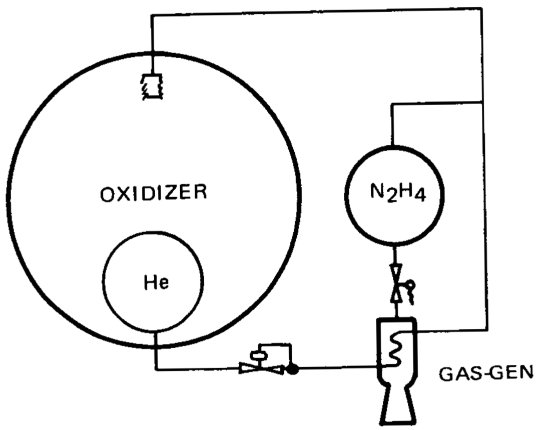
COLD-STORED, ENGINE-HEATED He
(BASELINE)



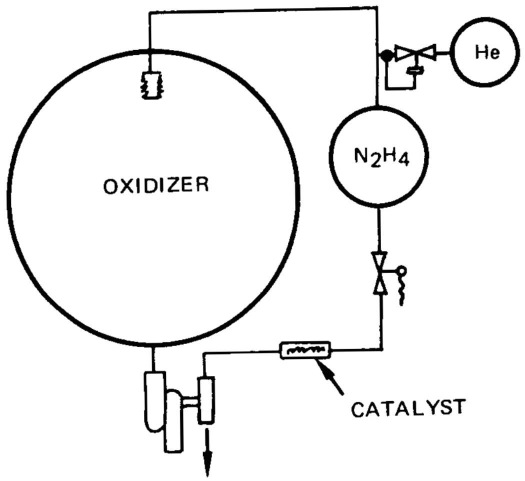
AMBIENT He



AMBIENT He WITH SOLID-
CHARGE AUGMENTATION



COLD-STORED, GAS-GEN
HEATED HELIUM



AMBIENT He WITH
HYDRAZINE DRIVEN
TURBOPUMP

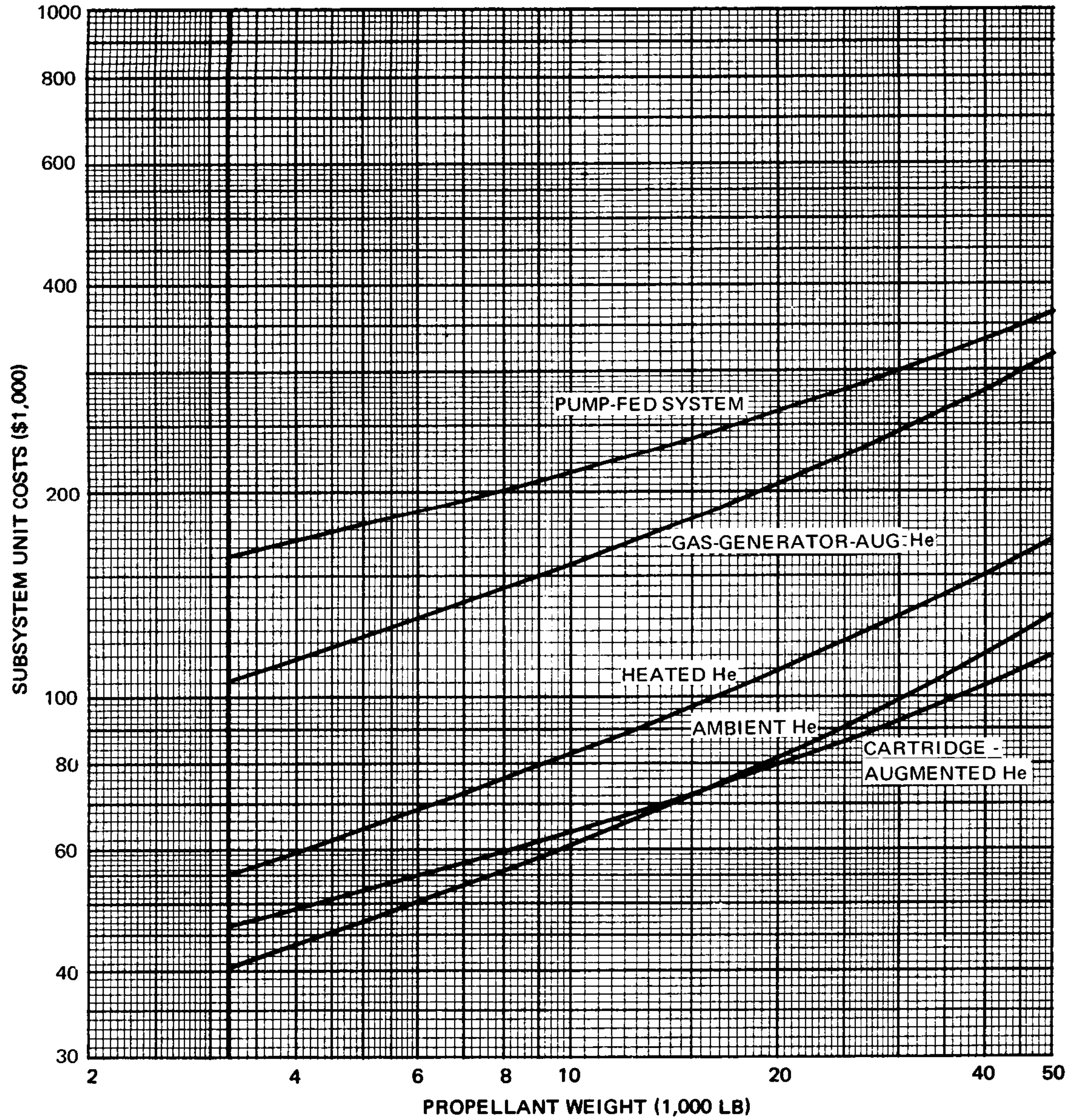
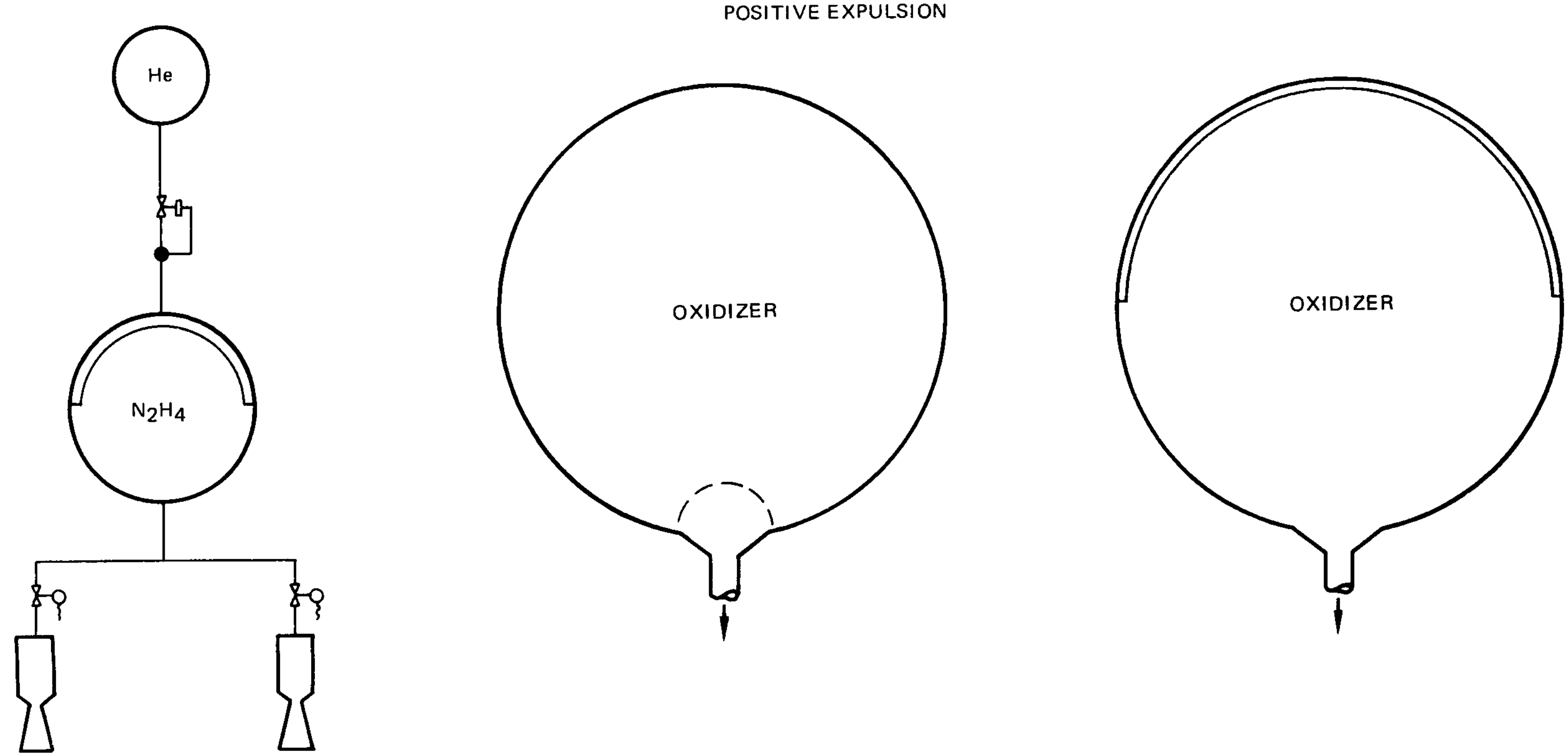


Figure 3-16 Subsystem Unit Cost Summary -- Expulsion System

SUBSYSTEM CLASS: PROPELLANT SETTLING
BASELINE: ULLAGE ROCKETS
ALTERNATES: SCREEN
POSITIVE EXPULSION



HYDRAZINE SETTLING MOTORS

(BASELINE)

SCREEN IN TANK SUMP

MAIN TANK EXPULSION DIAPHRAGM

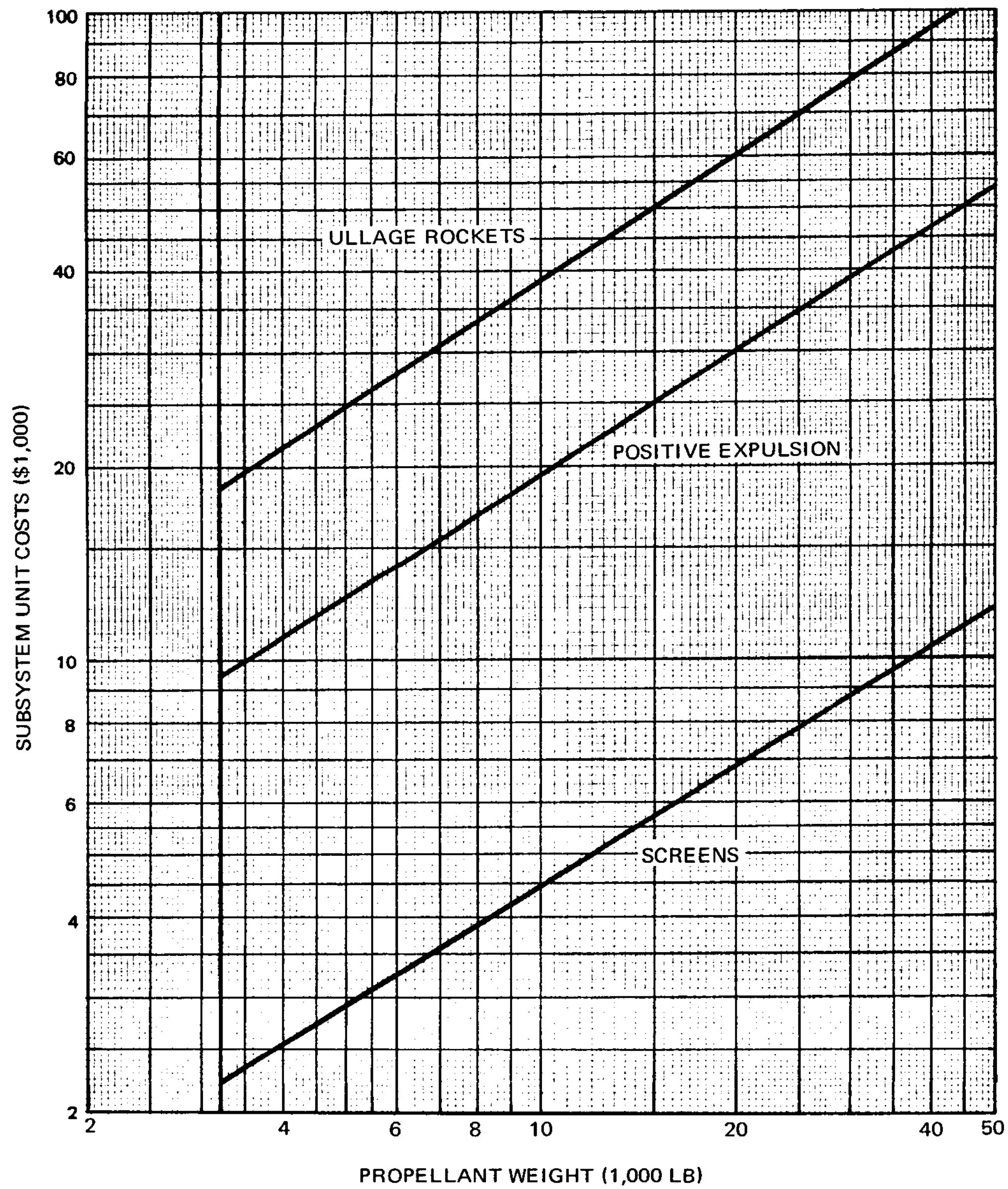
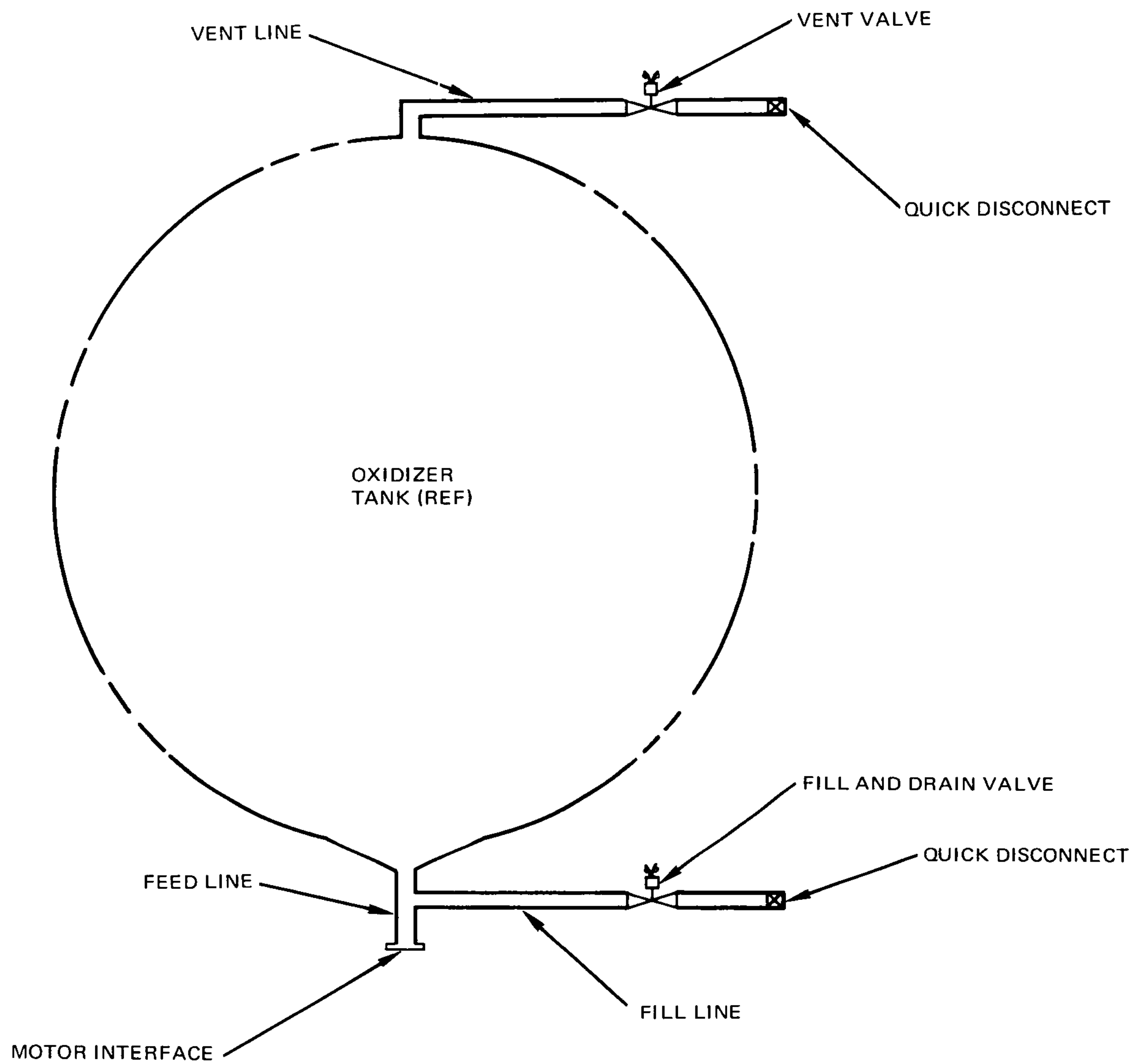


Figure 3-17 Subsystem Unit Cost Summary -- Propellant Settling

FILL, FEED AND VENT SYSTEM



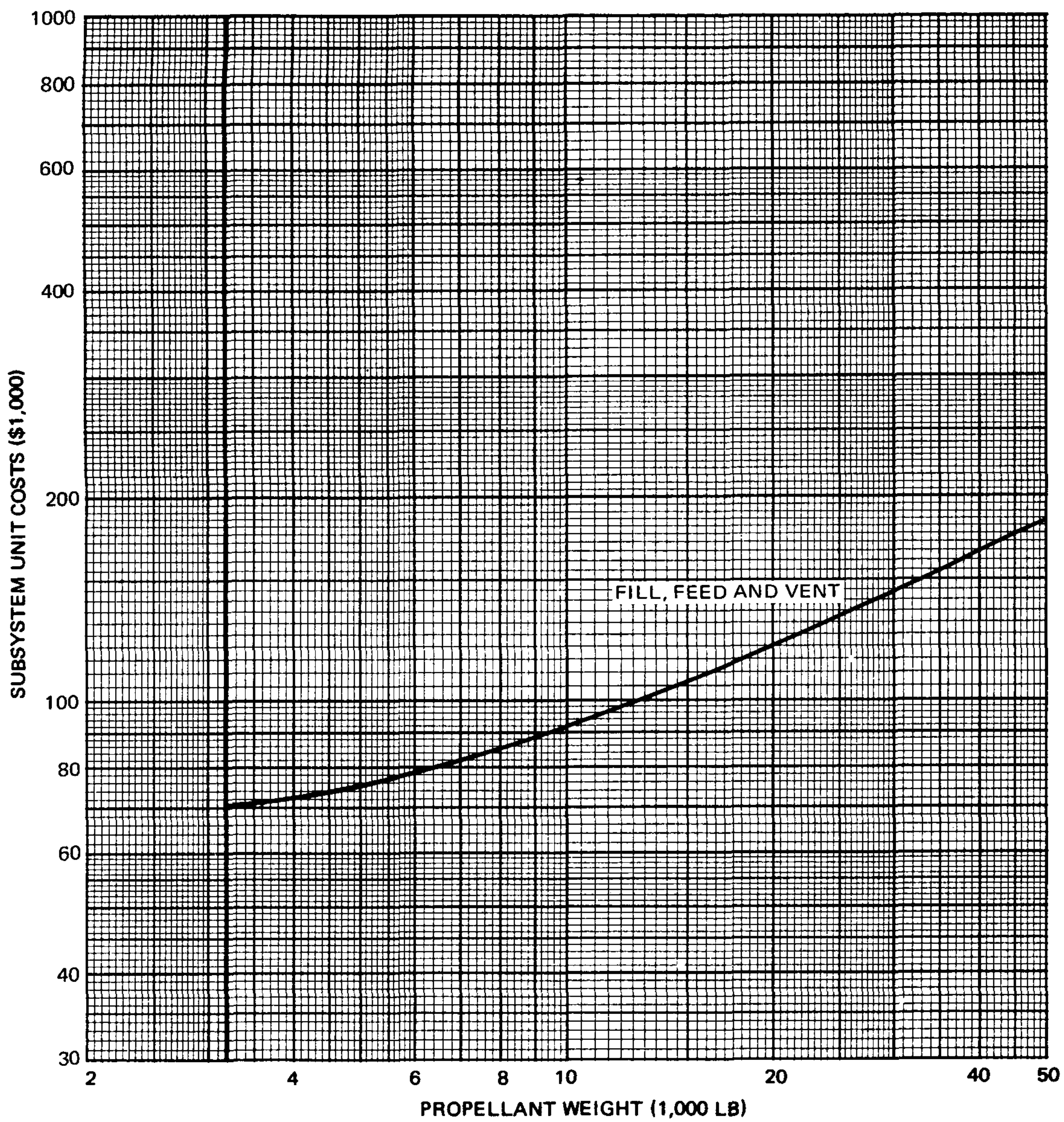
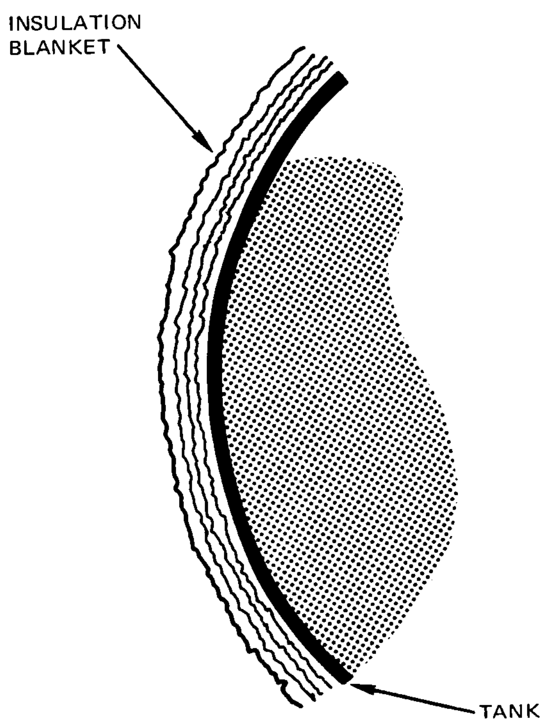
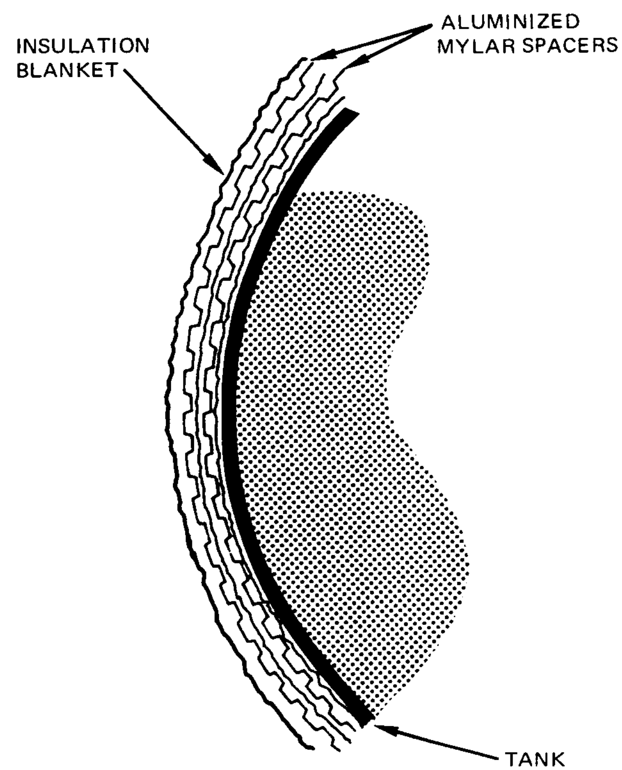


Figure 3-18 Subsystem Unit Cost Summary -- Fill, Feed, and Vent

SUBSYSTEM CLASS: INSULATION
BASELINE: UNINSULATED
ALTERNATES: TANK-MOUNTED NRC-2
TANK-MOUNTED DIMPLAR



TANK-MOUNTED NRC-2



TANK-MOUNTED DIMPLAR

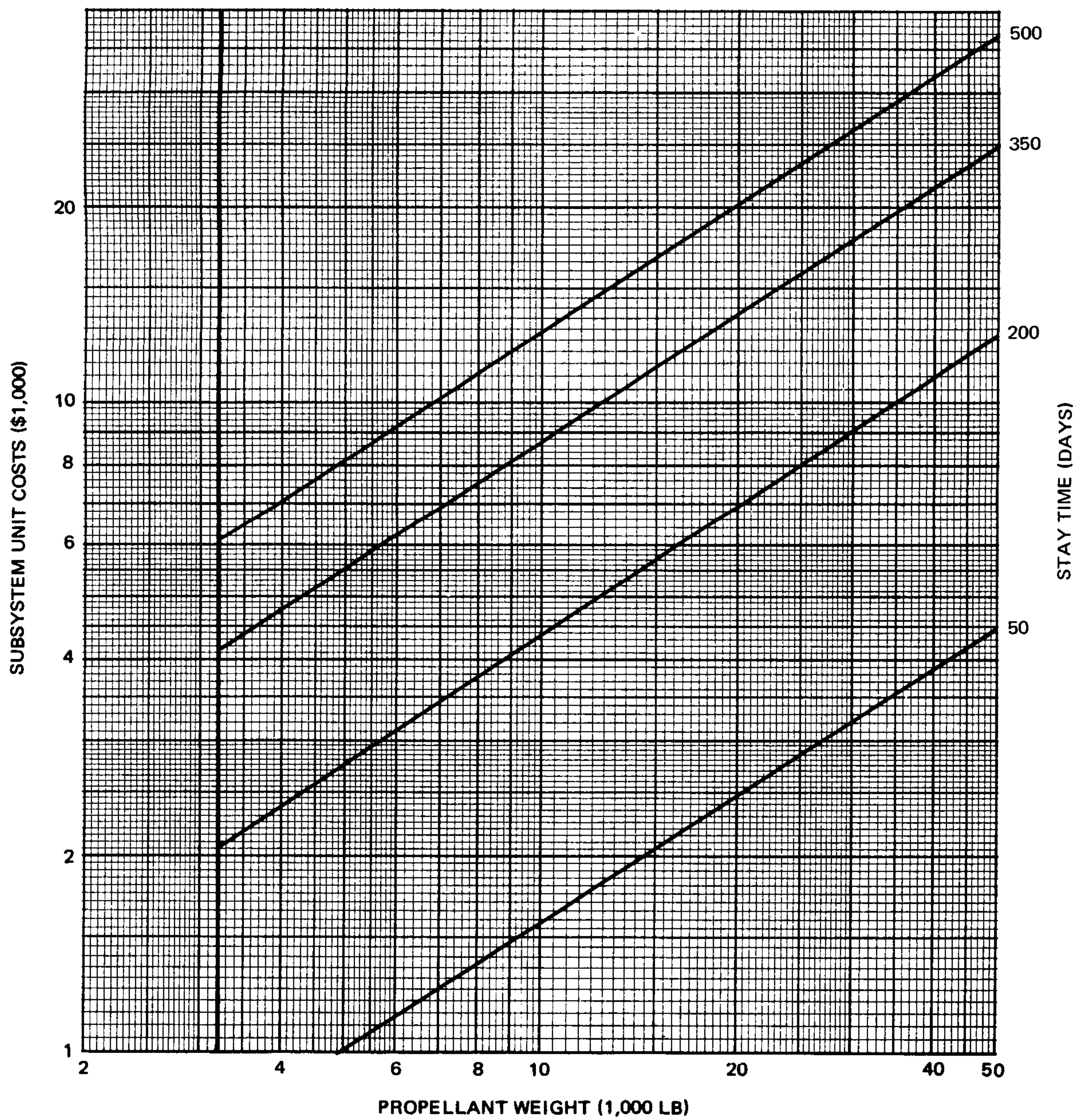
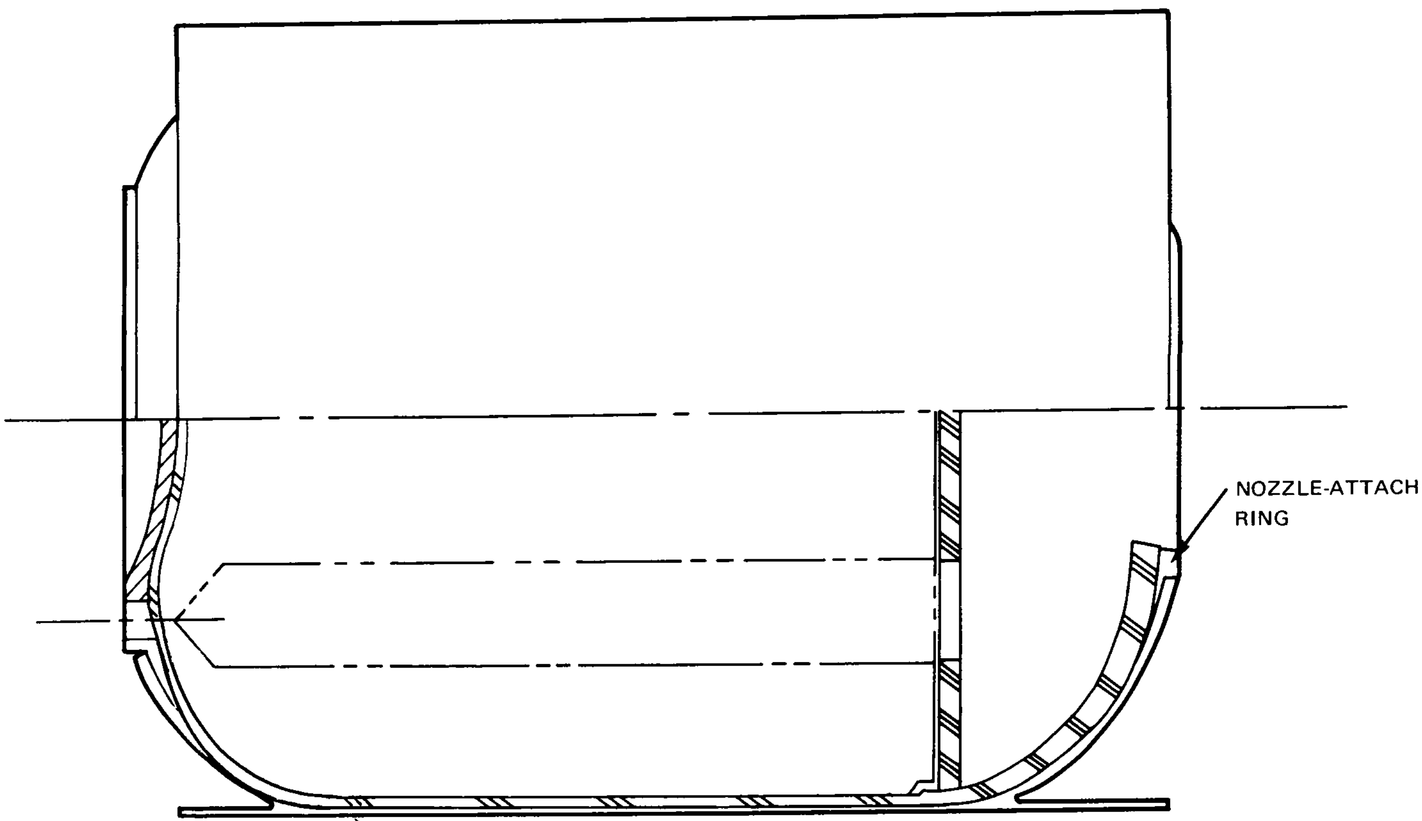


Figure 3-19. Subsystem Unit Cost Summary – Insulation

SUBSYSTEM CLASS: COMBUSTION CHAMBER
BASELINE: FIBER GLASS
ALTERNATES: HIGH-STRENGTH STEEL
TITANIUM



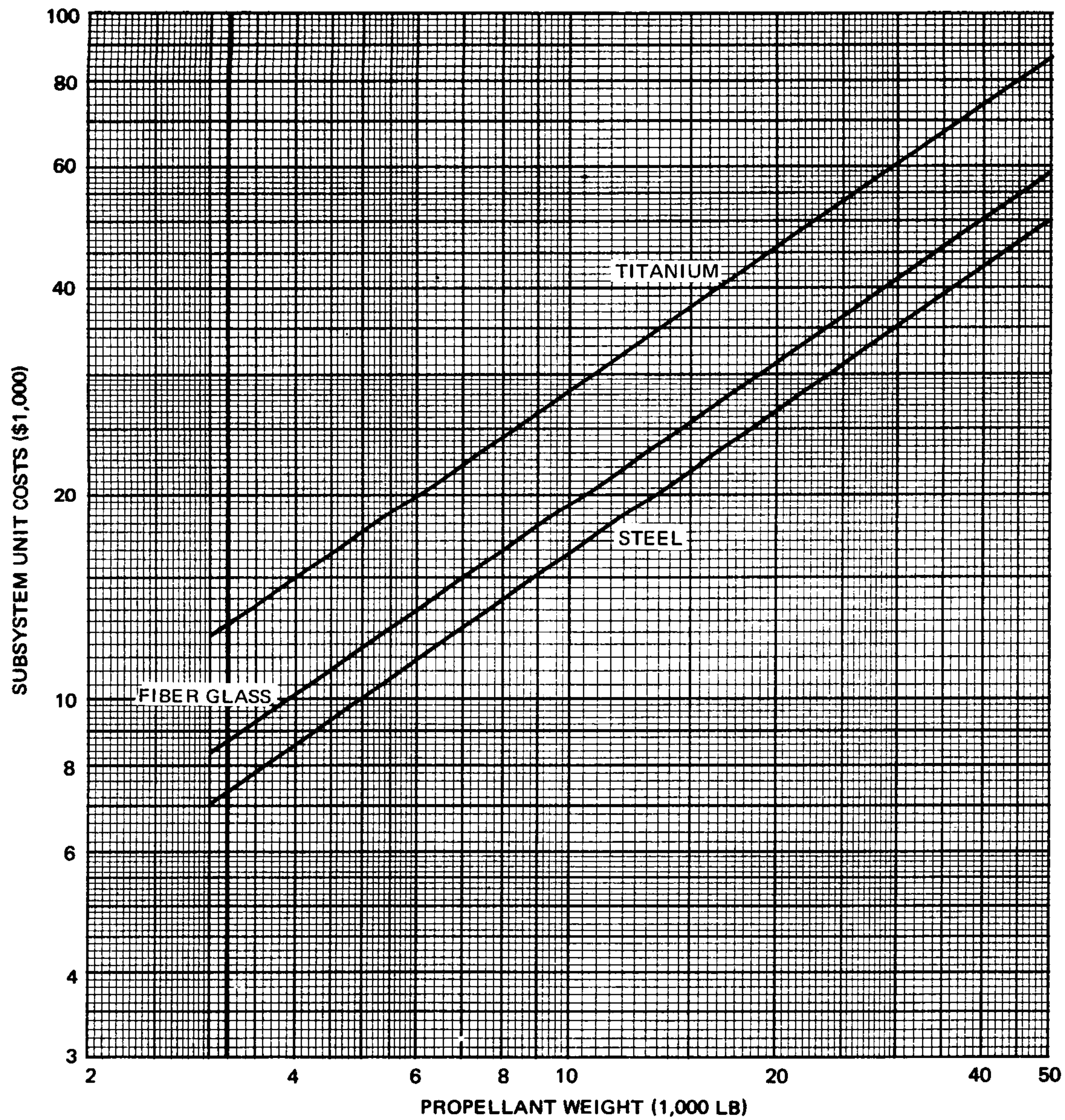
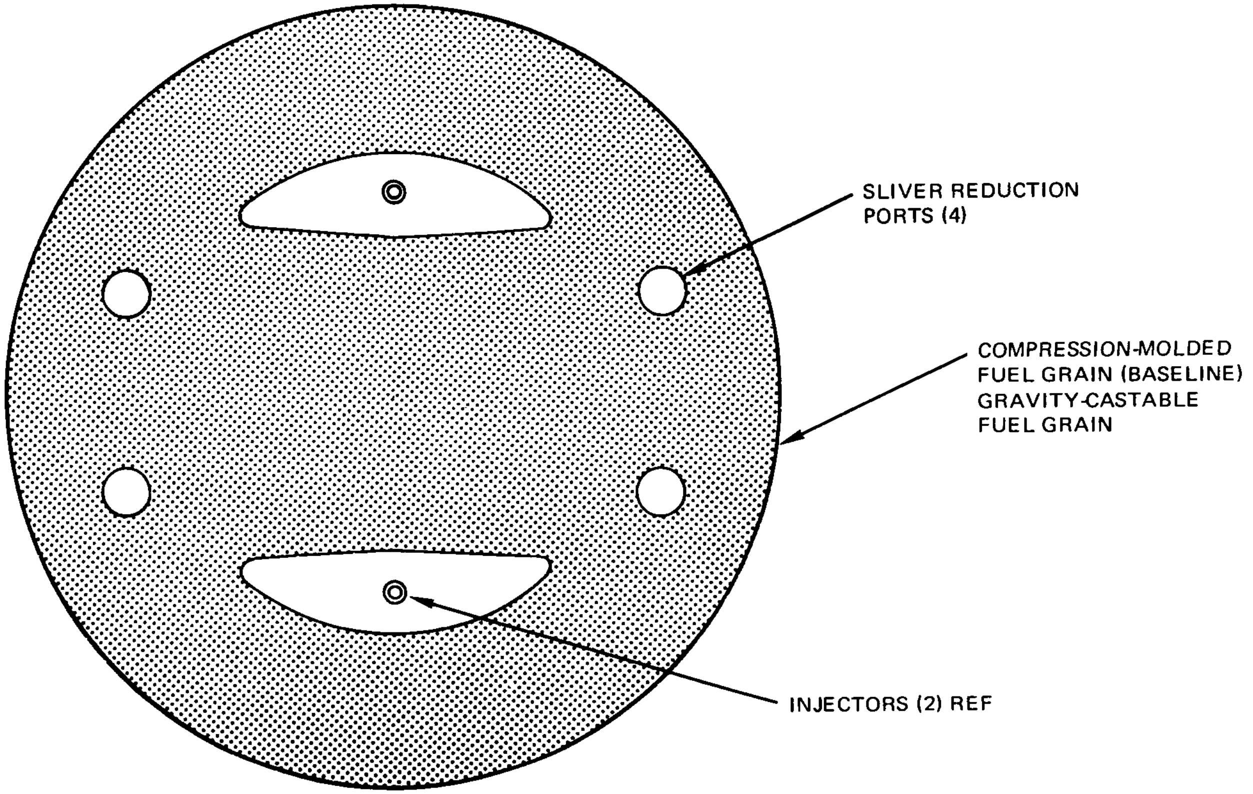


Figure 3-20 Subsystem Unit Cost Summary -- Combustion Chamber

SUBSYSTEM CLASS: FUEL GRAIN
BASELINE: COMPRESSION MOLDED
ALTERNATES: GRAVITY CASTABLE



NOTE: REPRESENTATIVE GRAIN DESIGN ILLUSTRATED. REASONABLE CHANGES IN GRAIN DESIGN WILL NOT SIGNIFICANTLY AFFECT COSTS.

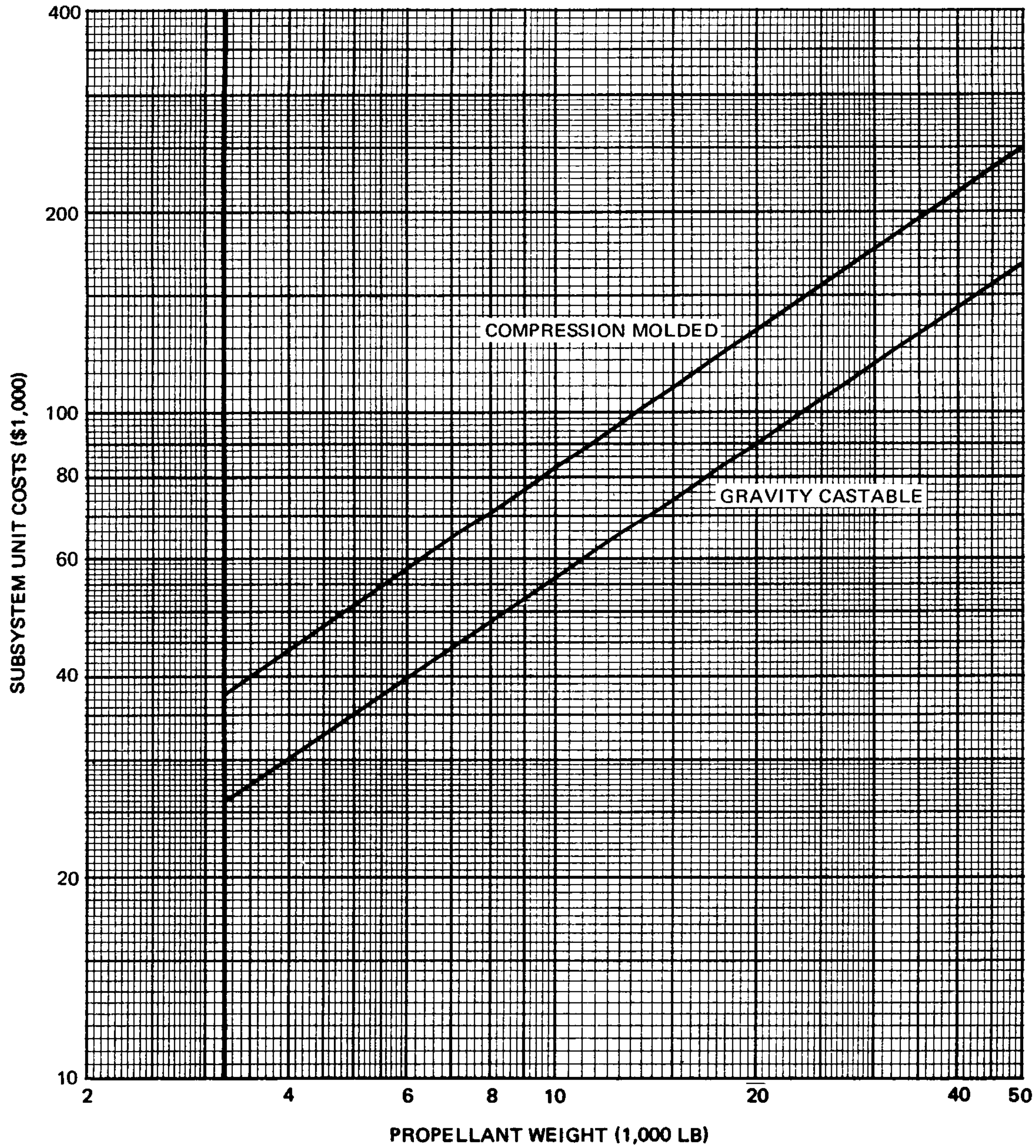
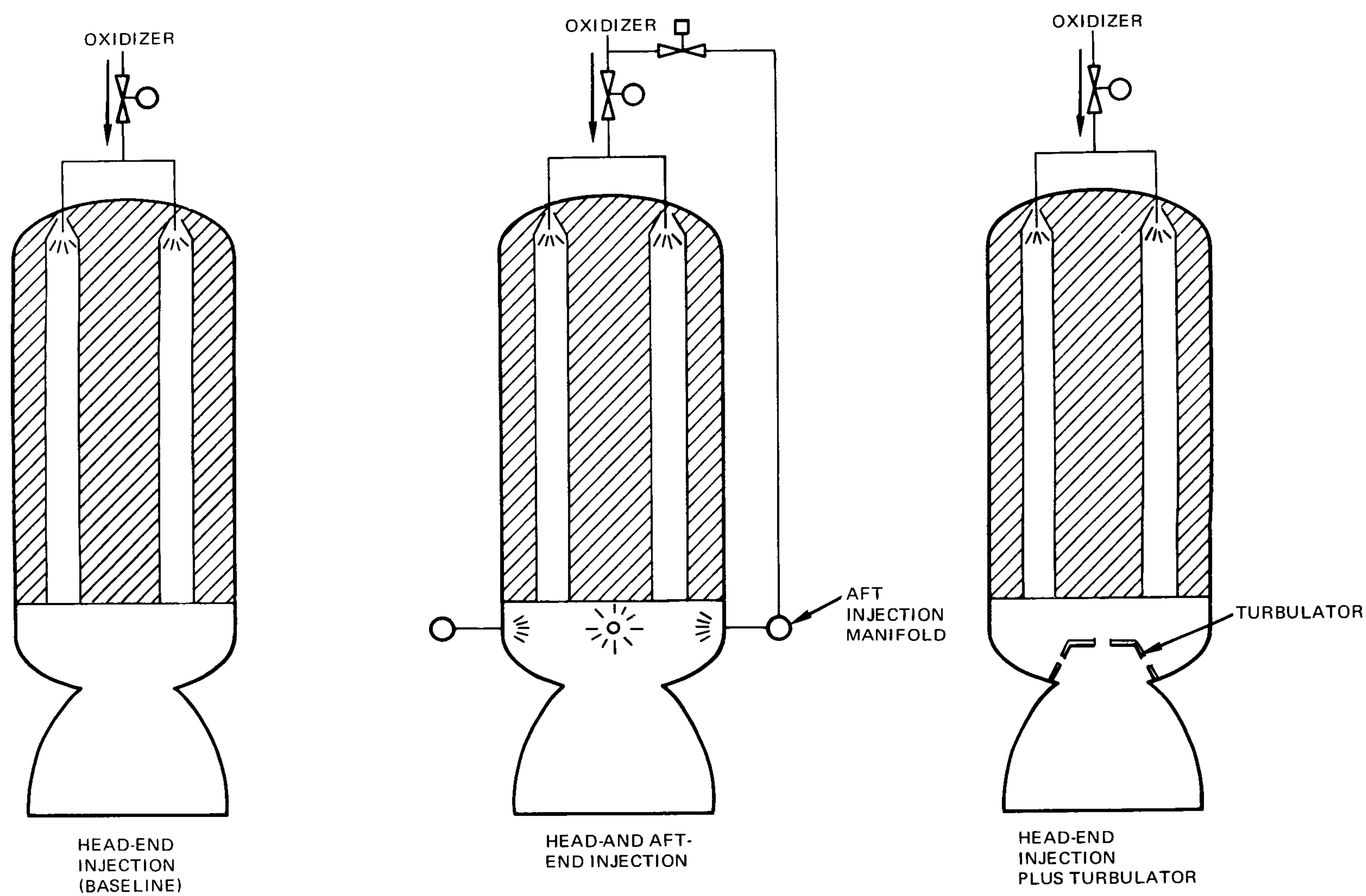


Figure 3-21 Subsystem Unit Cost Summary -- Fuel Grain and Insulation

SUBSYSTEM CLASS: INJECTION SYSTEM
BASELINE: HEAD END - ONLY
ALTERNATES: HEAD END + AFT END INJECTION
HEAD END INJECTION + TURBULATOR



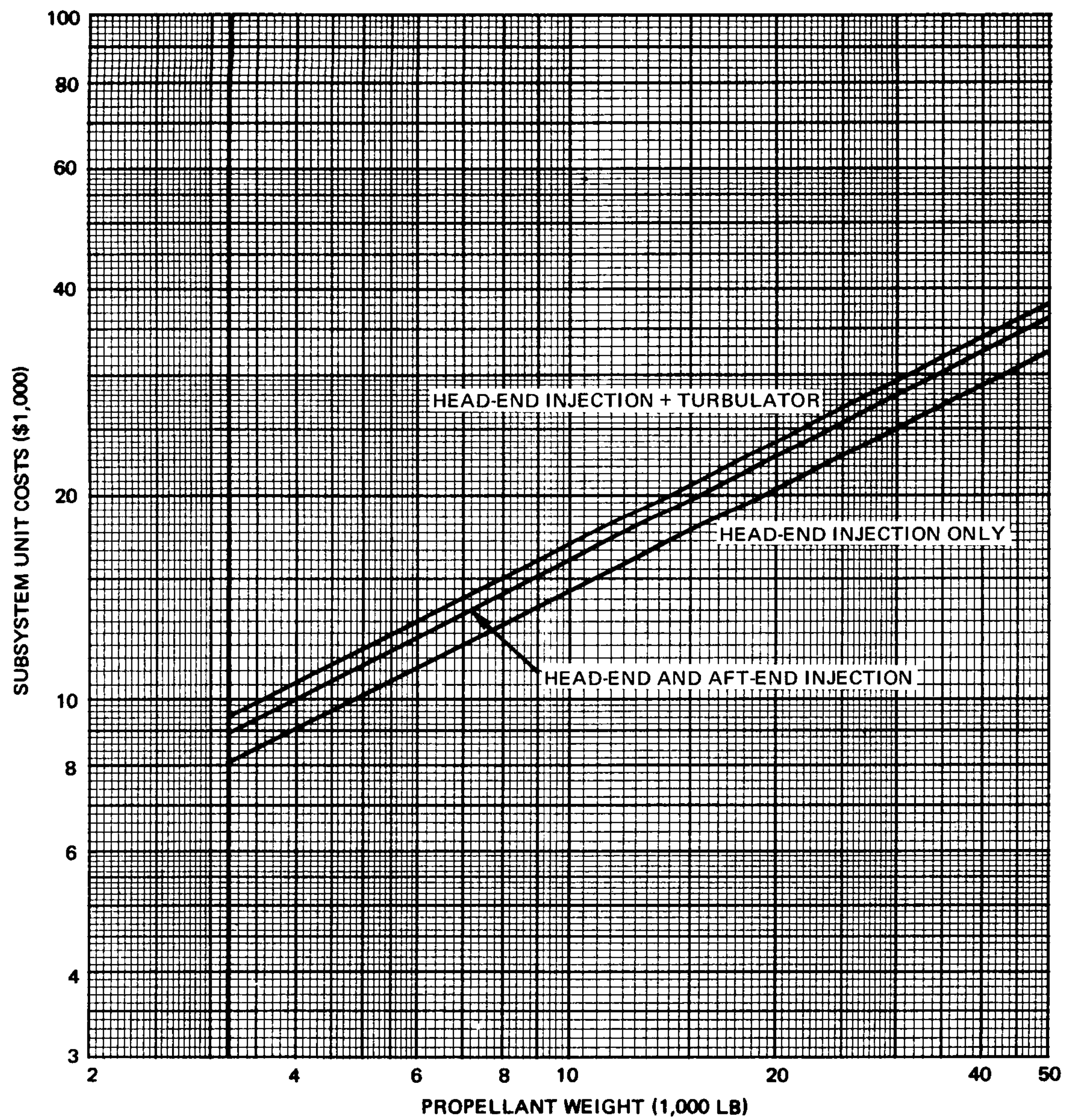
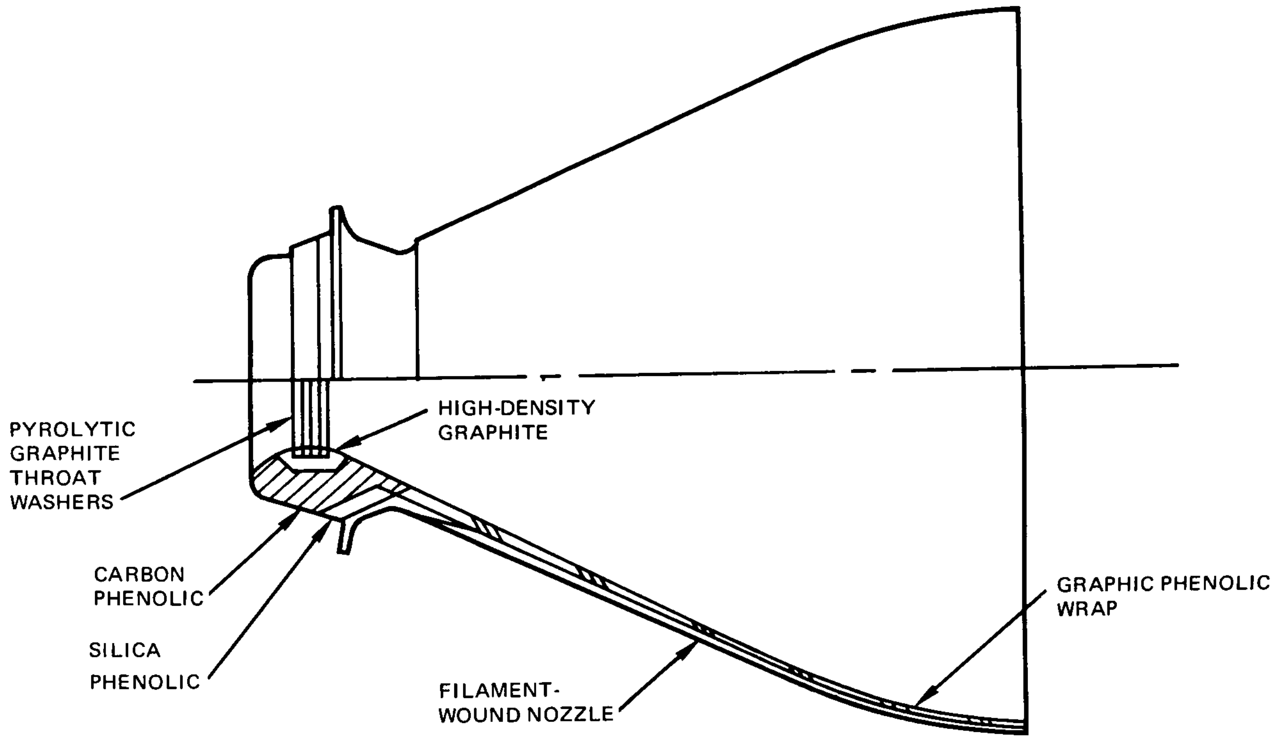


Figure 3-22 Subsystem Unit Cost Summary -- Injection System

SUBSYSTEM CLASS: NOZZLE

BASELINE: ABLATIVE

NO ALTERNATE CONFIGURATIONS



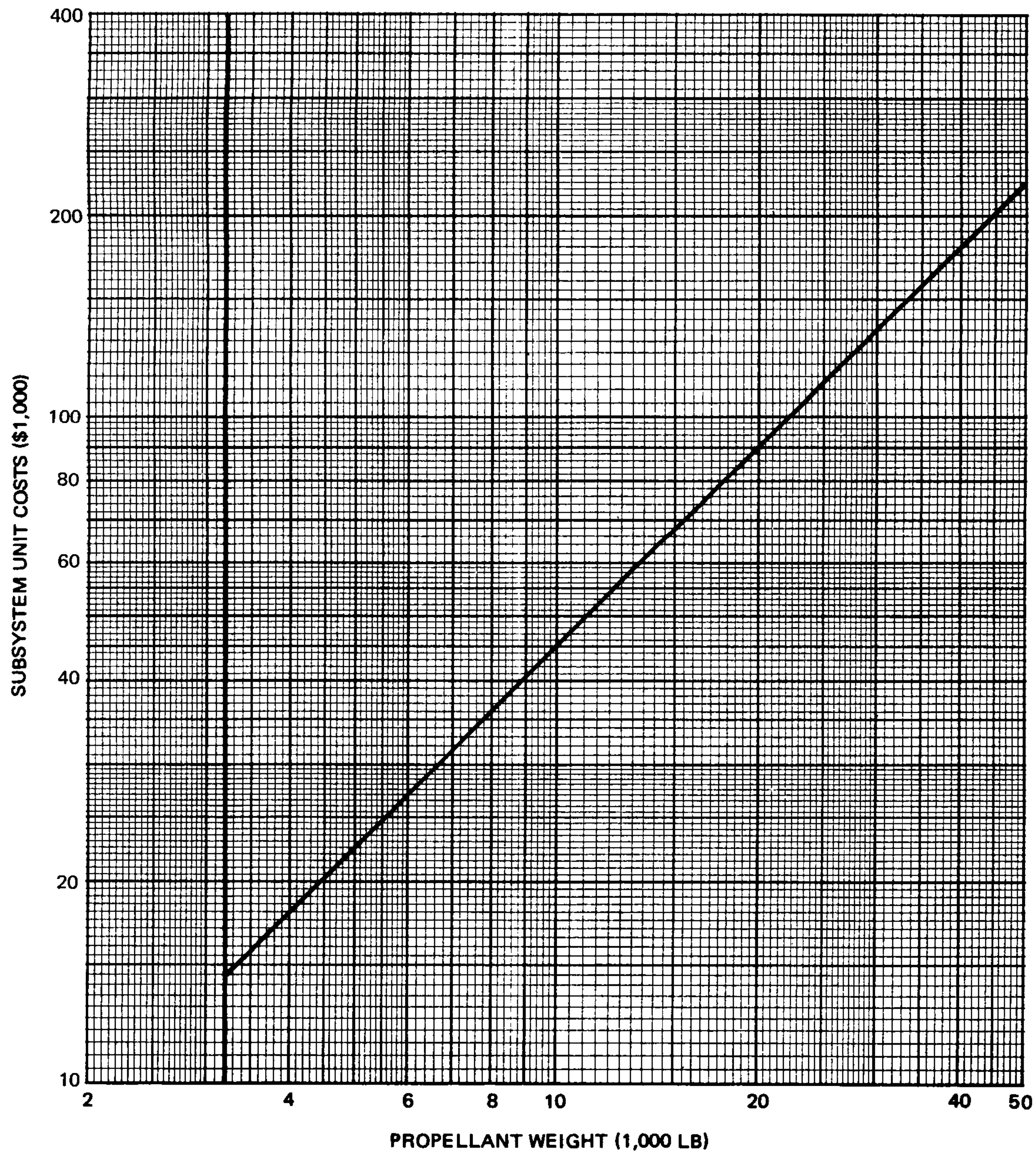
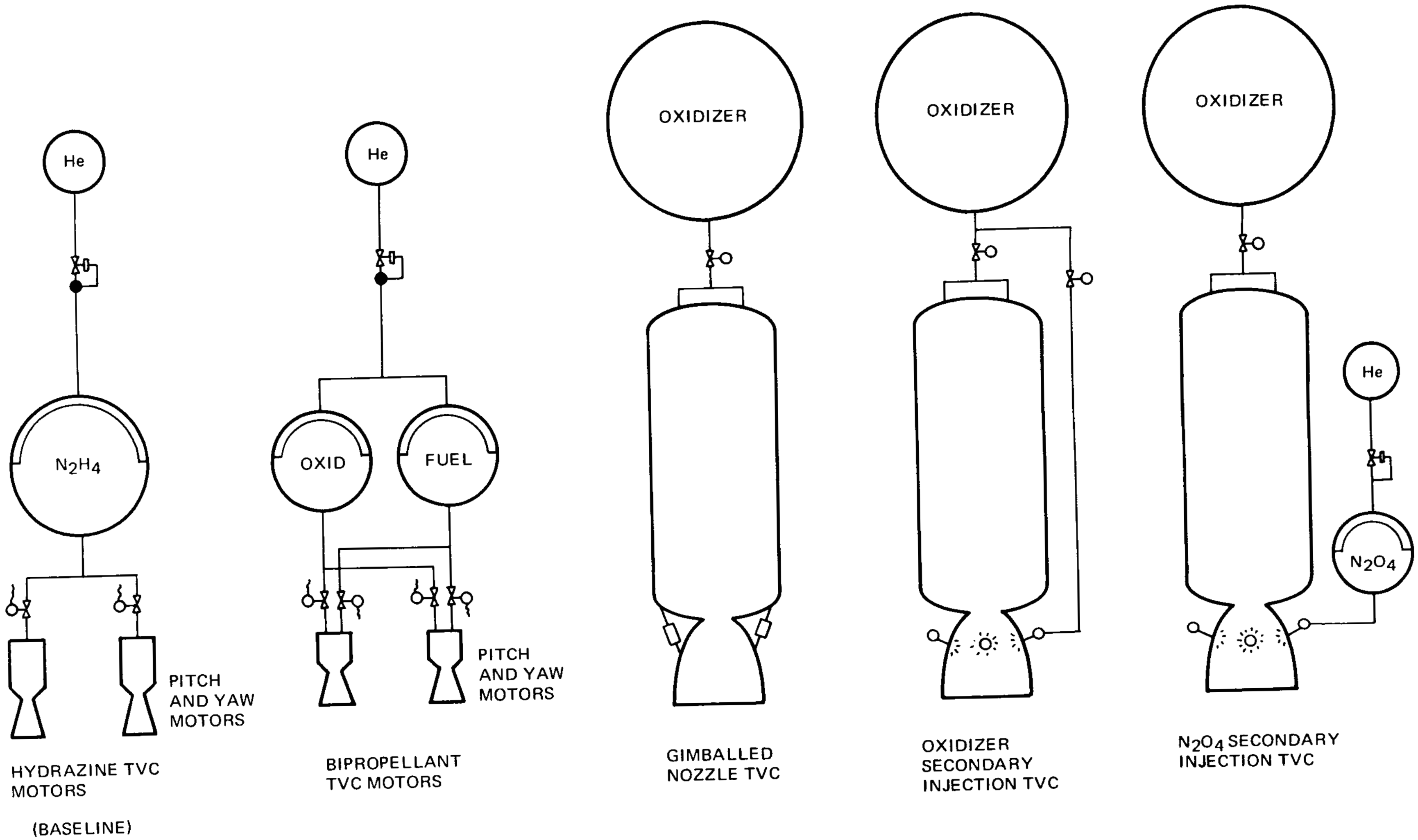


Figure 3-23 Subsystem Unit Cost Summary -- Nozzle

SUBSYSTEM CLASS: THRUST VECTOR CONTROL
BASELINE: MONOPROPELLANT RCS
ALTERNATES: GIMBALLED NOZZLE
N_2O_4 SECONDARY INJECTION
OXIDIZER SECONDARY INJECTION
BIPROPELLANT RCS



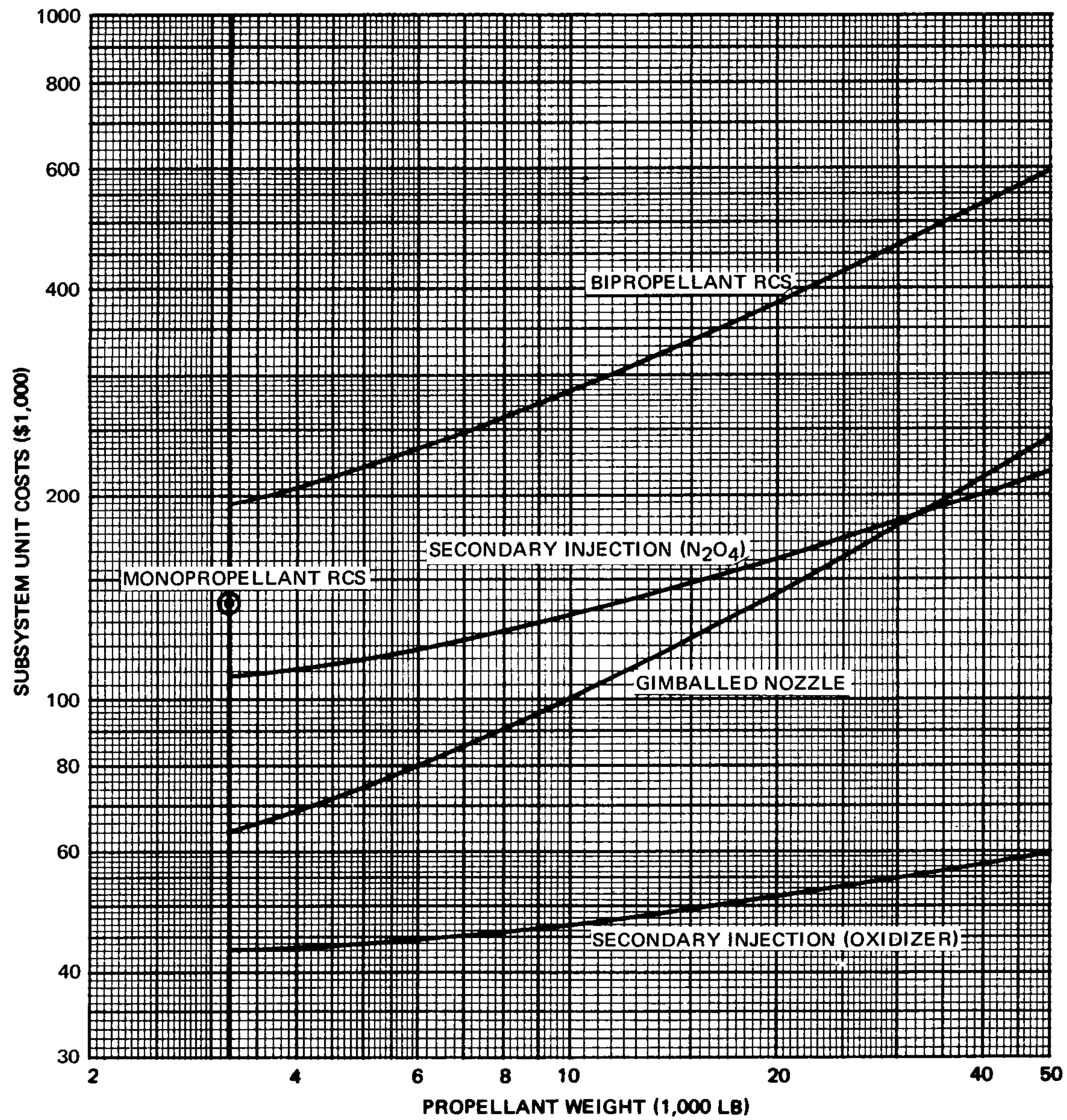
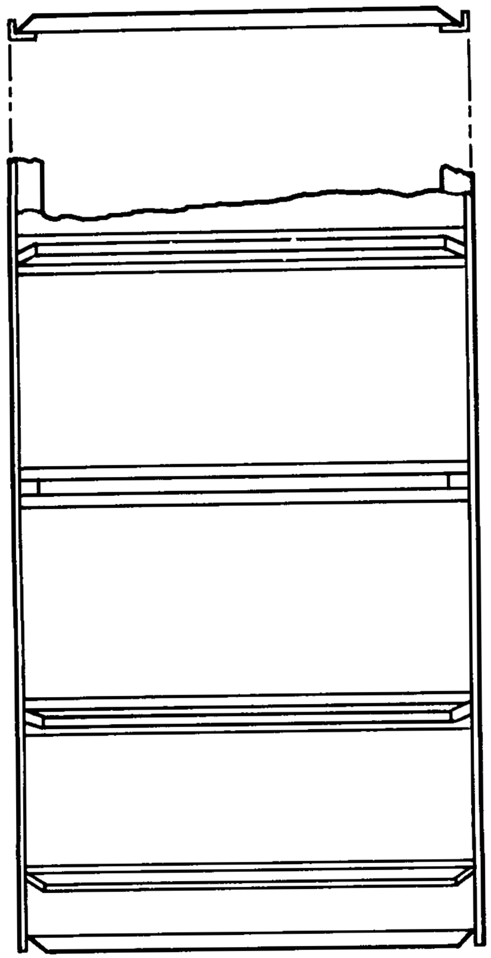
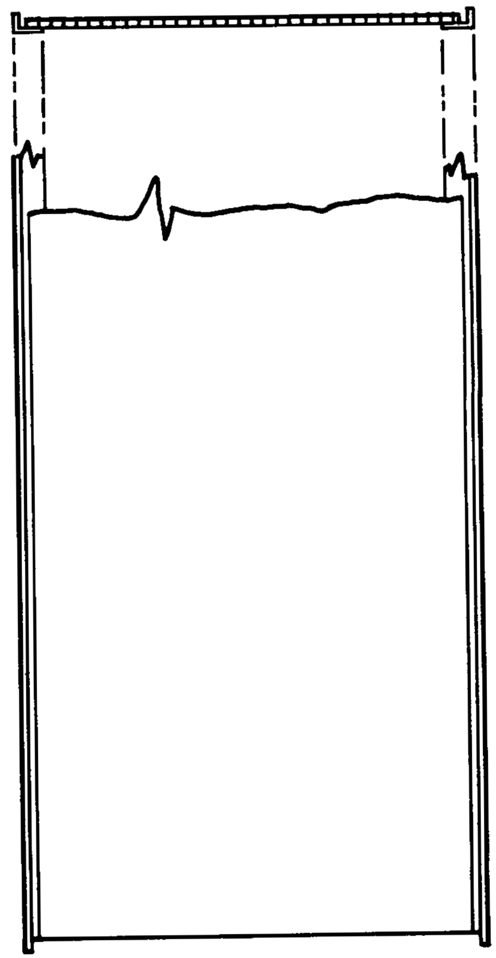


Figure 3-24 Subsystem Unit Cost Summary -- Thrust Vector Control

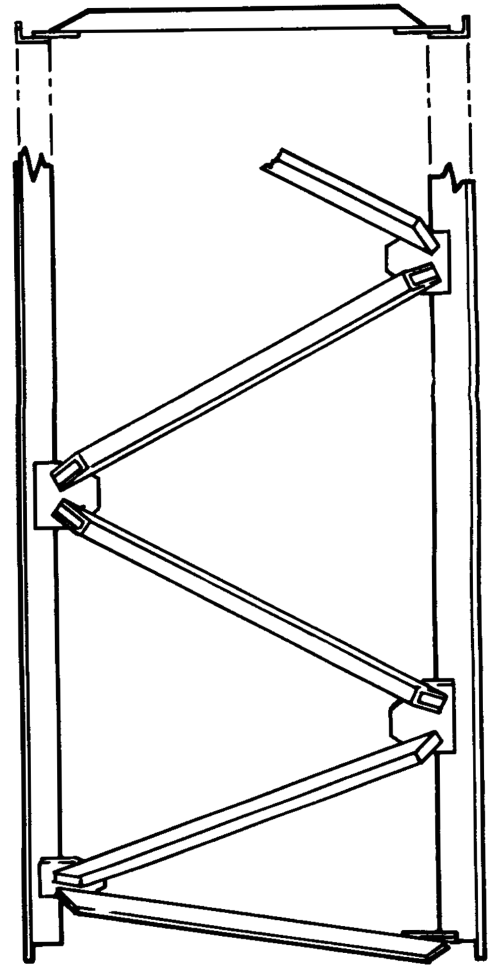
SUBSYSTEM CLASS: PAYLOAD SUPPORT STRUCTURE
BASELINE: SKIN AND STRINGER
ALTERNATES: SANDWICH CONSTRUCTION;
TRUSS CONSTRUCTION



SKIN AND STRINGER
(BASELINE)



SANDWICH



TRUSS

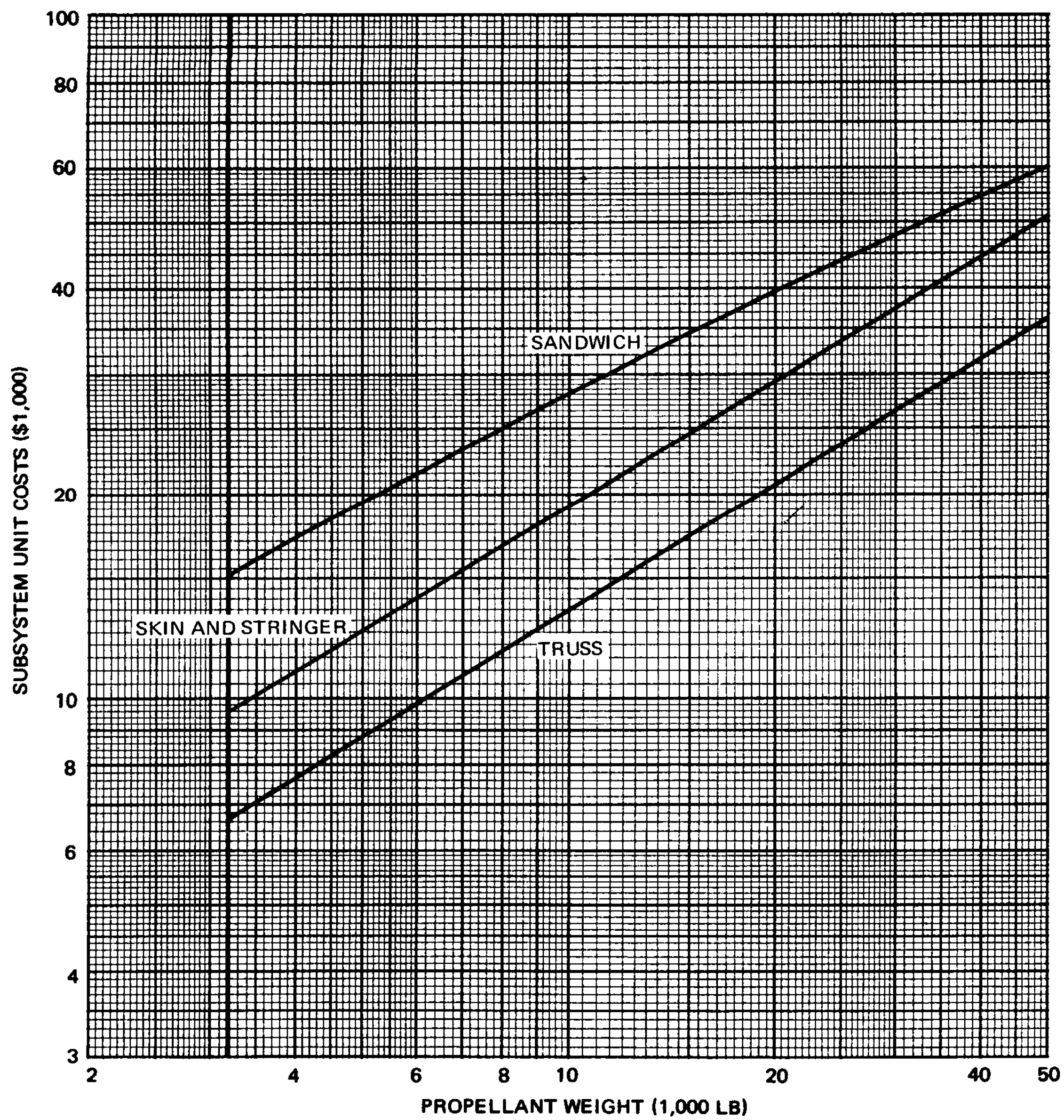
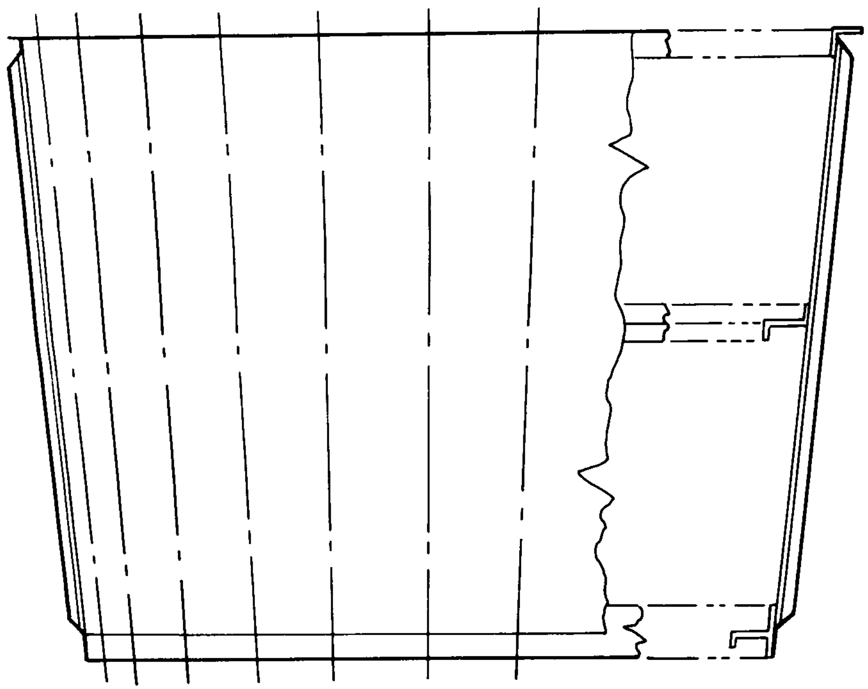


Figure 3-25 Subsystem Unit Cost Summary -- Payload Support Structure

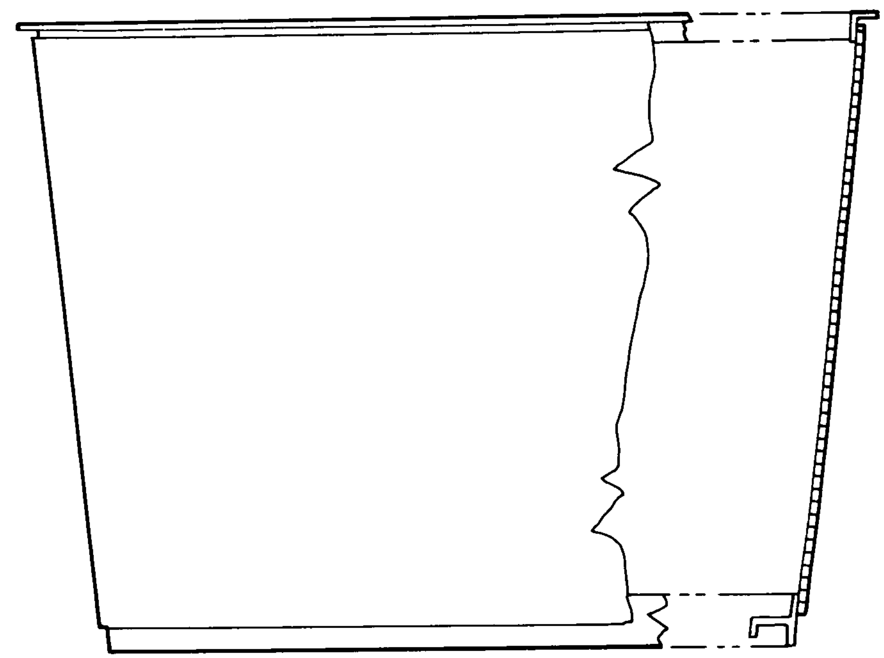
SUBSYSTEM CLASS: THRUST STRUCTURE

BASELINE: SKIN AND STRINGER

ALTERNATES: SANDWICH CONSTRUCTION



SKIN AND STRINGER
(BASELINE)



SANDWICH

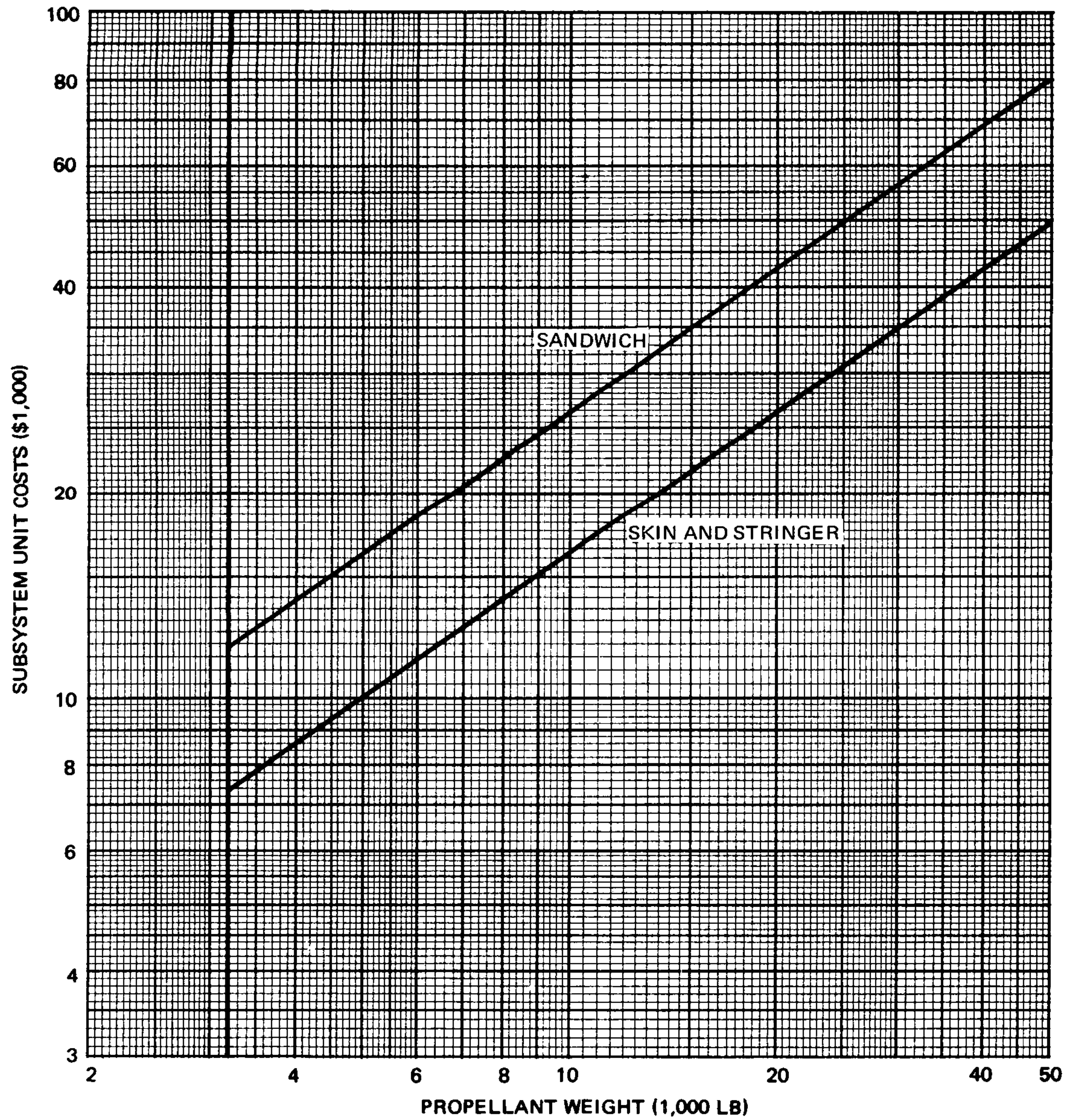
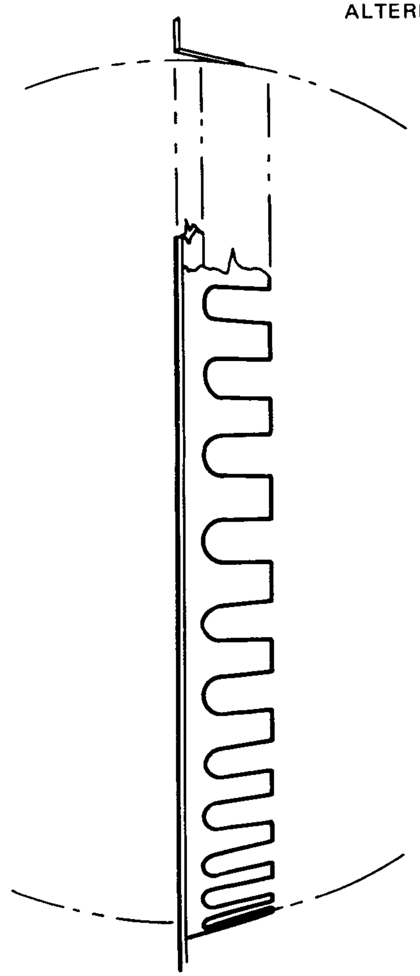


Figure 3-26 Subsystem Unit Cost Summary -- Thrust Structure

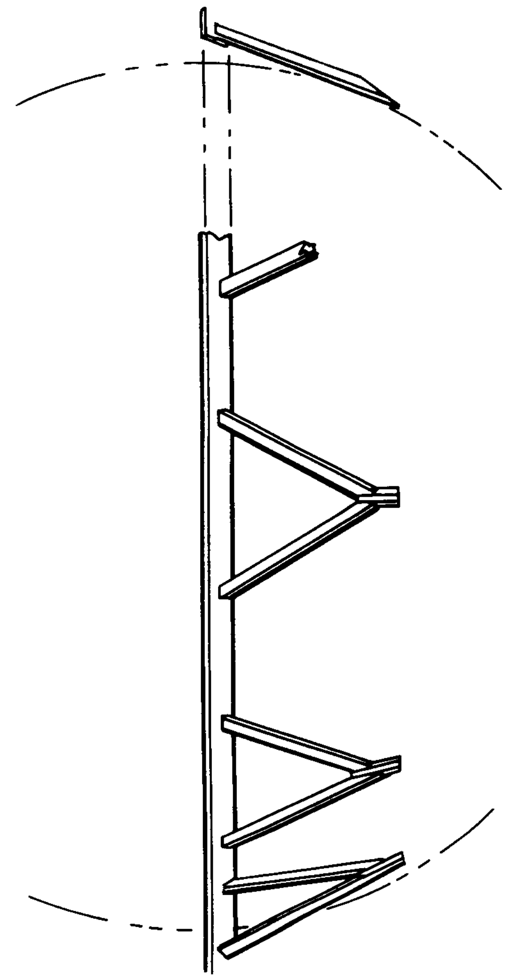
SUBSYSTEM CLASS: TANK SUPPORT STRUCTURE

BASELINE: CONE

ALTERNATES: MULTIPLE A-FRAMES



CONE
(BASELINE)



MULTIPLE A-FRAME

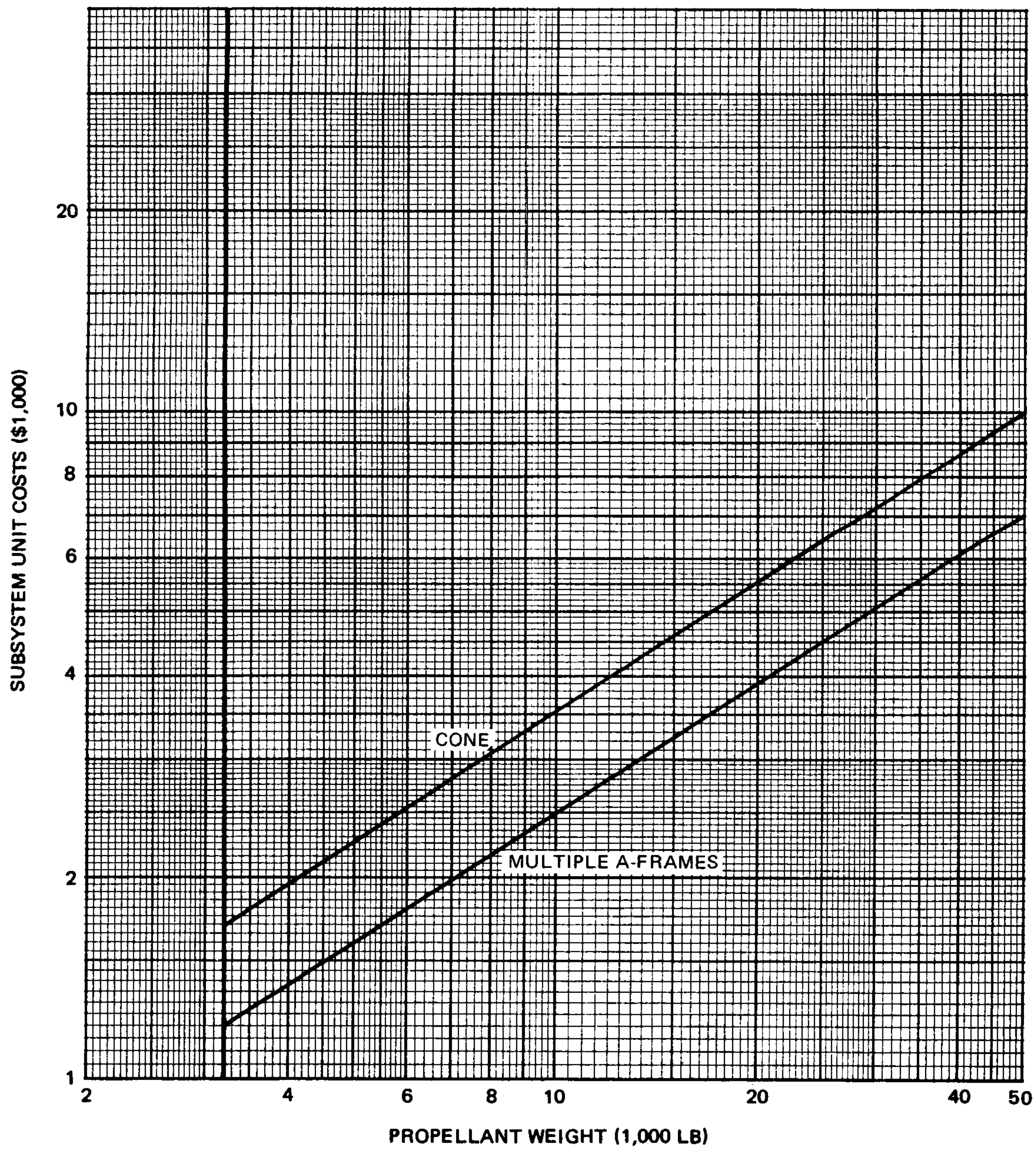
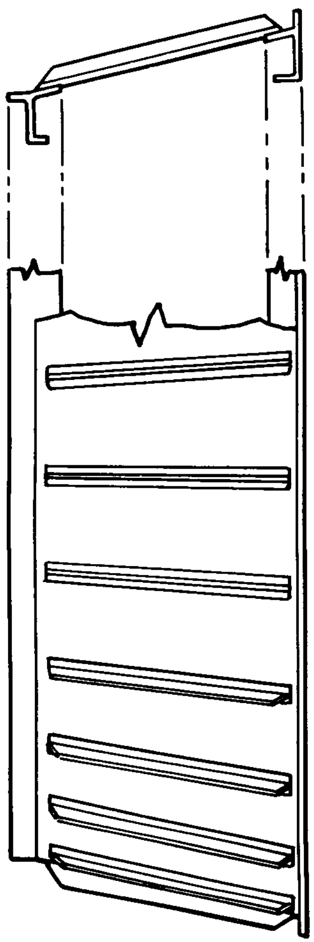
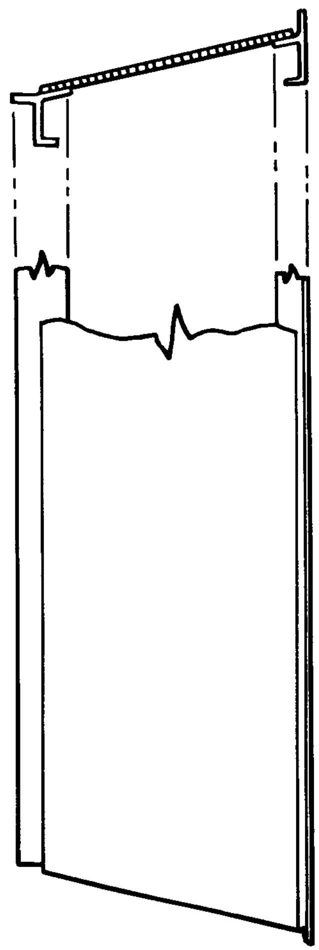


Figure 3-27 Subsystem Unit Cost Summary -- Tank Support

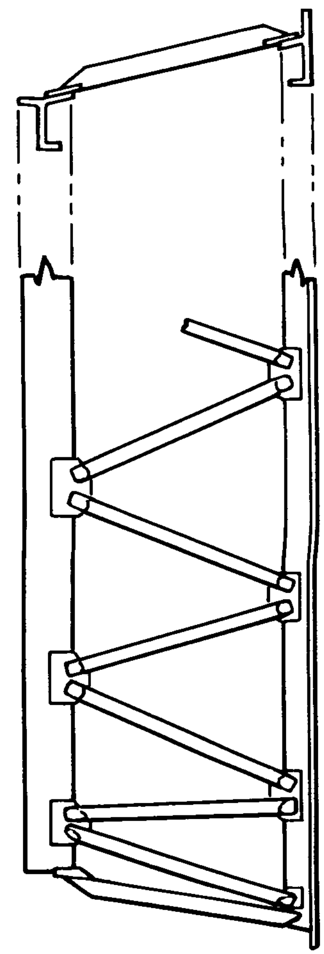
SUBSYSTEM CLASS: INTERSTAGE ADAPTOR
BASELINE: SKIN AND STRINGER
ALTERNATES: SANDWICH CONSTRUCTION; TRUSS CONSTRUCTION



SKIN AND STRINGER (BASELINE)



SANDWICH CONSTRUCTION



TRUSS CONSTRUCTION

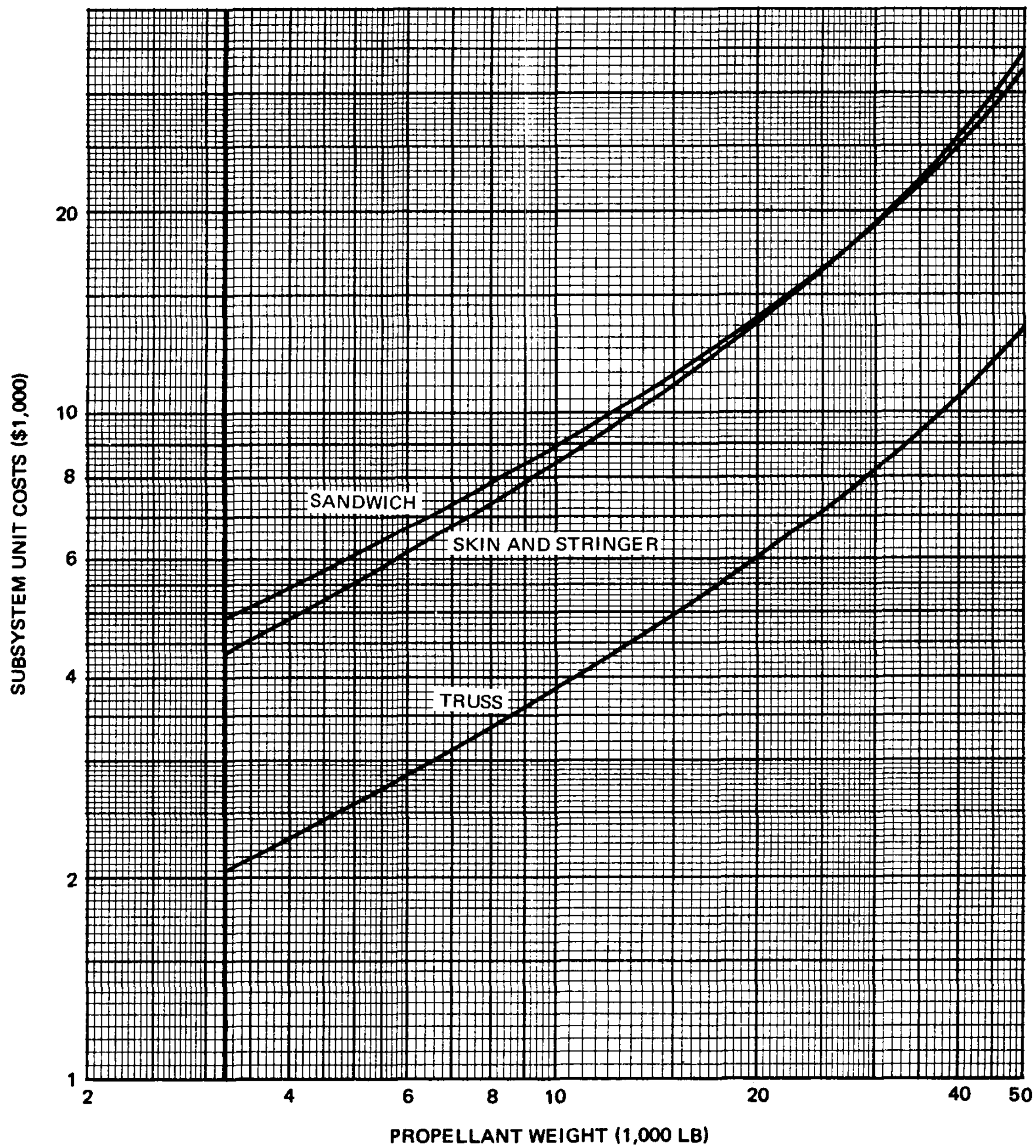


Figure 3-28 Subsystem Unit Cost Summary -- Interstage Adaptor

Section 4
SYSTEM INTEGRATION

System integration encompasses all of those development functions associated with major systems which occur after subsystem and component development have essentially been completed. These operations can be roughly divided into system development, which is comprised of assembling and testing the set of subsystems which form each of the major systems, and propulsion system integration, which is the final operation and consists of checkout and ground firings of a complete propulsion system plus all necessary support equipment.

4.1 SYSTEM DEVELOPMENT

The four major systems which constitute the propulsion stage are the feed, fuel, thrust vector control (TVC), and structure. Of these, the TVC system sometimes functions as a subsystem of another major system and sometimes as a completely independent system of its own, depending upon the selection of the TVC mode of operation. For example, when either gimballed nozzle or secondary injection is used, the TVC must be integrated into and developed with the fuel system; when hydrazine or bipropellant reaction control motors are used, the TVC is developed independently. For uniformity, all TVC candidates were treated together and appear in the subsystem development section (Section 3).

Further, the stage structure, being comprised of relatively independent structural subsystems, is not developed as an integrated unit until overall stage integration.

Consequently, no TVC system or structural development data appear here. System development can therefore be reduced to discussions of the feed systems and fuel systems.

System development costs are reflected in the expenses associated with the fabrication of test hardware and special test equipment, manpower requirements at test facilities and for data reduction, and design engineering activity on the system level. The treatment of these costs is summarized on the following page.

Hardware costs are simply the product of the number of sets needed in the development phase, N_{sets}, and the cost of a single set. The number of sets is a function of the number of singular tests and the number of commonality tests, where singular tests represent those in which the hardware is not reusable and commonality tests represent those in which it is. For example, a hot firing of a fuel system would be a singular test; a cold-flow test of a feed system would be a commonality-type test. The commonality-test quantities are divided by a reusability factor, f, which accounts for the number of tests a single set of hardware can tolerate.

Test quantity requirements are dependent upon the system design criteria. These relationships are shown in Figure 4-1 for the feed system and Figure 4-2 for the fuel system. On the figures, the number of tests required for the baseline design criteria is noted; to this must be added the sum of the test requirements for each of the alternate design criteria. It can be seen that for the feed system, all tests are commonality tests. Further, a single set of hardware can be reused for any number of tests within the limits required. Therefore, for the feed system, $f = N_{commonality\ tests}$, and $N_{singular\ tests} = 0$, so the total number of sets required for any feed system development

SYSTEM DEVELOPMENT COST SUMMARY

$$C_{\text{System Development}} = C_{\text{Hardware}} + C_{\text{Special Test Equipment}} + C_{\text{Test Operations}} + C_{\text{Engineering and Subcontractor Management}}$$

$$C_{\text{Hardware}} = N_{\text{Sets}}\, C_{\text{Set}}$$

$$N_{\text{Sets}} = N_{\text{Singular Tests}} + \frac{N_{\text{Commonality Tests}}}{f}$$

$$C_{\text{Set}} = \Sigma \text{ Subsystem Unit Cost}$$

$$C_{\text{Special Test Equipment}} = \Pi(f_1)\, C_{\text{STE B/L}}$$

$$f_1 = f\,(\text{Alternate Subsystems})$$

$$C_{\text{Test Operations}} = (\Pi f_2)\, k\, \dot{c}_{\text{T. O.}_{\text{B/L}}}\, (L_{\text{B/L}} + \Delta L)$$

$$f_2 = f\,(\text{Alternate Subsystems})$$

$$k = f\,(\text{Oxidizer Selection})$$

$$L = f\,(\text{Design Criteria})$$

$$\Delta L = f\,(N_{\text{Tests}})$$

$$C_{\substack{\text{Engineering and}\\ \text{Subcontractor Management}}} = K\, W_P^n$$

program is one. The fuel system is handled in a similar manner, except that it contains a mix of singular tests and commonality tests. Commonality tests on a fuel system stem from the fact that more than one criterion can be tested on a single firing. However, at the most, only two criteria, restartability and throttle ratio, are likely to be combined on a single firing (stay time requirements are satisfied by vacuum storage tests); therefore, the reusability factor for fuel systems is two. The other element in hardware costs, C_{set}, is obtained from the generalized cost data for each of the contributing subsystems. In this case, unit costs (rather than development costs) are used as it is assumed that subsystem development has been completed and that system development simply requires the purchase of a sufficient number of sets of hardware to fulfill the test requirements.

Special test equipment costs are factored from the costs of special test equipment of the baseline configuration at the appropriate propellant weight. These data are shown in Figure 4-3. The factors, f_1 in Table 4-1, are based upon the relative complexity of developing each of the subsystems compared with the equivalent baseline subsystems. The overall complexity factor is the product of the subsystem factors.

Test operations costs represent those expenses associated with staffing and operating the test facility and are dependent upon the system complexity and the length of time the facility must be kept in operation. For alternate subsystems and design criteria, test operations costs are extrapolated from those for the baseline (Figure 4-4). System complexity is dependent upon the subsystems used; a complexity factor, f_2, relative to test operations for each of the candidate subsystems, is shown in Table 4-1. As in special test equipment costs, the overall factor is the product of the subsystem factors.

The length of the test program is dependent upon the system design criteria since the more difficult criteria will require extra system tests to substantiate the design which, in turn, will require a longer testing phase. The overall test program then is the sum of of a fixed length, equal to the baseline test phase, and an incremental length addition, equal to the number of extra tests multiplied by the time it takes to set up and conduct a single test.

A last factor, k, enters into the test operations costs to account for the type of oxidizer, storable versus cryogenic. Since only fluorine-based oxidizers have been considered within the data presented, the cyrogenic oxidizer is typified by F_2 or FLOX and the storable by $ClOF_3$ or $ClOF_5$. The storables cost about the same as the cryogens but, of course, are simpler to store and handle. Feed system development which requires extensive handling and flow testing of the oxidizer, is less expensive when a storable is used. Development of the fuel system however, which requires large quantities of oxidizer but uses it only as a testing medium with relatively little handling, is relatively unaffected by oxidizer type.

Engineering and subcontractor management costs are comprised of design engineering, which represents those design functions associated with system assembly and preparation of system specification drawings, and subcontractor management, which represents subcontractor expenses associated with management of the fuel system. Both of these functions are indirectly related to system size, since historically, as systems increase in size they also increase in complexity.

Table 4-1 (page 1 of 2)

SUBSYSTEM COMPLEXITY FACTOR SUMMARY

		Complexity Factor			
Subsystem Class	Subsystem Type	f_1 (Special Test Equipment)	f_2 (System Development Test Operations)	f_3 (System Integration Test Operations)	f_4 (Aero-space Ground Equipment)
Tankage	Sphere	1.00	1.00	1.00	1.00
	Cylinder	1.00	1.00	1.00	1.00
	Torus	1.06	1.05	1.02	1.00
	Sphere cluster	1.12	1.05	1.02	1.02
Expulsion system	Heated He (nozzle HE)	1.00	1.00	1.00	1.00
	Ambient He	0.95	0.90	0.94	0.96
	Cartridge-augmented, heated He	1.00	0.92	0.95	1.01
	Gas-generator-augmented, heated He	1.10	1.10	1.05	1.03
	Turbopump	1.20	1.15	1.10	1.09
Propellant settling system	Ullage rockets	1.00	1.00	1.00	1.00
	Screens	0.90	1.10	0.95	0.98
	Positive expulsion	1.15	1.15	1.02	1.00
Insulation	Uninsulated	1.00	1.00	1.00	1.00
	NRC-2	1.20	1.12	1.07	1.02
	Dimplar	1.20	1.12	1.07	1.02

Table 4-1 (page 2 of 2)

Subsystem Class	Subsystem Type	Complexity Factor f_1 (Special Test Equipment)	f_2 (System Development Test Operations)	f_3 (System Integration Test Operations)	f_4 (Aero-space Ground Equipment)
Combustion Chamber	Fiber glass	1.00	1.00	1.00	1.00
	Steel	1.00	0.98	1.00	1.00
	Titanium	1.00	0.98	1.00	1.00
Injection system	Head end only	1.00	1.00	1.00	1.00
	Head and aft end	1.15	1.10	1.05	1.01
	Head end + turbulator	1.10	1.05	1.00	1.00
Nozzle	Ablative	1.00	1.00	1.00	1.00
Thrust vector control	Hydrazine RCS	1.00	N/A	1.00	1.00
	Bipropellant RCS	1.05	N/A	1.05	1.02
	Gimballed nozzle	1.15	1.20	1.10	1.06
	N_2O_4 secondary injection	1.20	1.20	1.15	1.06
	Oxidizer secondary injection	1.20	1.30	1.15	1.03
Structure	All	1.00	N/A	1.00	1.00

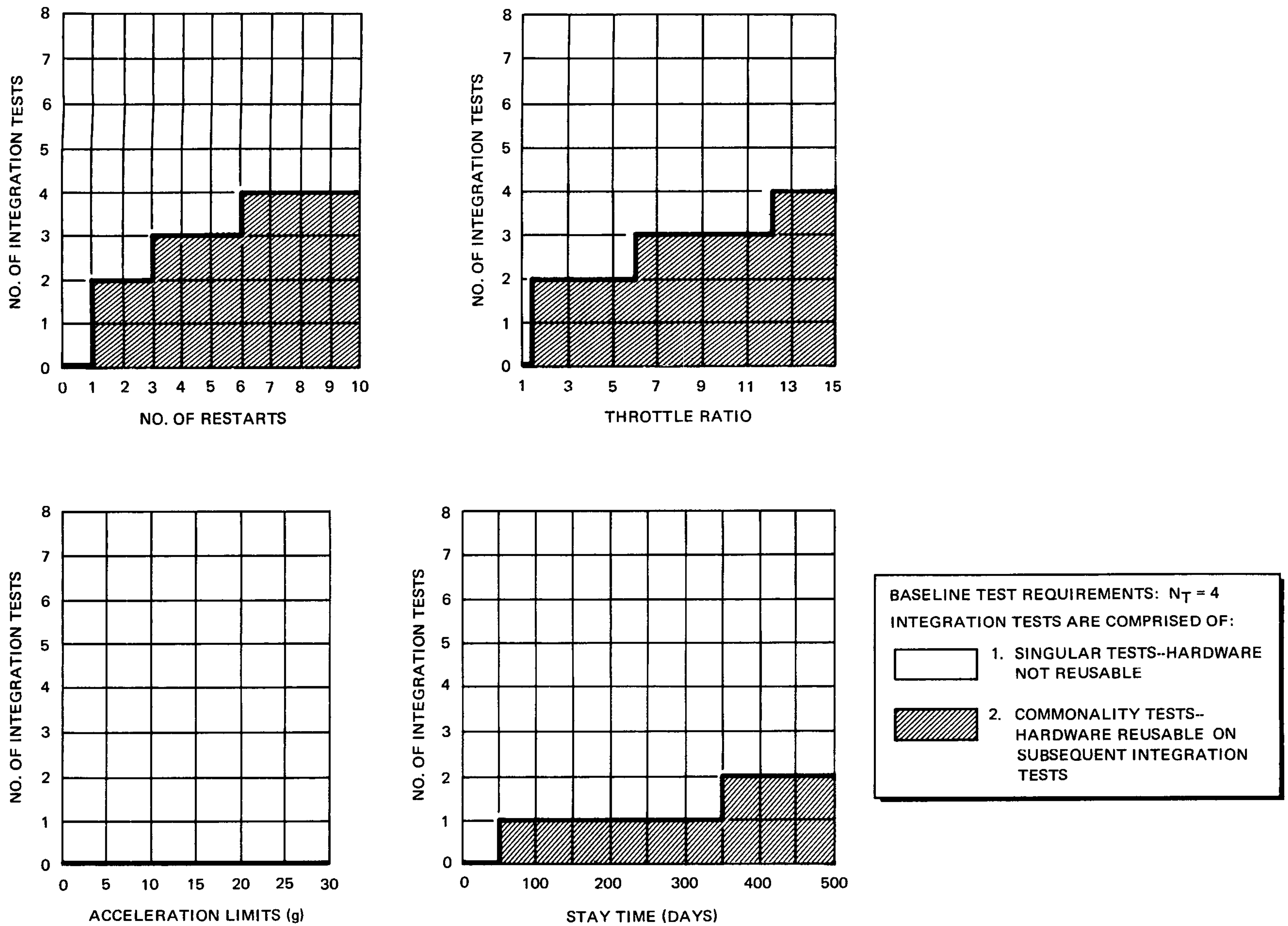


Figure 4-1 System Integration Test Summary - - Feed System

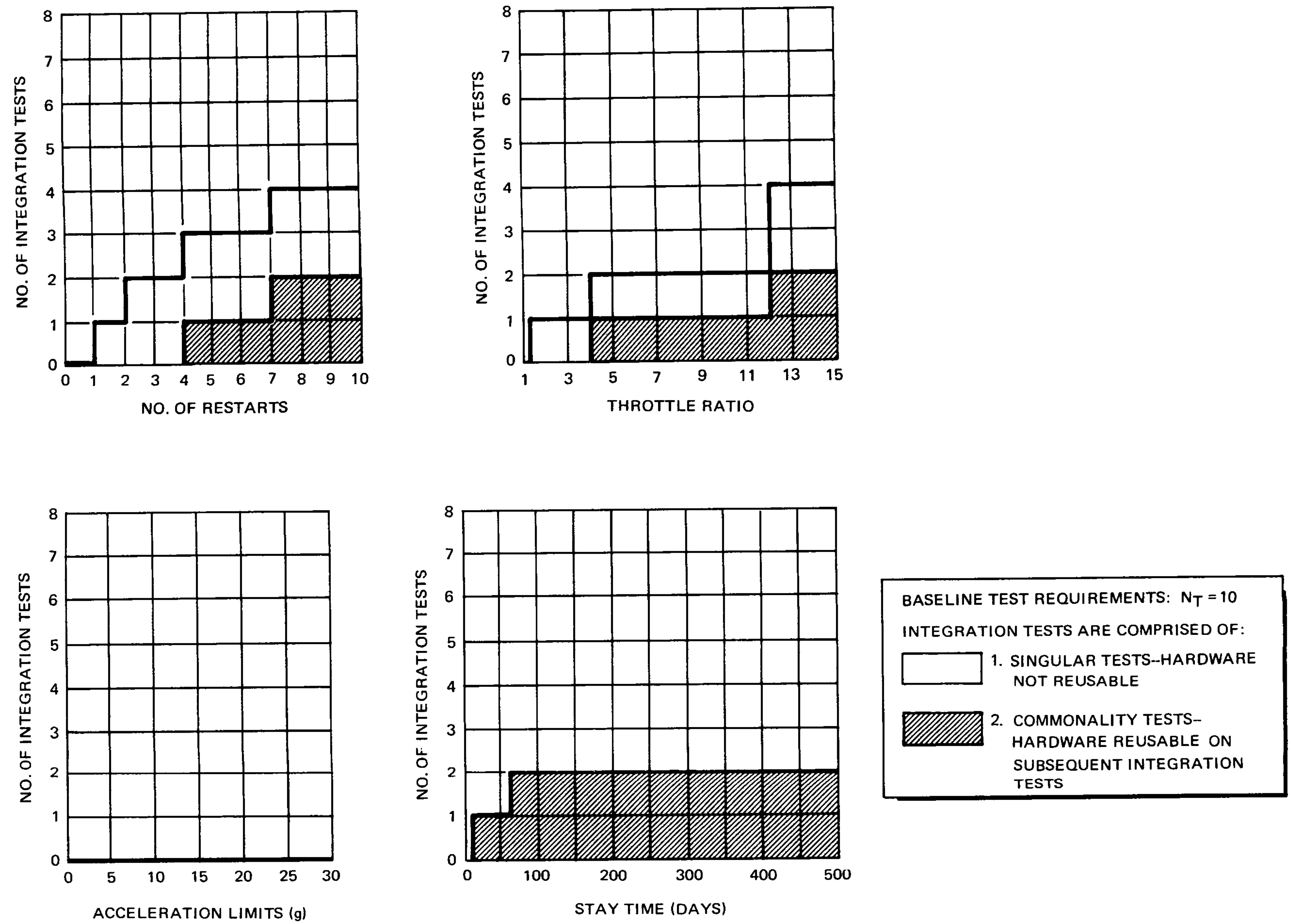


Figure 4-2 System Integration Test Summary - - Fuel System

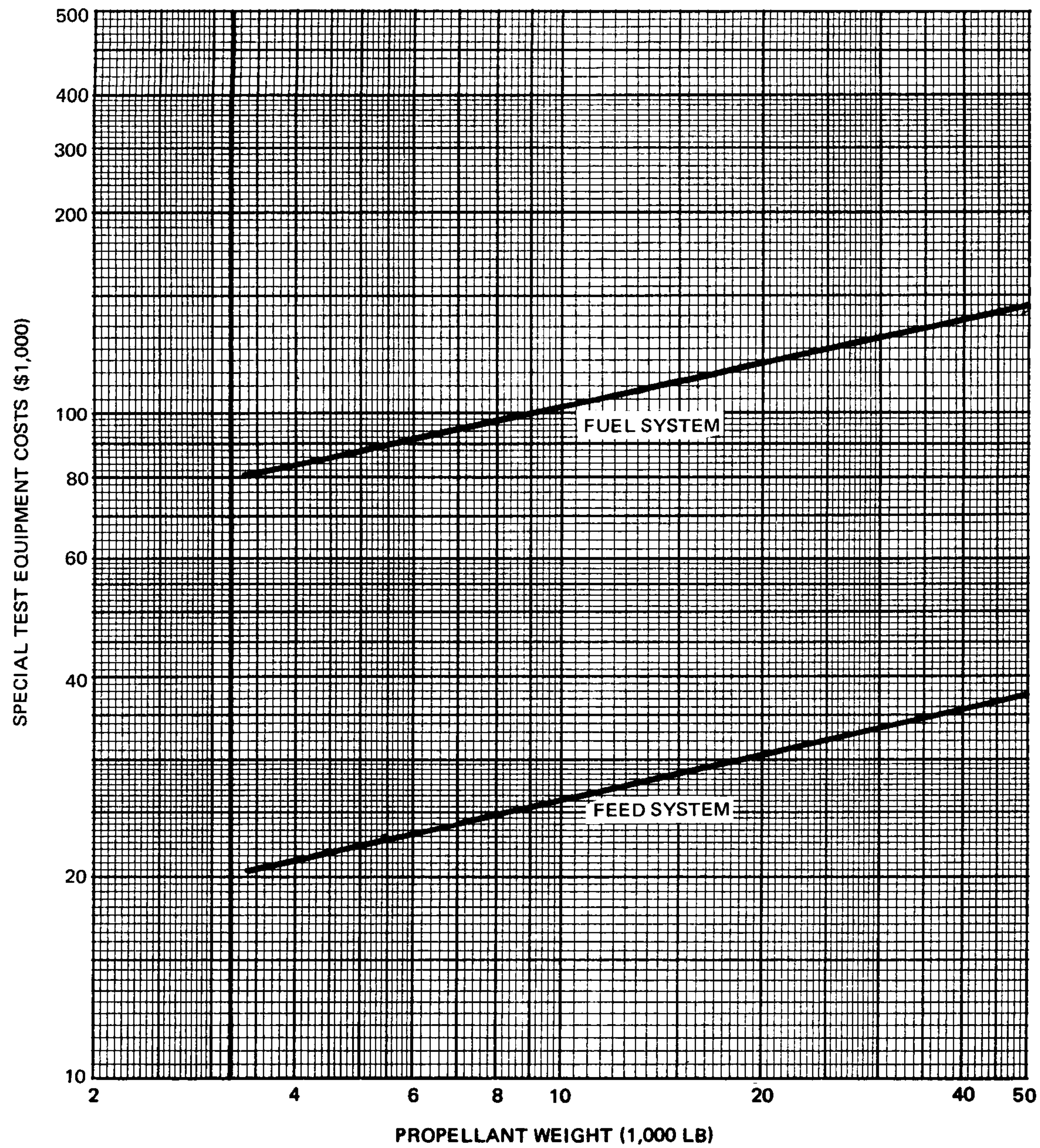


Figure 4-3 Special Test Equipment -- Baseline System Cost Summary

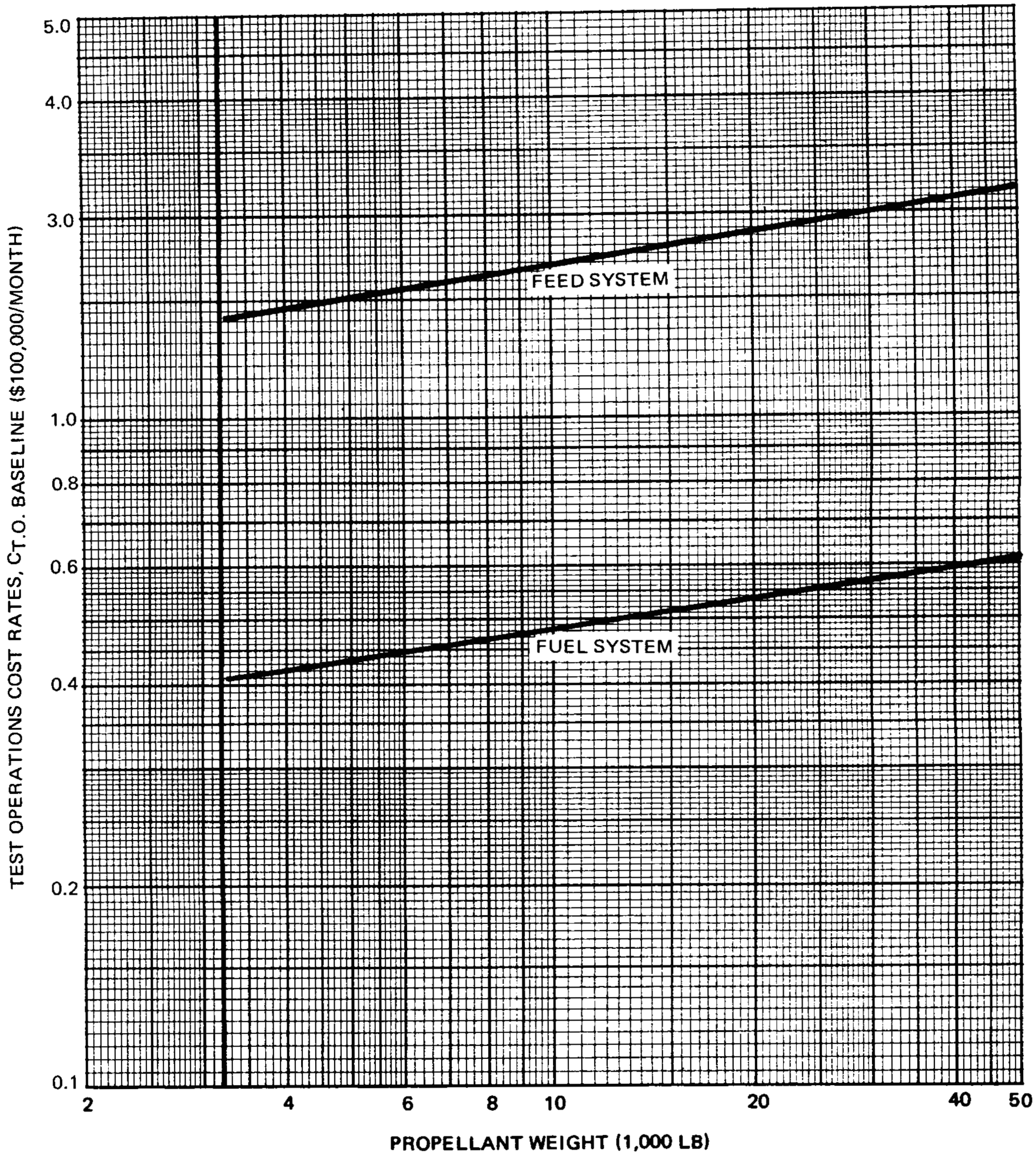


Figure 4-4 System Test Operations -- Baseline Cost Summary

4.2 PROPULSION SYSTEM INTEGRATION

Propulsion system integration, or all systems testing, represents the culmination of the ground test program in which all systems are integrated and tested as a single functioning unit. The elements which constitute system integration costs are shown on the following page.

As before, hardware costs are basically the product of the number of sets of hardware and the cost of a single set. However, a distinction must be made between which systems are reusable and which are not. For example, a new fuel system is needed for each ground firing; the feed system and structure can be reused indefinitely. The reusability of the TVC system is dependent upon the type of system selected. Since only two ground firings are required in the all system test program, hardware purchases are simply for either one or two units, depending upon their reusability.

Test operations costs are also obtained in a manner similar to those for system development, the main differences being the values of the factors used in the equations. Table 4-2 lists the subsystem complexity factors, f_3, applicable to all system test operations. Duration of the test program, L, is partially dependent upon size of the system, since size tends to have an influence on assembly and test time. The system size/program length relationship is shown in Figure 4-5. The effects of increased complexity with size are accounted for in the $W_p^{.14}$ expression.

Aerospace ground equipment (AGE) costs are dependent upon subsystem complexity and are factored from the baseline AGE costs shown in Figure 4-6. Subsystem complexity factors for AGE, f_4, are listed in Table 4-2; the overall factor, as for test operations, is the product of the subsystem factors.

SYSTEM INTEGRATION SUMMARY

$$C_{System\ Integration} - C_{Hardware} + C_{Test\ Operations} + C_{Aerospace\ Ground\ Equipment} + C_{System\ Design\ Engineering}$$

$$C_{Hardware} = N_{Tests}\ \Sigma\, k_1\, C_{set}$$

$$N_{Tests} = 2$$

$$k_1 = f\ (\text{System Reusability})$$

$$C_{Set} = C_{Feed\ System} + C_{Fuel\ System} + C_{Thrust\ Vector\ Control} + C_{Structure}$$

$$C_{Hardware} = C_{Feed\ System} + 2\, C_{Fuel\ System} + C_{Thrust\ Vector\ Control}^{*} + C_{Structure}$$

$$C_{Test\ Operations} = \Pi\, (f_3)\, k\, \dot{c}_{T.O.\ B/L}\, W_P^{.14}\, L$$

$$f_3 = f\ (\text{Subsystem Complexity})$$

$$k = f\ (\text{Oxidizer Selection})$$

$$L = f\ (\text{System Size})$$

$$C_{Aerospace\ Ground\ Equipment} = \Pi\, (f_4)\, C_{Aerospace\ Ground\ Equipment_{B/L}}$$

$$f_4 = f\ (\text{Subsystem Complexity})$$

$$C_{System\ Design\ Engineering} = \Pi\, (C_{Dev}/C_{Dev\ B/L})\, C_{SDE\ B/L}$$

*TVC System costs appear only if the hydrazine RCS or the bipropellant RCS system is selected. The other TVC systems are included as part of the fuel system hardware.

System design engineering costs, which include those expenses associated with preparation of top-level assembly and installation drawings, inboard profiles, and specification control drawings, are adjusted from those of the baseline by ratioing alternate subsystem development costs to the baseline costs. System design engineering costs are then the product of the subsystem cost ratios and the baseline system design engineering costs.

4.3 SYSTEM ENGINEERING AND PROGRAM MANAGEMENT

A final cost element, which is normally carried through the duration of the program, is represented by overall program management expenses, which include program control requirements, manufacturing, engineering and test management, and contract data control. System engineering includes responsibility for analysis and documentation of system integration, definition of software requirements, and design, performance, and cost tradeoff studies.

The size and scope of these functions are statistically related to overall program size; they can therefore be most readily obtained through the application of empirical cost factors to total program costs. These factors are 6% for systems engineering and 16% for program management.

Development program costs are the sum of subsystem development, system development, system integration, system engineering, and program management. This represents all nonprofit expenses associated with the ground-test phase of a development program. Total program costs to the user agency would be equal to these costs plus contractor fees.

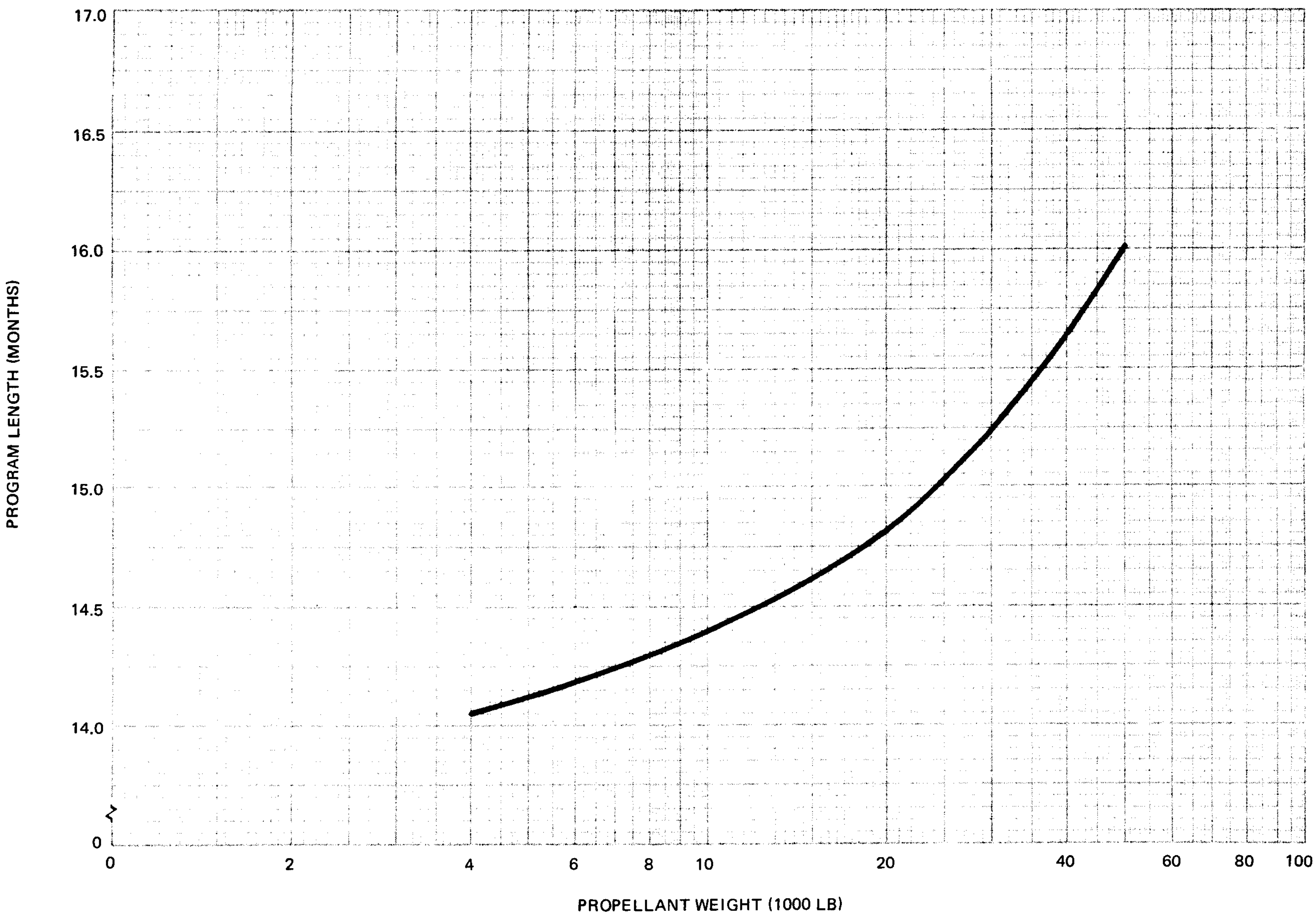


Figure 4-5 Propulsion System Integration -- Test Operations Schedule Requirements

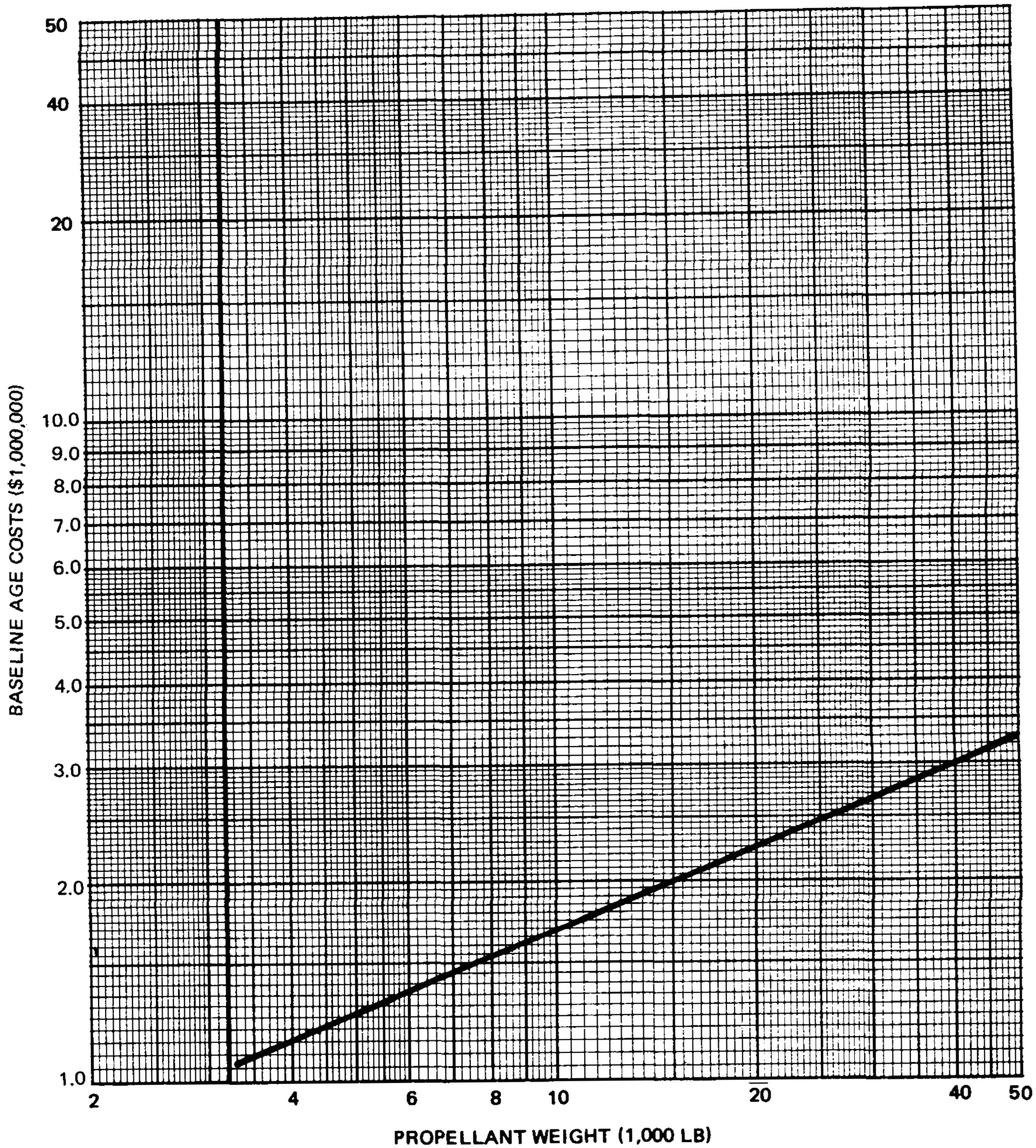


Figure 4-6 Baseline Hybrid System Aerospace Ground Equipment Costs

Section 5
SCHEDULES

Development schedules are presented in this section for all systems and subsystems, together with a method for assembling them in a manner which will enable the user to arrive at an overall program duration based upon his system requirements. Subsystem schedules for each subsystem class are shown in Figures 5-1 through 5-14 (which appear after the text in this section). The vertical line at the zero time point on these figures represents the state of development at which each subsystem is ready for integration into the next higher level of system development. By working backwards from this point, the elapsed time to the point when development must be initiated can be found. This is indicated by the cross-hatched bars for subsystems designed to the baseline criteria.

The influence of alternate design criteria on these schedules is noted where necessary; the subsystem schedule should be lengthened accordingly if the selected design criteria correspond to those shown. Criteria not shown have no effect on the subsystem development schedule (even though they may have an effect upon development costs). In the case of the expulsion system (Figure 5-3), only the design criterion causing the greatest schedule increase should be considered as it can be assumed that the others will be developed in parallel.

The master phasing schedule is shown in Figure 5-15 and must be used in conjunction with the subsystem development schedules. It is first necessary to determine the lengths of the feed-system and fuel-system integration phases. Here again, the cross-hatched bars show the schedule for the baseline design criteria. The dashed extensions represent the maximum schedule increase for alternate criteria. Therefore, the system integration phases will always fall somewhere within the dashed bars. The proper lengths for these bars, in months, are found from the equations in the bottom of the figure and from the data in Figures 4-1 and 4-2.

To combine the schedule data, the schedule for one subsystem type for each of the subsystem classes should be entered on the appropriate line of Figure 5-15. As an aid in the preparation of the composite schedule, transparencies of Figure 5-15 are included in the envelope at the back of the report. The subsystem timelines under the feed system should end at the same time feed system integration begins. Similarly, the fuel subsystem timelines should end where fuel system development begins. The TVC and structural subsystem time lines should end at the vertical line on Figure 5-15 where propulsion system integration begins. It should be noted, however, that the TVC system entry is dependent upon the TVC system selected.

Finally, the length of the system integration phase is obtained from Figure 4-6. The total program schedule is then the sum of the times required for propulsion system integration and the longer of feed system integration plus its subsystems and fuel integration plus its subsystems. To illustrate the method by which a program schedule is generated, a schedule for the sample stage defined in Section 2 is shown in Figure 5-16.

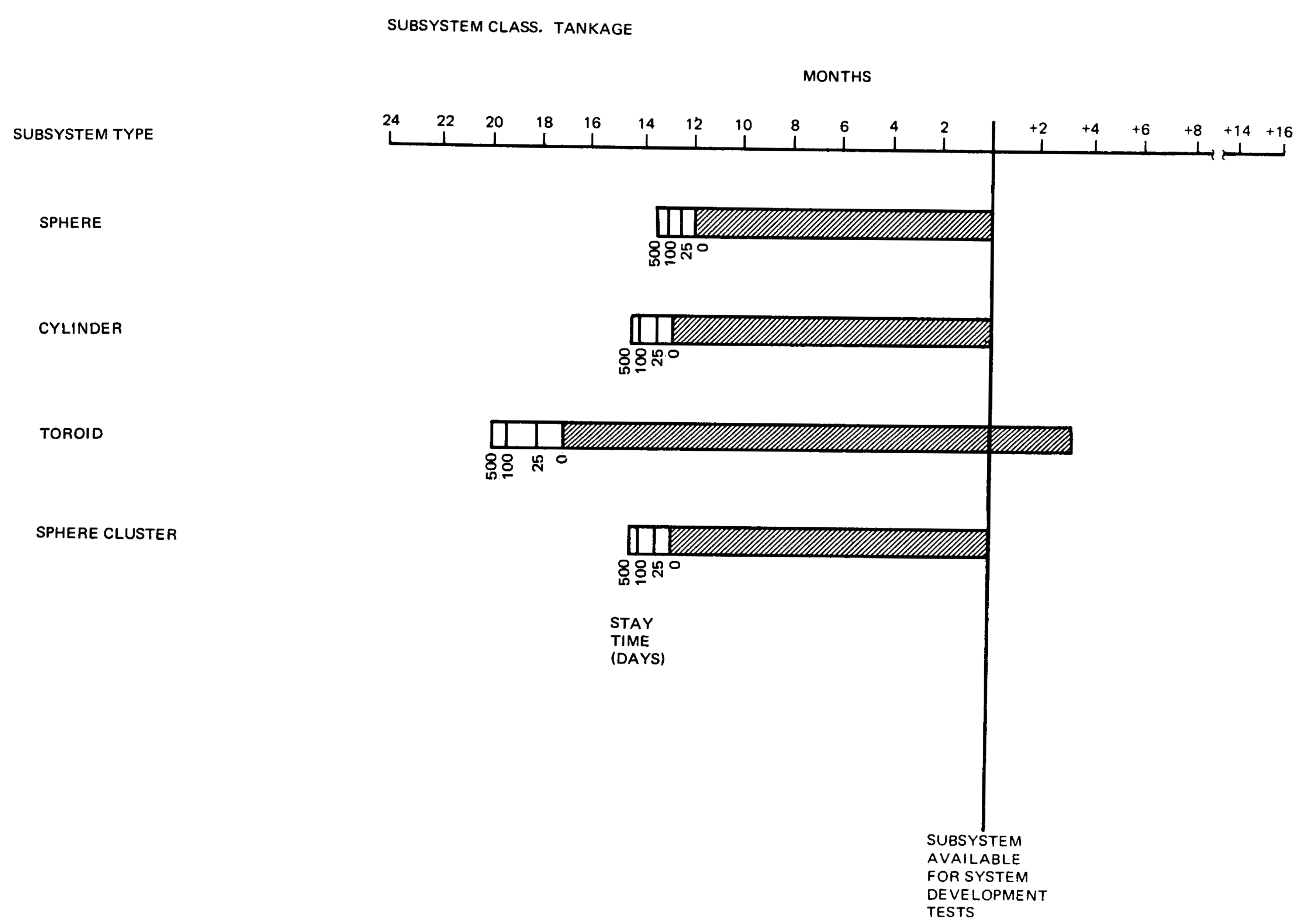


Figure 5-1 Subsystem Development Schedule -- Tankage

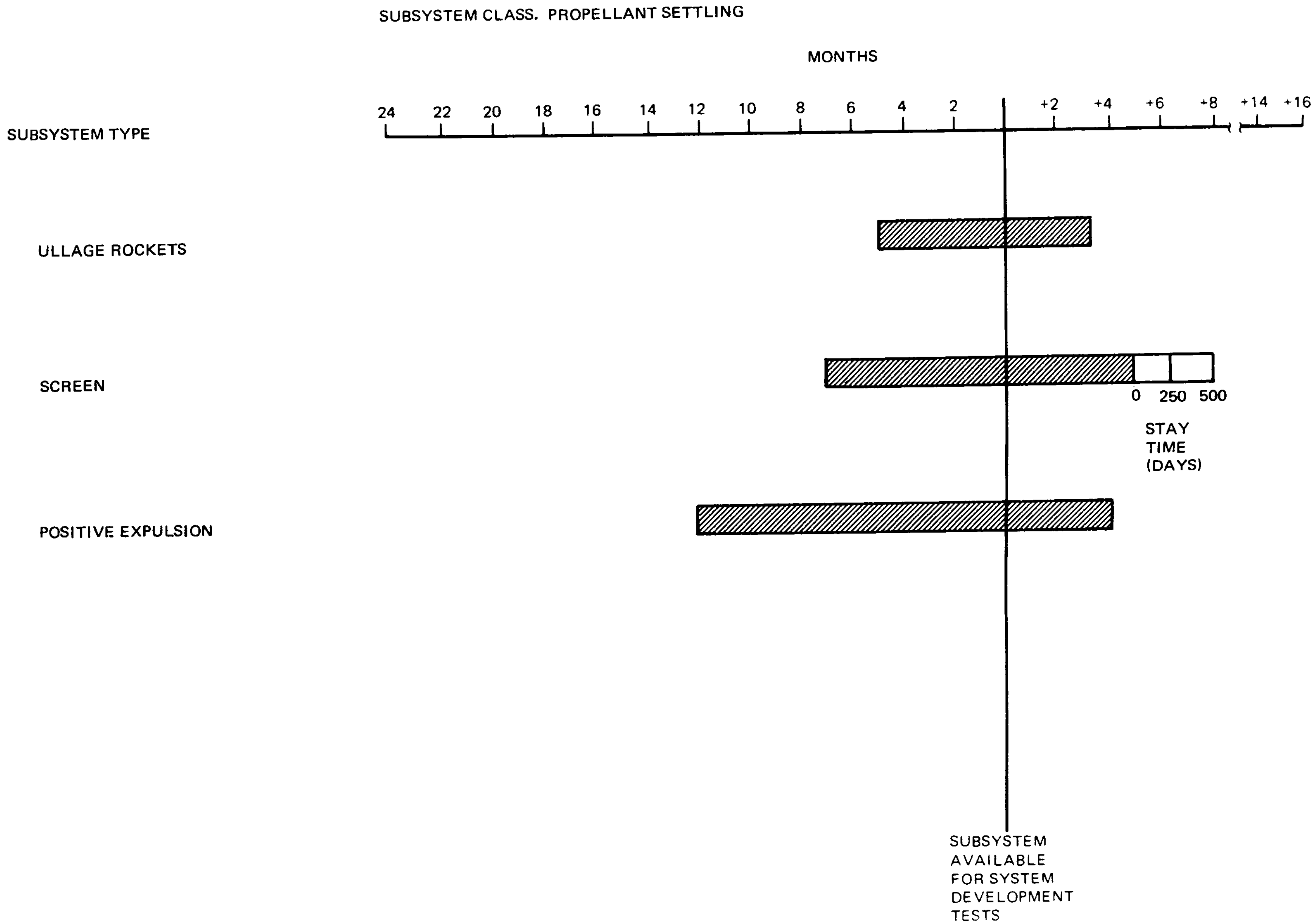


Figure 5-2 Subsystem Development Schedule -- Propellant Settling

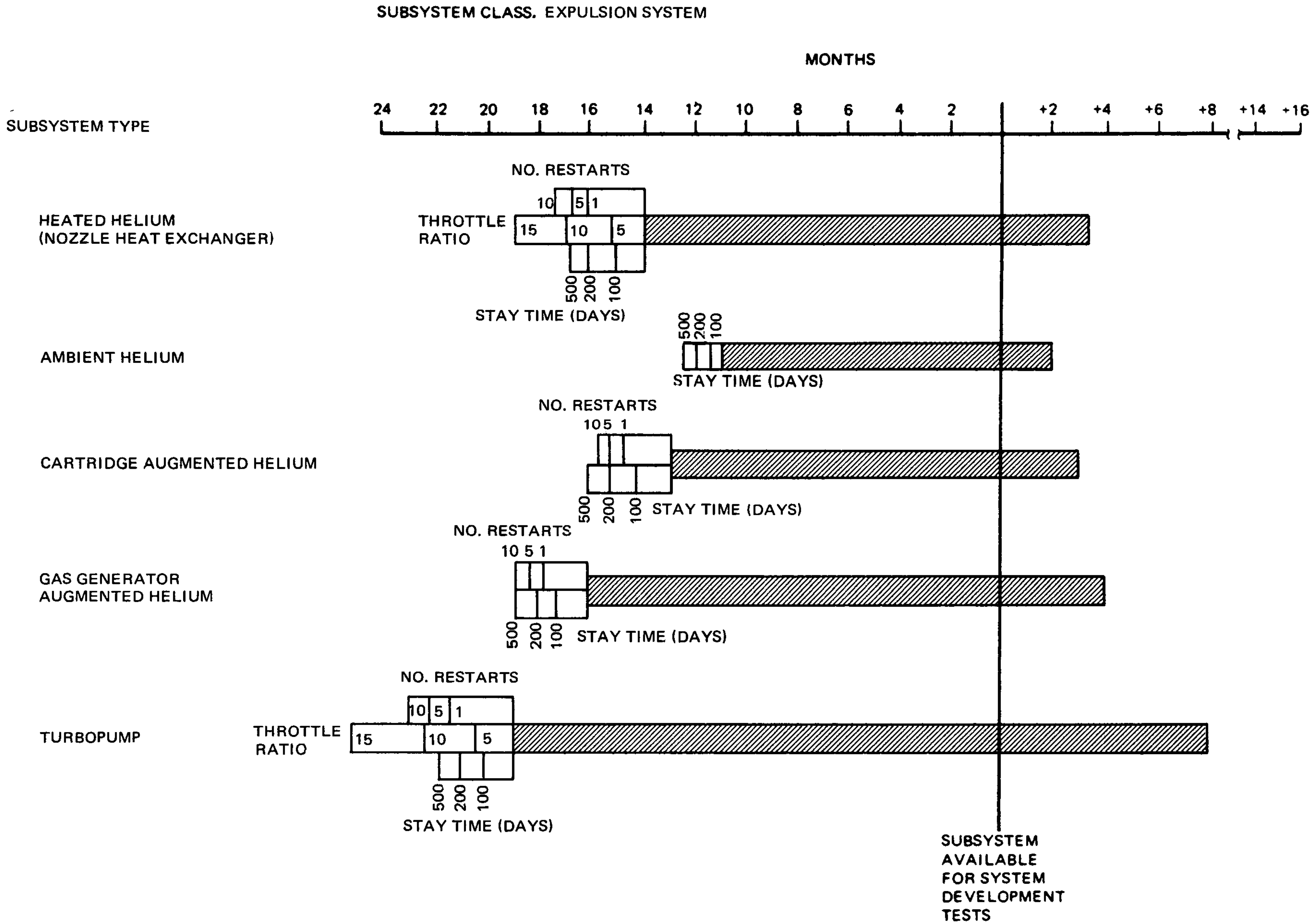


Figure 5-3 Subsystem Development Schedule -- Expulsion System

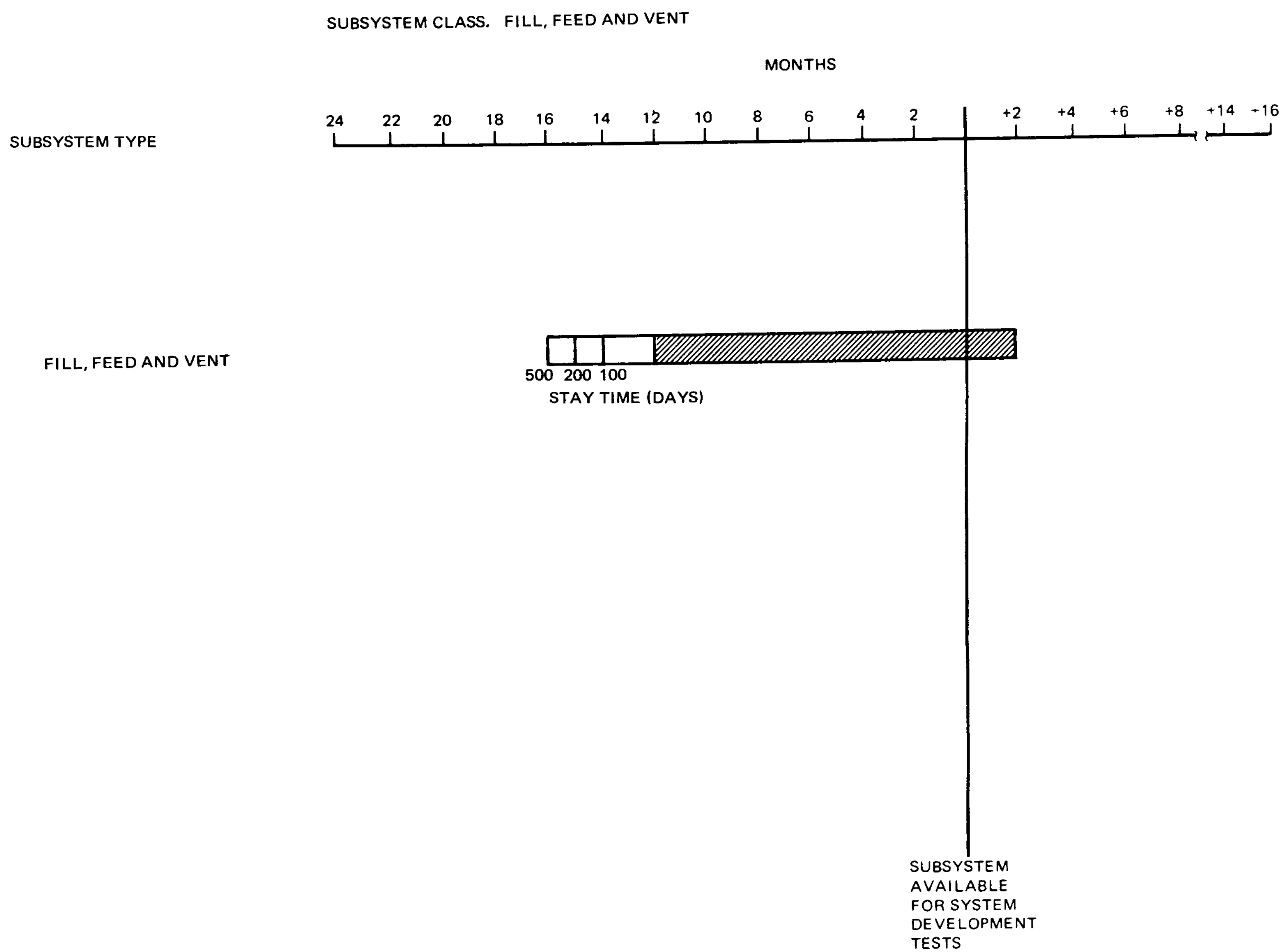


Figure 5-4 Subsystem Development Schedule -- Fill, Feed and Vent

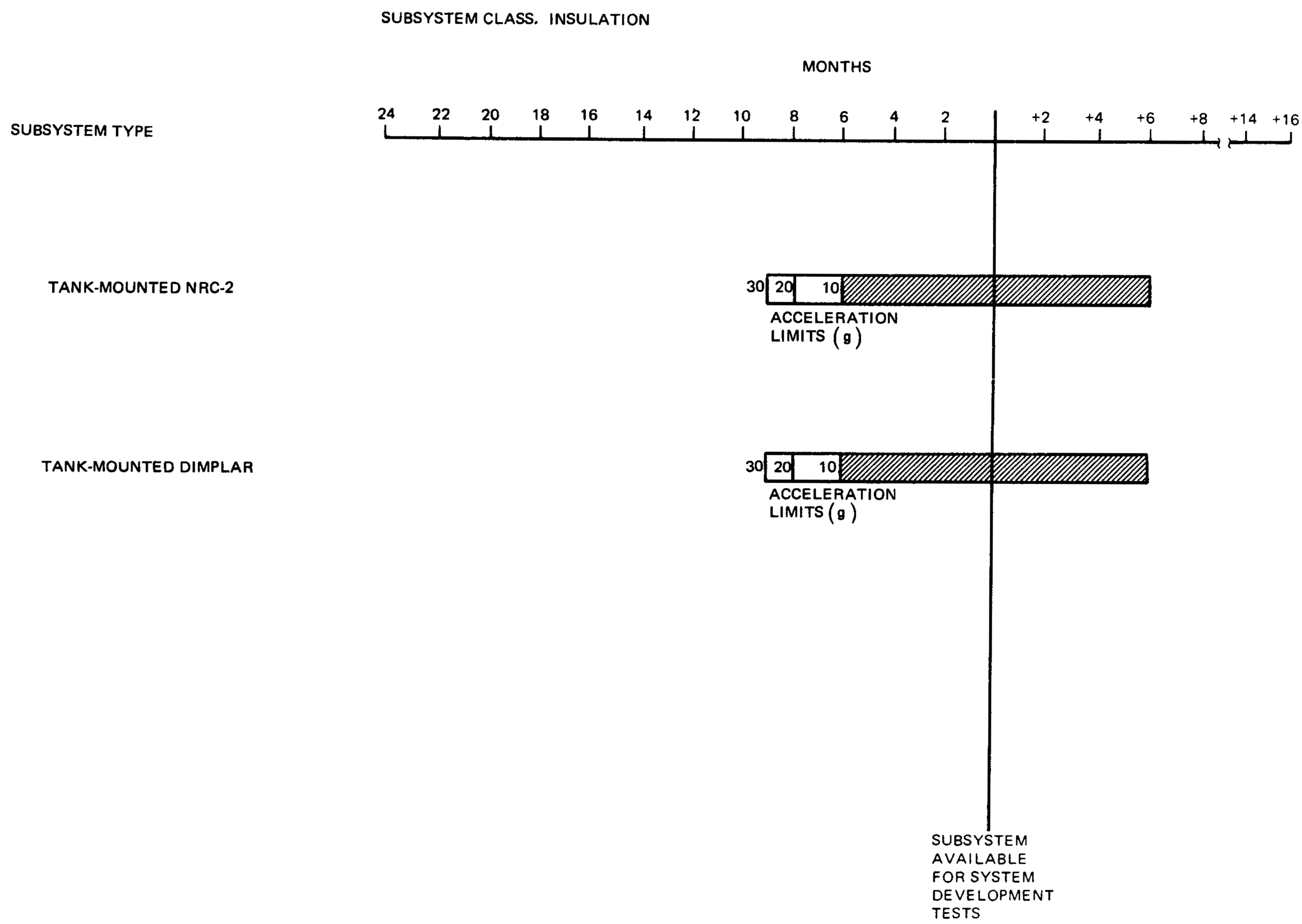


Figure 5-5 Subsystem Development Schedule -- Insulation

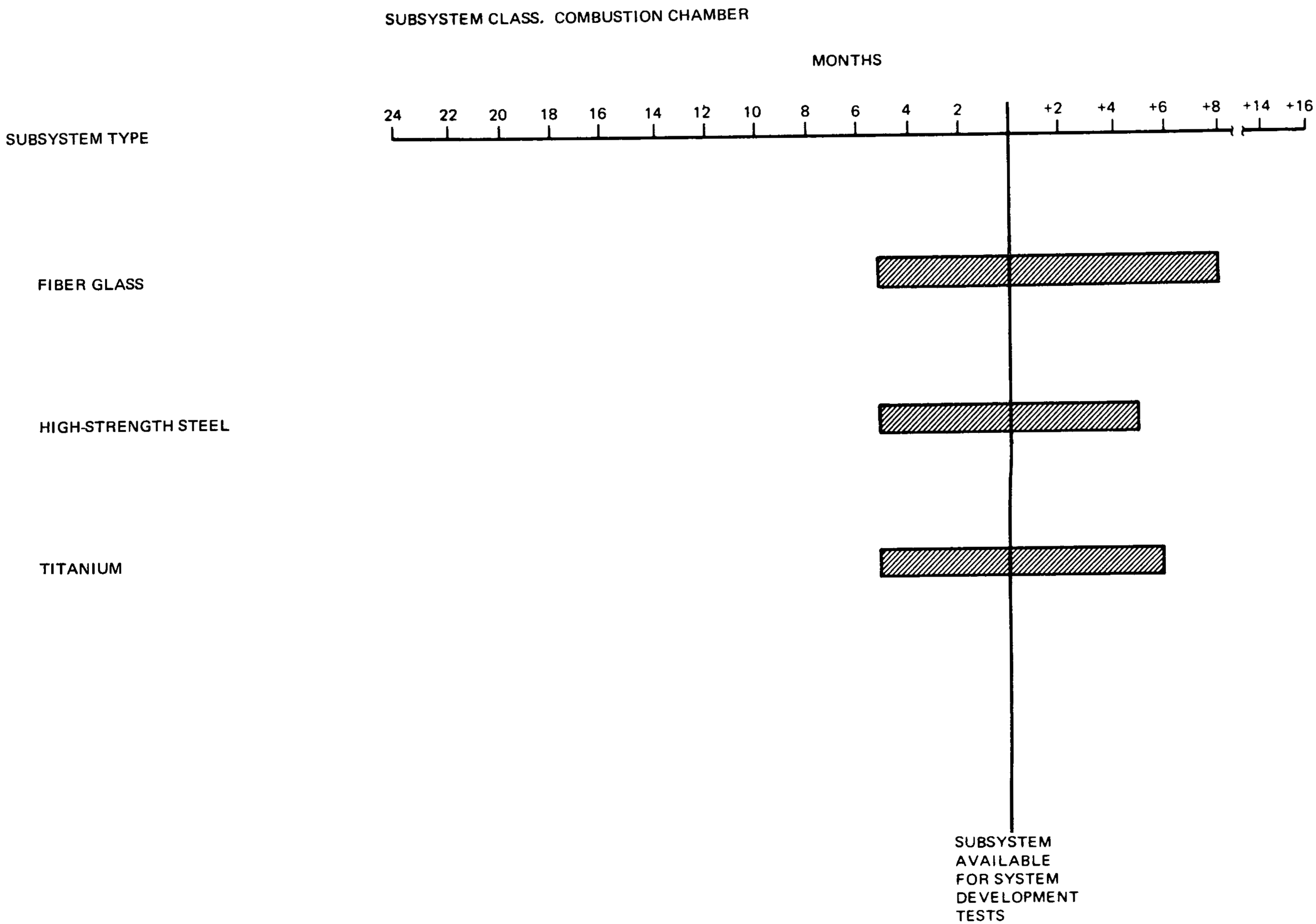


Figure 5-6 Subsystem Development Schedule -- Combustion Chamber

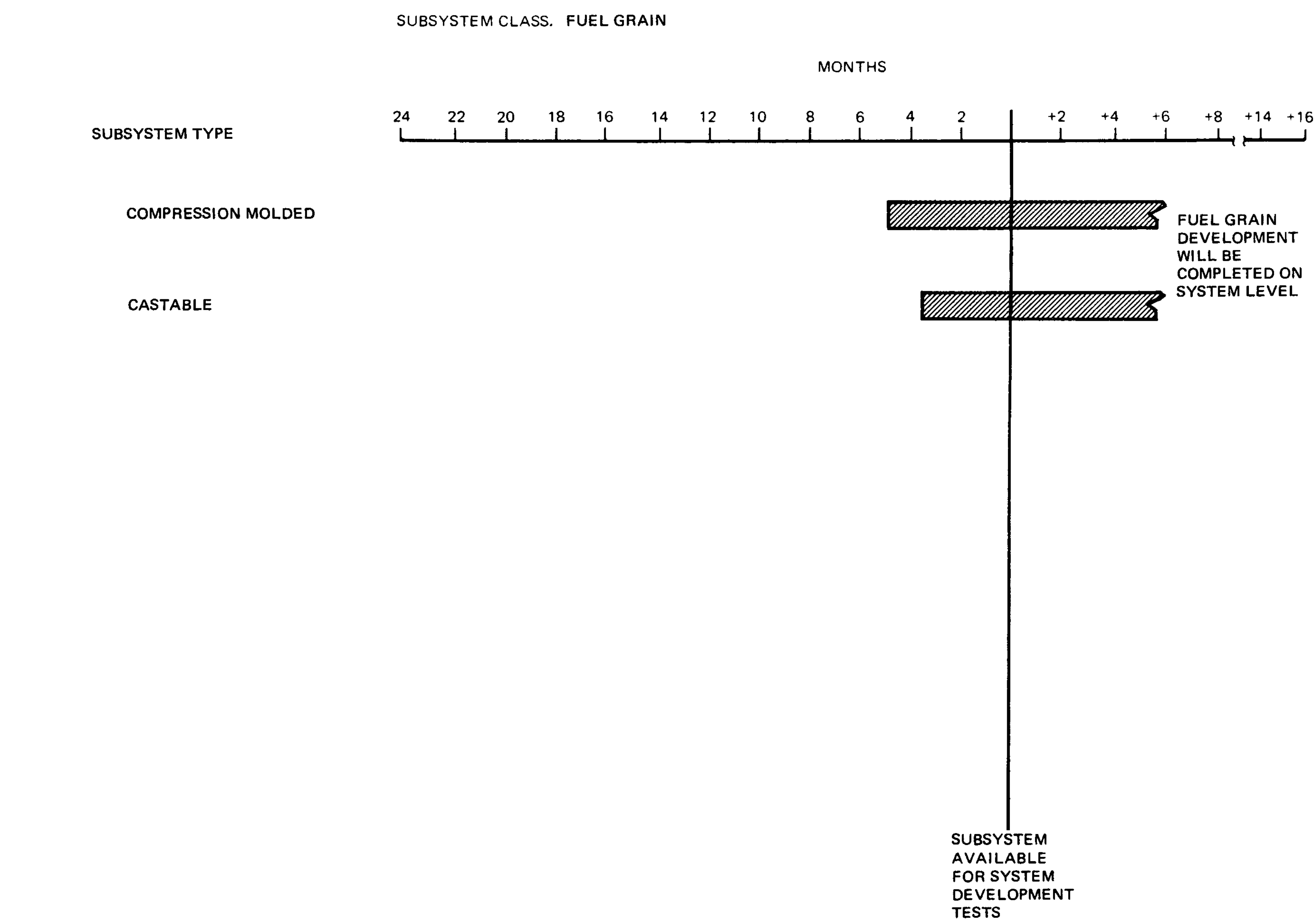


Figure 5-7 Subsystem Development Schedule -- Fuel Grain

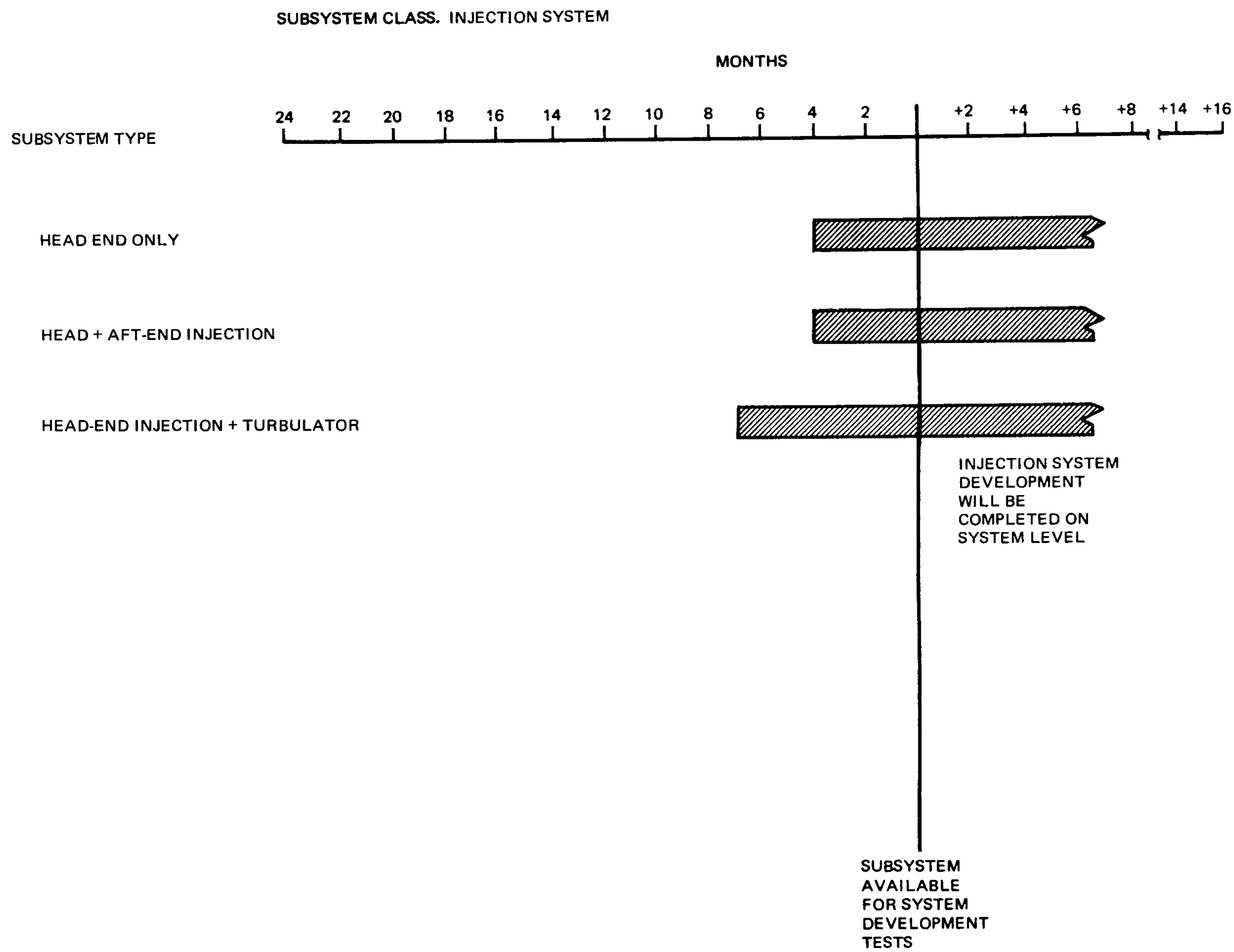


Figure 5-8 Subsystem Development Schedule -- Injection System

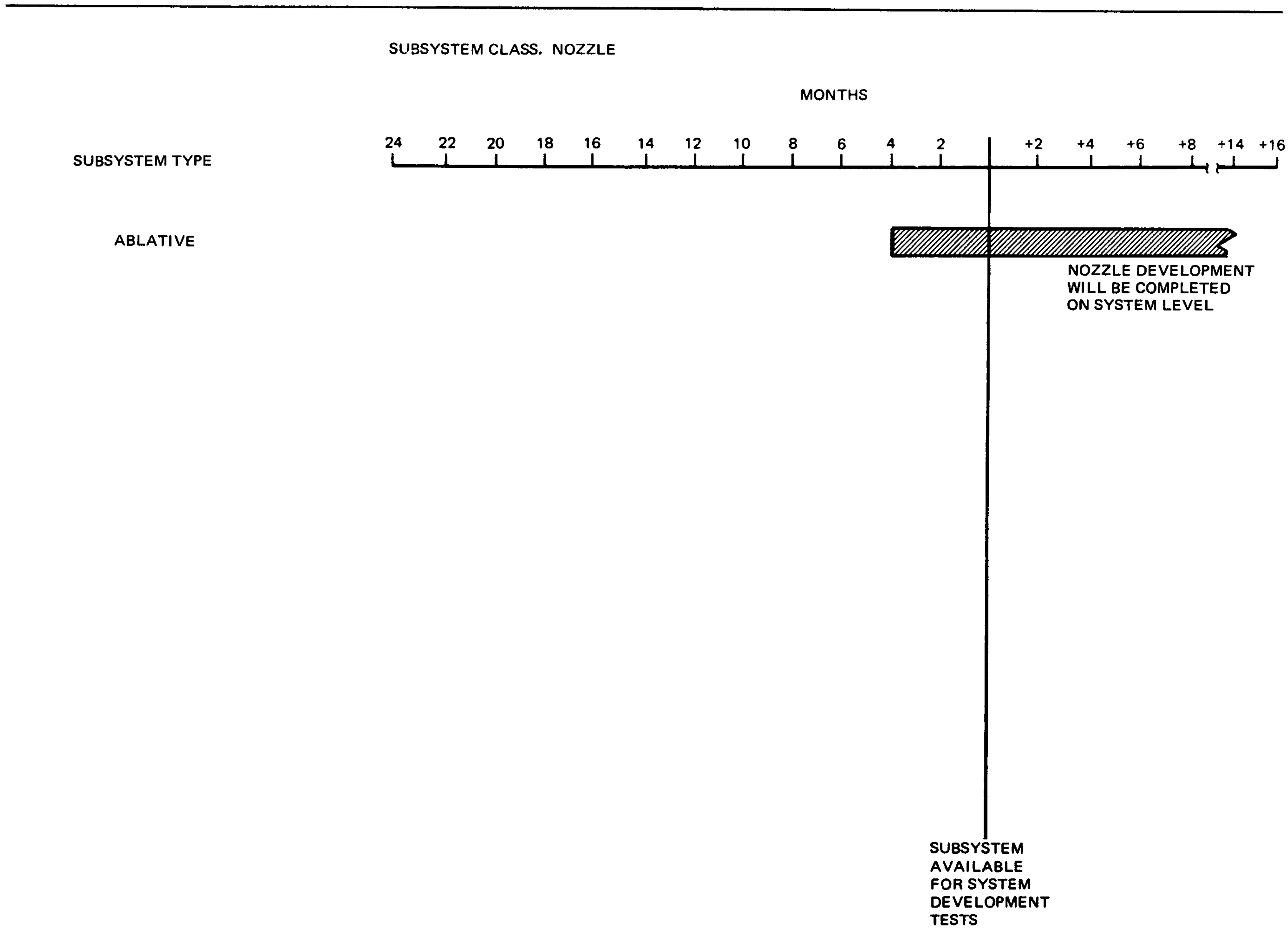


Figure 5-9 Subsystem Development Schedule -- Nozzle

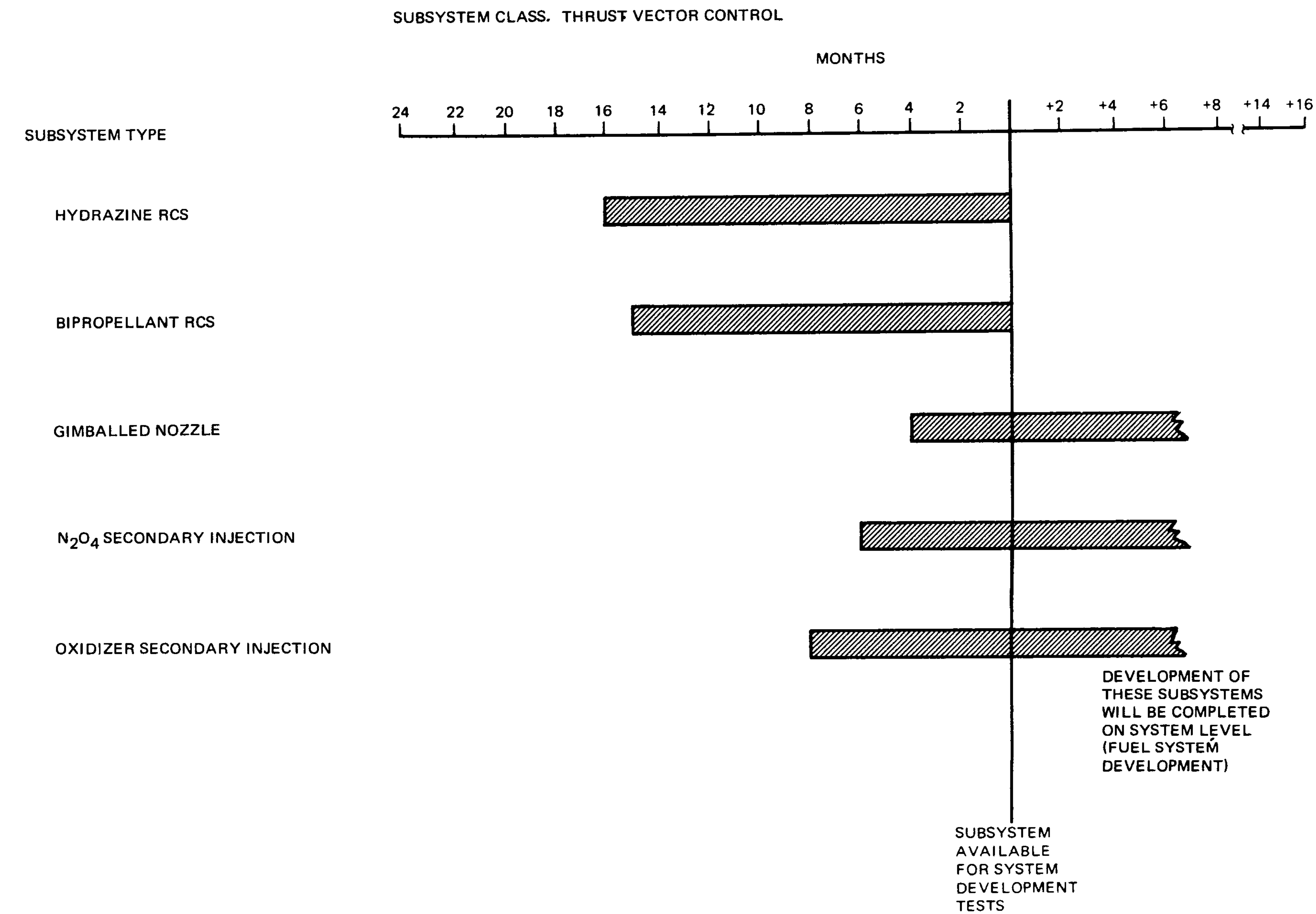


Figure 5-10 Subsystem Development Schedule -- Thrust Vector Control

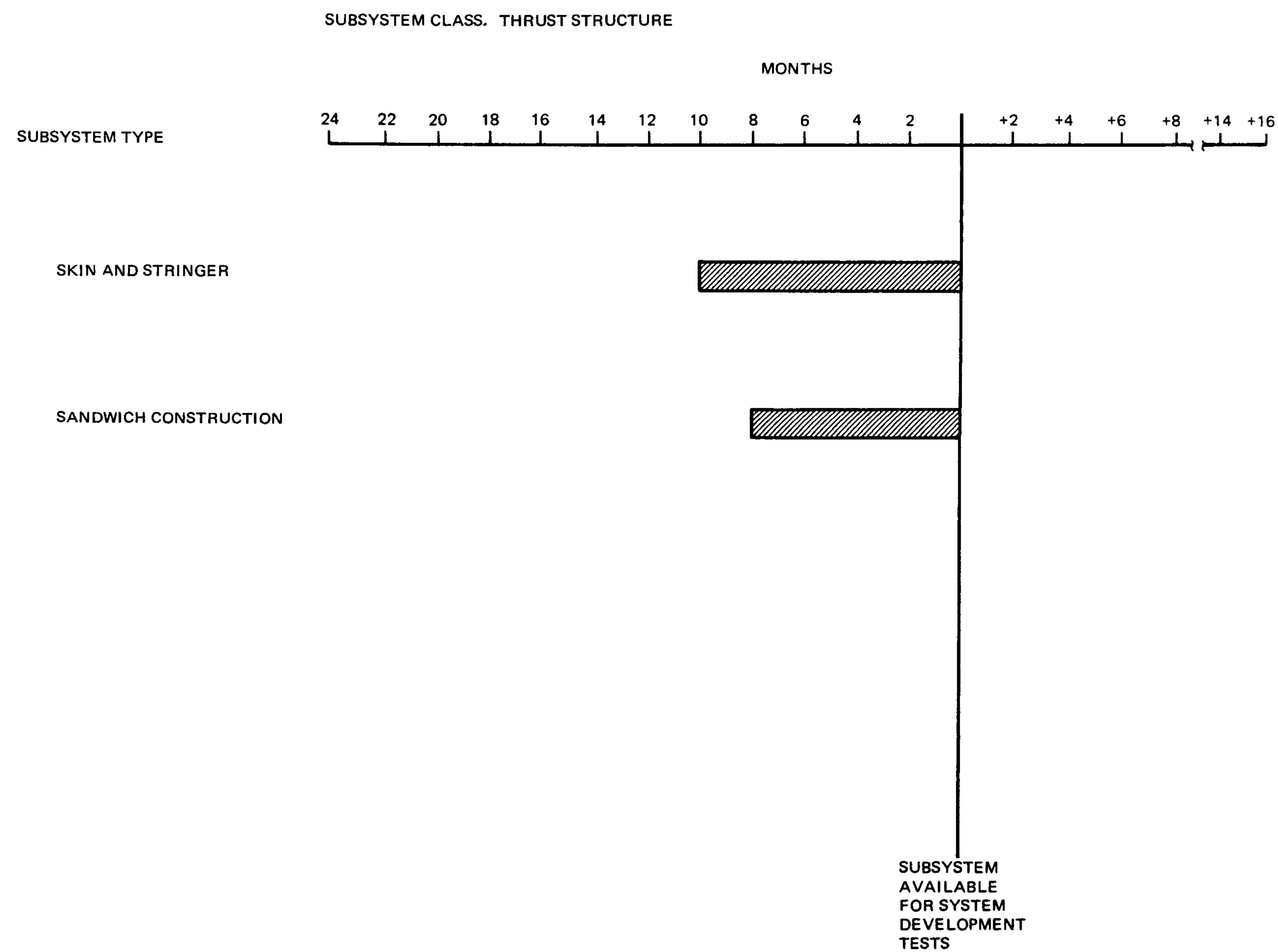


Figure 5-11 Subsystem Development Schedule -- Thrust Structure

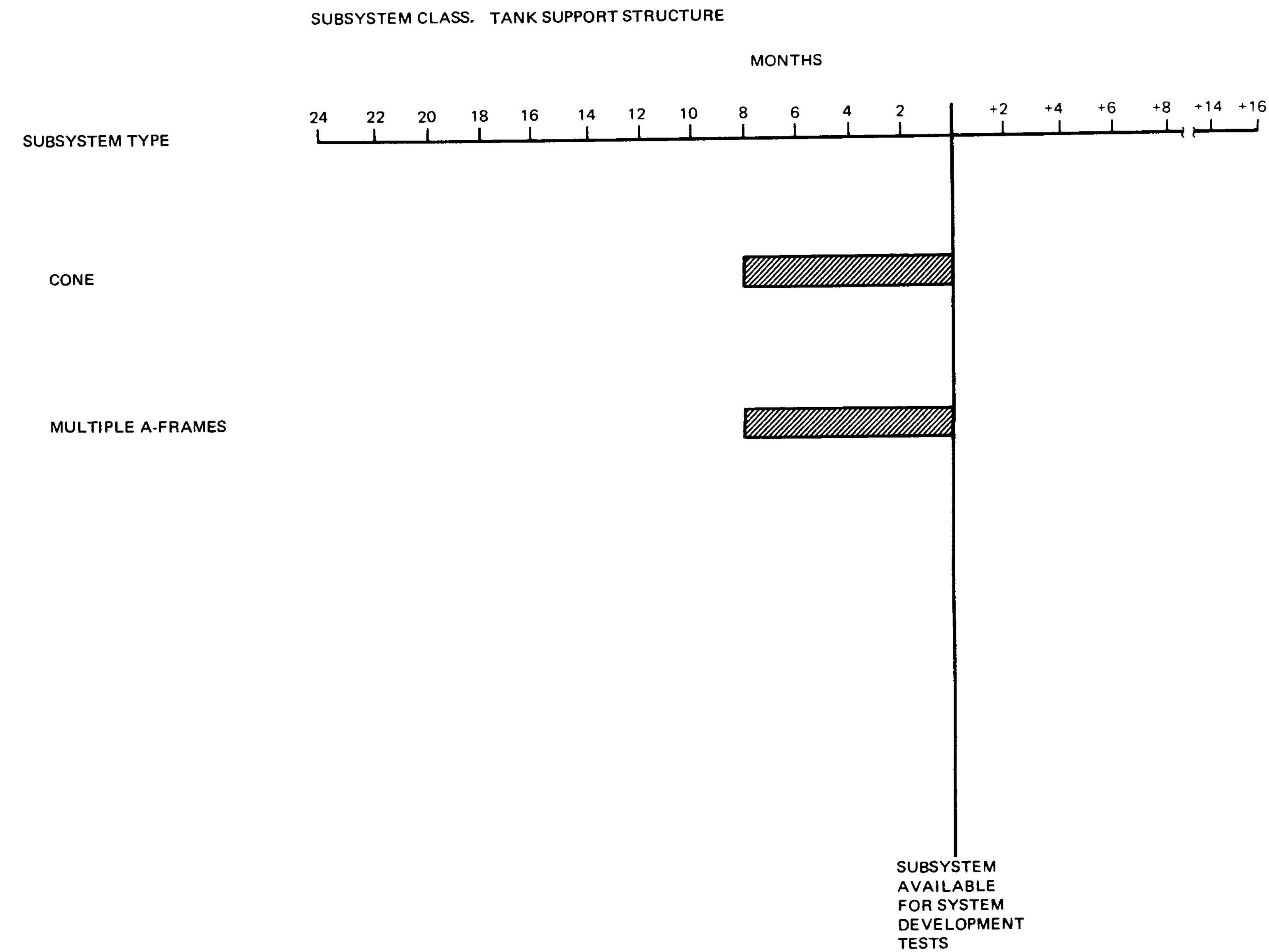


Figure 5-12 Subsystem Development Schedule -- Tank Support Structure

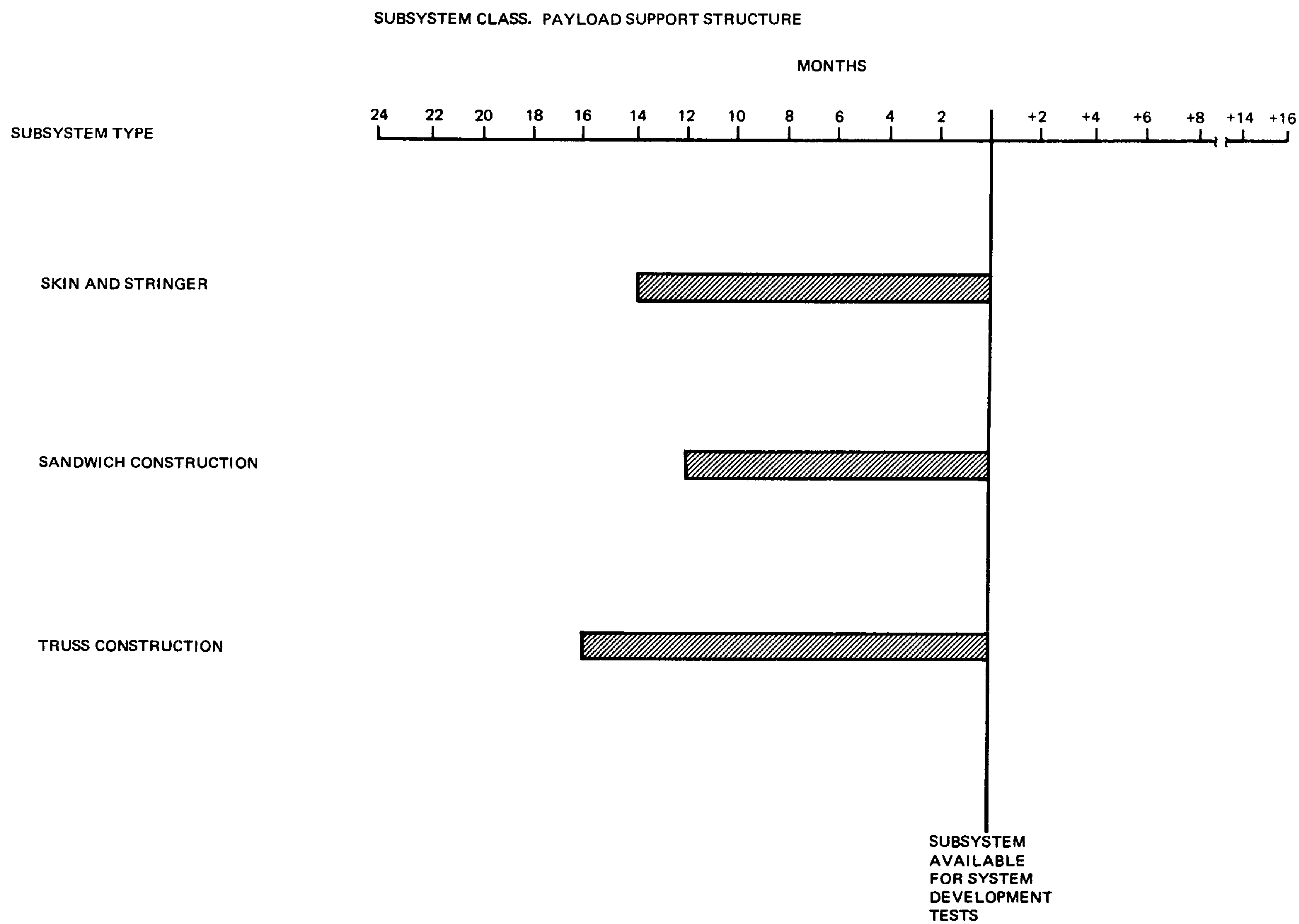


Figure 5-13 Subsystem Development Schedule -- Payload Support Structure

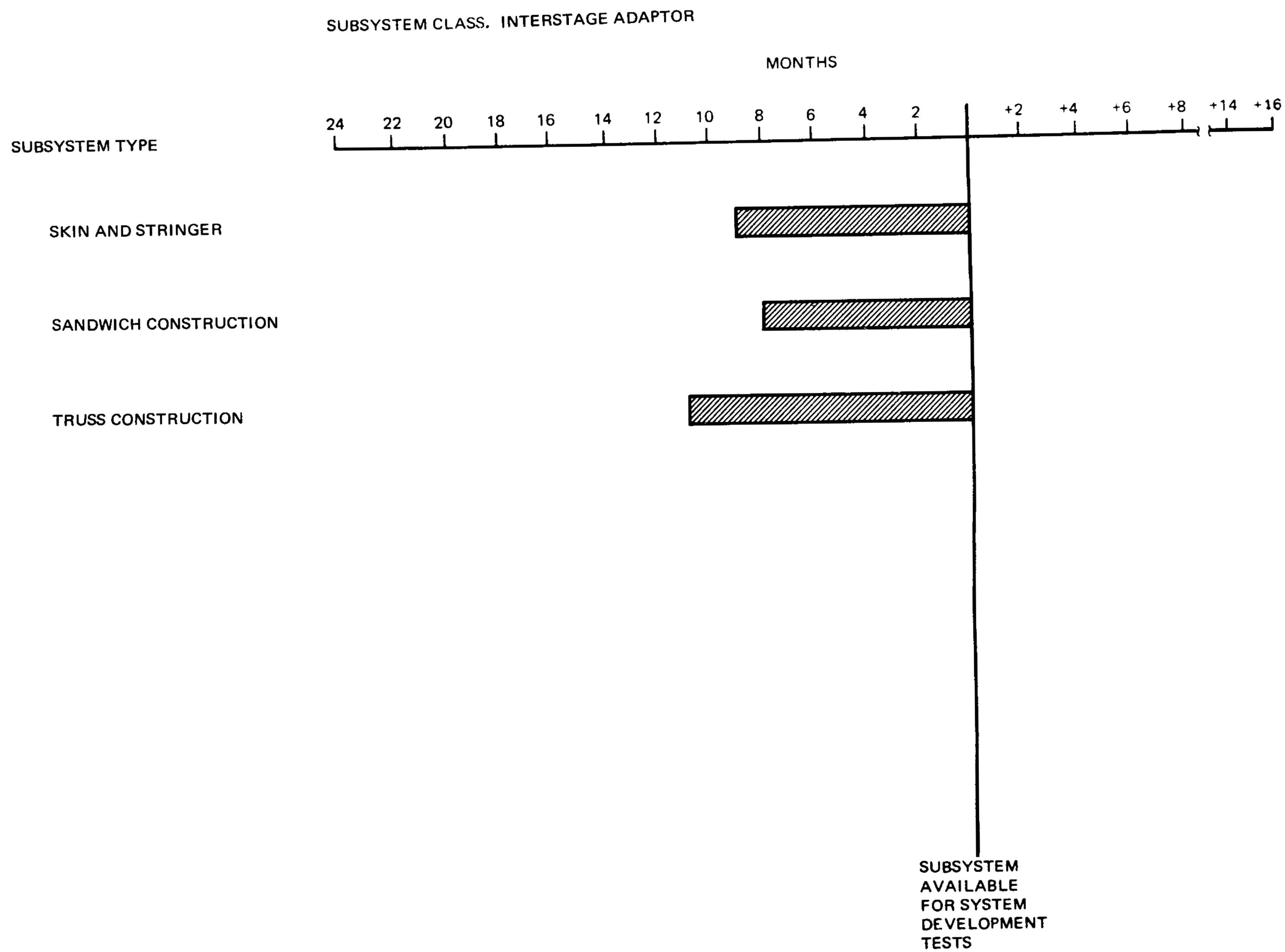


Figure 5-14 Subsystem Development Schedule -- Interstage Adaptor

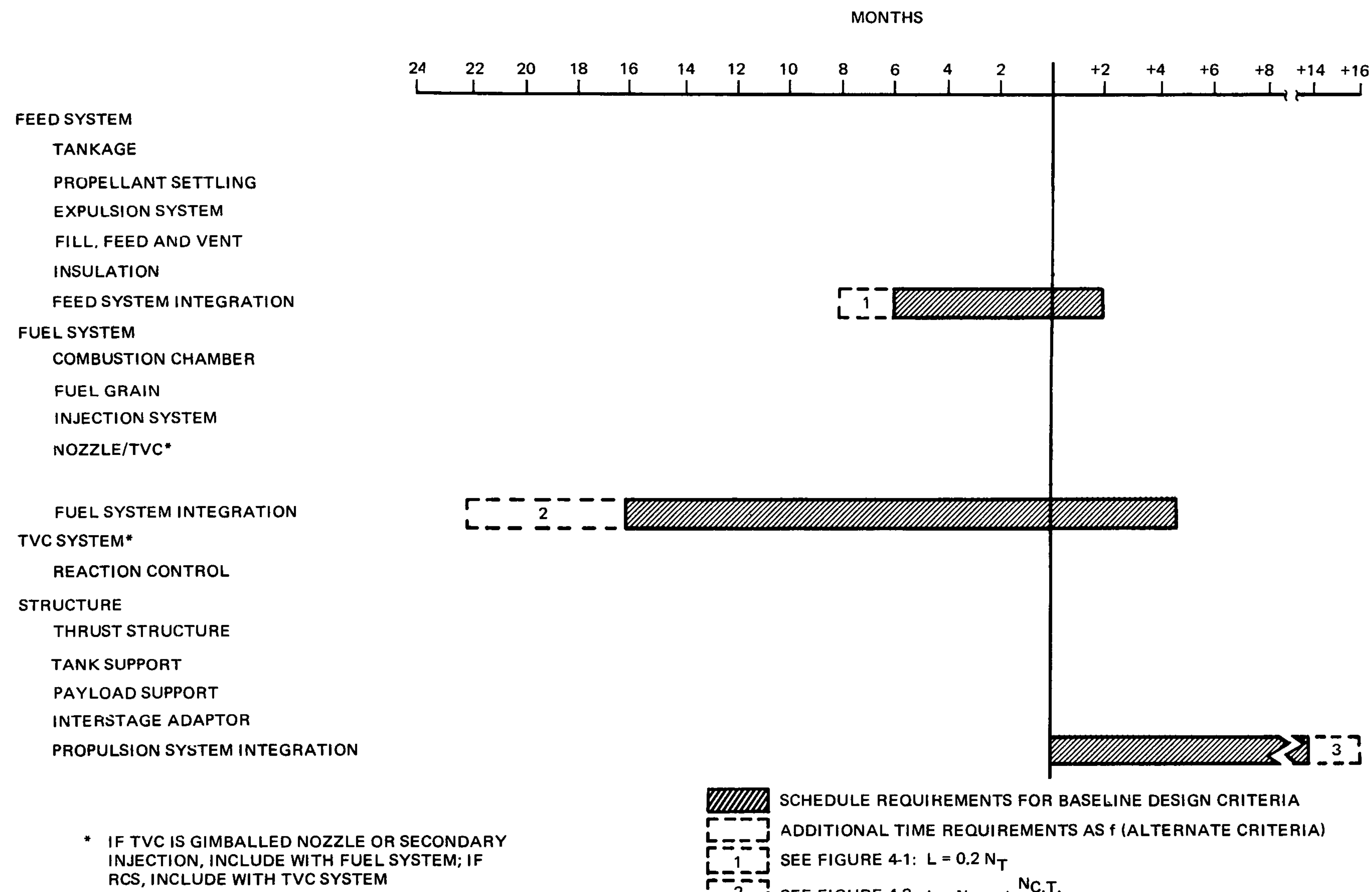


Figure 5-15 Propulsion System Integration -- Master Phasing Schedule

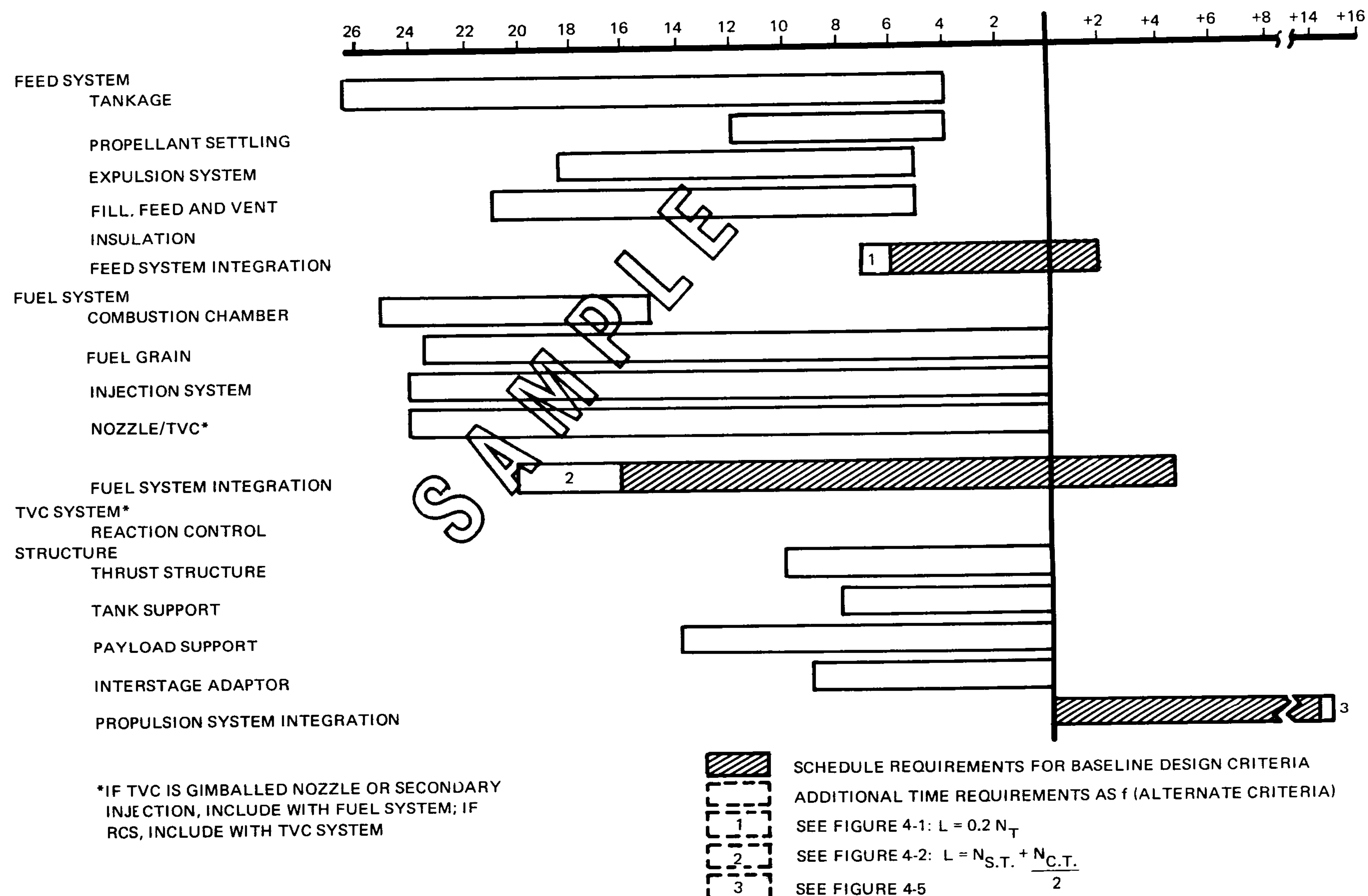


Figure 5-16. Propulsion System Integration Master Phasing Schedule